Hyper-Millennium project
a huge cosmological simulation for the next generation of large-scale structure survey

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Volker Springel

Gyeongju, Korea
10/2024

Formation and evolution of large scale structures

Important for:

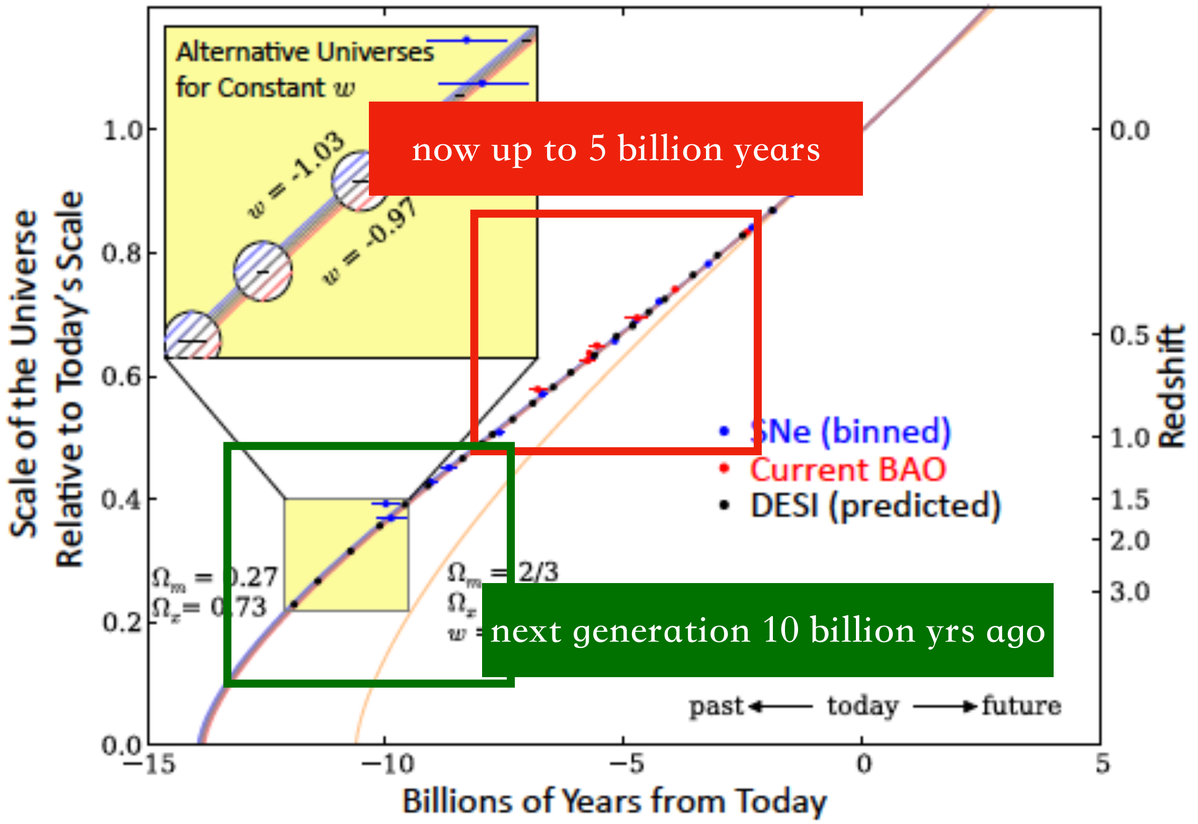
Growth history of the Universe

Nature of dark energy

Nature of dark matter

Inflation theory

General relativity



Next generation of large scale structure surveys

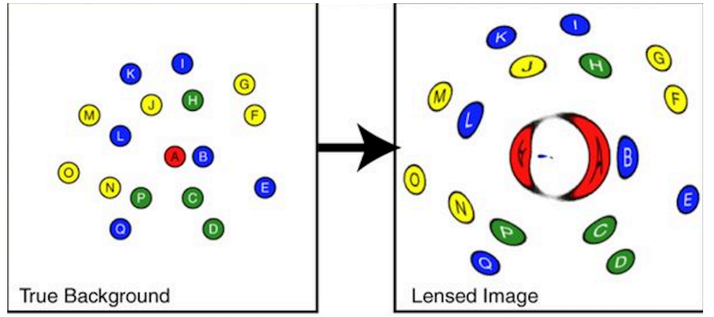
further, fainter

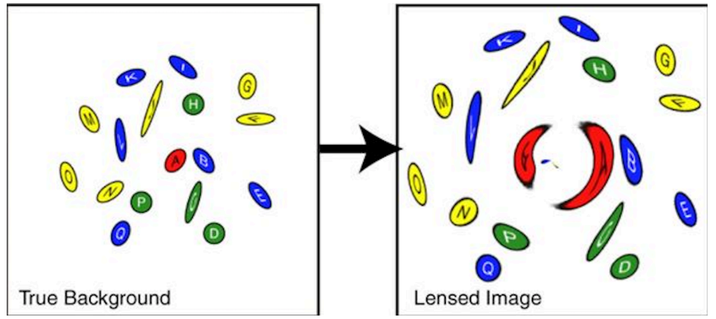
Simulations are crucial for modern cosmology

- To understand complex physical processes related to various cosmic probs（BAO、RSD、Weak lensing and etc.)
- To meet the requirement of accurate Cosmology (1%)

  selection effects, systematic uncertainties,

  statistic uncertainties





Next Generation Large-scale Surveys

Name	Sky coverage (degree)	Wavelength （nm）
CSST	17,500	255-1000
LSST	18,000	320-1050
EUCLID	15,000	550-920 1000-2000
DESI	14,000	360-980

Cosmic probs: BAO(boxsize > 2Gpc)、RSD、Weak lensing and etc.

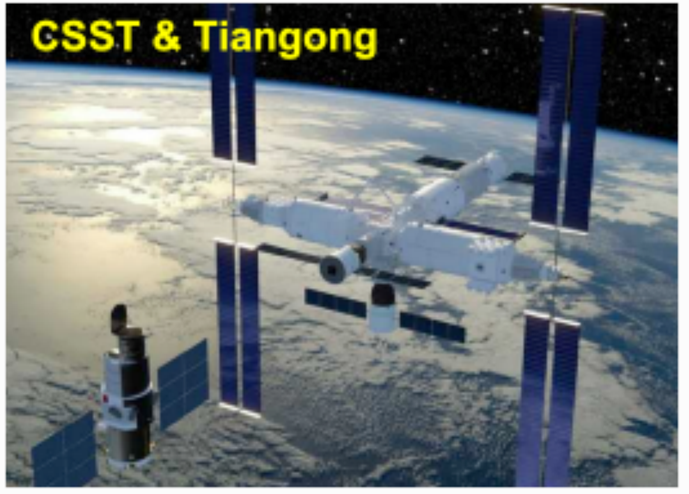
Tracers: QSOs, LRGs(massive), ELGs(low masses—>high resolution), and etc.

China Space Station Telescope

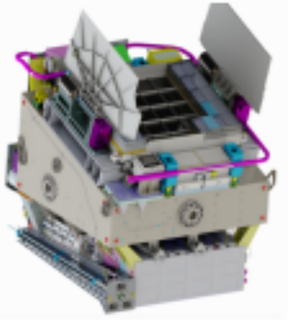
CSST/Xuntian: A serviceable 2m wide-field space telescope co-orbiting with the China Manned Space Station (Tiangong)

First gen. instr.: Survey Camera (SC), THz Spectrometer (THz), Multichannel Imager (MCI), Integral Field Spectrograph (IFS), Cool-Planet Imaging Coronagraph (CPI-C)

Mission: wide-area multiband imaging & slitless spectroscopic survey (7yr); other key programs & GO programs (1.5+yr)

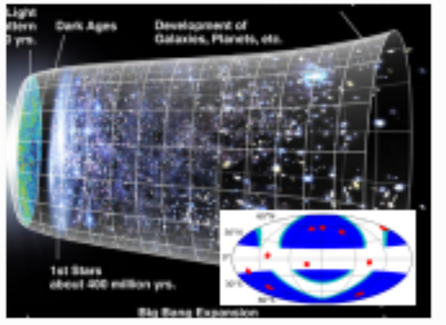


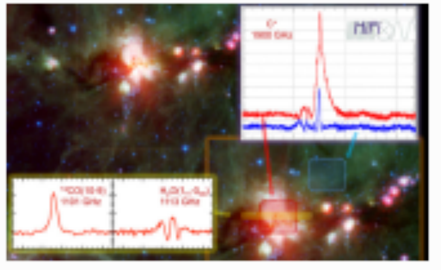
Zhan 2011, SCPMA, 41, 1441
2021, Chin. Sci. Bull. 66, 1290

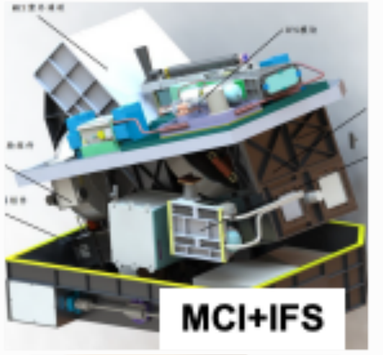


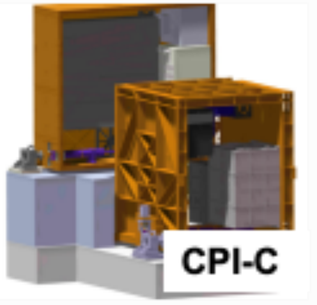
Survey Cam

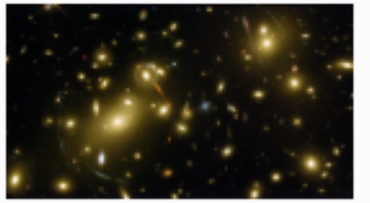


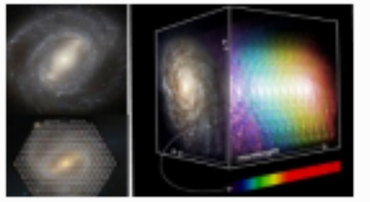










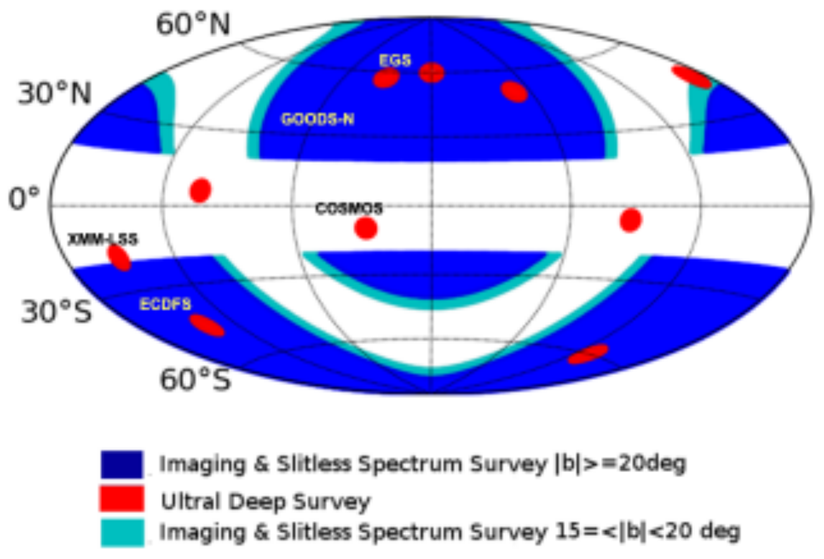




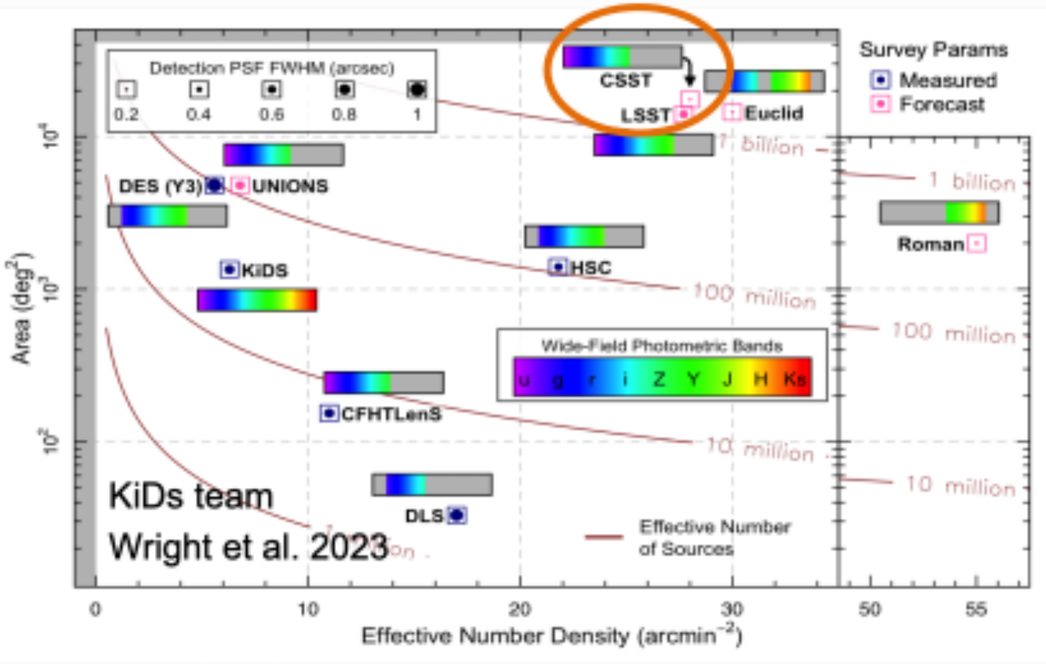
Credit: Hu Zhan

Survey Specifications

- **17500□°imaging : 255-1000nm (NUV, u, g, r, i, z, y), g≥26^m, (5σ, point source, AB mag)**
- **17500□°slitless spect: 255-1000nm, 3 bands, R≥200, ≥22-23^m**
- **400□°deep imaging & spect: ≥1^m deeper than wide field**
- **300□′ XDF (MCI): simultaneous observation in 3 bands, V ≥ 30^m**



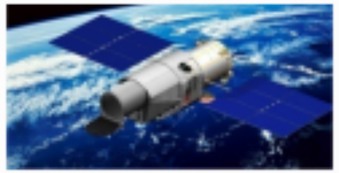
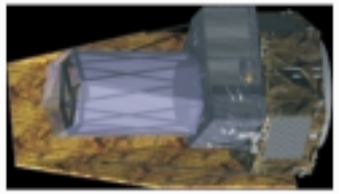
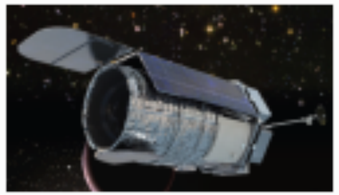
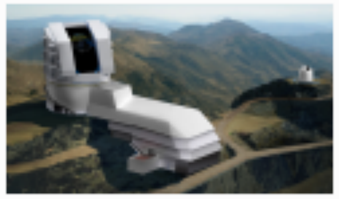
Ecliptic coordinates
Field selection for demo only



The CSST is highly competitive and also complementary to other projects.

Credit: Hu Zhan

Comparison with Other Projects

	Project	Site/ orbit	Field of view	PSF's R_{EE80}	Num of pixels	Survey area	Wavelength coverage	Num of Filters	Spect
			deg^2	"	10^9	deg^2	nm		
	CSST	LEO	**1.1**	**0.15** 0.074/pix	**2.6**	**17500**	**255**—1000	7	yes
	Euclid	L2	0.56	~0.23	0.6	15000	550—920	1	no
			0.55	pix lmt	0.07		1000—2000	3	yes
	Roman	L2	0.28	~0.24	0.3	~2000	927—2000	4	yes
	Rubin	Chile	9.6	~0.54	3.2	18000	320—1050	6	no

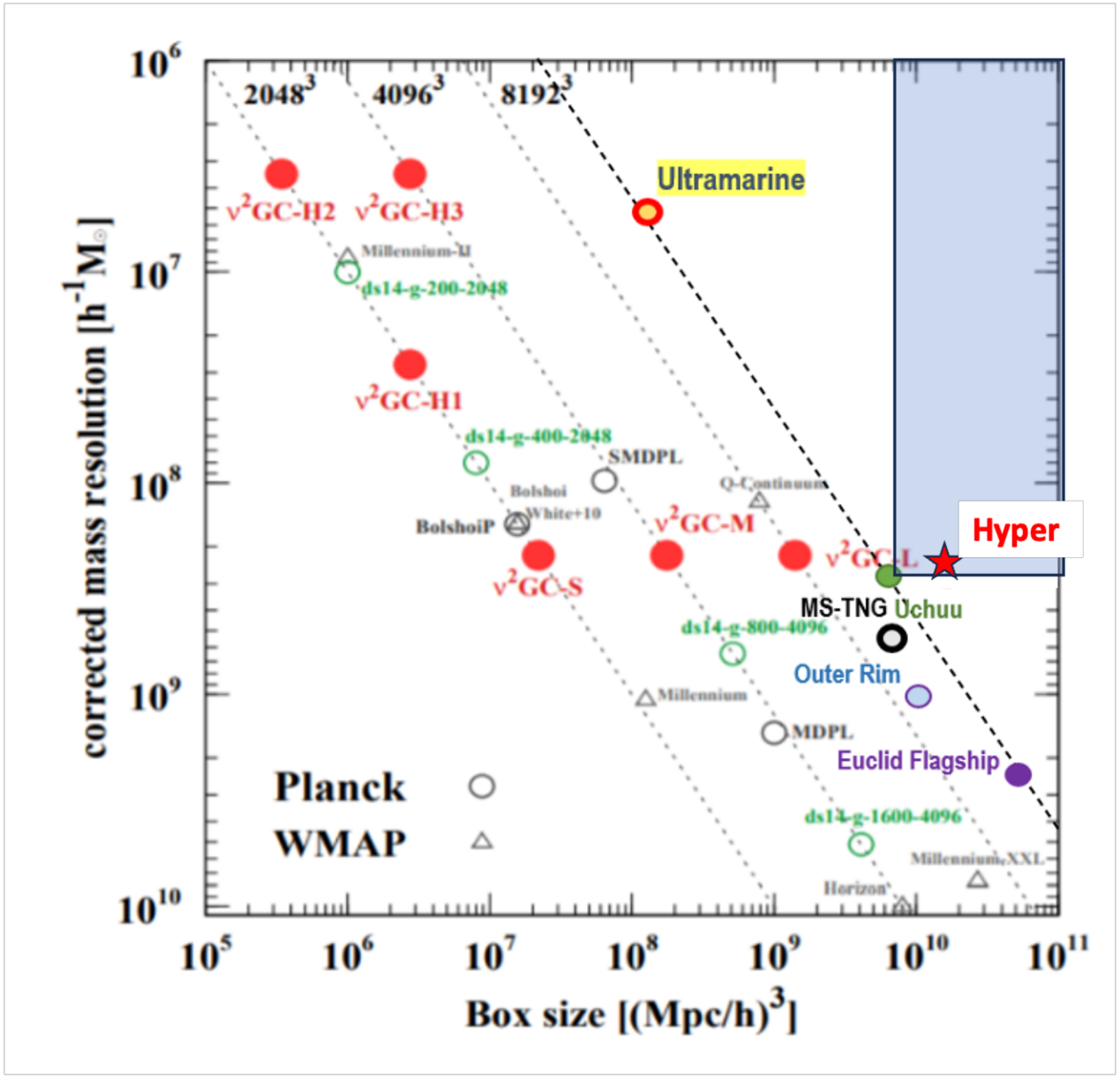
Credit: Hu Zhan

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Cosmic probs: BAO(boxsize > 2Gpc)、RSD、Weak lensing and etc.

Tracers: QSOs, LRGs(massive), ELGs(low masses—>high resolution), and etc.



Cosmological simulations

Large box： > 2Gcp/h

High resolution: <3.8d10Msun

Hyper-Millennium

Hyper-Millennium

Large volume + high resolution (z = 20 —0, 100 snapshots)

$\Omega_{\rm m}$	0.3111
Ω_{Λ}	0.6889
$\Omega_{\rm b}$	0.0490
h	0.6766
σ_8	0.8102
$n_{\rm s}$	0.9665

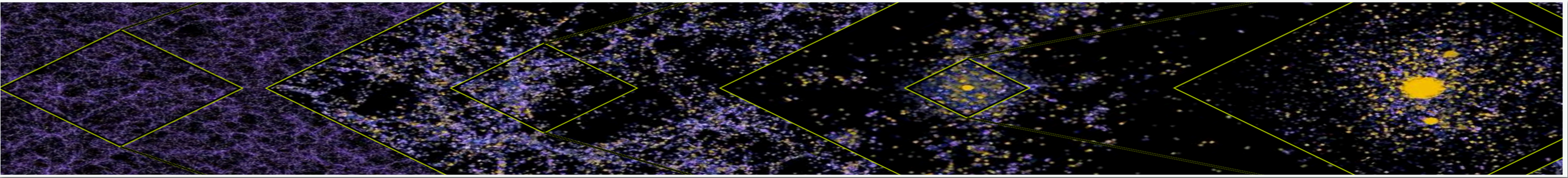
	Hyper-Millennium
Volume	$2.5^3[h^{-3}\mathrm{Gpc}^3]$
Particles number	$16128^3 \sim 4.195 \times 10^{12}$
Particle mass	$3.21 \times 10^8 \mathrm{M}_\odot$





Largest N-body cosmological simulation in the world.

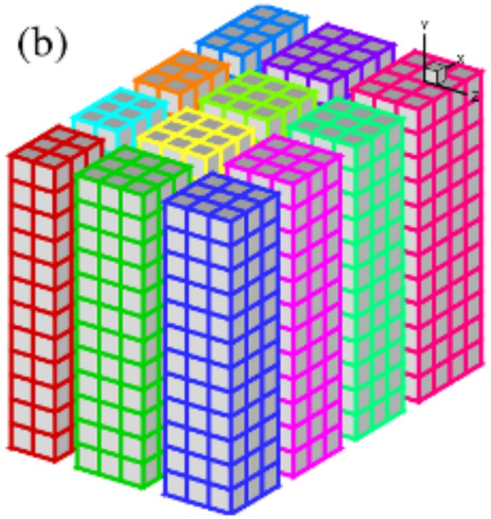
Volume is 125 times the Millennium simulation and the resolution is higher by a factor of 3

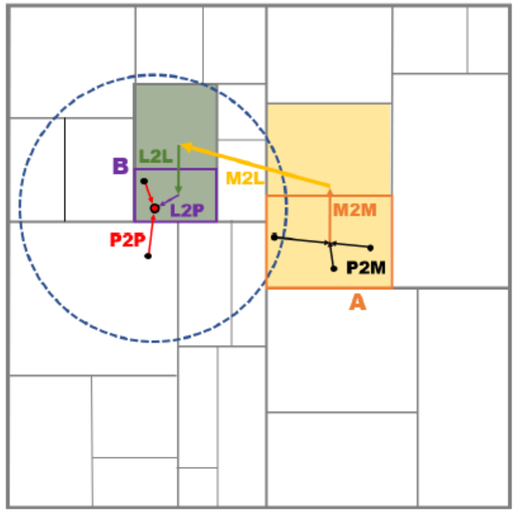


PhotoNs— a Cosmological simulation code for GPU Machine



- PM – Long range force
- FMM– short range force





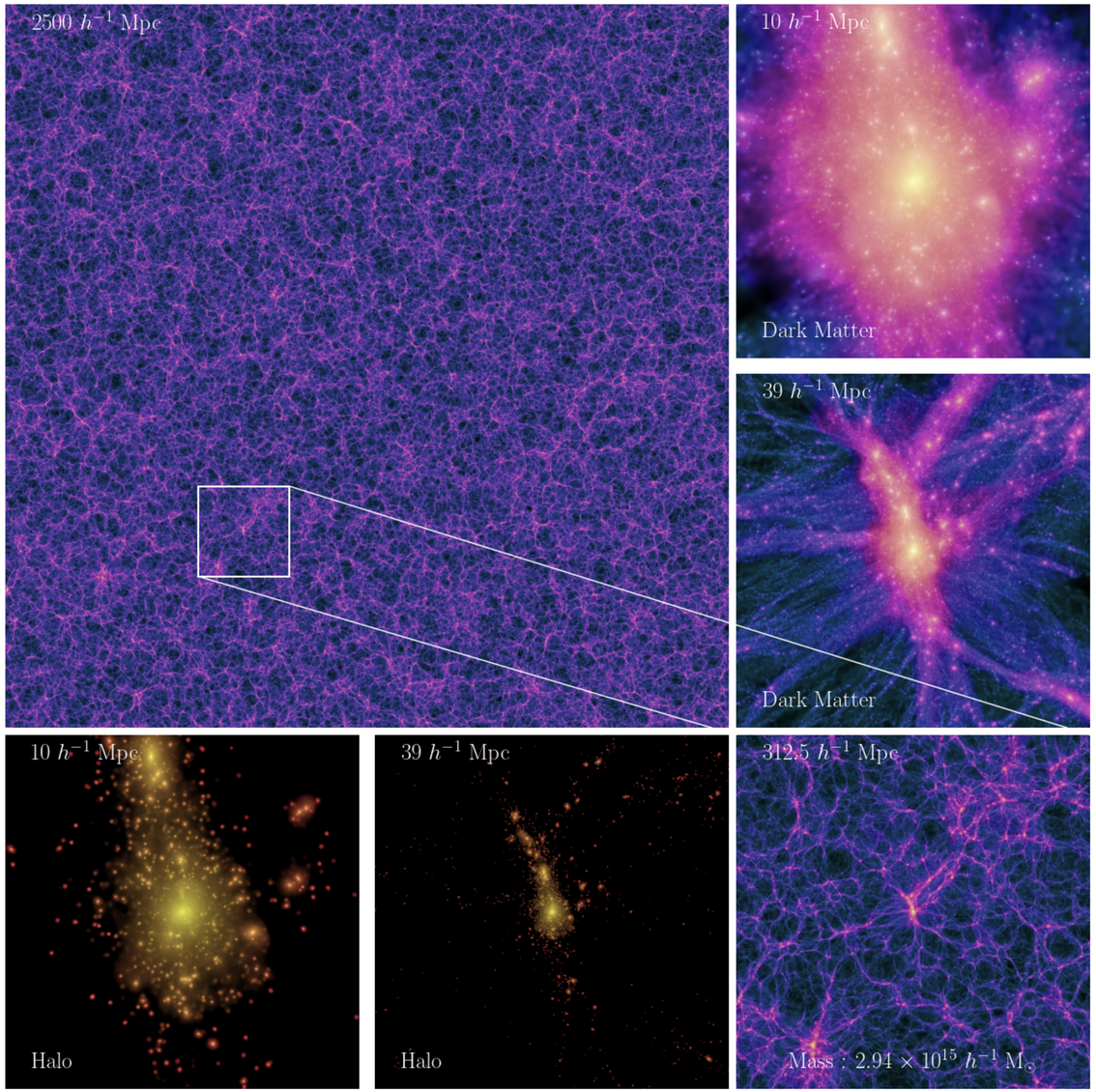
- 4000 Computing nodes
(1 32core cpu and 4 64c DCU

- Wall-Clock time~17 Days

FFT: pencil decompostion

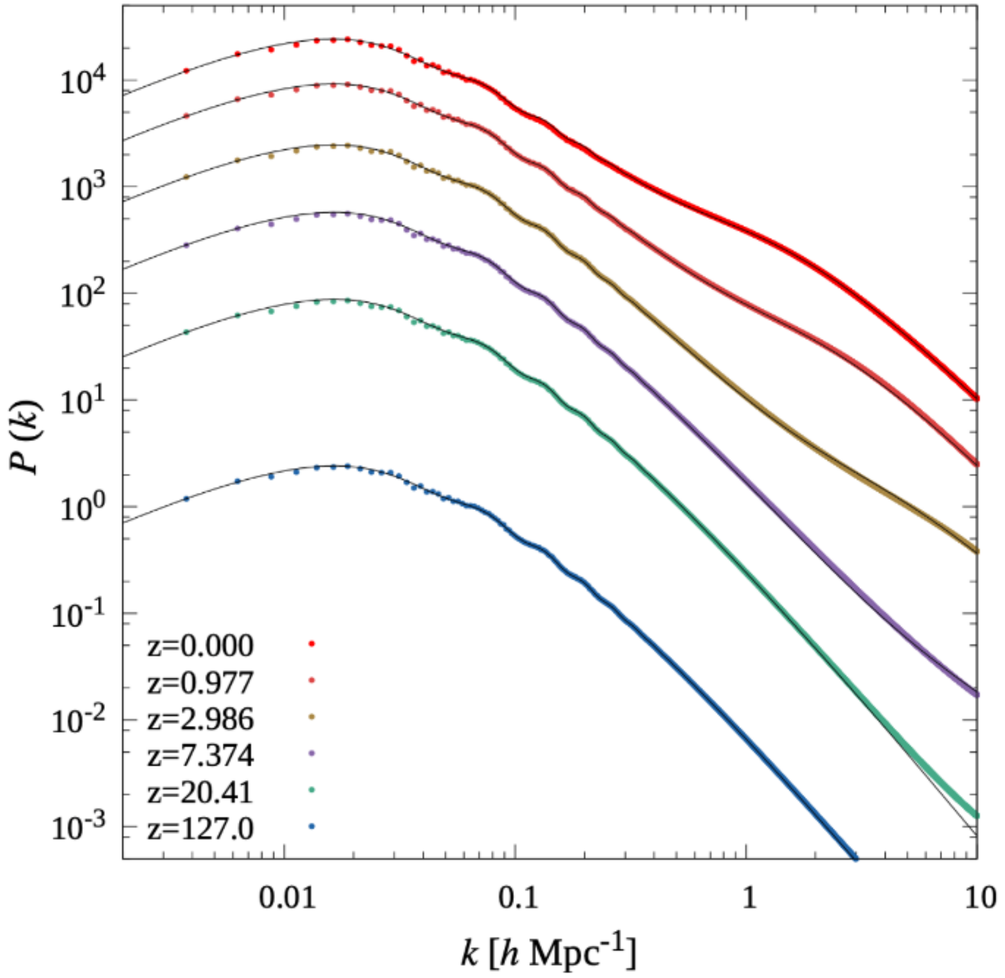
Wang et al. 2019; 2022

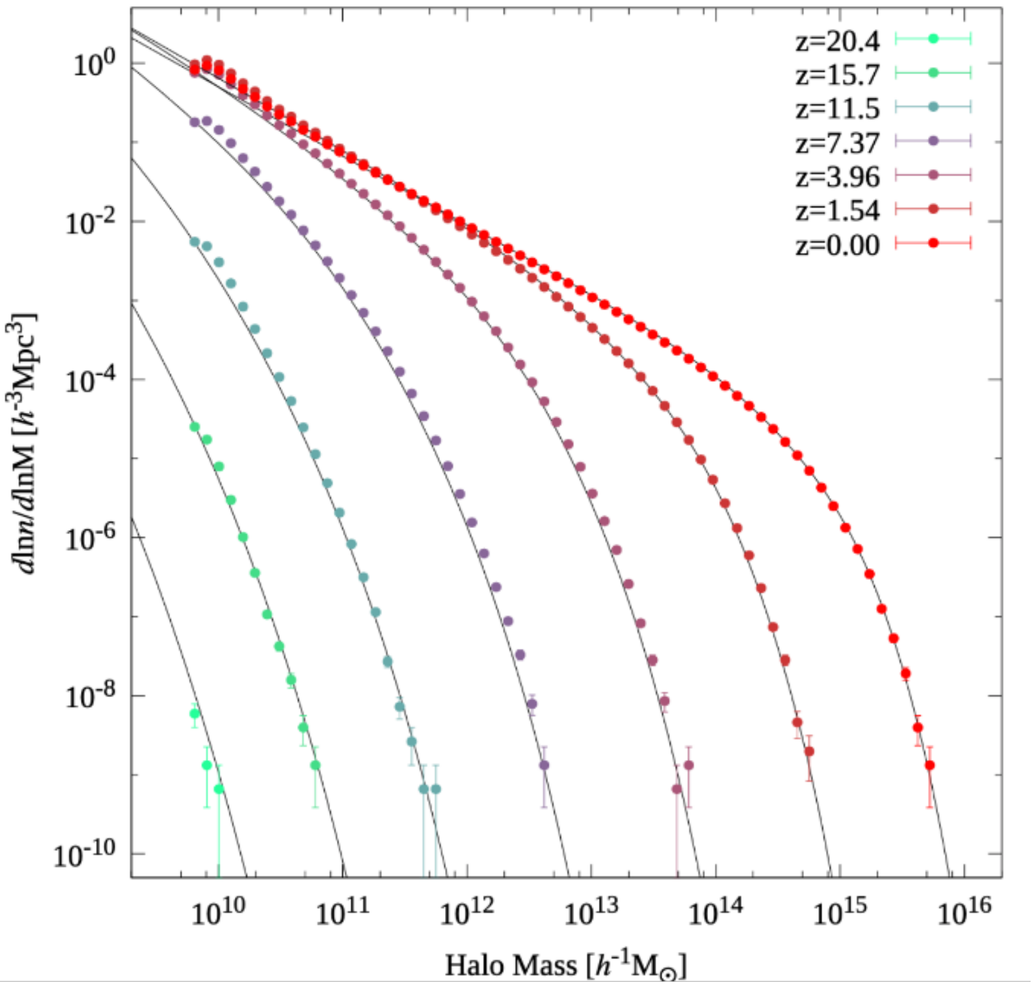
Current status



- **Main body: dark matter particle from z = 127-0, FOF**
- **post-processes: subhalo (SUBFIND), merger tree**

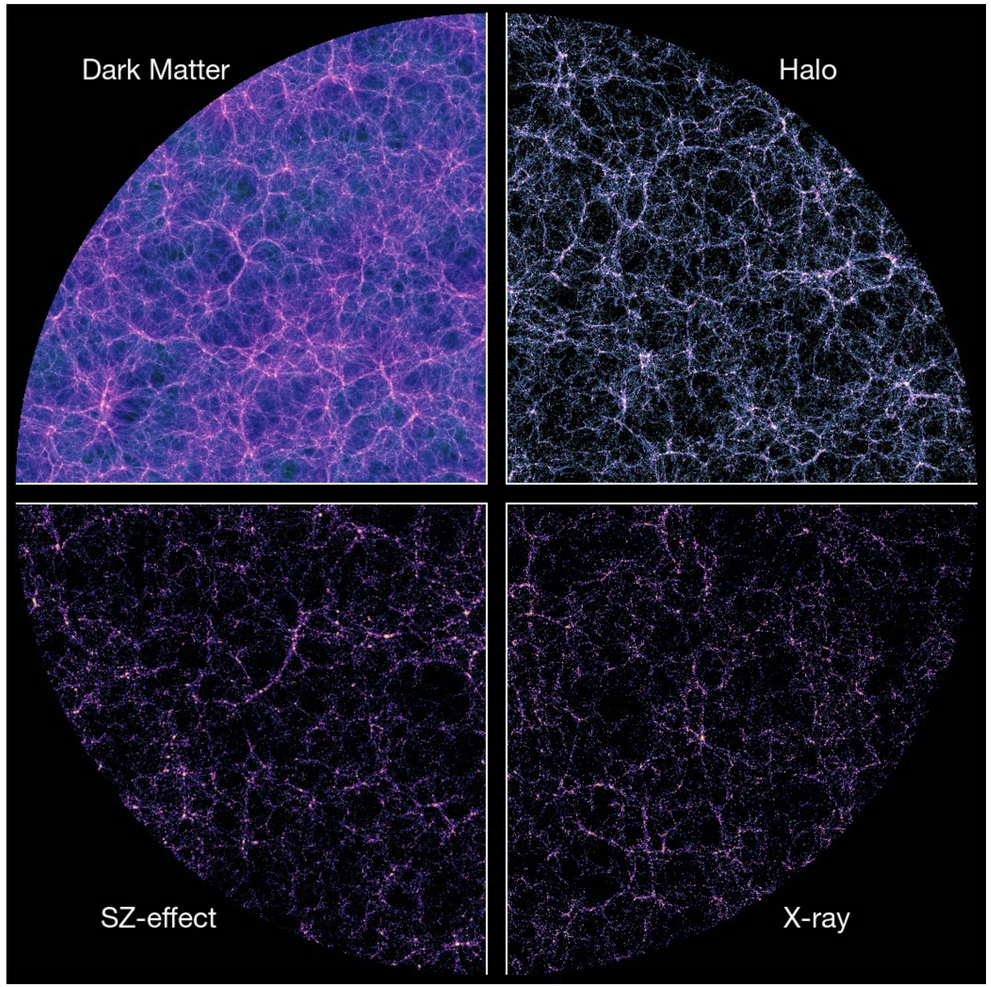
Hyper-Millennium: Power spectrum and the halo mass functions

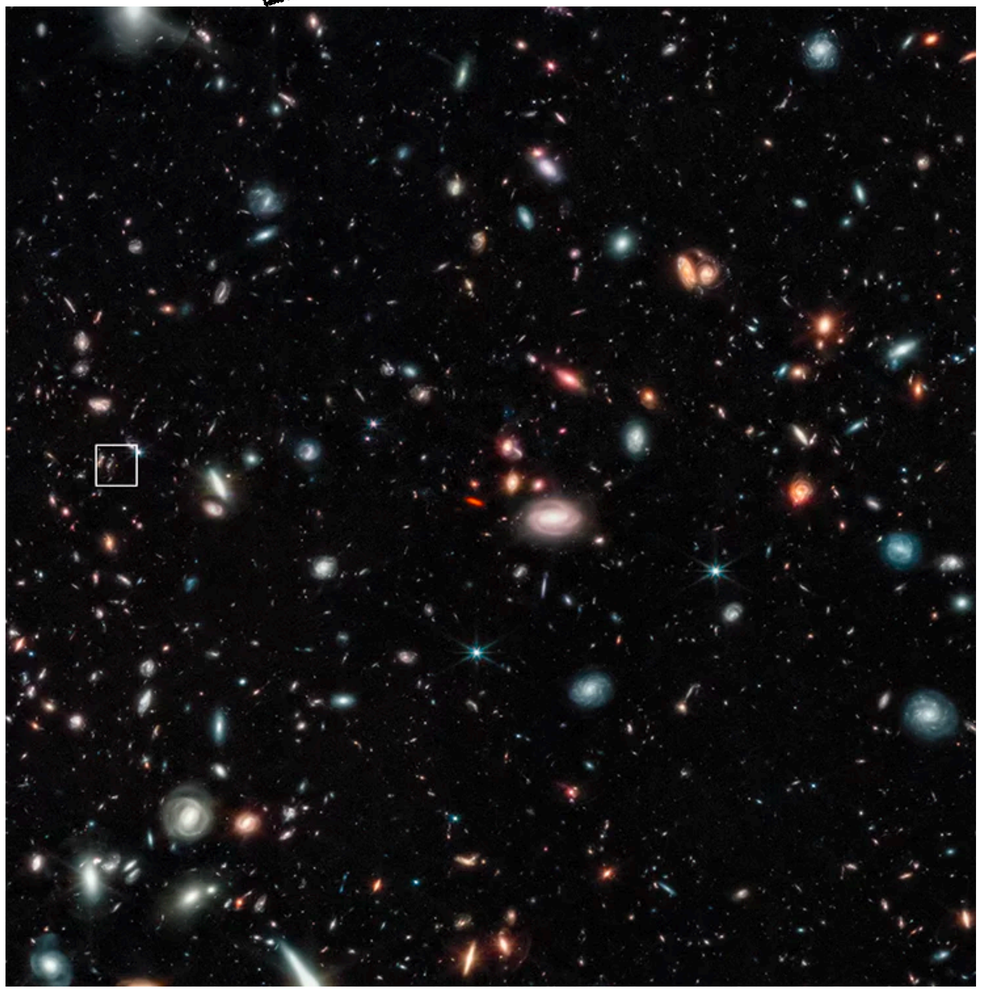




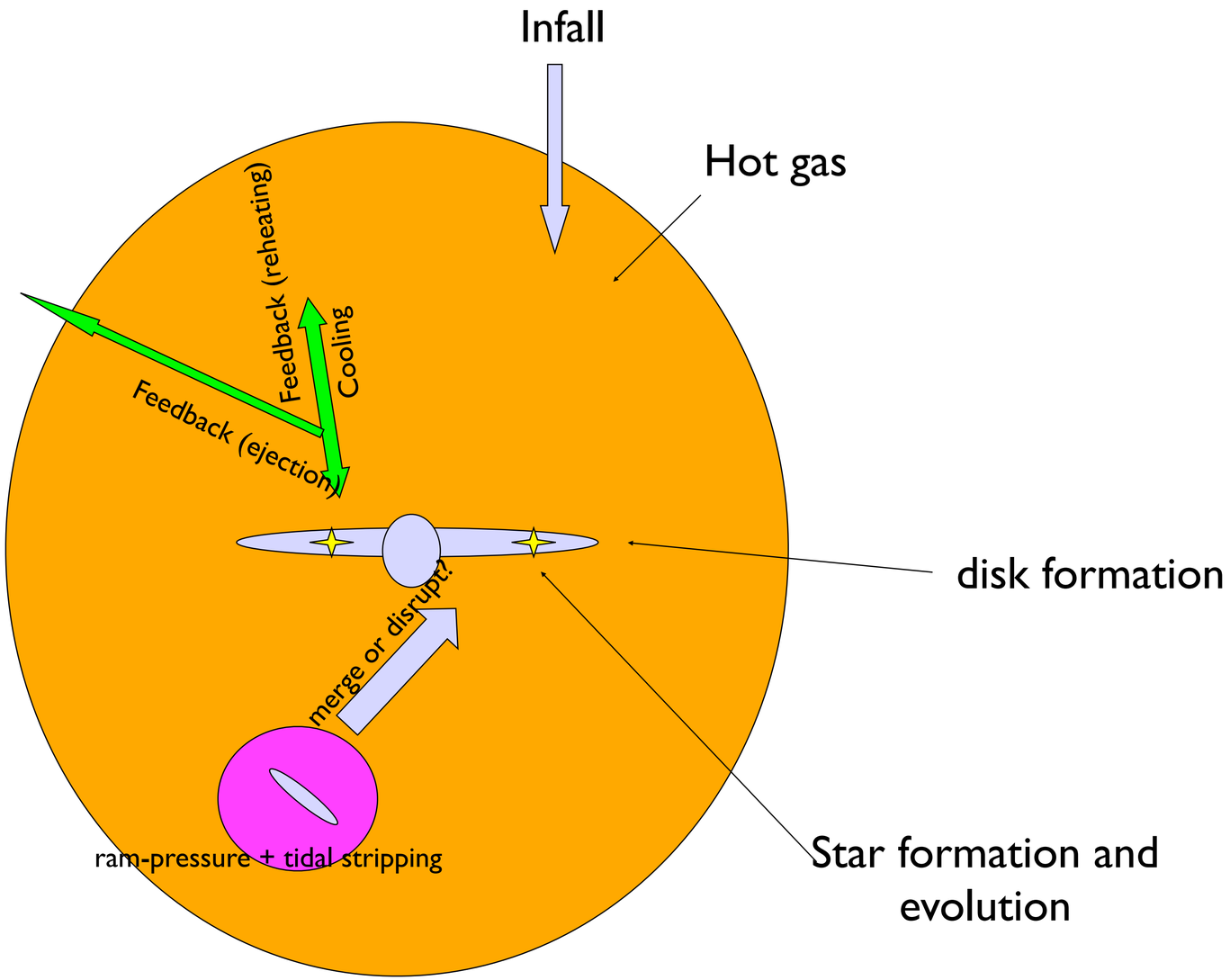
From “Dark” to “Bright”

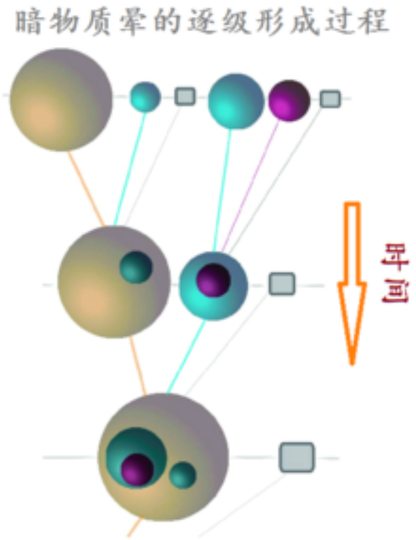
Semi-analytical galaxy formation models



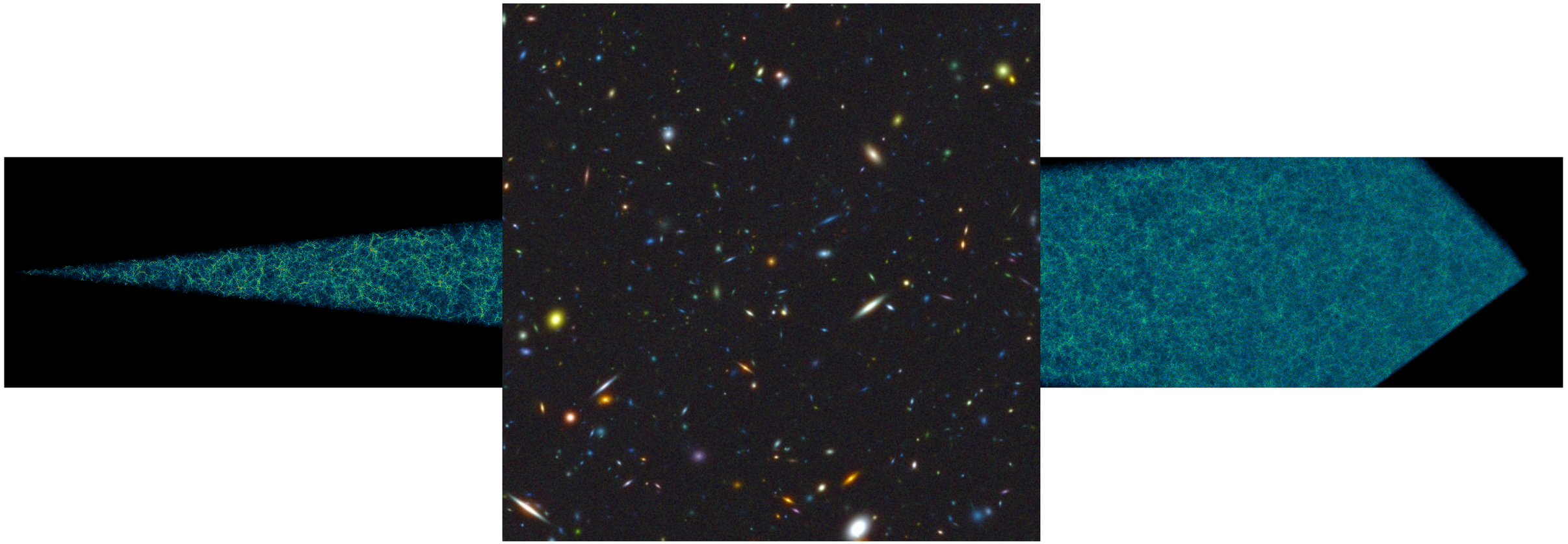


Galaxy formation models（L-Galaxies）





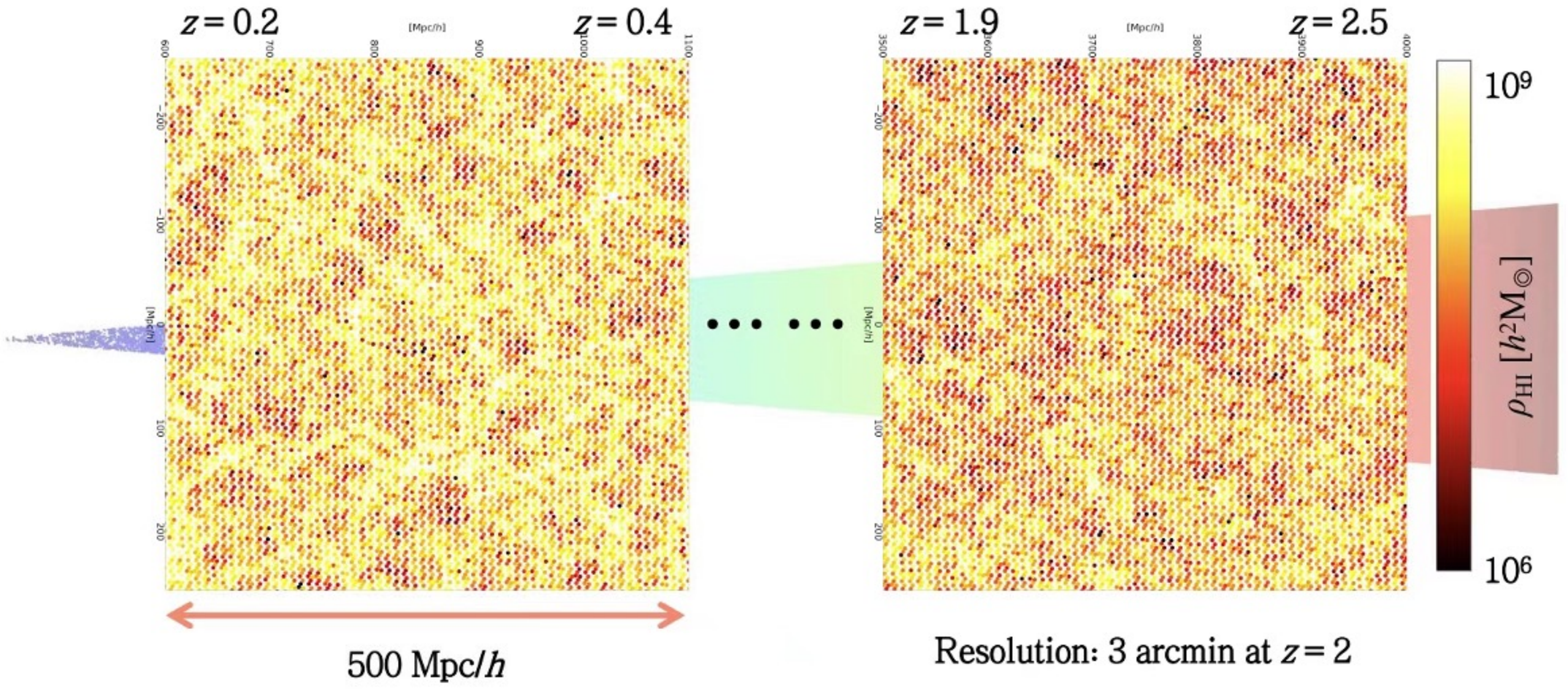
Semi-analytic galaxy catalogs



HI map

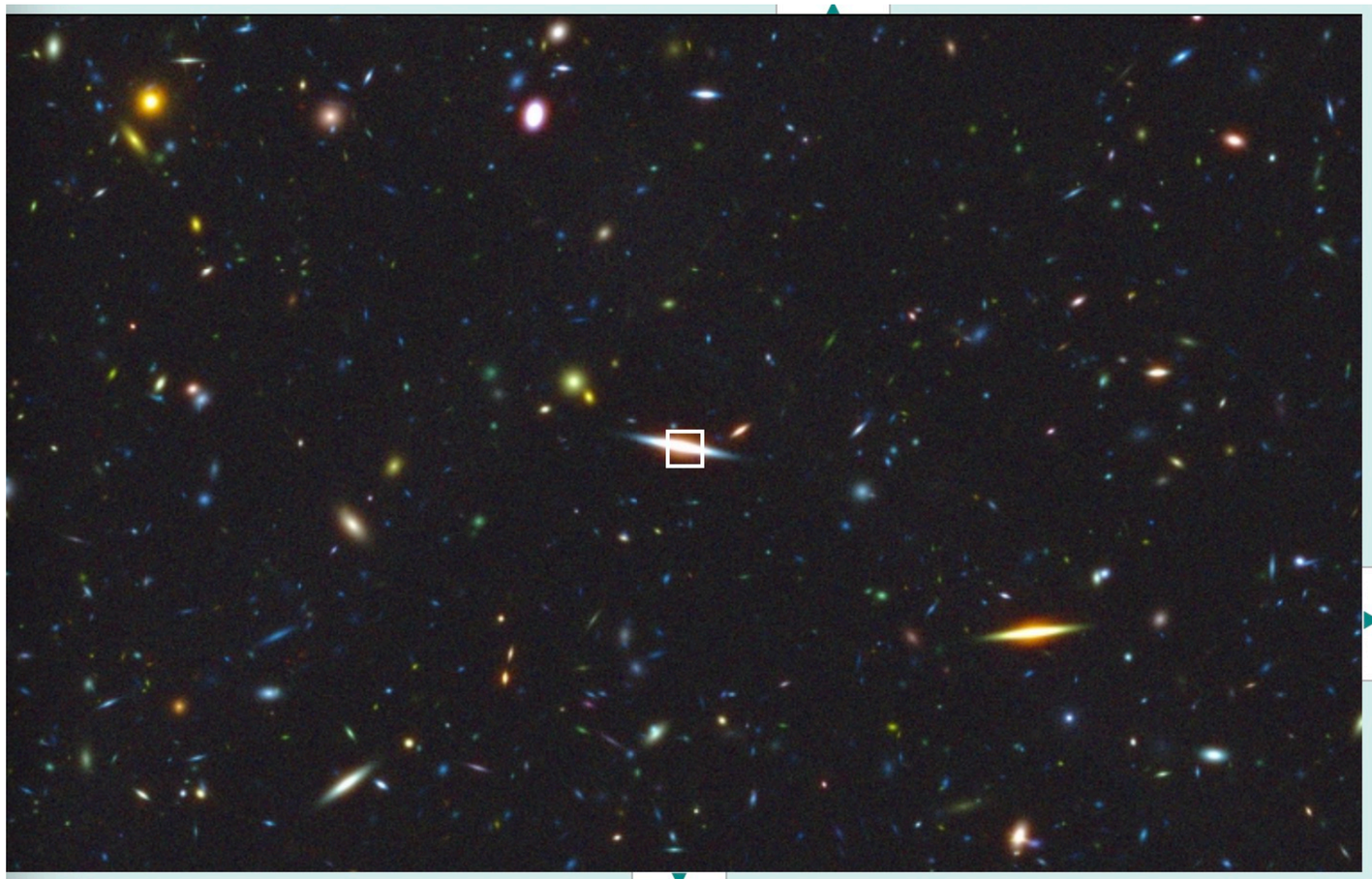
Applications: HI intensity mapping

中科院国家天文台
计算宇宙学团组
Computational Cosmology Group



Liu et al. in prep

Semi-analytic galaxy catalogue —Galaxies



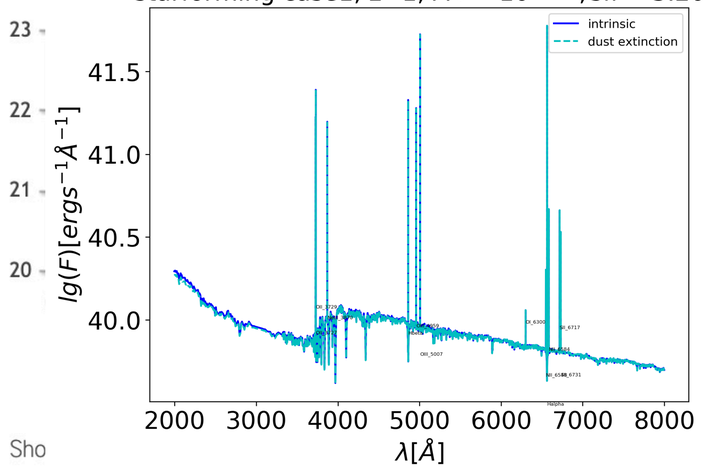
All galaxies | Complete halos

Rank ▲	ID	FOF-ID	RA	Dec	Type	Snap	Redshift
1	213020001000028	35021400019996	-0.0007	-0.0032	0	35	1.619
2	46004909000010	53004500008396	-0.0009	-0.0033	0	53	0.286

Showing 1 to 2 of 2 entries

Galaxy Details

starforming case1, z~1, $M_* = 10^{10.03}$, $sfr = 3.20$

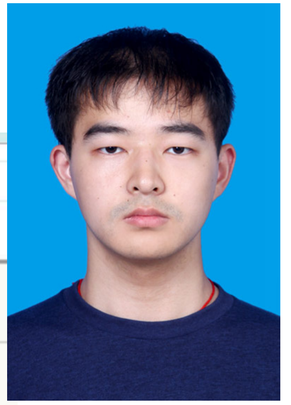


Sho

index	property ▲	value
31	ACS435	21.899126
32	ACS475	21.562439
33	ACS606	21.029741
34	ACS625	20.915651
35	ACS775	20.765907
36	ACS814	20.740894
37	ACS850	20.670172
12	b	21.836212
61	blackholemass	0
59	bulgemass	0

Showing 1 to 10 of 80 entries

First | Previous | 1 | 2 | 3 | 4 | 5 | Next | Last



裴文祥

Physical properties + observables

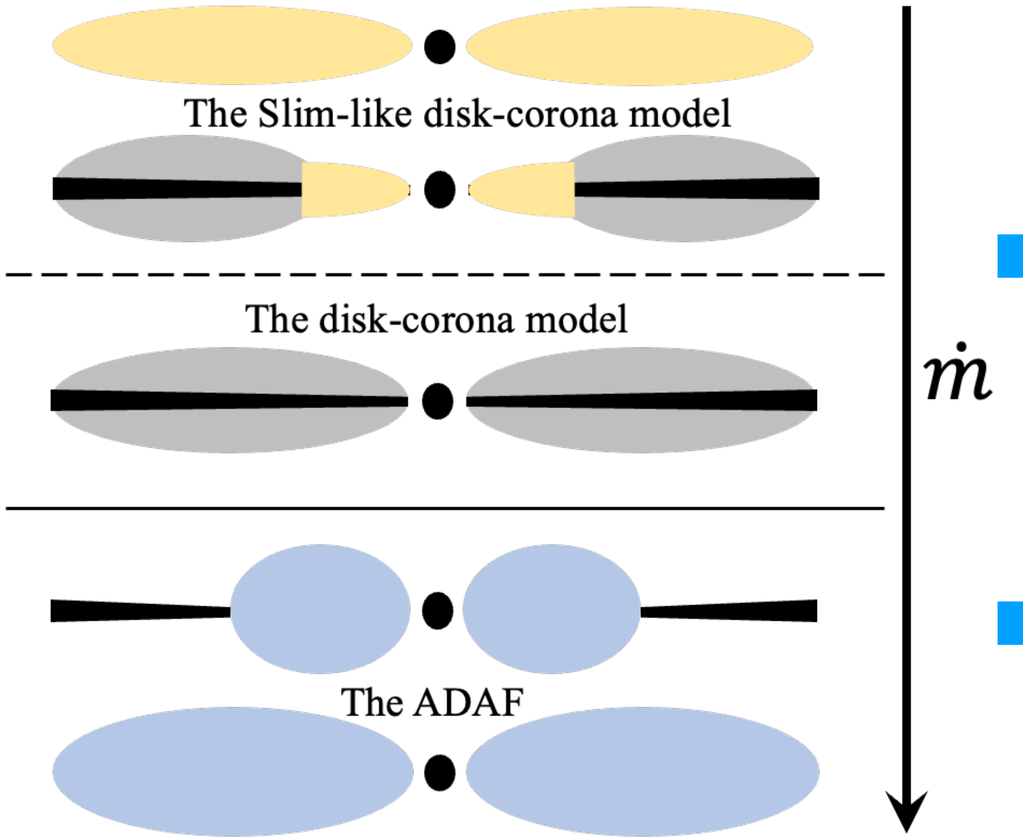
Semi-analytic galaxy catalogue —AGNs

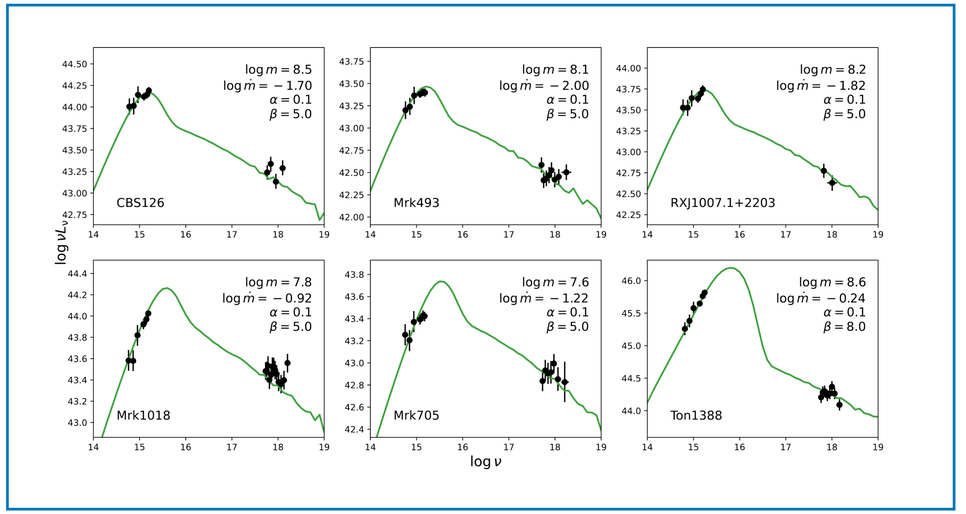
Too simple assumptions in many previous cosmological simulations

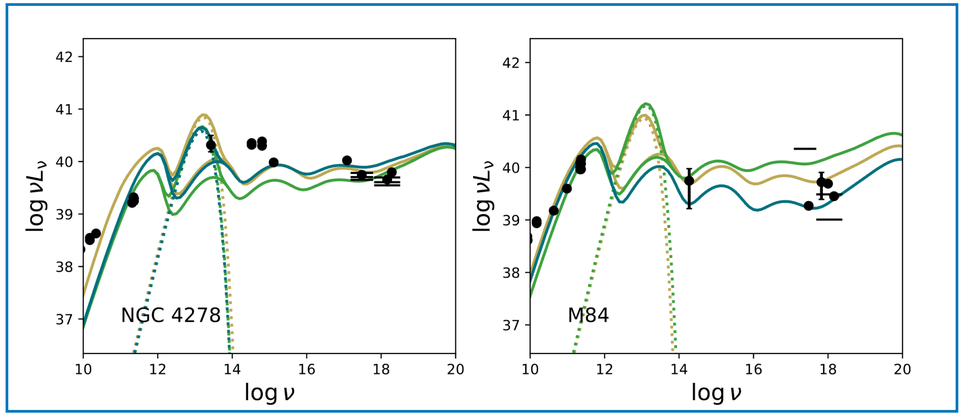
$$L_{\rm bol} \sim \alpha \dot{m} c^2 \qquad L_\lambda = F(L_{\rm bol})$$

Su+ in prep



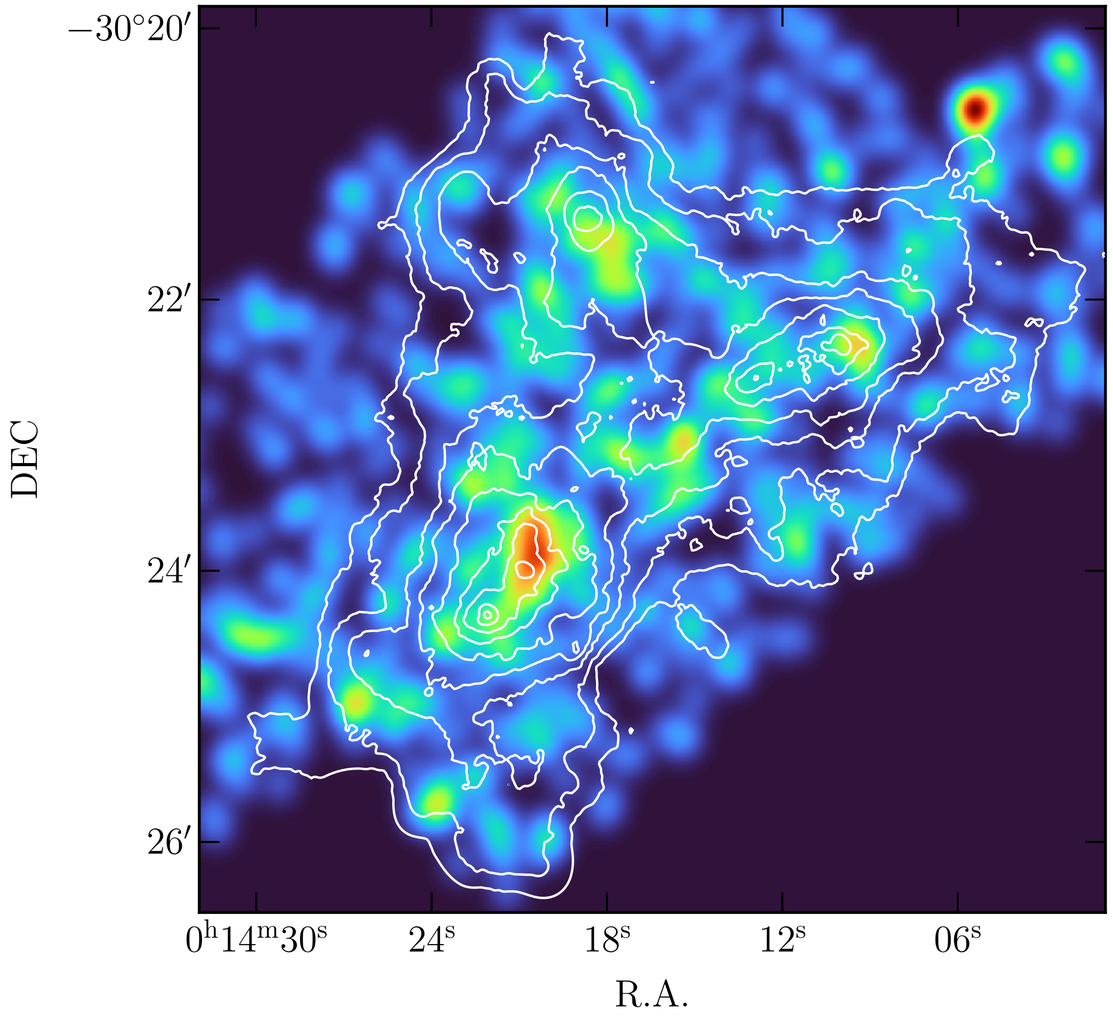




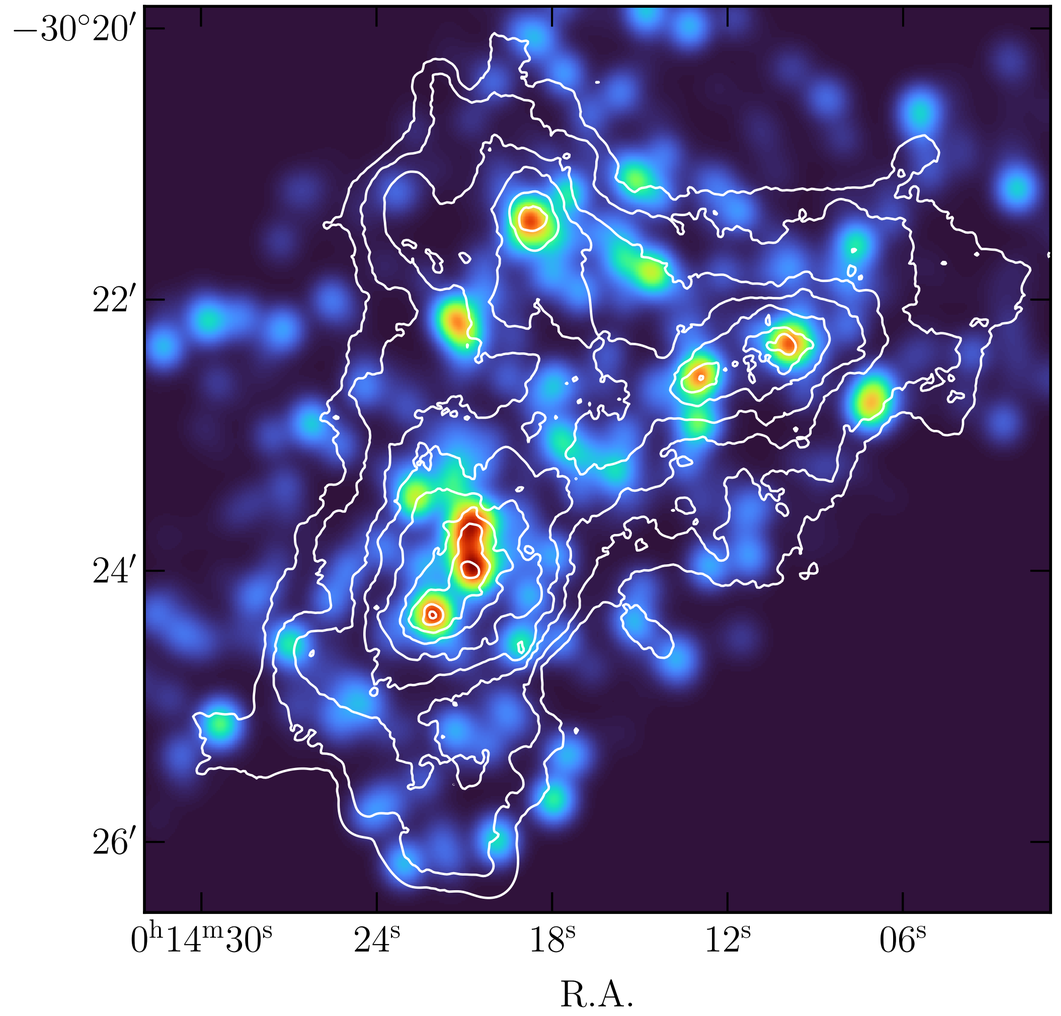


Reproduce individual clusters: Abell 2774 :

cluster galaxy number density

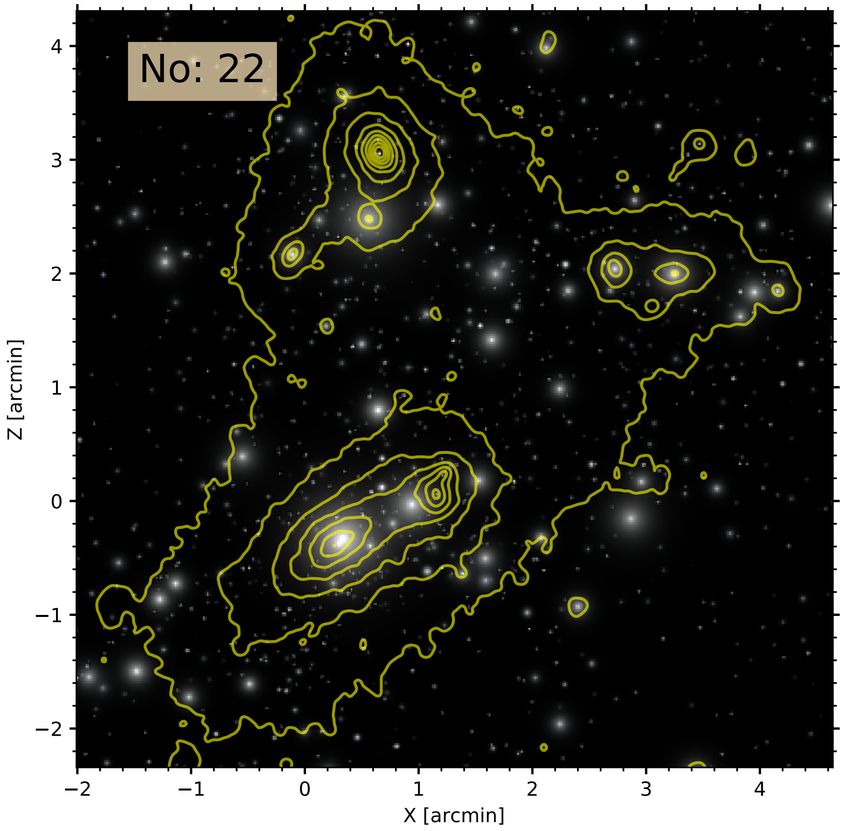


cluster galaxy luminosity

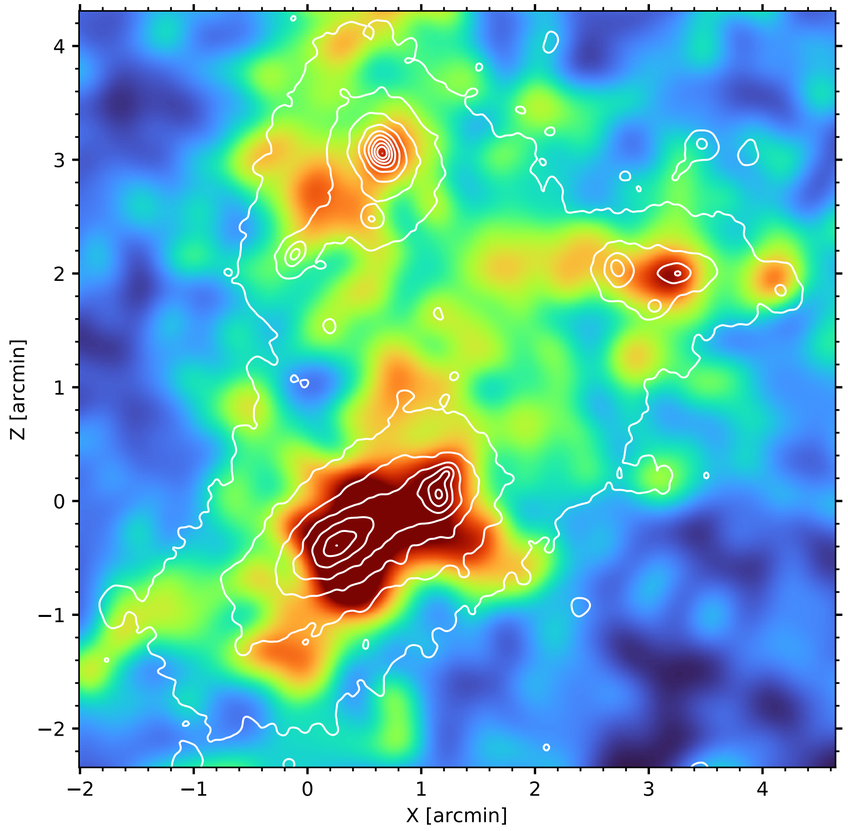


Abell 2774 analogs in Hyper Millennium (2)

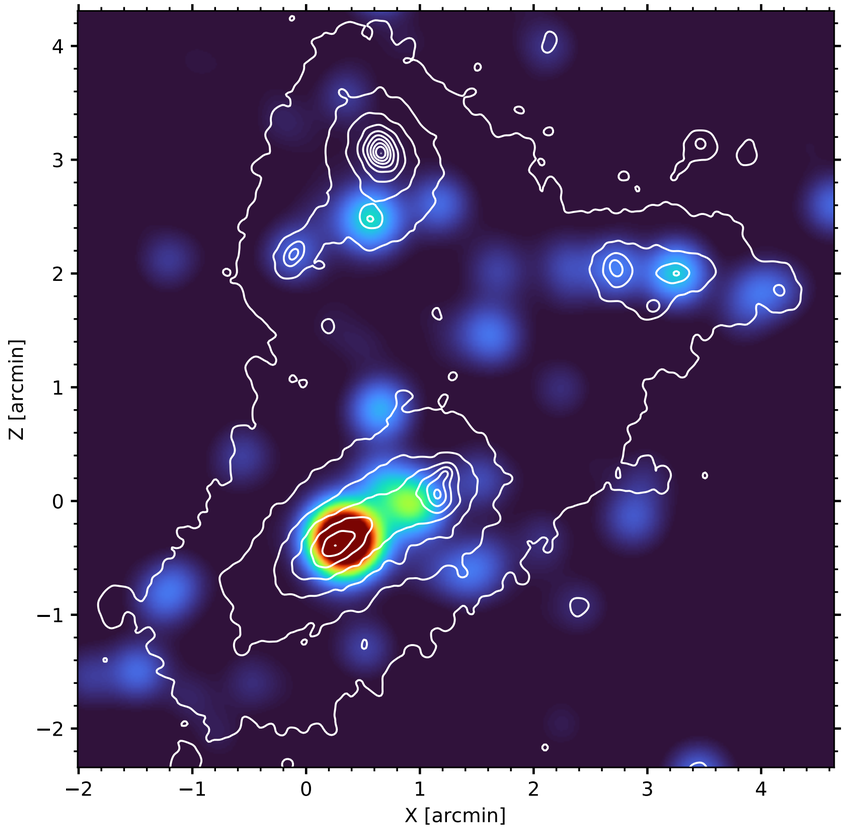
The mock JWST color-composite image using the filters of F444W, F277W and F115W



galaxy number density

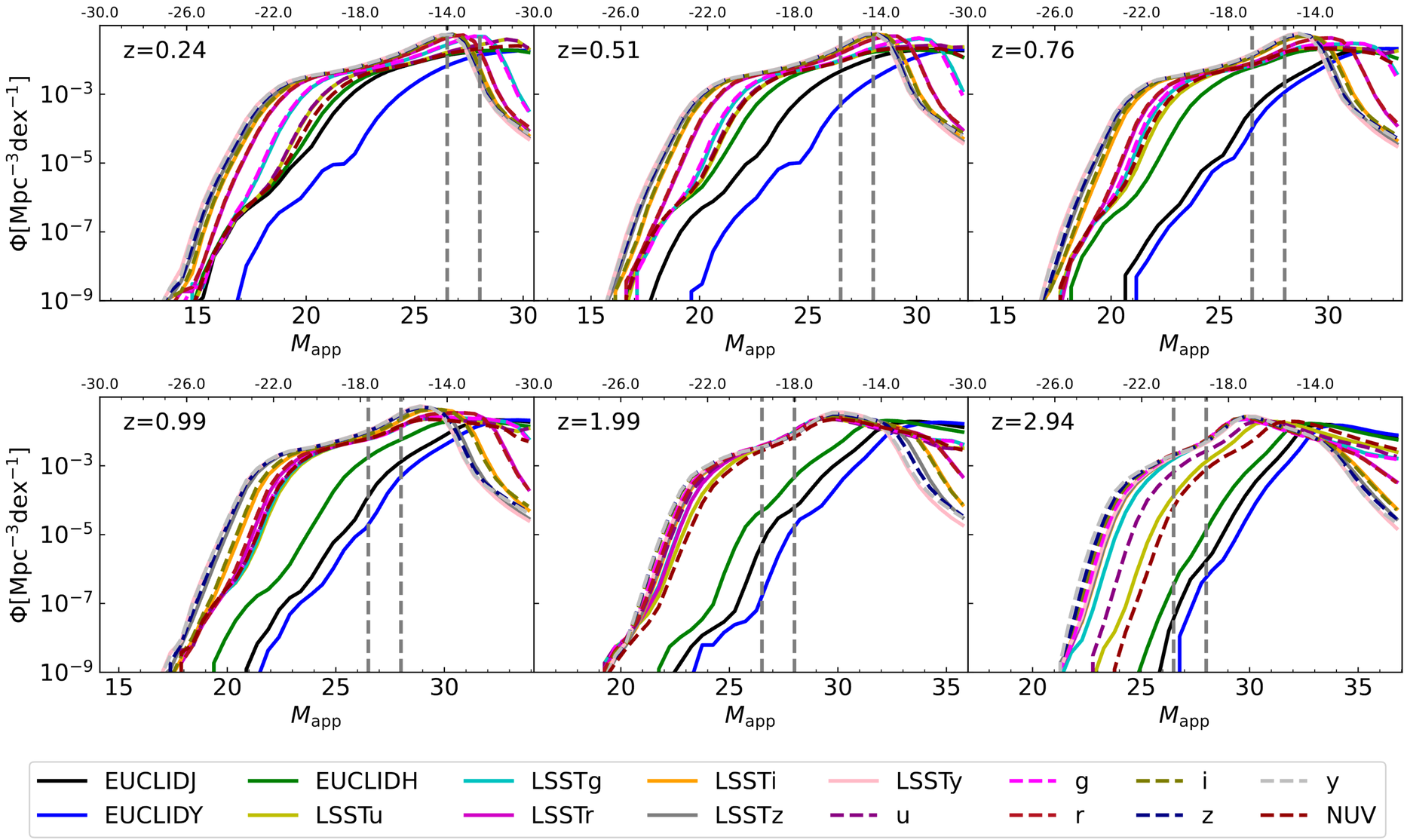


galaxy luminosity

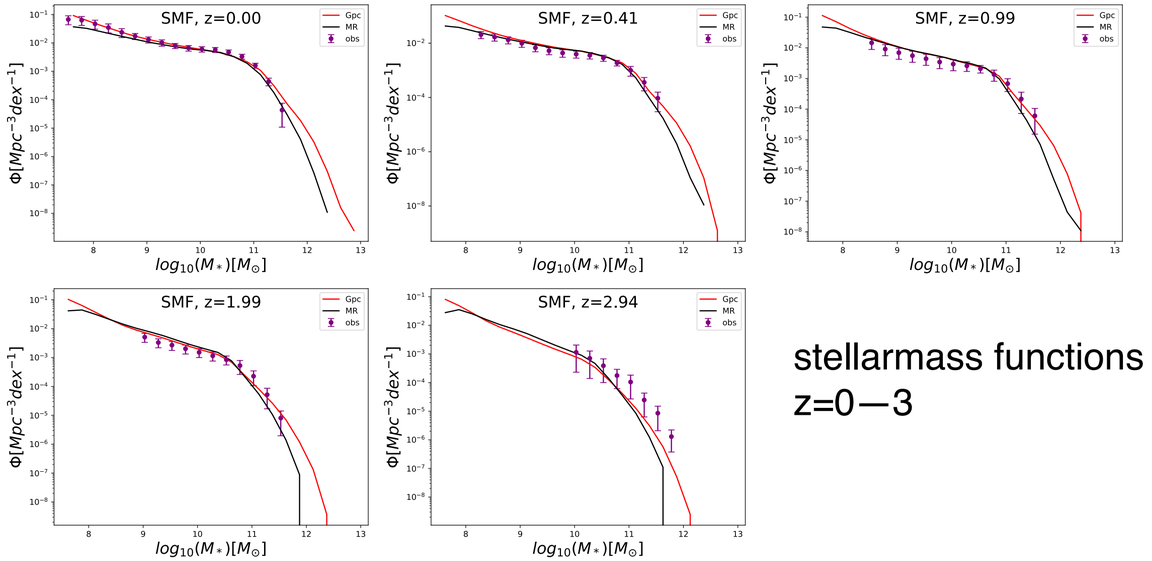


Smoothed with $\sigma \sim 10''$

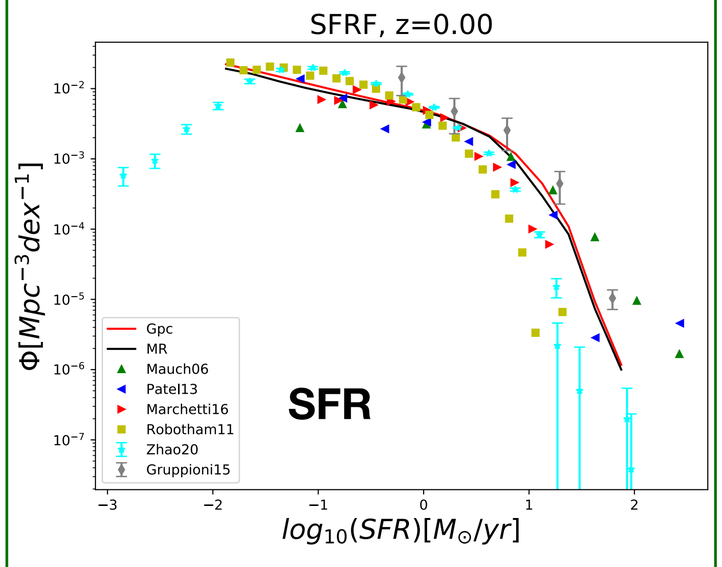
The new catalogue meet the resolution requirement for the next generation of large-scale surveys

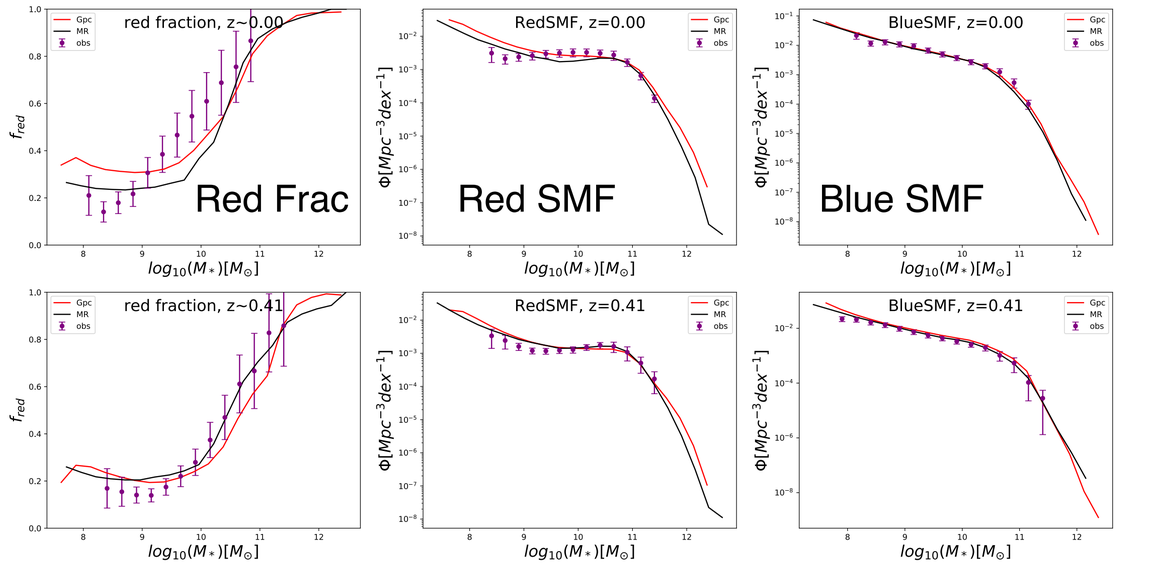


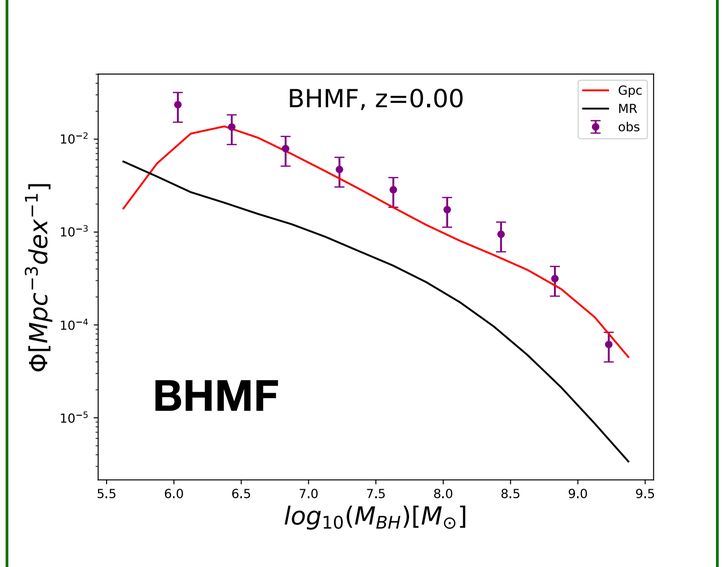
Reproduce many galaxy properties



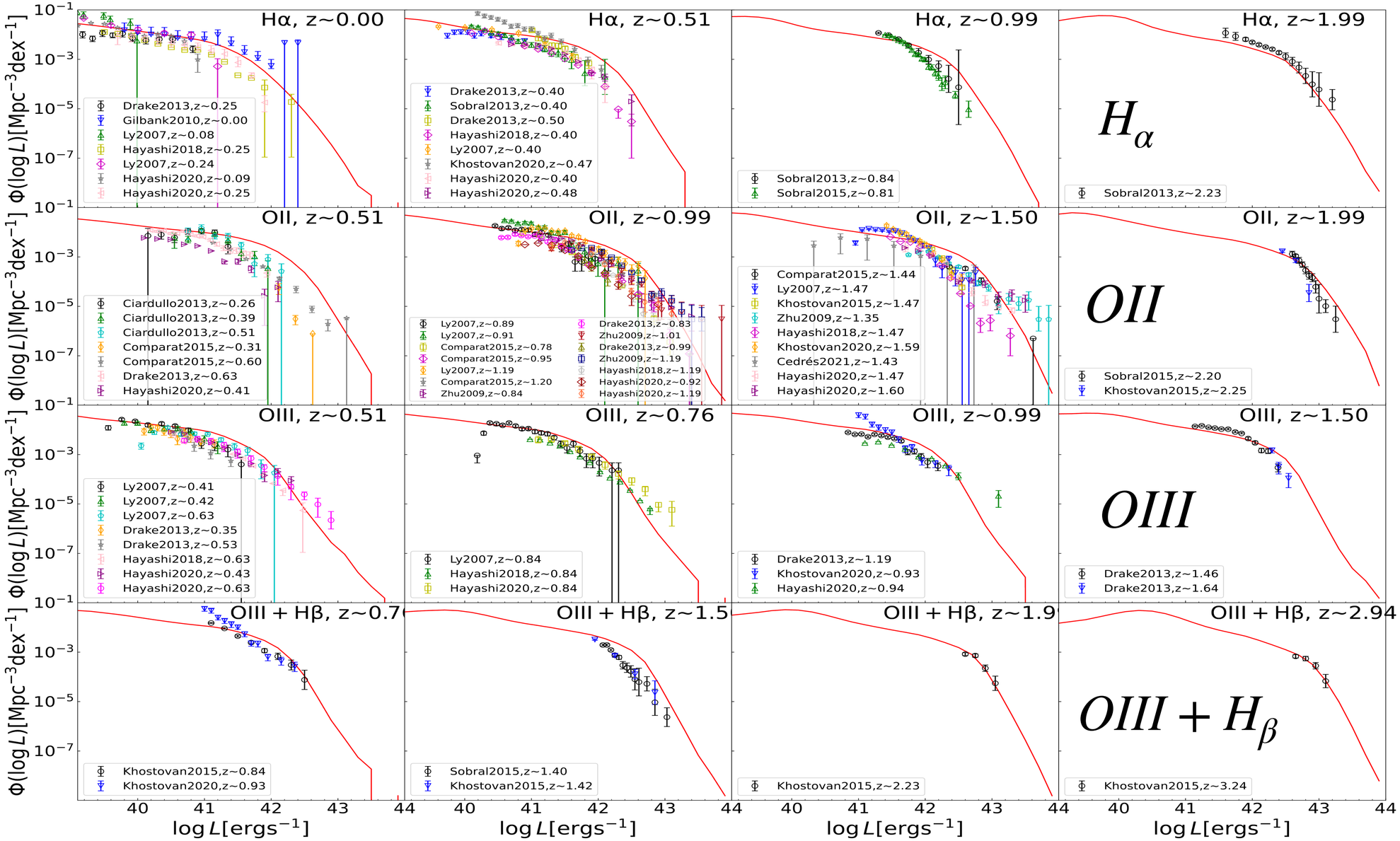
stellarmass functions
z=0—3



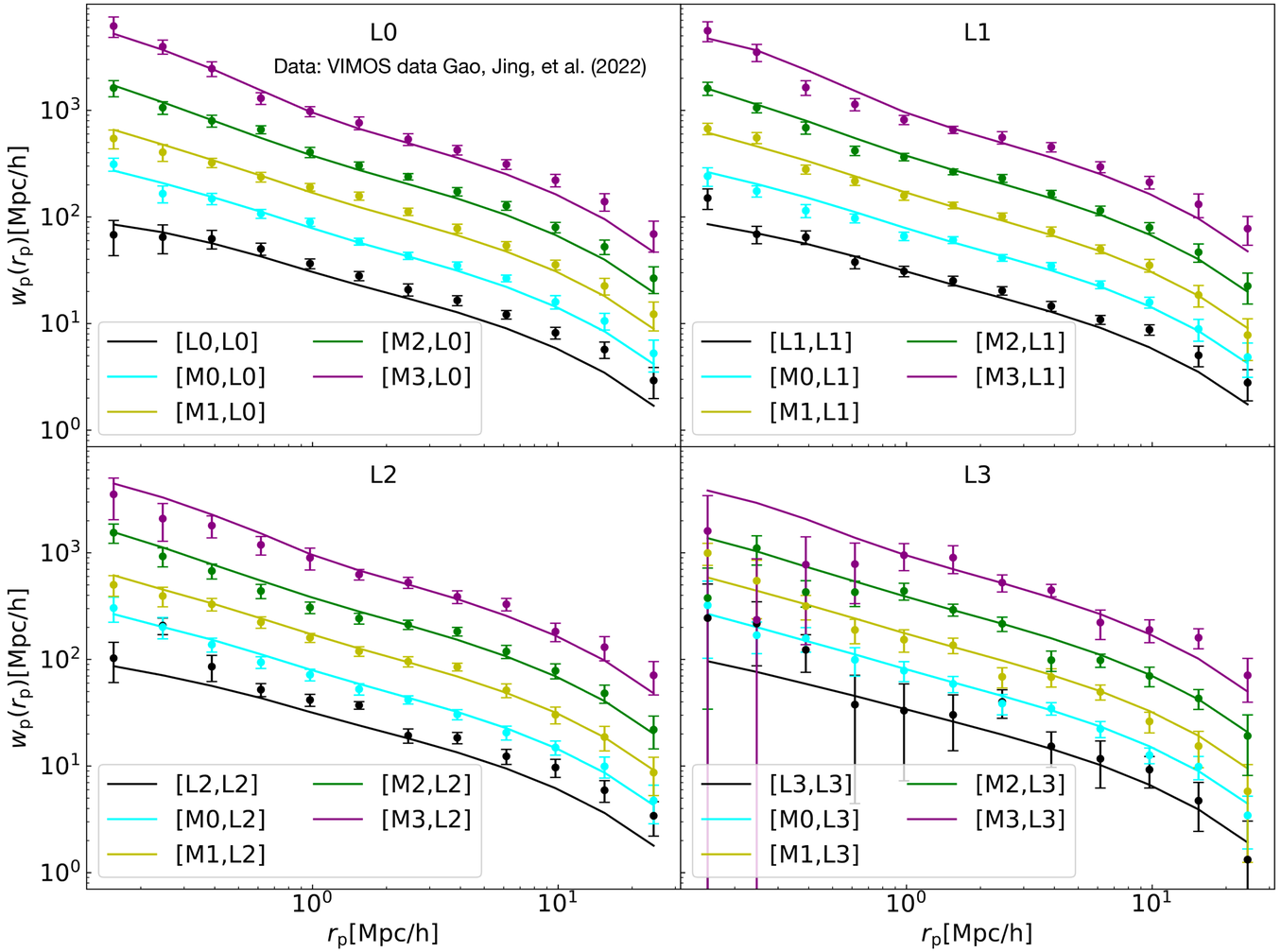




Emission line luminosity functions

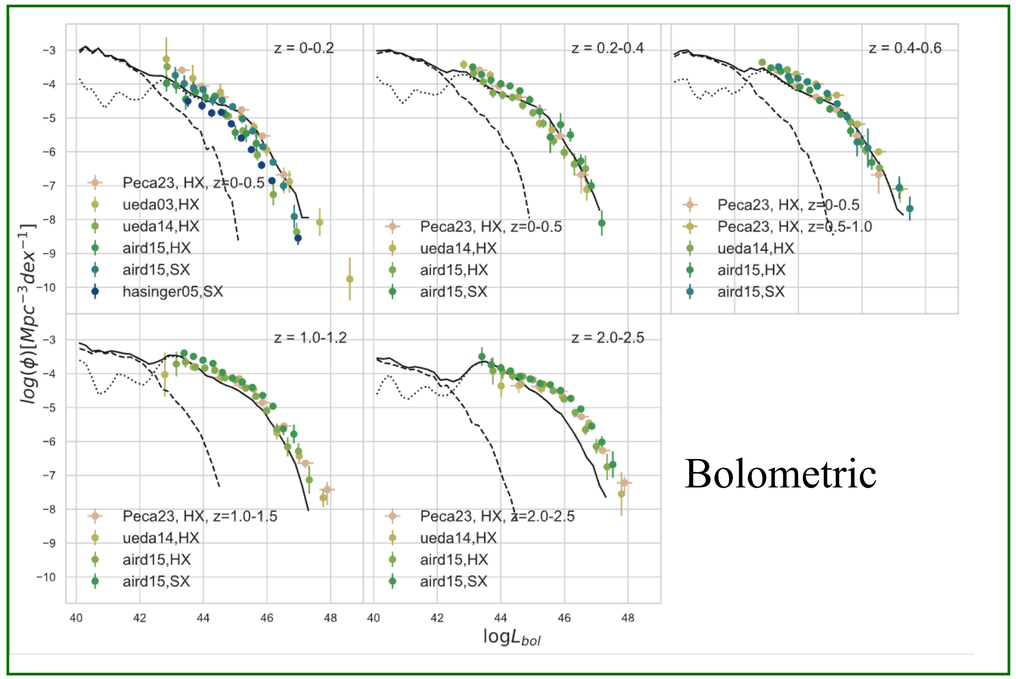


OII-selected Galaxy Correlation functions

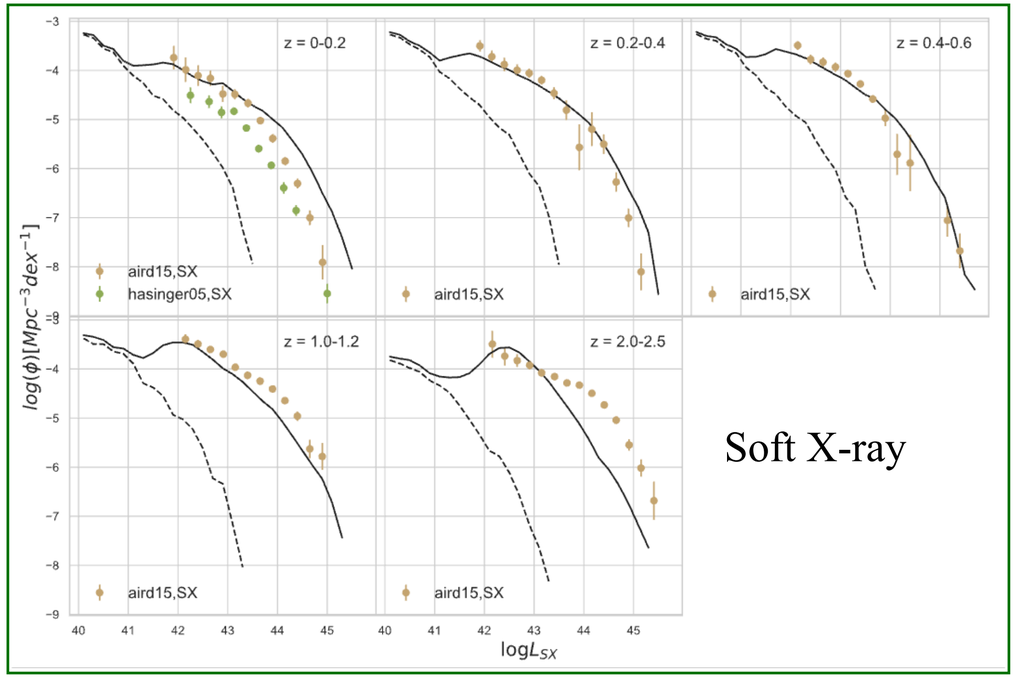


Pei + MNRAS (2024)

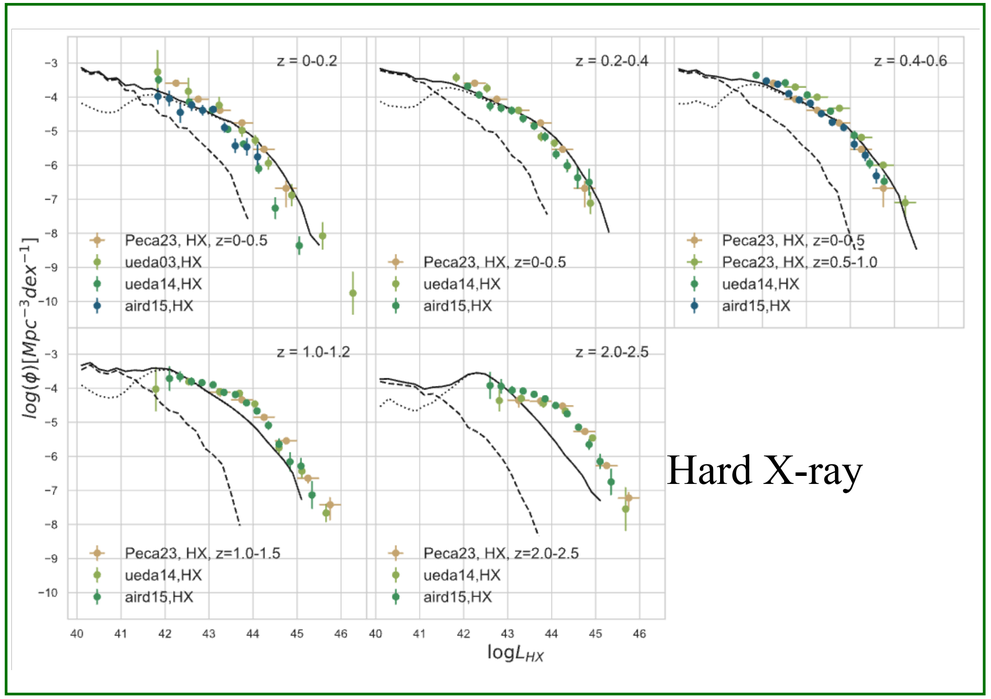
AGN Luminosity functions



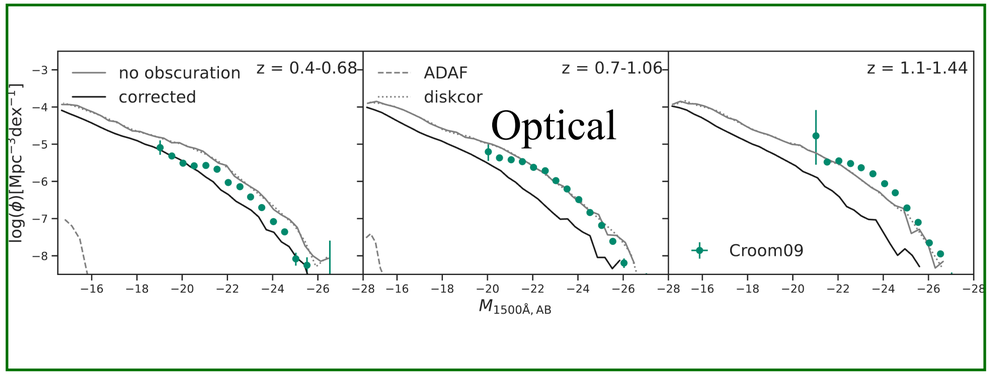
Bolometric



Soft X-ray



Hard X-ray



Optical

Reproduce the luminosity functions across optical to x-ray at most redshifts

Summary

- We finish the main body of the Hyper-Millennium; merger trees to come

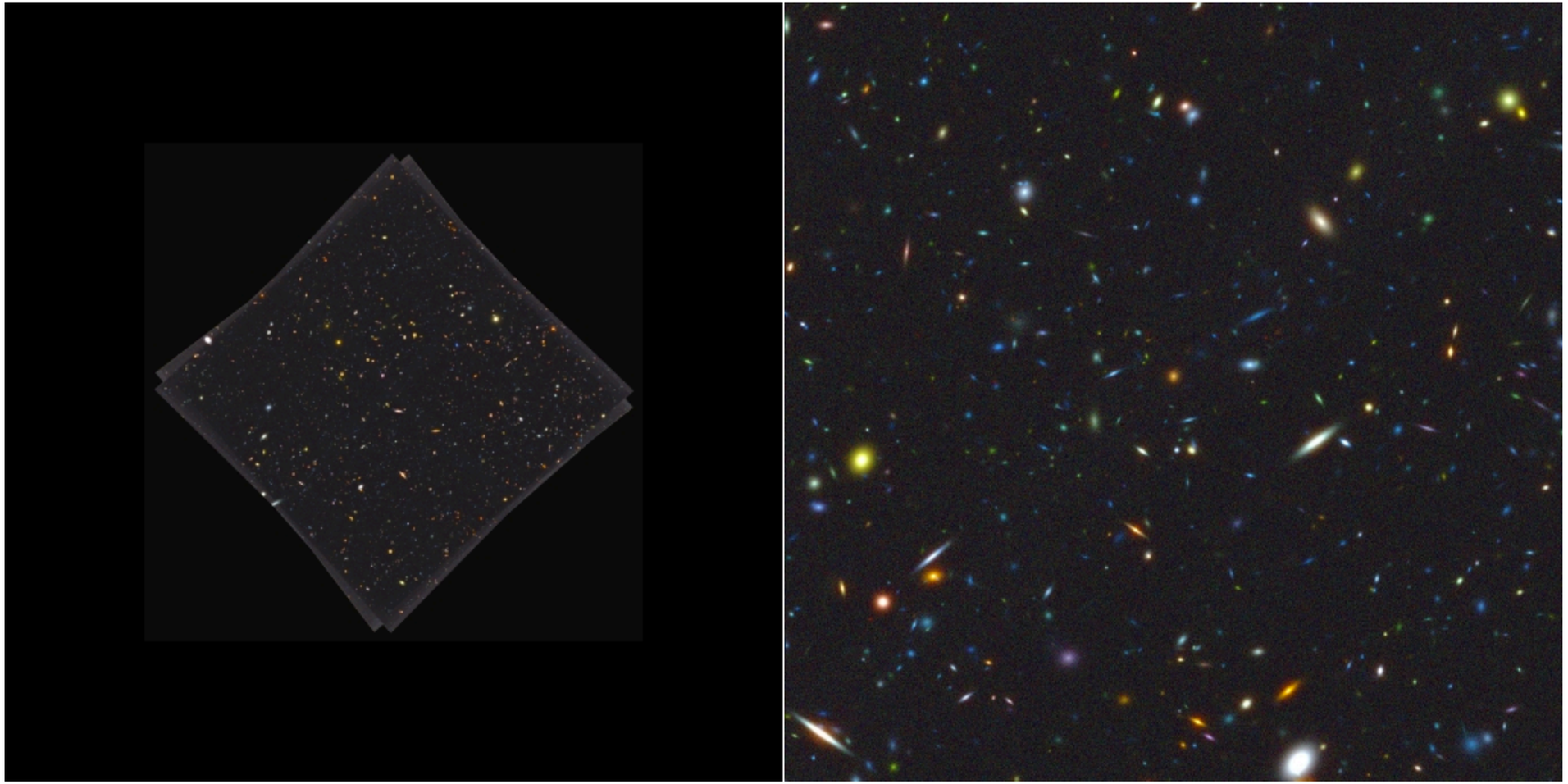
  The largest N-body cosmological simulation

  Volume $2.5^3[h^{-3}\mathrm{Gpc}^3]$, particle mass 3.2d8Msun, Particle number 4 trillion

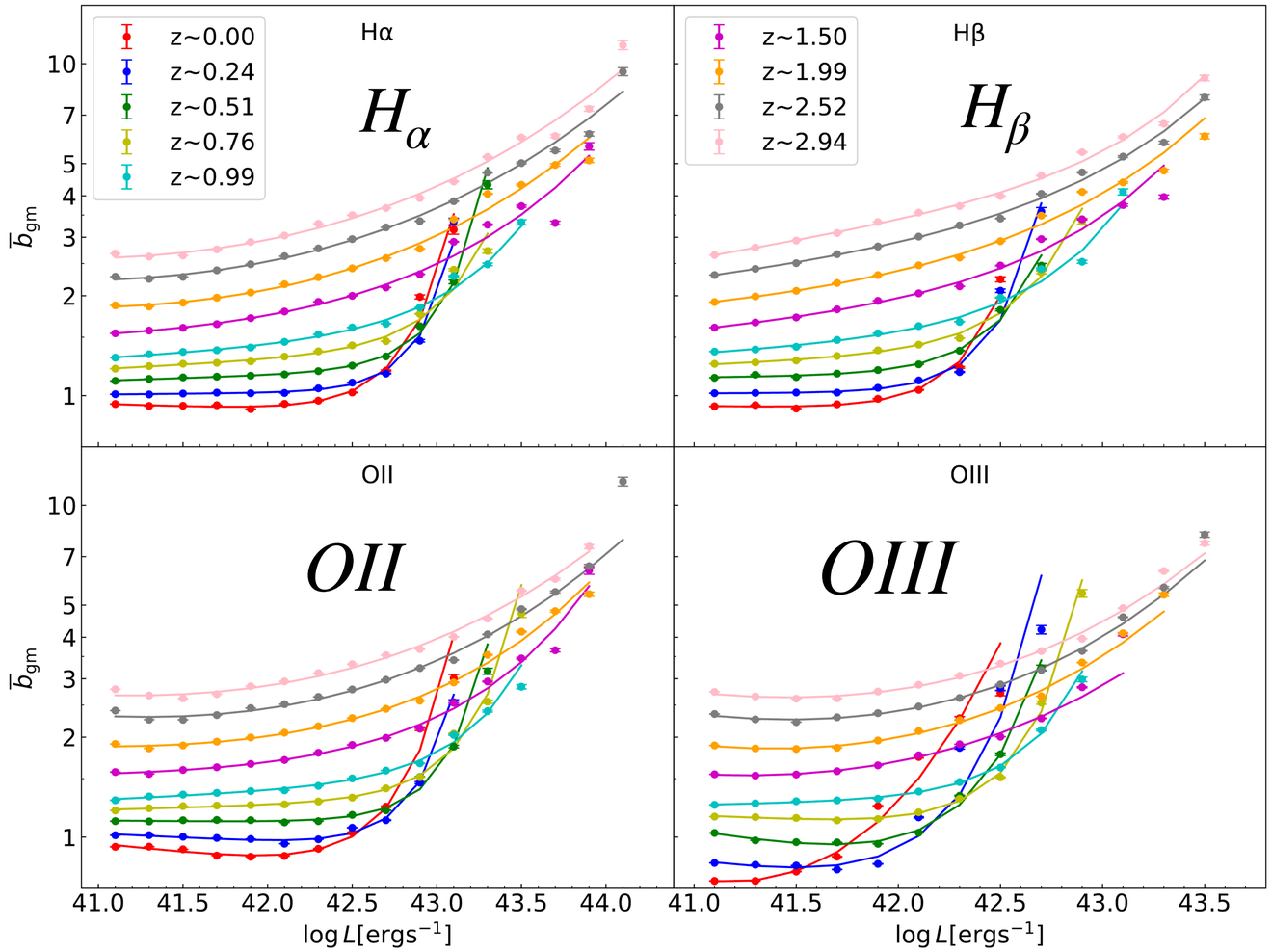
- Galaxy formation models
  - Improve semi-analytical models to reproduce many galaxy properties
  - Galaxy + AGN SED
- 50 square degree deep mock survey is ready with full SED for each mock galaxy

Thank you!

模拟星系



Applications: Bias as a function of luminosity and z

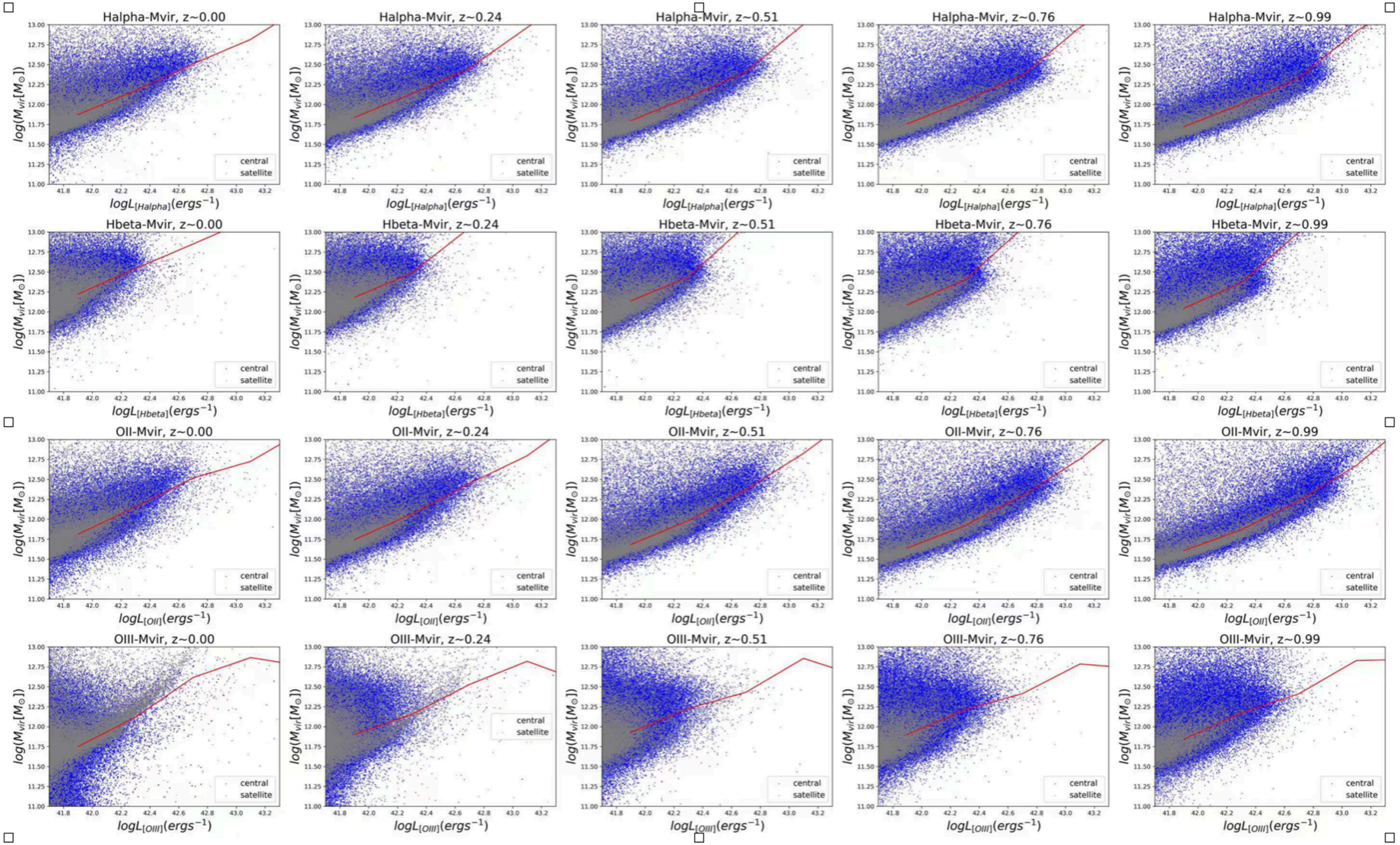


Fitting fomular

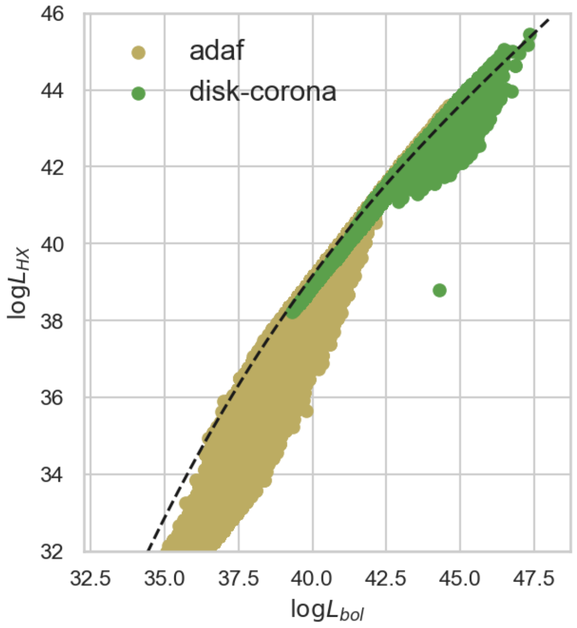
$$\overline{b}_{\rm gm}(L) = \Phi_{\rm L} \cdot (\frac{L}{L_*})^{\alpha} \cdot e^{\frac{L}{L_* \cdot 10^{\beta}}}$$

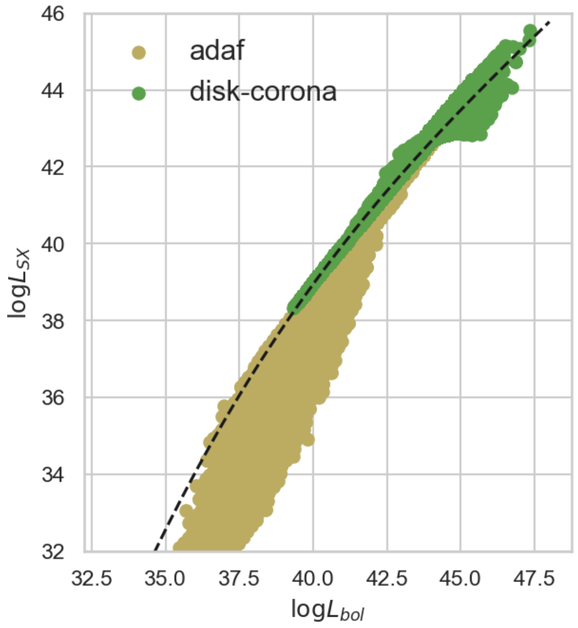
Applicable to many large-scale structure studies, in cluding BAO, RSD, lensing and etc.

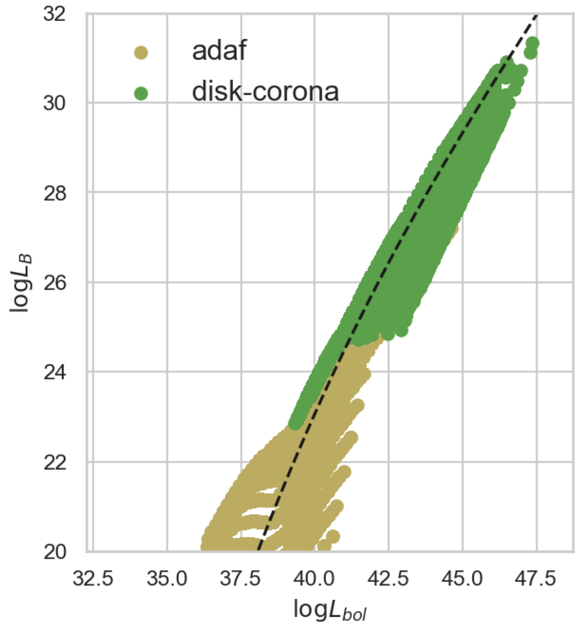
Pei + MNRAS (2024)


Halpha-Mvir, z~0.00
Halpha-Mvir, z~0.24
Halpha-Mvir, z~0.51
Halpha-Mvir, z~0.76
Halpha-Mvir, z~0.99
Hbeta-Mvir, z~0.00
Hbeta-Mvir, z~0.24
Hbeta-Mvir, z~0.51
Hbeta-Mvir, z~0.76
Hbeta-Mvir, z~0.99
OII-Mvir, z~0.00
OII-Mvir, z~0.24
OII-Mvir, z~0.51
OII-Mvir, z~0.76
OII-Mvir, z~0.99
OIII-Mvir, z~0.00
OIII-Mvir, z~0.24
OIII-Mvir, z~0.51
OIII-Mvir, z~0.76
OIII-Mvir, z~0.99
$log(M_{vir}[M_\odot])$
$logL_{[Halpha]}(ergs^{-1})$
$logL_{[Hbeta]}(ergs^{-1})$
$logL_{[OII]}(ergs^{-1})$
$logL_{[OIII]}(ergs^{-1})$
central
satellite

AGN scaling relations







$$\log_{10}(L_{\rm HX}/L_{\rm bol}) = -1.54 - 0.24\mathcal{L} - 0.012\mathcal{L}^2 + 0.0015\mathcal{L}^3$$

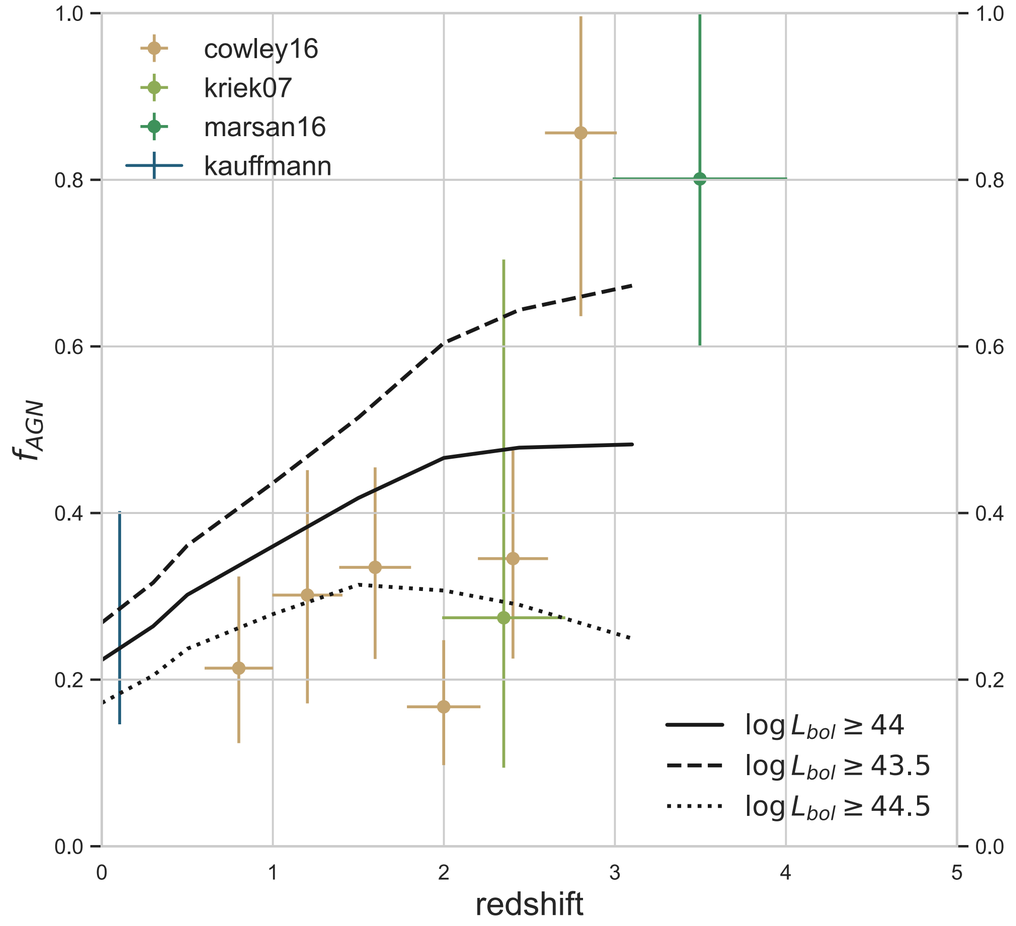
$$\log_{10}(L_{\rm SX}/L_{\rm bol}) = -1.65 - 0.22\mathcal{L} - 0.012\mathcal{L}^2 + 0.0015\mathcal{L}^3$$

$$\log_{10}(\nu_{\rm B}L_{\nu_{\rm B}}/L_{\rm bol}) = -0.80 + 0.067\mathcal{L} - 0.017\mathcal{L}^2 + 0.0023\mathcal{L}^3$$

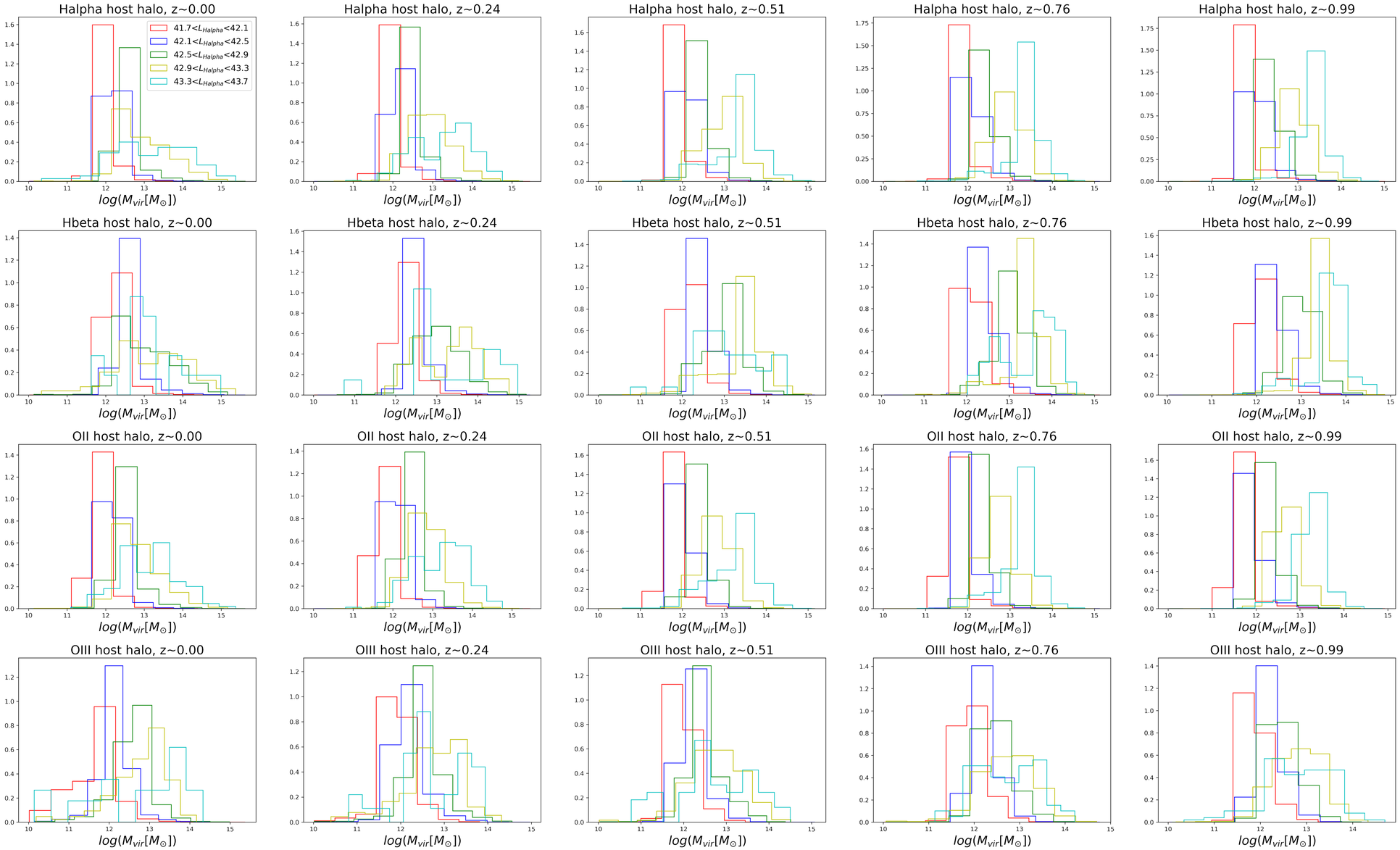
Consistent with the scaling relation by Marconi et al. (2004)

Su+ in prep

AGN fractions



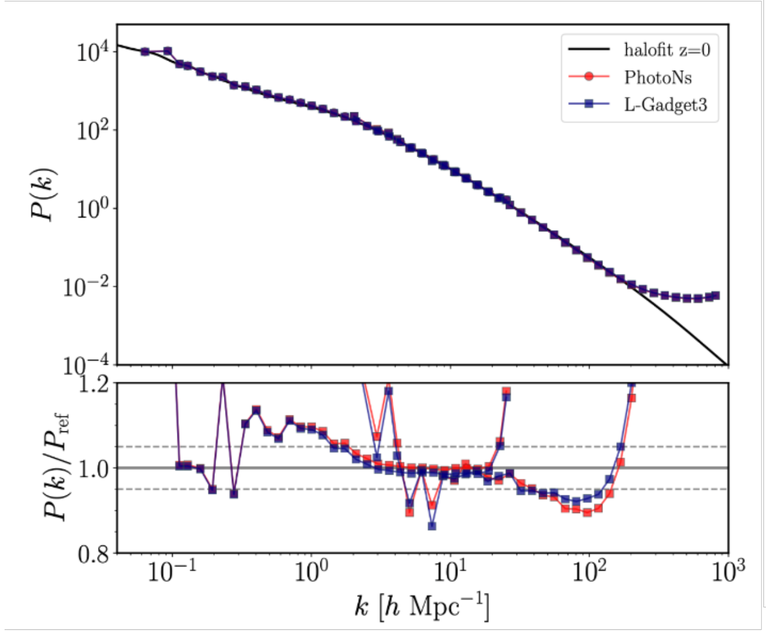
Su+ in prep


Halpha host halo, z~0.00
Halpha host halo, z~0.24
Halpha host halo, z~0.51
Halpha host halo, z~0.76
Halpha host halo, z~0.99
Hbeta host halo, z~0.00
Hbeta host halo, z~0.24
Hbeta host halo, z~0.51
Hbeta host halo, z~0.76
Hbeta host halo, z~0.99
OII host halo, z~0.00
OII host halo, z~0.24
OII host halo, z~0.51
OII host halo, z~0.76
OII host halo, z~0.99
OIII host halo, z~0.00
OIII host halo, z~0.24
OIII host halo, z~0.51
OIII host halo, z~0.76
OIII host halo, z~0.99
41.7<L_Halpha<42.1
42.1<L_Halpha<42.5
42.5<L_Halpha<42.9
42.9<L_Halpha<43.3
43.3<L_Halpha<43.7
log(M_vir[M_⊙])

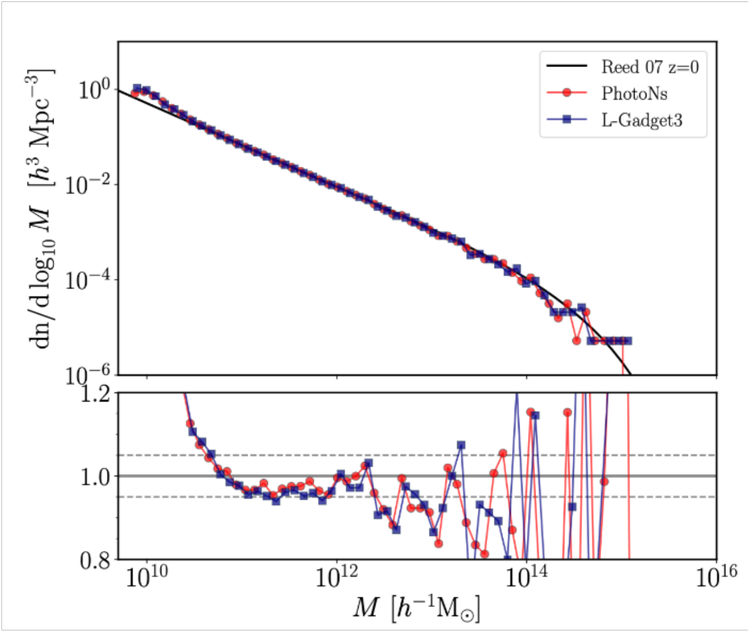
Project	Site/ orbit	Launch /op	FoV	R_{EE80}	Num pixels	Area	Wavelength	Num Filters	Spect
			deg^2	″	10^9	deg^2	nm		
CSST	LEO	~2024	**1.1**	**0.15** **0.074/pix**	**2.5**	**17500**	**255**—1000	≥6	yes
Euclid	L2	2022	0.56 0.55	>0.2 pix lmt	0.6 0.07	15000	550—920 1000—2000	1 3	no yes
Roman	L2	>2025	0.28	>0.2	0.3	~2000	927—2000	4	yes
Rubin	Chile	2023	9.6	~0.54	3.2	18000	320—1050	6	no

Comparison between PhotoNs and Gadget

Power spectrums



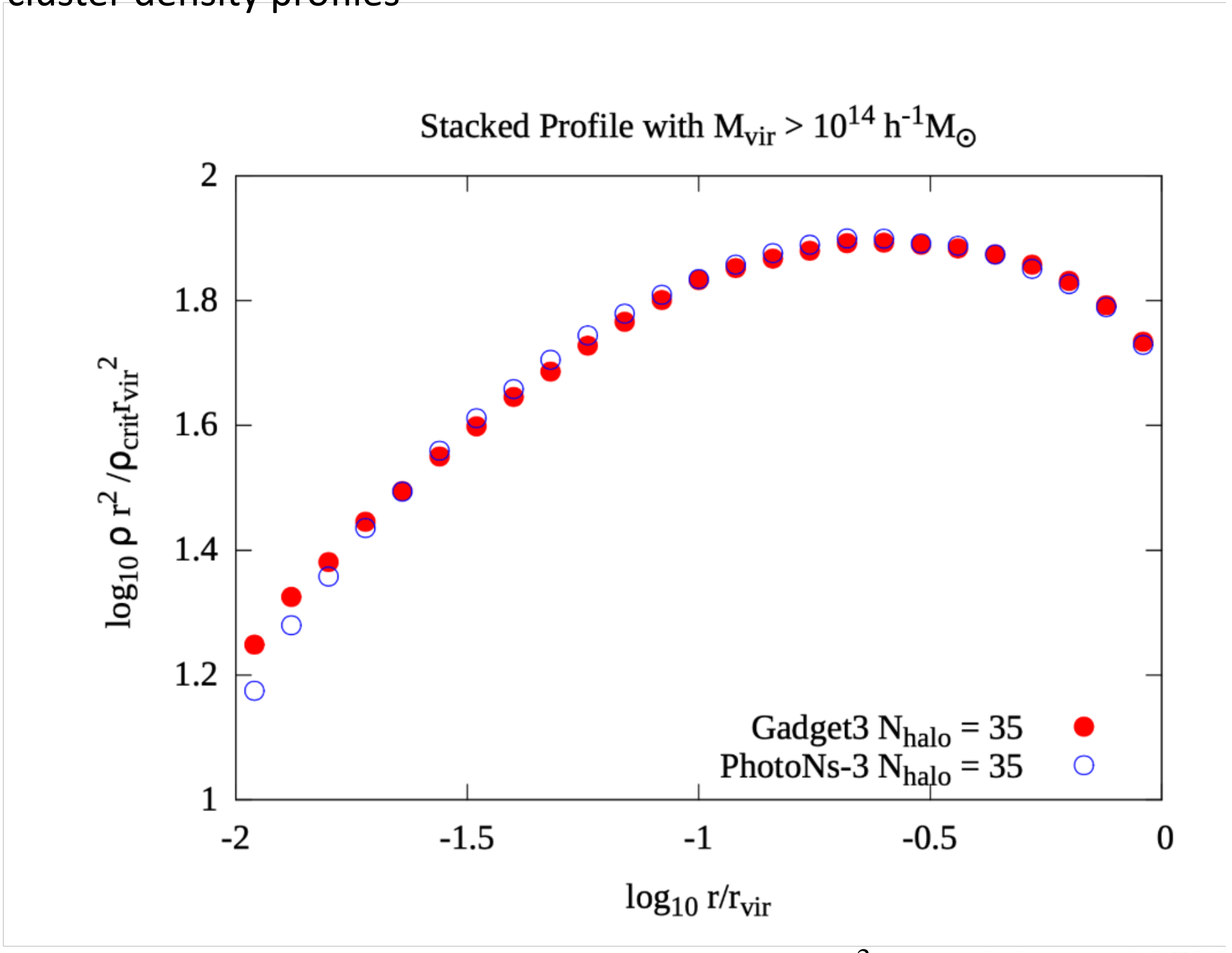
Halo mass functions



768^3 particles + 125Mpc/h

Comparison between PhotoNs and Gadget

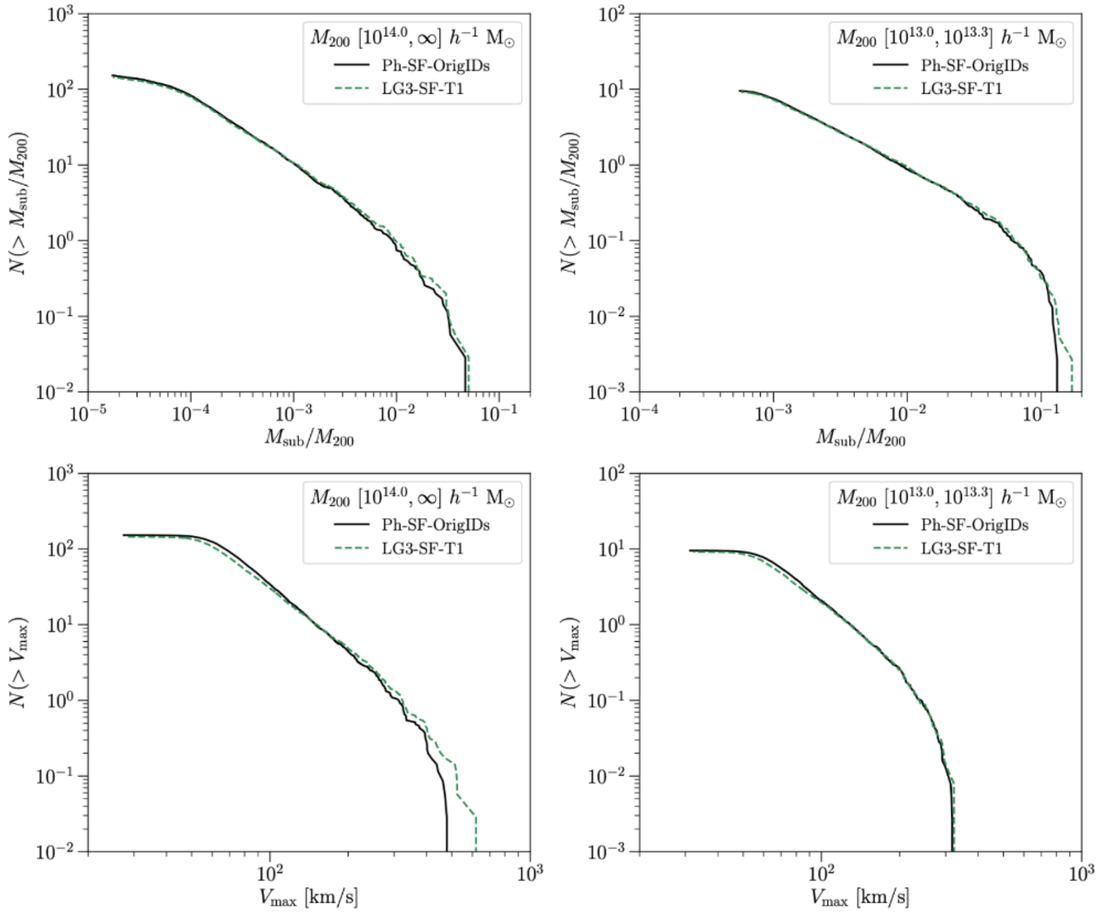
Stacked cluster density profiles



768^3 particles + 125Mpc/h

Comparison between PhotoNs and Gadget

Subhalo mass functions

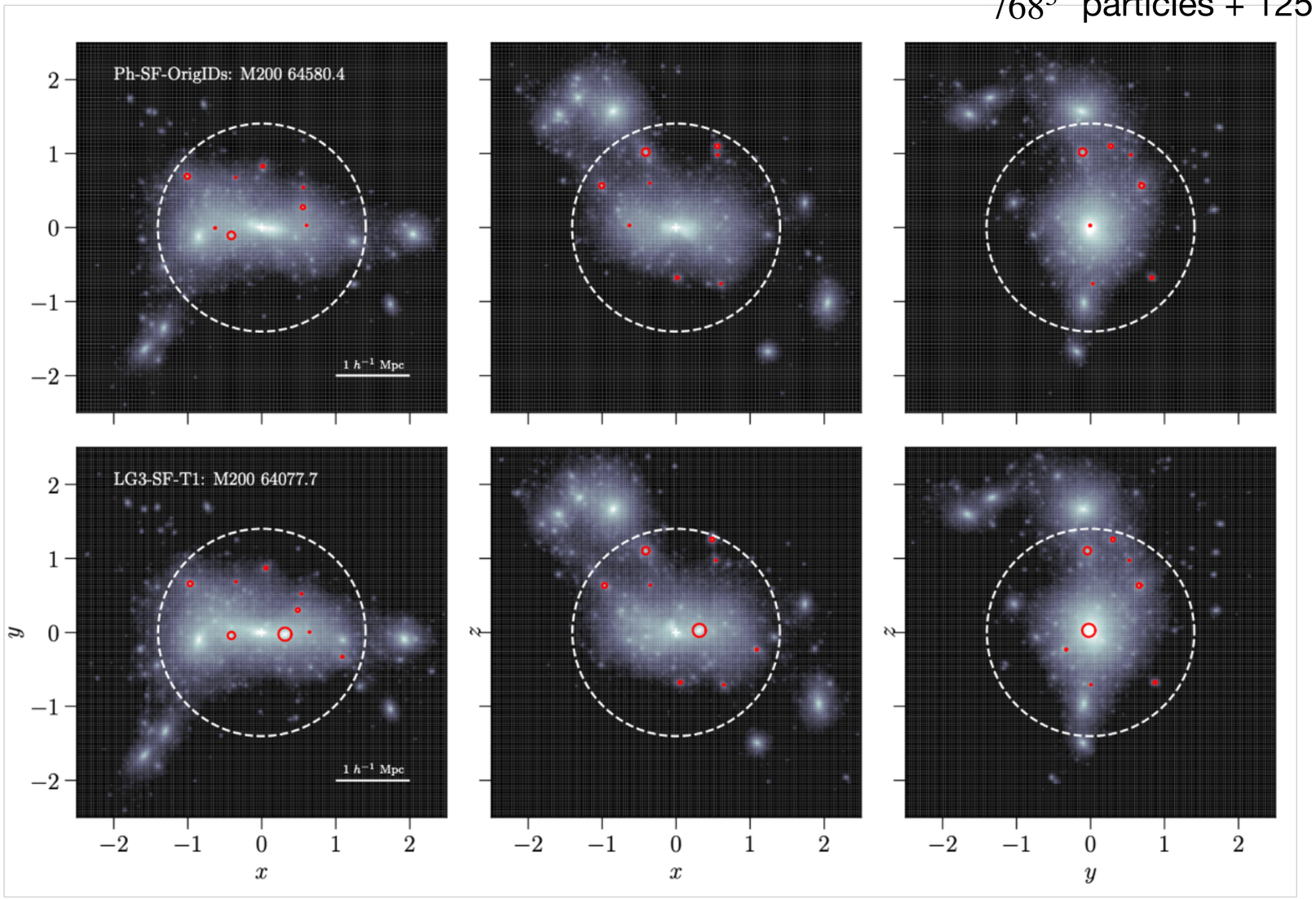


768^3 particles + 125Mpc/h

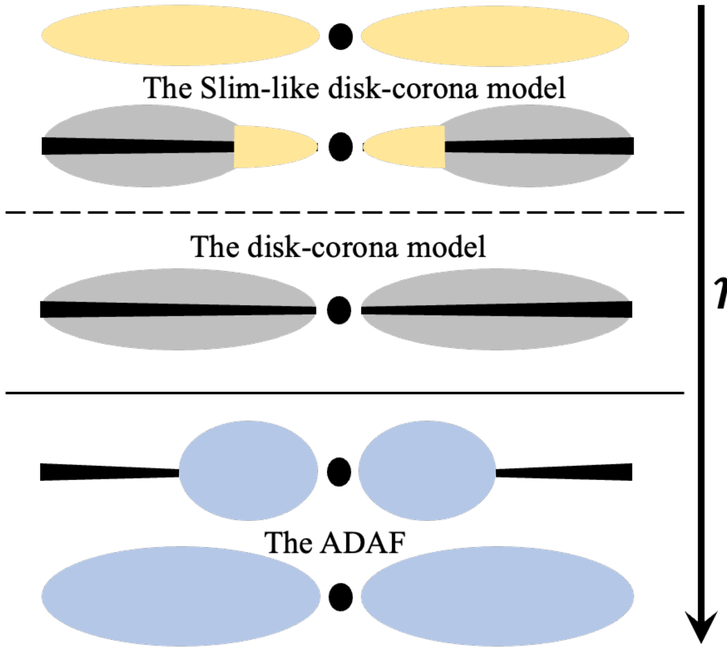
Comparison between PhotoNs and Gadget

Projections of top 10 most massive subhalo in the most mass cluster

768^3 particles + 125Mpc/h



Spectral energy distributions of AGN



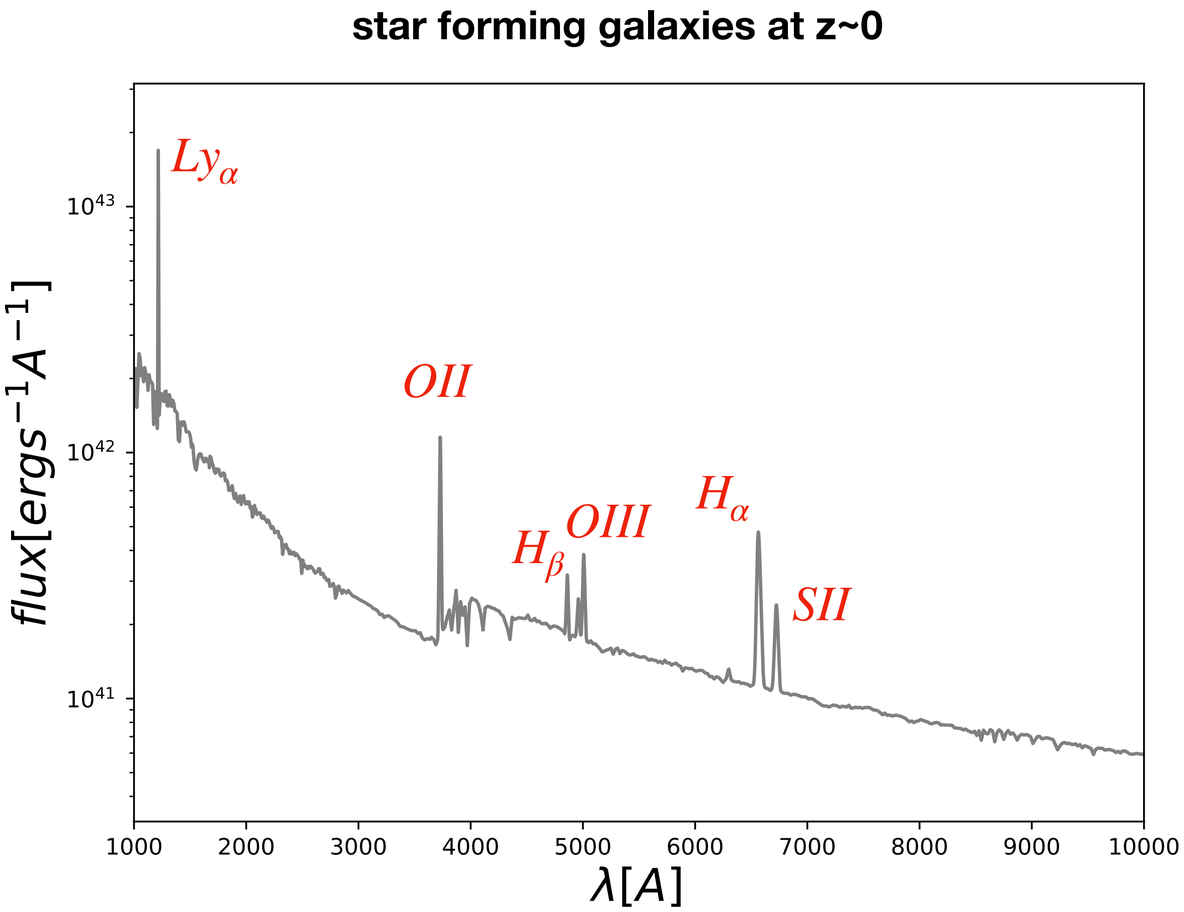


	geometry	Optical depth	temperature	Radiation	luminosity	Accretion rate
Slim disk	Thick	thick	Hot	Blackbody	∝ln $\dot{M}$	$\dot{m}$>0.1
Thin disk	Thin	Thick	Cool	Blackbody	∝$\dot{M}$	0.003<$\dot{m}$≤0.1
ADAF	thick	Thin	Hot, two temperature	Synchrotron, bremsstrahlung, inverse-compton	∝$\dot{M}$^2	$\dot{m}$≤0.003

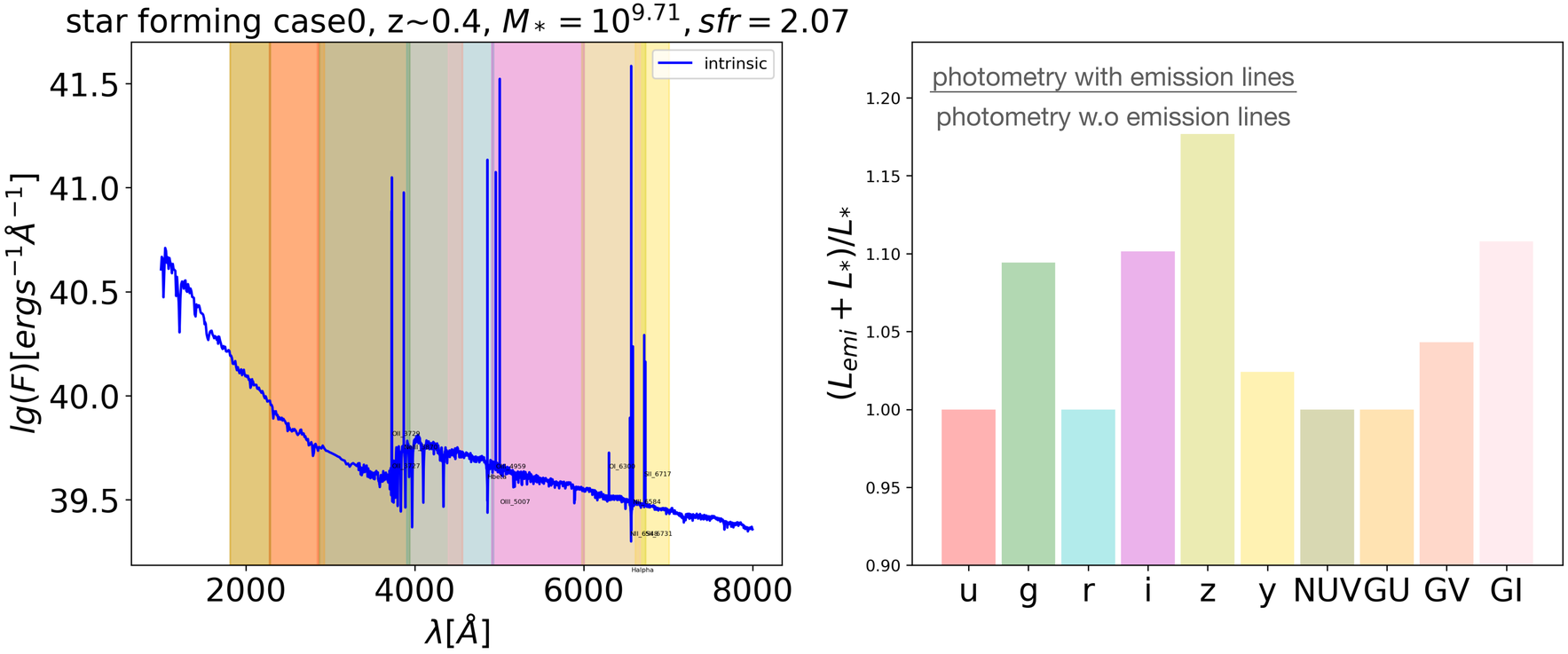
- Emission lines
  - Line ratios - CLOUDY13.03
    - geometry
    - chemical content
    - ionizing spectrum
    - metallicity (Z)
    - ionizing parameter (U)
    - Hydrogen density (n_H)



裴文祥

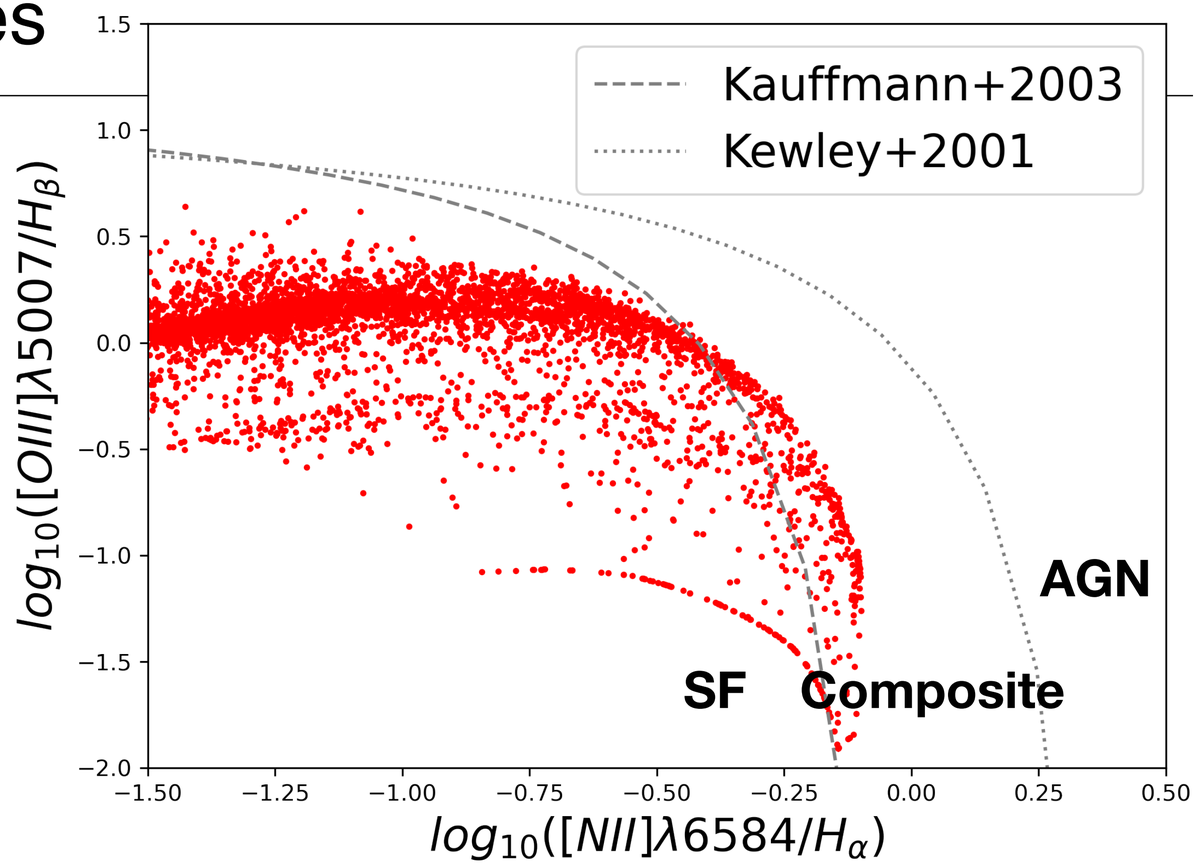


- For a typical star forming galaxies, the photometry could be changed with or without emission lines. In particular, in z band, in this particular case it could reaches 17%
- The photo-z accuracy can be improved by a factor of 2.5 by including emission lines' contribution (Ilbert et al. 2009)



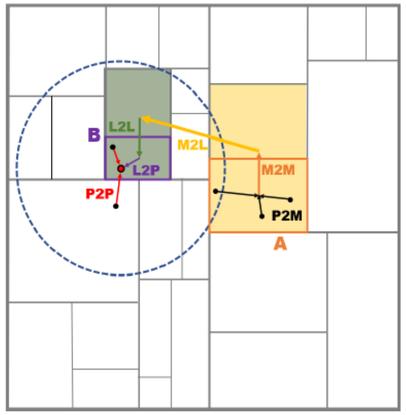
Galaxy Emission Lines

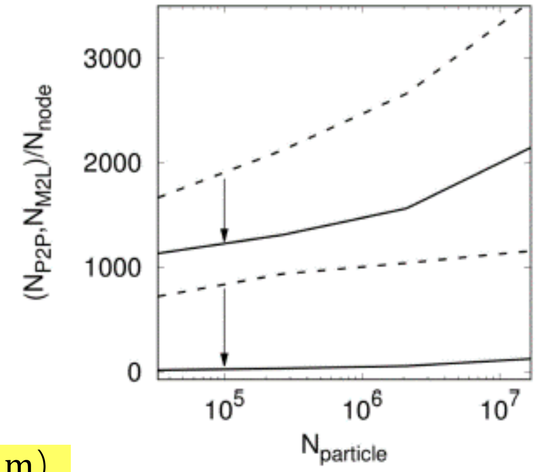
- Emission lines
  - Line ratios - CLOUDY13.03
    - geometry
    - chemical content
    - ionizing spectrum
    - metallicity (Z)
    - ionizing parameter (U)
    - Hydrogen density (n_H)

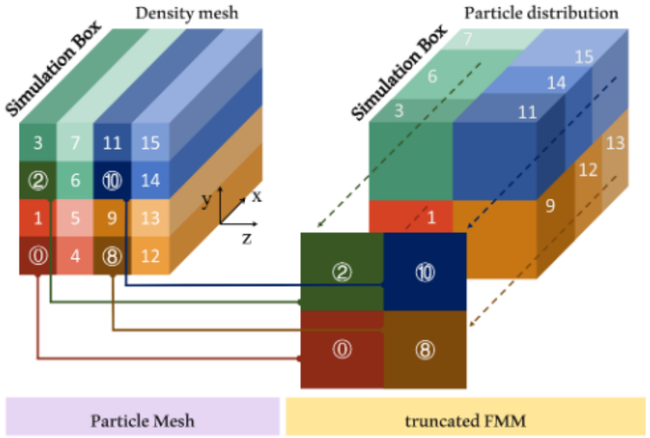


Particle-Mesh + Fast-Multipole-Method (PM-FMM)

- PM-FMM is O(N) algorithm than a TreePM (O(NlogN))
- The gravitational potential at a certain point (*red point with black circle*) in Region A is generated by a group of particles in region B, the information is passed by 7 operators (level by level)
- The most expensive operator P2P is carried out on GPU-type device to reduce the computing time.
- Upgrade the particle-mesh convolution method for better pencil decomposition.







O （ N * p + n $\log_2$ n + m $\log_2$ m）

Q. Wang, 2018, 2021ab, 2022