A detailed cosmological hydrodynamical simulation showing a complex galaxy cluster. The scene is dominated by a bright, yellowish-white central region, likely representing the core of a galaxy or a dense concentration of stars and gas. This core is surrounded by a vast field of blue and white stars, interspersed with wispy, translucent clouds of gas and dust. The overall color palette is a mix of deep blues, bright whites, and warm yellows, creating a rich, multi-colored stellar population. The background is a dark, star-filled space, suggesting a large-scale view of a galaxy cluster or a similar astrophysical environment.

Cosmological hydrodynamical simulation and Subaru Prime Focus Spectrograph

*East Asian Meeting on Large Galaxy Surveys for
Cosmology and Galaxy Formation
YITP, Kyoto; 05/06/2025*

Ken Osato

Center for Frontier Science, Chiba University



**Part I:
Cosmological
hydrodynamical
simulation**

Galaxy Formation Hydrodynamical Simulations

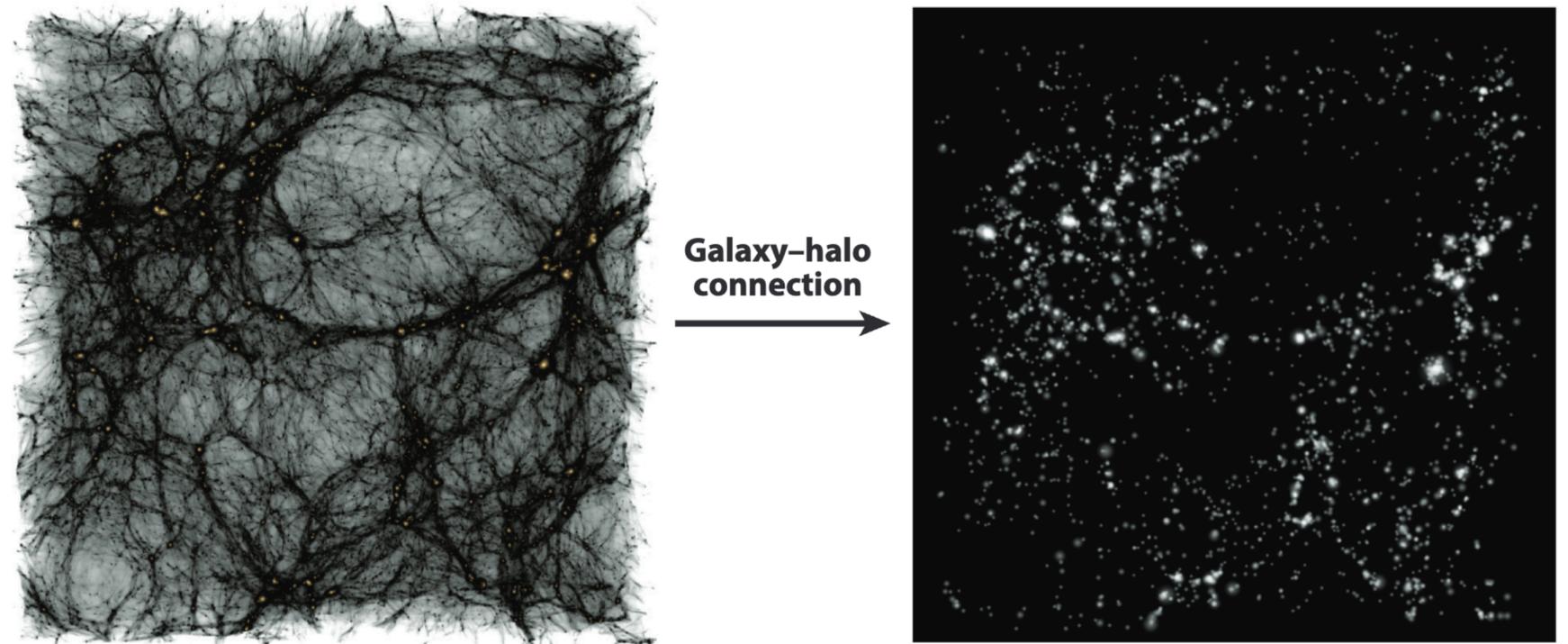
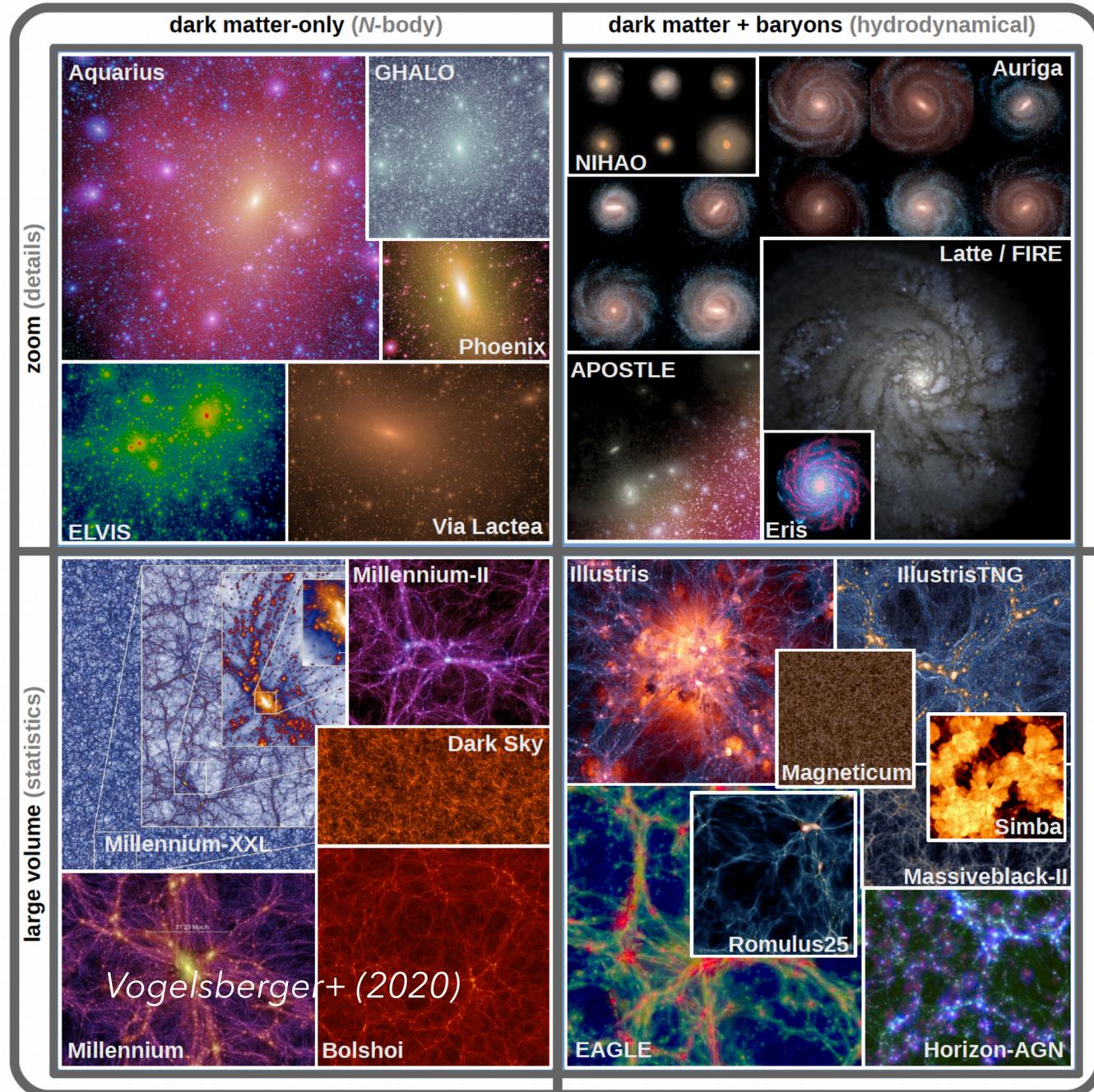
N-body

Hydro

• **Galaxy-halo connection**

Zoom

Cosmological



Approaches to modeling the galaxy-halo connection

Physical models		Empirical models		
Hydrodynamical simulations	Semianalytic models	Empirical forward modeling	Subhalo abundance modeling	Halo occupation models
Simulate halos and gas; star formation and feedback recipes	Evolution of density peaks plus recipes for gas cooling, star formation, feedback	Evolution of density peaks plus parameterized star formation rates	Density peaks (halos and subhalos) plus assumptions about galaxy-(sub)halo connection	Collapsed objects (halos) plus model for distribution of galaxy number given host halo properties

Wechsler & Tinker, 2018

Galaxy Formation Hydrodynamical Simulations

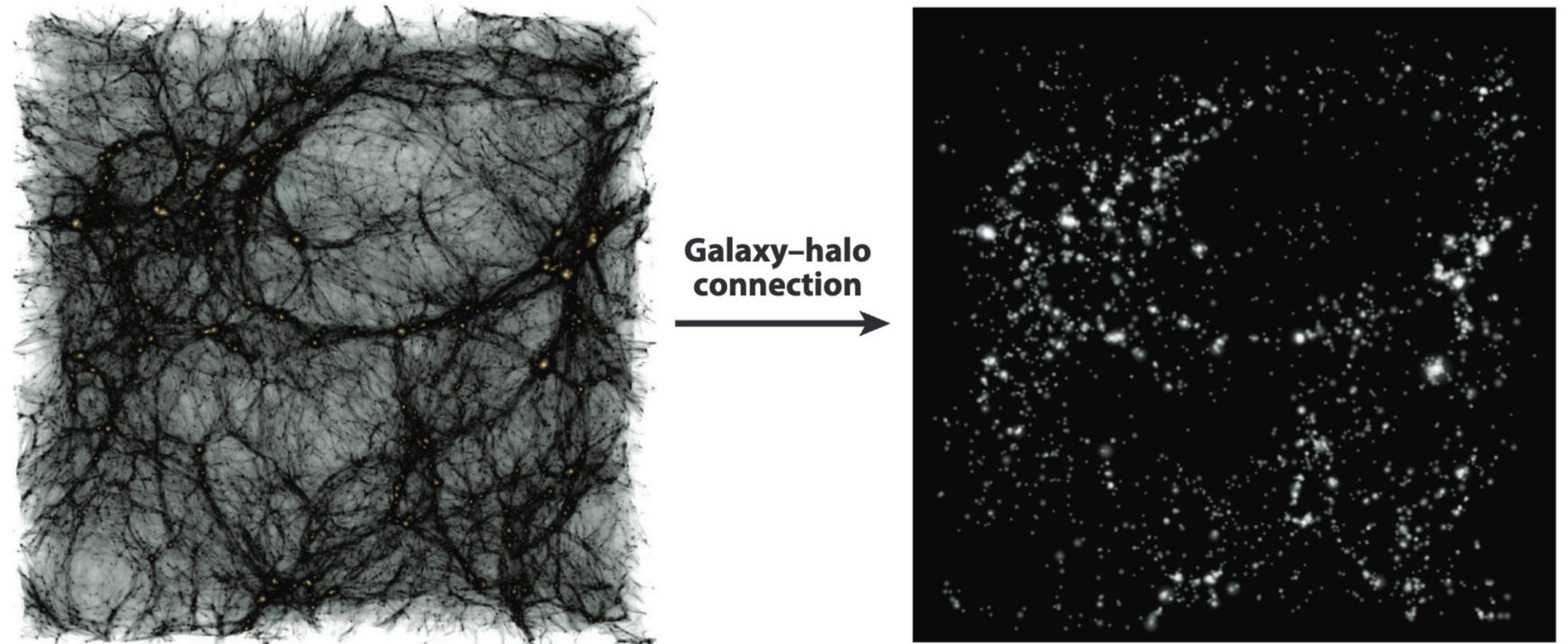
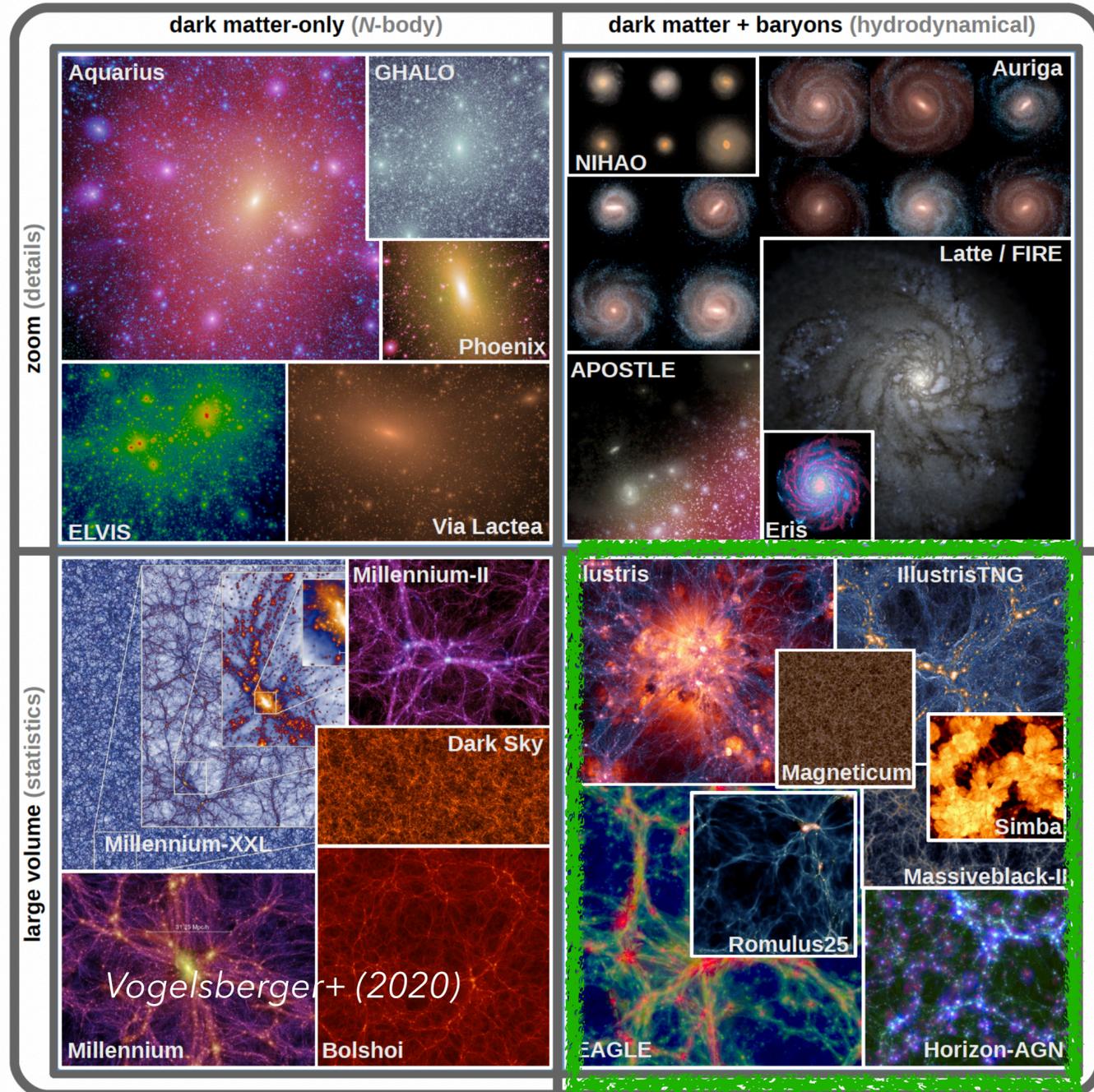
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Hydro

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Cosmological



Approaches to modeling the galaxy-halo connection

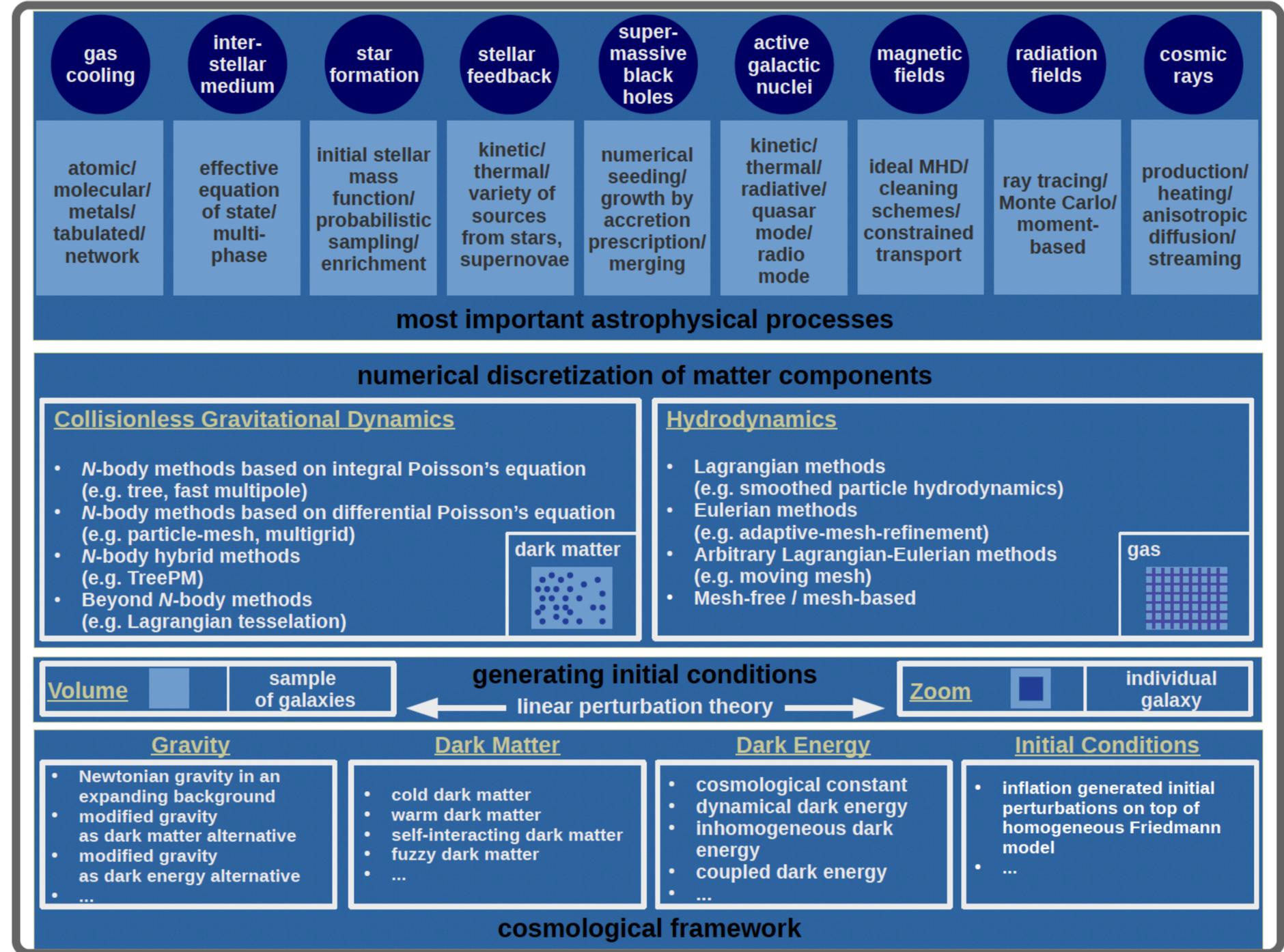
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This talk

Wechsler & Tinker, 2018

Physical Processes in Hydrodynamical Simulations

- ▶ Long range physics (kpc-Mpc)
 - Gravity
 - Hydrodynamics
- ▶ Subgrid physics/baryon phys. (AU - pc, kpc)
 - Star formation
 - Cooling (UV/X-ray background)
 - Stellar feedback (wind, SNe)
 - BH growth/AGN feedback
 - and more advanced ones*
 - Magnetic field
 - Cosmic rays
 - Radiative transfer



Vogelsberger+ (2020)

Hydrodynamics: Lagrangian v.s. Eulerian

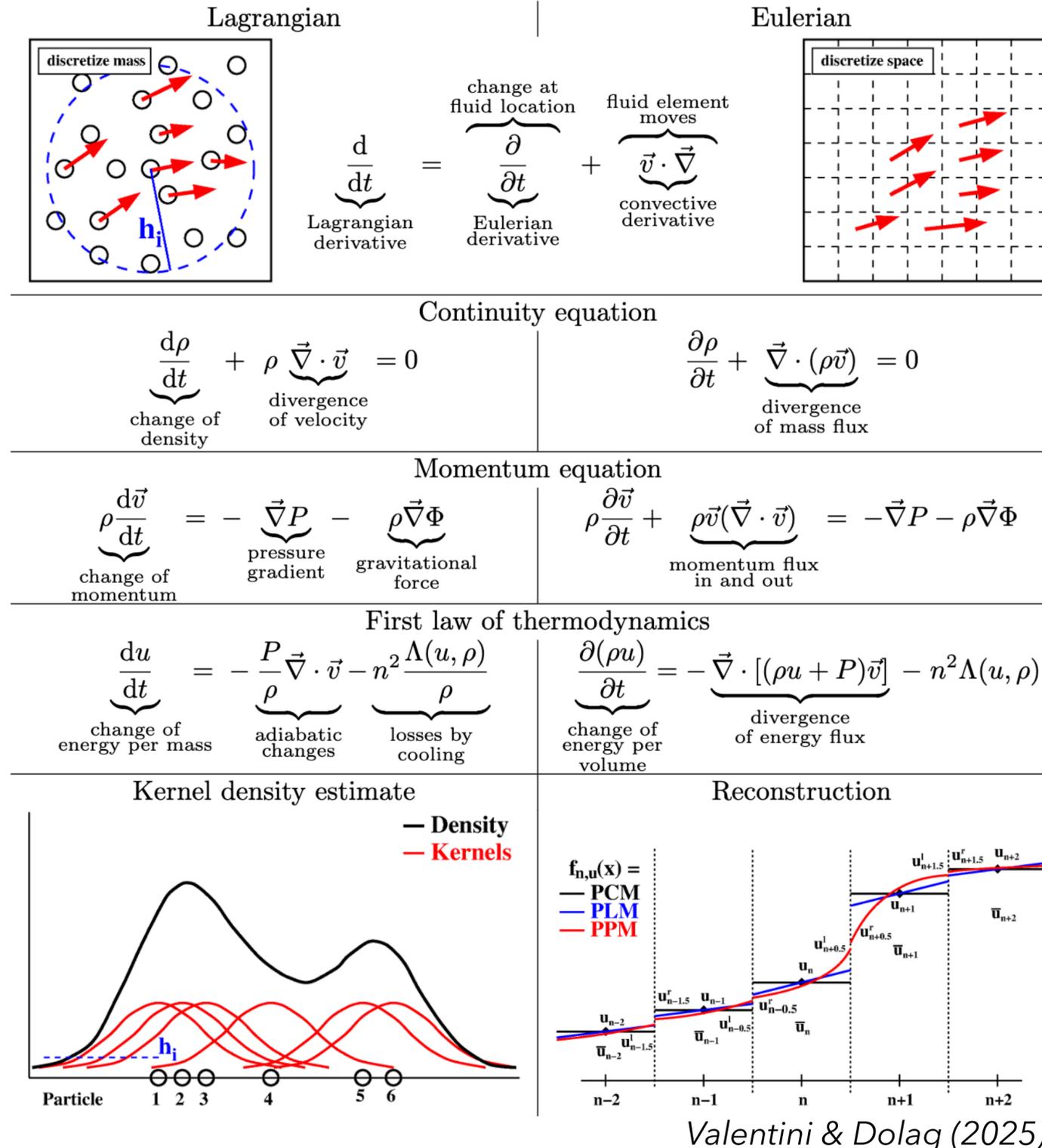
► **Lagrangian**
discretize with *particles*

✓ **Pros**

Robust computation
High density regions
resolved with more
particles

✗ **Cons**

Too robust even in
unphysical situations
Underdense region
not well resolved



► **Eulerian**
discretize with *grids*

✓ **Pros**

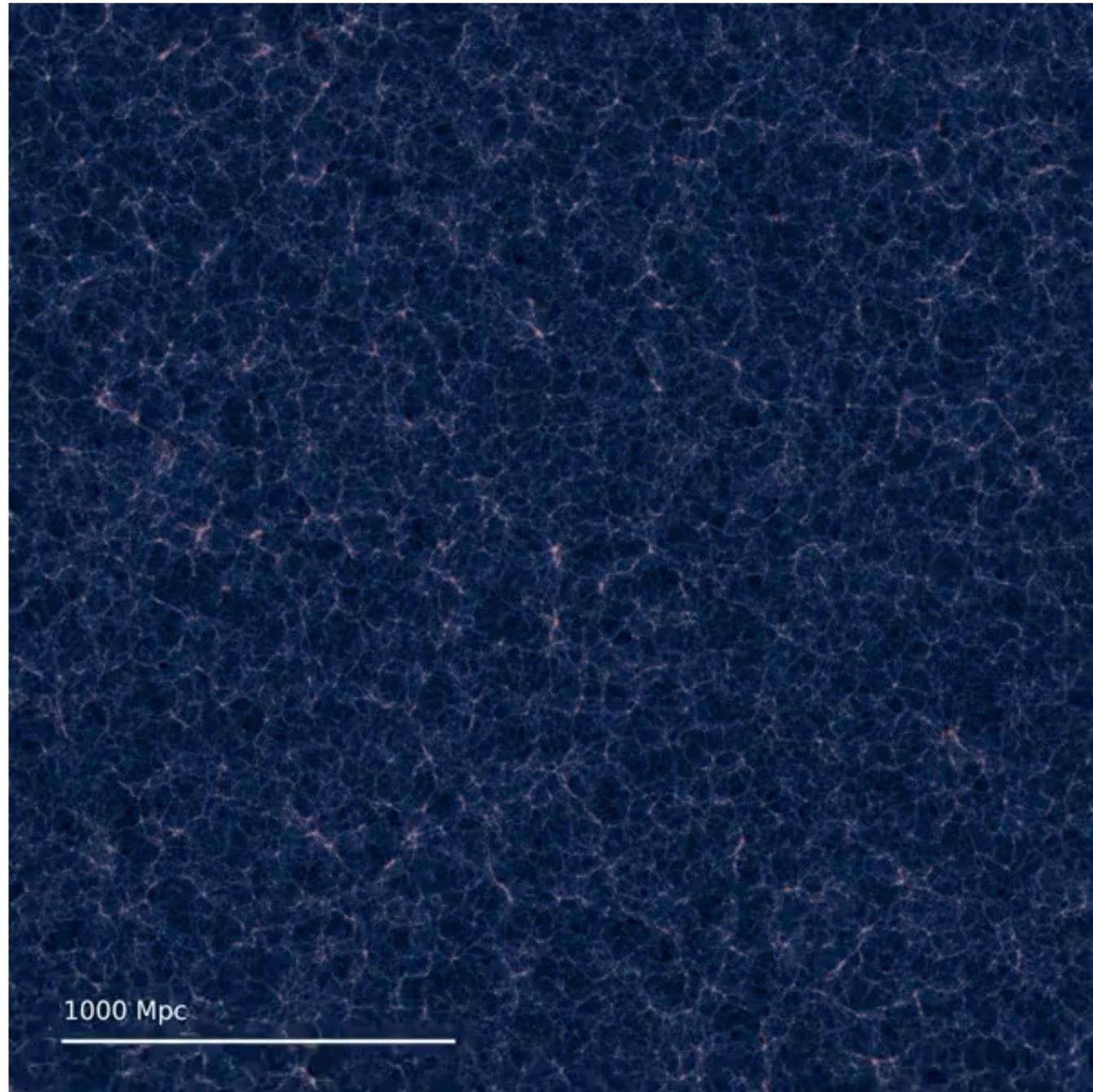
Uniform resolution
Better scaling

✗ **Cons**

Take costs even for
underdense regions
(can be mitigated
with mesh refinement)

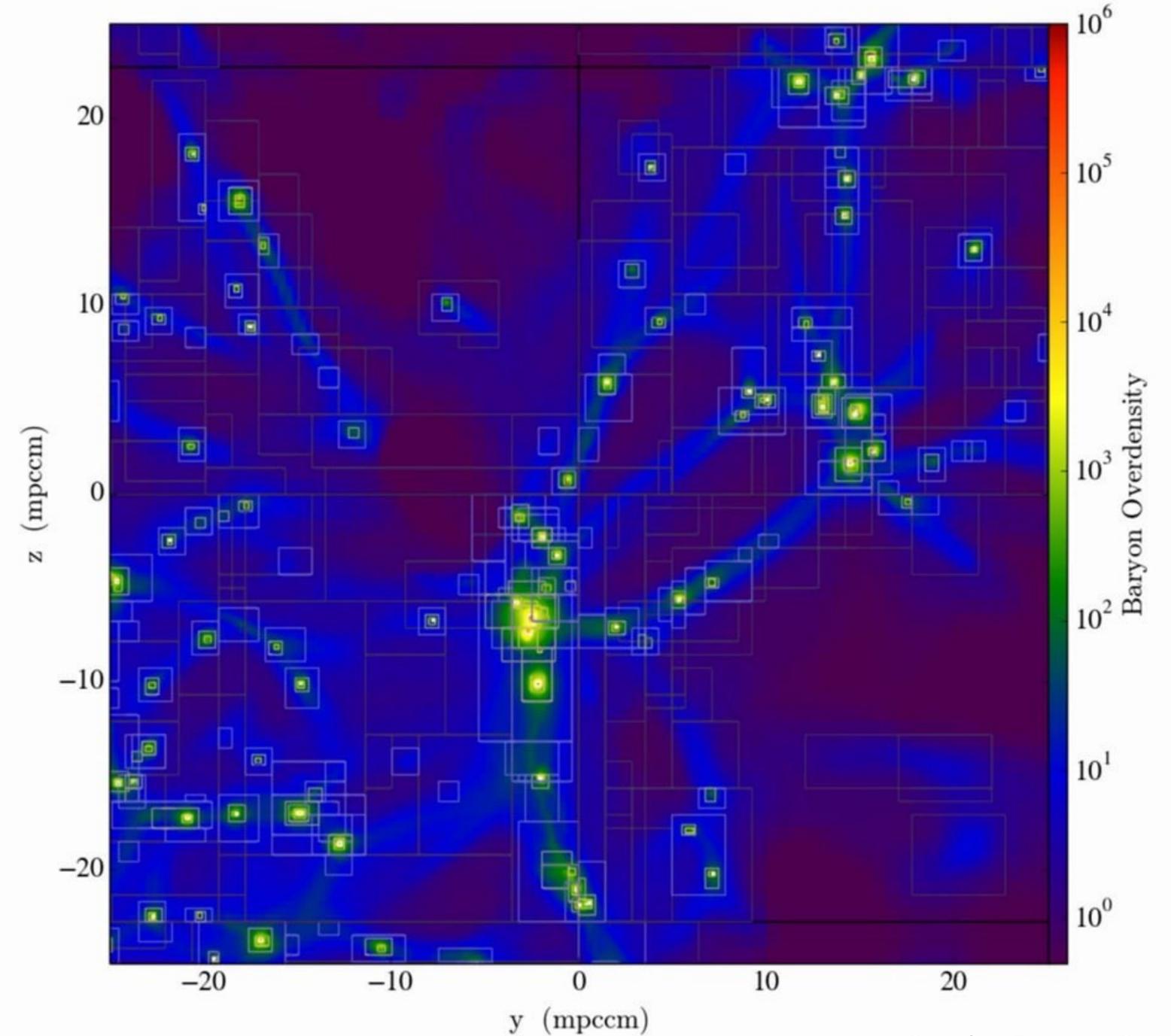
Hydrodynamics: Lagrangian v.s. Eulerian

► SWIFT: SPH (Lagrangian)



Credit: FLAMINGO team

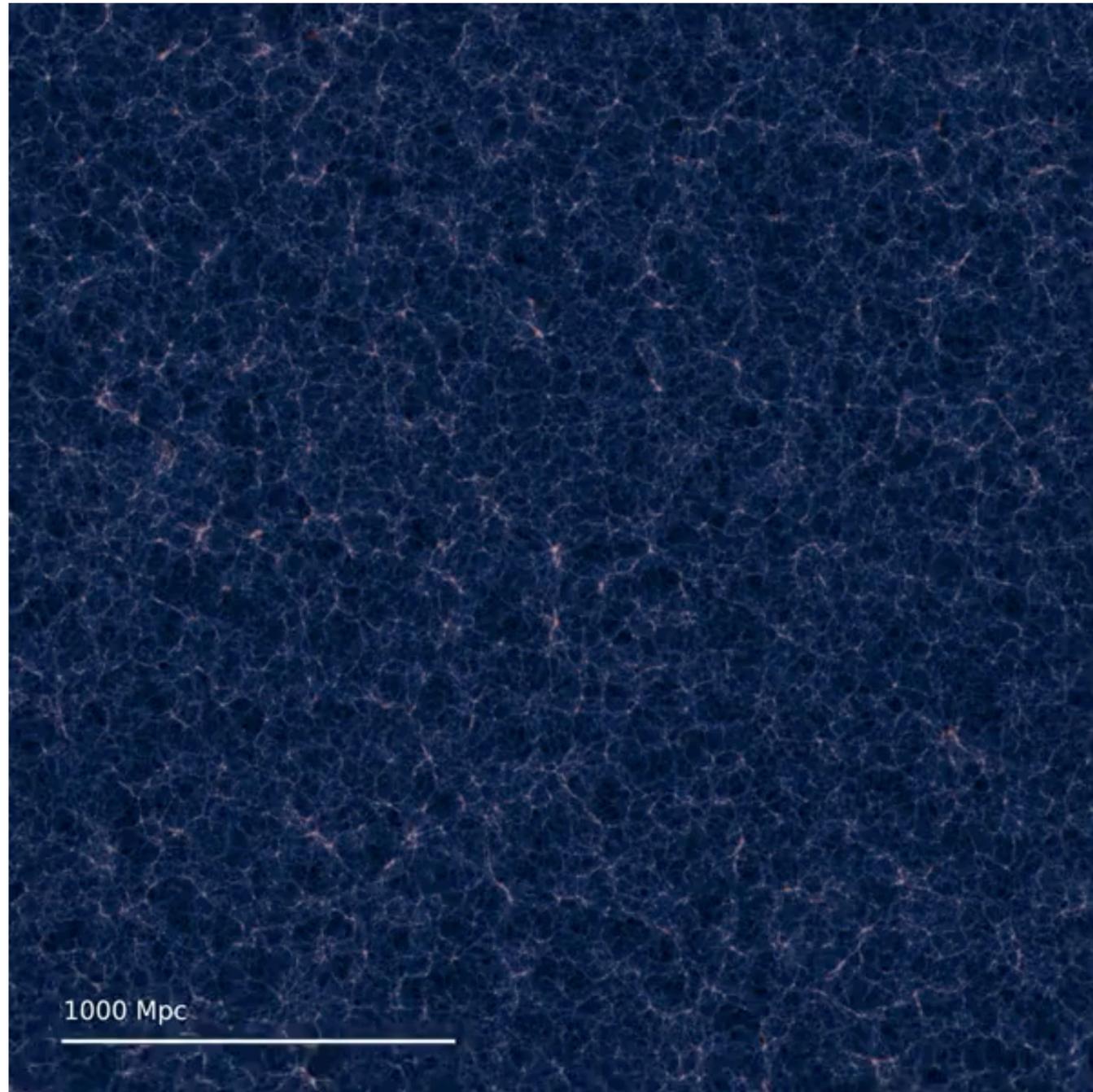
► Enzo: AMR (Eulerian)



Credit: Britton Smith

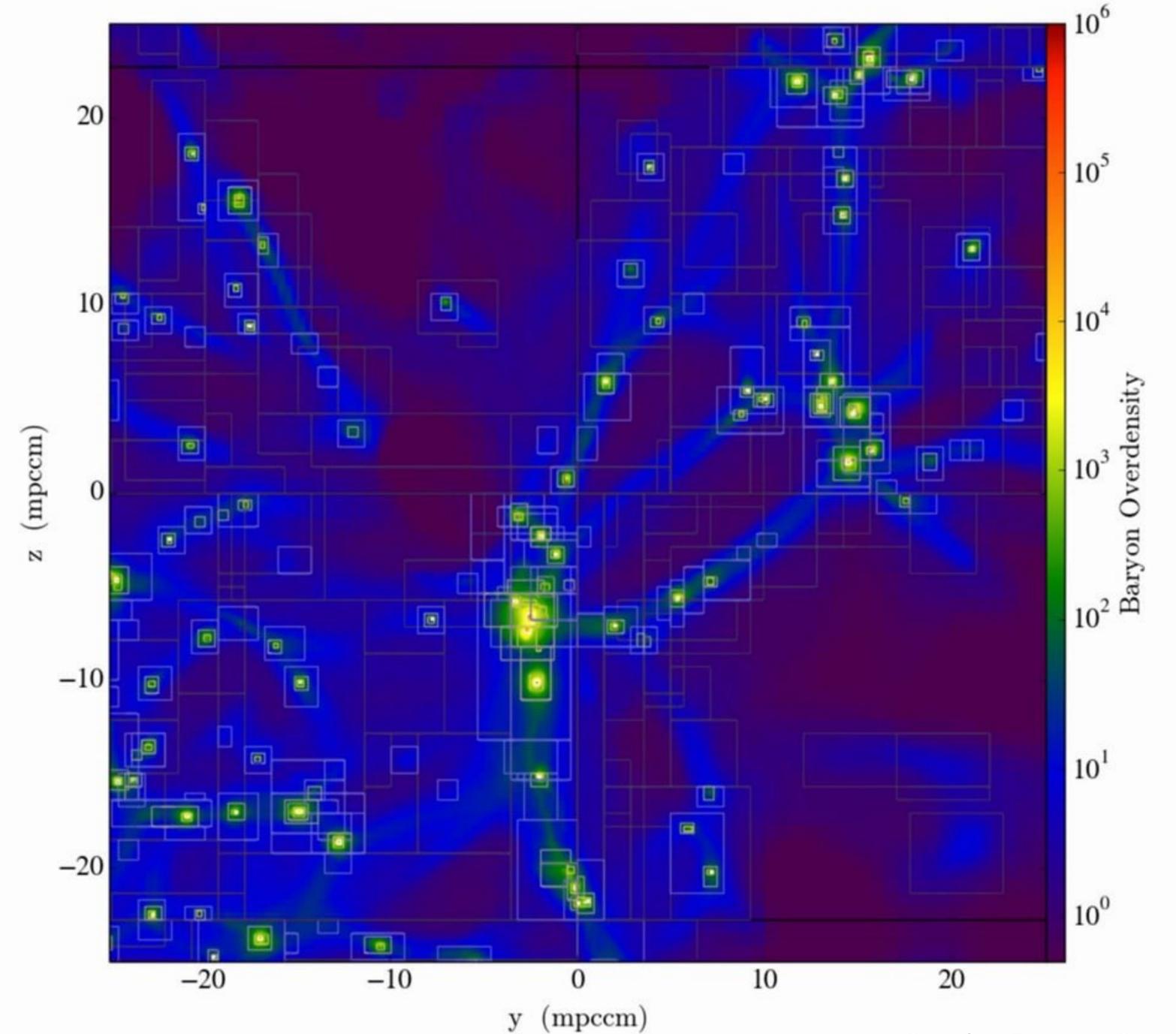
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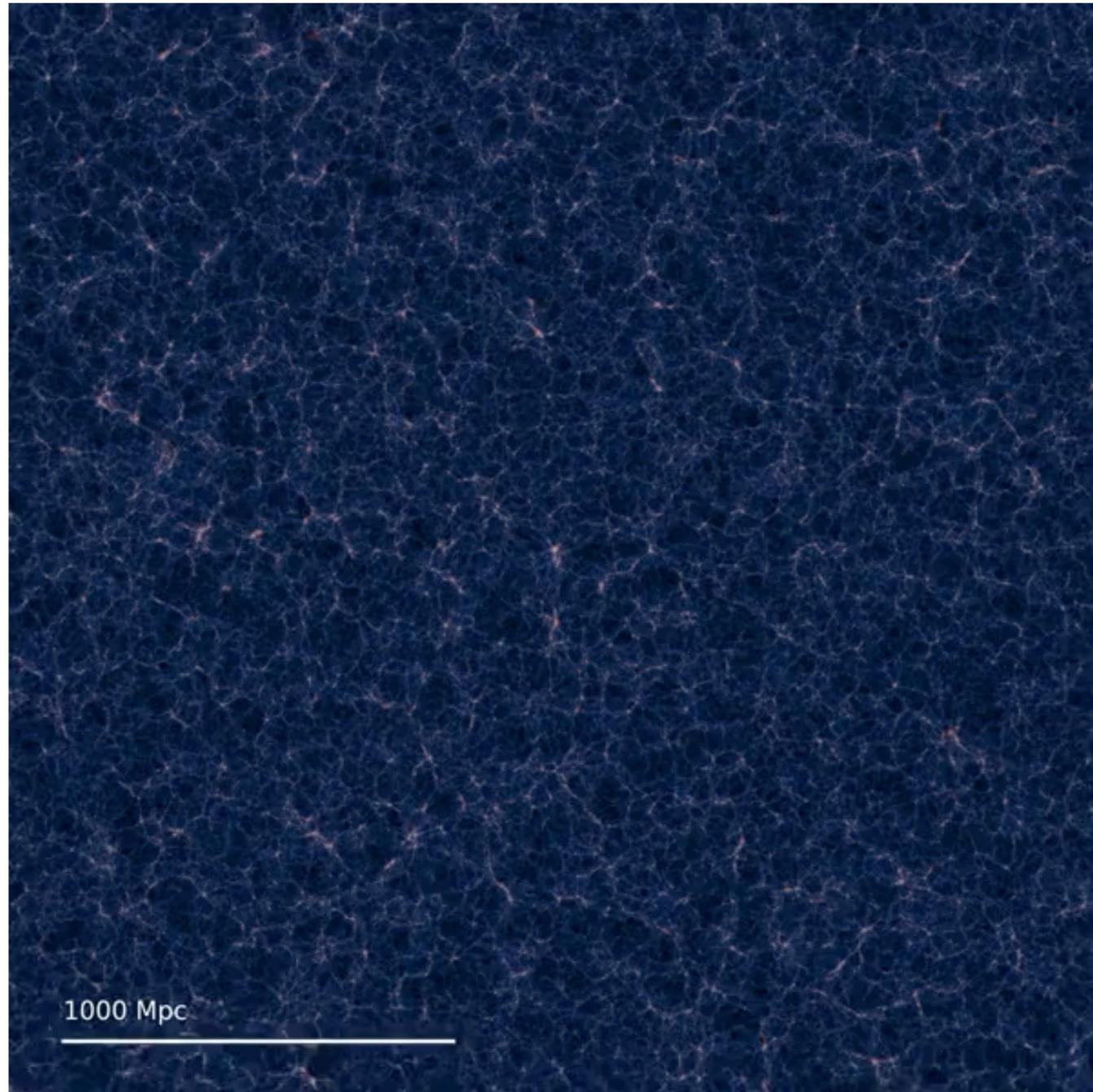
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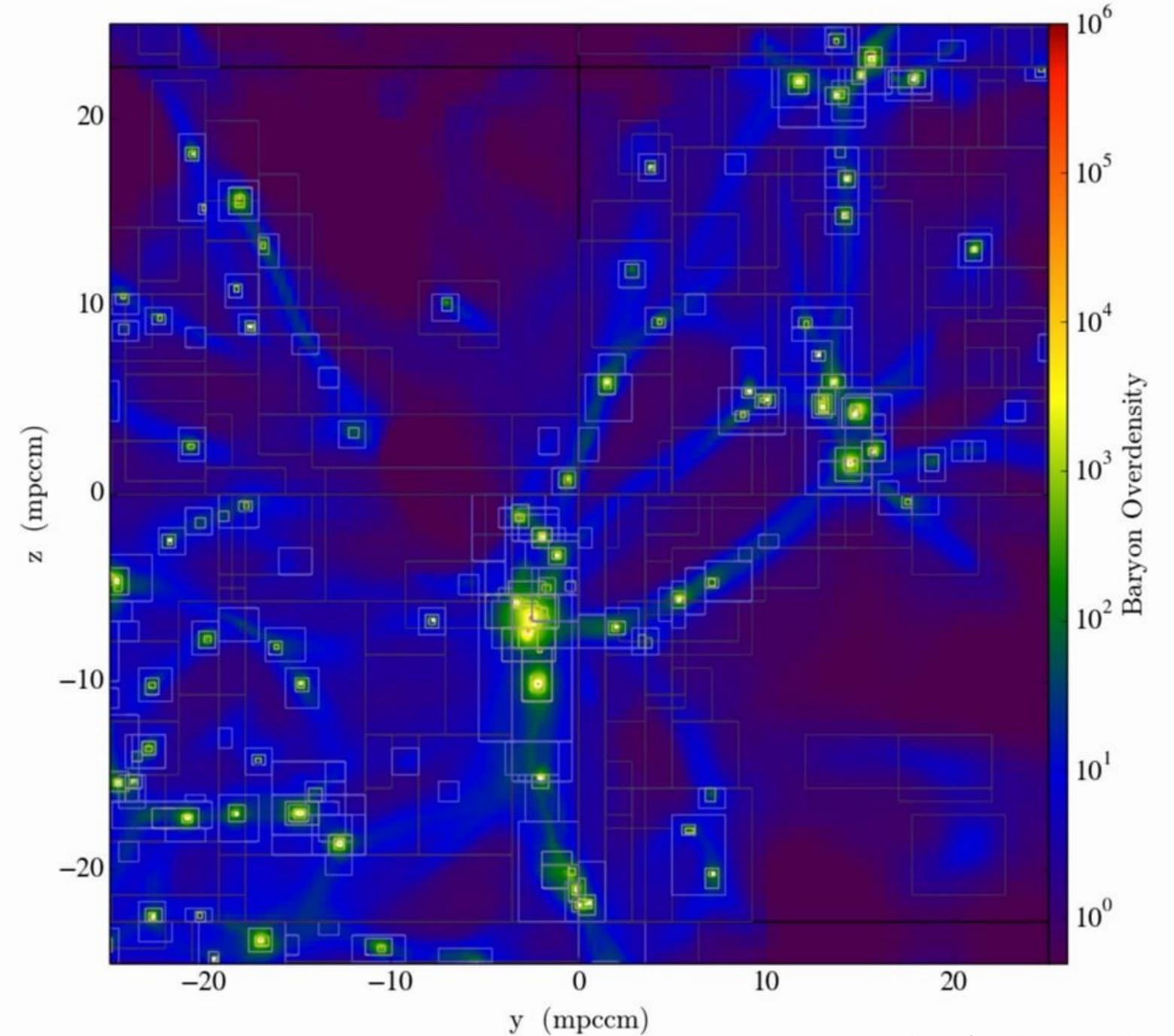
Hydrodynamics: Lagrangian v.s. Eulerian

► SWIFT: SPH (Lagrangian)



Credit: FLAMINGO team

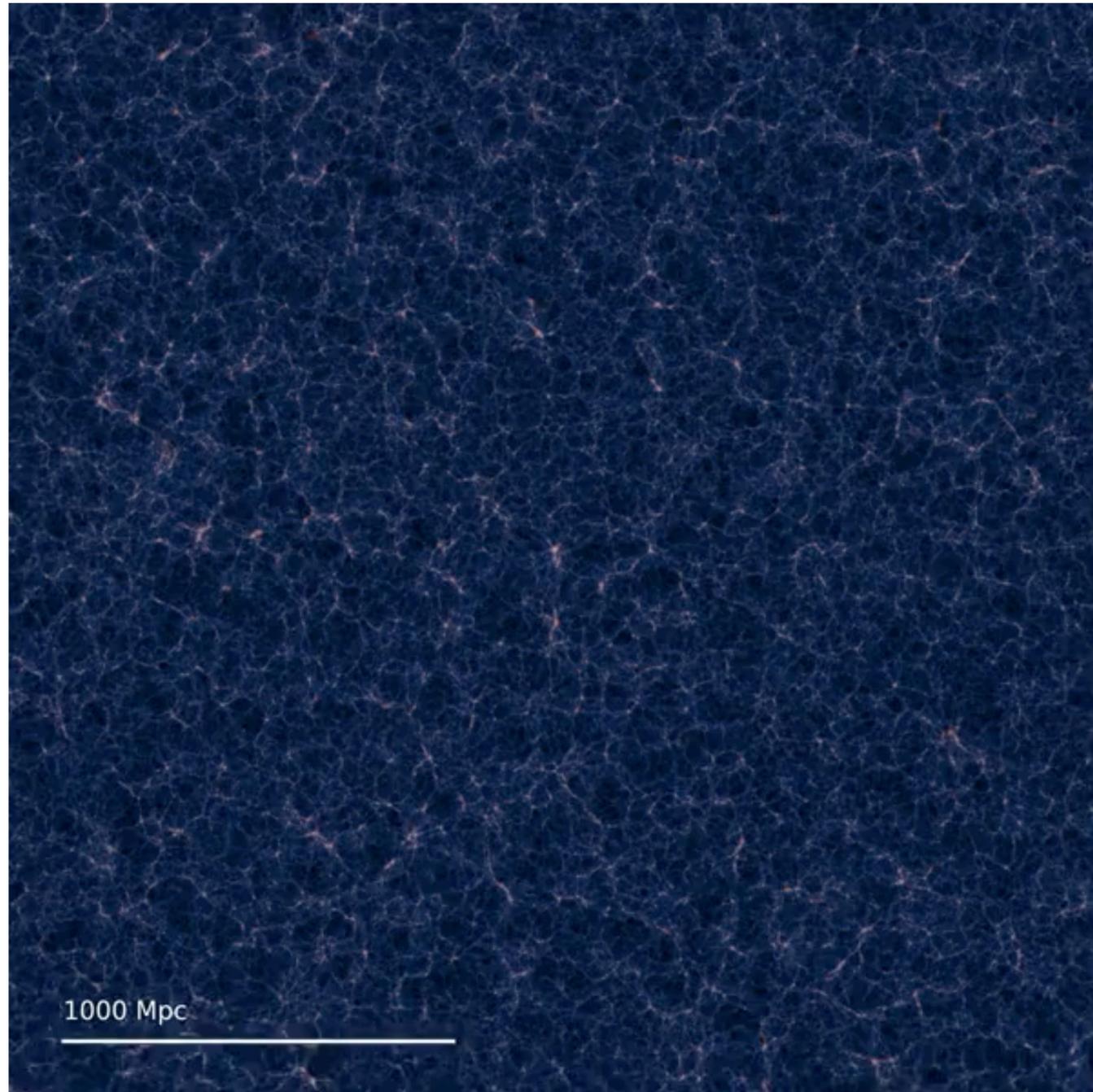
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Credit: Britton Smith

Hydrodynamics: Lagrangian v.s. Eulerian

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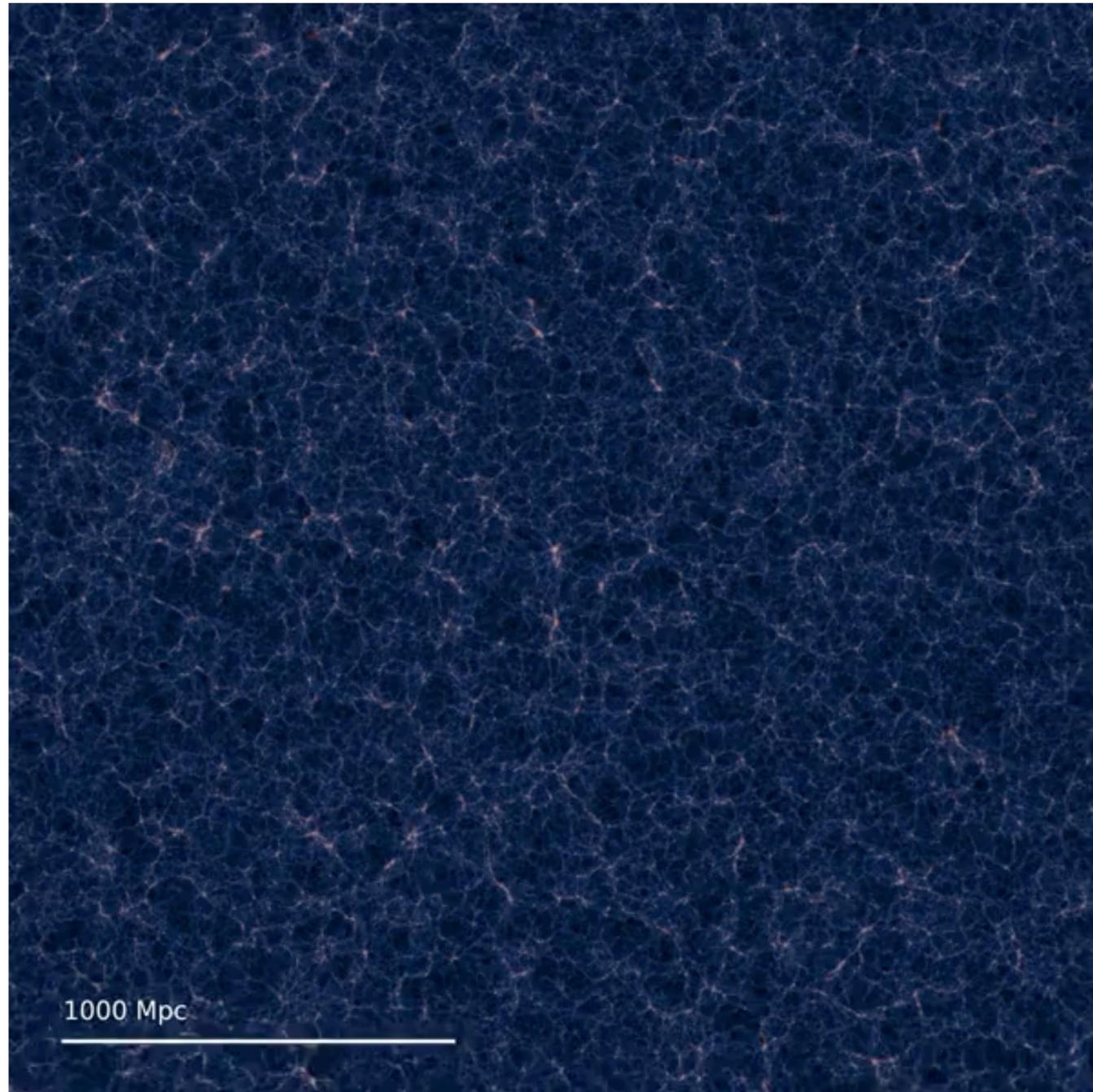


Credit: FLAMINGO team

- ▶ Hereafter, we focus only on Lagrangian (particle) methods.
- ▶ *Nomenclature*
 - *N*-body (DM only) simulation
= DM particles (collisionless)
 - Hydrodynamical simulation
= DM particles (collisionless)
+ gas particles (collisional)
+ star particles (collisionless)
- ◆ Caveat: Each particle does not correspond to a physical element (molecule, star), but an *assembly* of them (typically, 10^5 - $10^7 M_{\text{sun}}$).

Hydrodynamics: Lagrangian v.s. Eulerian

▶ SWIFT: SPH (Lagrangian)



Credit: FLAMINGO team

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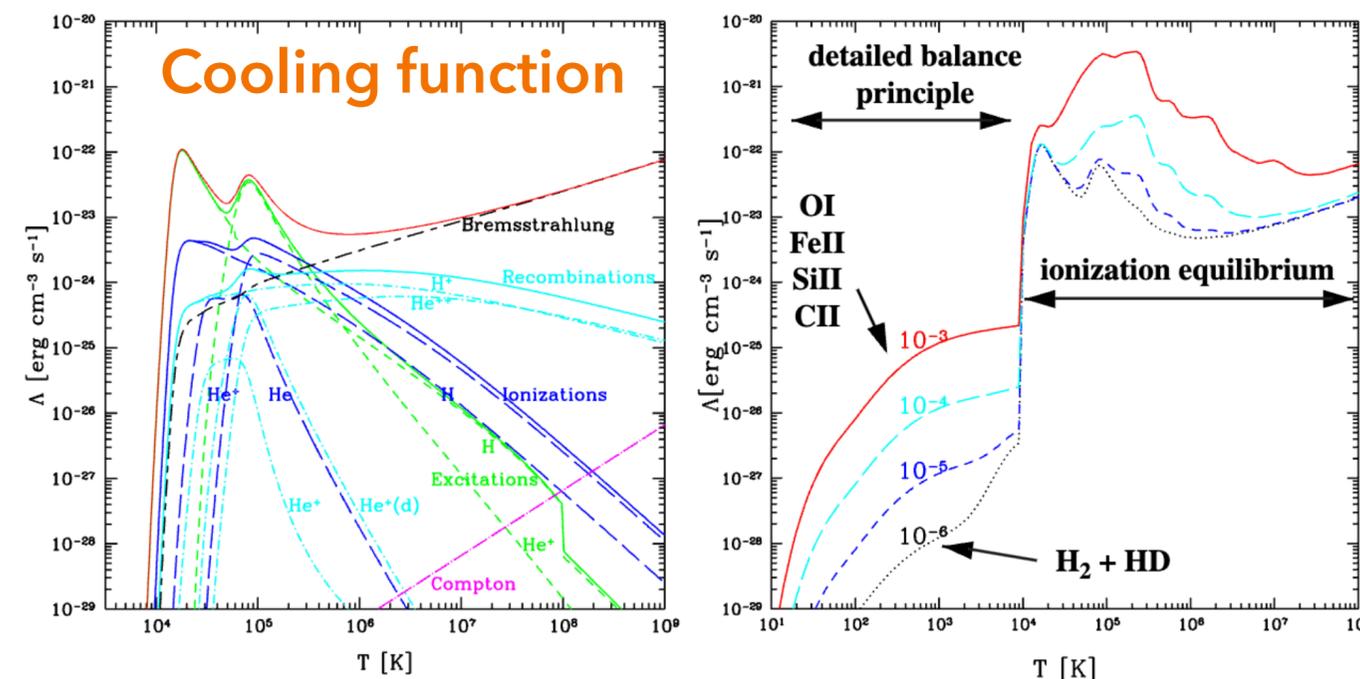
Radiative Cooling and Star Formation

- Radiative cooling

Gas cools through emissions. The cooling rate depends on the chemical composition.

- Multi-phase ISM model (Springel & Hernquist, 2003)

- **Hot gas:** cools due to thermal instability
- **Cold clouds:** deplete due to star formation, evaporate due to SN
- **Stars:** form from cold clouds, recycle to hot gas as SN



Maio+ (2007)

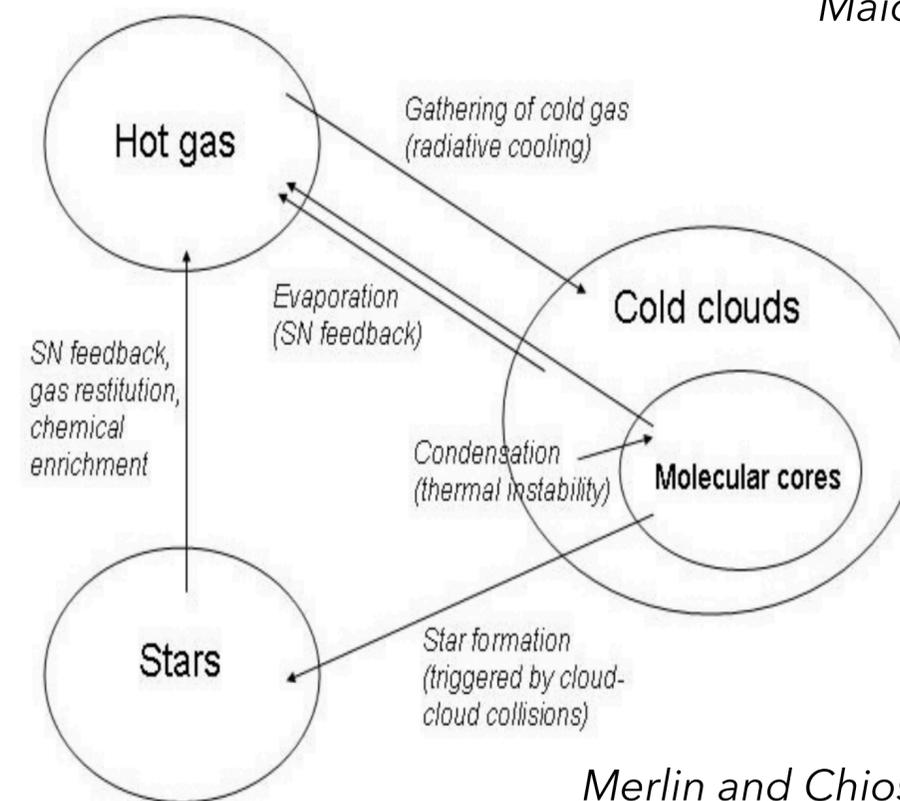
$$C \quad \frac{d\rho_c}{dt} = \underbrace{-\frac{\rho_c}{t_\star}}_{\text{SN evaporation}} - \underbrace{A\beta \frac{\rho_c}{t_\star}}_{\text{Star formation}} + \underbrace{\frac{1-f}{u_h - u_c} \Lambda_{\text{net}}(\rho_h, u_h)}_{\text{Thermal instability}}$$

$$H \quad \frac{d\rho_h}{dt} = \underbrace{\beta \frac{\rho_c}{t_\star}}_{\text{SN evaporation}} + \underbrace{A\beta \frac{\rho_c}{t_\star}}_{\text{Star formation}} - \underbrace{\frac{1-f}{u_h - u_c} \Lambda_{\text{net}}(\rho_h, u_h)}_{\text{Thermal instability}}$$

$$S \quad \frac{d\rho_\star}{dt} = \underbrace{\frac{\rho_c}{t_\star}}_{\text{SN explosion}} - \underbrace{\beta \frac{\rho_c}{t_\star}}_{\text{Star formation}} = (1 - \beta) \frac{\rho_c}{t_\star}$$

SN evaporation

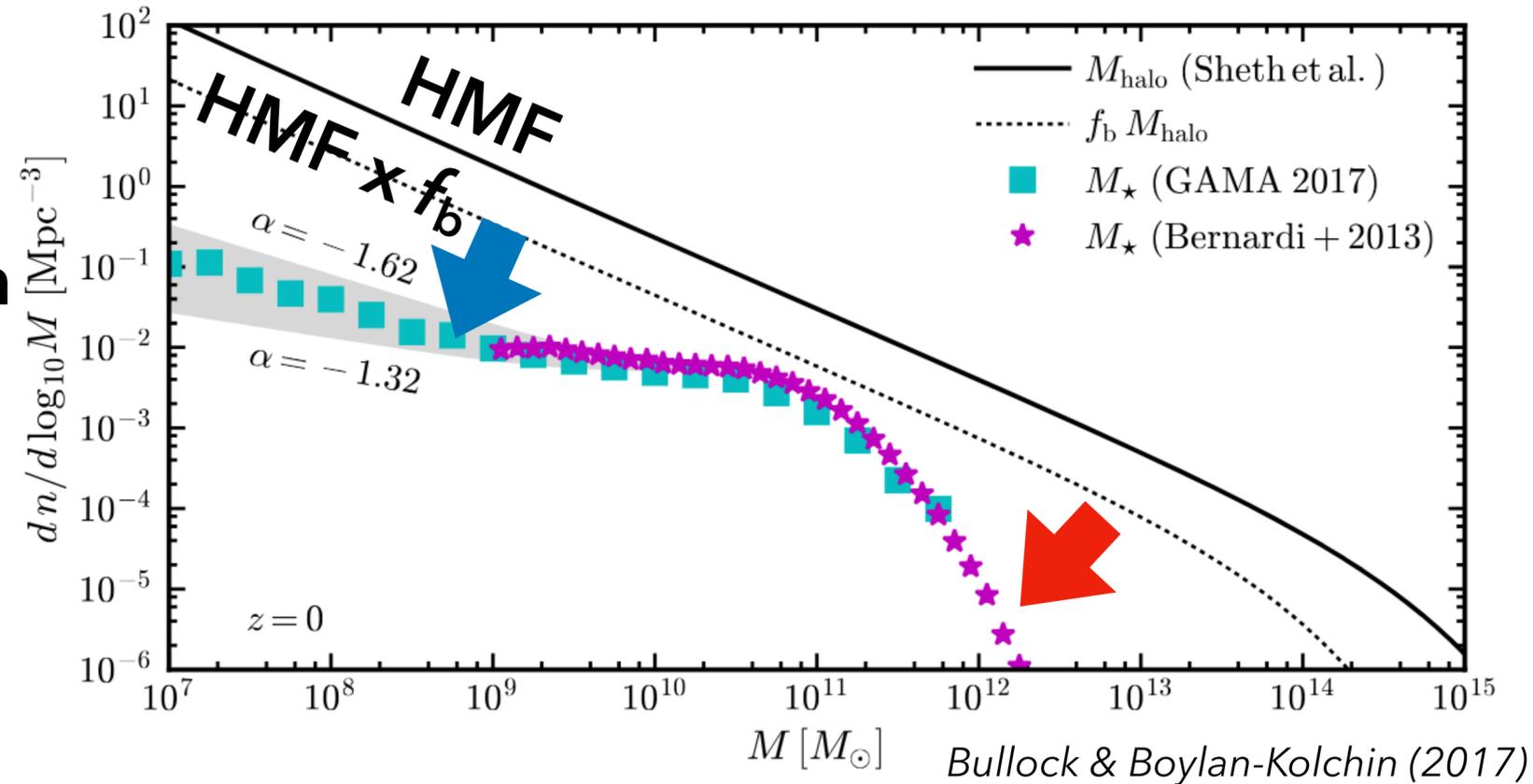
SN explosion



Merlin and Chiosi (2007)

Stellar and AGN Feedback

- **Stellar mass function**

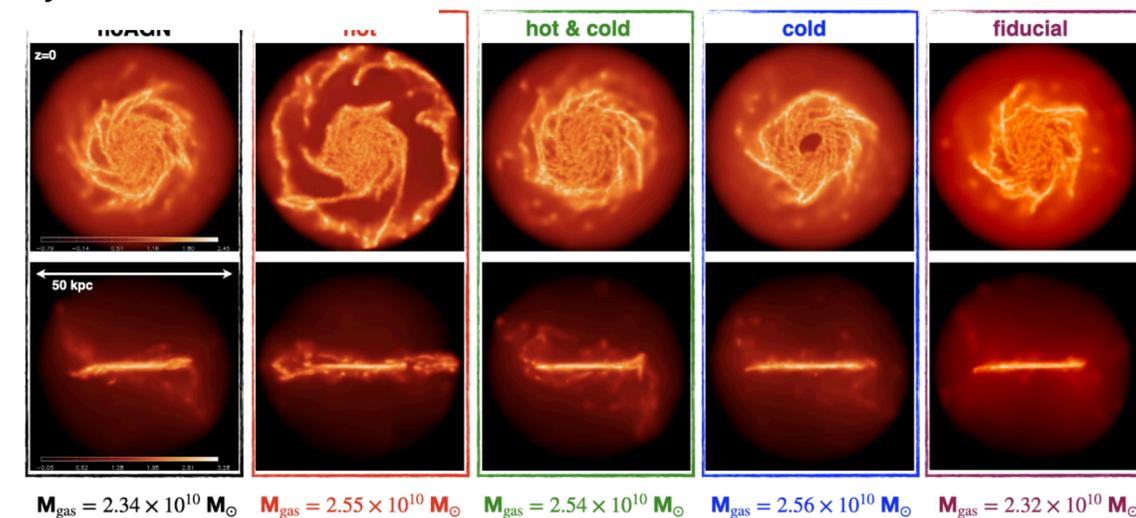


- **AGN feedback (SMBH)** quenches star formation of massive galaxies.

- **Stellar feedback (galactic winds, SNe)** regulates star formation at low-mass galaxies, produces metals for SNe

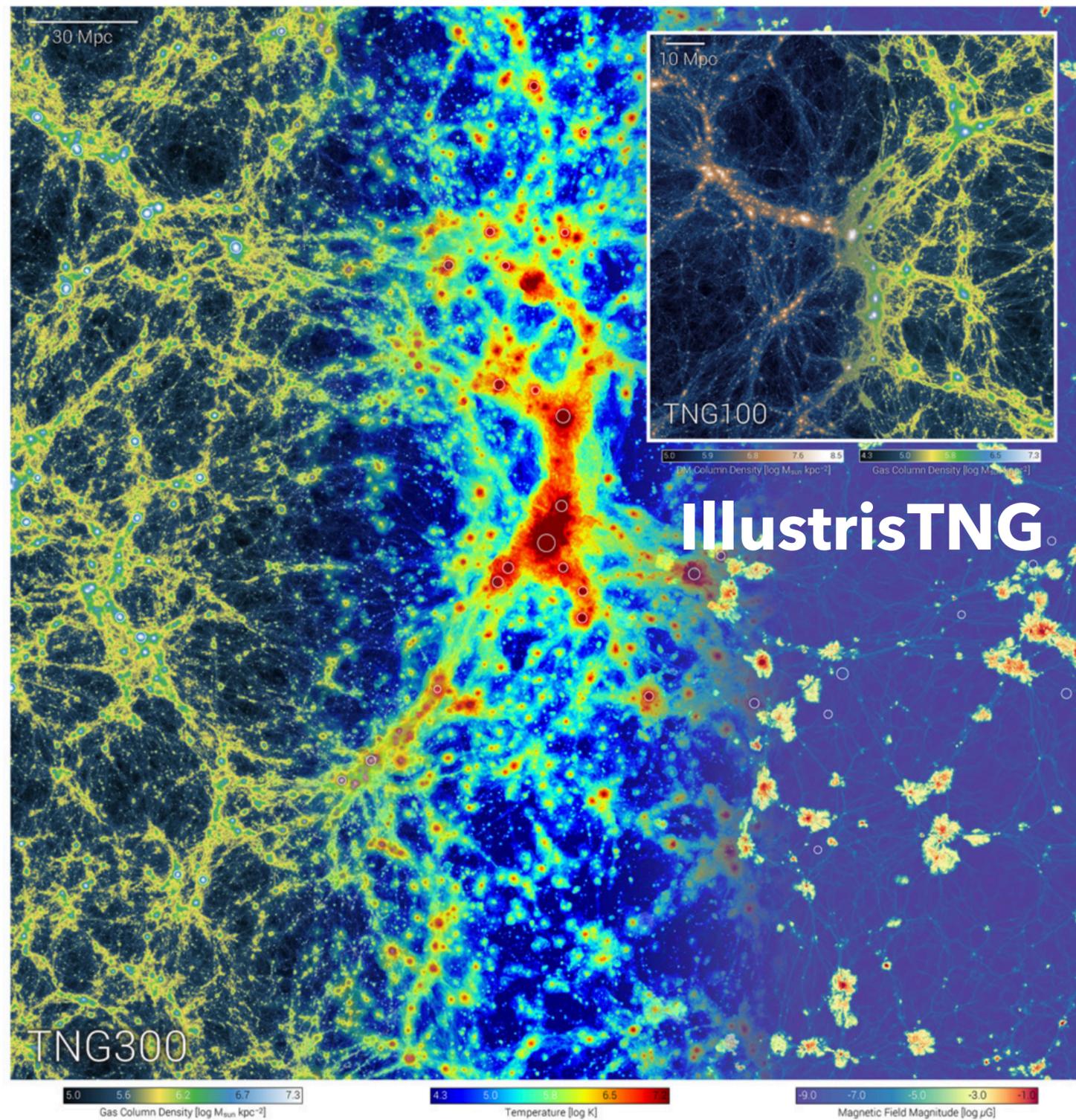
- ◆ **Challenges in feedback process**

- How energy/momentum is transferred to gas: thermal or kinetic?
- AGN accretion has multiple modes: quasar and radio. Hydro sims can have enough resolution for AGN activity?



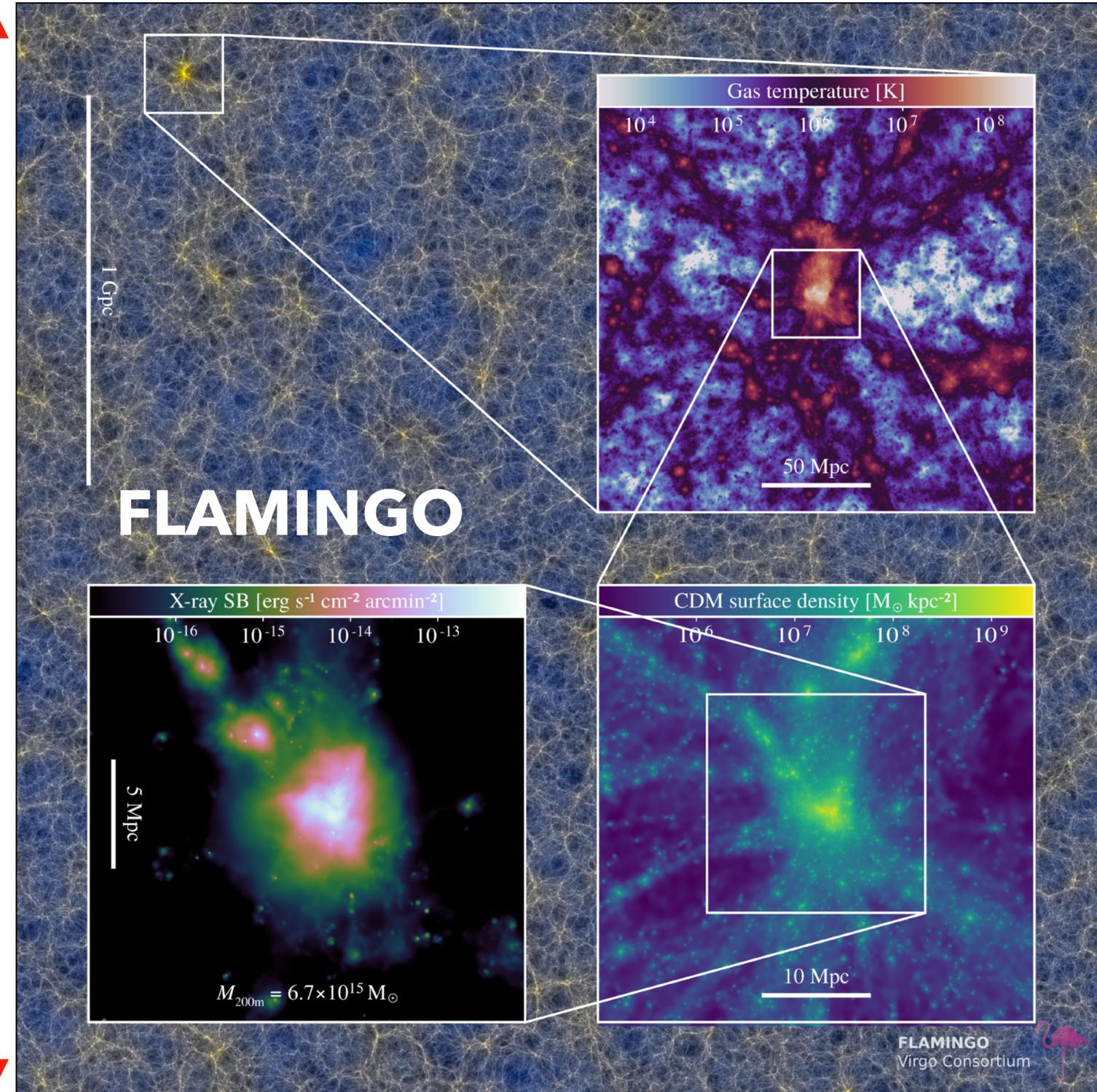
Valentini+ (2020)

State-of-the-Art Hydrodynamical Simulations



2.8 Gpc

300 Mpc



State-of-the-Art Hydrodynamical Simulations

Table 2: Recent structure and galaxy formation simulations

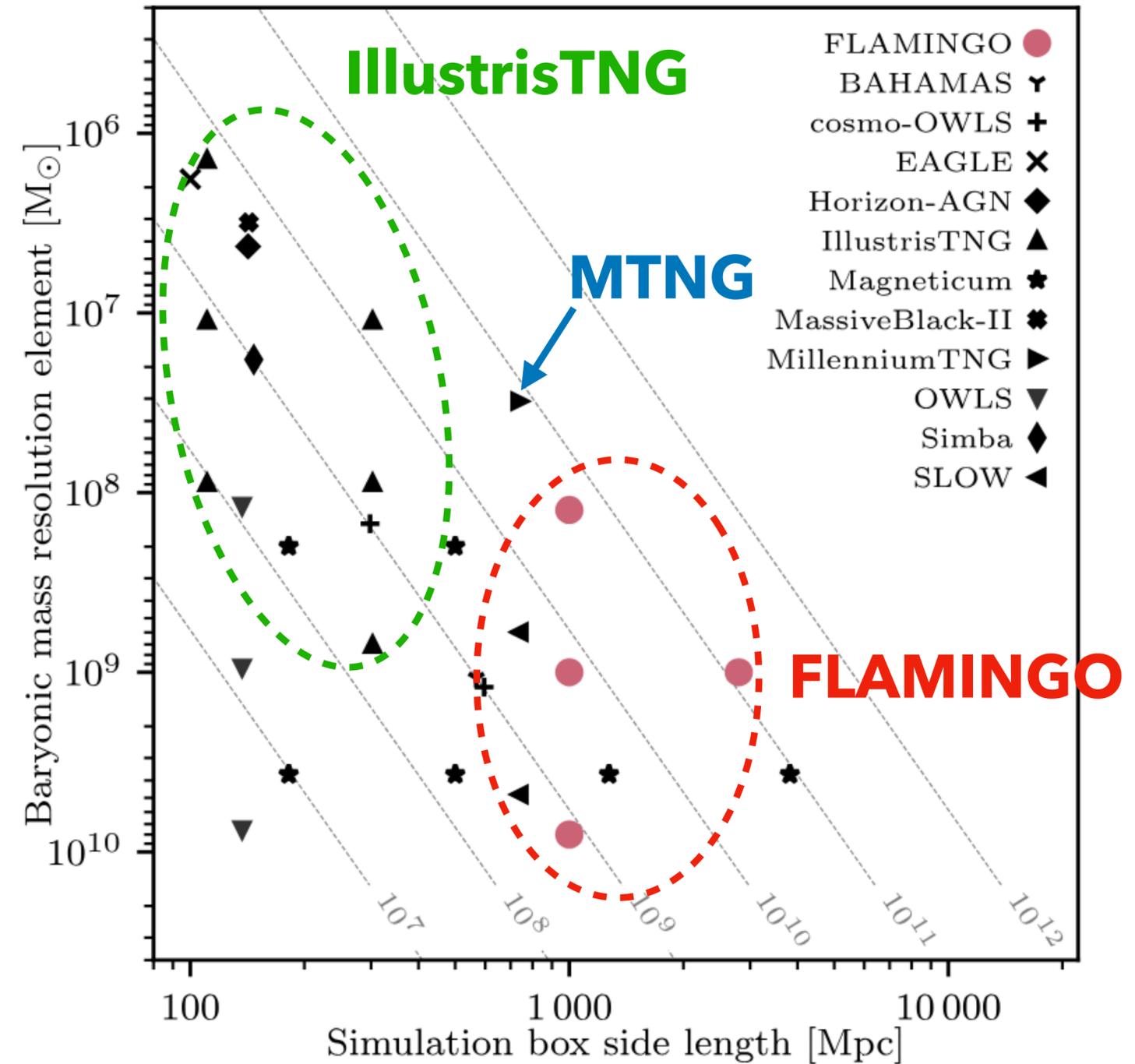
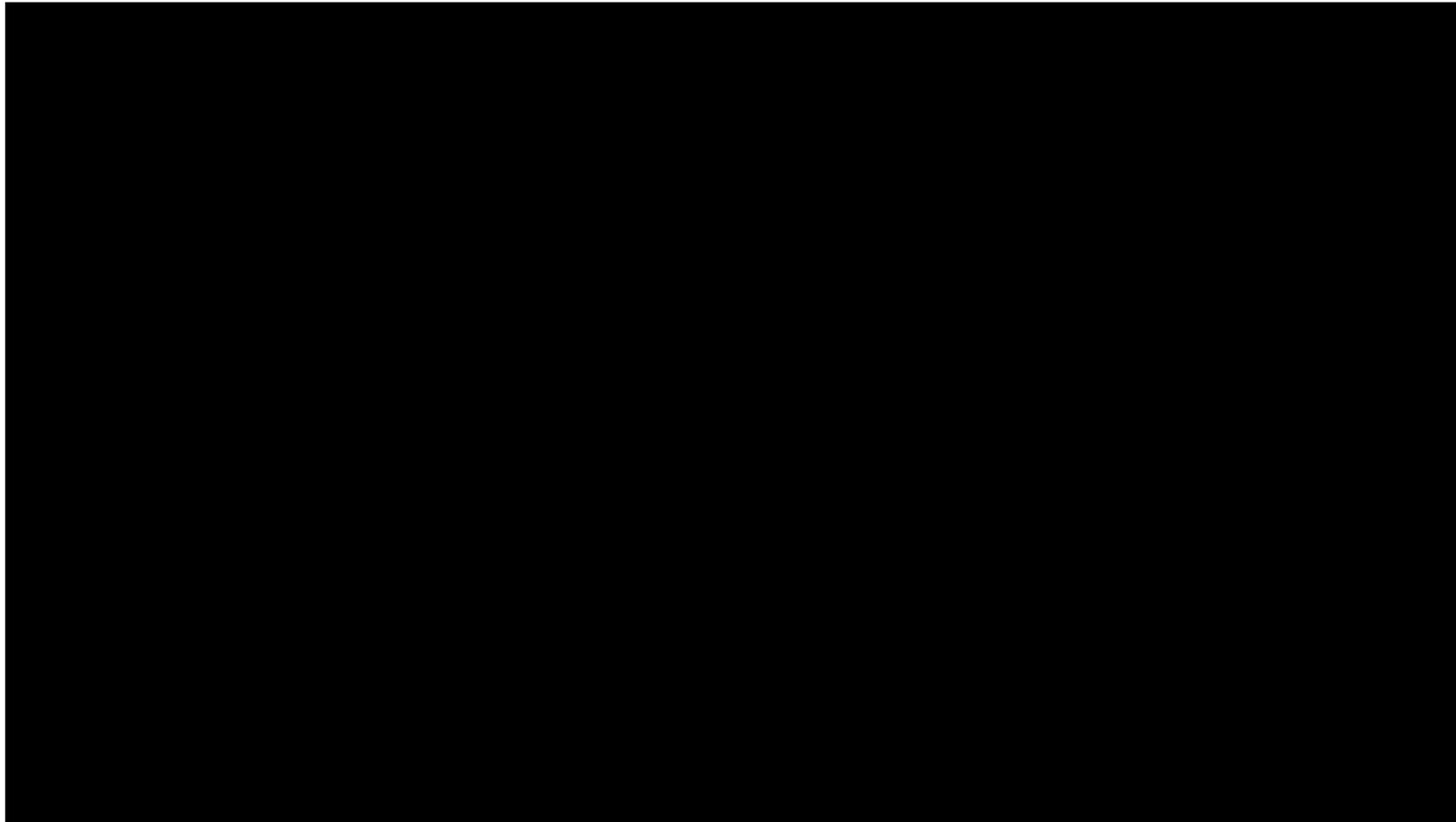
simulation	volume	method ^a	mass resolution ^b	spatial resolution ^c	primary reference
	[Mpc ³]		[M _⊙]	[kpc]	
+ baryons					
Illustris	107 ³	TreePM+MMFV	6.7×10 ⁶ /1.3×10 ⁶	1.42/0.71	Vogelsberger et al. (2014) ¹⁴⁹
Horizon-AGN	142 ³	PM/ML+AMR	8.0×10 ⁷ /1.0×10 ⁷	1.0/1.0	Dubois et al. (2014) ³⁸⁰
EAGLE	100 ³	TreePM+SPH	9.7×10 ⁶ /1.8×10 ⁶	0.7/0.7	Schaye et al. (2015) ¹²⁴
MassiveBlack-2	143 ³	TreePM+SPH	1.6×10 ⁷ /3.2×10 ⁶	2.64/2.64	Khandai et al. (2015) ³⁸¹
Bluetides ^d	574 ³	TreePM+SPH	1.7×10 ⁷ /3.4×10 ⁶	0.24/0.24	Feng et al. (2016) ³⁸²
Magneticum	68 ³	TreePM+SPH	5.3×10 ⁷ /1.1×10 ⁷	1.4/0.7-1.4	Bocquet et al. (2016) ⁸⁵
MUFASA	74 ³	TreePM+MLFM	9.6×10 ⁷ /1.8×10 ⁷	0.74/0.74	Daveé et al. (2016) ³⁸³
BAHAMAS	571 ³	TreePM+SPH	5.5×10 ⁹ /1.1×10 ⁹	0.25/0.25	McCarthy et al. (2017) ³⁸⁴
Romulus25	25 ³	Tree/FM+SPH	3.4×10 ⁵ /2.1×10 ⁵	0.25/0.25	Tremmel et al. (2017) ³⁸⁵
IllustrisTNG ^e	111 ³	TreePM+MMFV	7.5×10 ⁶ /1.4×10 ⁶	0.74/0.19	Springel et al. (2018) ⁸⁷
Simba ^f	147 ³	TreePM+MLFM	1.4×10 ⁸ /2.7×10 ⁷	0.74/0.74	Davé et al. (2019) ¹⁸²

Vogelsberger+ (2020)

State-of-the-Art Hydrodynamical Simulations

- ◆ Modern hydrodynamical simulations can trace **physics with wide dynamic range on cosmological scales.**

- **TNG-50**

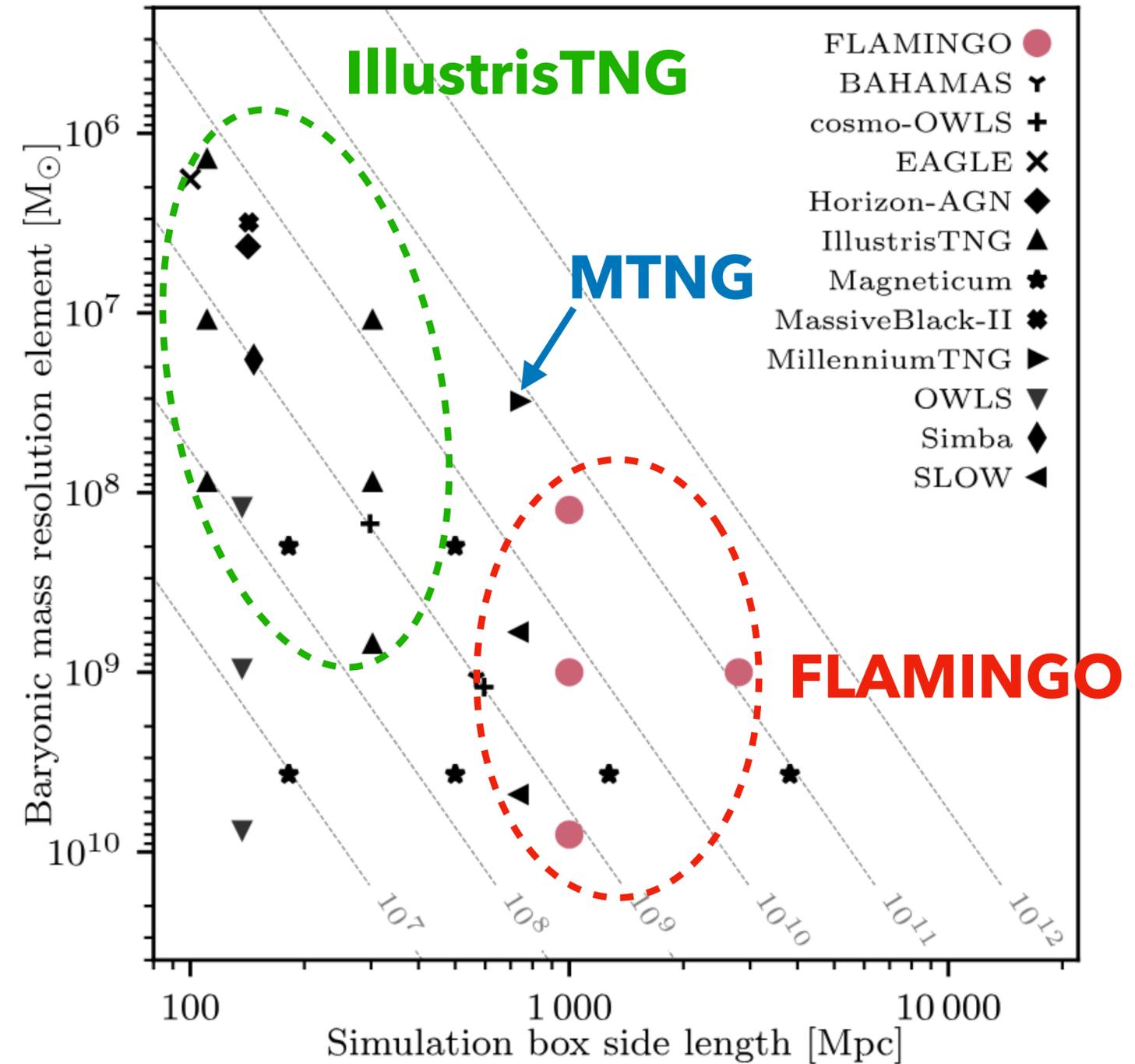
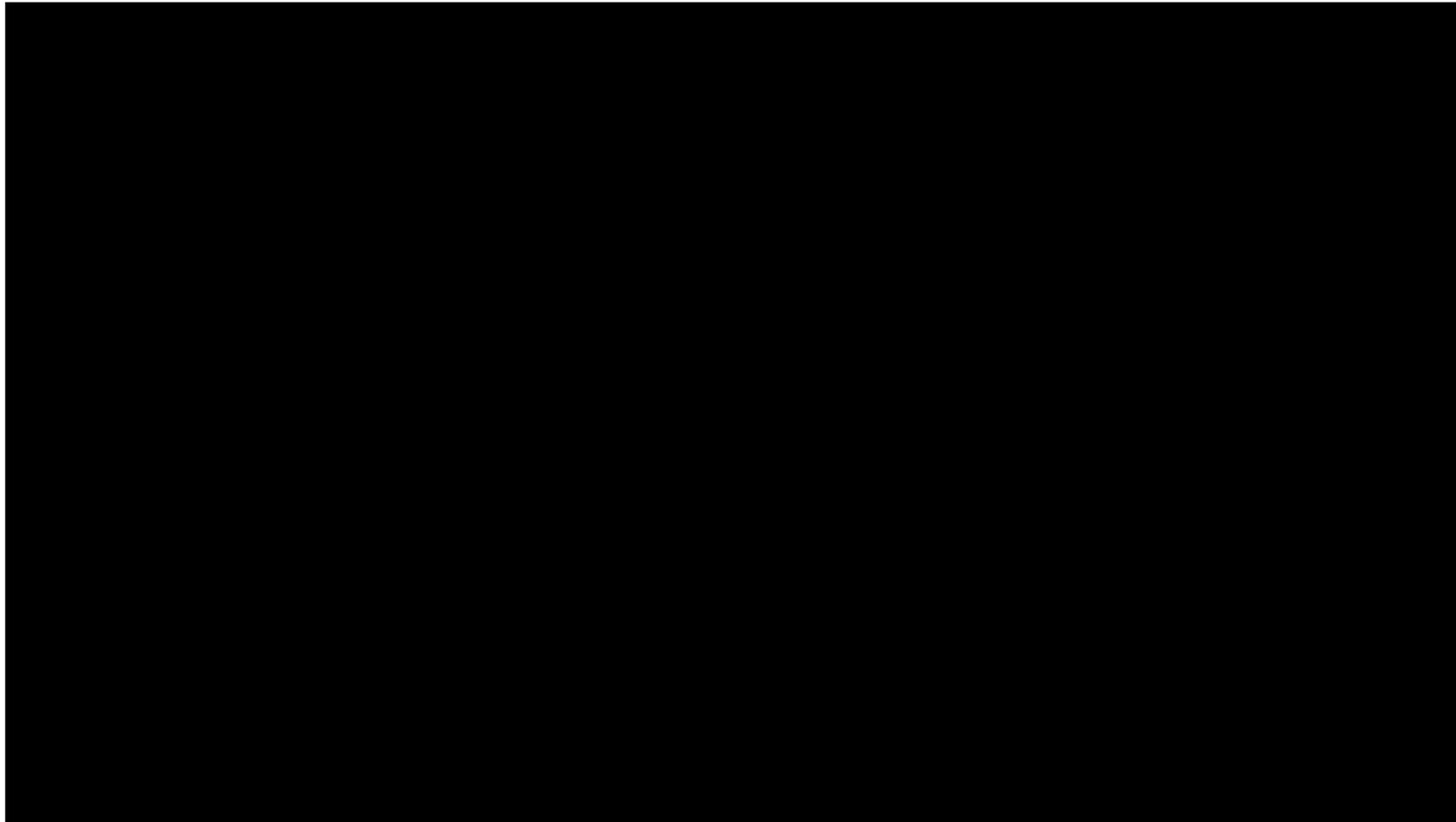


Schaye+ (2023)

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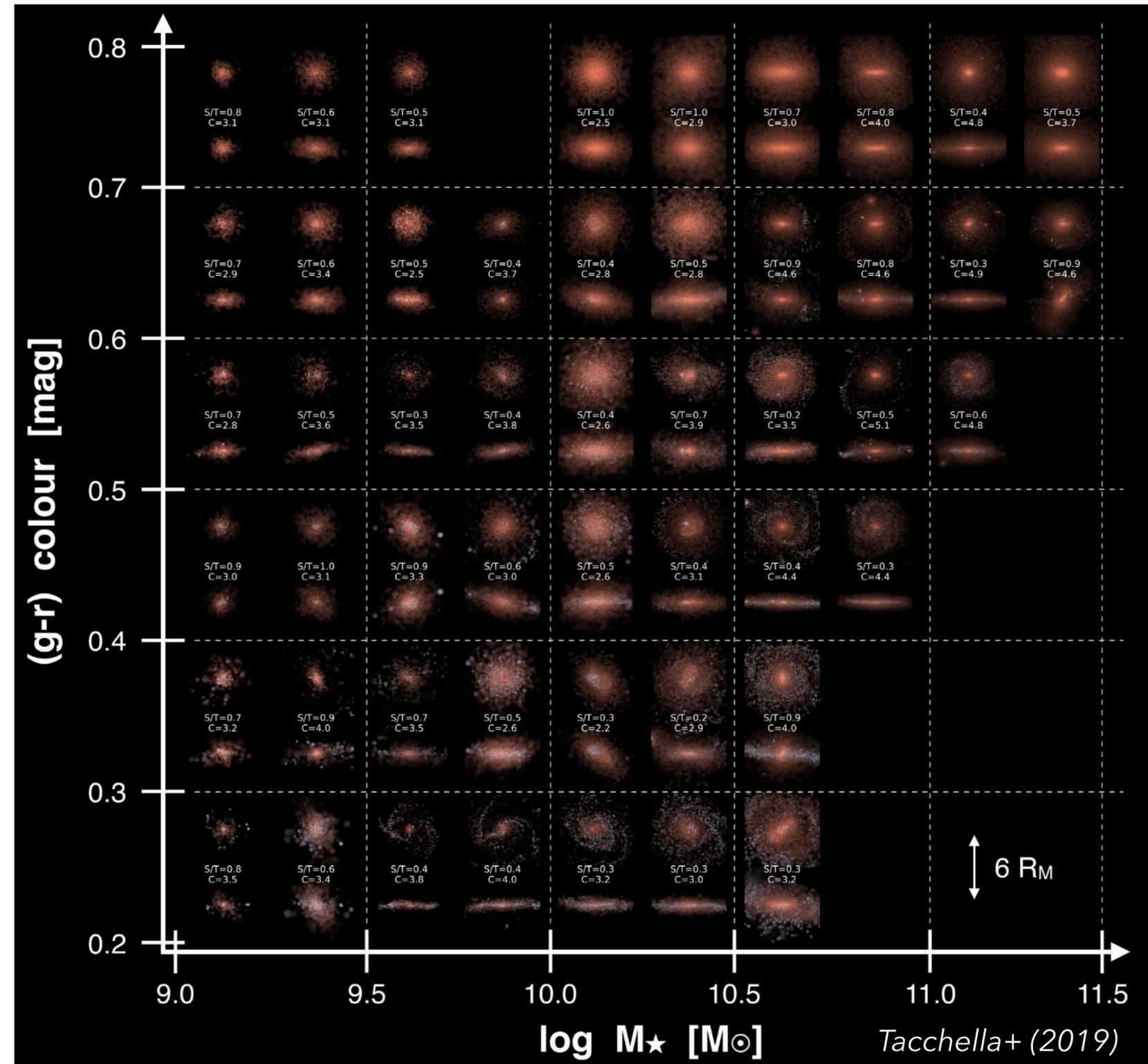
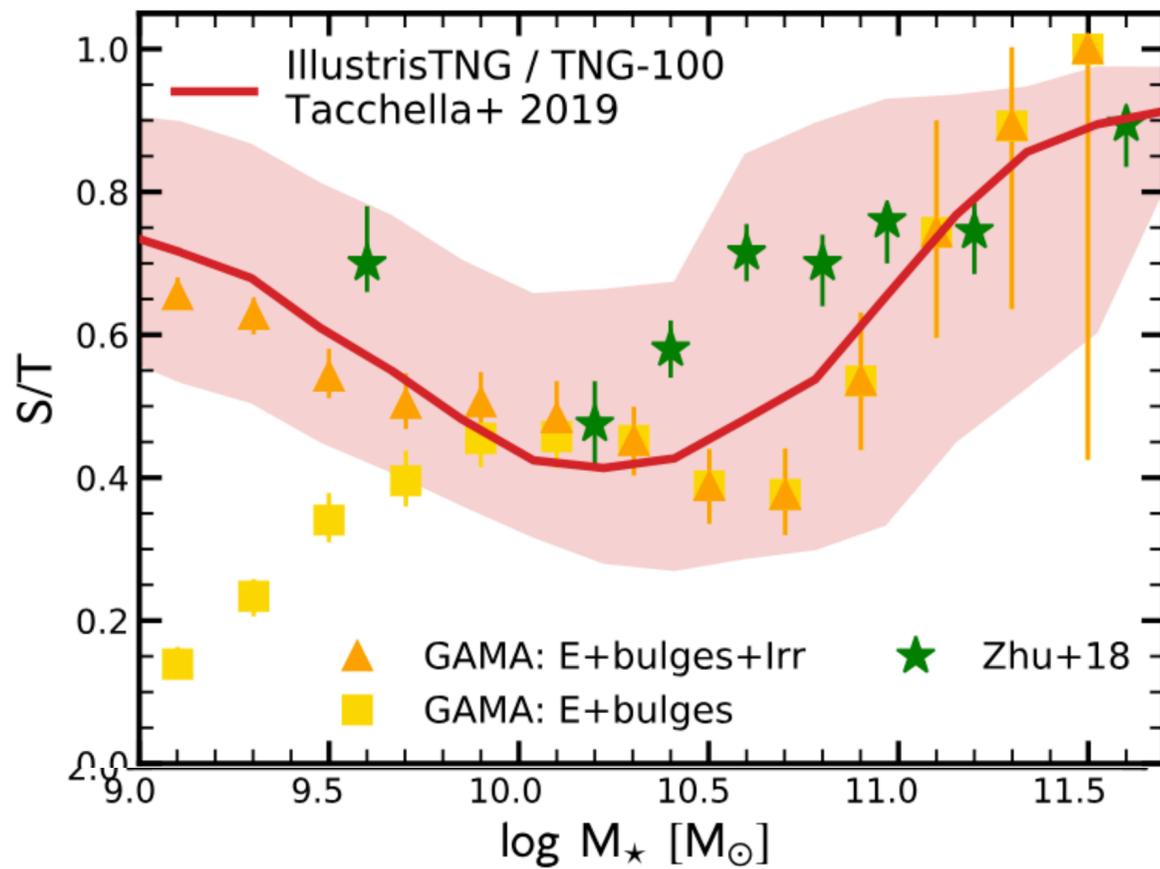


Schaye+ (2023)

Morphology of Simulated Galaxies

- ◆ Local properties such as galaxy morphology are also reproduced in hydrodynamical simulations.

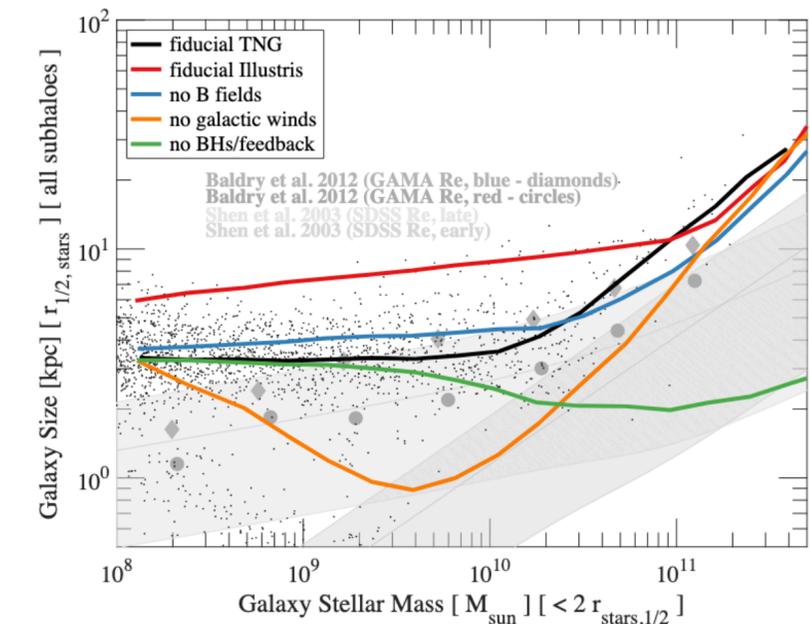
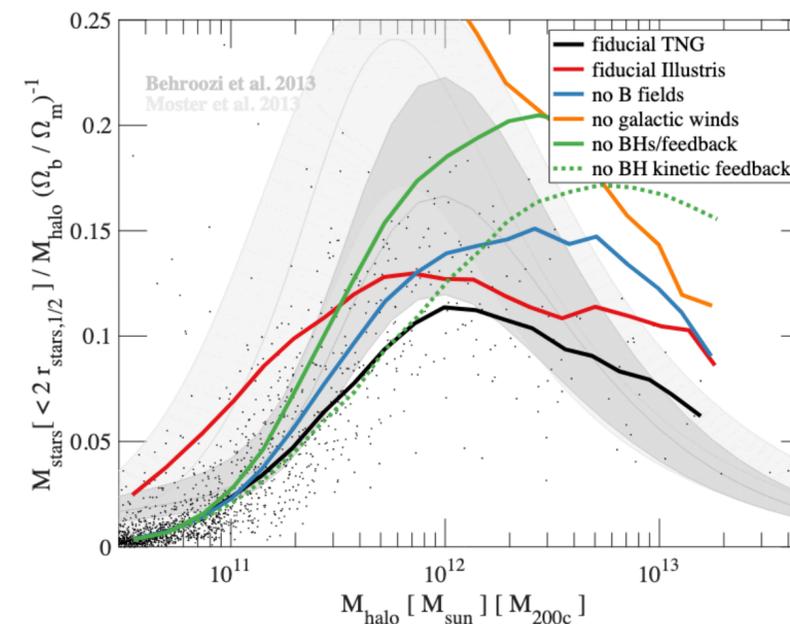
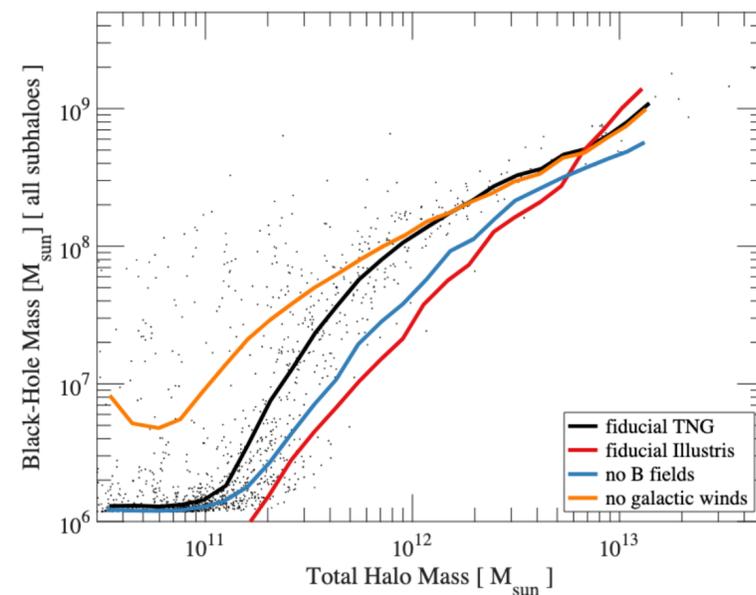
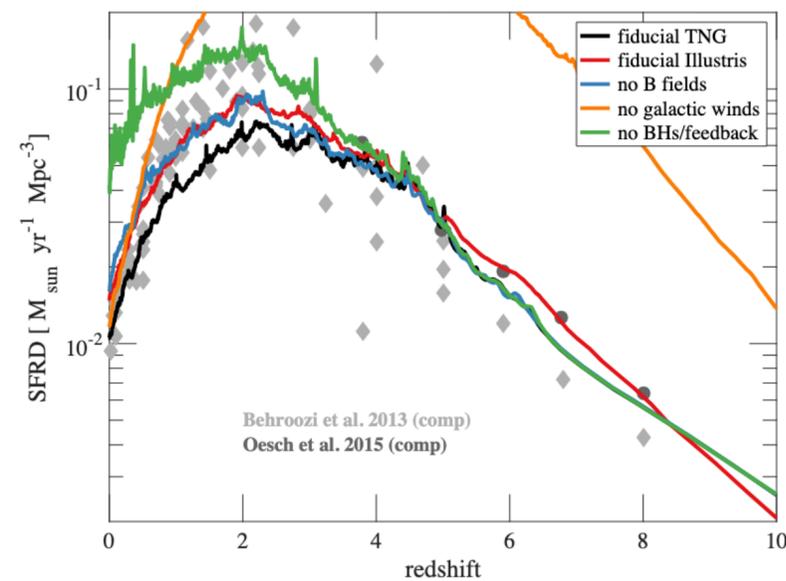
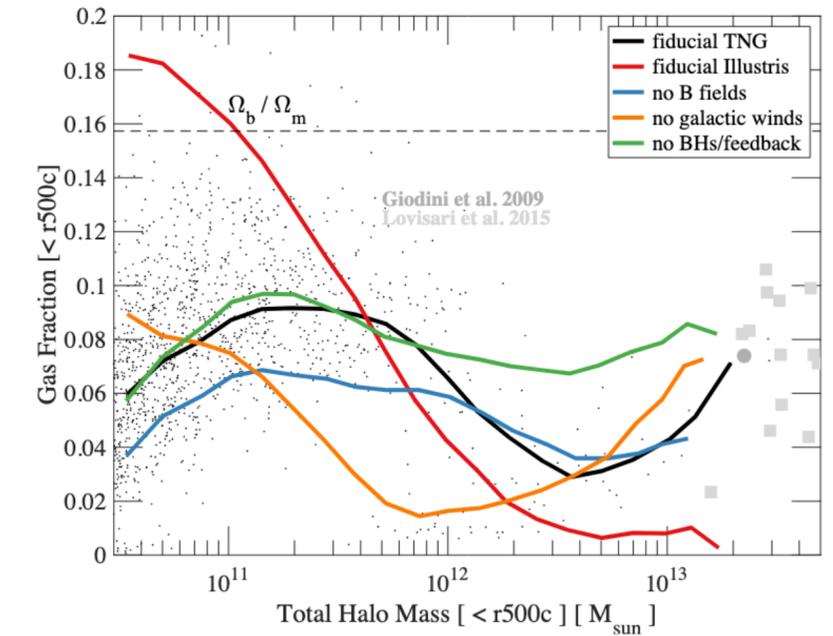
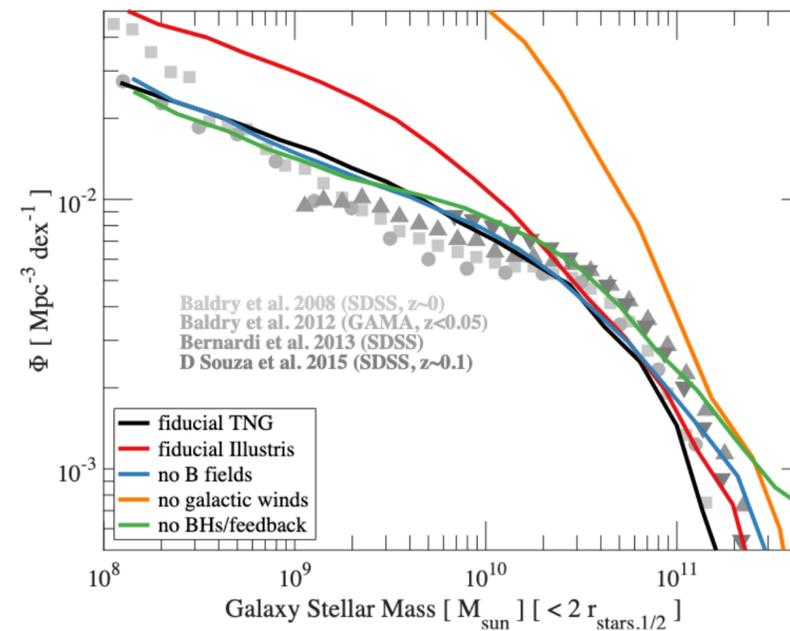
Spheroidal (Bulge) / Total



Outcomes of Hydrodynamical Simulations

◆ Hydrodynamical simulations can reproduce a wide variety of gas/galaxy/BH observations.

▶ **Caveat: Many free parameters are fit to reproduce observations!**



IllustrisTNG Illustris No B fields No winds No AGN

Pillepich+ (2018)

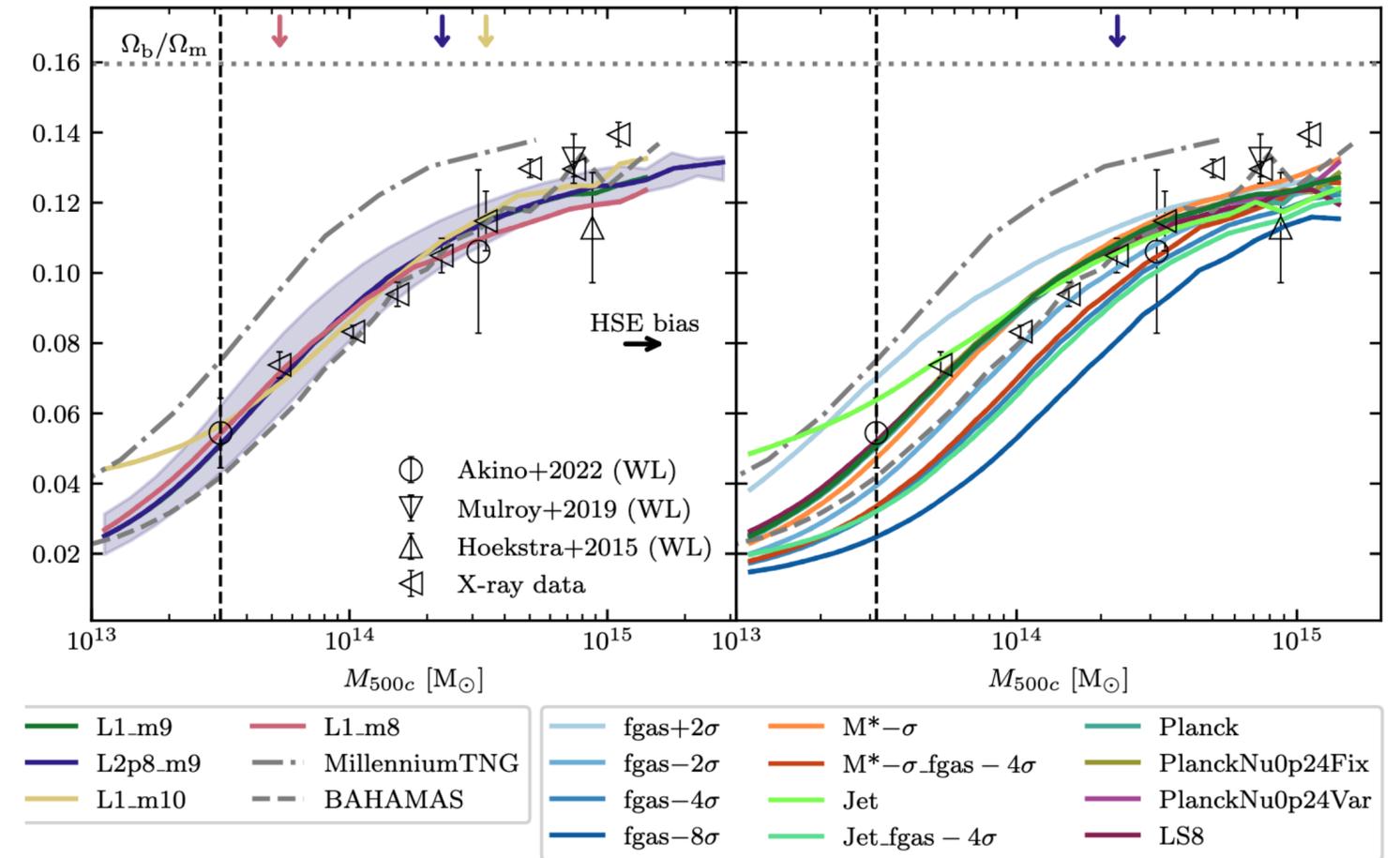
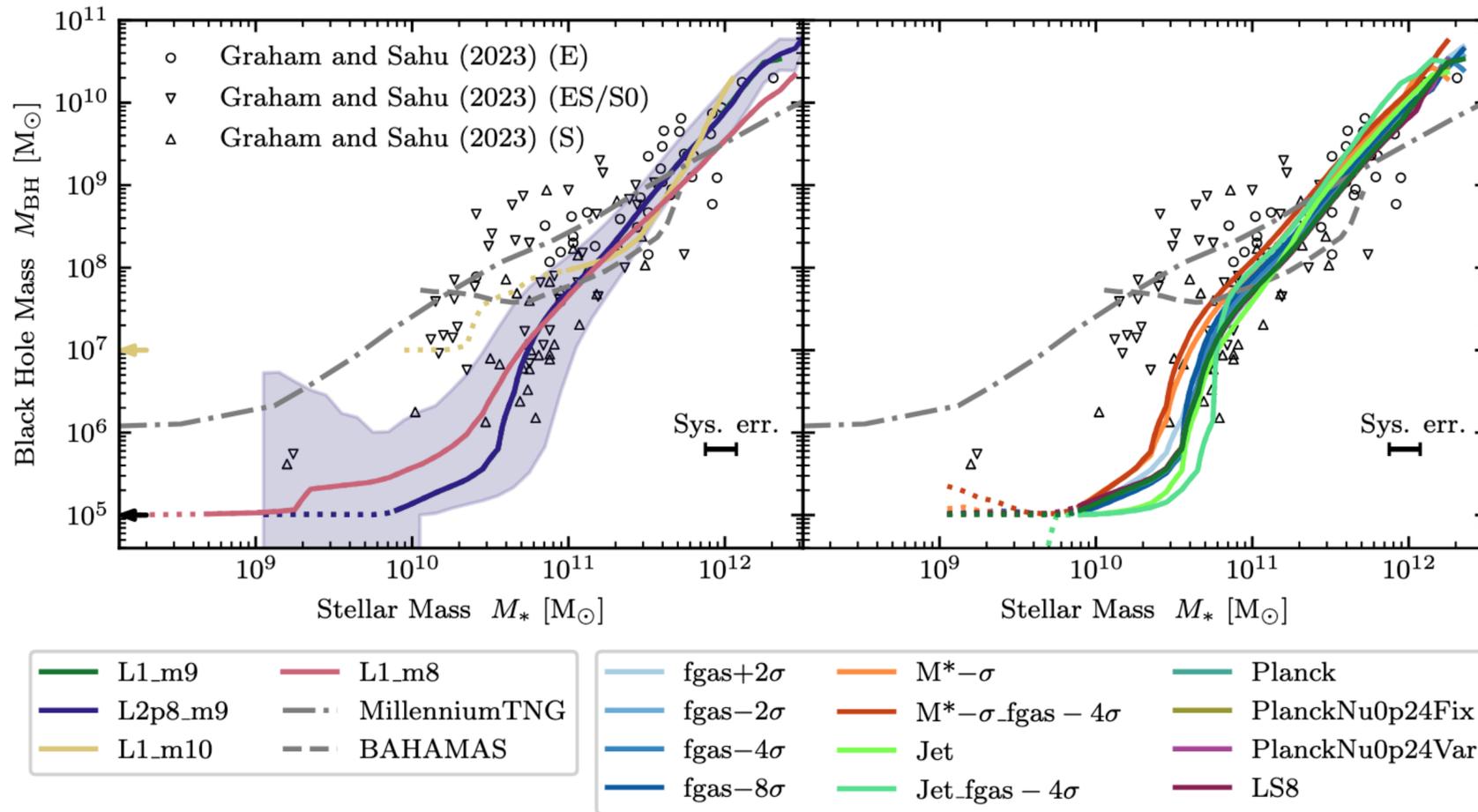
Outcomes of Hydrodynamical Simulations

◆ The effects of different subgrid physics can be addressed in hydro sims.

➔ Hydro sims are a powerful tool to quantify such effects on observables.

• BH mass

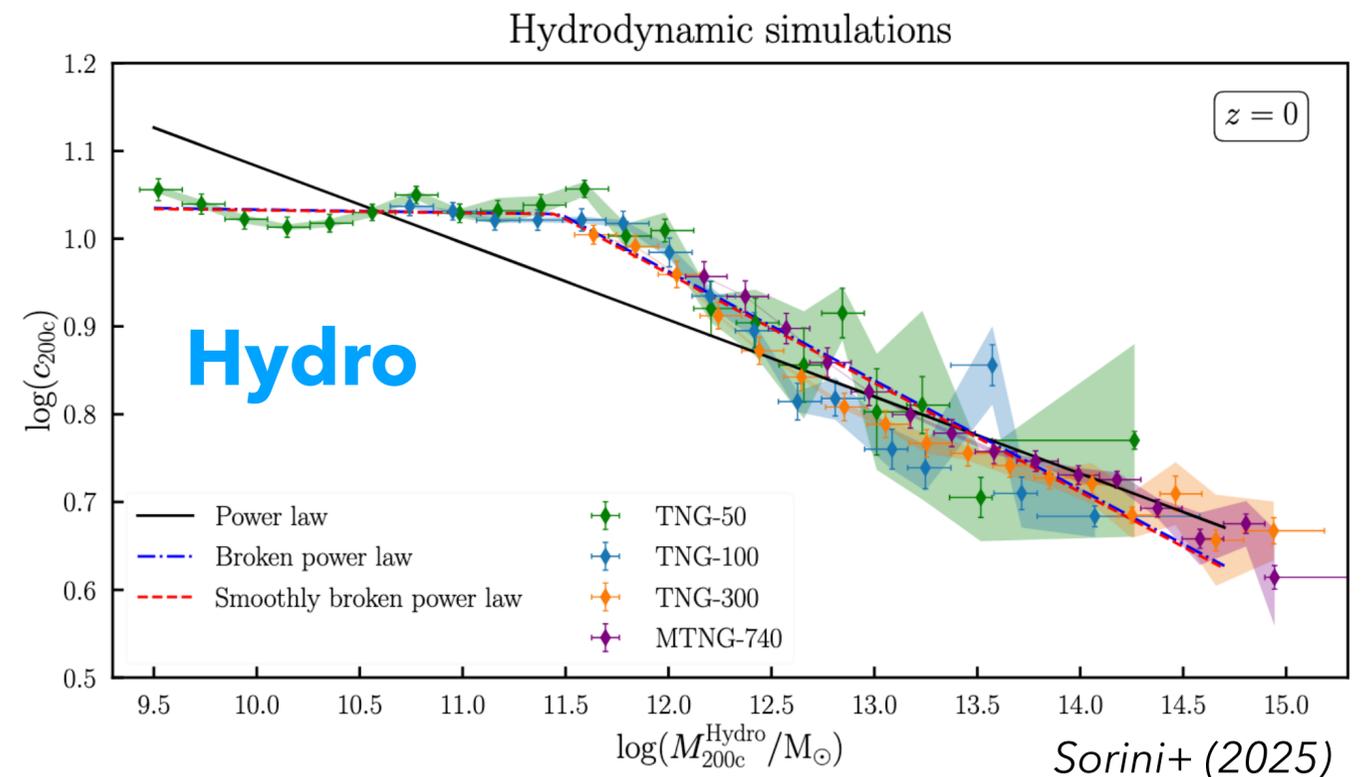
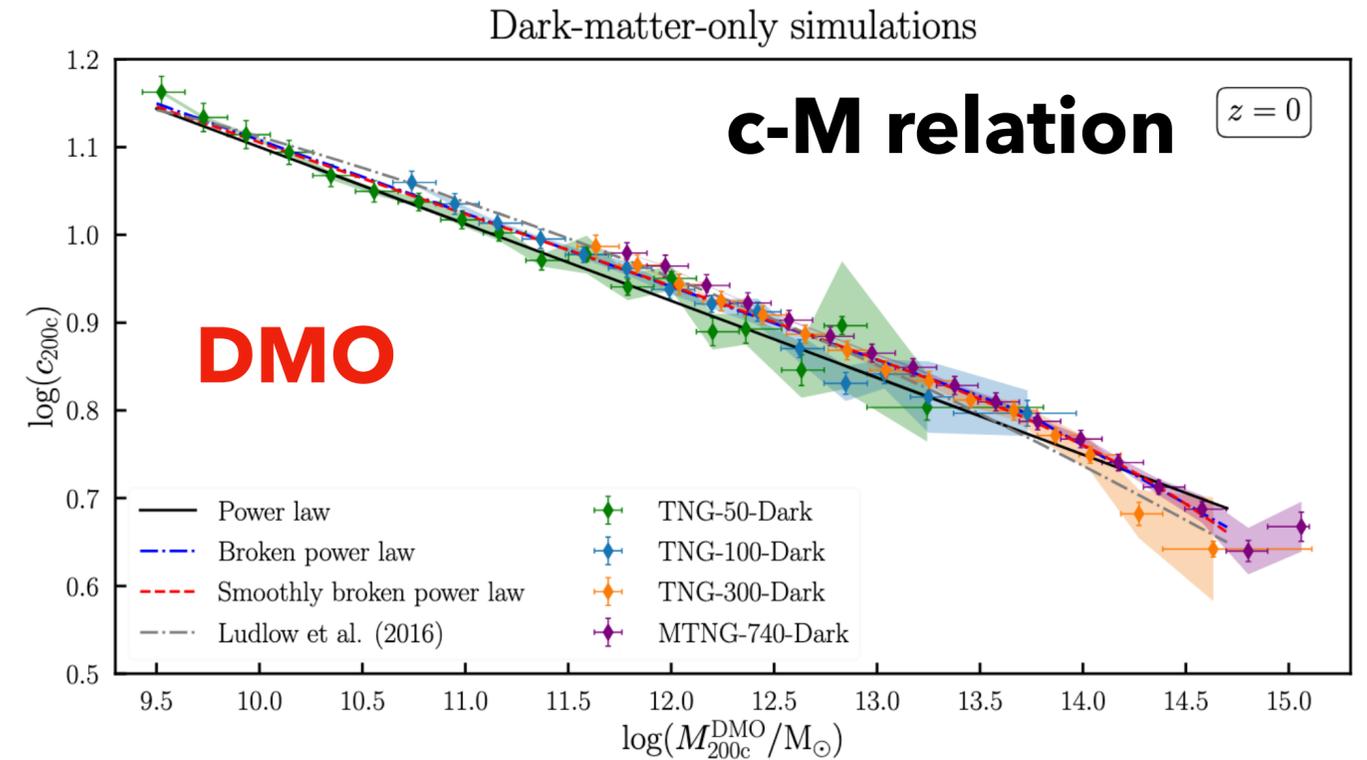
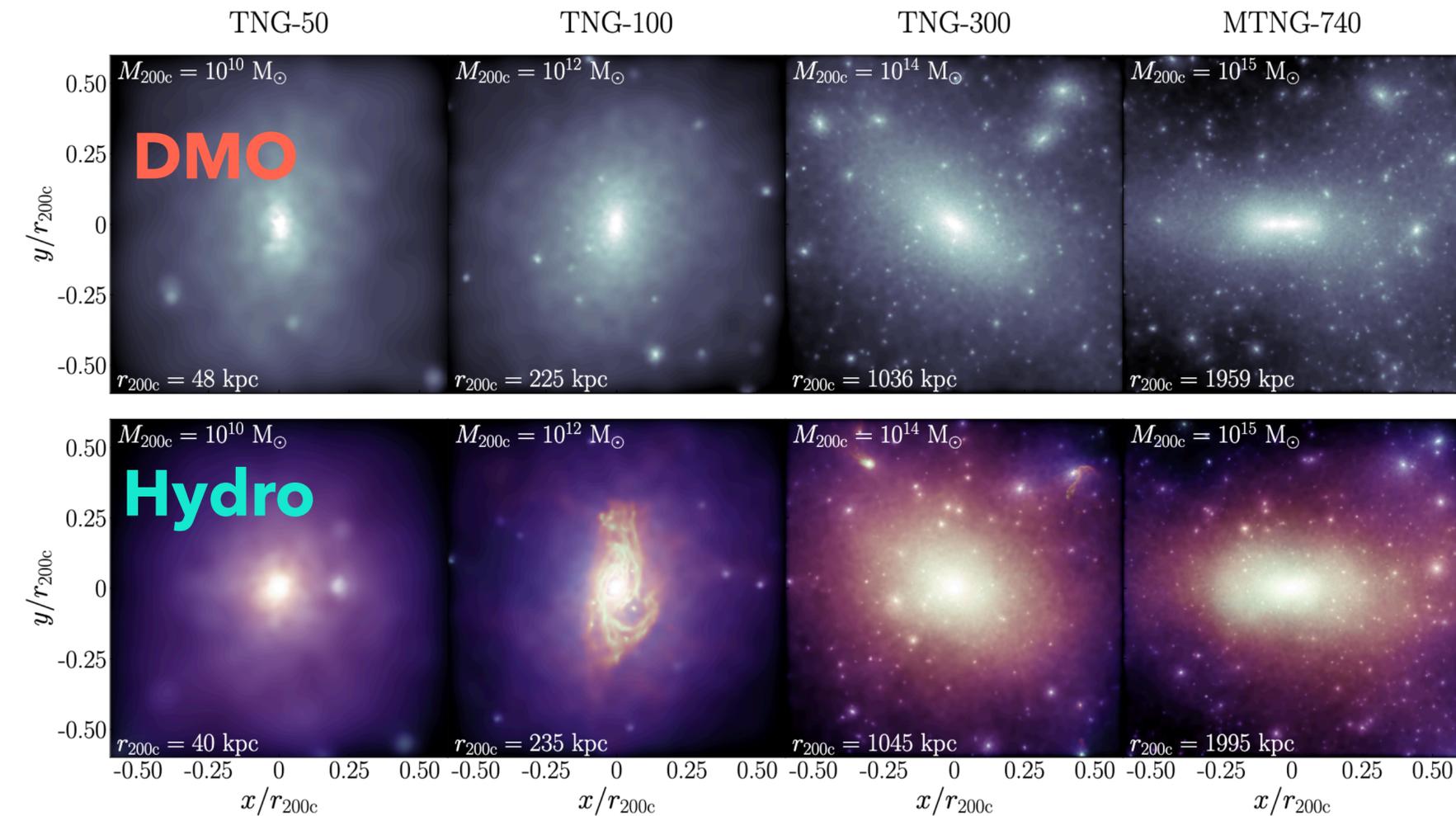
• Gas fraction in galaxy clusters



Schaye+ (2023)

Impacts of Baryon Physics on Dark Matter Halos

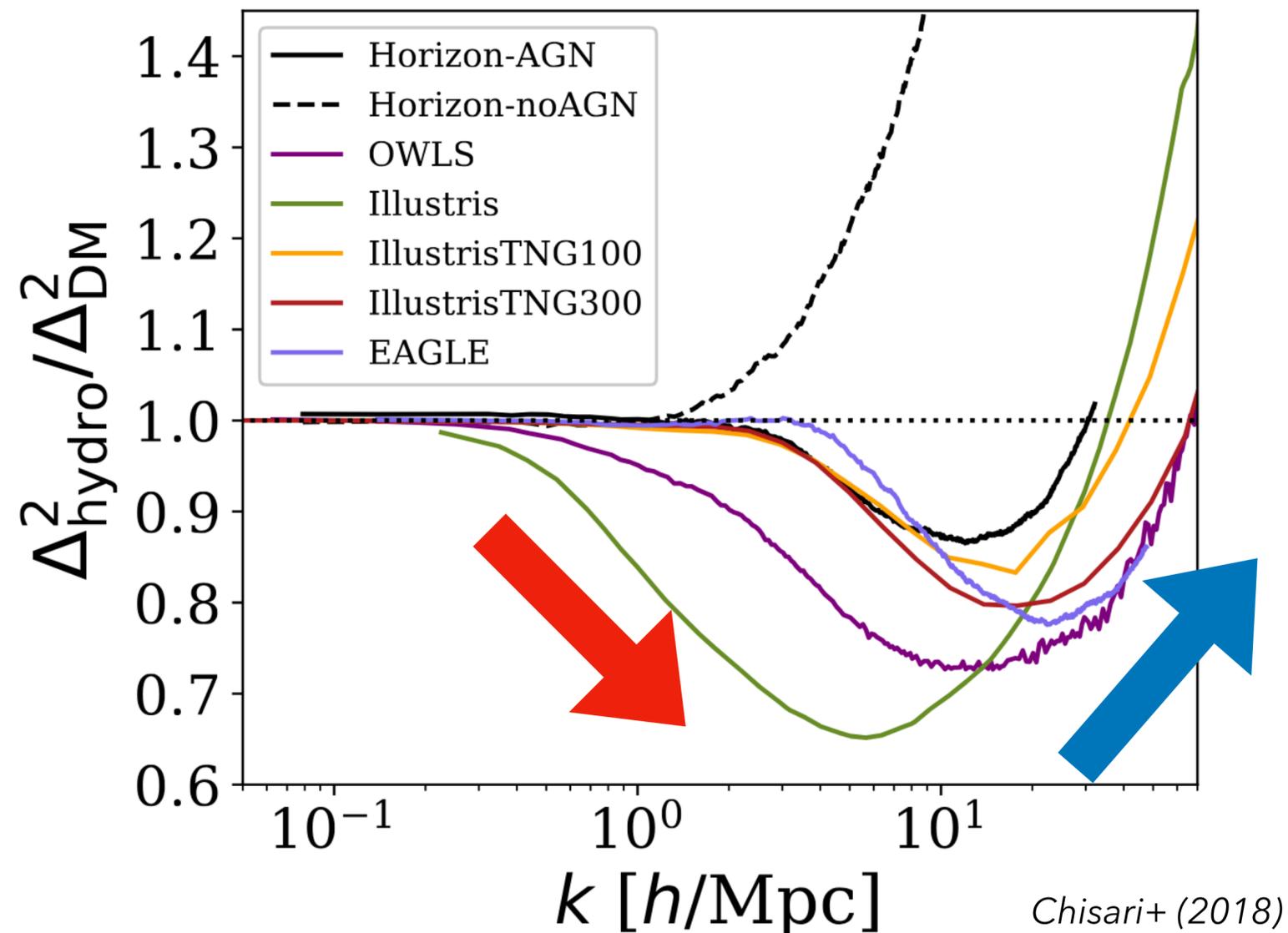
- ◆ Baryon physics disrupts density profiles of dark matter halos due to **adiabatic contraction** and **feedback processes**.



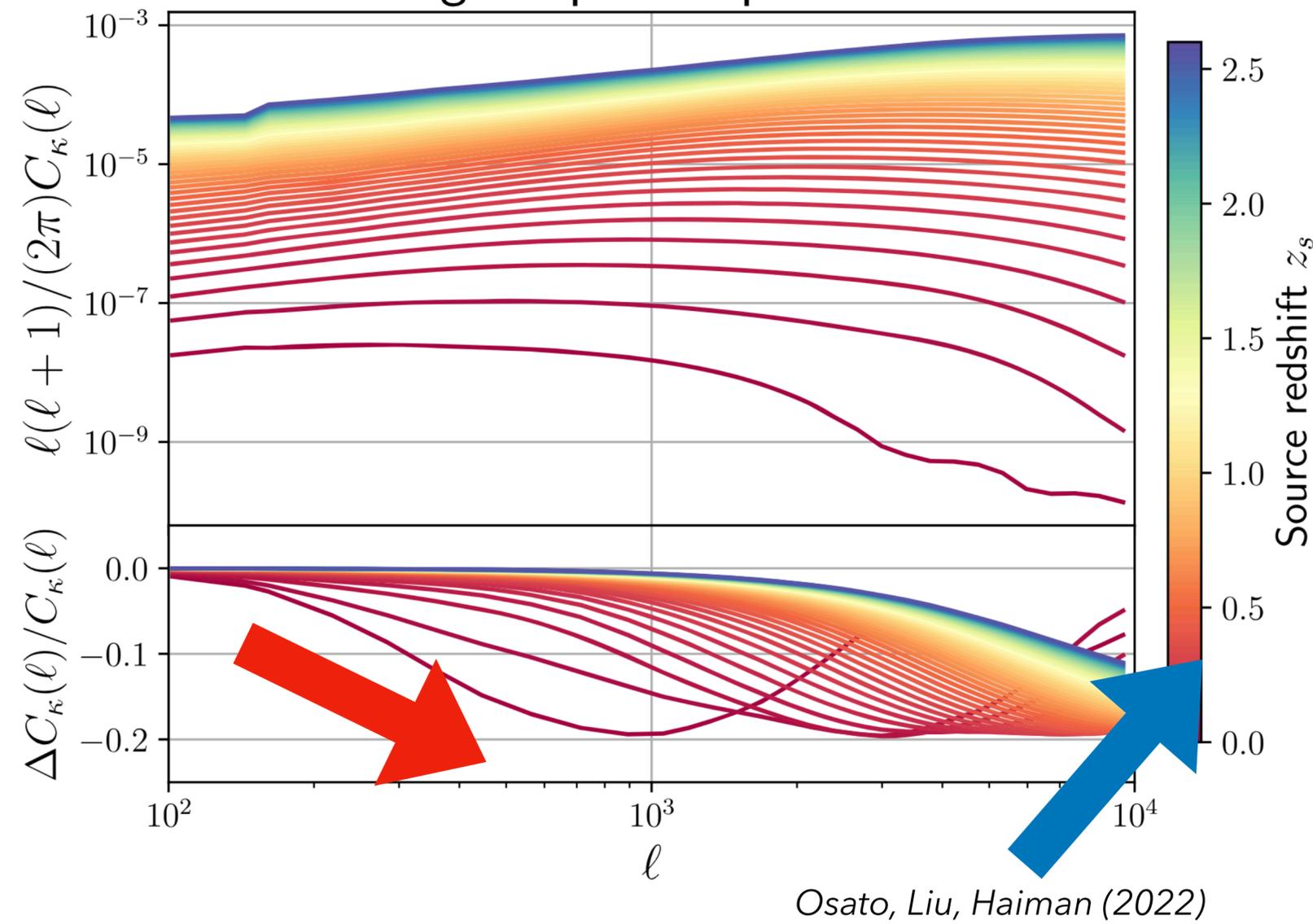
Impacts of Baryon Physics on Large-scale Structures

- ◆ **AGN feedback** suppresses growth of structures on scales of $k \sim 0.5-10 h/\text{Mpc}$.
- Radiative cooling** promotes contraction at very small scales ($k > 10 h/\text{Mpc}$).

- $P(k)$ ratio w/ and w/o baryon phys.



- Weak lensing power spectrum



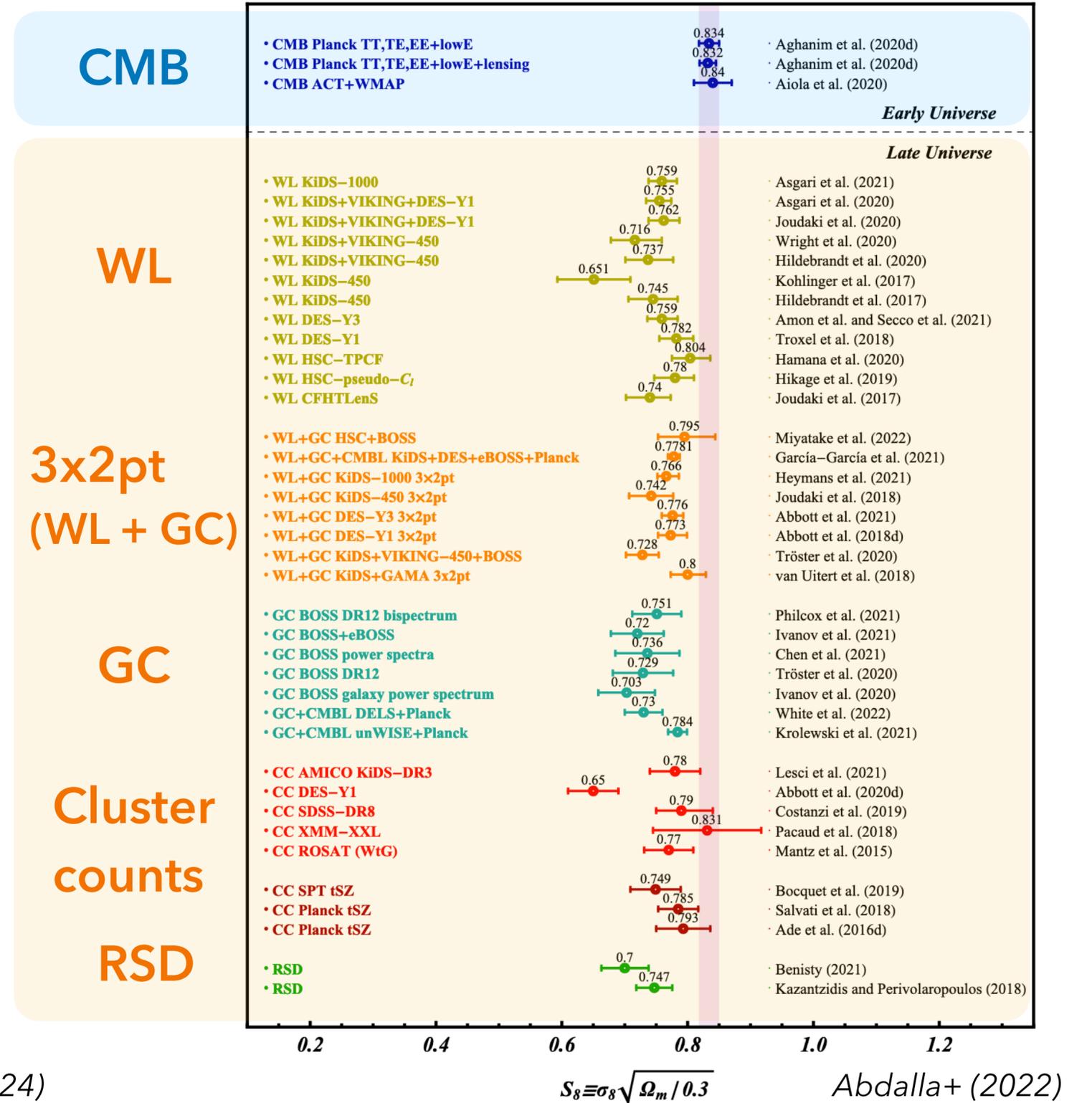
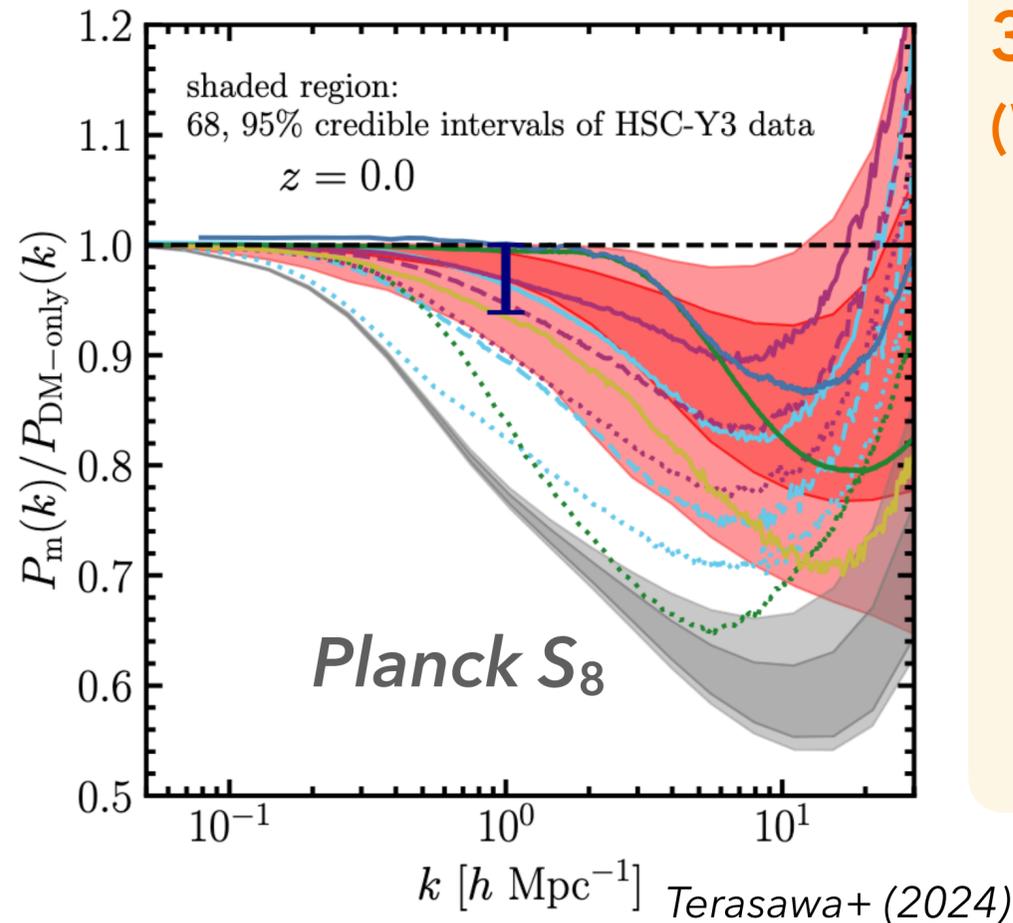
Baryon Physics Solves S_8 Tension?

◆ Inconsistency ($> 1-2\sigma$) of constraints on S_8 parameter (amplitude of density fluctuations) between **CMB** and **LSS** (WL, galaxy clustering, ...).

➔ Baryon physics is more active at low- z and suppresses growth of structures.

Promising mechanism to explain the S_8 tension!

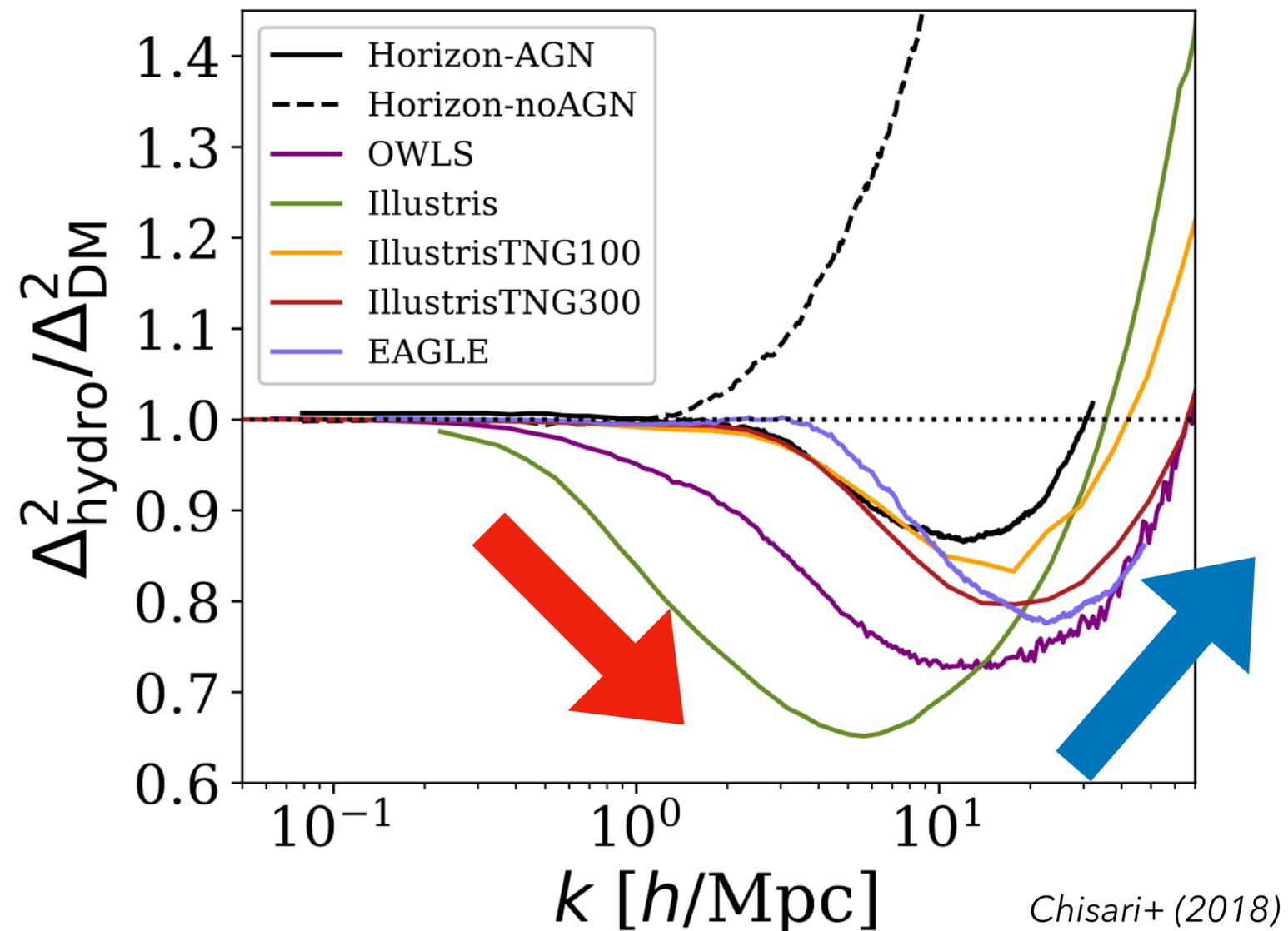
... but analysis of HSC Y3 WL with models with baryon physics incorporated still prefers low S_8 . AGN feedback is too weak to reconcile the tension.



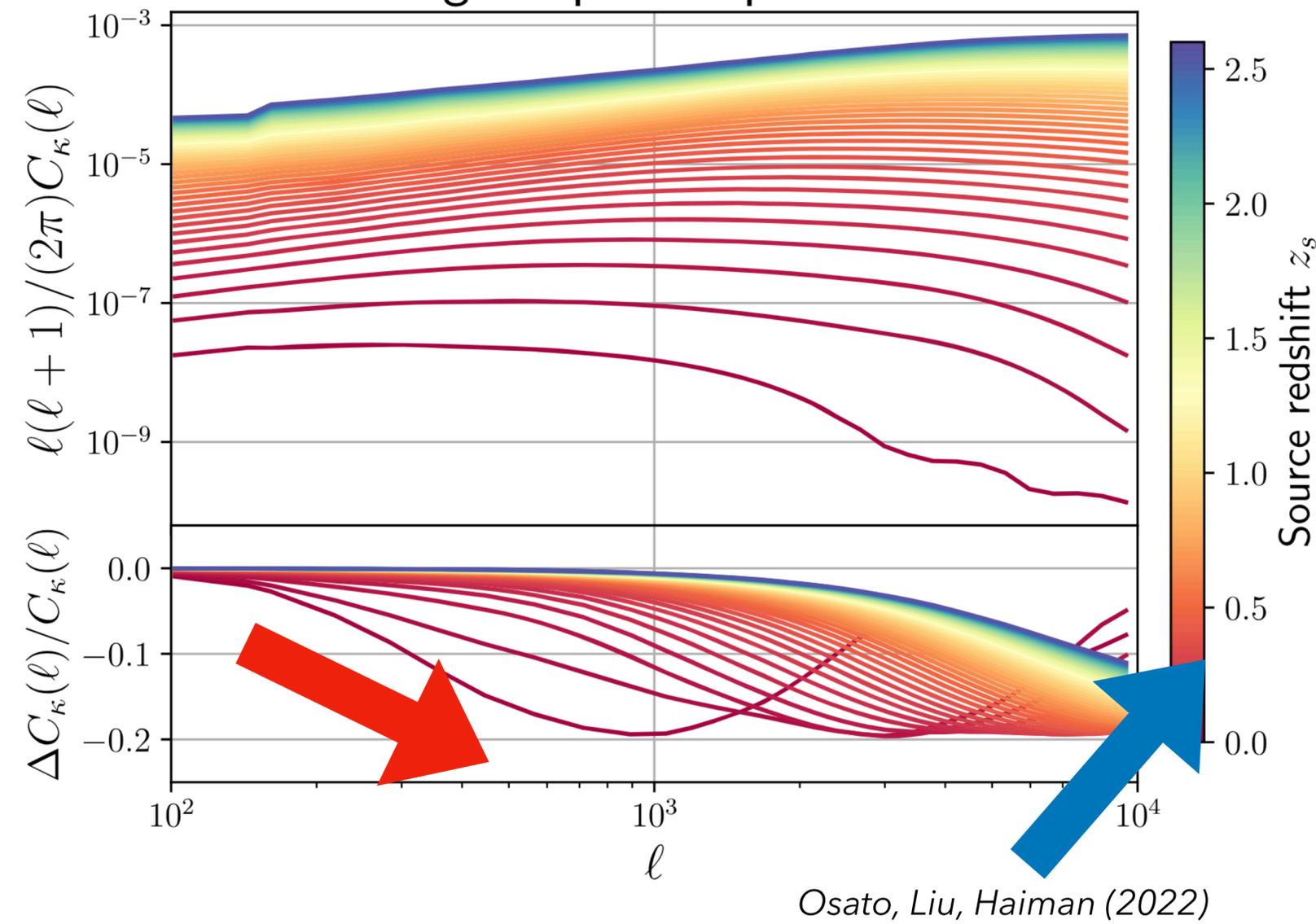
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Simulations as Virtual Multi-wavelength Observatory

- ◆ Hydrodynamical simulations give direct access to fundamental physical quantities.
 - ➔ But they are not usually direct observables in observations.
- We need to **connect simulations to observations**.

Dark matter density

Gas density

Gas velocity field

Stellar mass density

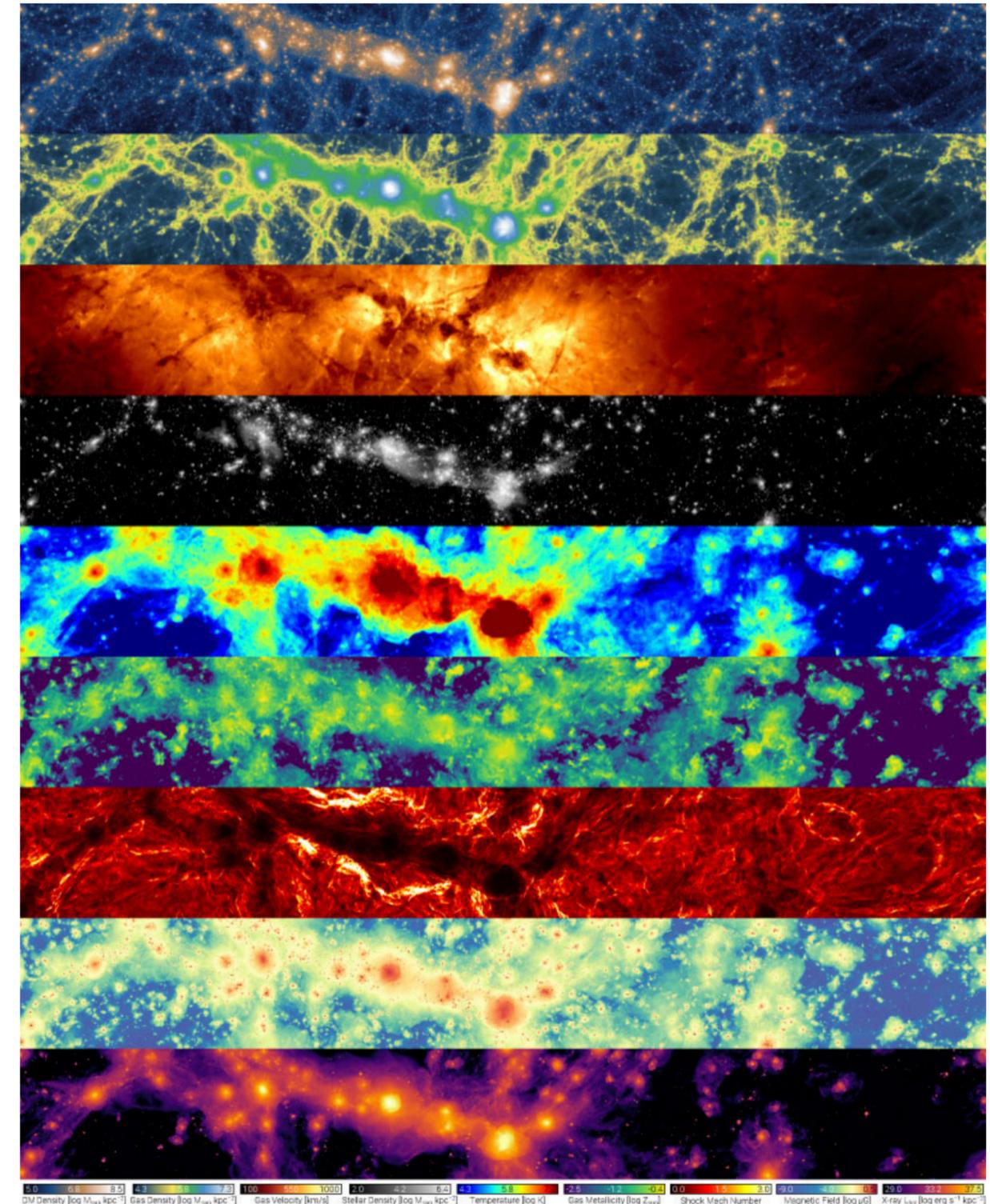
Gas temperature

Gas-phase metallicity

Shock Mach number

Magnetic field strength

X-ray luminosity

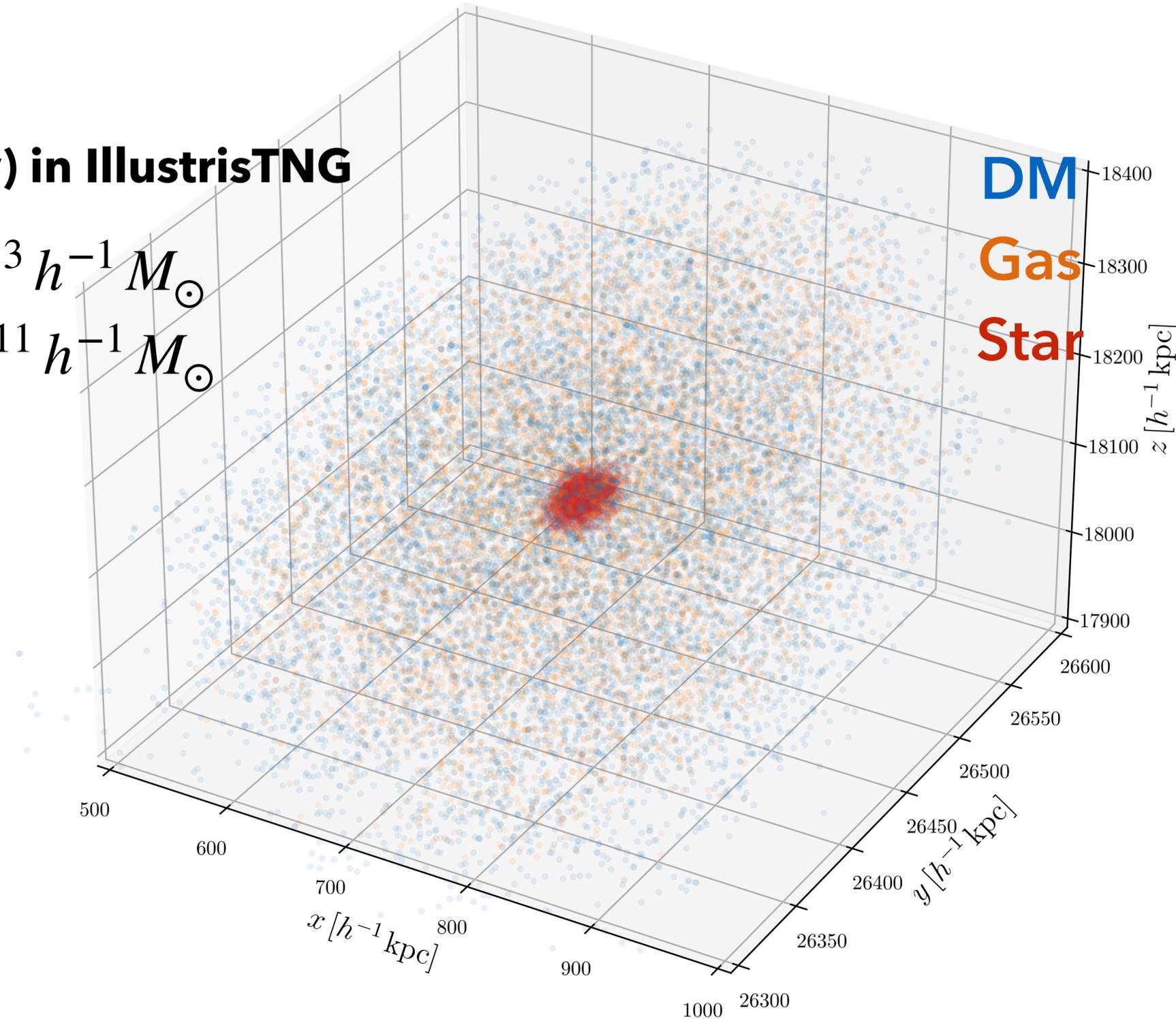


Simulating Galaxy Spectra from Hydrodynamical Simulations

- **Subhalo (=galaxy) in IllustrisTNG**

$$M = 3.85 \times 10^{13} h^{-1} M_{\odot}$$

$$M_* = 1.95 \times 10^{11} h^{-1} M_{\odot}$$

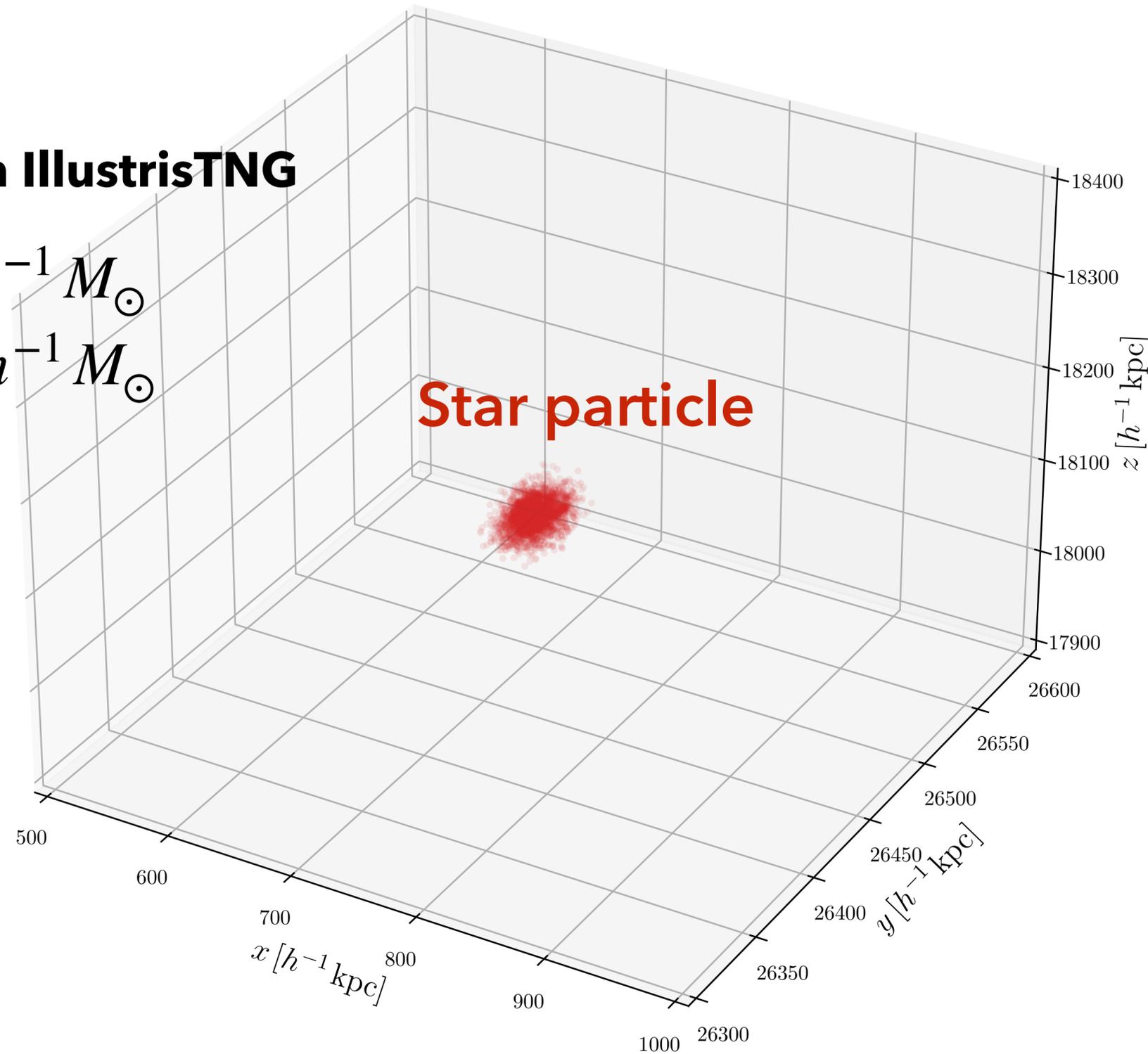


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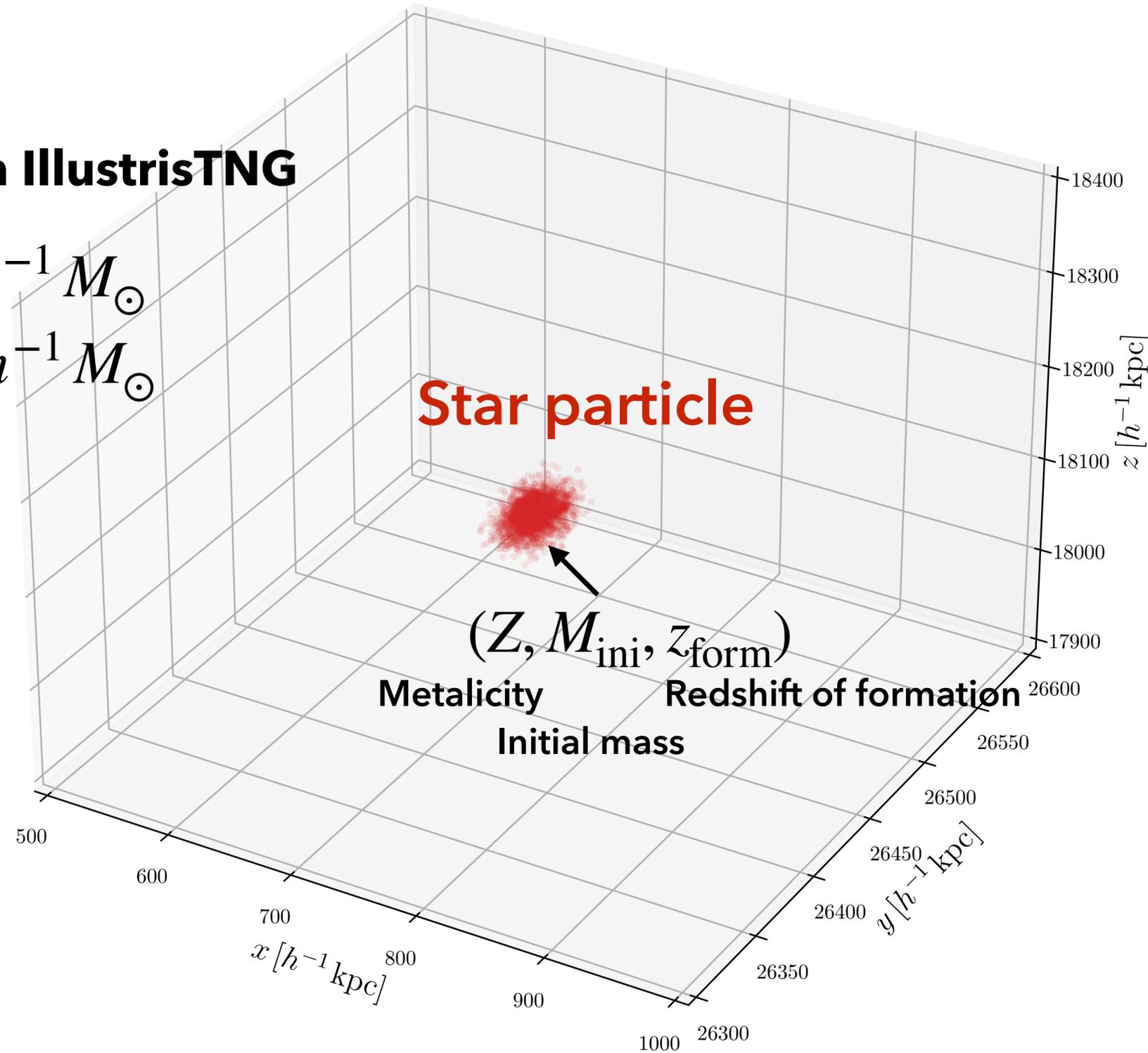


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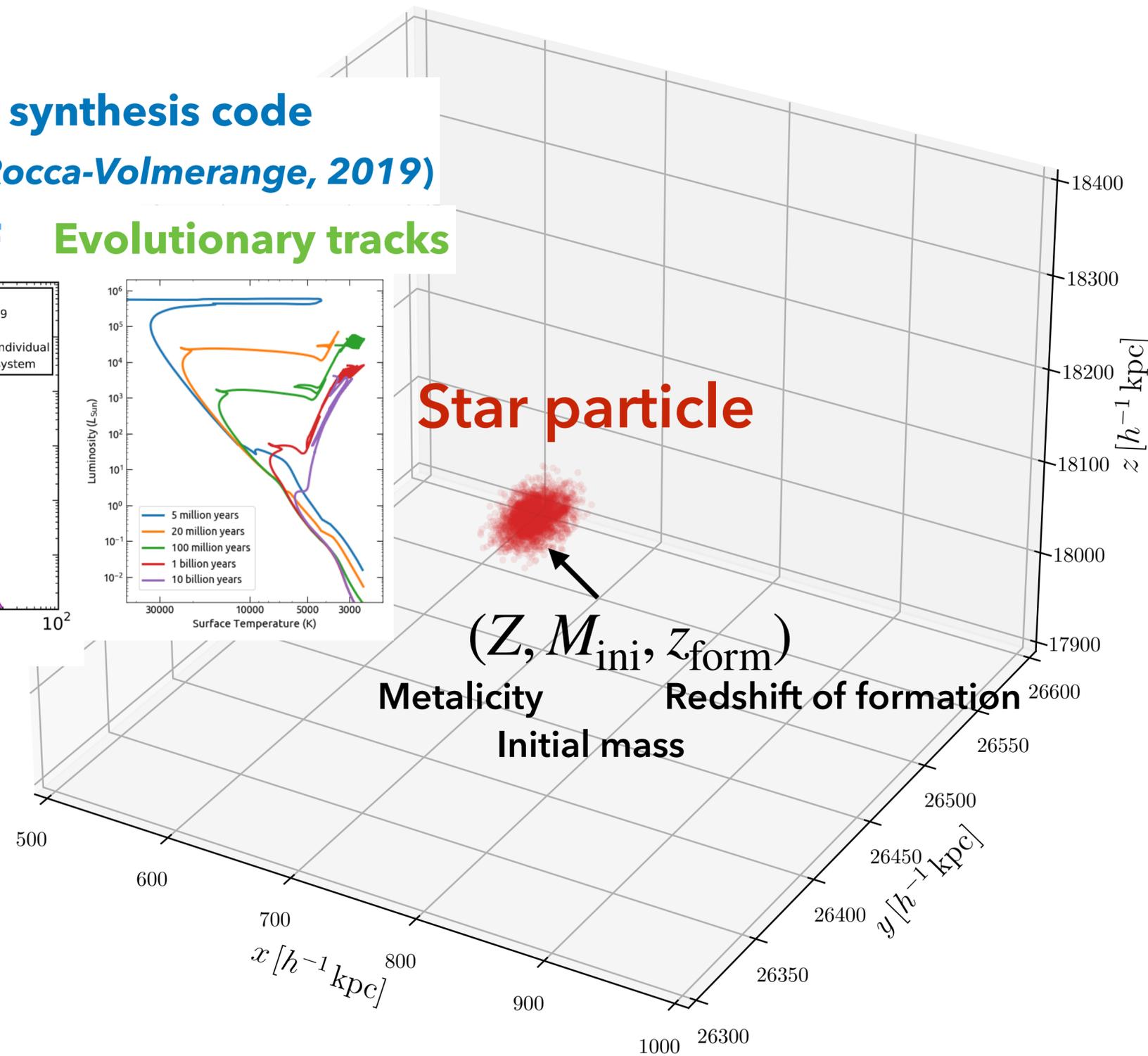
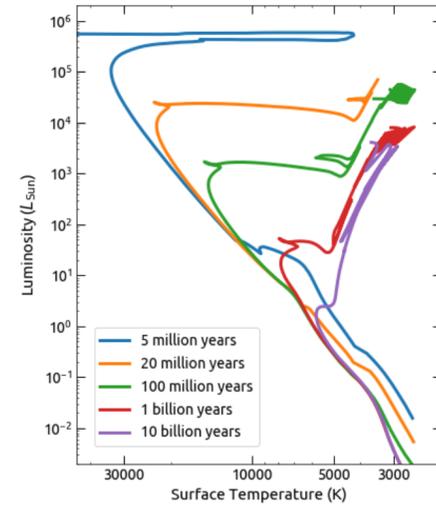
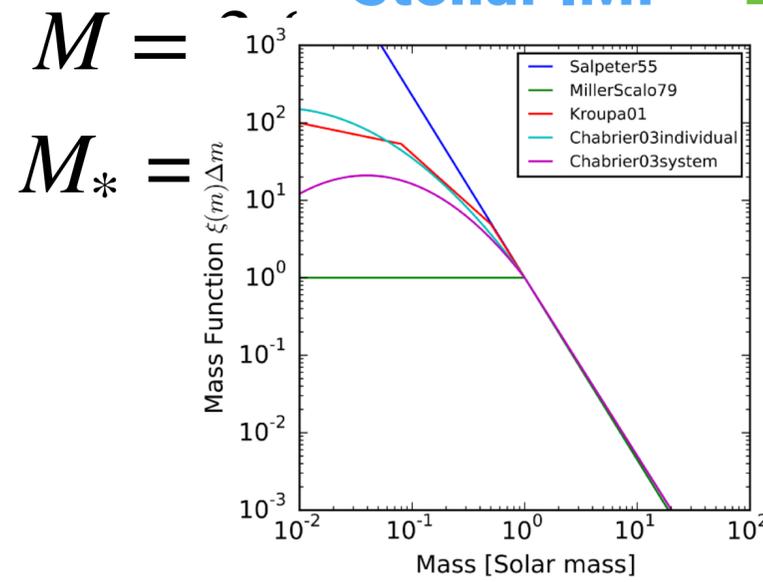
Simulating Galaxy Spectra from Hydrodynamical Simulations

Stellar population synthesis code

- **Su|** **PÉGASE-3** (*Fioc & Rocca-Volmerange, 2019*)

Stellar IMF

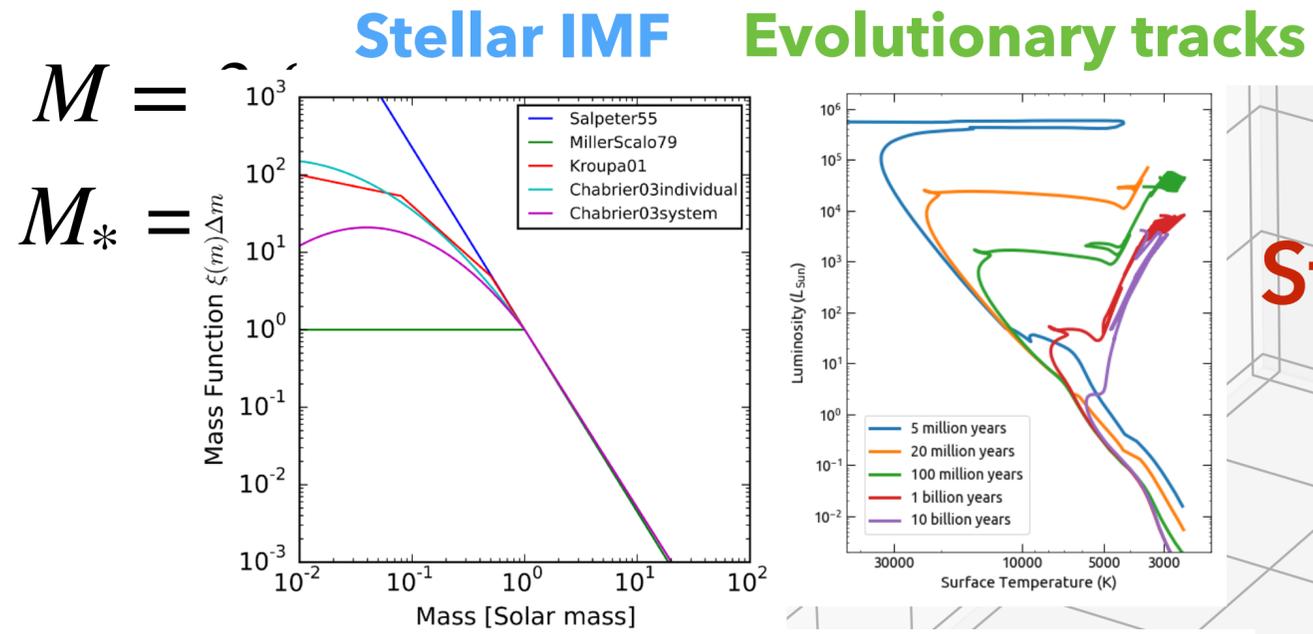
Evolutionary tracks



Simulating Galaxy Spectra from Hydrodynamical Simulations

Stellar population synthesis code

- **Su|** **PÉGASE-3** (*Fioc & Rocca-Volmerange, 2019*)



Star particle

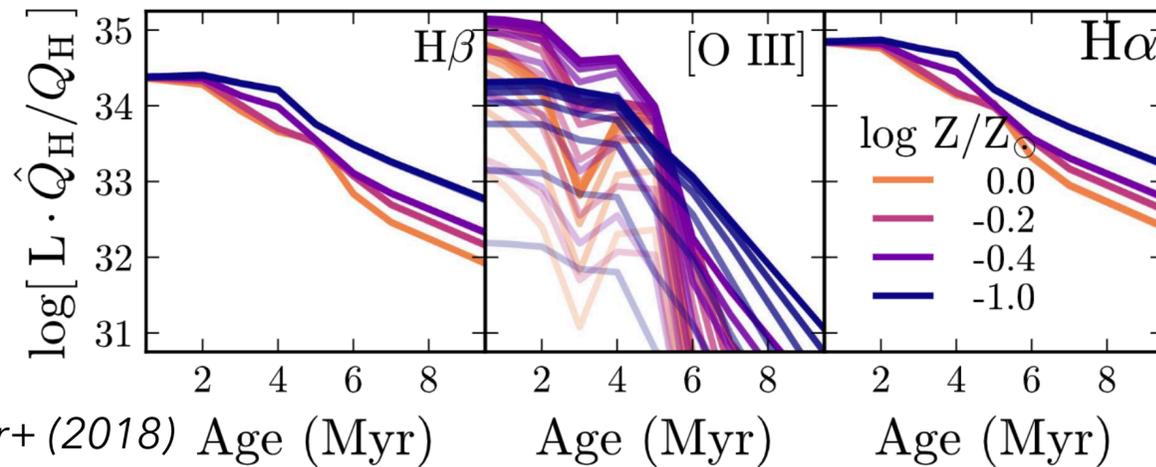
(Z, M_{ini}, z_{form})

Photo-ionization in nebular region

metallicity

Redshift of formation

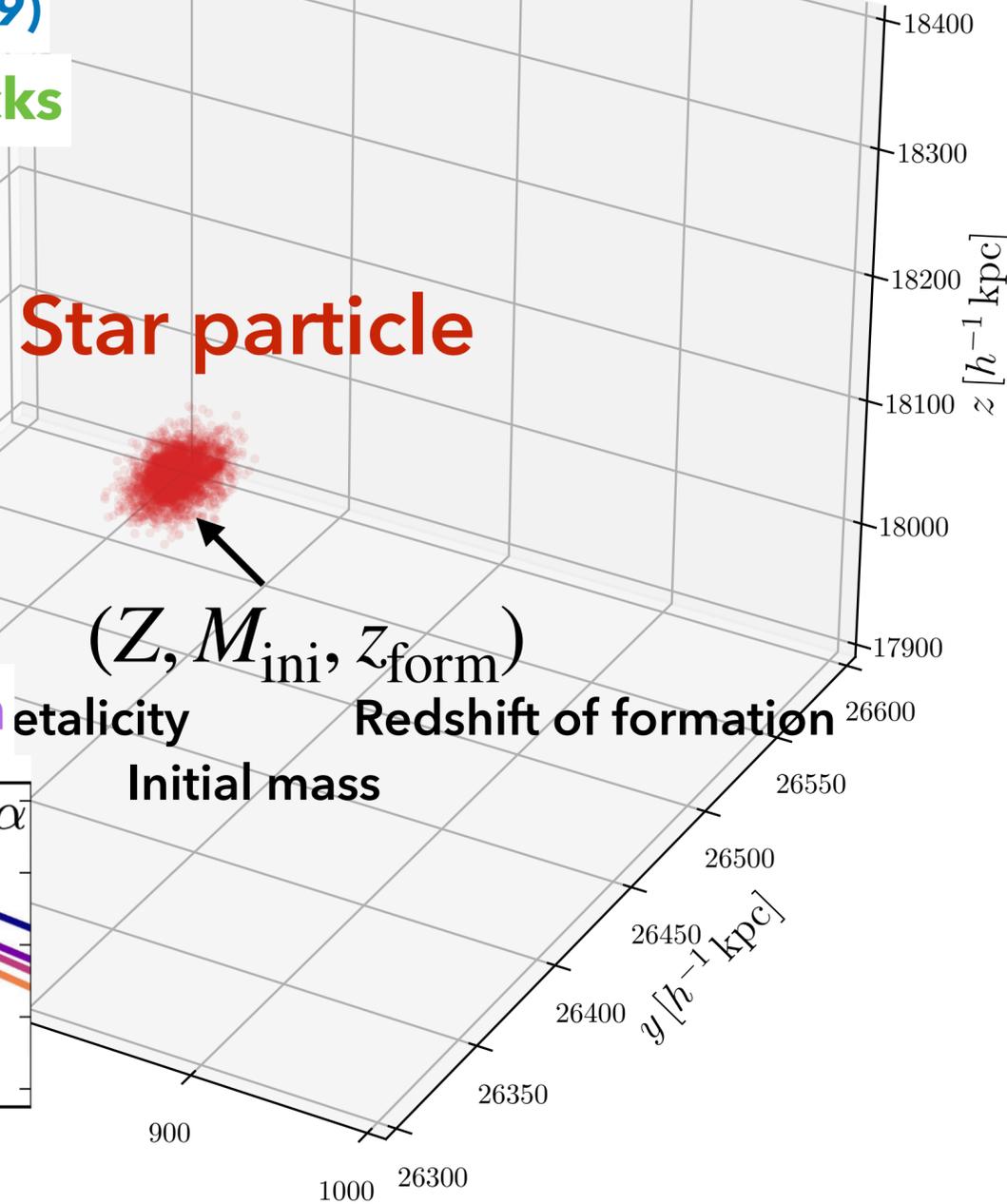
Initial mass



Byler+ (2018)

900

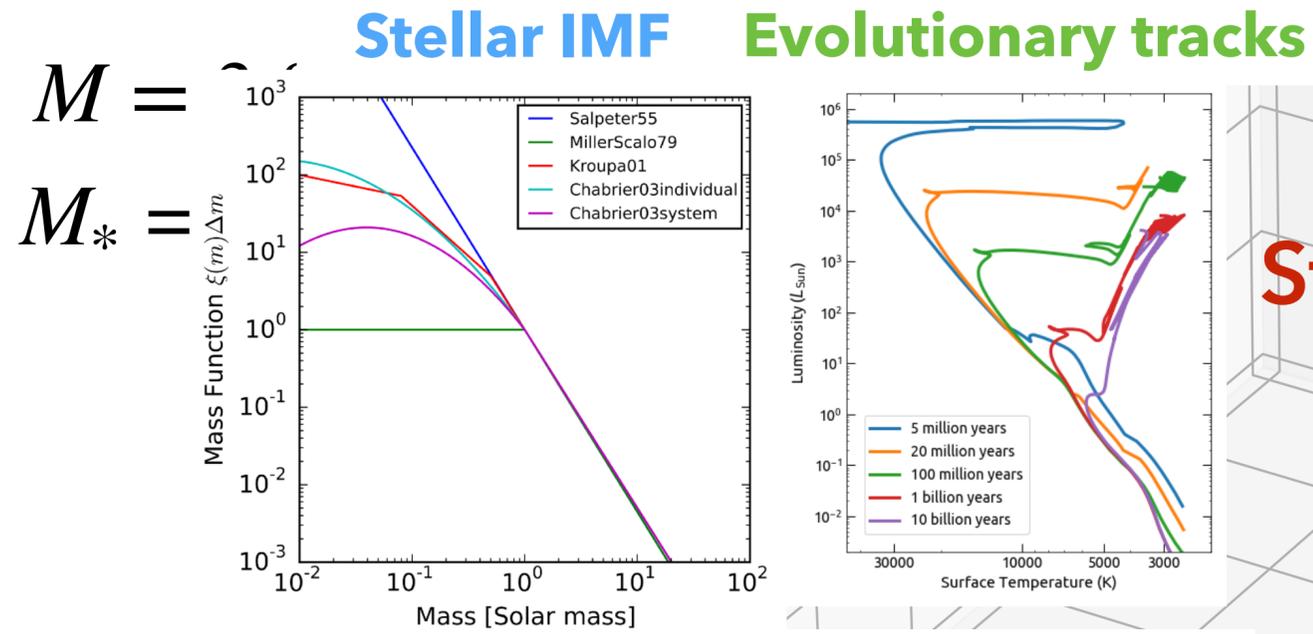
1000



Simulating Galaxy Spectra from Hydrodynamical Simulations

- **Su** **Stellar population synthesis code**
PÉGASE-3 (*Fioc & Rocca-Volmerange, 2019*)

**Spectral energy distribution:
Continuum + Nebular Lines**



Star particle

$(Z, M_{\text{ini}}, z_{\text{form}})$

Metallicity Redshift

Initial mass

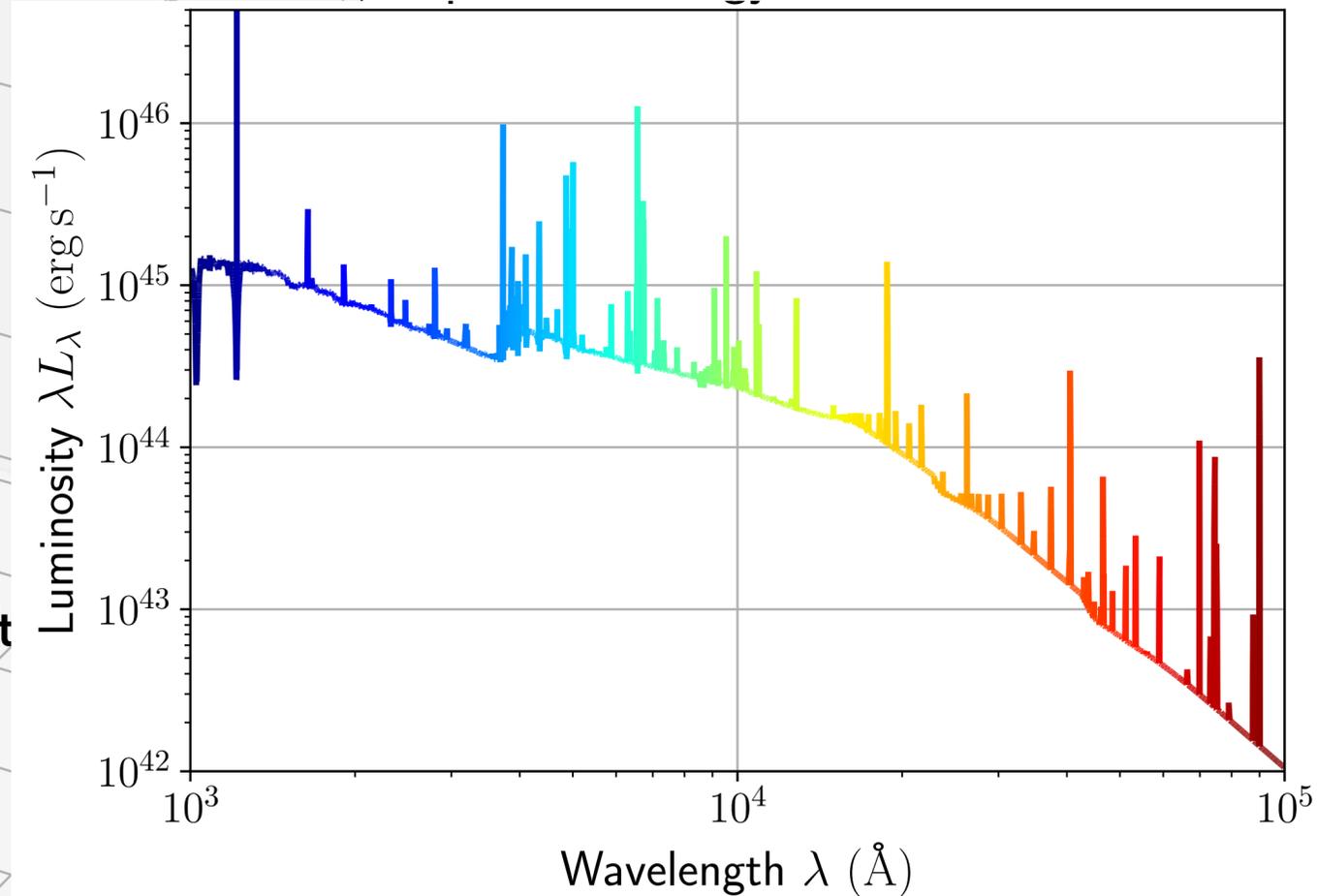
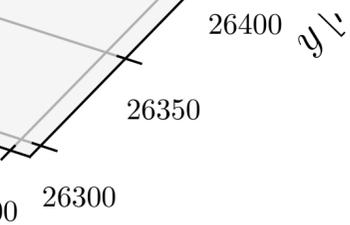
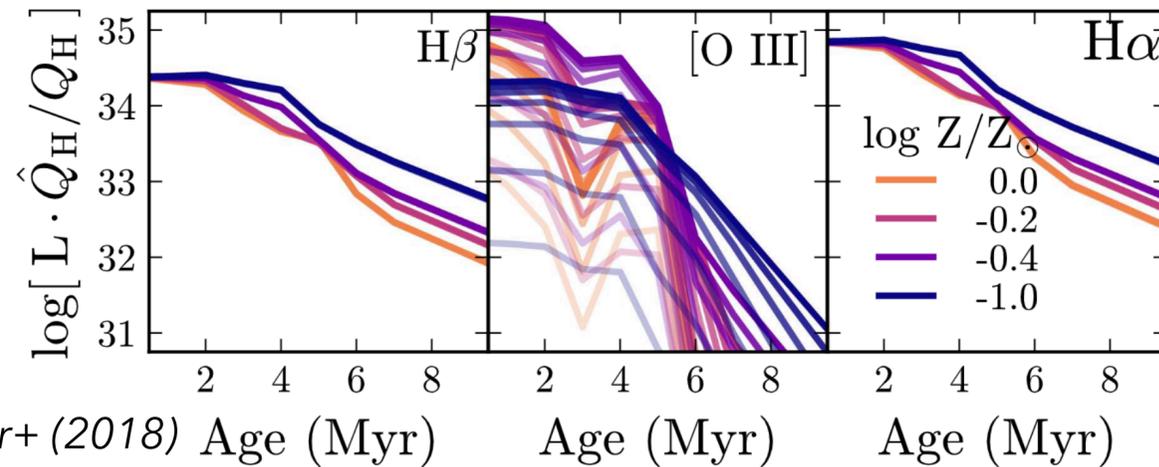
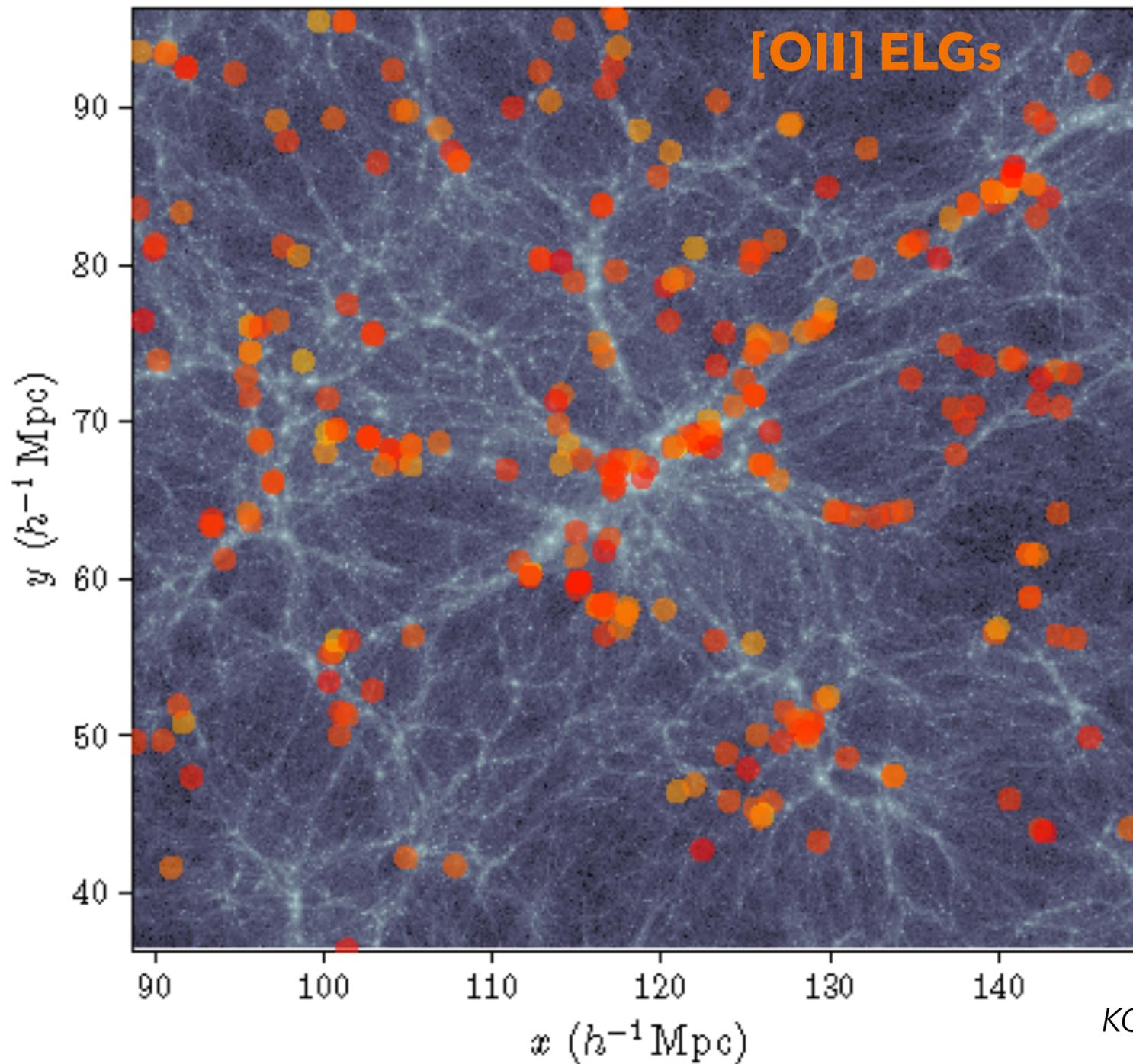
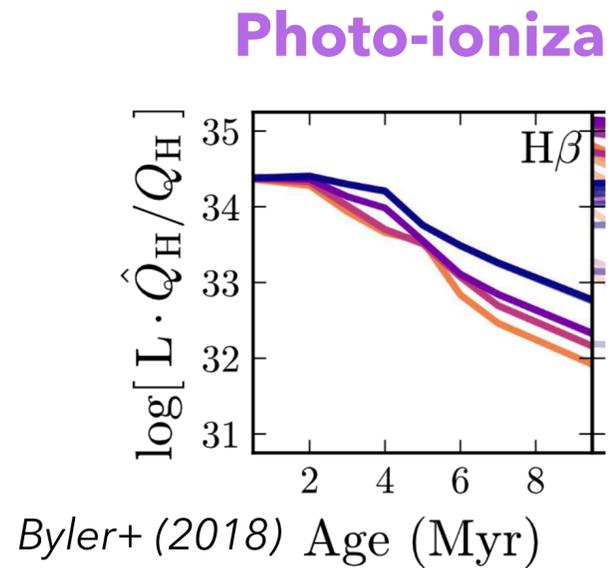
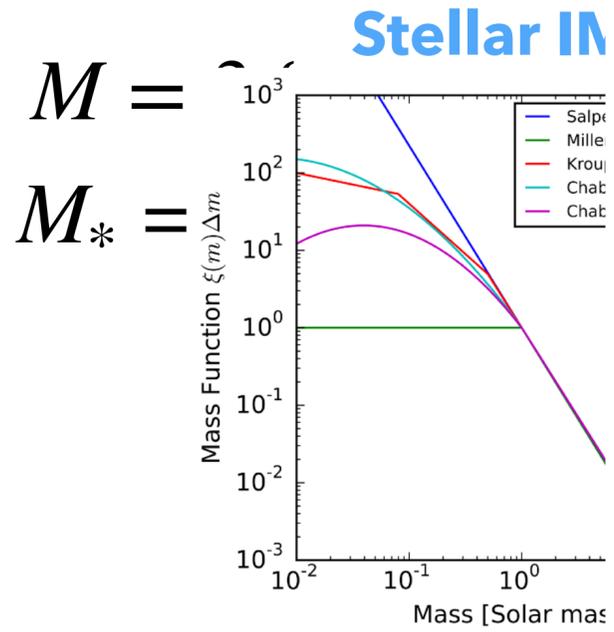


Photo-ionization in nebular region



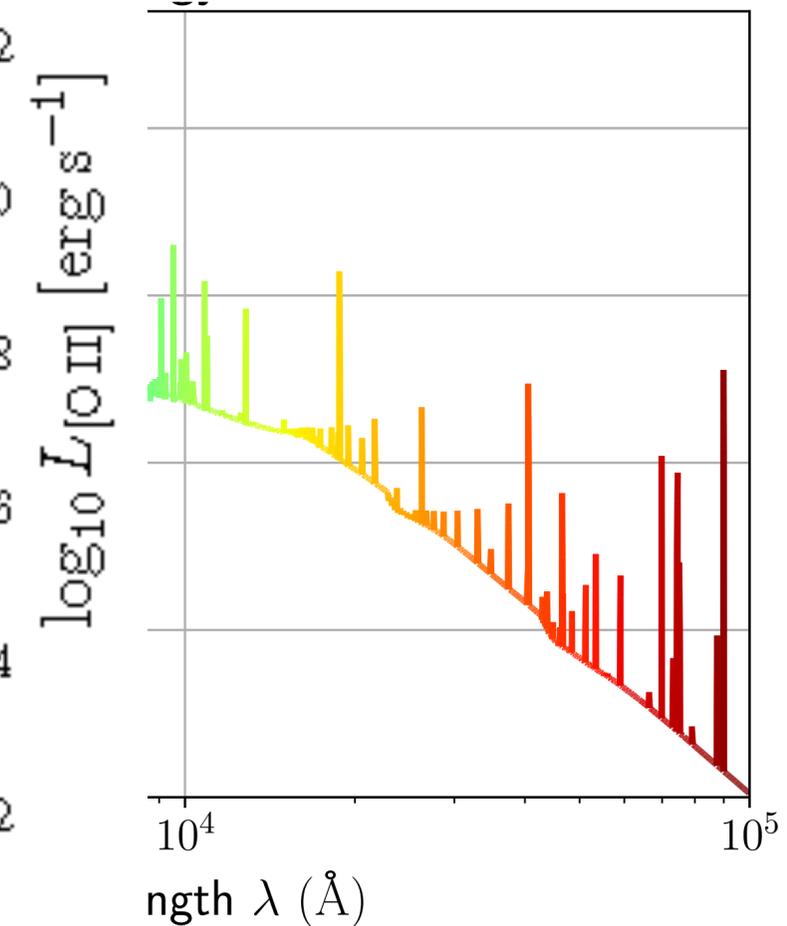
Simulating Galaxy Spectra from Hydrodynamical Simulations

- **Su1** Stellar population
- **PÉGASE-3** (Fioc &...



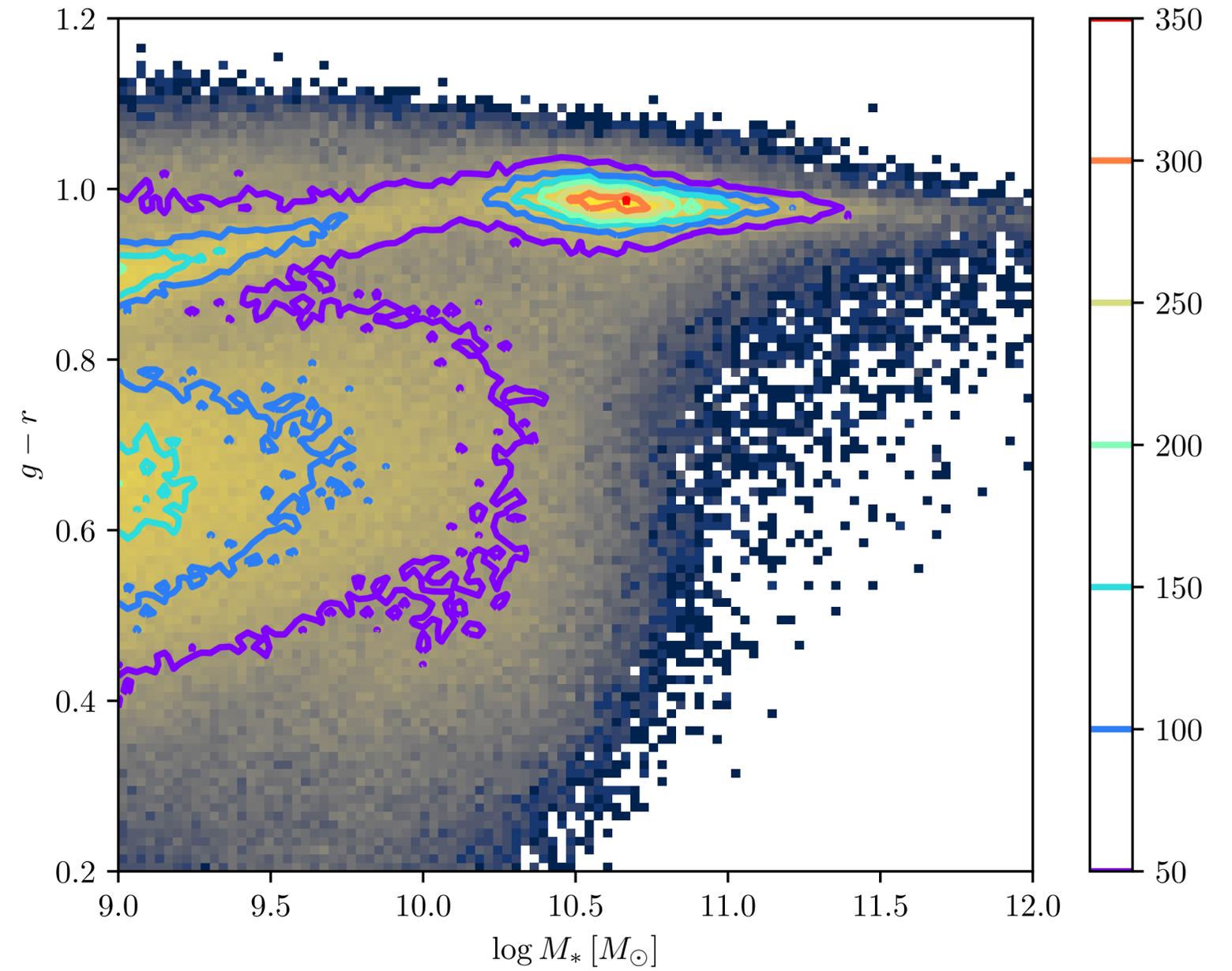
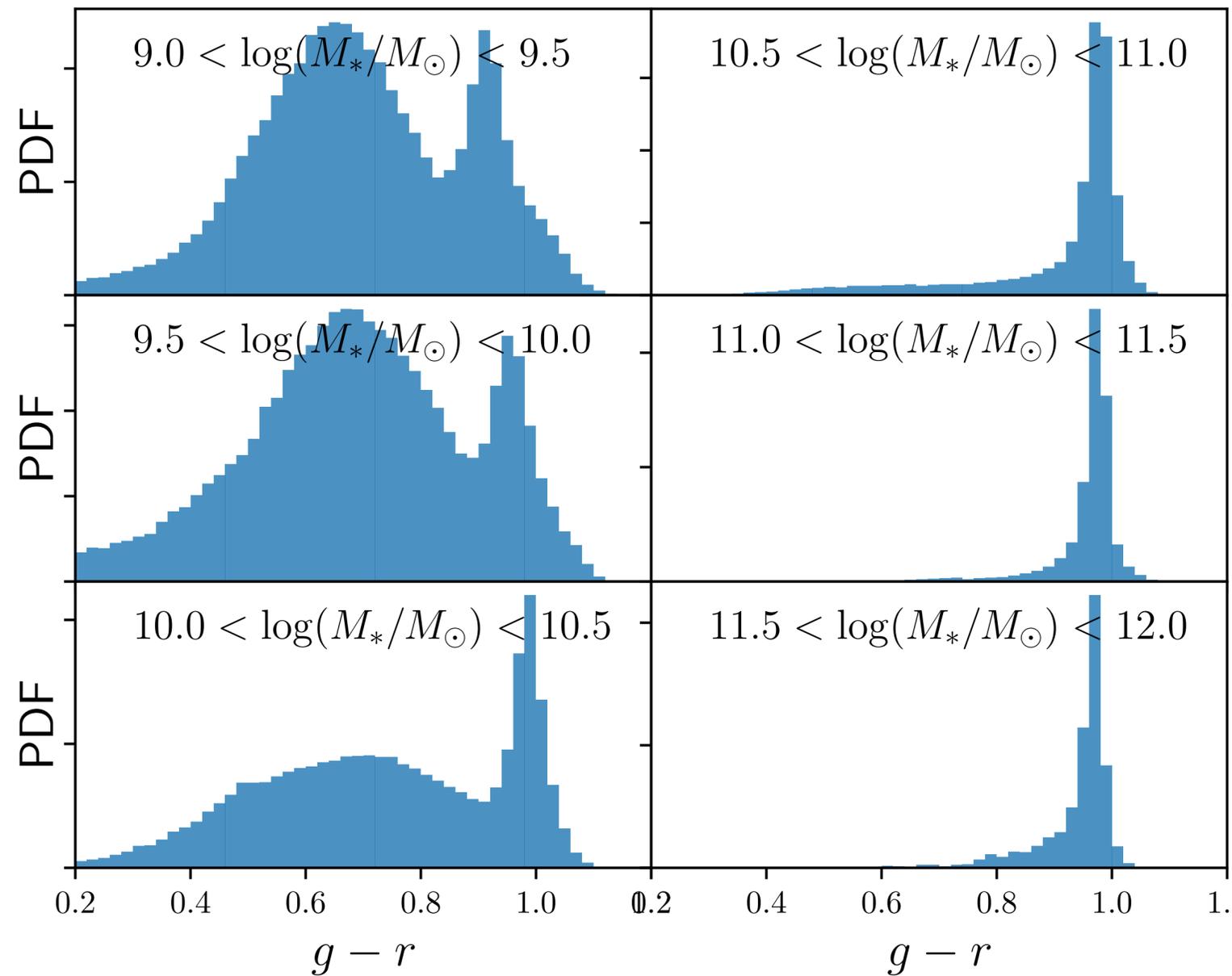
KO & Okumura (2023)

y distribution: Nebular Lines



Galaxy Colour Bimodality

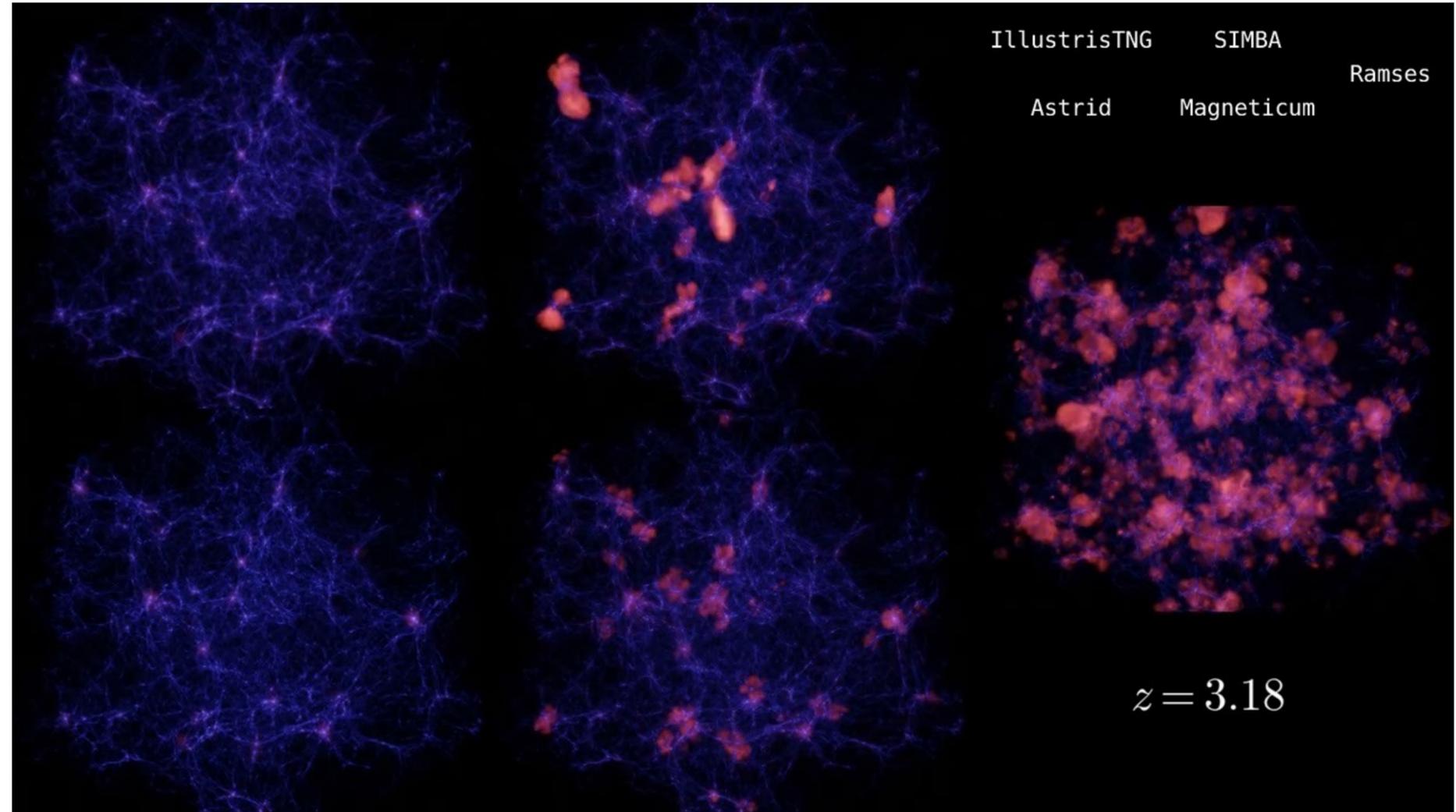
- **Bimodality can also be reproduced in simulations!**



◆ CAMELS (Cosmology and Astrophysics with Machine Learning Simulations)
Suite of N -body/hydrodynamical cosmological simulations:

- 7,208 N -body sims.
- 9,752 hydrodynamical sims.
- ▶ Cosmological parameters and AGN feedback parameters are sampled in Latin hyper cube.

➔ **Suitable for emulators and ML-based approaches**

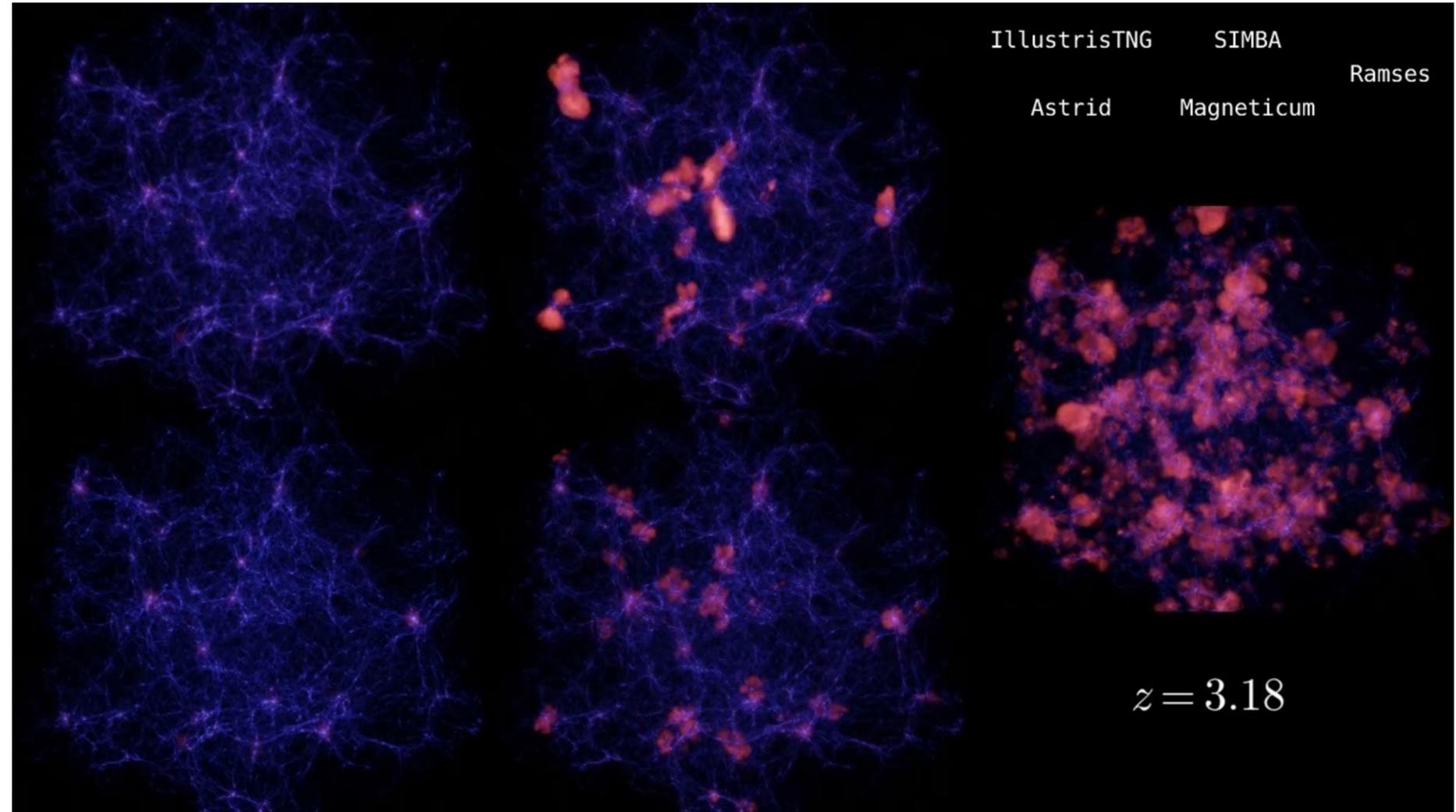


Villaescusa-Navarro+ (2020)

◆ CAMELS (Cosmology and Astrophysics with Machine Learning Simulations)
Suite of *N*-body/hydrodynamical cosmological simulations:

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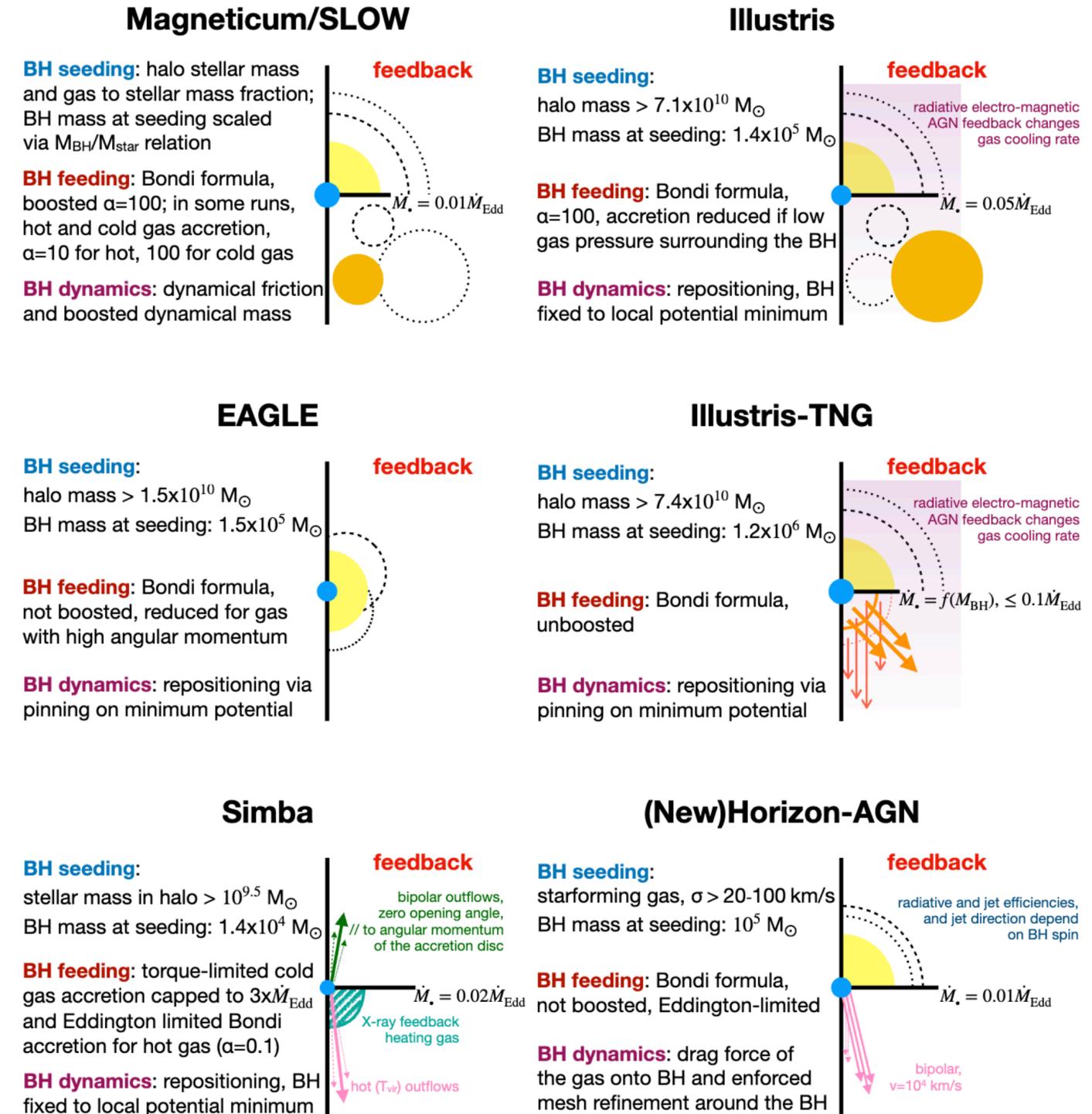
➔ **Suitable for emulators and ML-based approaches**



Villaescusa-Navarro+ (2020)

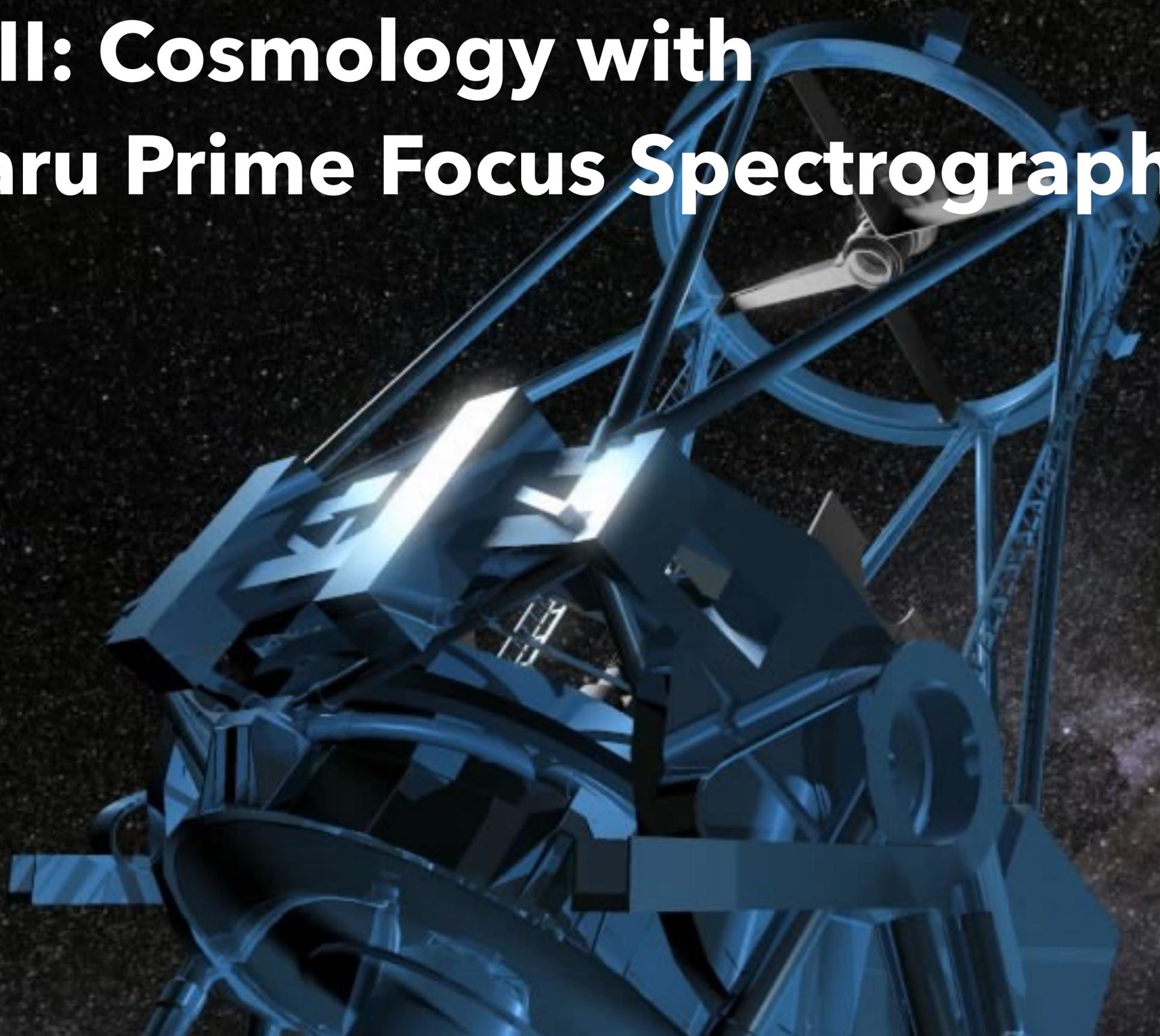
Challenges in Cosmological Hydrodynamical Simulations

- Computational challenge:**
 Hydro sims are typically much more (~x100-1000) expensive than DMO sims. It hinders large-box (~ Gpc) and multiple runs.
- Subgrid physics implementation:**
 In cosmological hydro sims, subgrid physics is always approximation and has large uncertainty. Different hydro sims employ different approaches.
- Astrophysical assumptions:**
 IMF, metal yields, etc. are accurate enough?

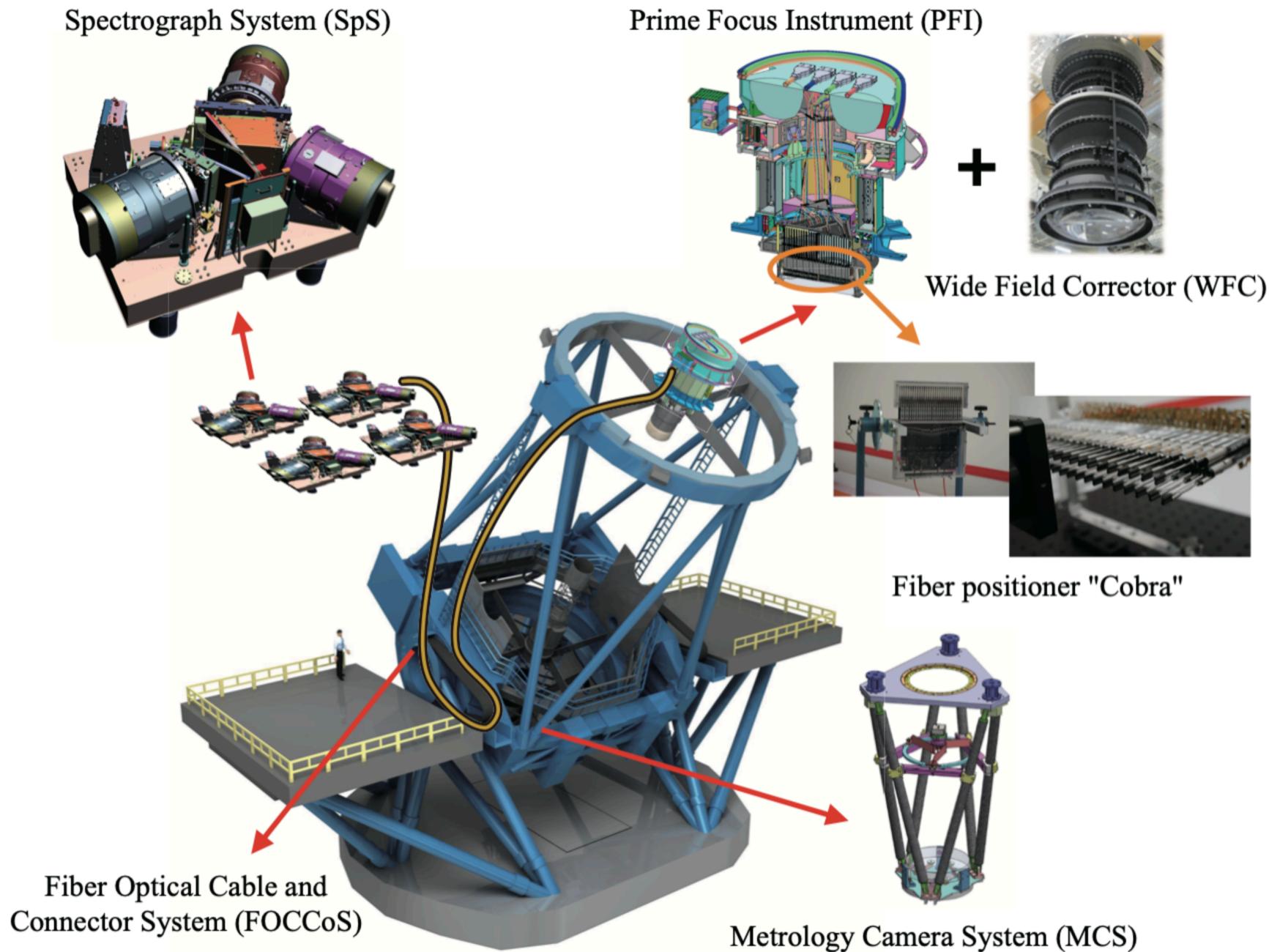


Valentini and Dolag (2025)

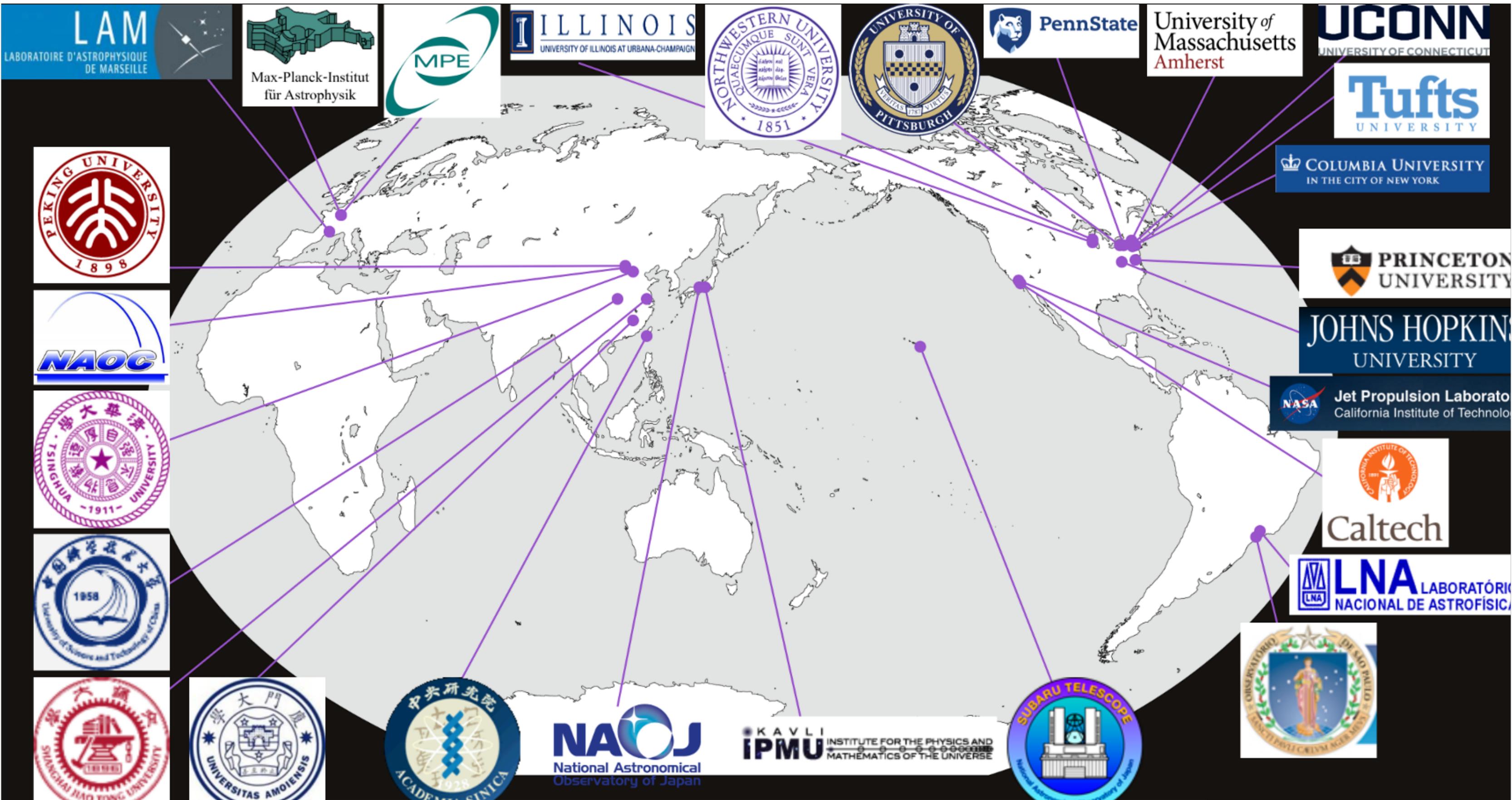
Part II: Cosmology with Subaru Prime Focus Spectrograph



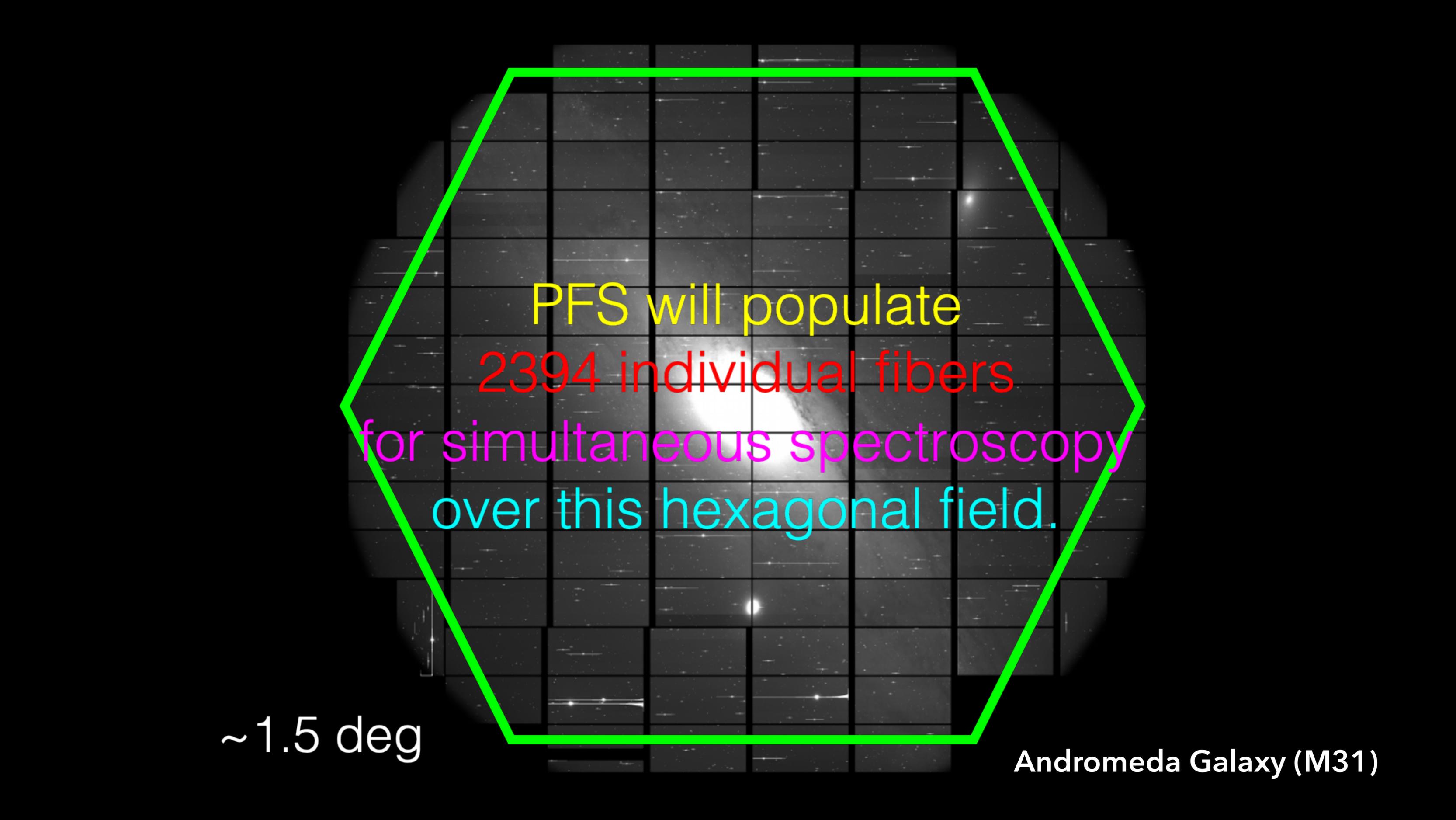
Subaru Prime Focus Spectrograph



- ~\$90M project, being led by Kavli IPMU (PI: Hitoshi Murayama, PM: Naoyuki Tamura, PS: Masahiro Takada)
- Institutes in 6 countries are also involved (US, France, Taiwan, Brazil, Germany, China)
- Mentioned in several places of US Astro2020
- **2394 fibers**, wide field-of-view, [0.38, 1.26]nm, 8.2m collecting power
- We start our large-scale surveys from early **2025**.
- Website: <https://pfs.ipmu.jp>
PFS blog: <https://pfs.ipmu.jp/blog/ja/>



5-years, 360 nights, survey started from March, 2025

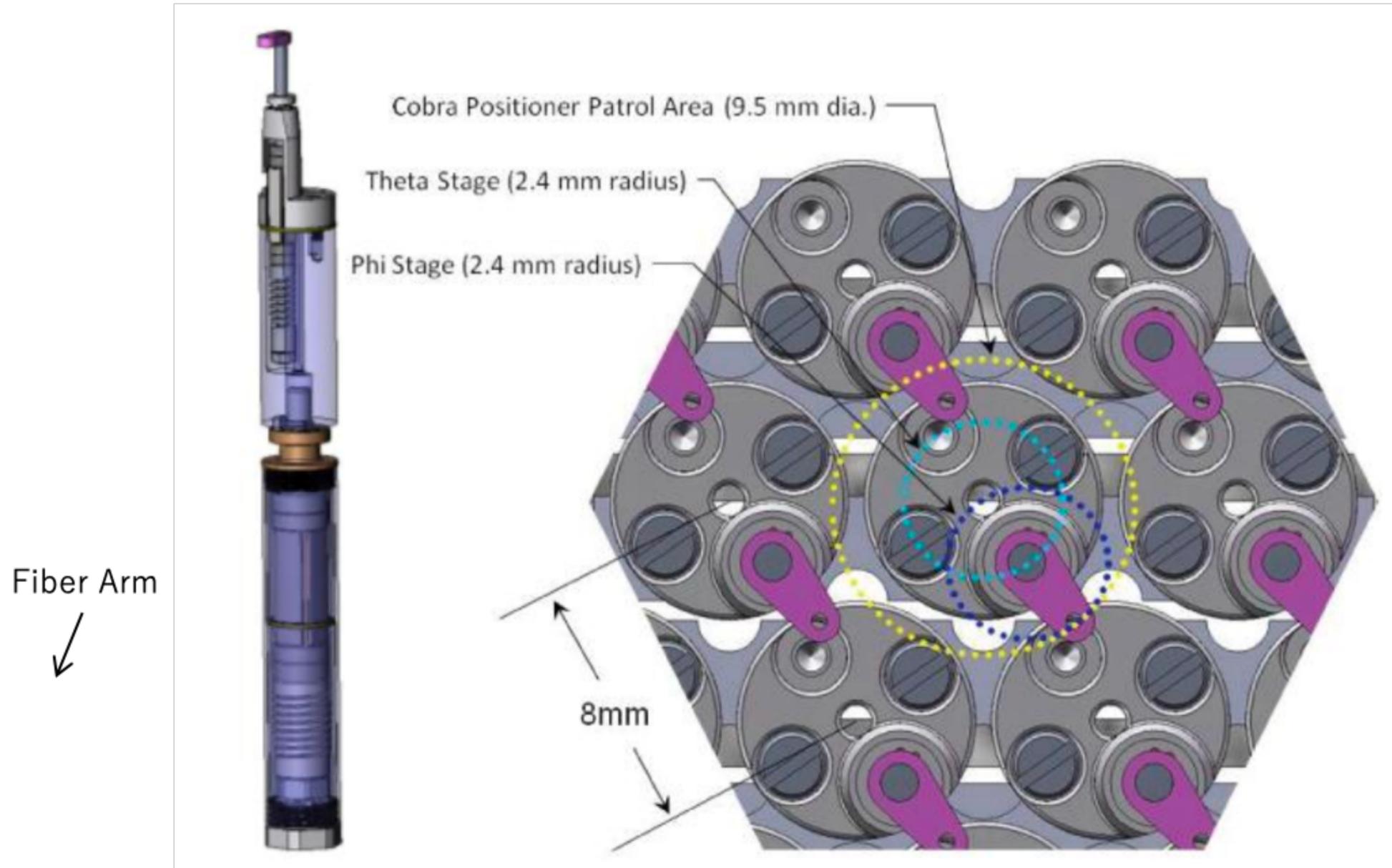


PFS will populate
2394 individual fibers
for simultaneous spectroscopy
over this hexagonal field.

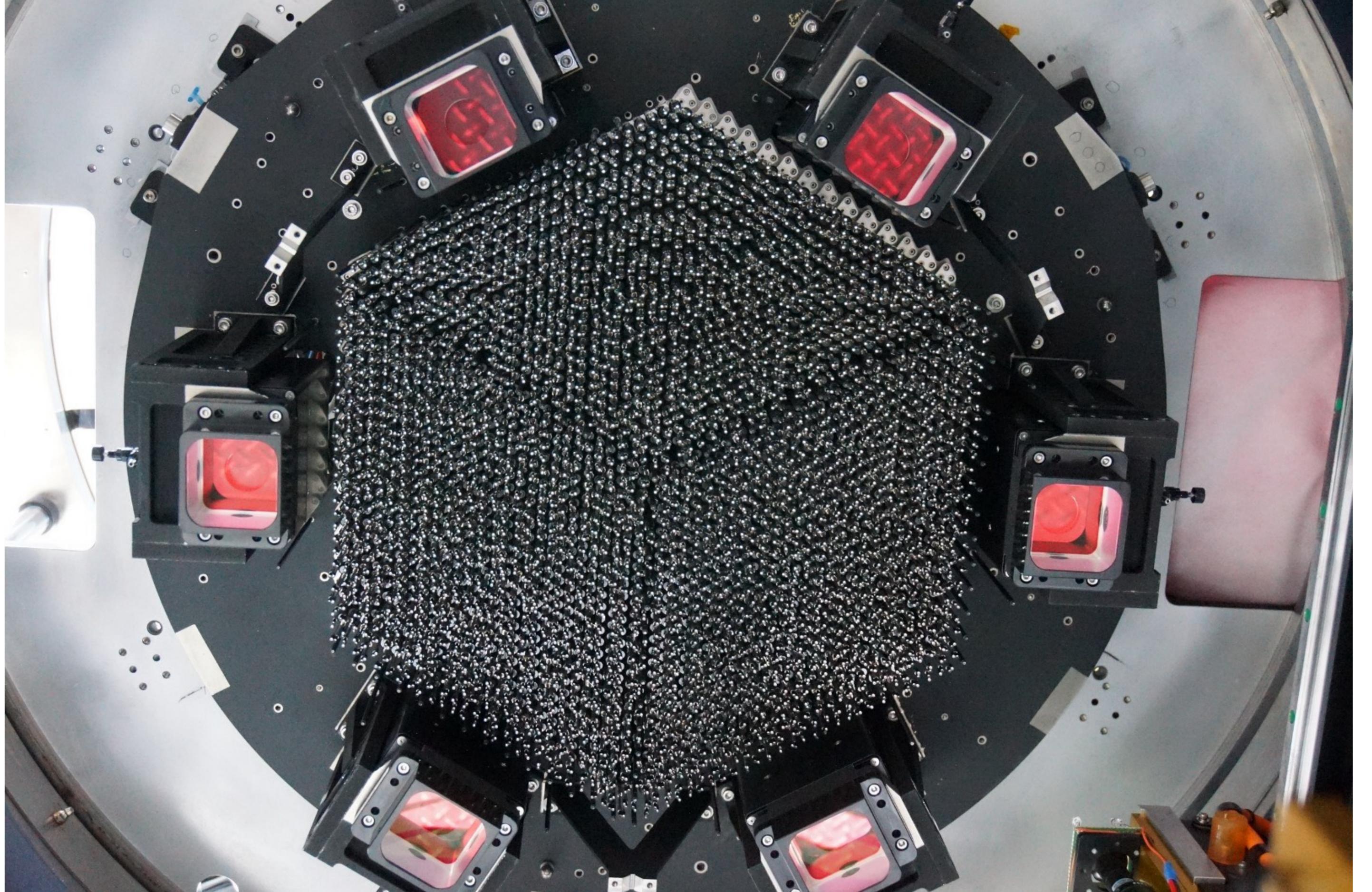
~1.5 deg

Andromeda Galaxy (M31)

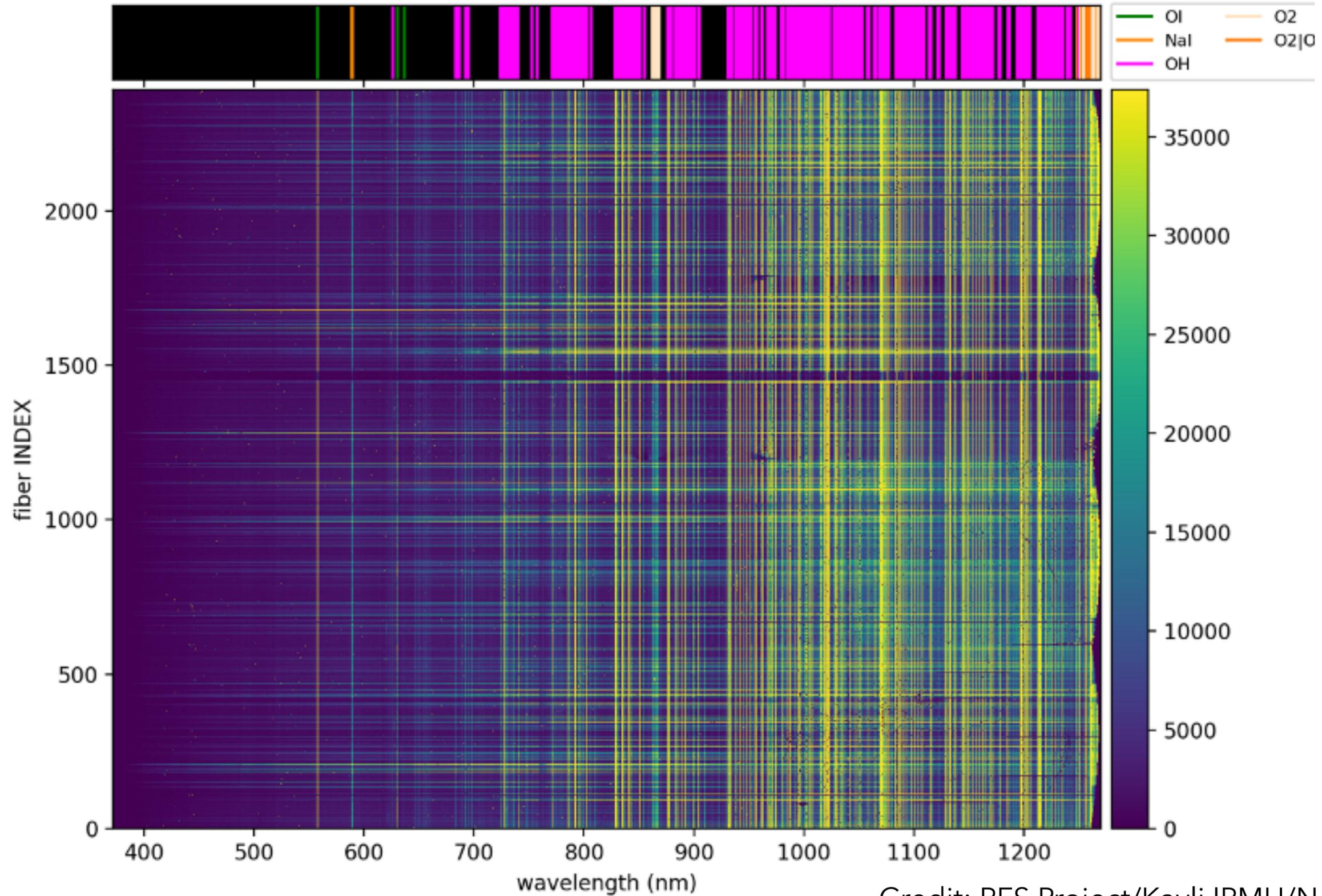
- JPL/Caltech contribution to PFS
- “Critical” component of PFS
- 2394 cobra positioners on the focal plane
- Requirement: $\sim 10\mu\text{m}$ (0.1”) positioning accuracy



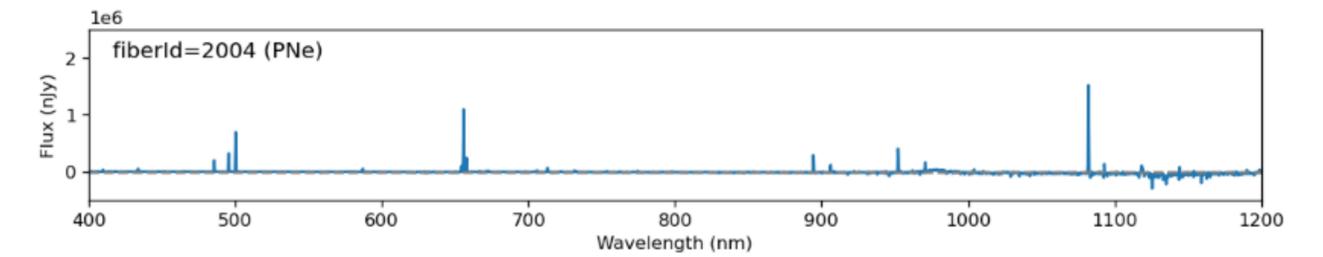
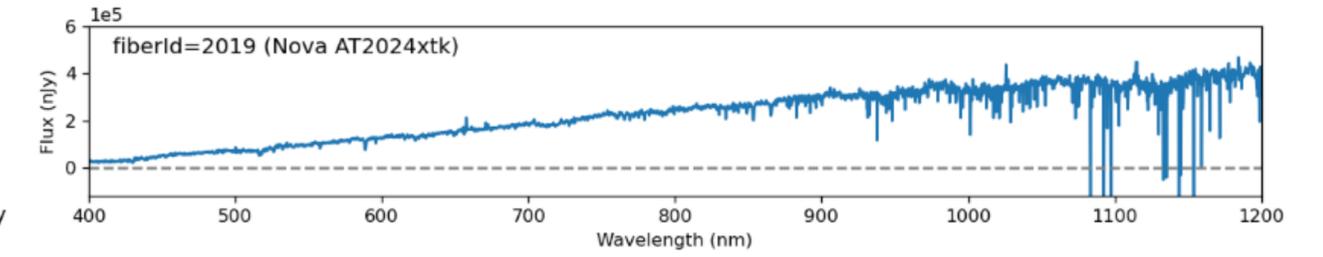
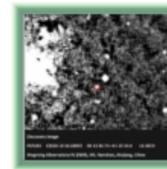
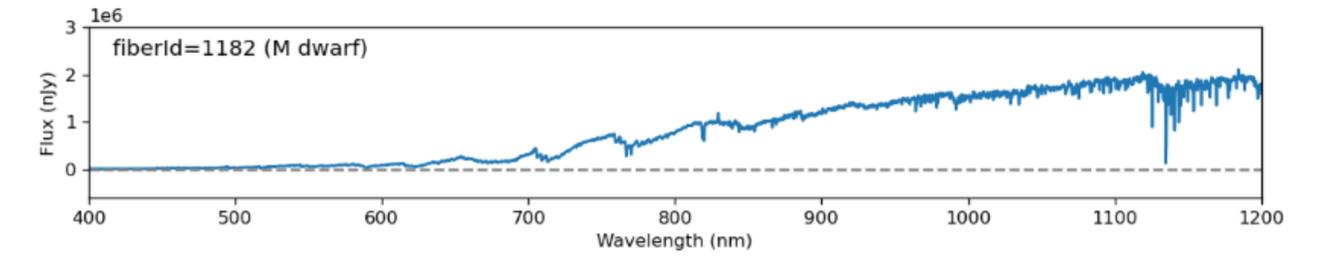
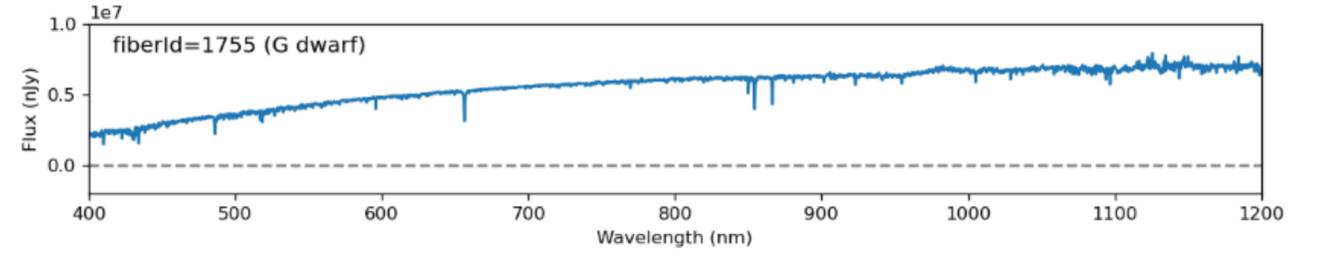
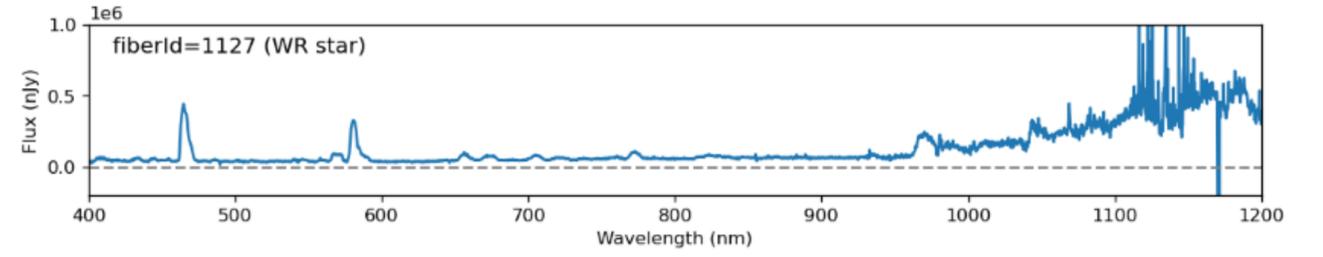
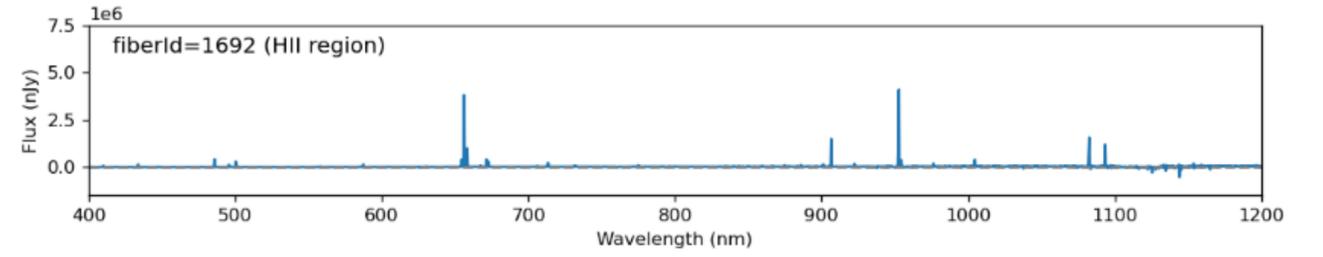
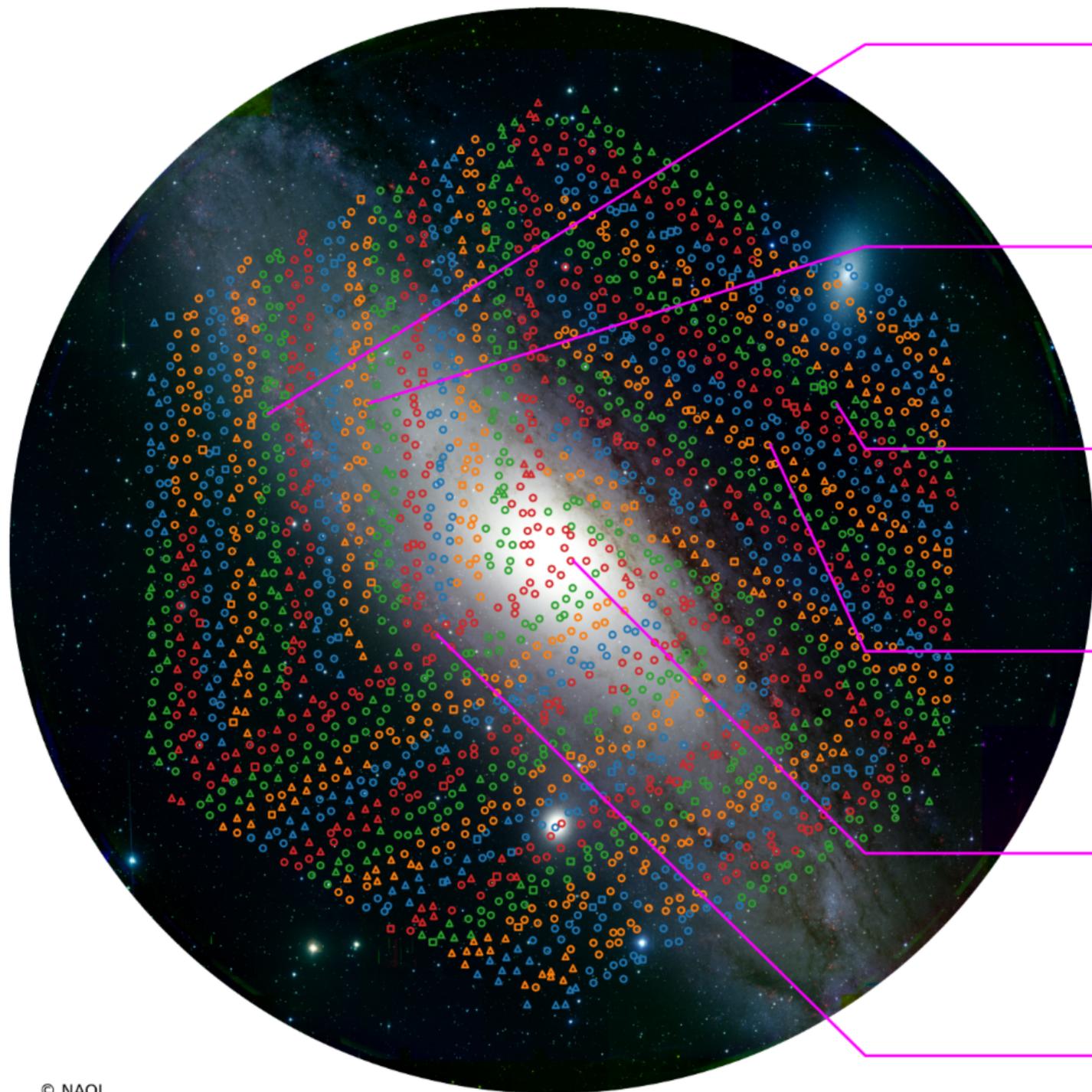
Copra module (57 positioners)



pfsMerged_114885_SM1,2,3,4
PPC_L_18485500
rhl/eng-2024-08 /work/drp/CALIB-2024-07-v6



Credit: PFS Project/Kavli IPMU/NAOJ

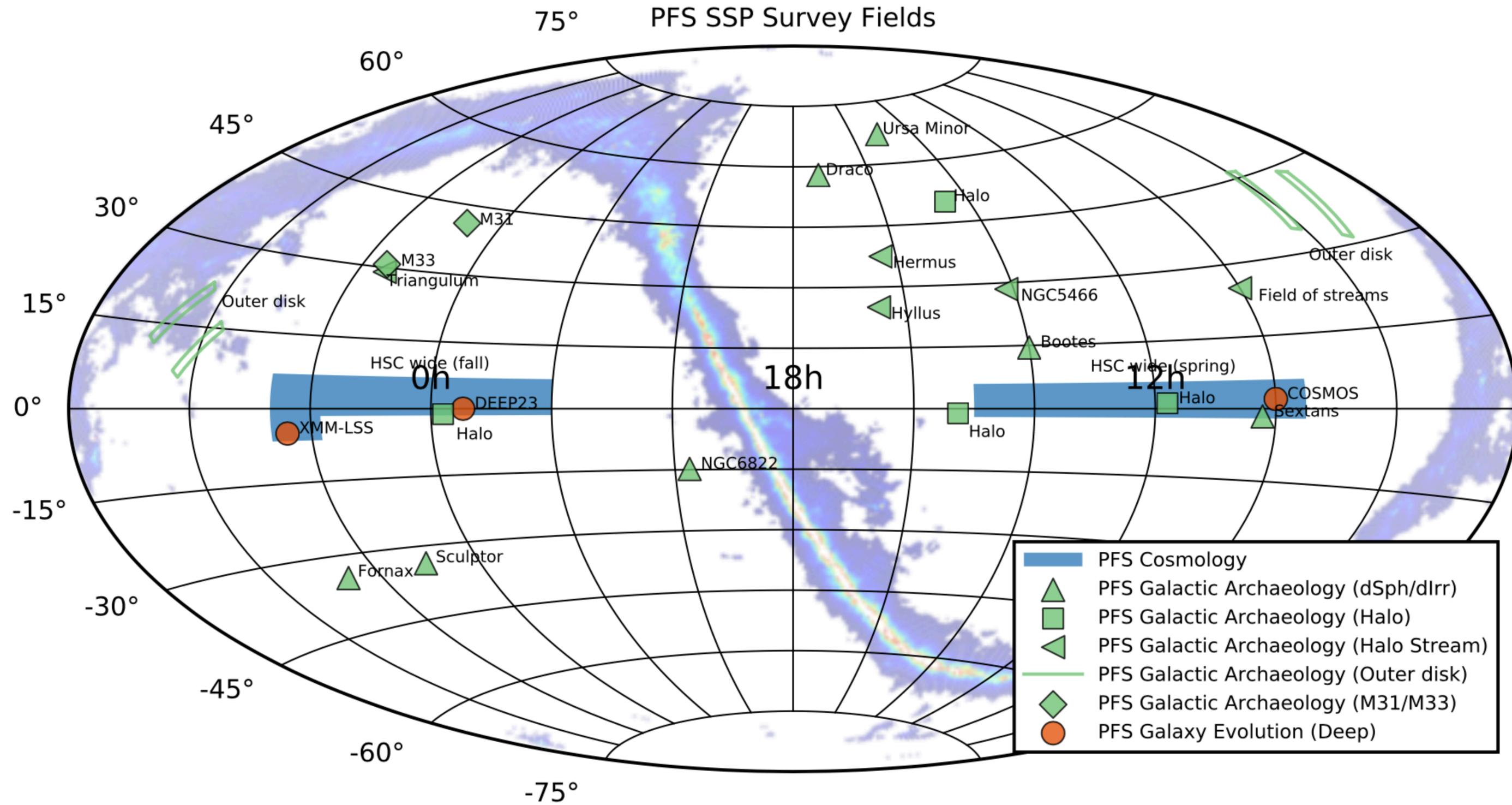


Xingming Observatory

© NAOJ

Credit: PFS Project/Kavli IPMU/NAOJ

PFS-SSP Survey Footprint



PFS-SSP Science Programmes

	Testing Λ CDM	Assembly history of galaxies	Importance of IGM
CO	<ul style="list-style-type: none"> • Nature & role of neutrinos • Expansion rate via BAO up to $z=2.4$ • PFS+HSC tests of GR 	<ul style="list-style-type: none"> • PFS+HSC galaxy association • Absorption probes with PFS/SDSS QSOs around PFS/HSC host galaxies 	<ul style="list-style-type: none"> • Search for emission from stacked spectra
GA	<ul style="list-style-type: none"> • Curvature of space: Ω_K • Primordial power spectrum • Nature of DM (dSphs) 	<ul style="list-style-type: none"> • Stellar kinematics and chemical abundances – MW & M31 assembly history 	<ul style="list-style-type: none"> • dSph as relic probe of reionization feedback • Past massive star IMF from element abundances
GE	<ul style="list-style-type: none"> • Search of MW dark halo • Small-scale tests of structure growth 	<ul style="list-style-type: none"> • Halo-galaxy connection: M_*/M_{halo} • Outflows & inflows of gas • Environment-dependent evolution 	<ul style="list-style-type: none"> • Physics of cosmic reionization via LAEs & 21cm studies • Tomography of gas & DM

Cosmology (CO) (~1200 sq. degs.): ~4M emission-line galaxy spectra

Galactic Archaeology (GA): stars in dSphs, streams and disk in MW and M31

Galaxy Evolution (GE) (~15 sq. degs.): ~a few 10^5 high S/N galaxy spectra

Target selection is based on the HSC data.

Competitors: DESI, *Euclid*, VLT MOONS

Cosmology of Emission Line Galaxy Clustering

- **Emission line galaxies (ELGs):**

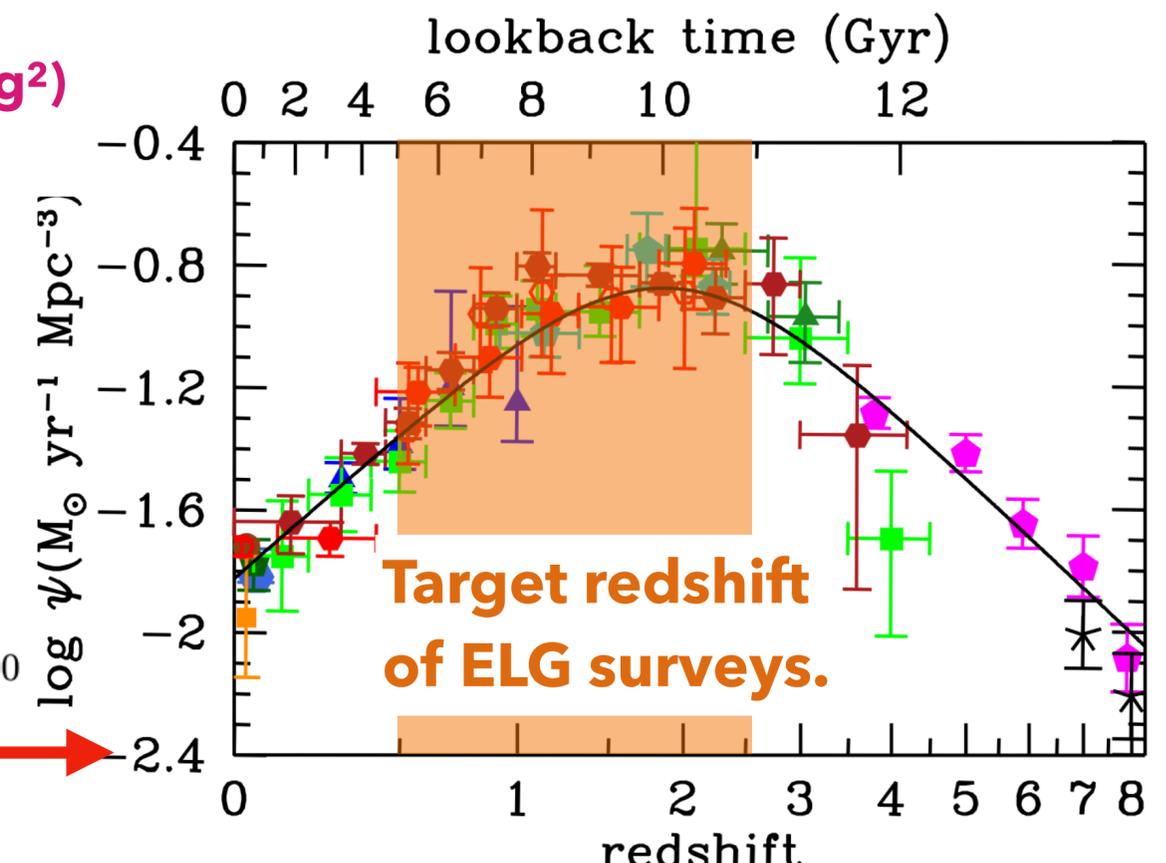
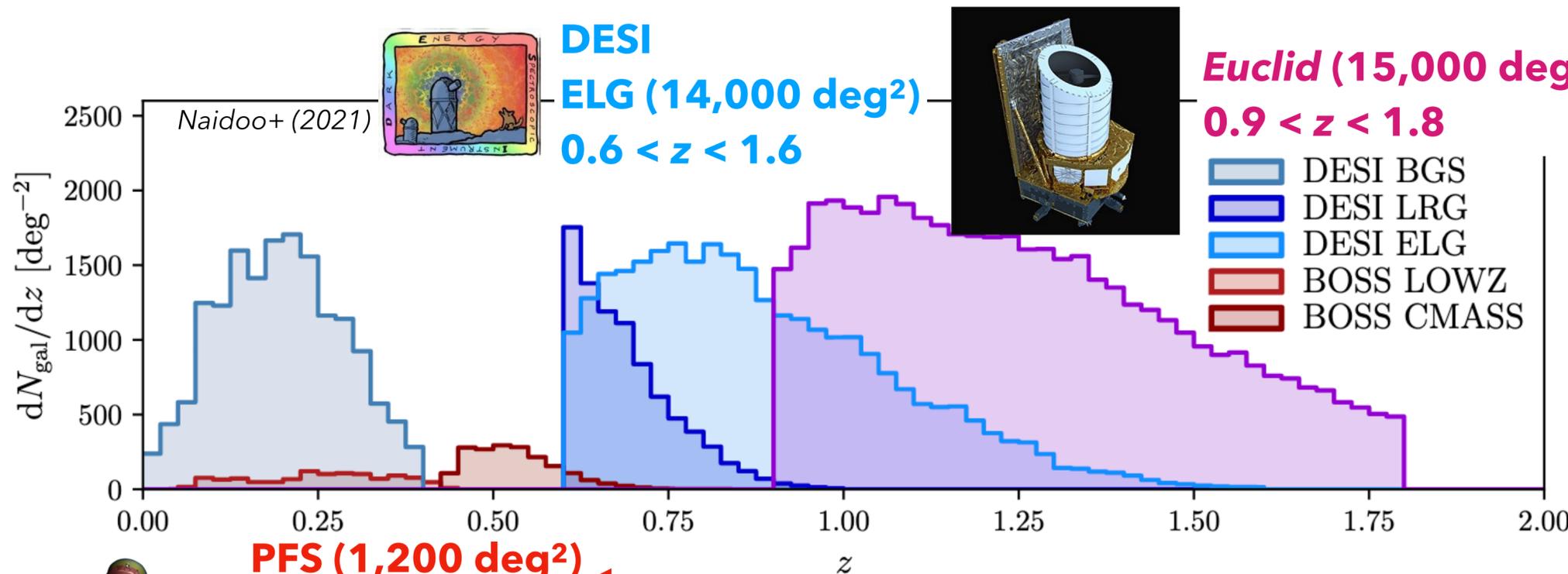
ELGs are characterized by strong emission lines (H α , [O II], etc.) from ionized gas.

The emission is sourced by short-lived massive stars, and thus, **traces the star-formation activity**.

→ ELGs are **blue star-forming galaxies** and a large number of ELGs are expected to be detected.

- Number density of ongoing/upcoming spec. surveys

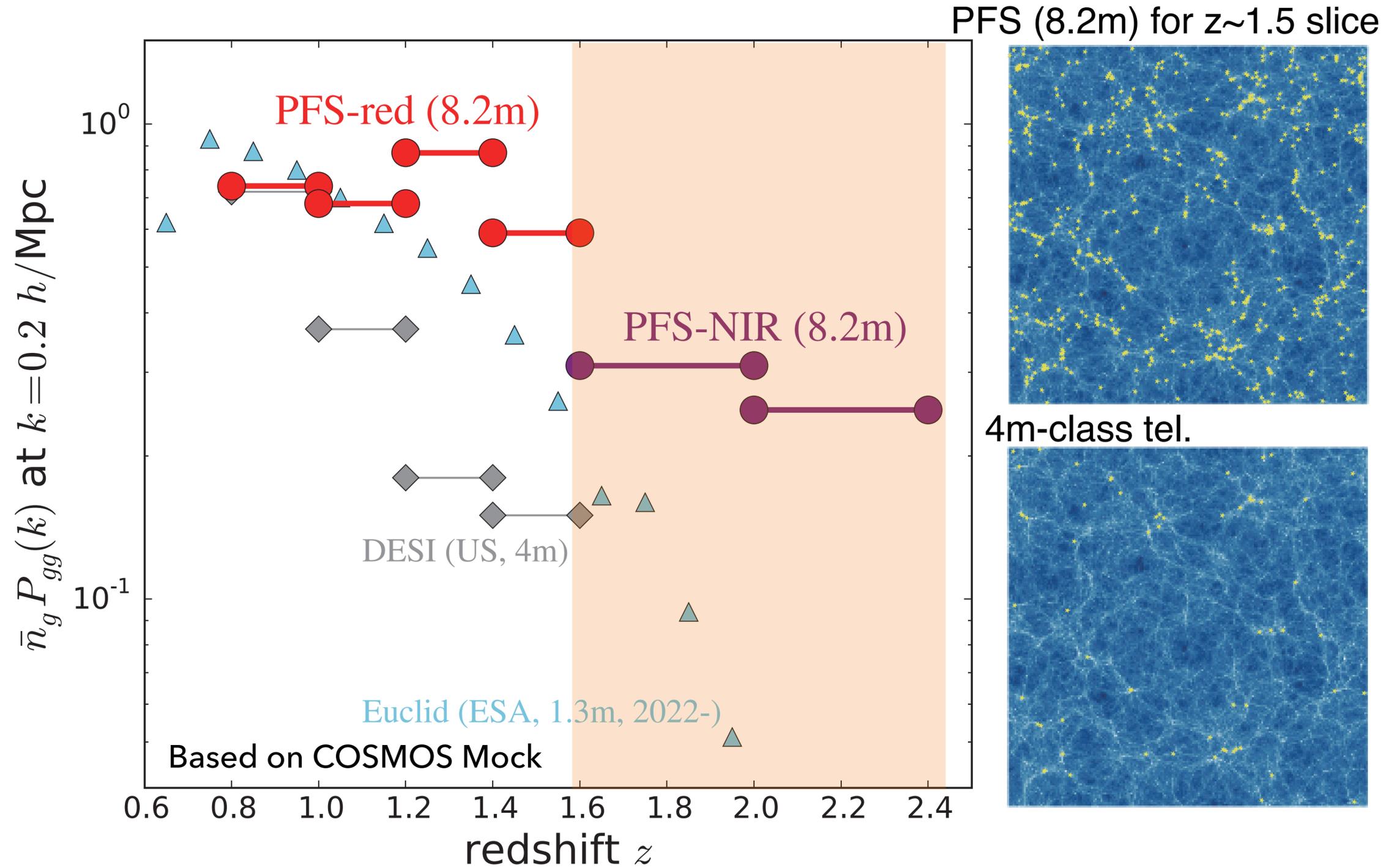
- Star formation rate density



Madu & Dickinson (2014)

Power of 8.2m Aperture

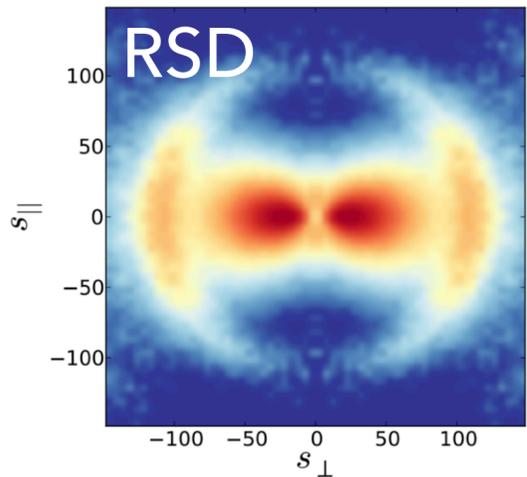
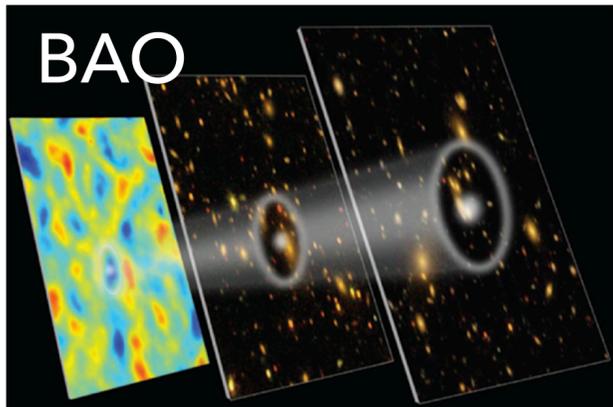
◆ Thanks to NIR, high- z ($z = 1.6-2.4$) galaxies are unique to PFS!



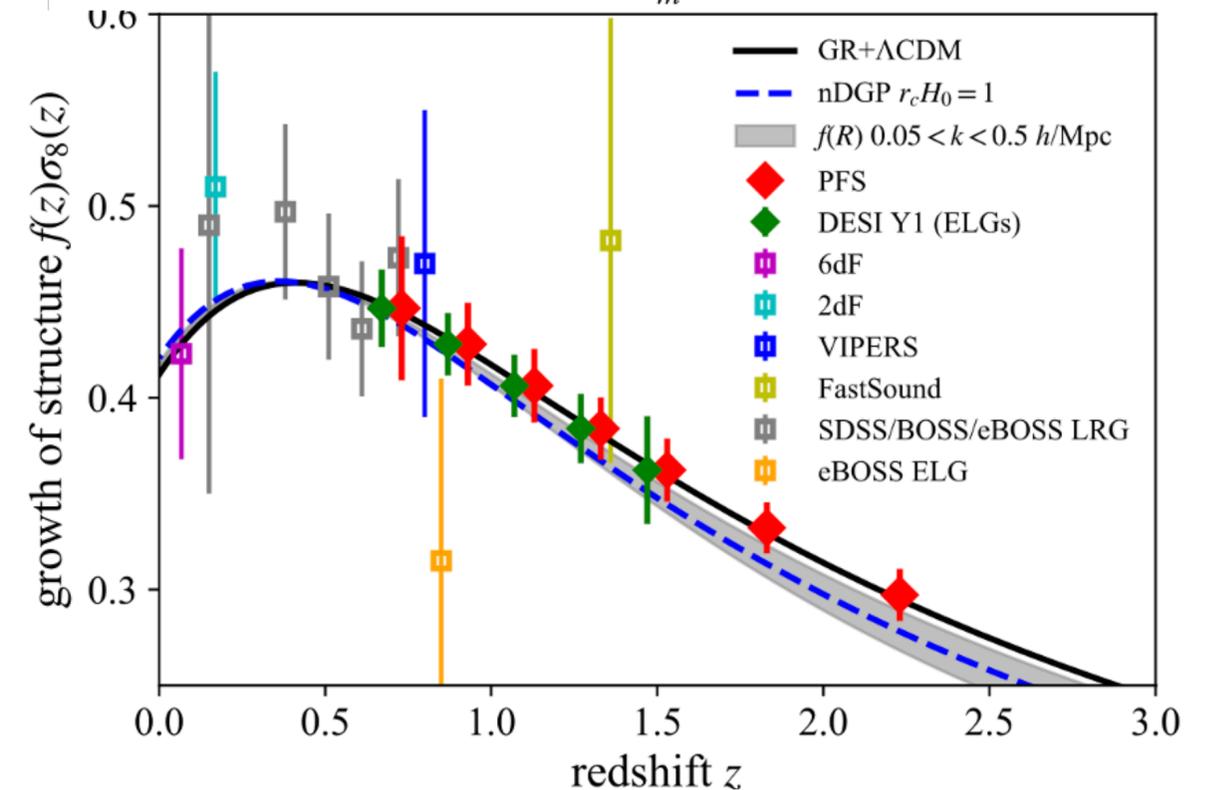
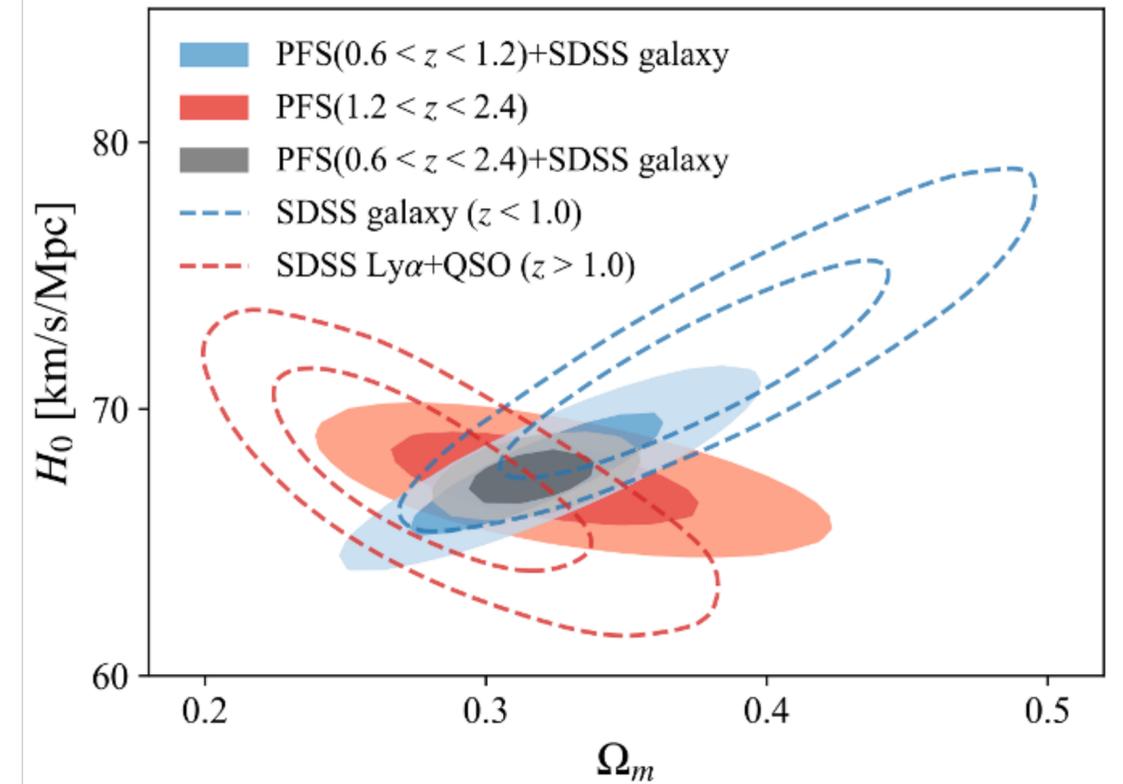
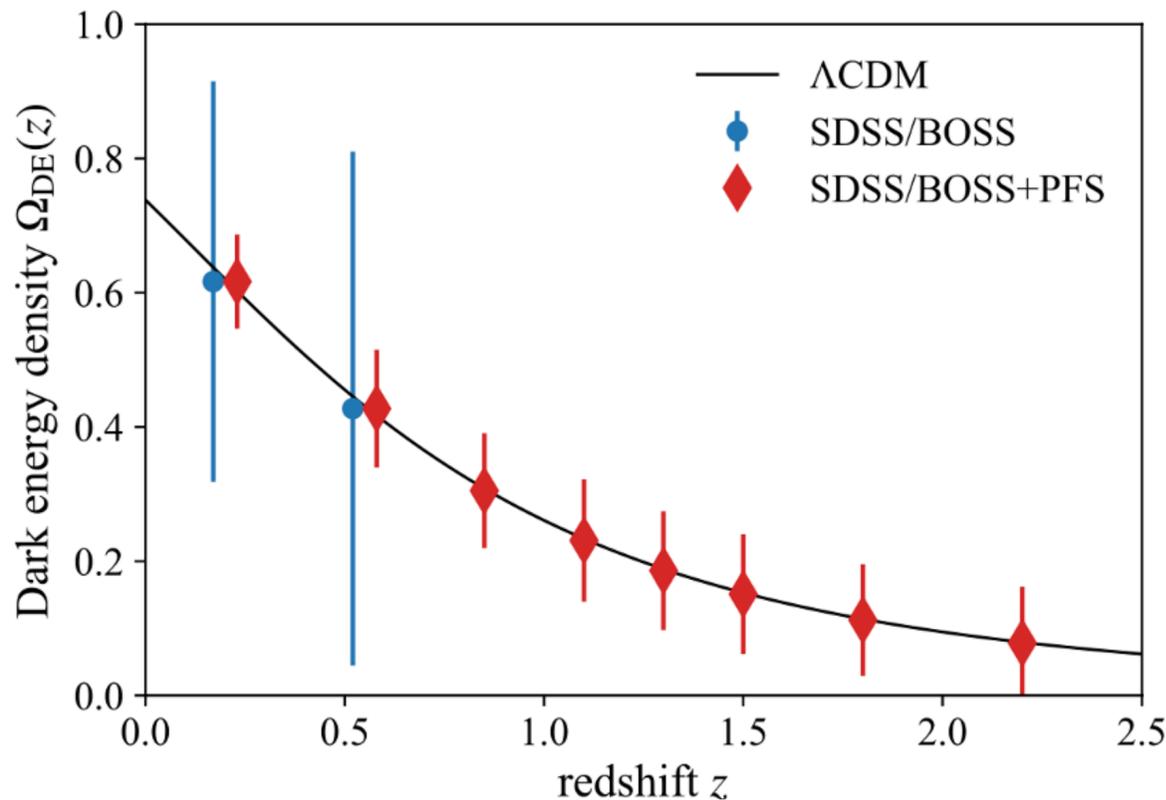
PFS Cosmology

◆ Primary science goals of PFS Cosmology

- A stringent test of Λ CDM using BAO and RSD
- Galaxy clustering and 3x2pt combined with HSC
- Addressing H_0 and S_8 tensions
- Weighing massive neutrinos



PFS SSP Proposal



H_0 tension

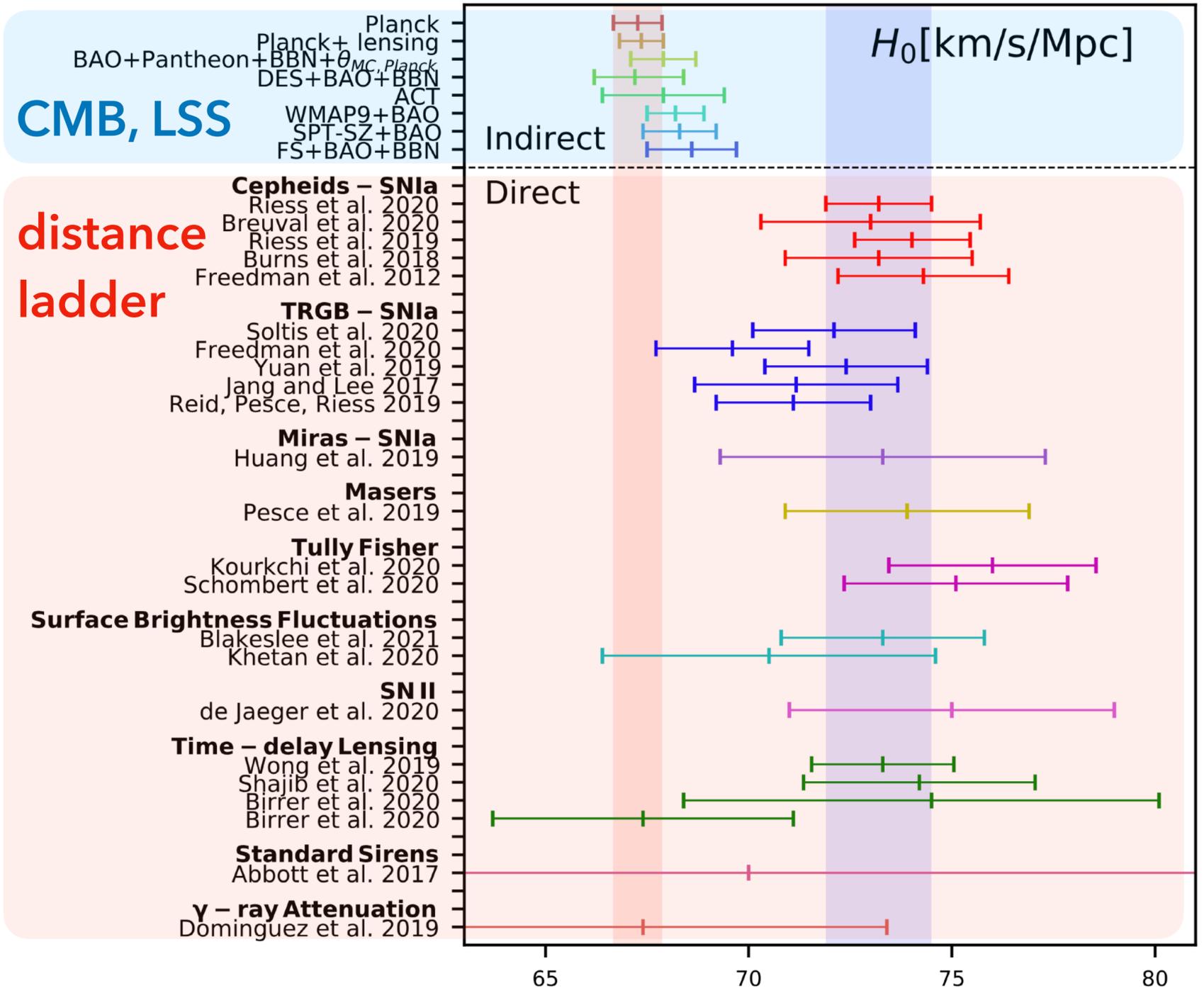
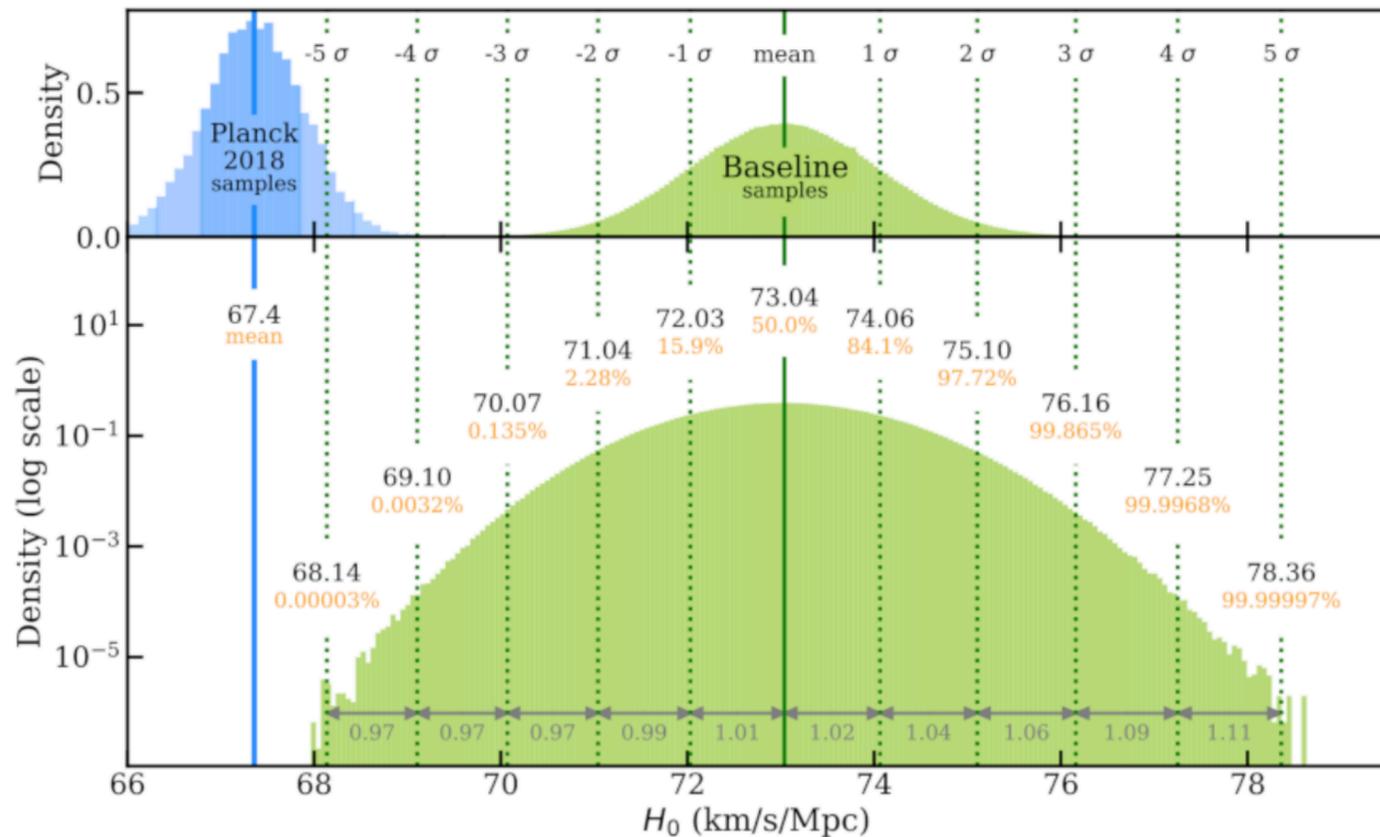
◆ Inconsistency ($> 3\sigma$) of constraints on Hubble parameter between **Indirect (CMB, LSS)** and **Direct (distance ladder)** measurements.

Planck 2018 (CMB)

Planck Collaboration, 2020

SH0ES (SN Ia)

Riess+, 2022



Di Valentino (2021)

Which Models Resolve Anomalies?

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

ArXiv:2203.06142

**Cosmology Intertwined:
A Review of the Particle Physics, Astrophysics, and Cosmology
Associated with the Cosmological Tensions and Anomalies**

Elcio Abdalla,¹ Guillermo Franco Abellán,² Amin Aboubrahim,³ Adriano Agnello,⁴ Özgür Akarsu,⁵ Yashar

VII. Cosmological Models Proposed to Solve the H_0 and the S_8 Tensions

- A. Addressing the H_0 Tension
- B. Addressing the S_8 Tension
- C. Addressing Both the H_0 and S_8 Tensions
- D. Early-Time Alternative Proposed Models
 - 1. Axion Monodromy
 - 2. Early Dark Energy
 - 3. Extra Relativistic Degrees of Freedom
 - 4. Modified Recombination History
 - 5. New Early Dark Energy
- E. Late-Time Alternative Proposed Models
 - 1. Bulk Viscous Models
 - 2. Chameleon Dark Energy
 - 3. Clustering Dark Energy
 - 4. Diffusion Models
 - 5. Dynamical Dark Energy

◆ **Many (too many!) models are proposed but no definitive one yet**

- 6. Emergent Dark Energy
- 7. Graduated Dark Energy - AdS to dS Transition in the Late Universe
- 8. Holographic Dark Energy
- 9. Interacting Dark Energy
- 10. Quintessence Models and their Various Extensions
- 11. Running Vacuum Models
- 12. Time-Varying Gravitational Constant
- 13. Vacuum Metamorphosis
- F. Modified Gravity Models
 - 1. Effective Field Theory Approach to Dark Energy and Modified Gravity
 - 2. $f(T)$ Gravity
 - 3. Horndeski Theory
 - 4. Quantum Conformal Anomaly Effective Theory and Dynamical Vacuum Energy
 - 5. Ultra-Late Time Gravitational Transitions
- G. Specific Solutions Assuming FLRW
 - 1. Active and Sterile Neutrinos
 - 2. Cannibal Dark Matter
 - 3. Decaying Dark Matter
 - 4. Dynamical Dark Matter
 - 5. Extended Parameter Spaces Involving A_{lens}
 - 6. Cosmological Scenario with Features in the Primordial Power Spectrum
 - 7. Interacting Dark Matter
 - 8. Quantum Landscape Multiverse
 - 9. Quantum Fisher Cosmology
 - 10. Quartessence
 - 11. Scaling Symmetry and a Mirror Sector
 - 12. Self-Interacting Neutrinos
 - 13. Self-Interacting Sterile Neutrinos
 - 14. Soft Cosmology
 - 15. Two-Body Decaying Cold Dark Matter into Dark Radiation and Warm Dark Matter
- H. Beyond the FLRW Framework
 - 1. Cosmological Fitting and Averaging Problems
 - 2. Data Analysis in an Universe with Structure: Accounting for Regional Inhomogeneity and Anisotropy
 - 3. Local Void Scenario

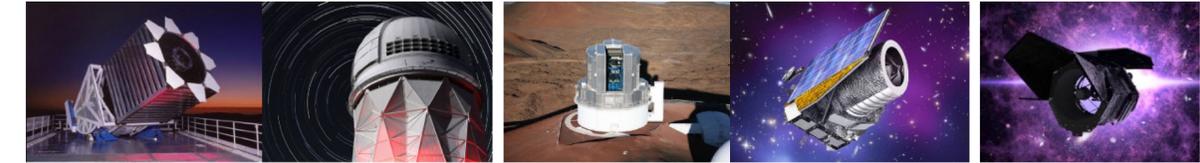
Stage-III/IV Imaging/Spectroscopic Surveys

- Imaging surveys



	KiDS	DES	HSC	<i>Euclid</i>	LSST	<i>Roman</i>
Mirror diameter [m]	2.6	4.0	8.2	1.2	8.4	2.4
Galaxy density [arcmin⁻²]	11	25	25	30	30	50
Survey area [deg²]	1,500	5,000	1,400	14,000	18,000	2,000

- Spectroscopic surveys



	eBOSS	DESI	PFS	<i>Euclid</i>	<i>Roman</i>
Instrument	1000 fibers	5000 fibers	2400 fibers	Slitless	Slitless
Redshift	0.7-1.1	1.1-1.6	0.8-2.4	0.7-2.1	1.0-2.8
Survey area [deg²]	9,000	14,000	1,200	14,000	2,000

Summary

- Hydrodynamical simulations have been a powerful tool for galaxy formation. With the help of large-scale supercomputer and improvement in numerical algorithms, simulations on cosmological scales are possible.
- In cosmology, hydro sims can address the effect of baryonic physics, in particular, feedback effects, on large-scale structures to understand small-scale growth of structures.
- Hydro sims can serve as a multi-wavelength virtual observatory to simulate the entire process of large-scale structure analysis.
- Subaru PFS has just started science observations. It will provide high-quality spectroscopic measurements at high redshifts ($0.8 < z < 2.4$).