Alternative DM models in the context of galaxy formation

Caltech

FIRE

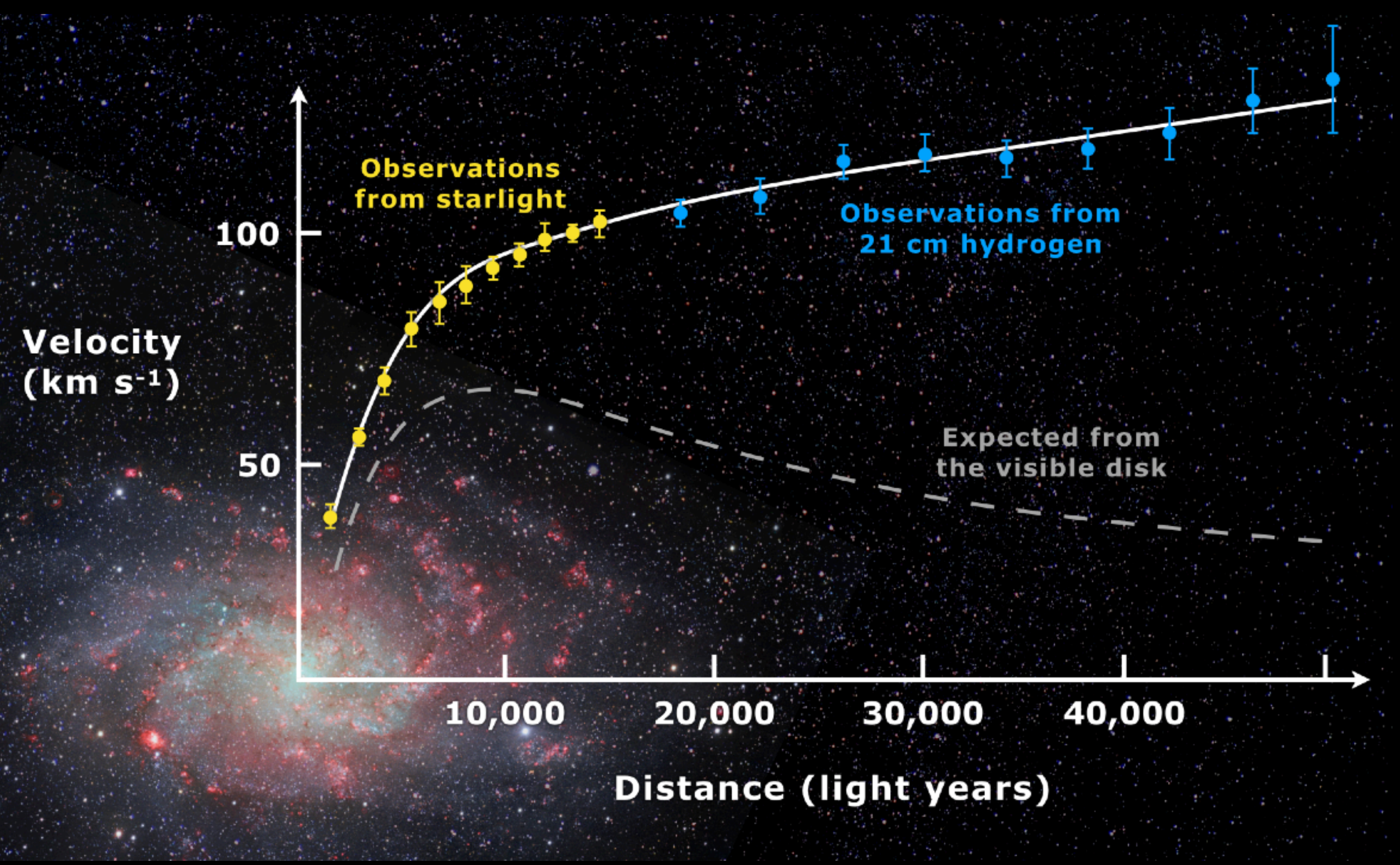
Feedback In Realistic Environments

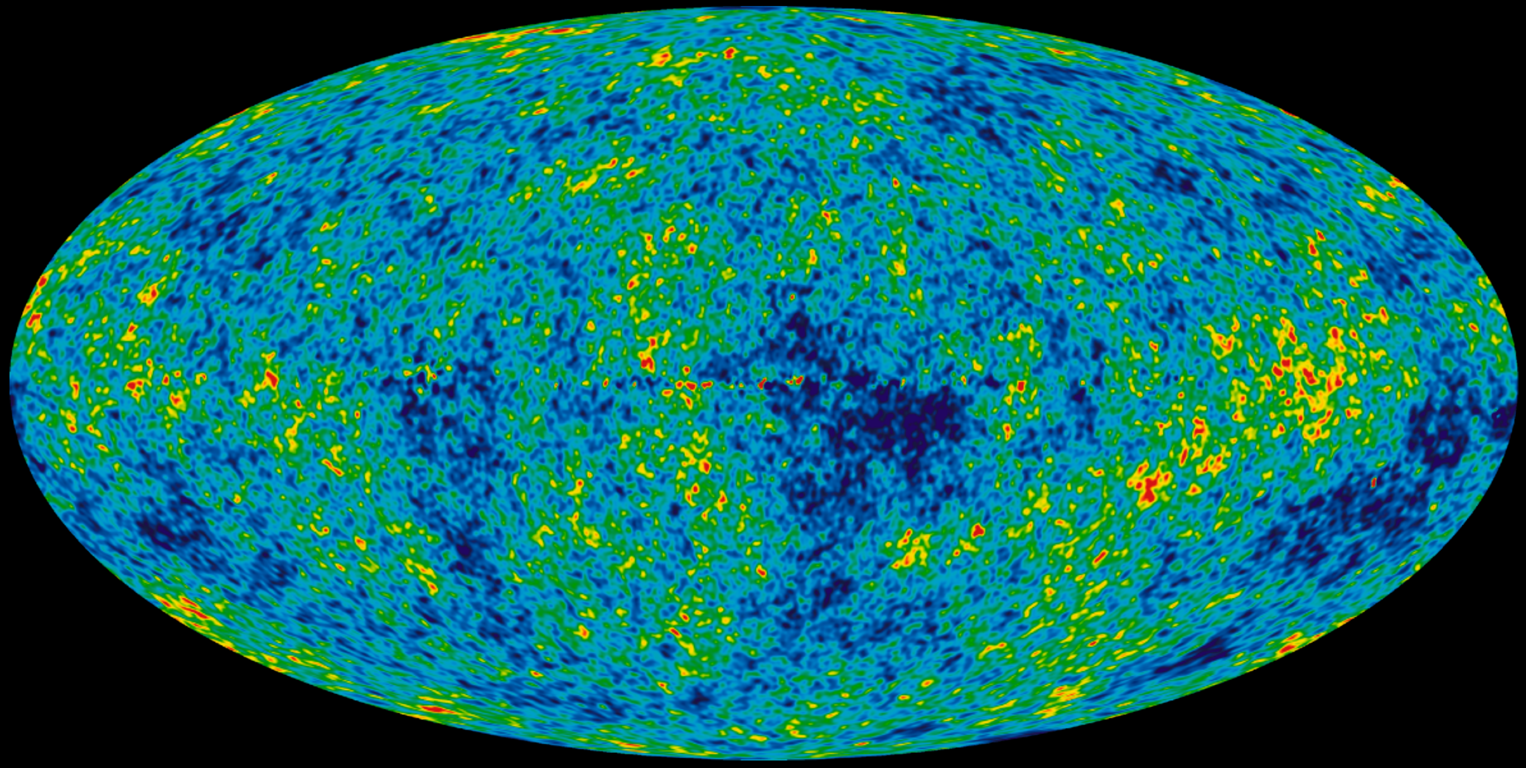
Xuejian (Jacob) Shen

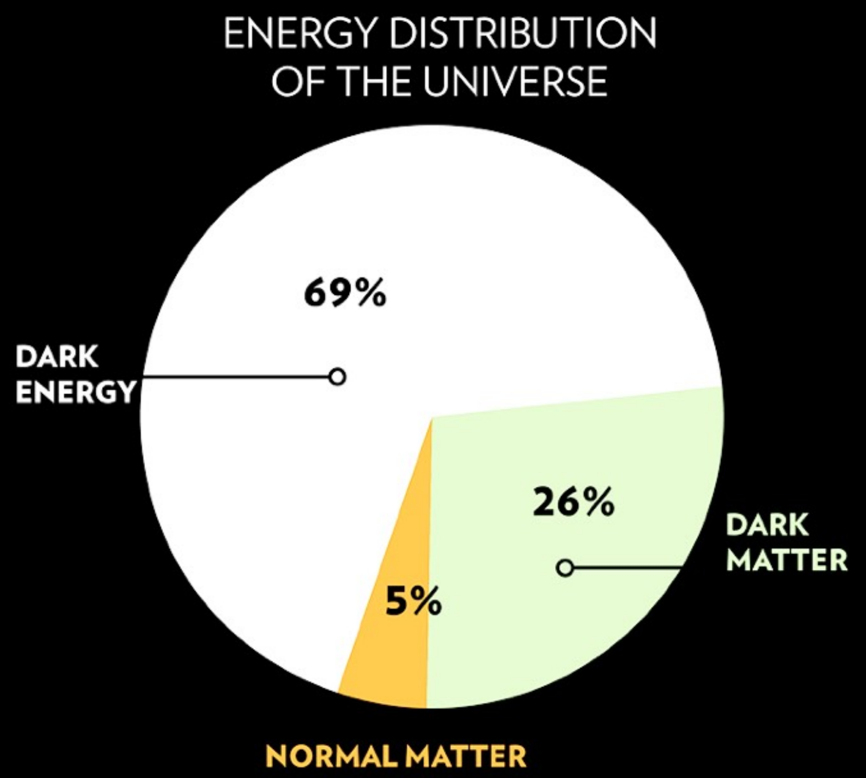
xuejianshen.github.io

Princeton Gravity Group 2022

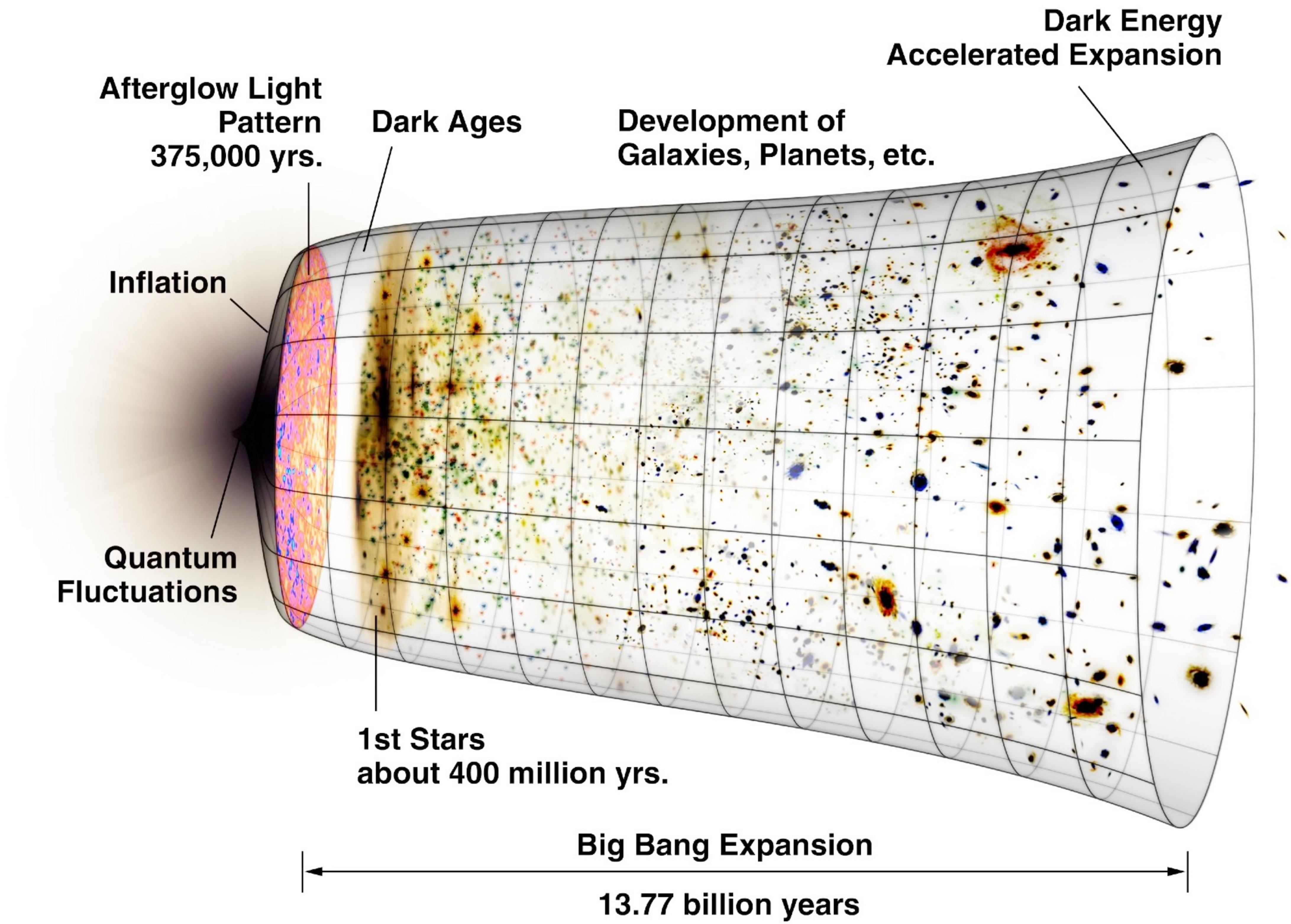
Evidences for Dark matter



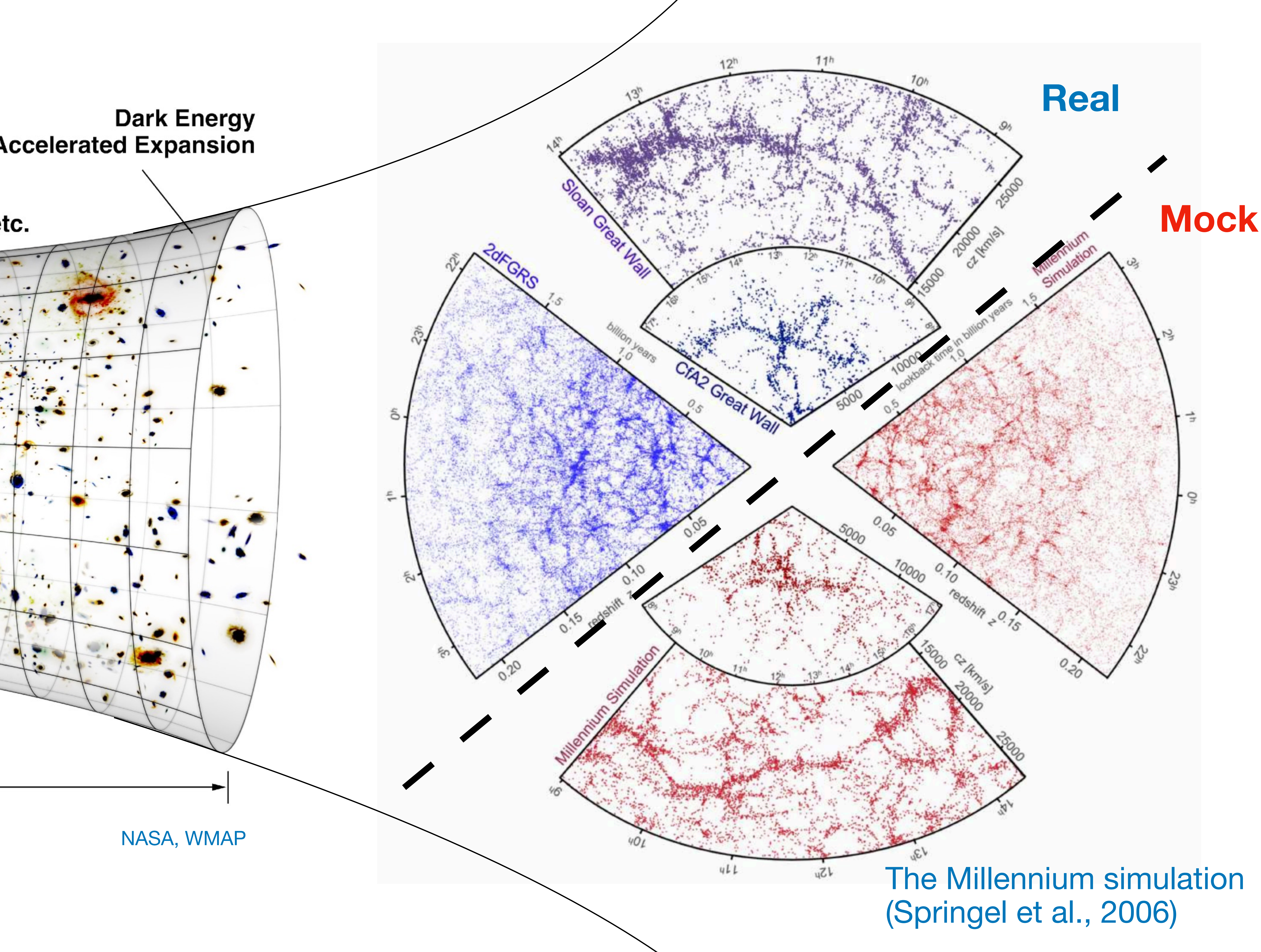




Driver for cosmic structure formation



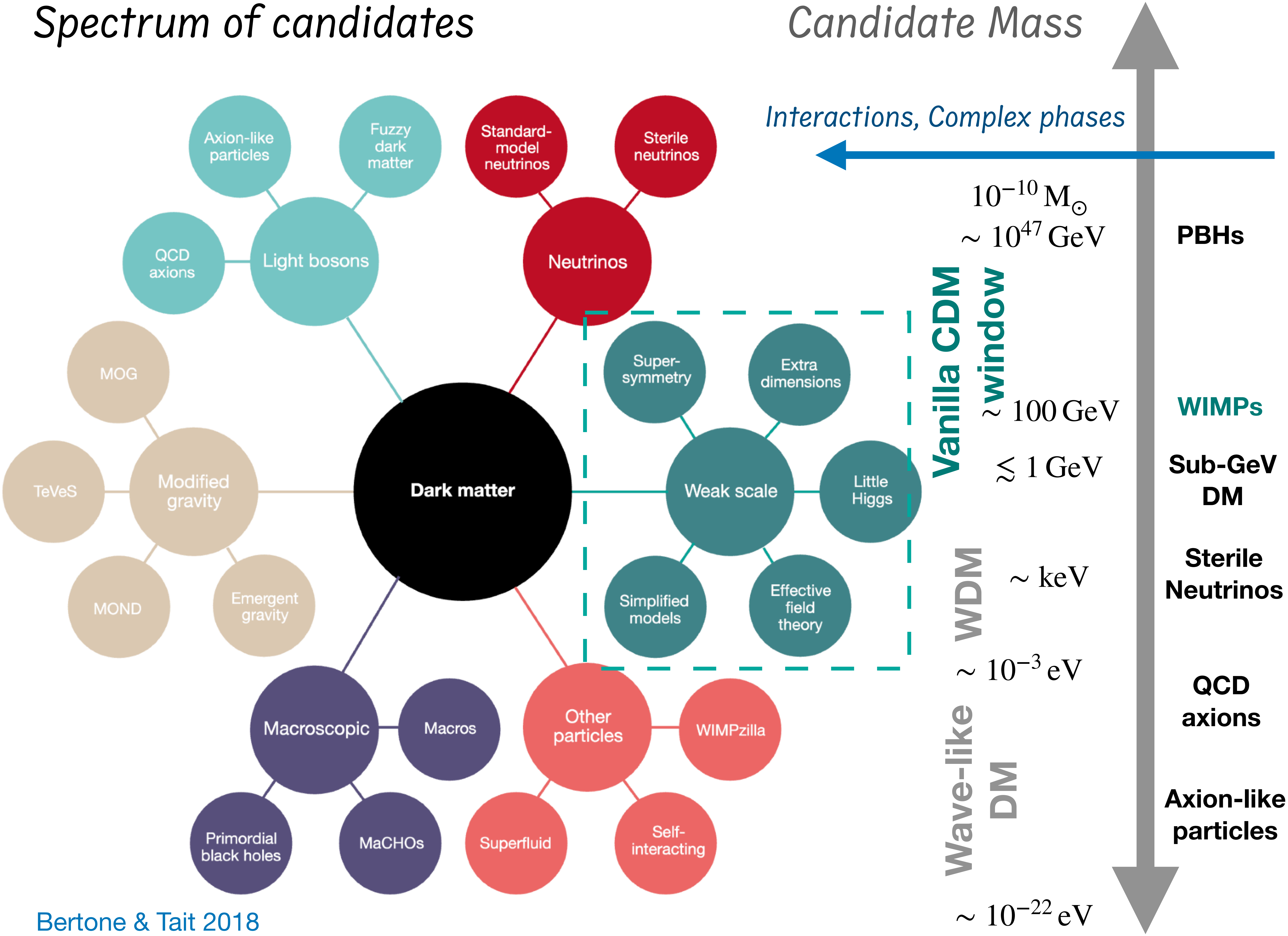
NASA, WMAP



NASA, WMAP

The Millennium simulation
(Springel et al., 2006)

Spectrum of candidates



Bertone & Tait 2018

Motivations from the small-scale issues (dwarf galaxies, $\lesssim \mathrm{kpc}$)

Local Group	Field
Missing Satellite	
Too-Big-to-Fail	e.g. Moore 1994, Oh 2011
e.g. Boylan-Kolchin et al. 2011, 2012	Core-Cusp
	Revisited: Diversity
New questions: satellite plane, ρ_c versus a_{peri} ...	e.g. Oman et al. 2015, Kaplinghat et al. 2019

Examples of alternative DM models

- WDM (e.g. sterile neutrinos)
  $m_{\mathrm{dm}} \sim \mathrm{kev}, \lambda_{\mathrm{fs}} \sim \mathrm{kpc}$
  lower satellite abundances
- SIDM (e.g. a hidden sectors)
  elastic, $\sigma_{\mathrm{m}} \sim 1\,\mathrm{cm}^2/g$
  kpc-size thermalized cores
- Fuzzy DM
  (e.g. axion-like particles)
  $m_{\mathrm{dm}} \sim 10^{22}\,\mathrm{eV}, \lambda_{dB} \sim \mathrm{kpc}$
  kpc-size soliton cores,
  quantum pressure suppression

Motivations from observational/experimental evidences

Stable WIMP-like candidates in beyond-standard-model theories

$m_\chi \sim 100\,\mathrm{GeV}$

Existence of particle DM

The "WIMP" miracle

CDM behavior on large-scale

$\mathcal{O}(1)\,\mathrm{kpc}$

WIMP/CDM alternatives

Small-scale puzzles

Null detection of WIMPs

i) specific implication to solve the small-scale issues

ii) models that tend to make dwarfs "less dense"

Theoretical

- Too many degrees-of-freedom
- candidate mass: 80 orders of magnitude

Empirical/Observational /Experimental

- Subject to interpretation
- Evolving as we have better understanding of the baryonic astrophysical processes

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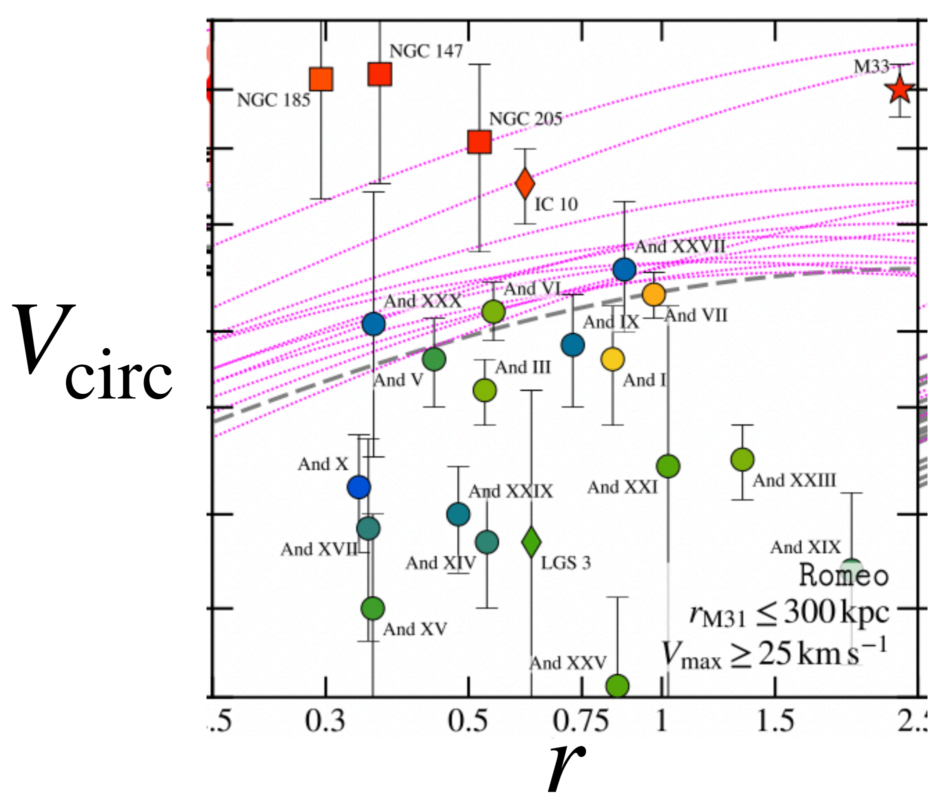
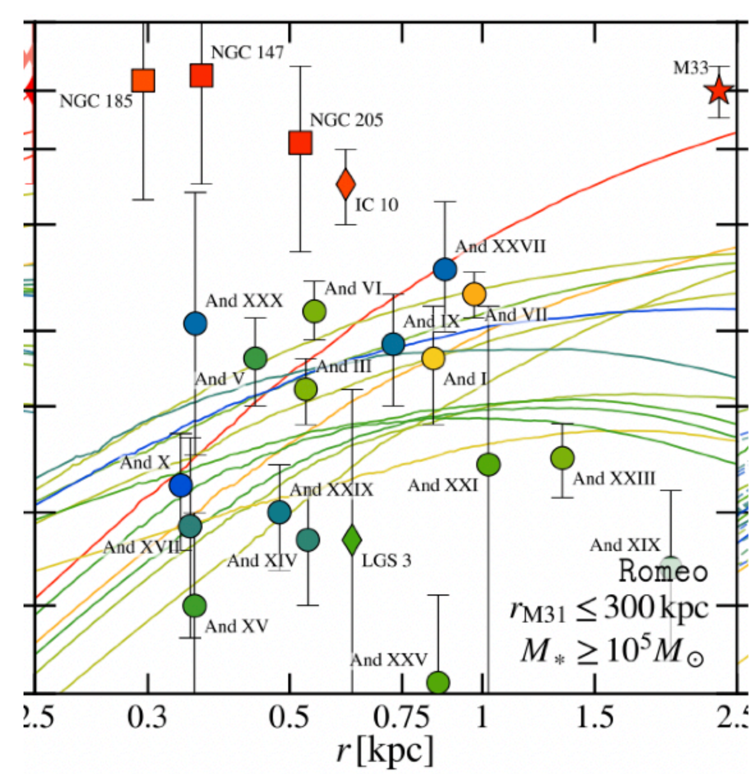
e.g. Simulated systems too dense?



Baryonic feedback creates cores?

ELVIS
Garrison-Kimmel et al. 2018

Not enough dense systems instead?



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Some generic beyond-standard-model theories $\longrightarrow$ Cosmological/Astrophysical phenomenology

Motivations from observational/experimental evidences

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- Too many degrees-of-freedom
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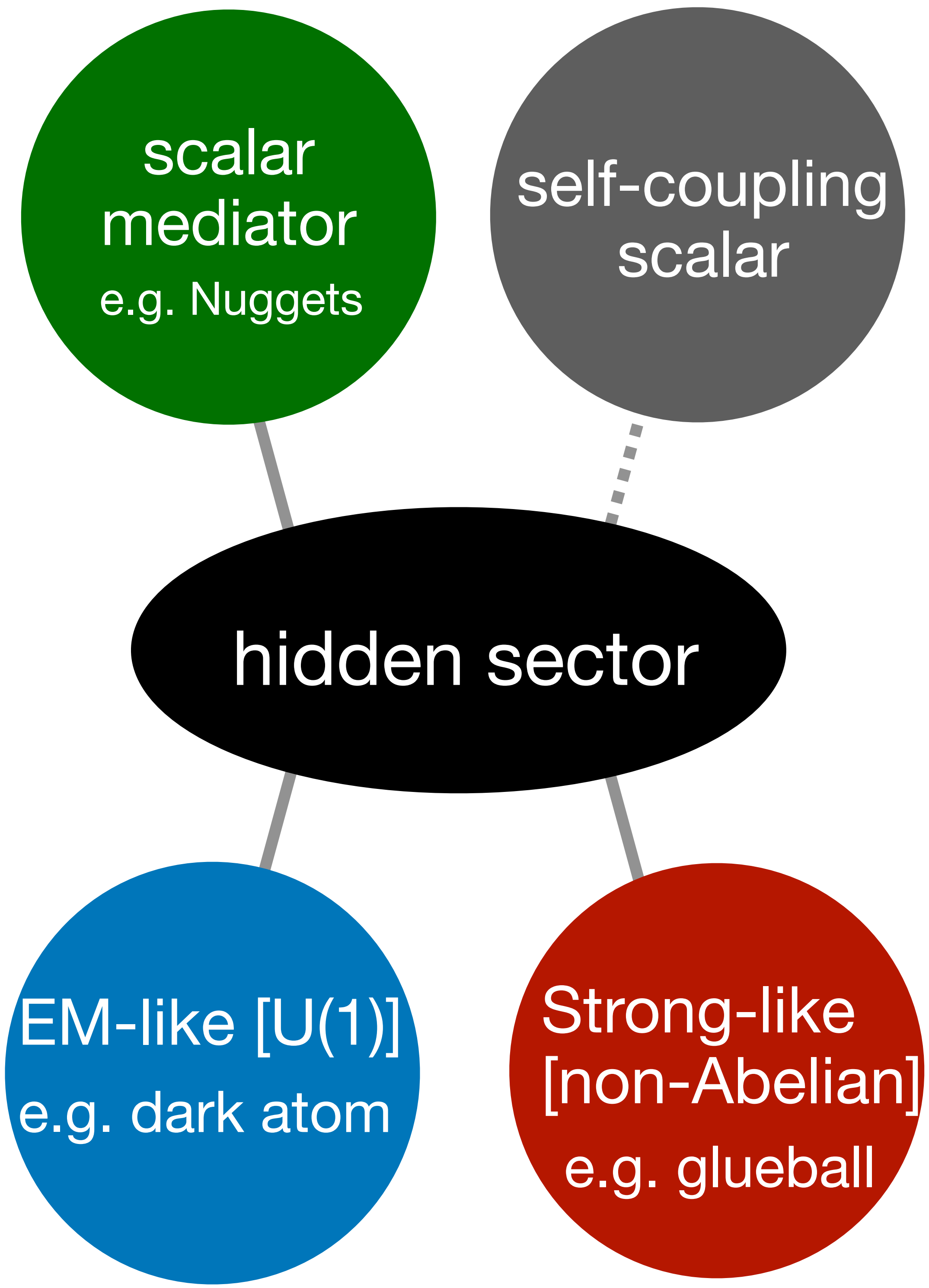
Some generic beyond-standard-model theories → Cosmological/Astrophysical phenomenology

- DM with dissipative self-interactions
- Post-inflationary QCD axions

SIDM – Hidden Sector DM

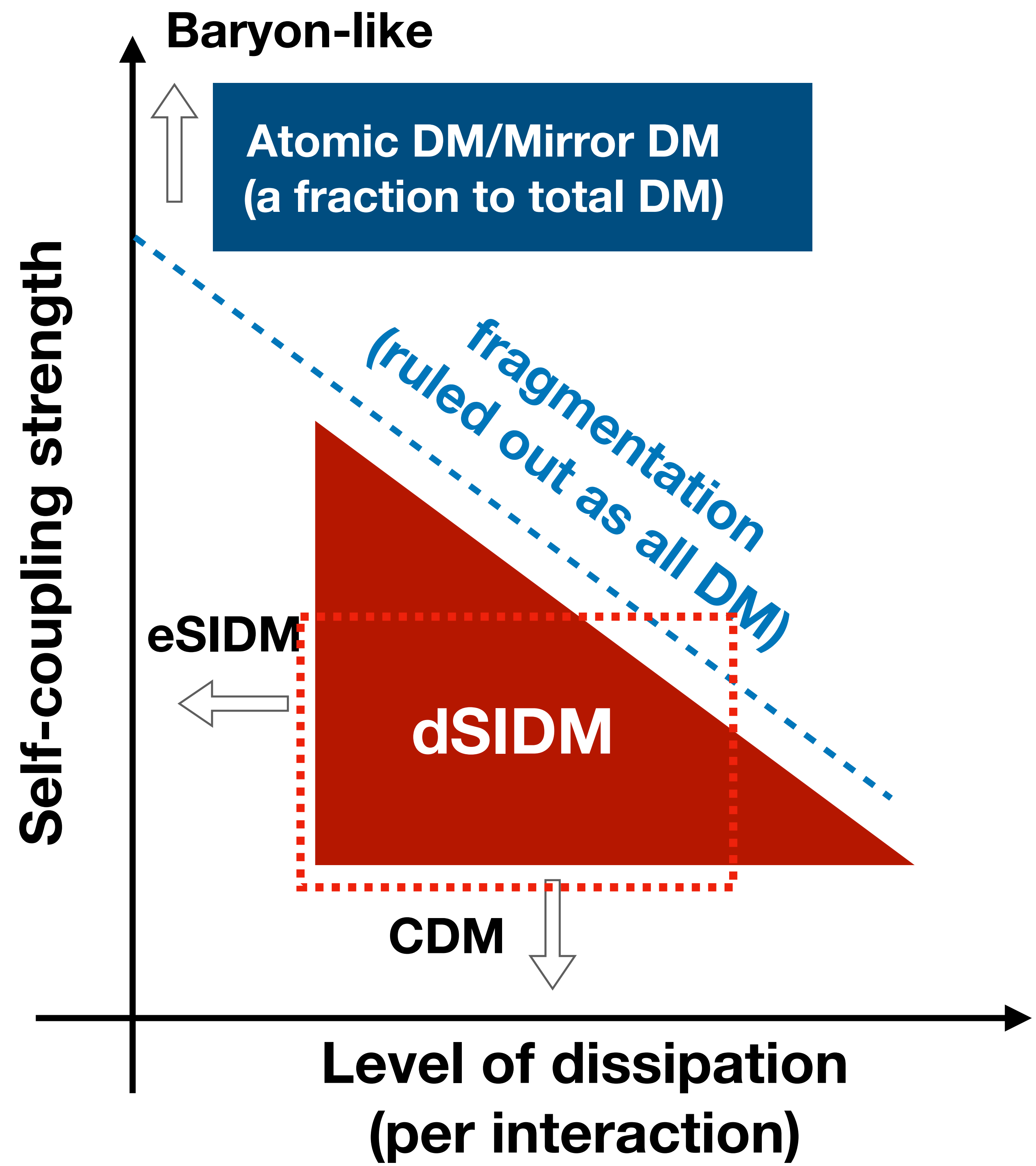
symmetry, mediator type



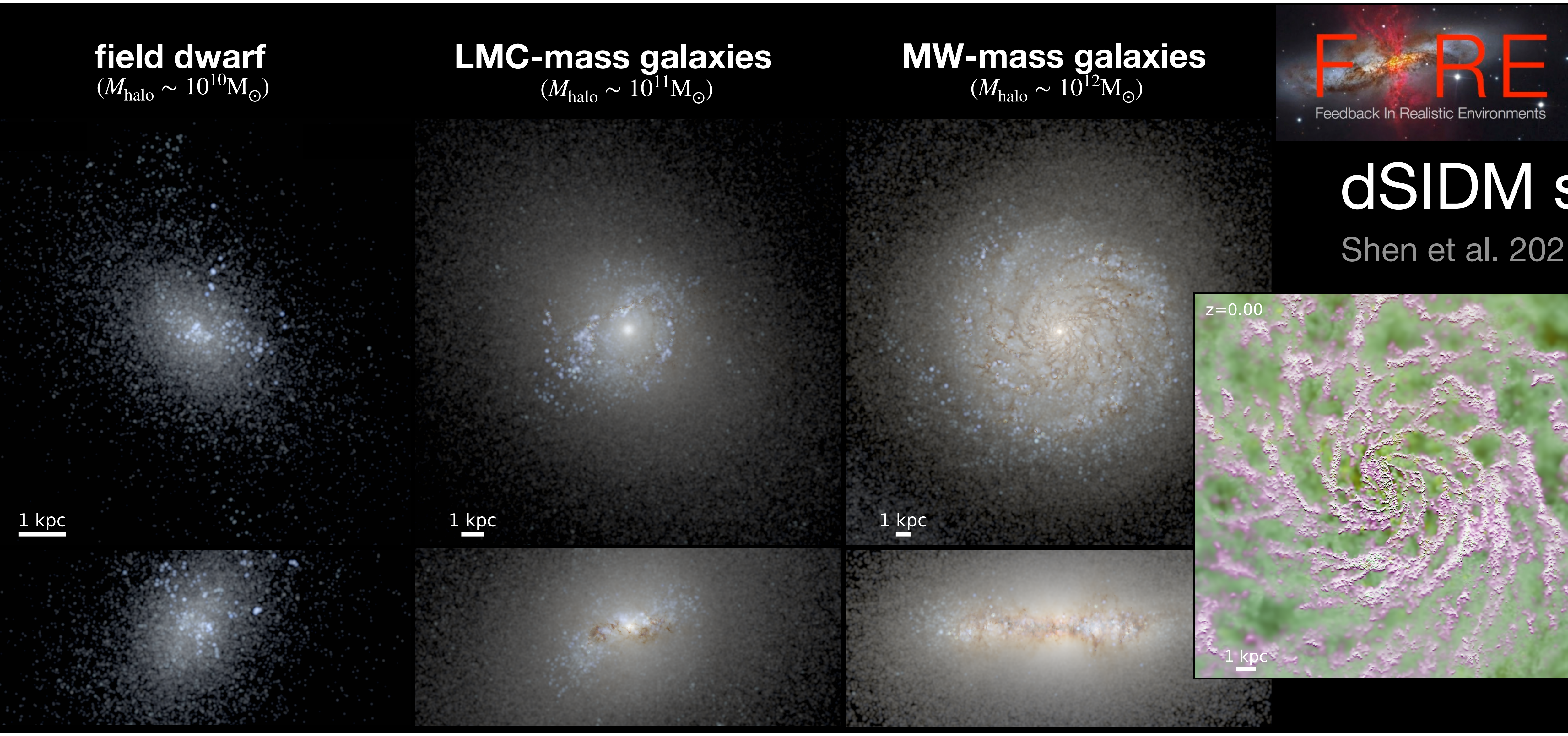
bound states, composites -> inelastic interactions

A simple parameterization:

corners of the parameter space that is not “obviously" ruled-out



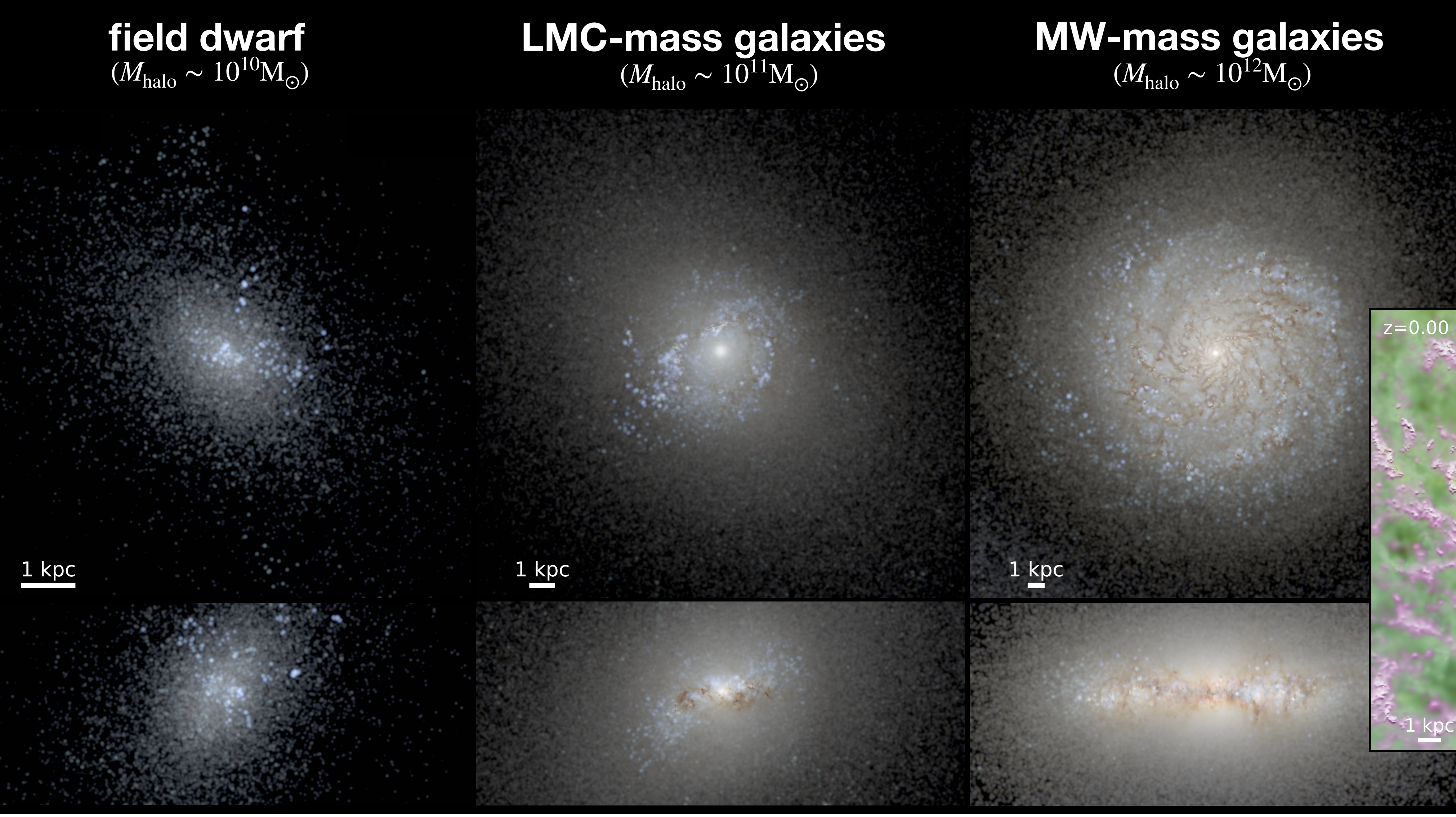
Cosmological Hydro Zoom-in Simulations



FIRE
Feedback In Realistic Environments

dSIDM suite

Shen et al. 2021, 2022



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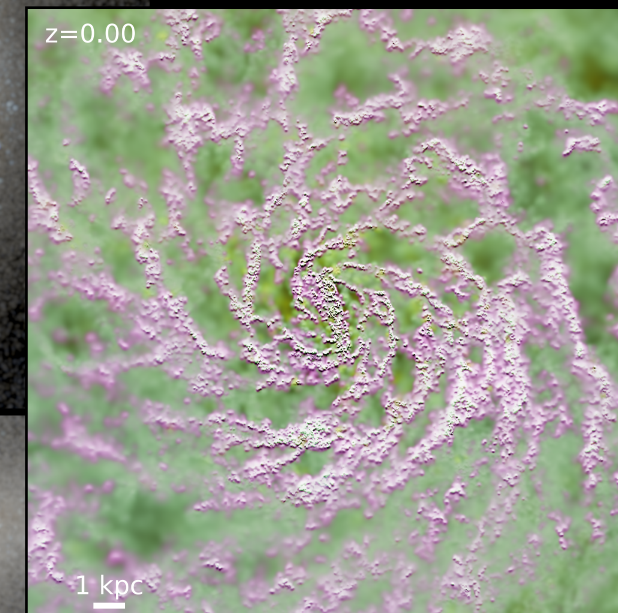


GIZMO

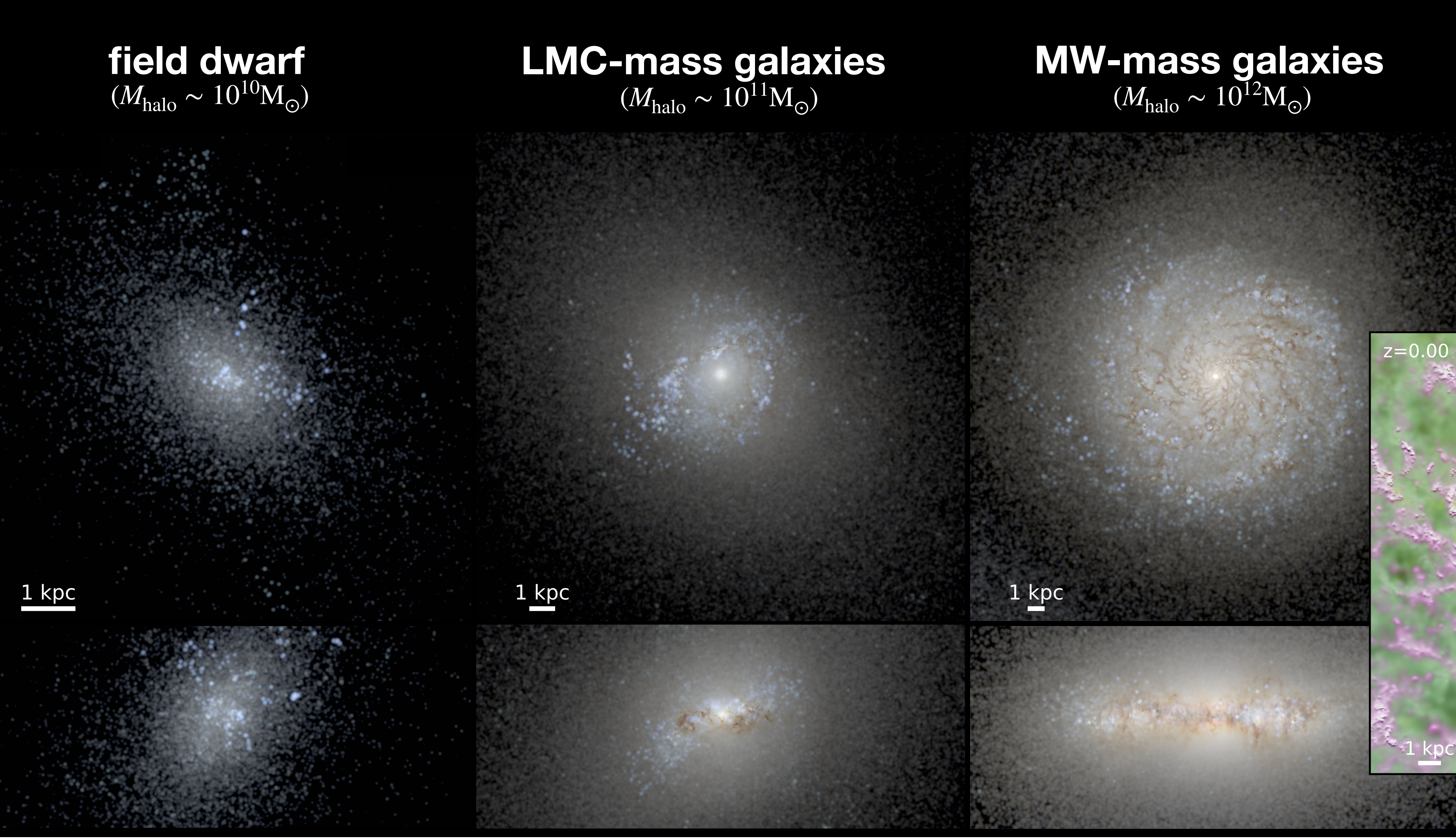
Hopkins 2015

Gravity: Tree-PM
Hydro : Quasi-Lagrangian
Meshless-Finite-Mass

FIRE-2 galaxy formation physics

- gas cooling & heating
- resolved multiphase ISM
- star formation
- feedback (supernovae/stellar winds, thermal/mechanical/radiative)
- etc.

Hopkins et al. 2018



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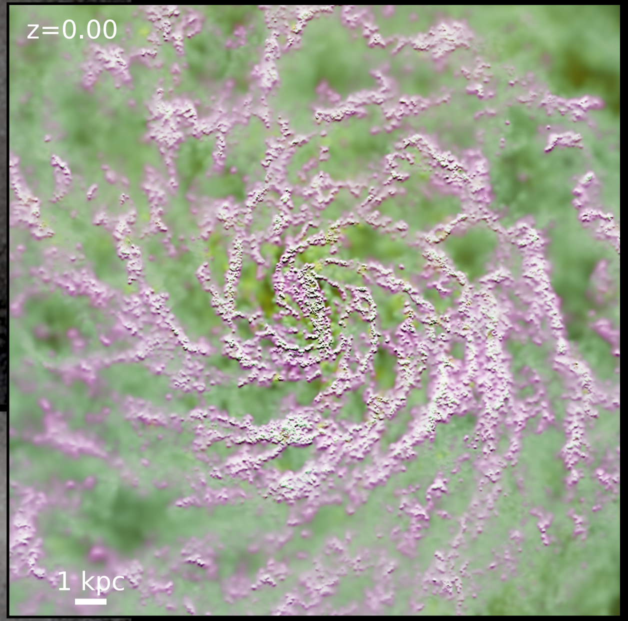
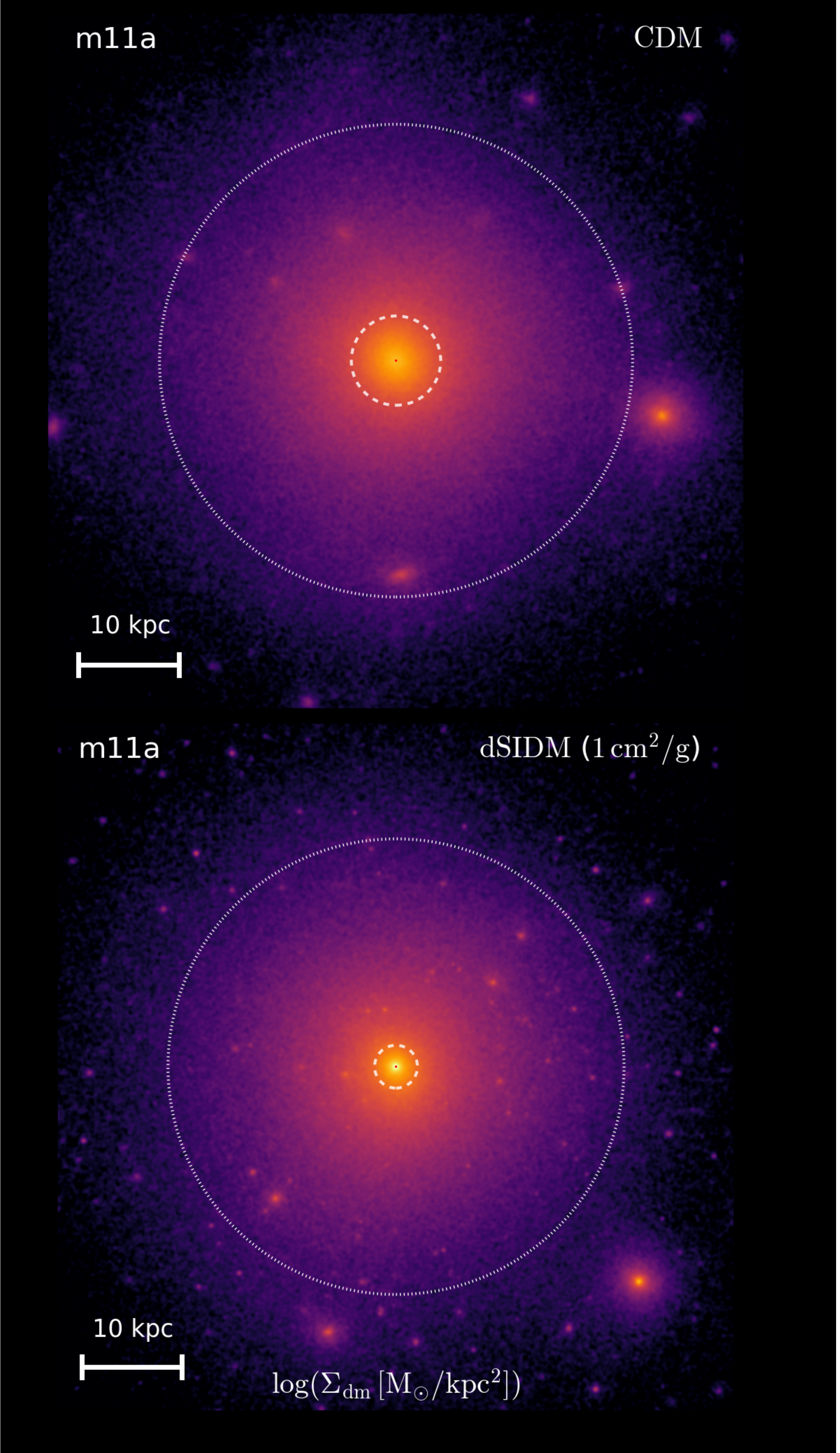


Dissipative DM self-interaction:

- scattering between discrete patches of DM in phase space (DM particles in sims.) in a Monte-Carlo fashion e.g. Rocha et al. 2013

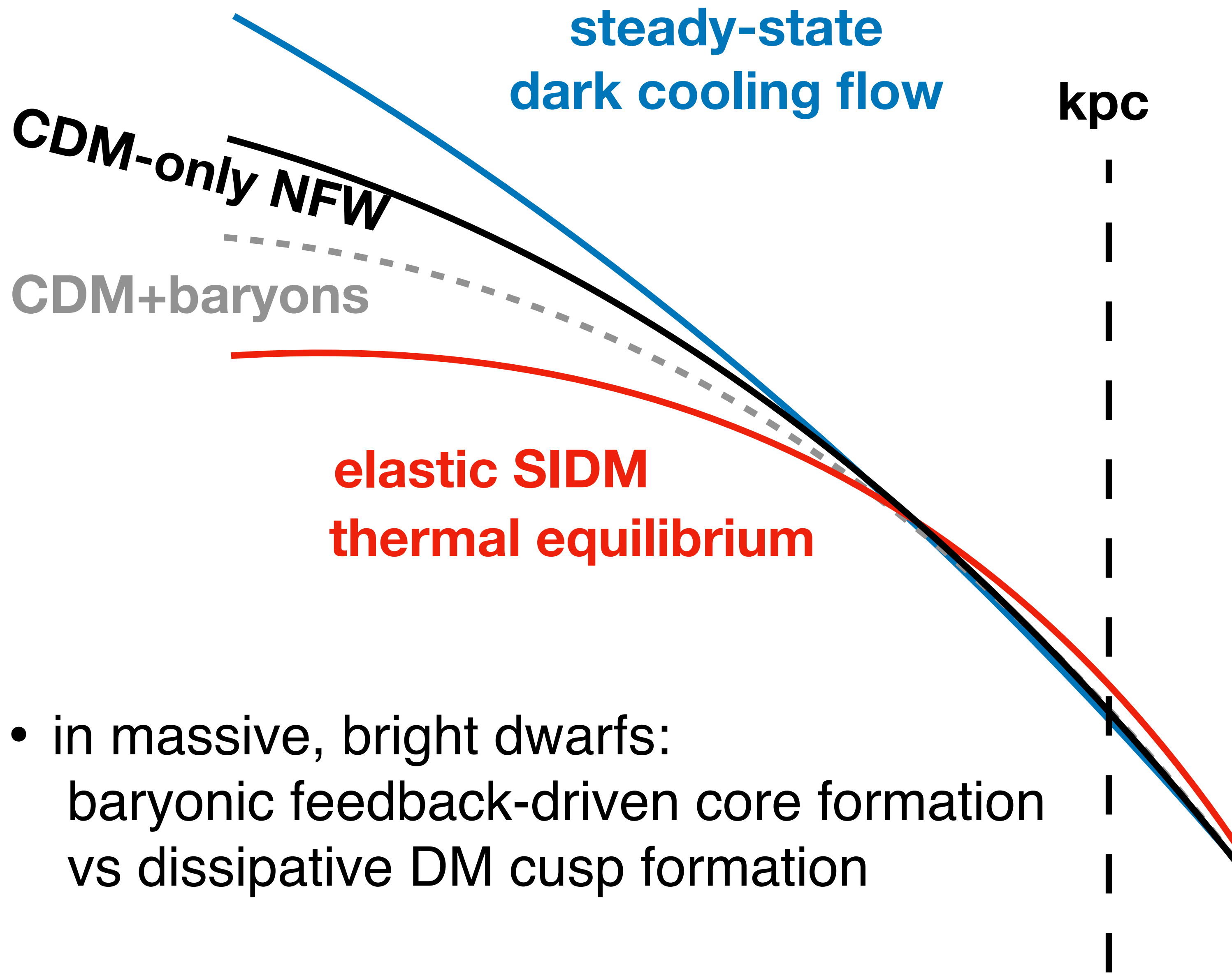
- a constant fractional ($f_{\rm diss}$) energy loss during each DM-DM self-interaction in the c.o.m. frame



Structure of dwarfs in dSIDM

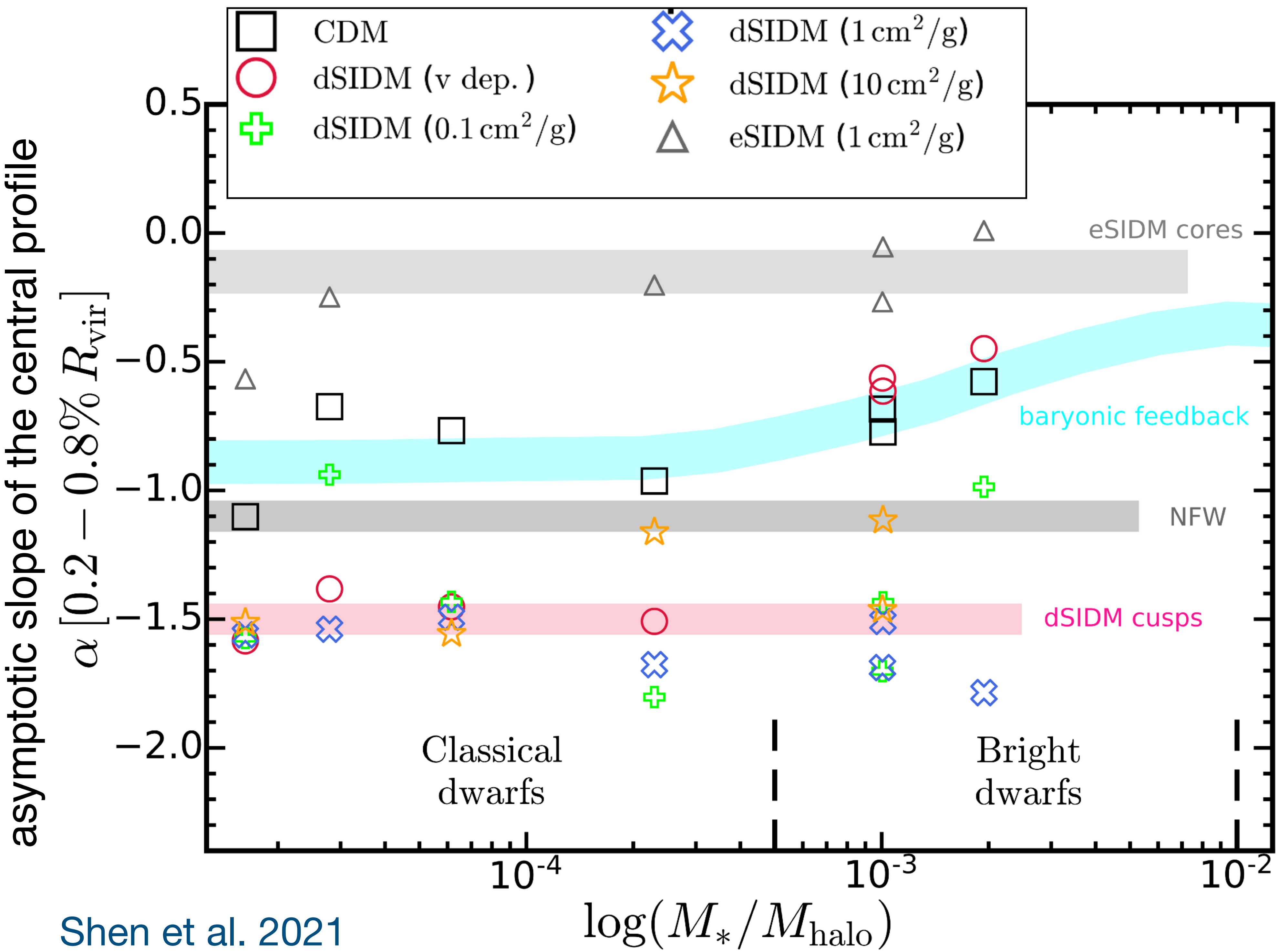
- Dark cusps, $\rho(r) \sim r^{-1.5\sim1.6}$, formed when

  $(\sigma/m)_{\rm eff} \gtrsim 0.1\,\mathrm{cm^2}/g, f_{\rm diss} \sim 0.5 \quad (t_{\rm ff} \ll t_{\rm cool} \lesssim t_{\rm H})$



- in massive, bright dwarfs:
  baryonic feedback-driven core formation
  vs dissipative DM cusp formation

Structure of dwarfs in dSIDM



➡ eSIDM cores

➡ **baryonic feedback**

➡ **NFW**
collisionless CDM

➡ **dSIDM cusps**
increasing scatter driven by baryonic feedback

Shen et al. 2021

→ more massive dwarfs typically have larger $M_*/M_{\rm halo}$

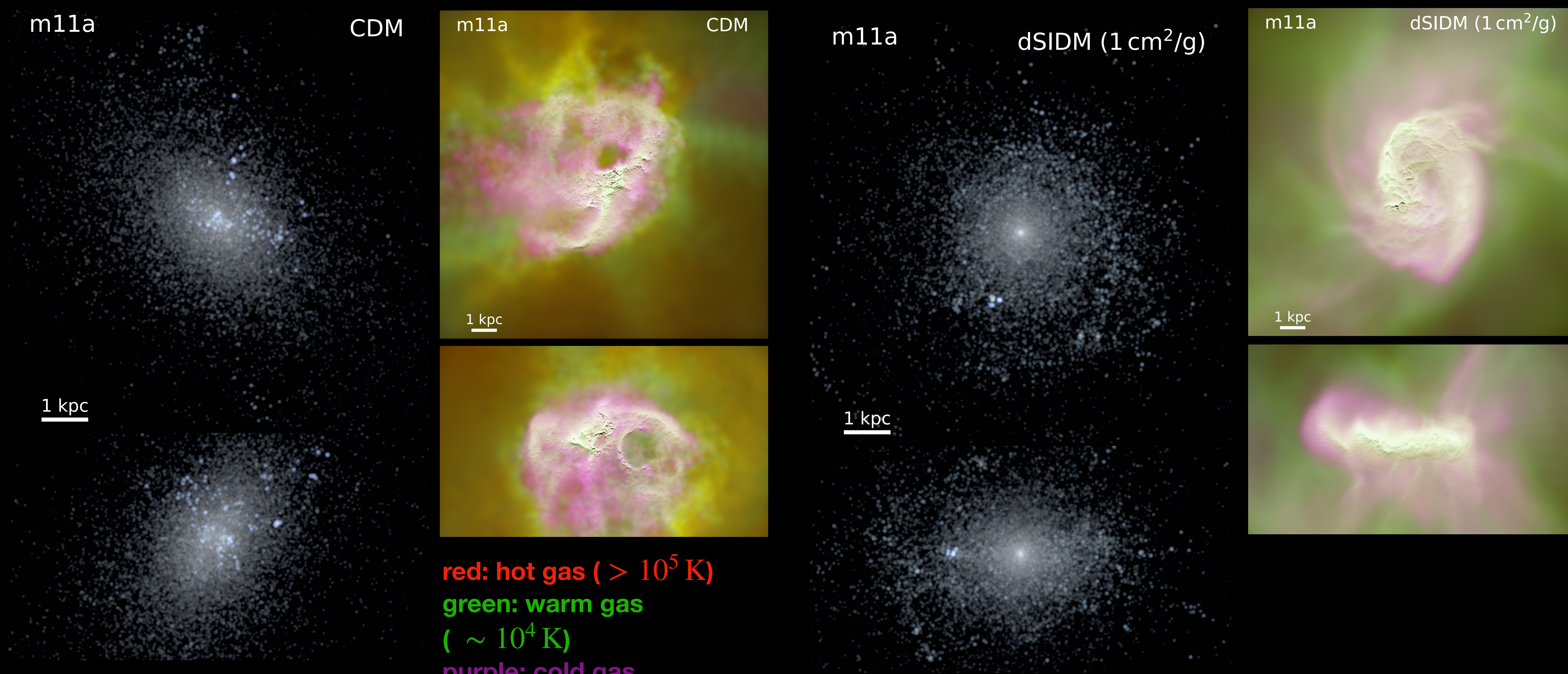
(MW-mass and beyond cusps hidden behind baryons)

Not just about dark matter: Promote disk formation?

CDM

dSIDM

$\sigma_{\mathrm{m}} = 1\mathrm{cm}^2/\mathrm{g}; f_{\mathrm{d}} = 0.5$



Synthetic image (SDSS u,g,r band)

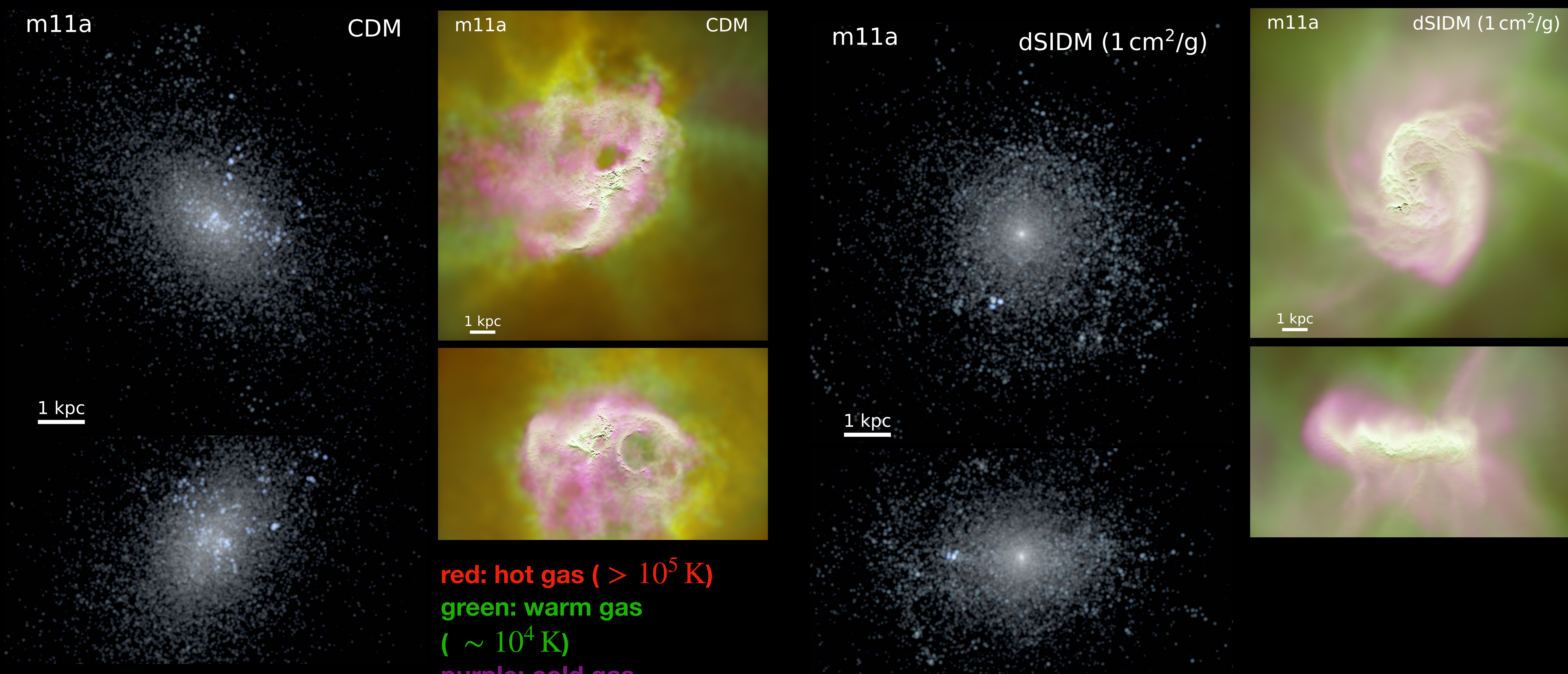
gas supply, cooling/thermodynamics, star formation model, feedback properties
sufficiently centrally-concentrated mass profile

Not just about dark matter: Promote disk formation?

CDM

dSIDM

$\sigma_{\rm m} = 1 {\rm cm}^2/{\rm g}; f_{\rm d} = 0.5$



Synthetic image (SDSS u,g,r band)

red: hot gas ($> 10^5$ K)

green: warm gas ($\sim 10^4$ K)

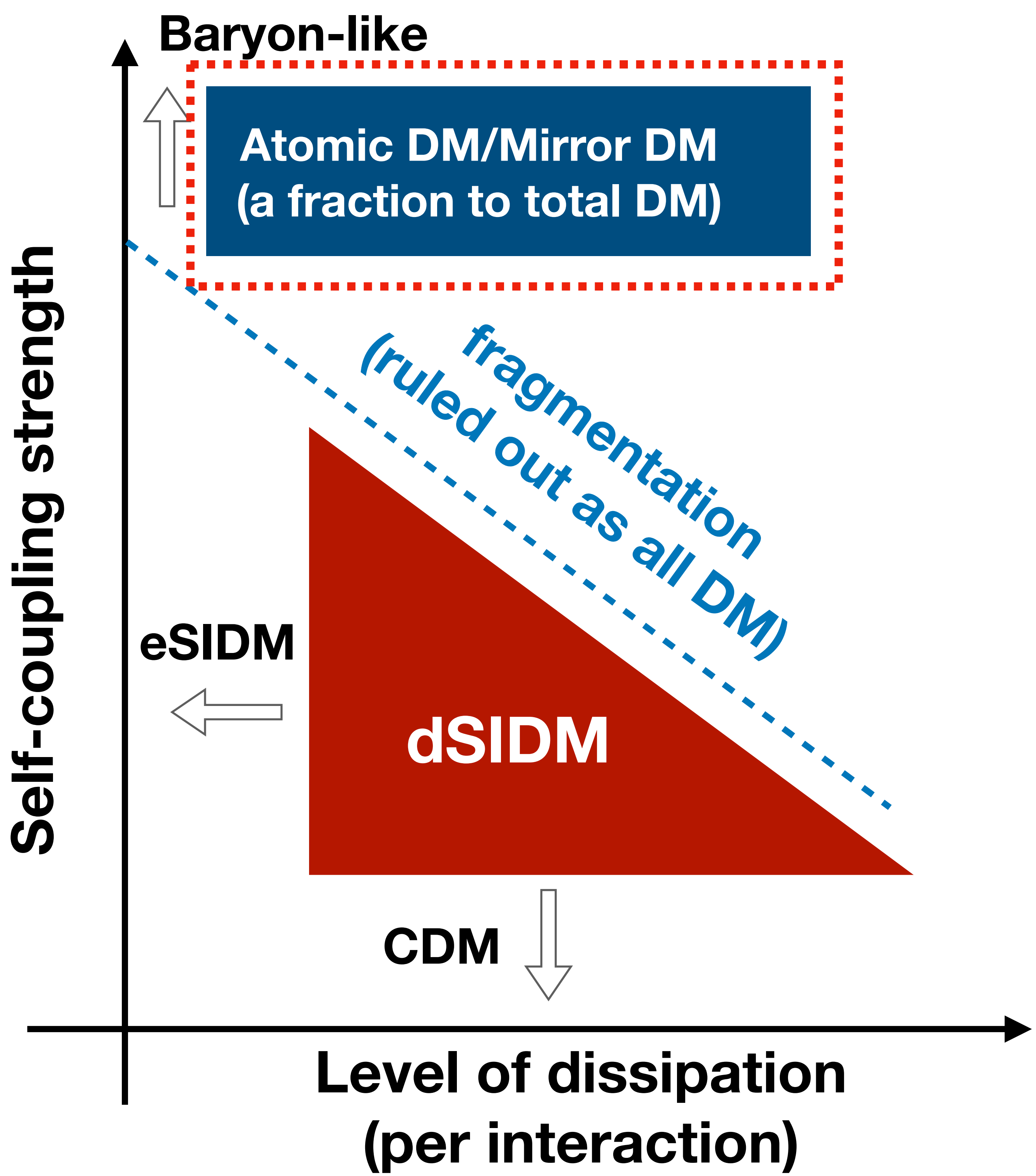
purple: cold gas ($\ll 10^4$ K)

gas supply, cooling/thermodynamics, star formation model, feedback properties

sufficiently centrally-concentrated mass profile

Atomic DM (a different corner of the parameter space)

In collaboration with Sandip Roy, Mariangela Lisanti (Princeton), David Curtin (U Toronto), Norman Murray (CITA, U Toronto) [Roy et al. in prep.]



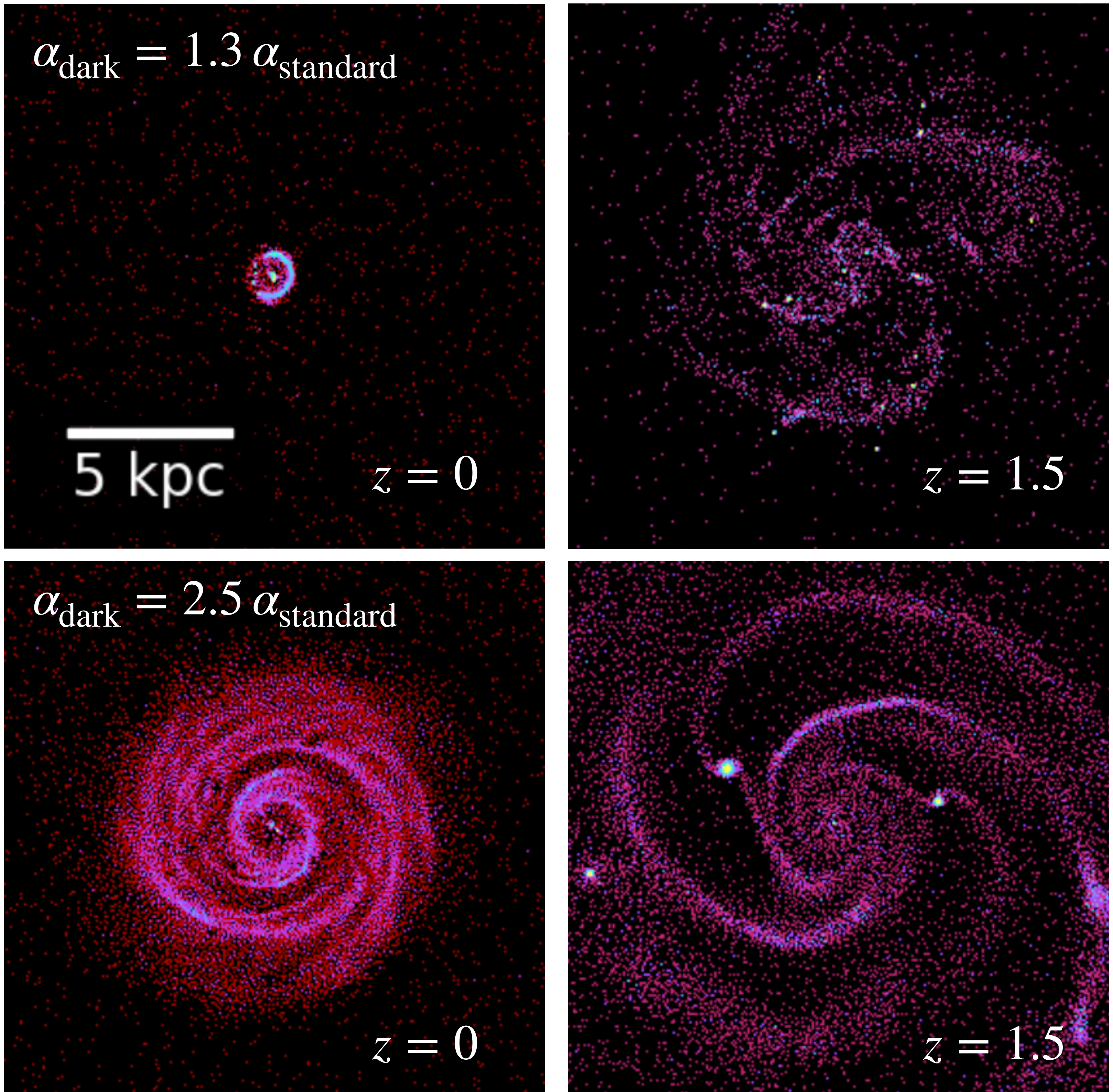
Highly-self-coupled atomic dark matter (fluid-like)

A multi-fluid setup in GIZMO with

- Self-consistent ICs
- Atomic cooling analogous to the baryons
- Sink particles form once becoming Jeans-unstable and self-gravitating
- Feedback/Meta-galactic radiation background/ Molecular cooling?

Atomic DM (a different corner of the parameter space)

[Roy et al. in prep.]



Preliminary results:

- Very early onset of sink formation & very efficient
- Proto dark disks always formed, but were not necessarily sustained at z=0
- DM Morphology sensitive to the cooling power in the dark sector
- …

QCD axions

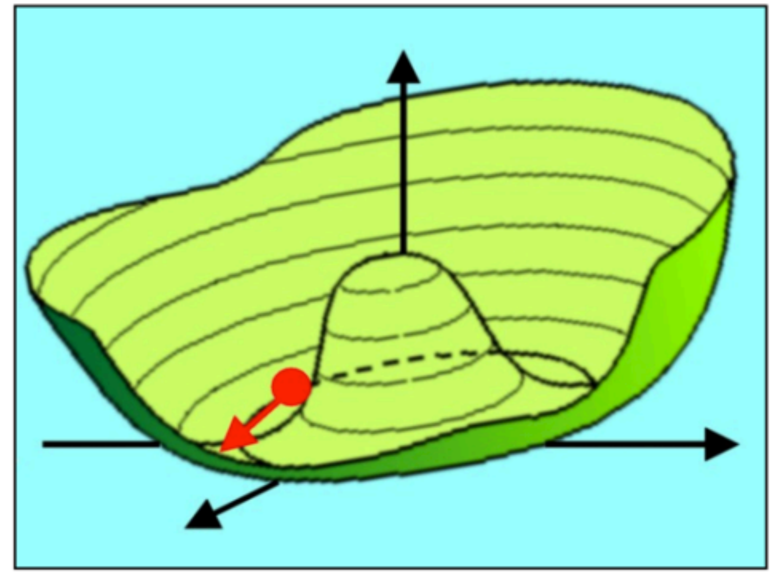
$\theta \in [0, 2\pi]$

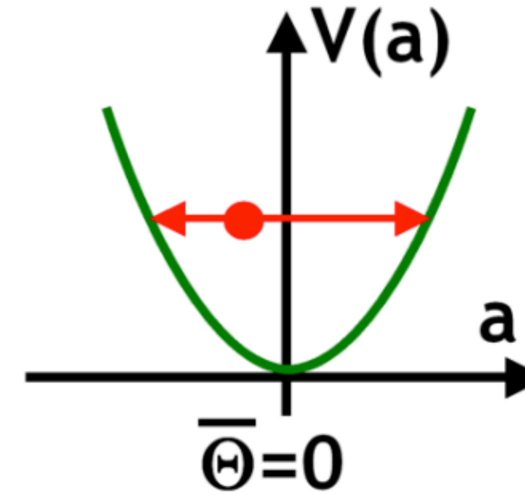
- Strong CP problem $\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$ $\bar{\theta} < 10^{-10}$.

- Peccei-Quinn solution

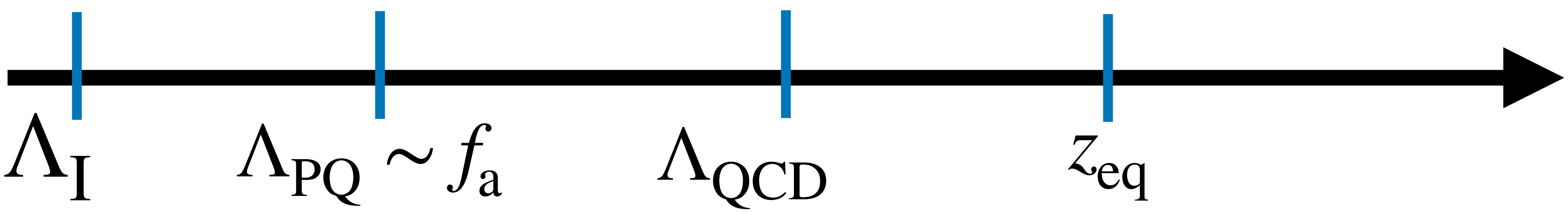
  Peccei & Quinn 1977

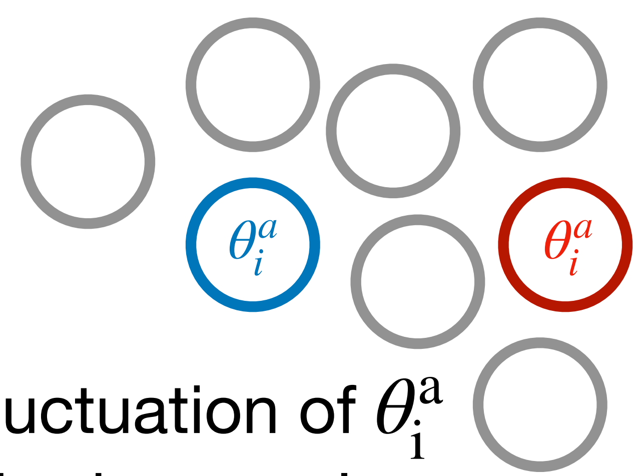
  promote θ to a field that can dynamically evolve to 0





Post-inflation Scenario



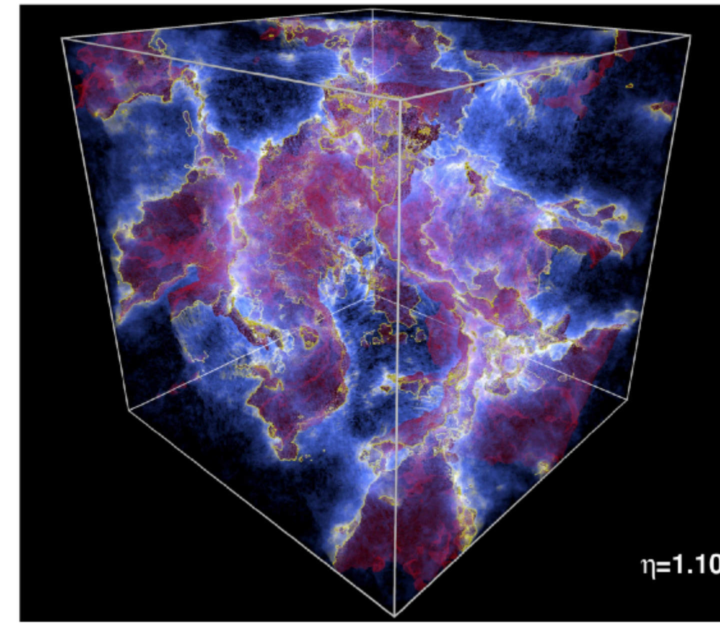


$O(1)$ fluctuation of $\theta_{\rm i}^{\rm a}$ at the horizon scale

misalignment: coherent oscillation of axion fields -> dark matter e.g. Weinberg 1978, Preskill et al. 1983

$$\Omega_a h^2 \simeq 0.65 \left(\frac{\bar{\theta}_{\rm ini}}{10^{-2}}\right)^2 \left(\frac{f_a}{10^{16}\,\mathrm{GeV}}\right)^{1.17}$$

QCD axions – miniclusters



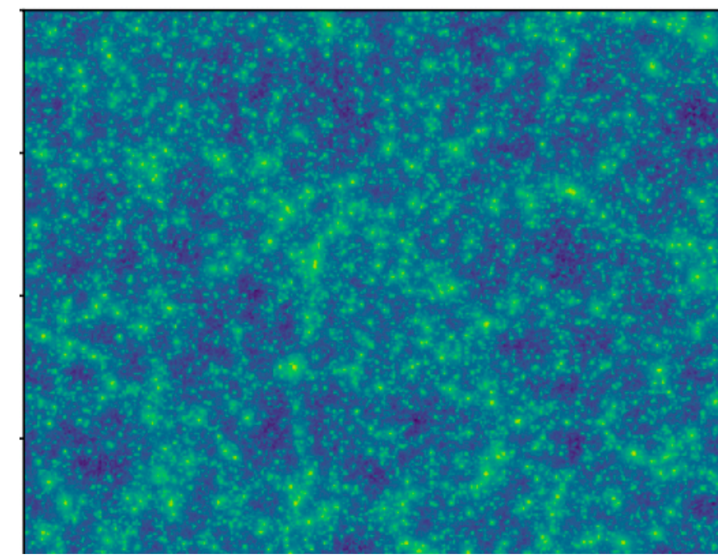
- initial population - lattice simulations

  e.g. Buschmann et al.,2019

$z \sim z_{\mathrm{eq}}$

- hierarchical assembly in a free field

  e.g. Xiao et al. 2021 (a semi-analytical Sheth-Tormen formalism calibrated based on Nbody simulations)



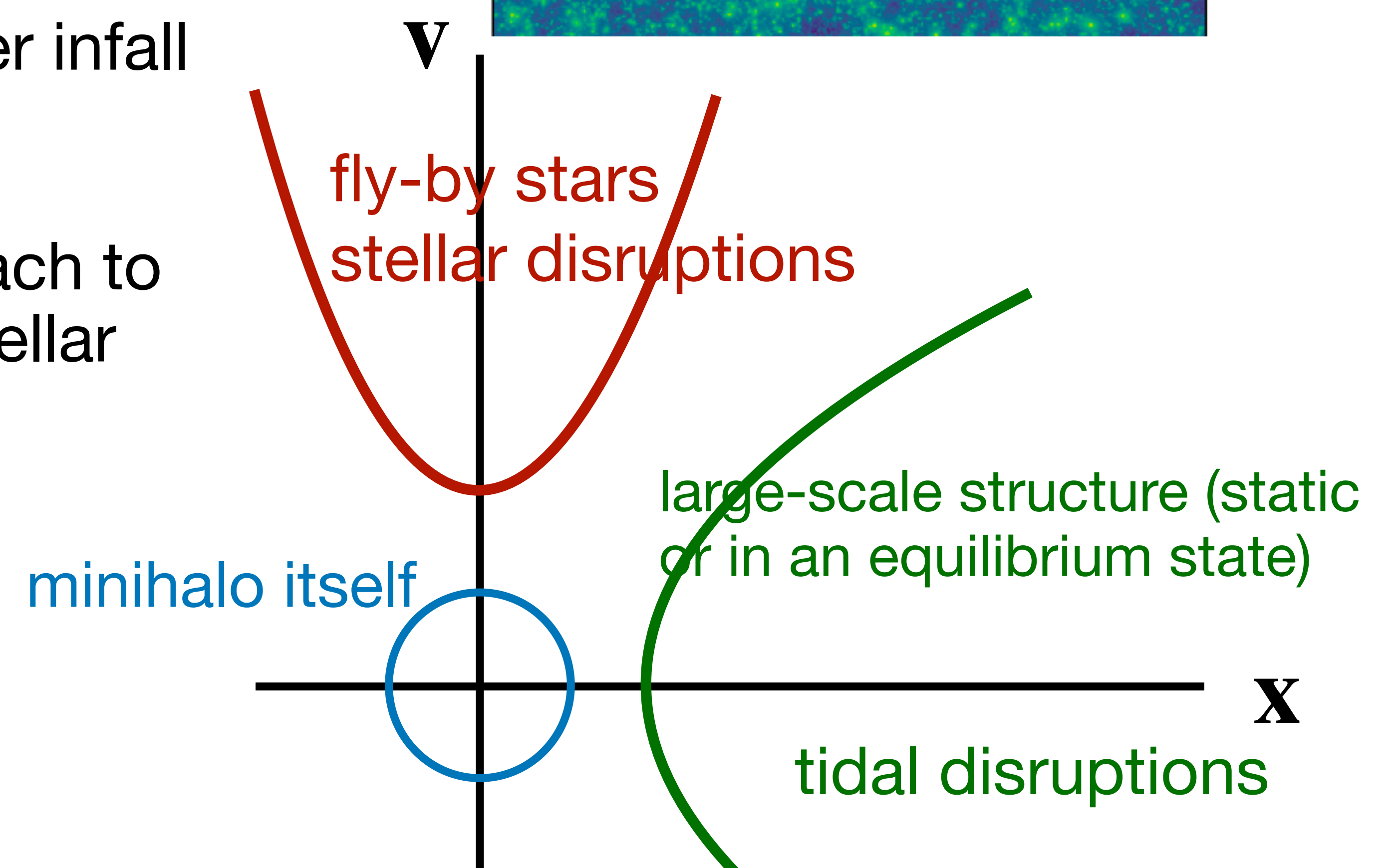
$z \sim 20$

- environmental effects after infall

  Shen et al. 2022

  a semi-analytical approach to combine infall, tidal & stellar disruption

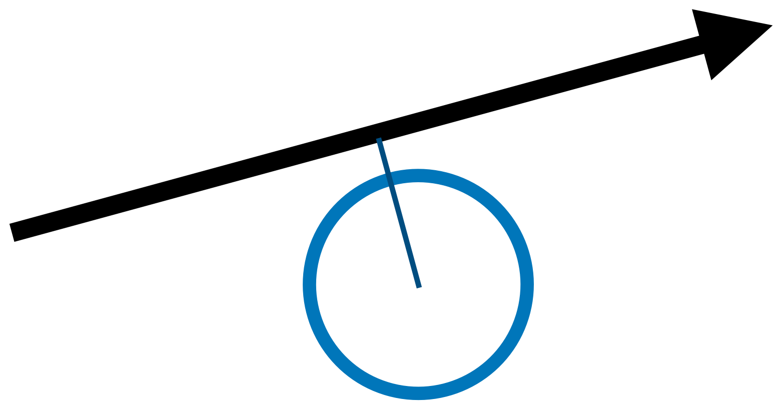
$z = 0$

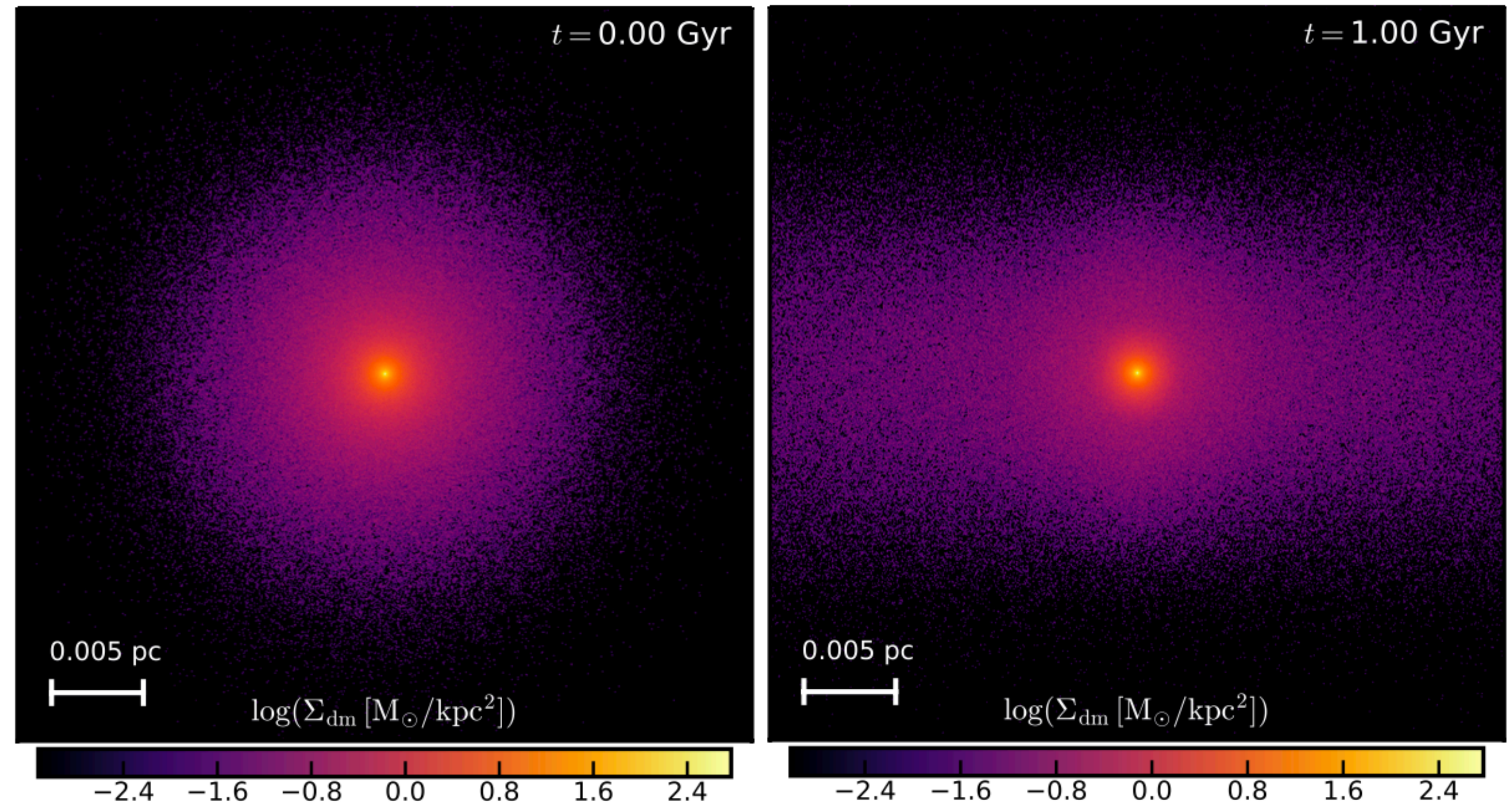


QCD axions – miniclusters – disruption

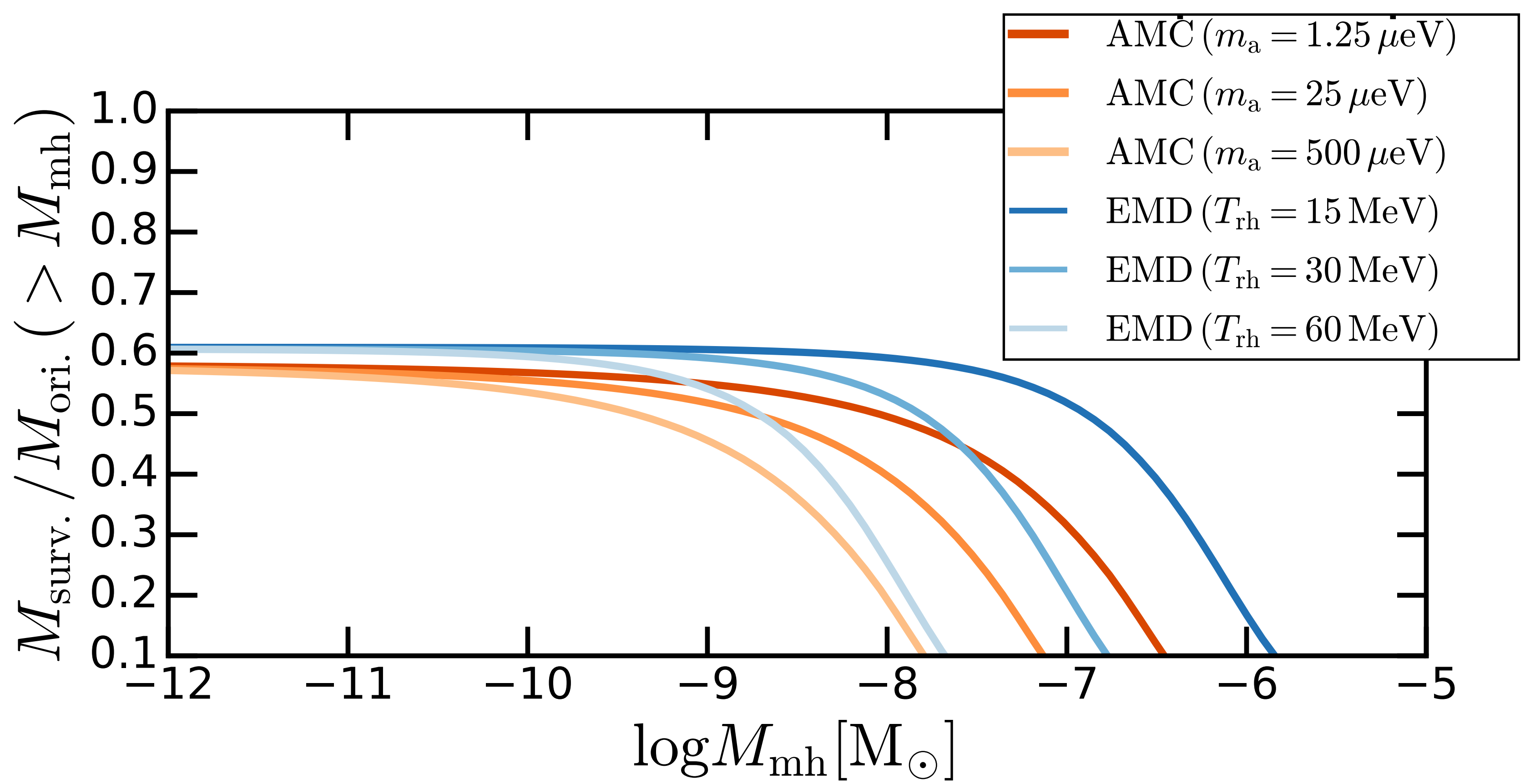
In collaboration with Huangyu Xiao (FermiLab), Kathryn Zurek, Philip Hopkins (Caltech)
[Shen et al. 2022]

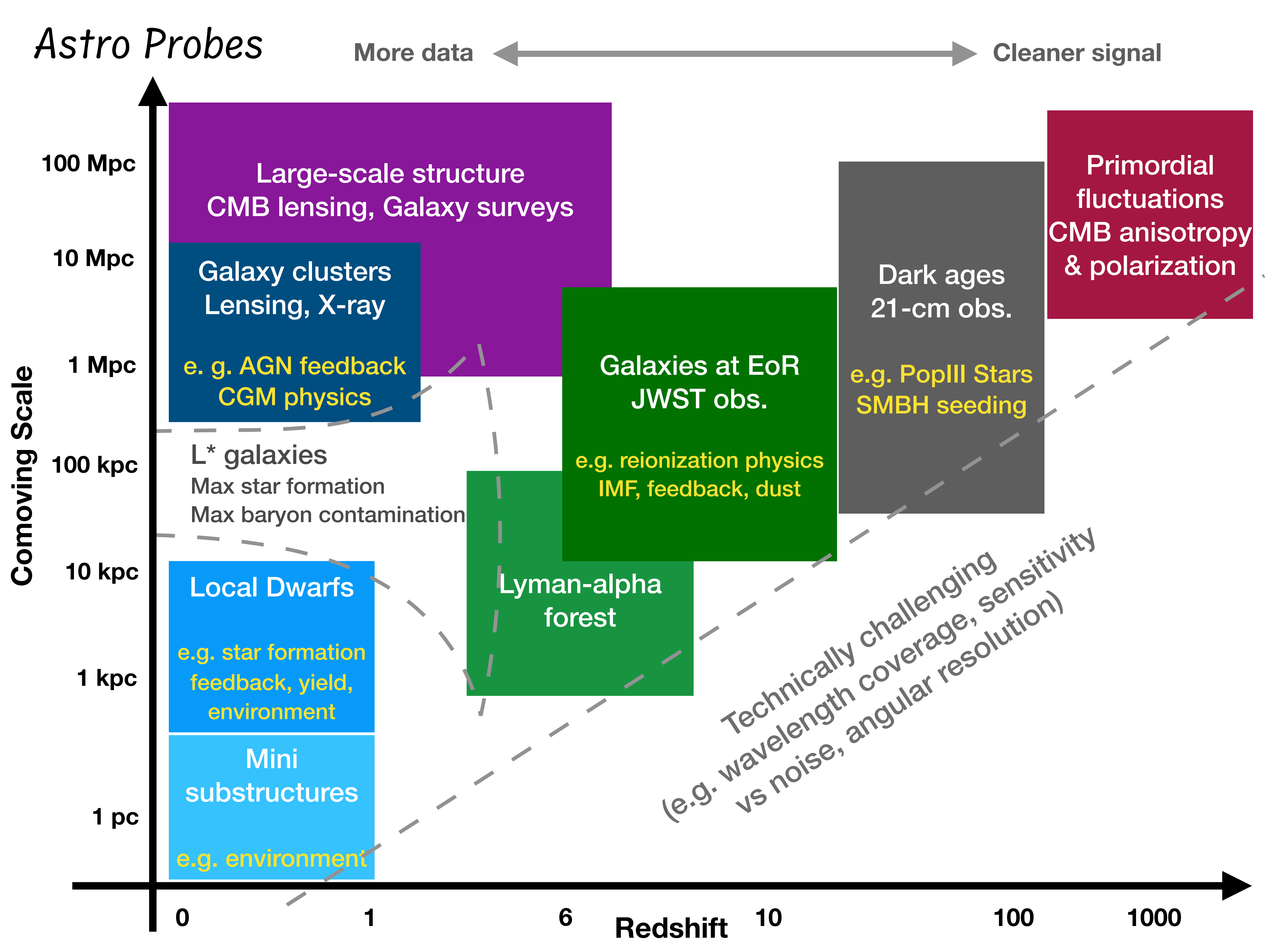
Idealized simulations of minihalo-star encounters



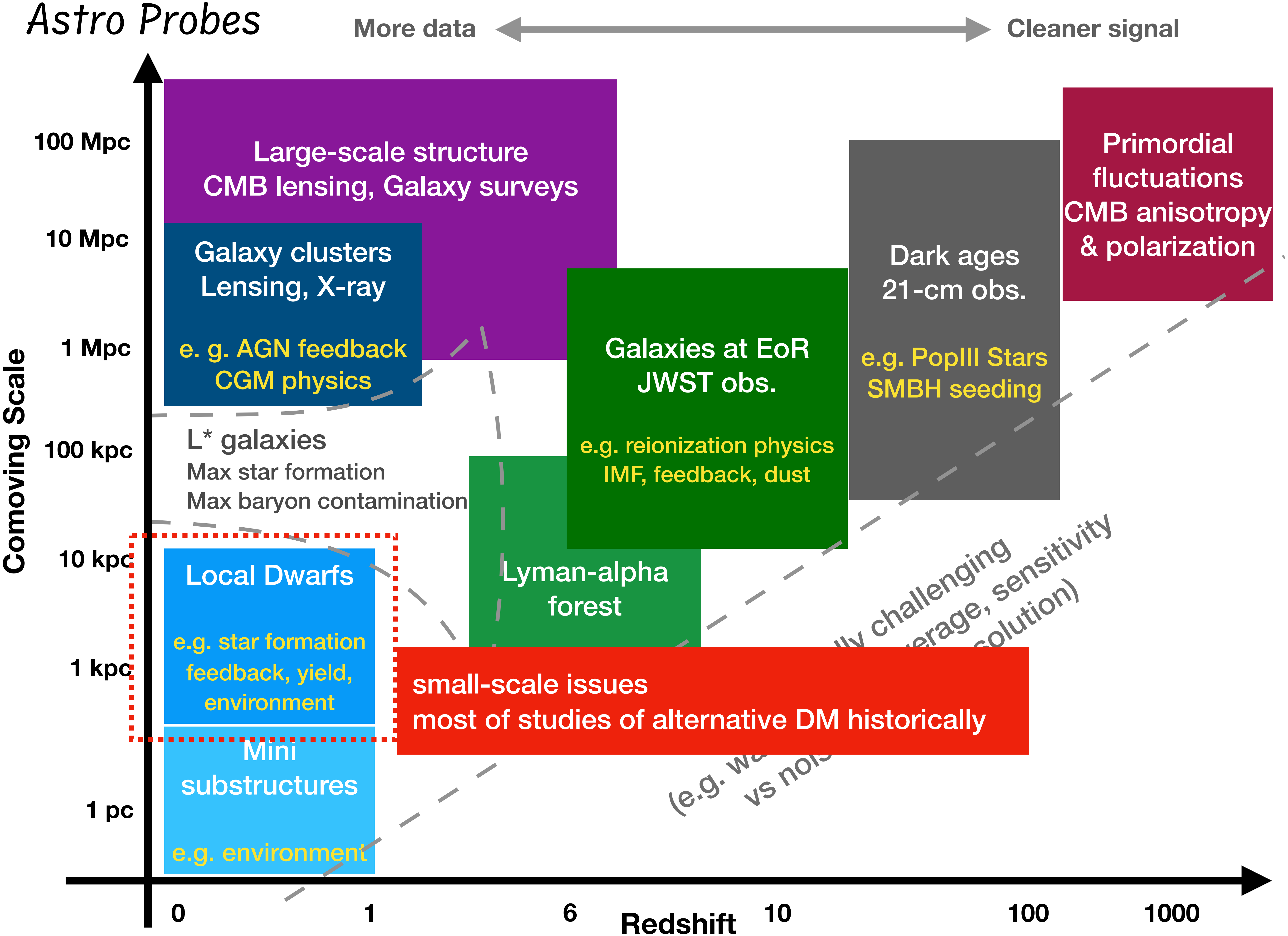


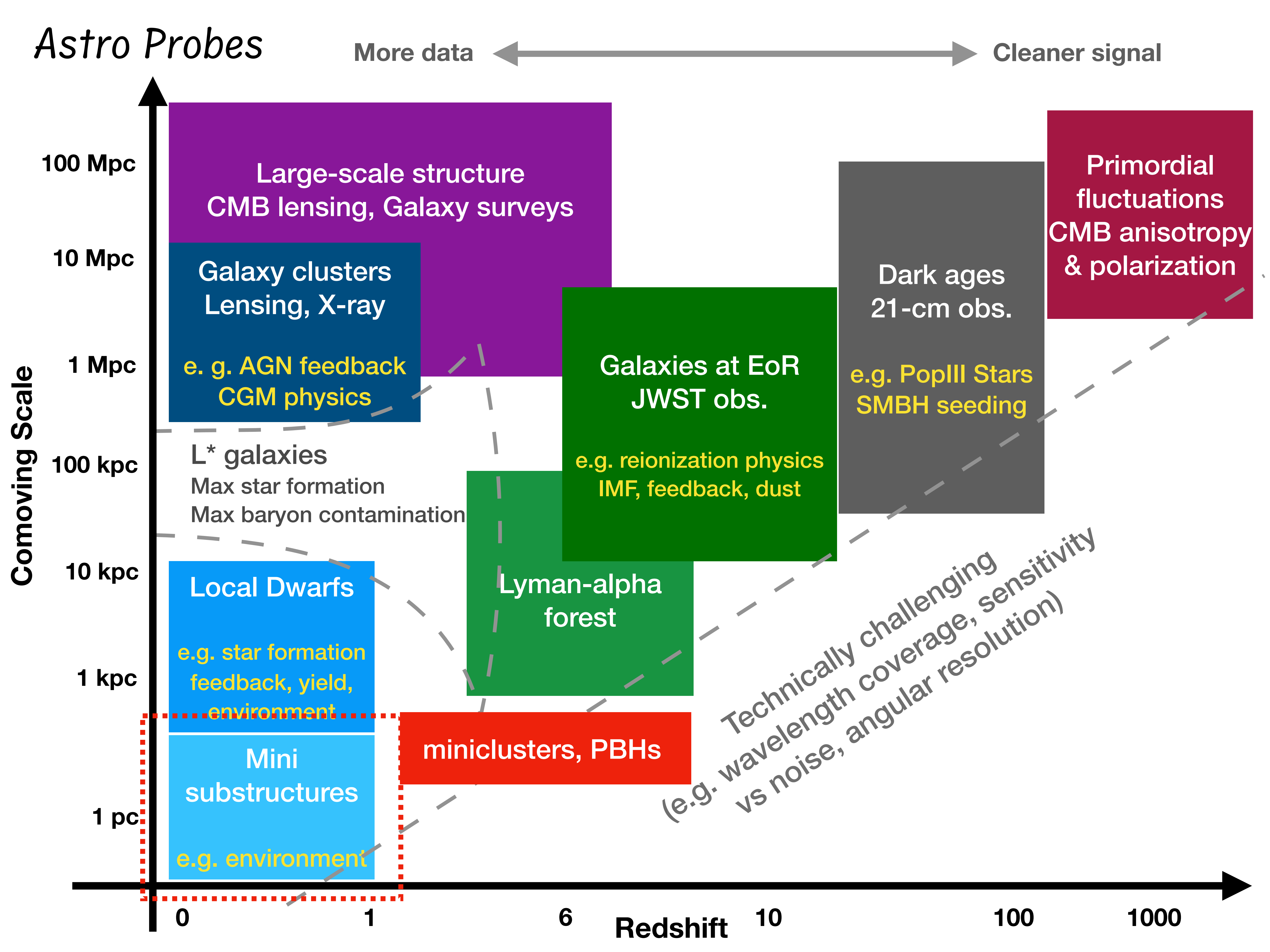
- stellar disruption is the dominant disruption mechanism
- about 60% survival rate at Solar neighborhood (insensitive to model choices)




Astro Probes
More data
Cleaner signal
Comoving Scale
100 Mpc
10 Mpc
1 Mpc
100 kpc
10 kpc
1 kpc
1 pc
Large-scale structure
CMB lensing, Galaxy surveys
Galaxy clusters
Lensing, X-ray
e. g. AGN feedback
CGM physics
L* galaxies
Max star formation
Max baryon contamination
Local Dwarfs
e.g. star formation
feedback, yield,
environment
Mini
substructures
e.g. environment
Galaxies at EoR
JWST obs.
e.g. reionization physics
IMF, feedback, dust
Lyman-alpha
forest
Dark ages
21-cm obs.
e.g. PopIII Stars
SMBH seeding
Primordial
fluctuations
CMB anisotropy
& polarization
Technically challenging
(e.g. wavelength coverage, sensitivity
vs noise, angular resolution)
0
1
6
Redshift
10
100
1000

Astro Probes

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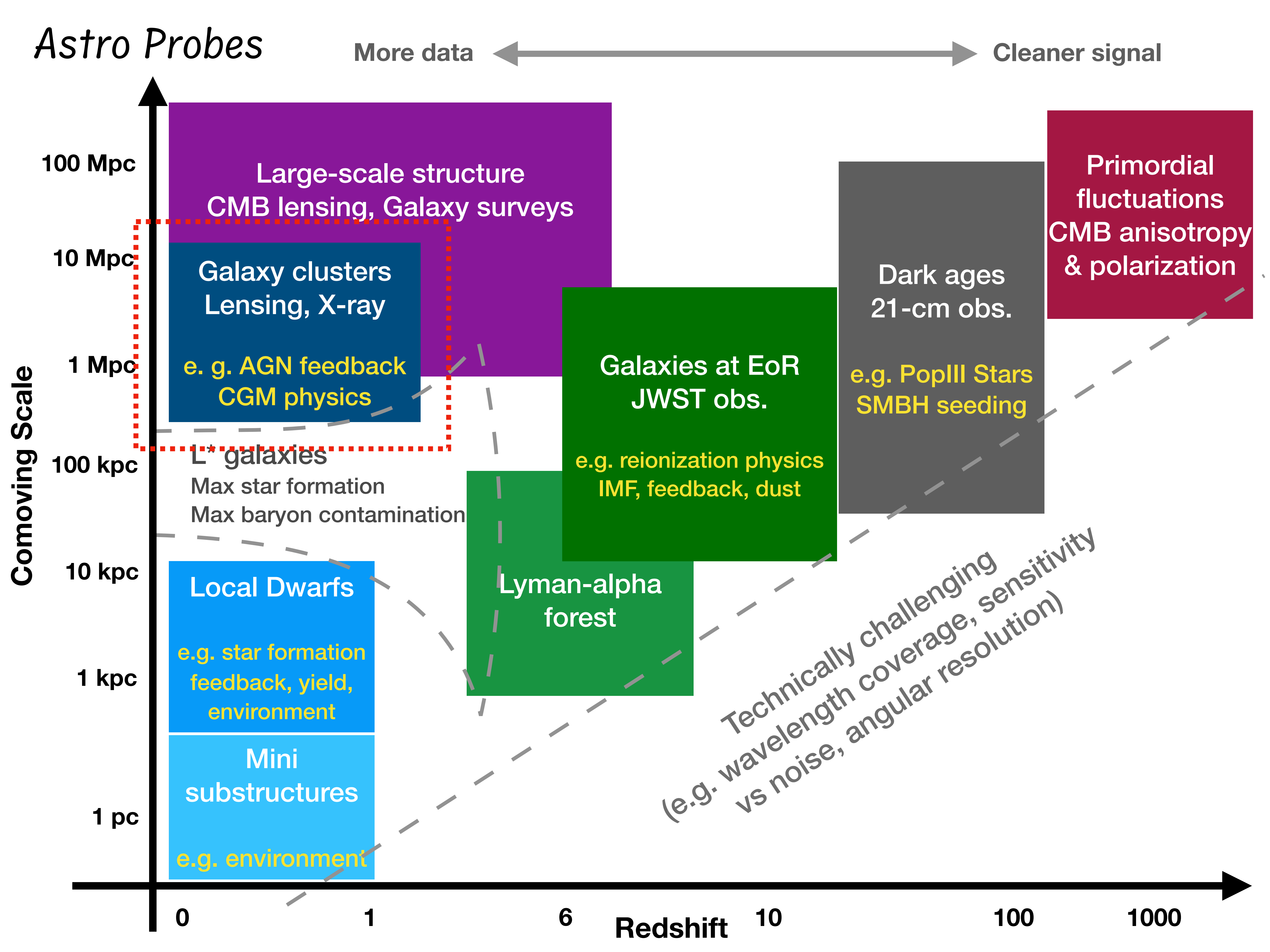

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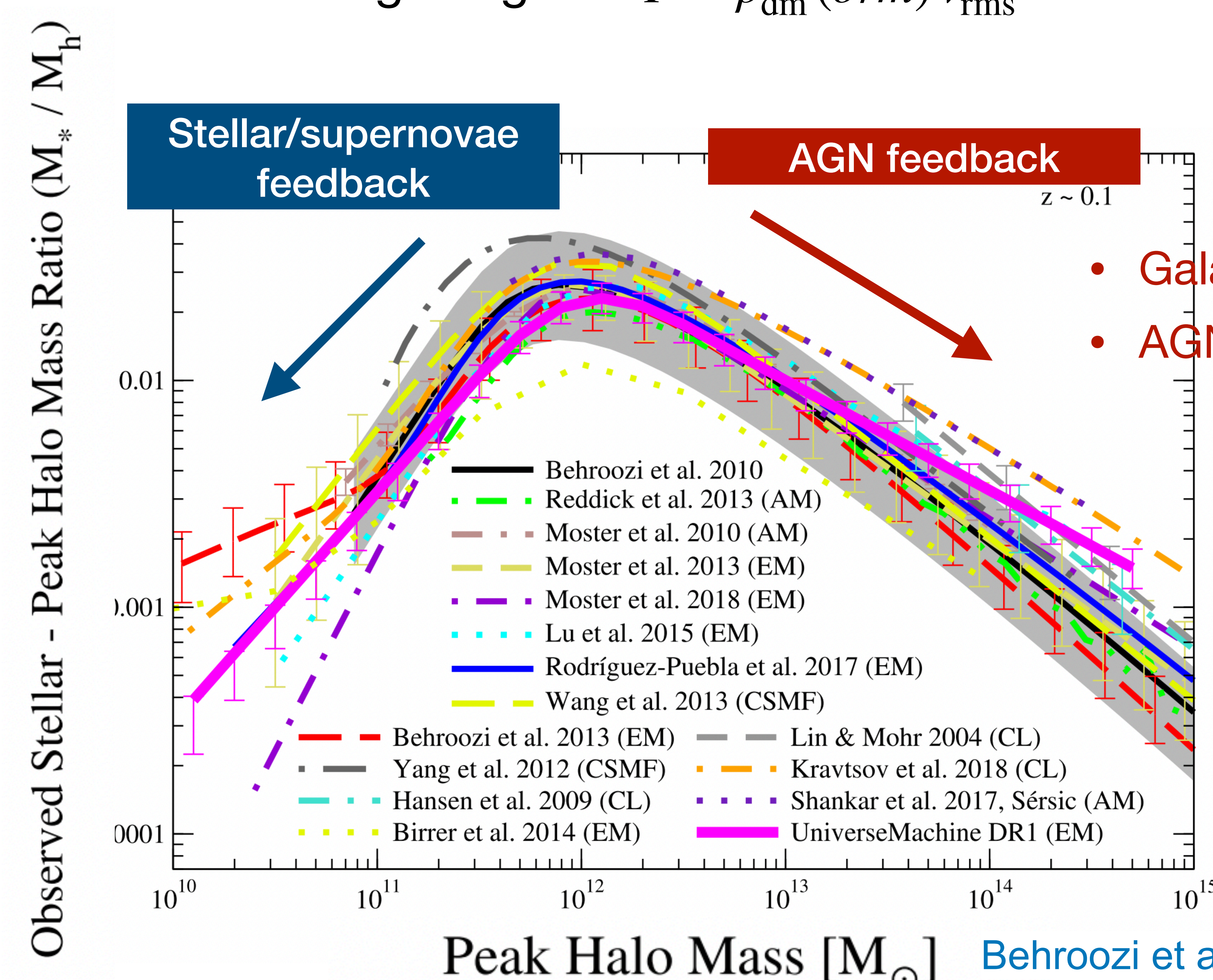
Redshift
10
100
1000

Massive galaxies to Galaxy clusters

- a mixture of observational probes

  strong lensing, X-ray, SZ effect, stellar kinematics, etc.

- stronger signal $\Gamma \sim \rho_{\rm dm}\,(\sigma/m)\,v_{\rm rms}$



Behroozi et al., 2019

Active research in theoretical astrophysics

- Galaxy quenching
- AGN downsizing

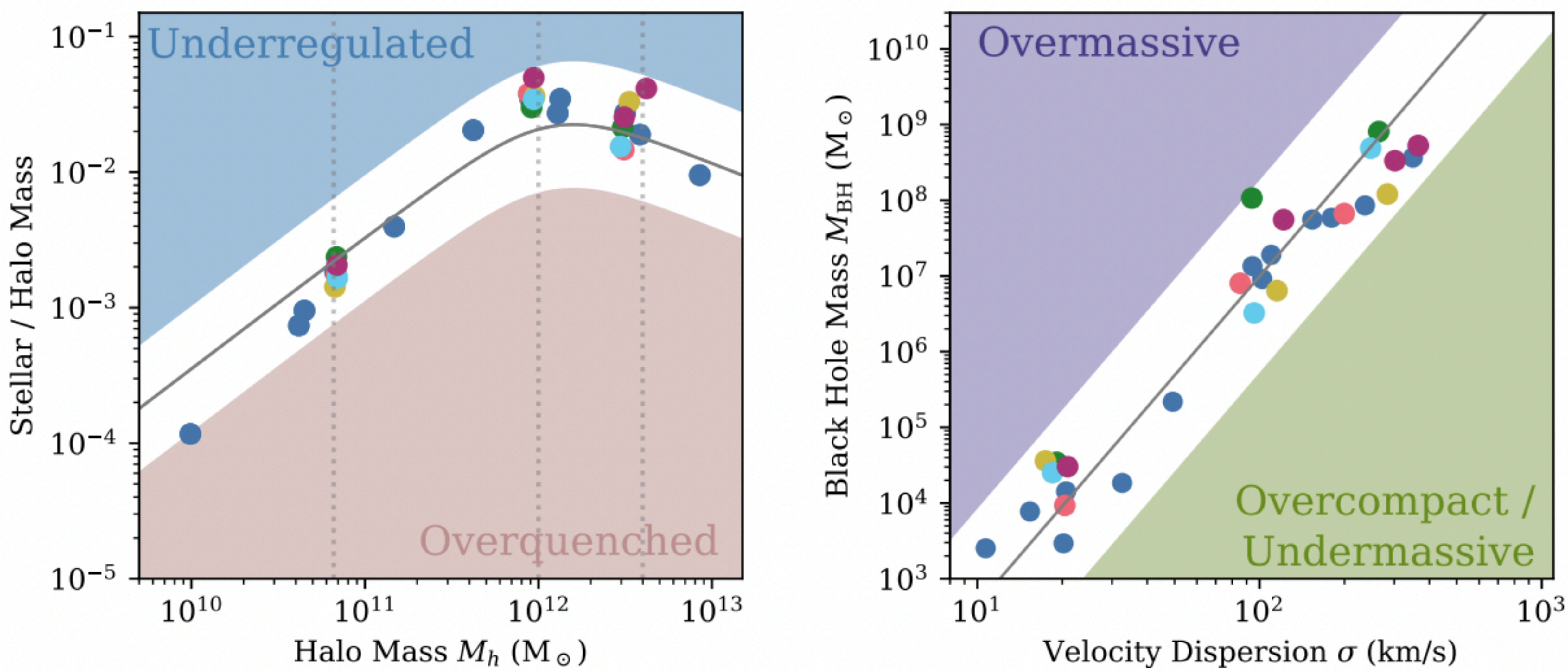
SMBH/AGN feedback?

- time and spatial scale
- geometry
- driving mechanism (radiative/mechanical)
- gas phase

Massive galaxies to Galaxy clusters

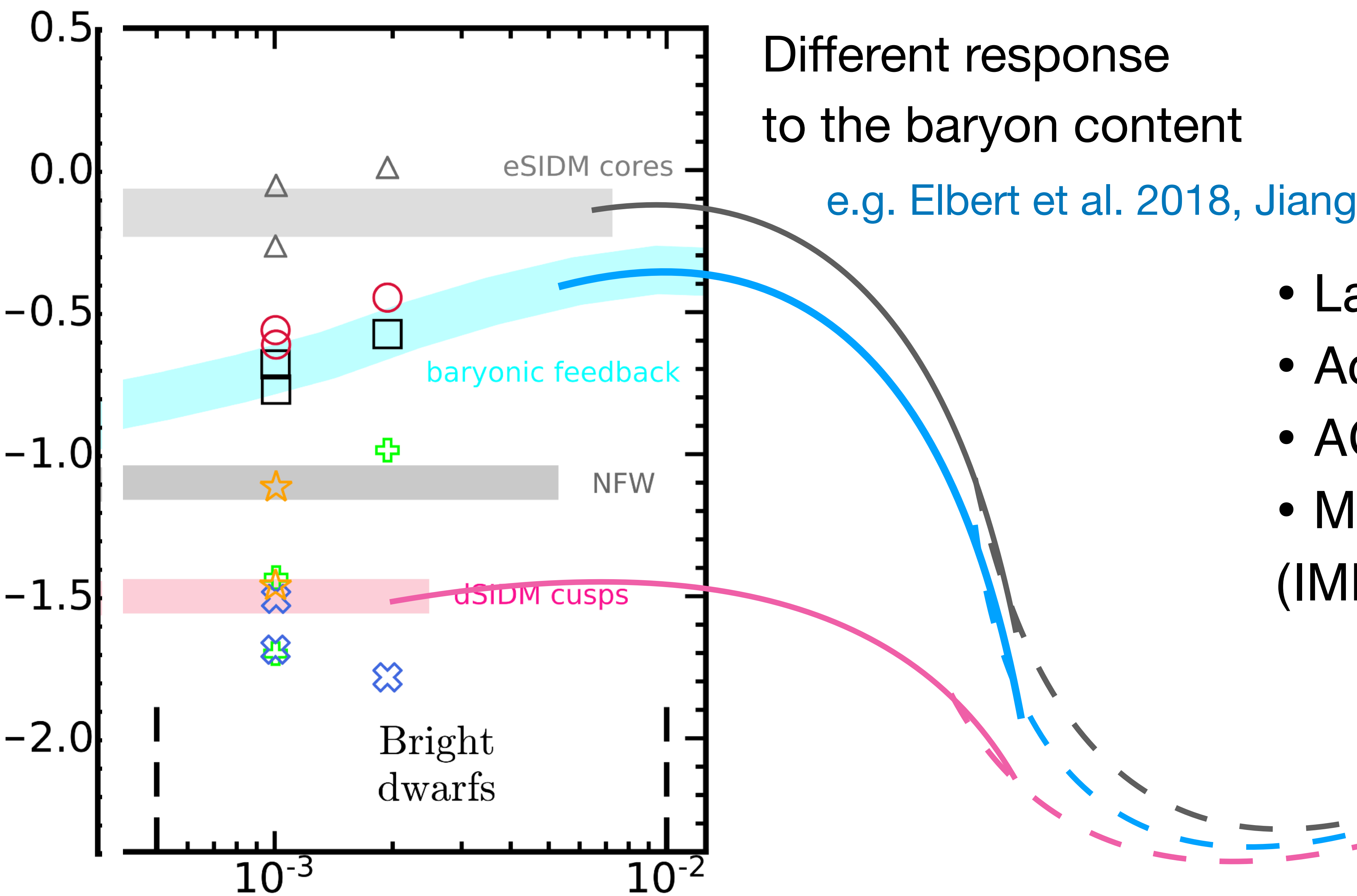
FIRE-3: BH seeding & accretion models, feedback channels, feedback geometry & numeric implementation

e.g. Su et al. 2021, Wellons et al. 2022,Hopkins et al. 2022



Wellons et al. 2022

Galaxy Clusters —— Density Profile



Different response to the baryon content

e.g. Elbert et al. 2018, Jiang et al. 2022

- Late-time dry mergers
- Adiabatic contraction
- AGN feedback
- Mass decomposition

(IMF in massive galaxies)

?

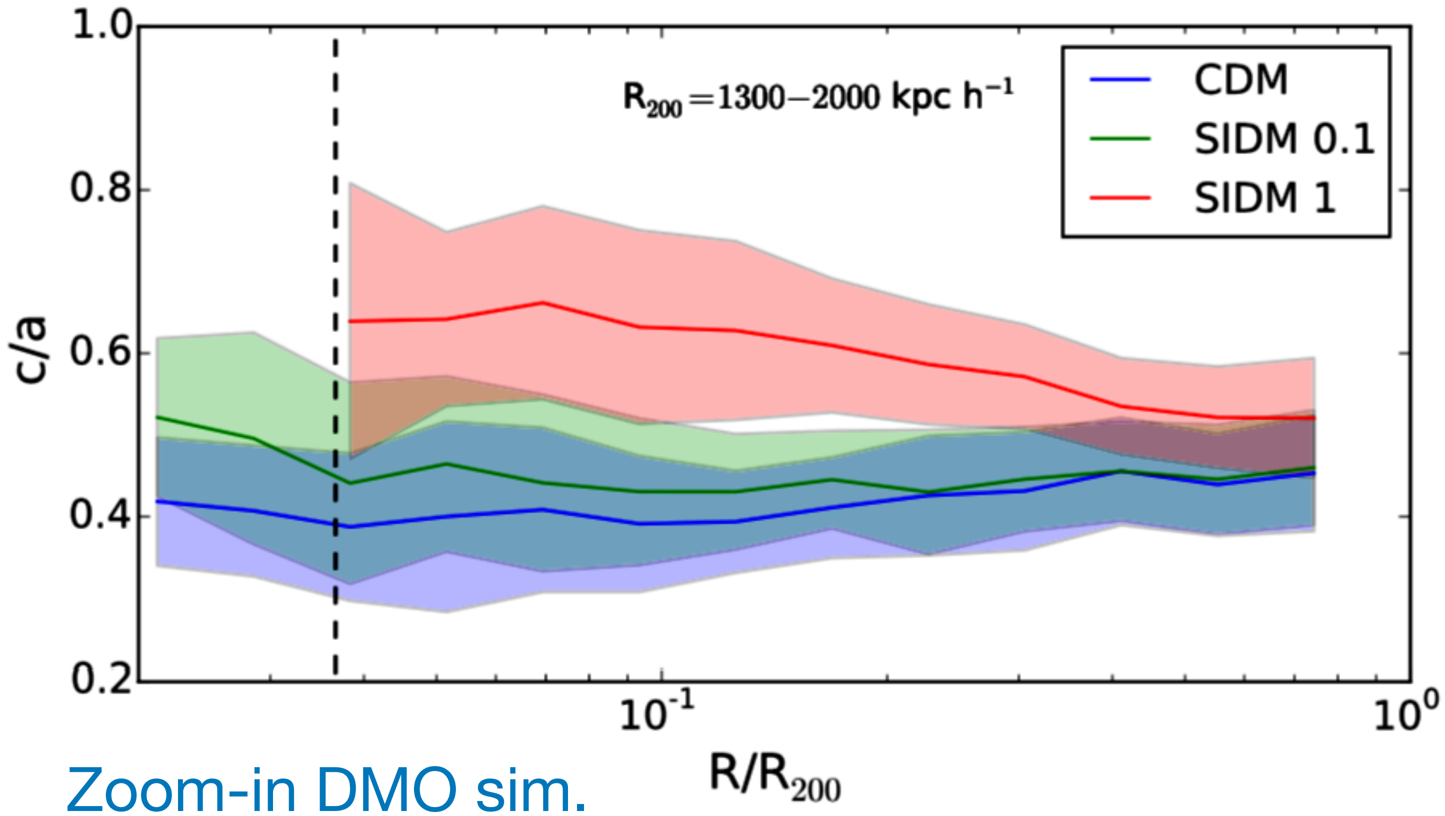
dwarfs

Baryon-dominance
Self-regulation

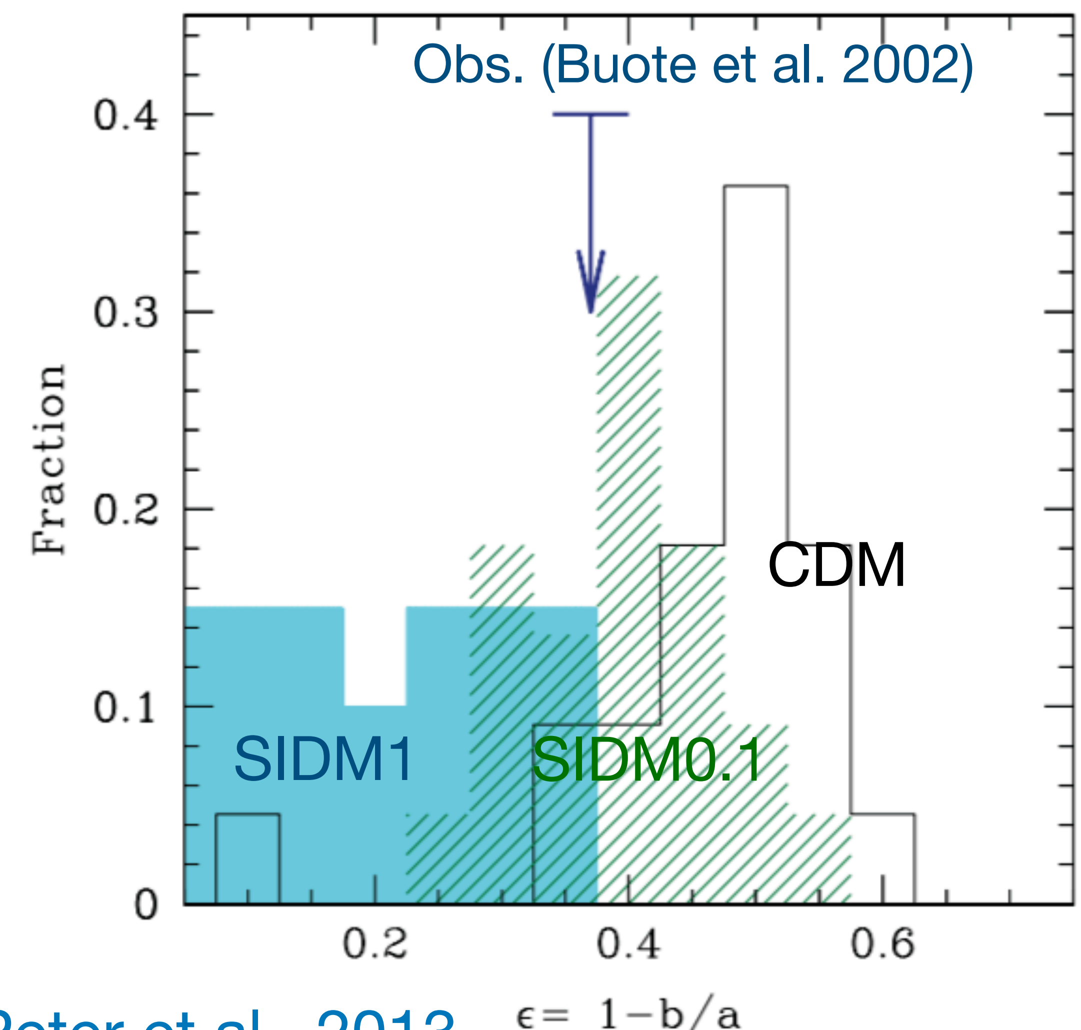
Clusters

Milky Way-mass

Galaxy Clusters —— Halo morphology



Zoom-in DMO sim.
(e.g. Brinckmann et al., 2017)



Peter et al., 2013

- Signals extend to large radii

$(R \gtrsim 20 - 30\,\%\, R_{\rm vir} \gg R^{\rm e}_{\rm BCG})$

- Less contamination from baryons

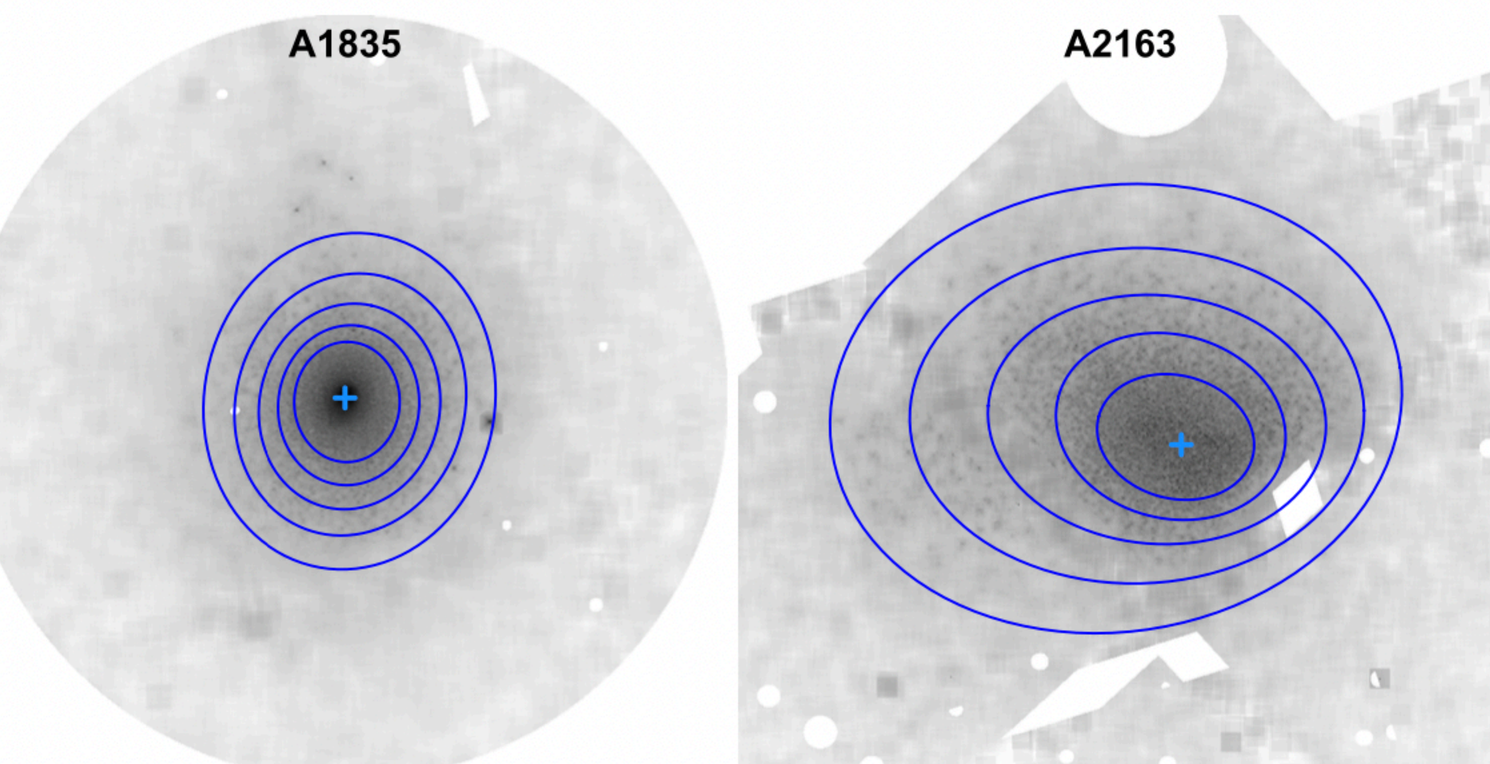
- Strong lensing and X-ray constraints

Halo morphology

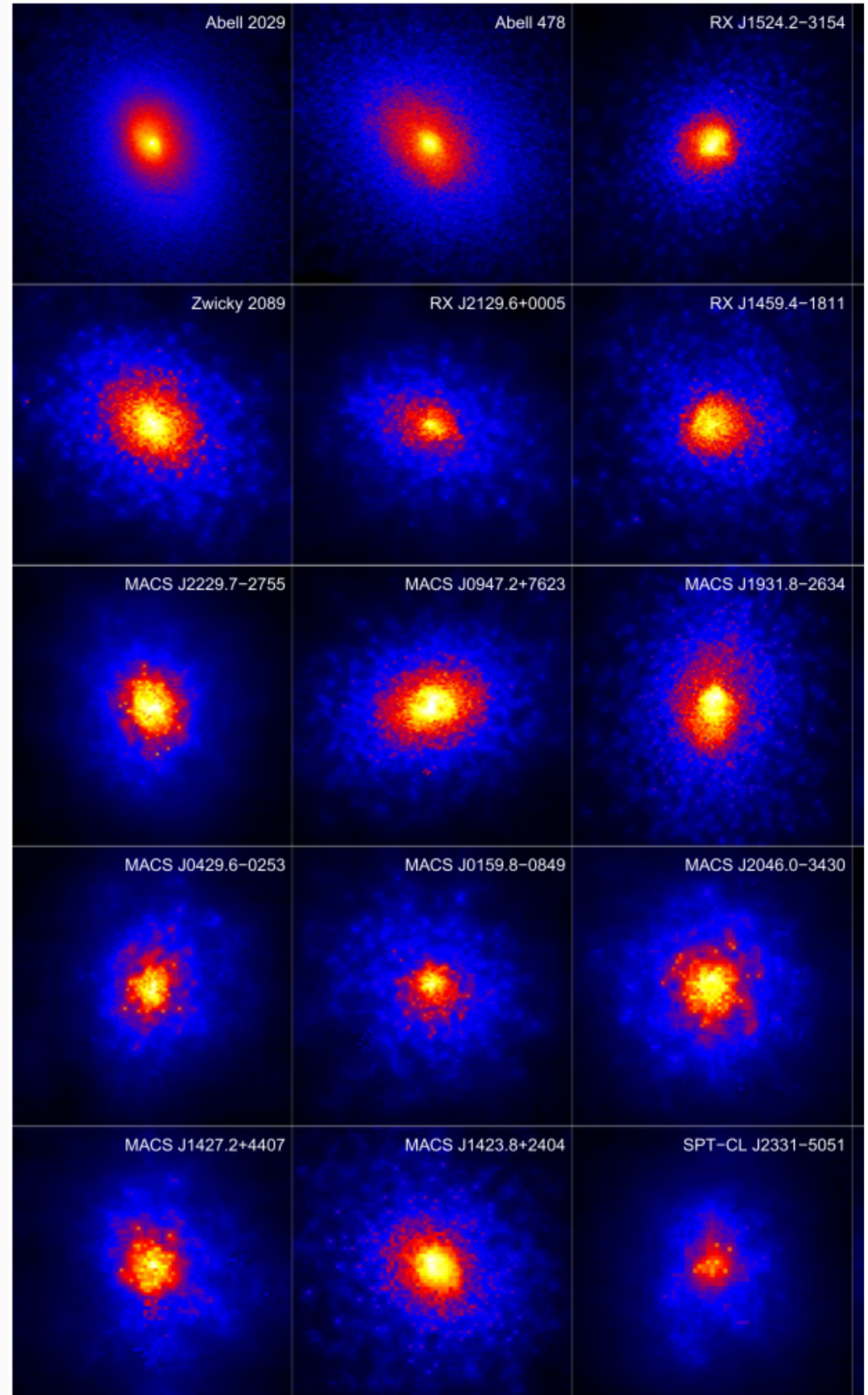
- ~ 100 relaxed clusters at $z \lesssim 0.5$ from the Chandra and ROSAT archive

Mantz et al., 2014, 2015

selected based on symmetry, alignment and peakiness of X-ray isophotes



Mantz et al., 2015



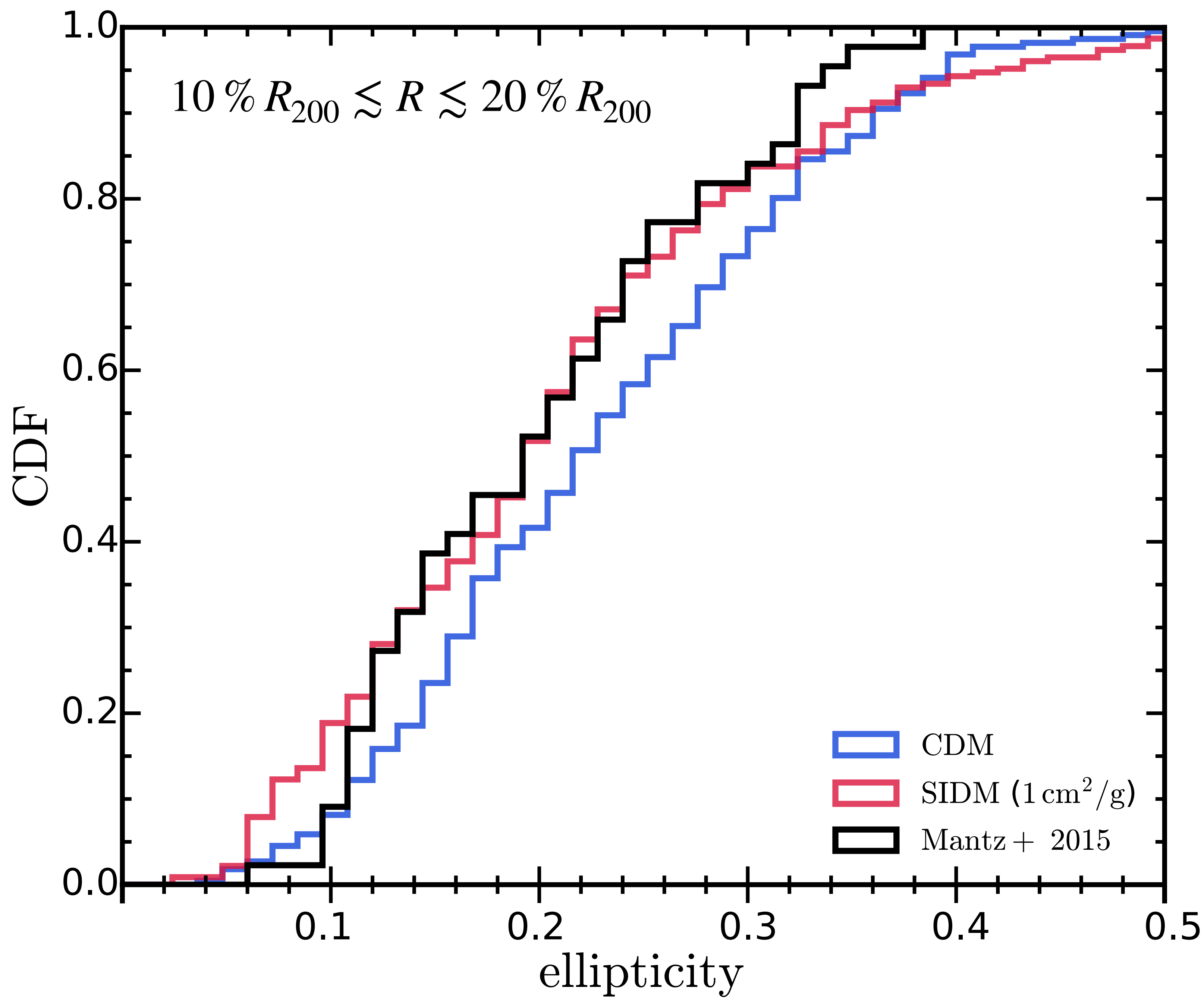
Simulations of cluster-mass halos in SIDM + adiabatic gas

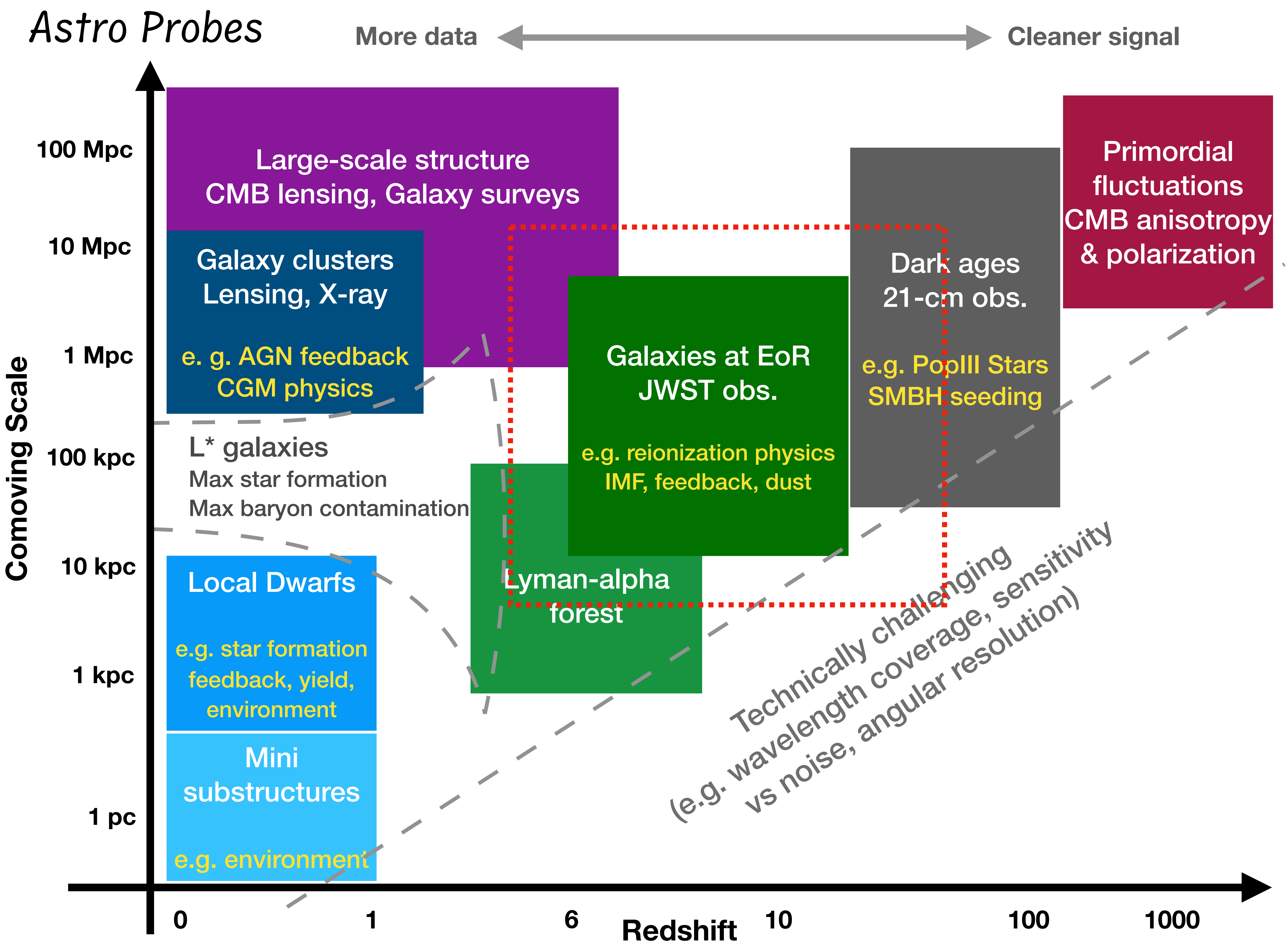
In collaboration with Thejs Brinckmann, Jesús Zavala (University of Iceland), David Rapetti (CU Boulder), Mark Vogelsberger (MIT), Adam Mantz (Stanford) [Shen et al. 2022]

- cosmological zoom-in simulations of ~ 20 $M_{\rm halo} \sim 10^{14}\,{\rm M}_\odot$ dynamically-relaxed halos
- Mock X-ray images & isophotes directly compared to the observed samples
- Observations tentatively favor SIDM $\sigma_{\rm m} \gtrsim 0.5\,{\rm cm}^2/{\rm g}$
- Baryonic physics effect?

  cool-core vs non-cool-core

  AGN feedback

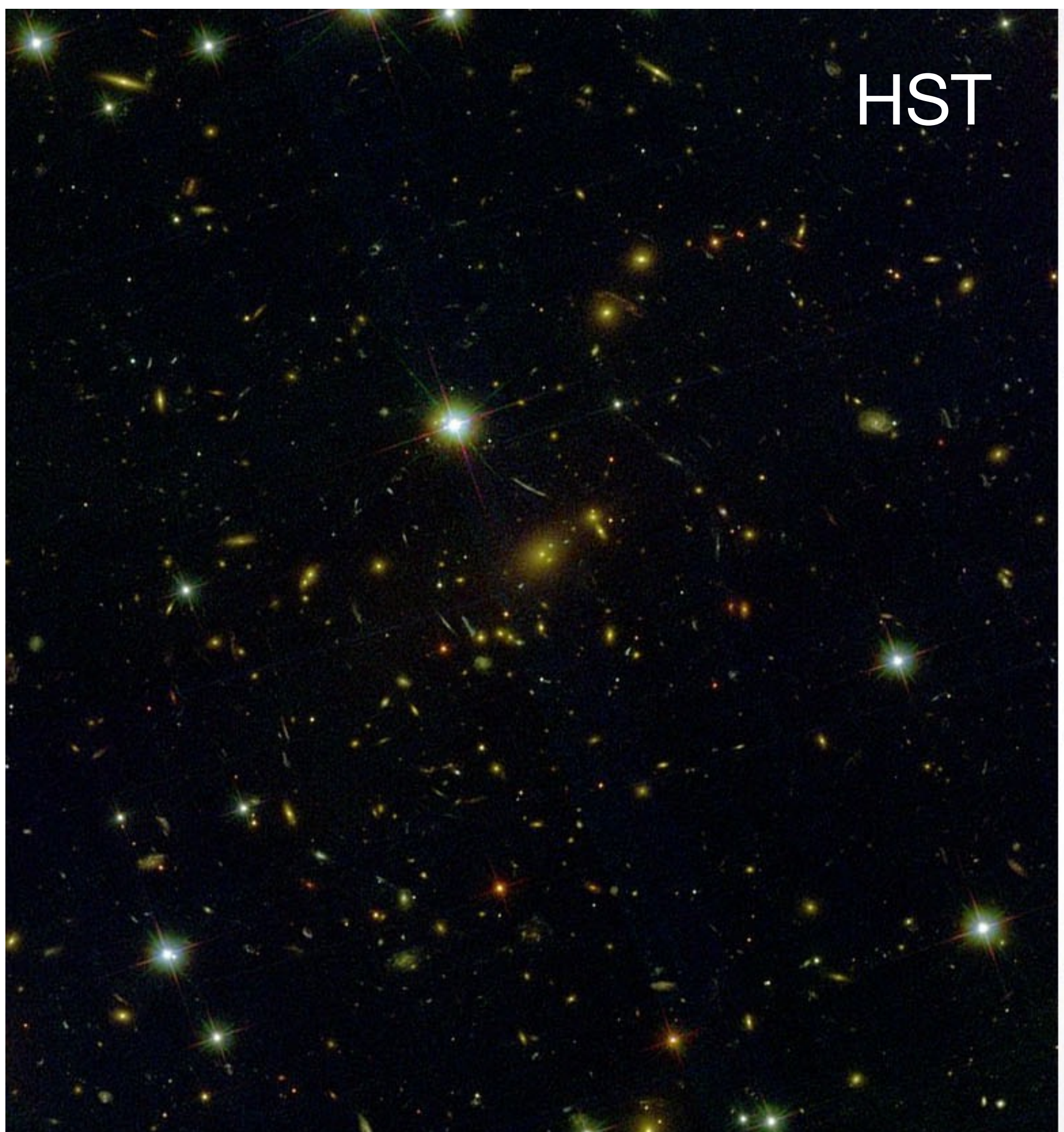



Astro Probes
More data
Cleaner signal
Comoving Scale
100 Mpc
10 Mpc
1 Mpc
100 kpc
10 kpc
1 kpc
1 pc
Redshift
0
1
6
10
100
1000
Large-scale structure
CMB lensing, Galaxy surveys
Galaxy clusters
Lensing, X-ray
e. g. AGN feedback
CGM physics
L* galaxies
Max star formation
Max baryon contamination
Local Dwarfs
e.g. star formation
feedback, yield,
environment
Mini
substructures
e.g. environment
Lyman-alpha
forest
Galaxies at EoR
JWST obs.
e.g. reionization physics
IMF, feedback, dust
Dark ages
21-cm obs.
e.g. PopIII Stars
SMBH seeding
Primordial
fluctuations
CMB anisotropy
& polarization
Technically challenging
(e.g. wavelength coverage, sensitivity
vs noise, angular resolution)

High-redshift galaxies

- New era of observations of early galaxies with JWST

deeper imaging	wavelength coverage higher redshift	spectroscopy optical emission lines



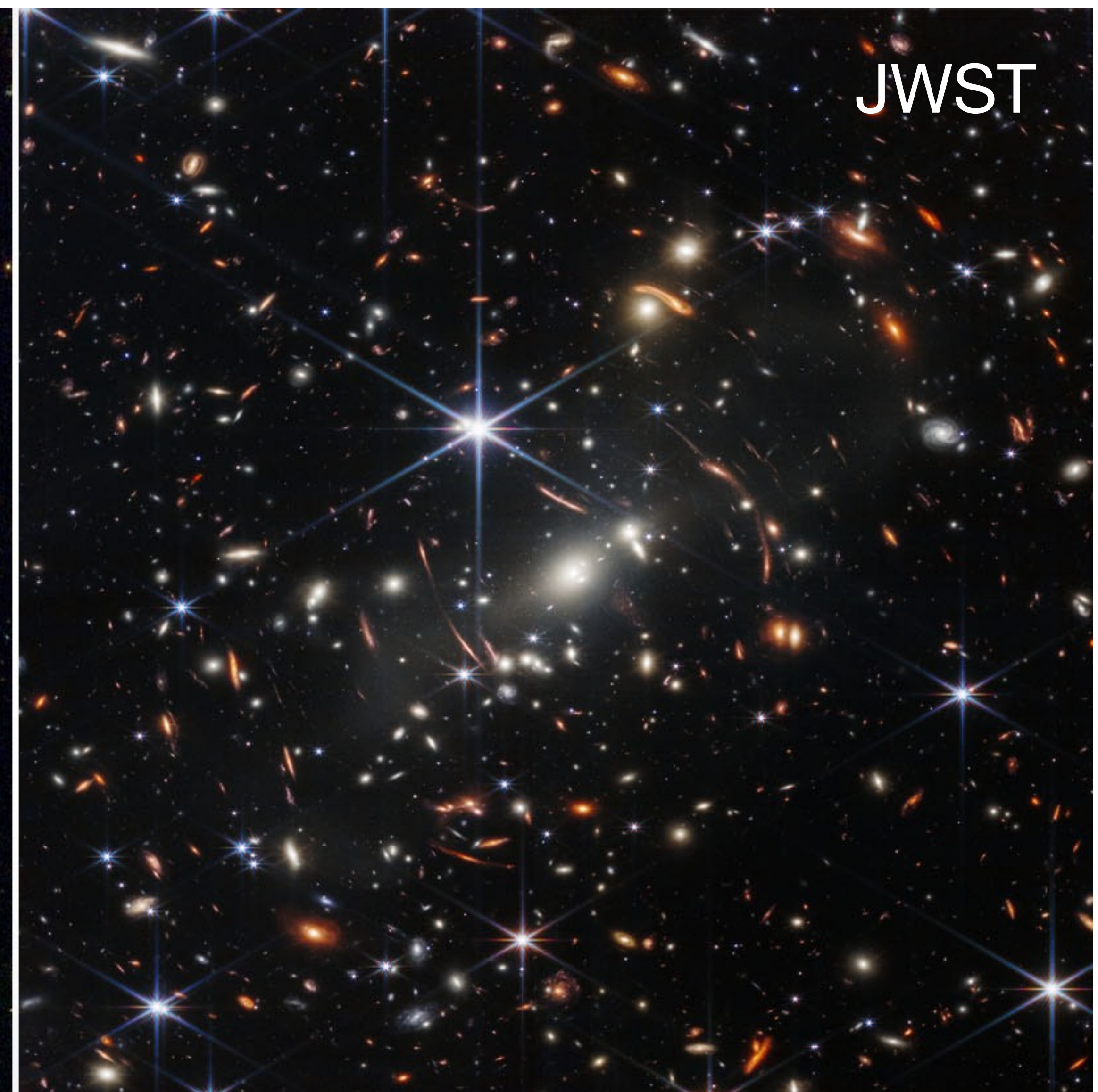


Image credit: NASA, ESA, CSA, and STScI

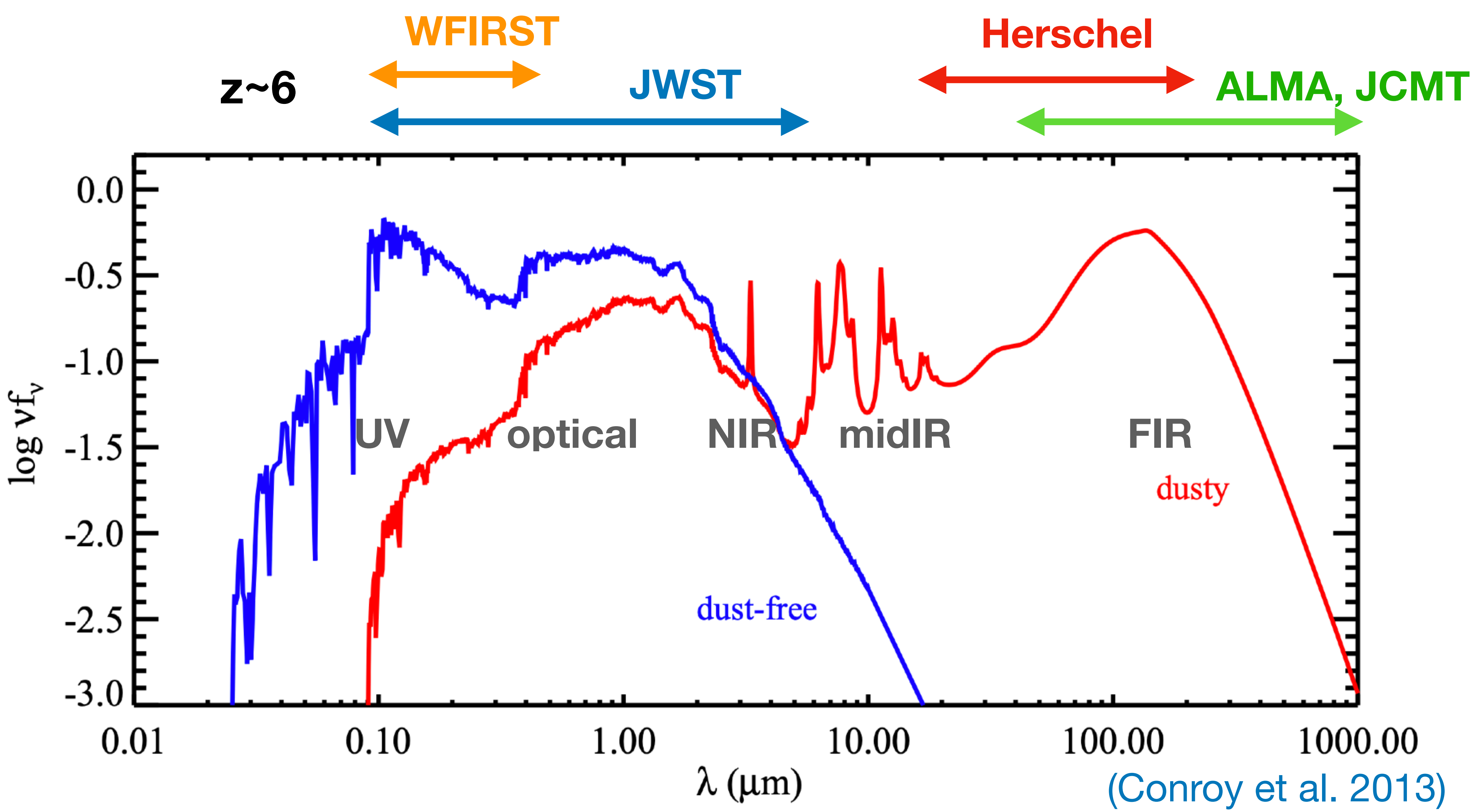
High-redshift galaxies

- New era of observations of early galaxies with JWST

deeper imaging

wavelength coverage
higher redshift

spectroscopy
optical emission lines



(Conroy et al. 2013)

High-redshift galaxies

- New era of observations of early galaxies with JWST

deeper imaging

wavelength coverage
higher redshift

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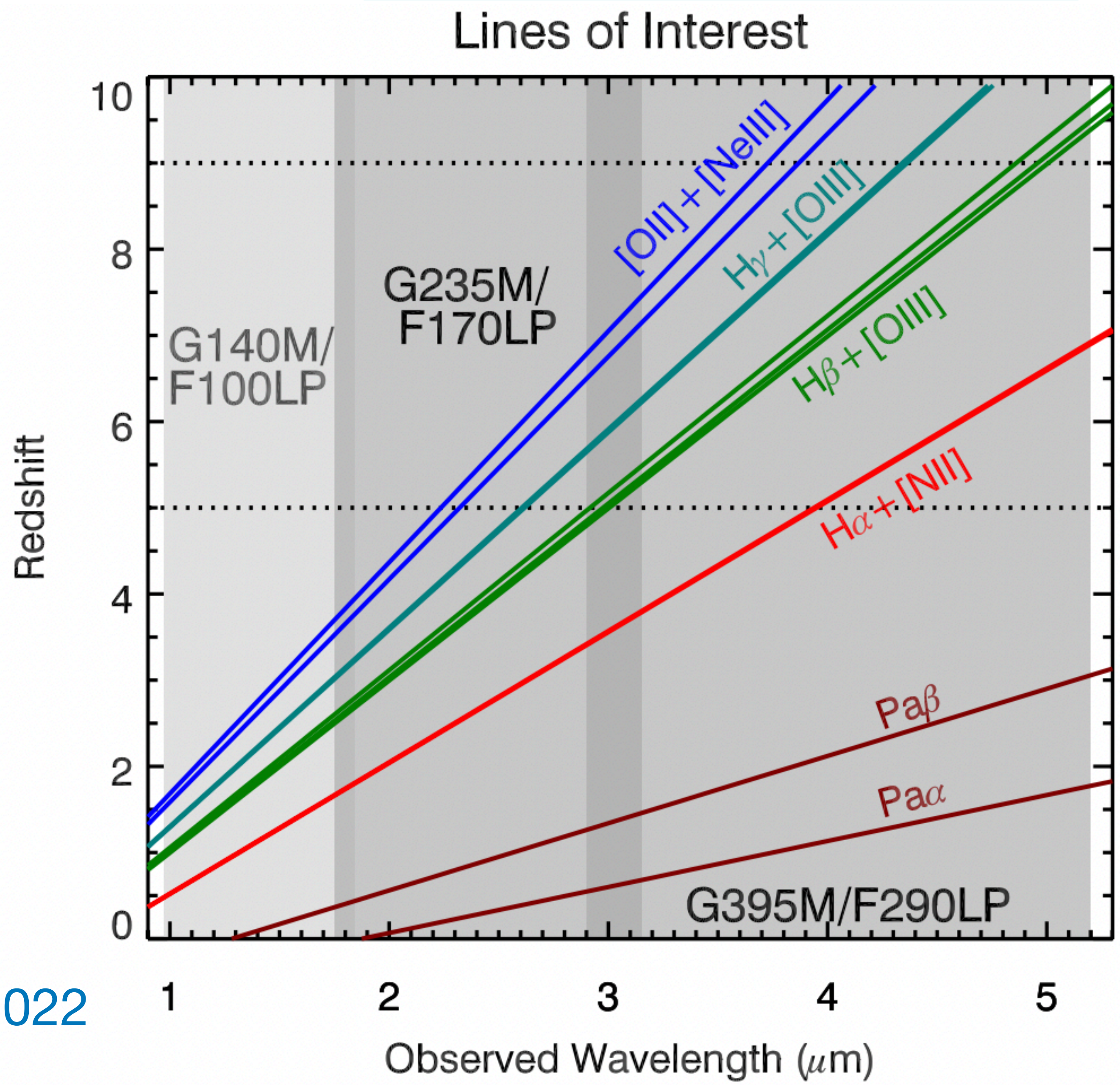
optical emission lines

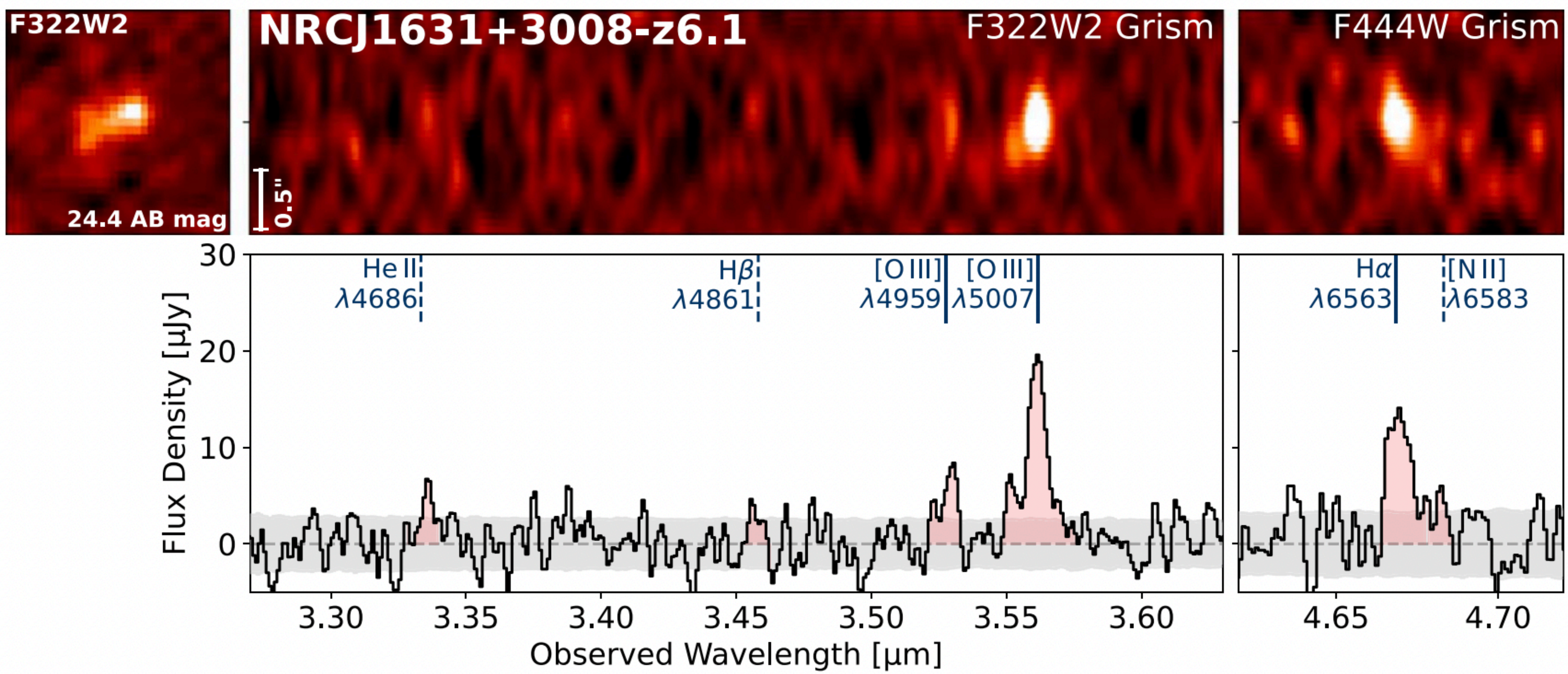


Trump et al. 2022

High-redshift galaxies

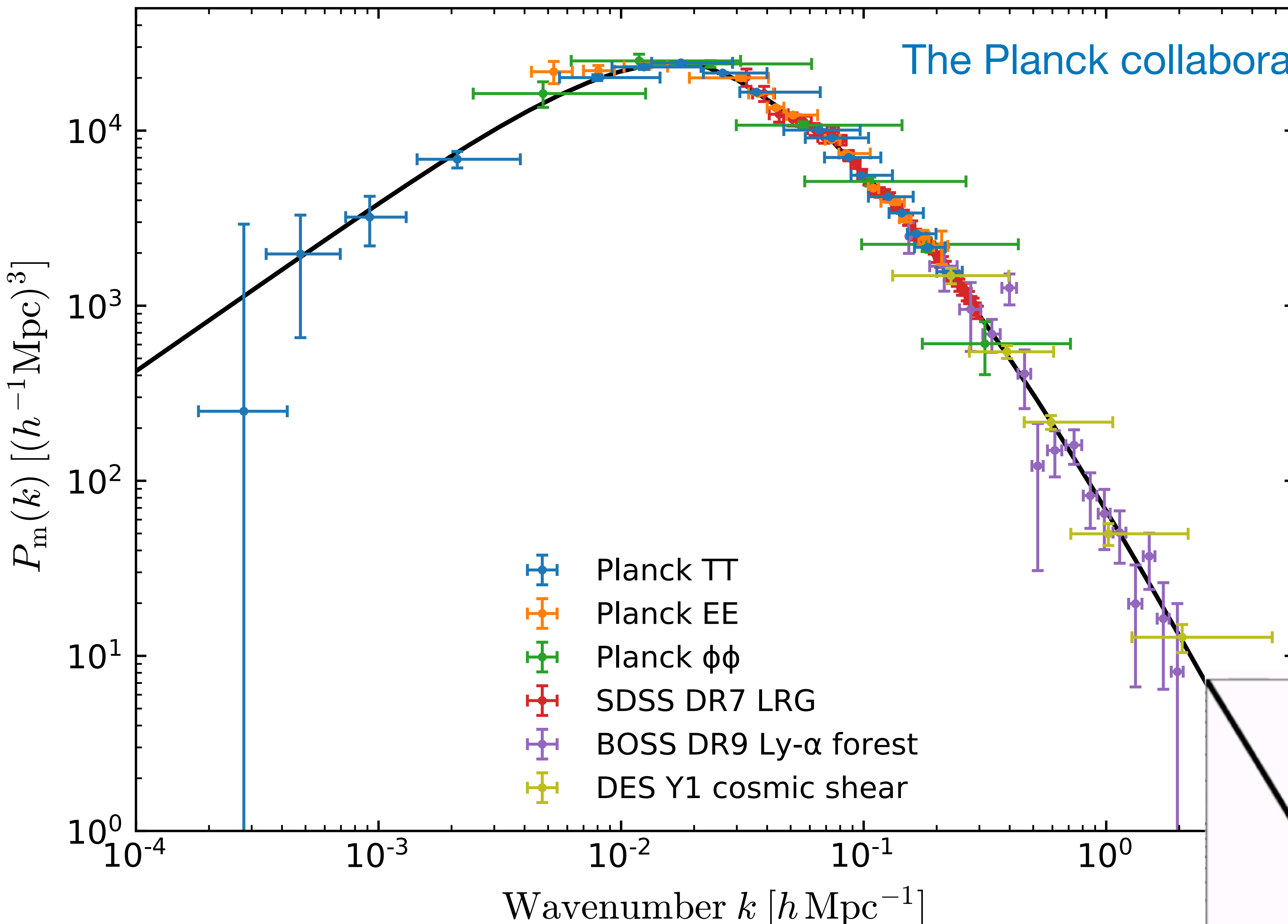
- New era of observations of early galaxies with JWST

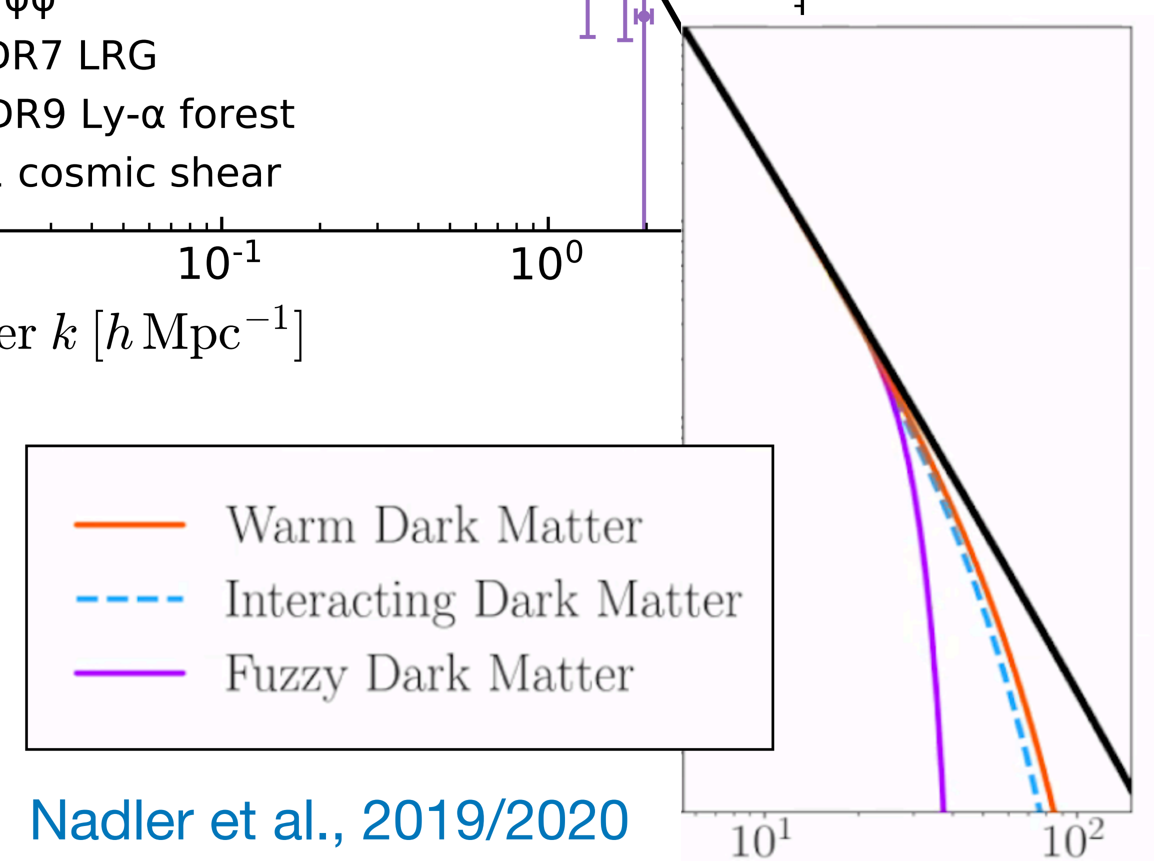
deeper imaging	wavelength coverage higher redshift	spectroscopy optical emission lines



a strong $[\mathrm{O\,III}]/\mathrm{H}\alpha$ emitter at $z = 6.11$ (Sun et al. 2022)

High-redshift galaxies – alternative dark matter



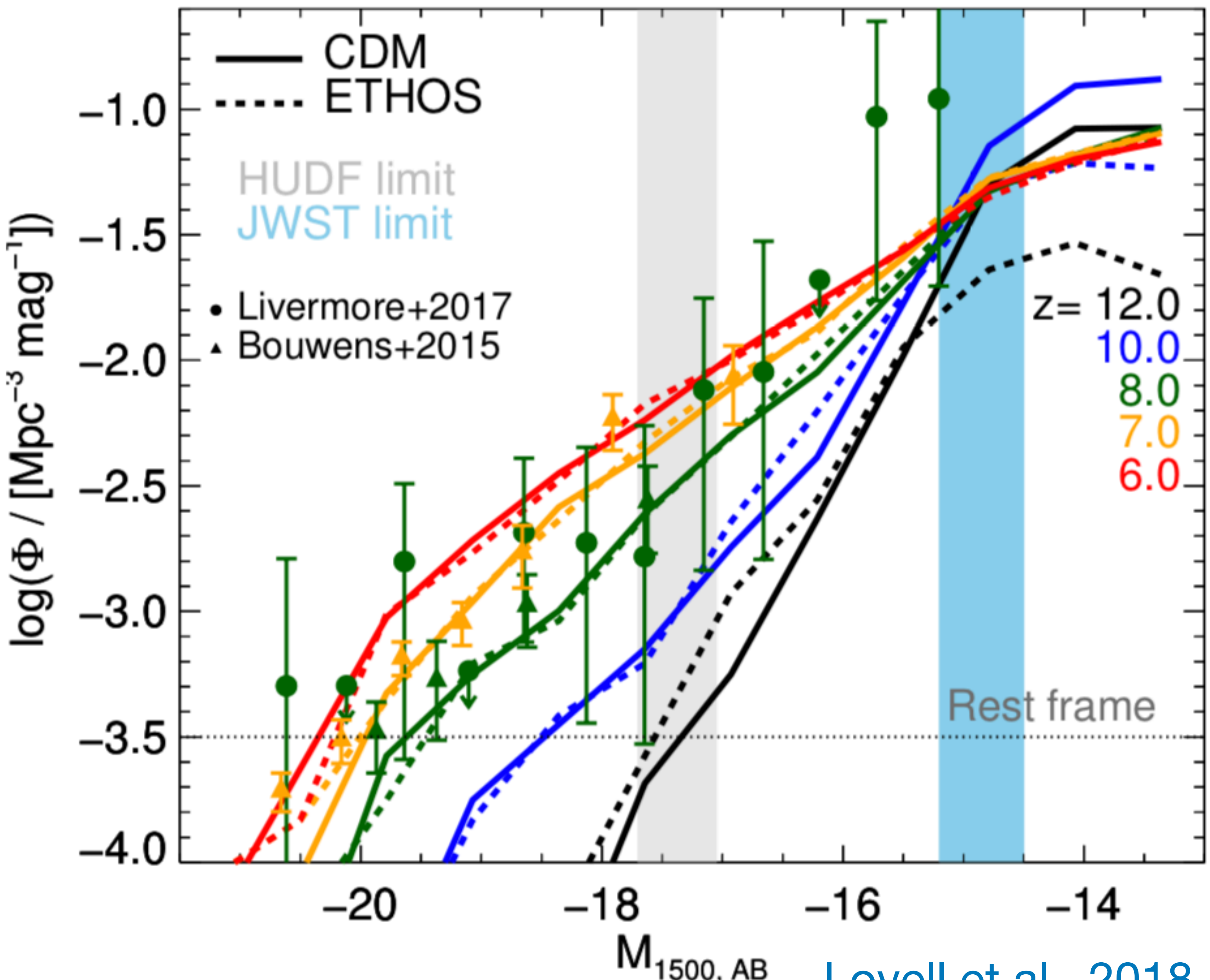


Nadler et al., 2019/2020

- Many alternative DM models predict small-scale suppression in the primordial power spectrum
- Delayed structure formation at high-z

High-redshift galaxies – alternative dark matter

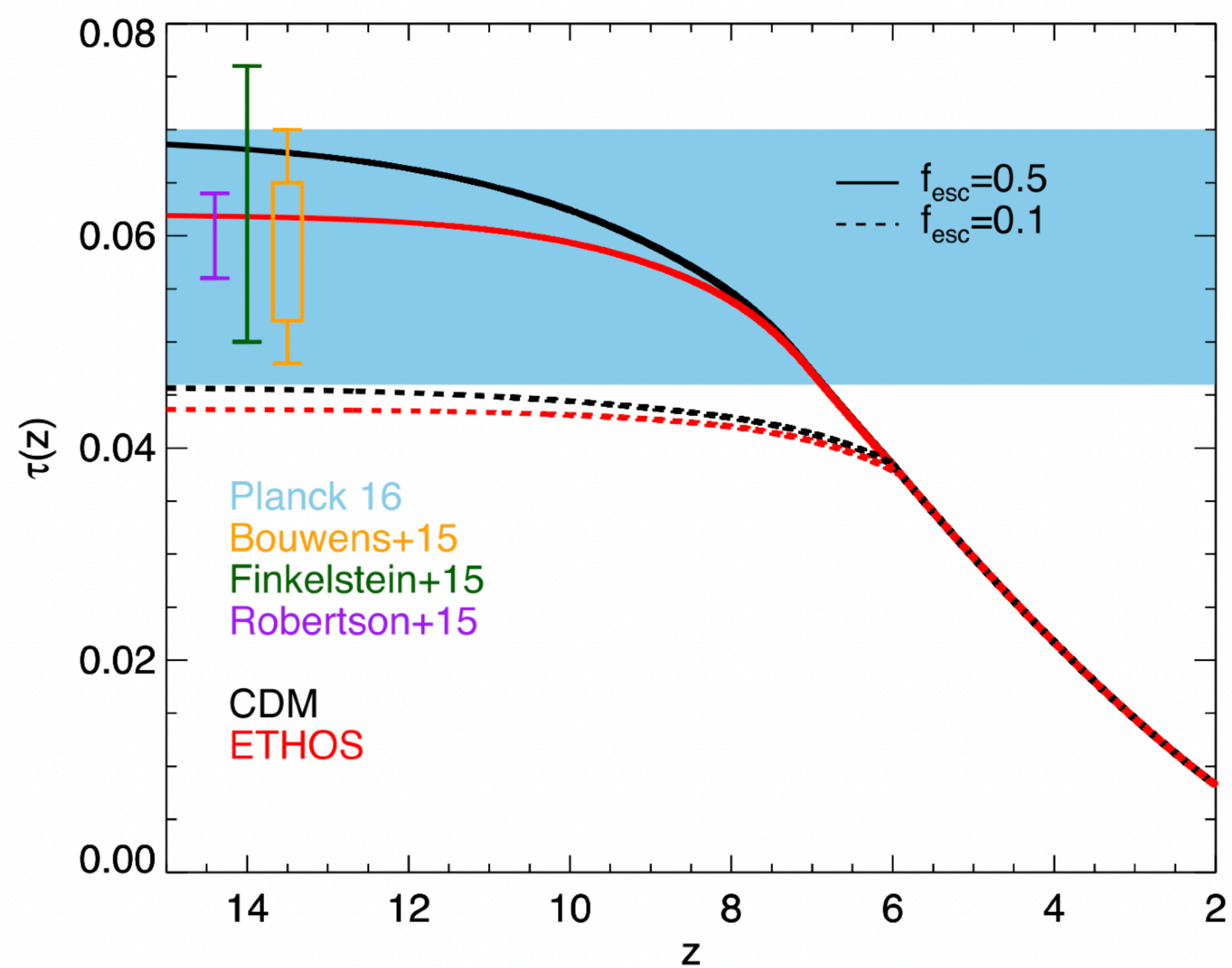
- Abundance of faint galaxies



Lovell et al., 2018

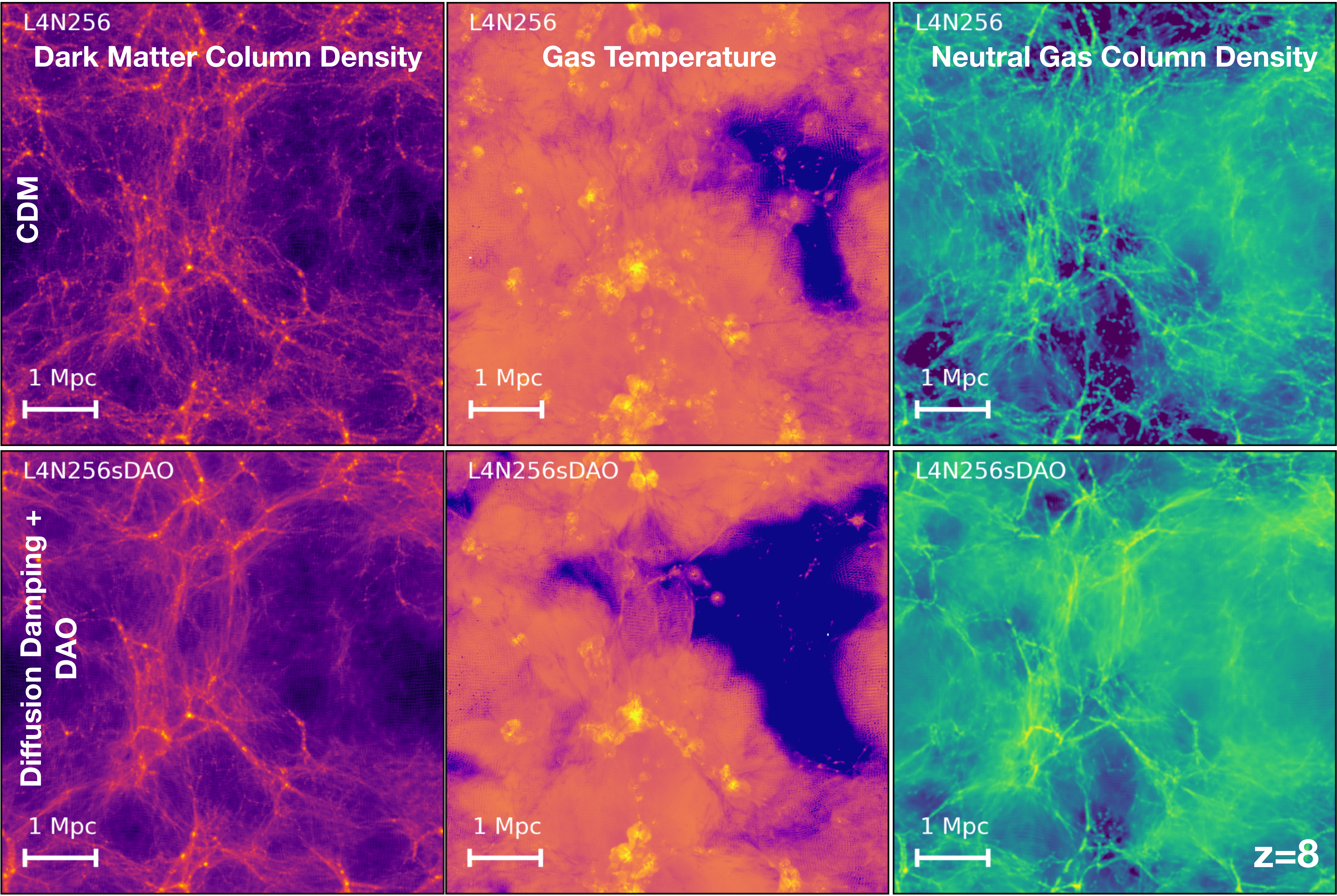
High-redshift galaxies — alternative dark matter

- Abundance of faint galaxies
- CMB optical depth



Lovell et al., 2018

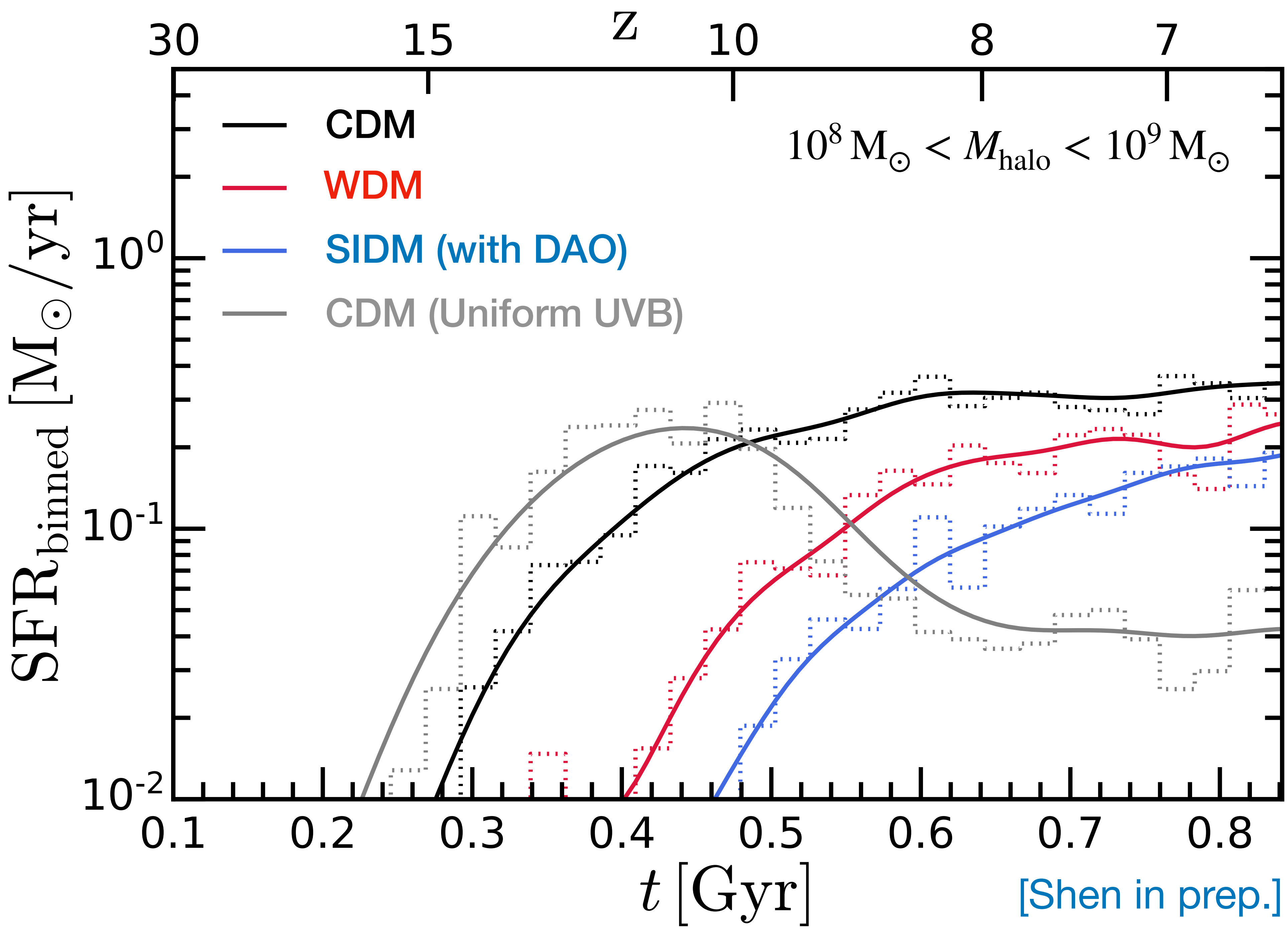
- IGM at Mpc scale Kannan et al. 2022, Smith et al. 2022, Borrow in prep., Shen in prep.



High-redshift galaxies – alternative dark matter

- Star formation & metal enrichment history
- Back-reaction of reionization on faint galaxies

THESAN-hr (Borrow in prep.)



[Shen in prep.]

Summary

Physically-motivated models, less explored

- DM with dissipative self-interactions
  dSIDM suite; Atomic DM
- QCD axions
  axion miniclusters with post-inflation origin

Regimes to study interplay of baryonic and DM physics

- Massive galaxies, galaxy clusters
  density profile, morphology
- High-redshift galaxies
  abundance of faint galaxies, reionization & IGM properties, star formation & metal enrichment history

Appendix