From the Early Universe to the Local Cosmos: Cosmological Mocks for Next-Generation Large-Scale Surveys

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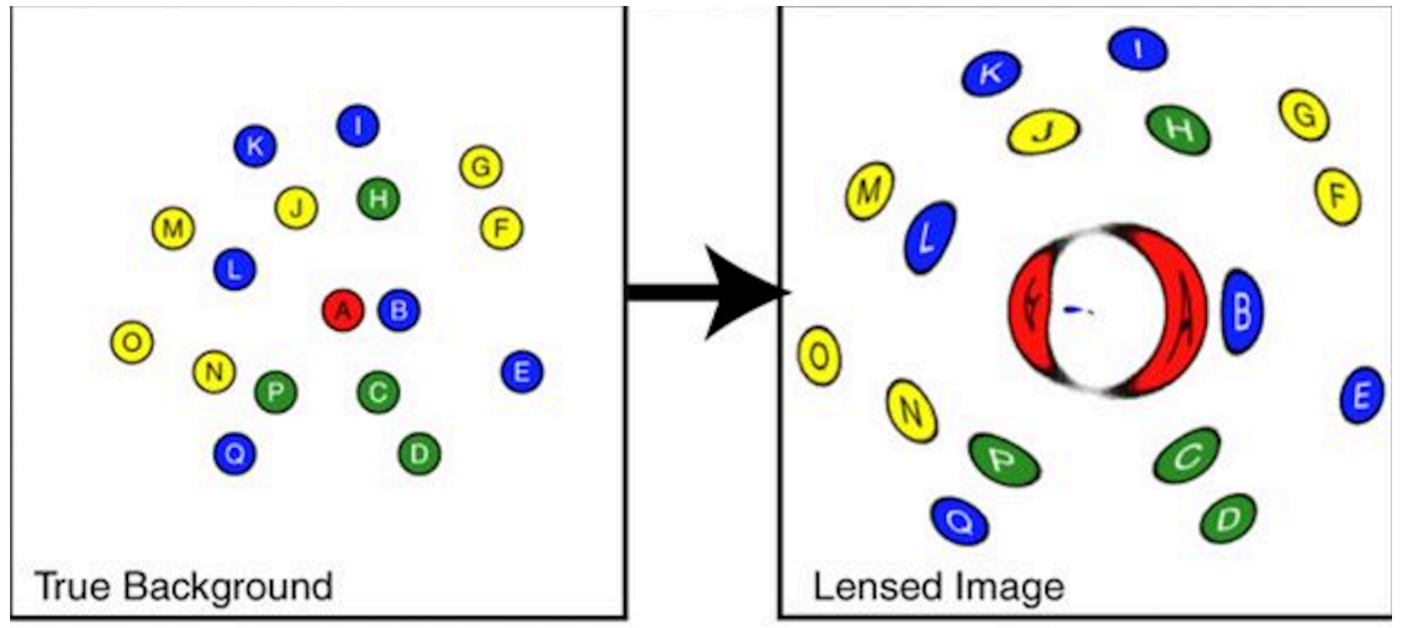
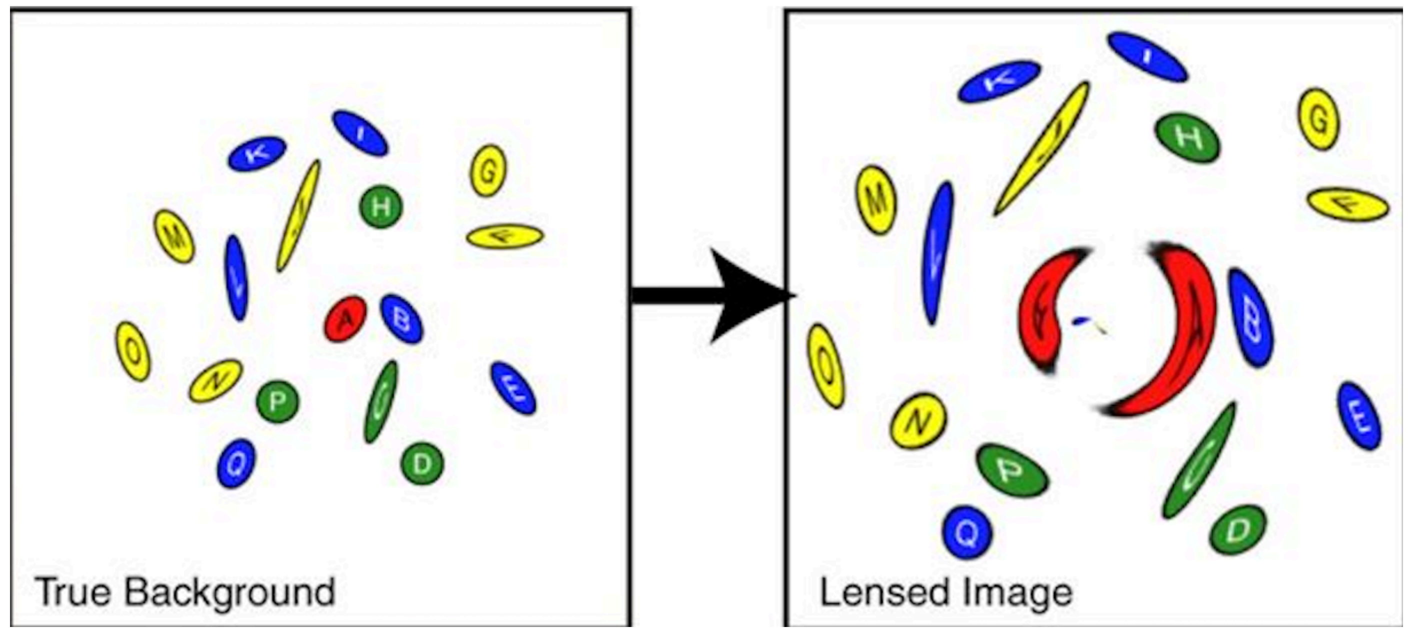
Simulations are crucial for modern cosmology

- 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

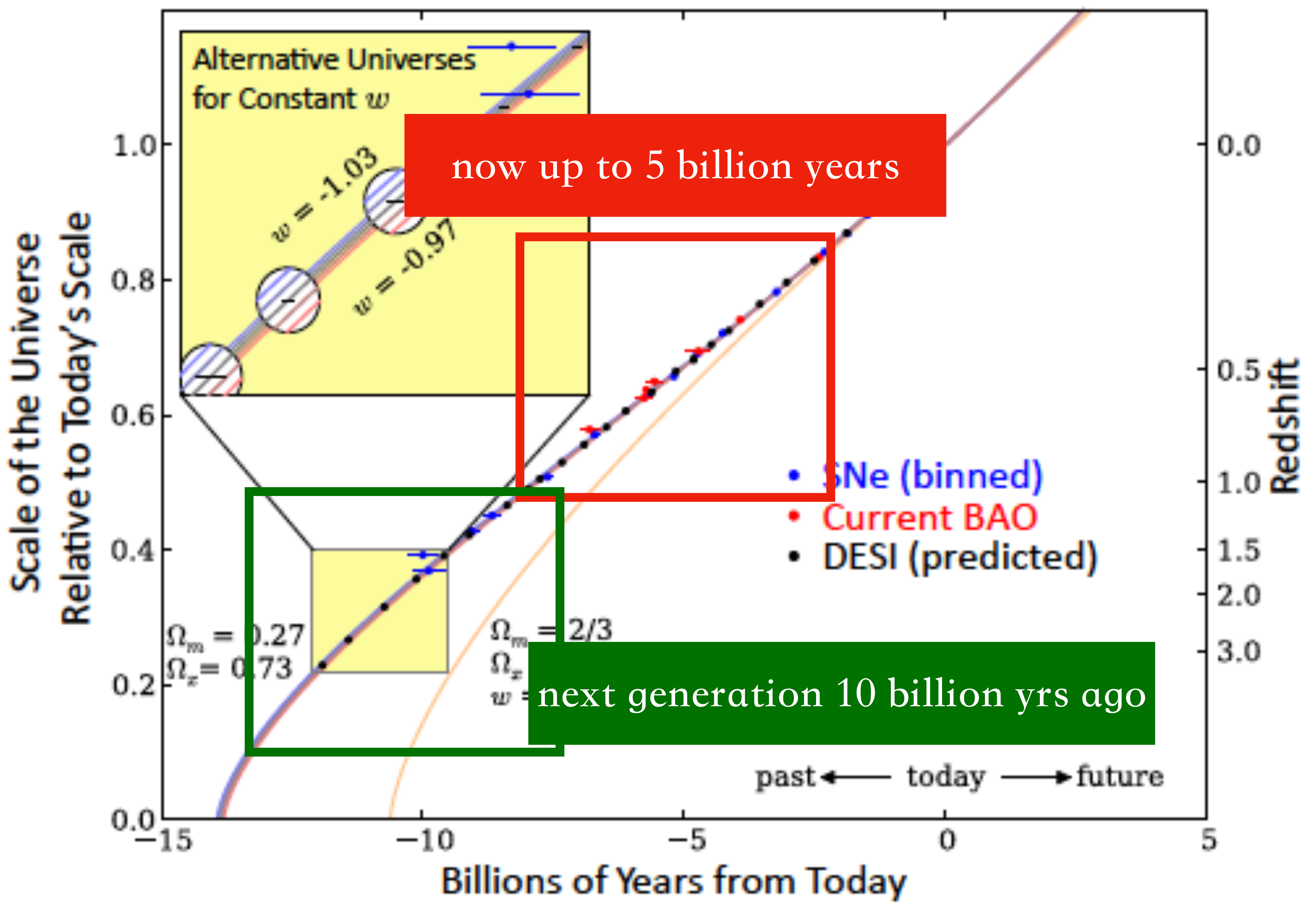




Next generation of large scale structure surveys

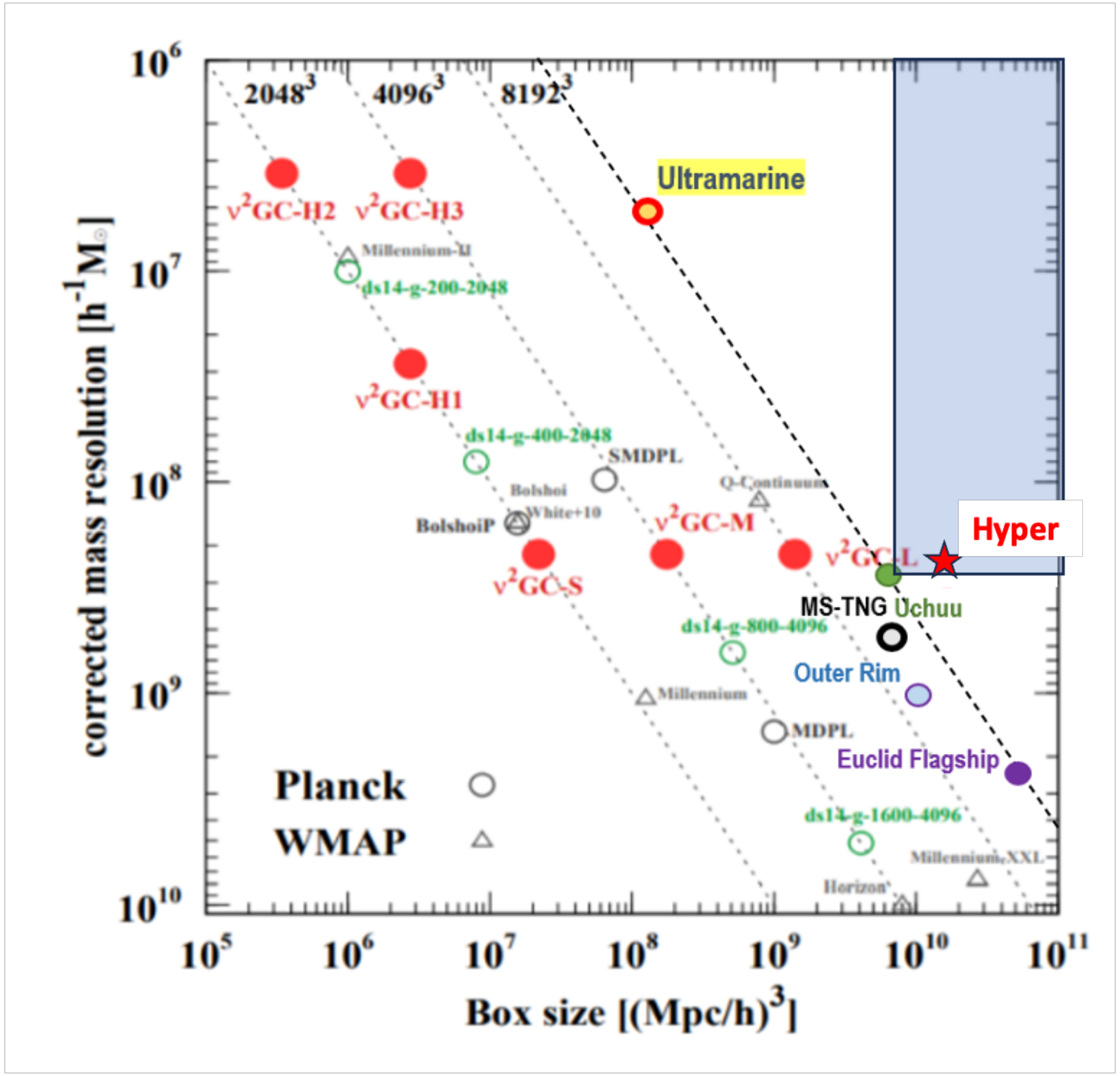
further, fainter

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.



Cosmological simulations

Large box： > 2Gcp/h

High resolution: <3.8d10Msun

Hyper-Millennium

Hyper-Millennium

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

Ω_m	0.3111
Ω_Λ	0.6889
Ω_b	0.0490
h	0.6766
σ_8	0.8102
n_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	$3.21 \times 10^8 \mathrm{M}_\odot$

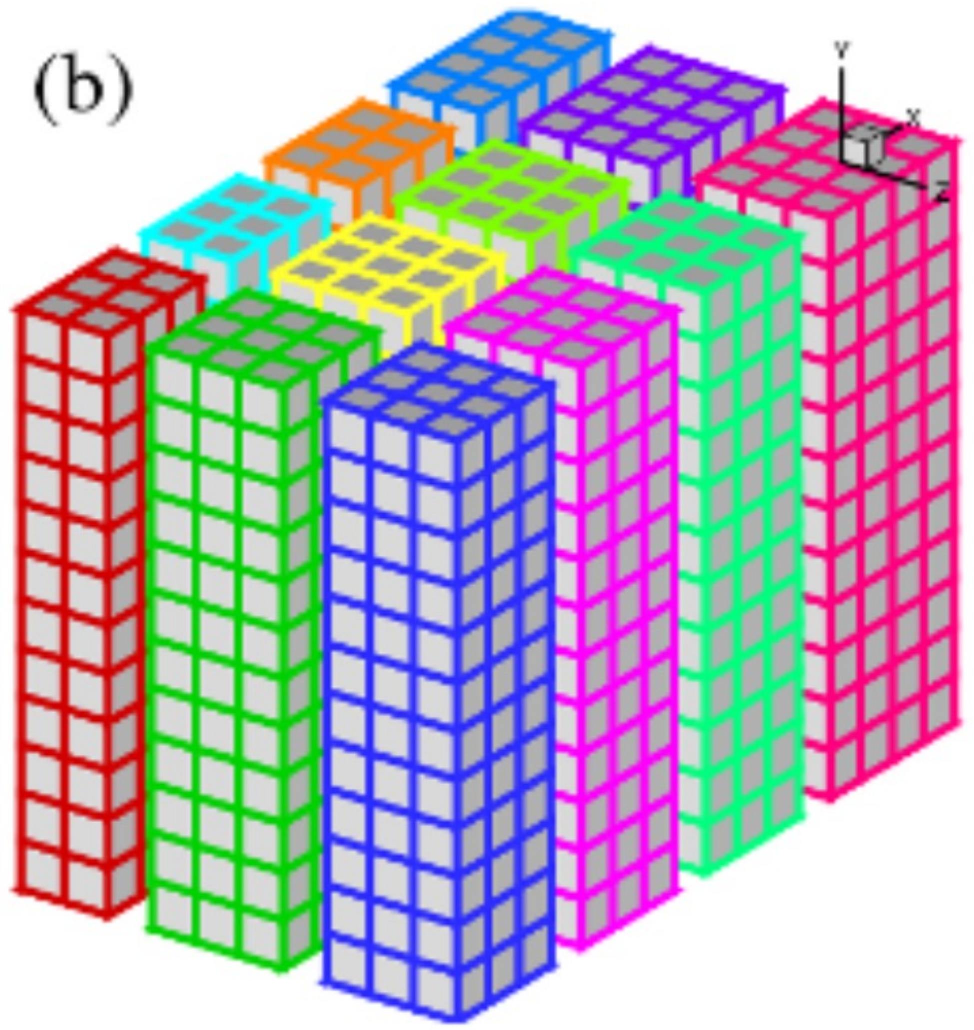
Li et al. in prep

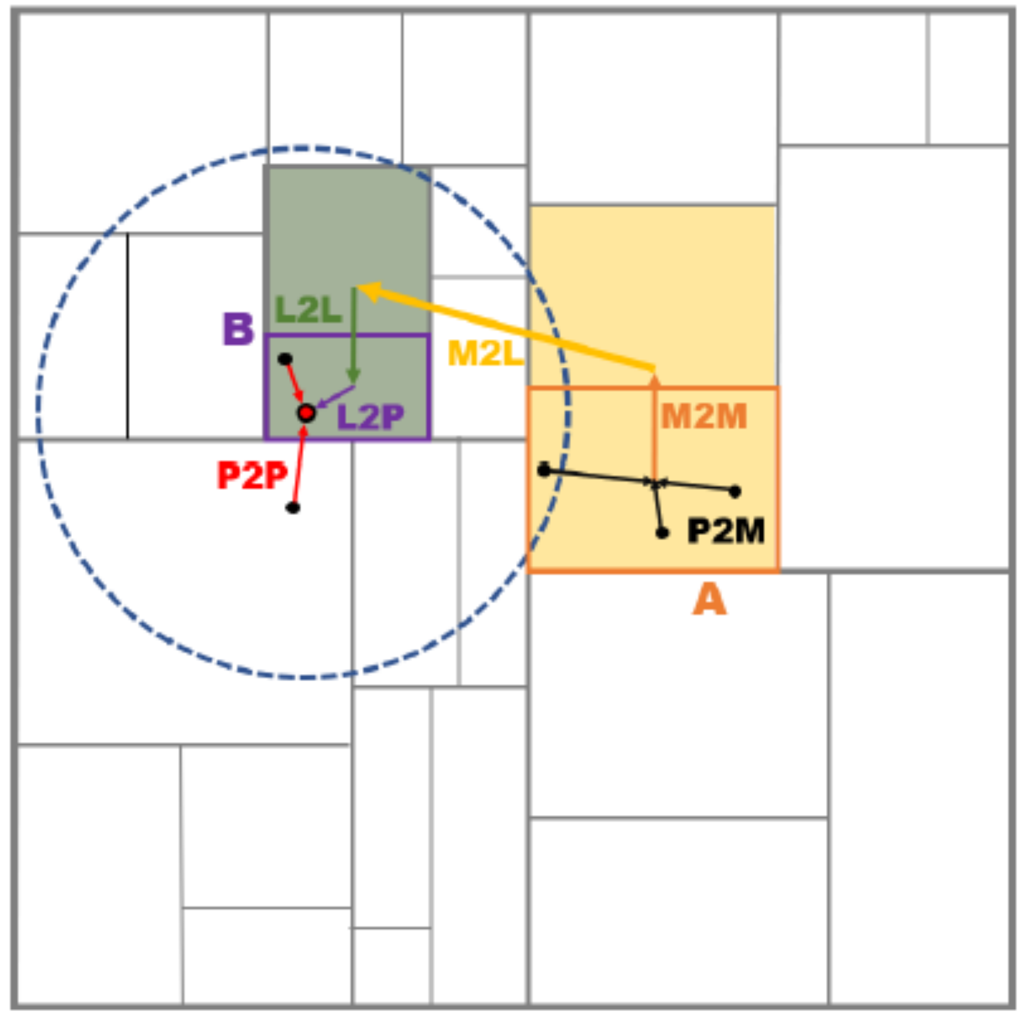
Largest N-body cosmological simulation in the world.

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



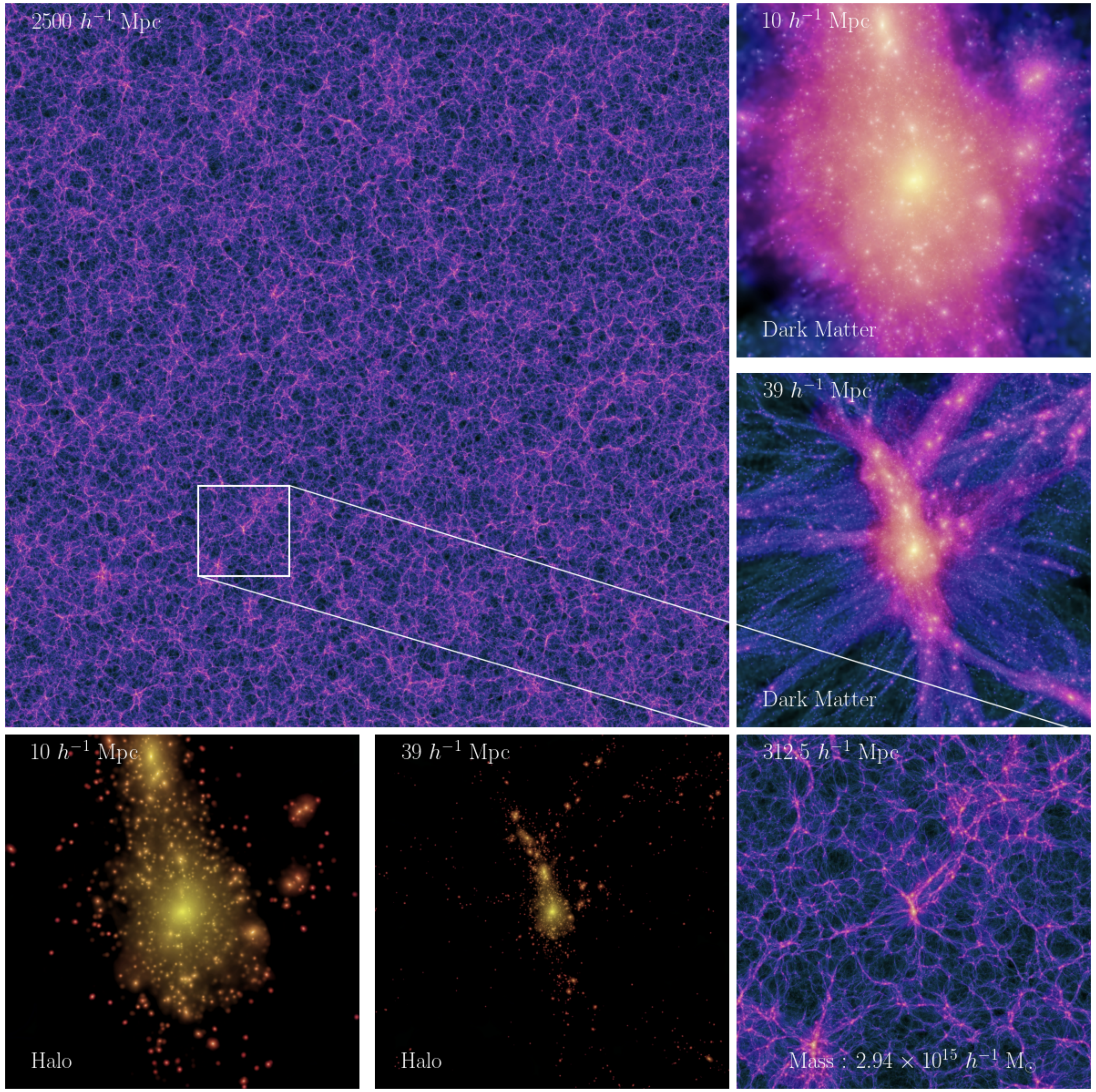


- 4000 Computing nodes (1 32core cpu and 4 64c DCU
- Wall-Clock time~17 Days

FFT: pencil decompostion

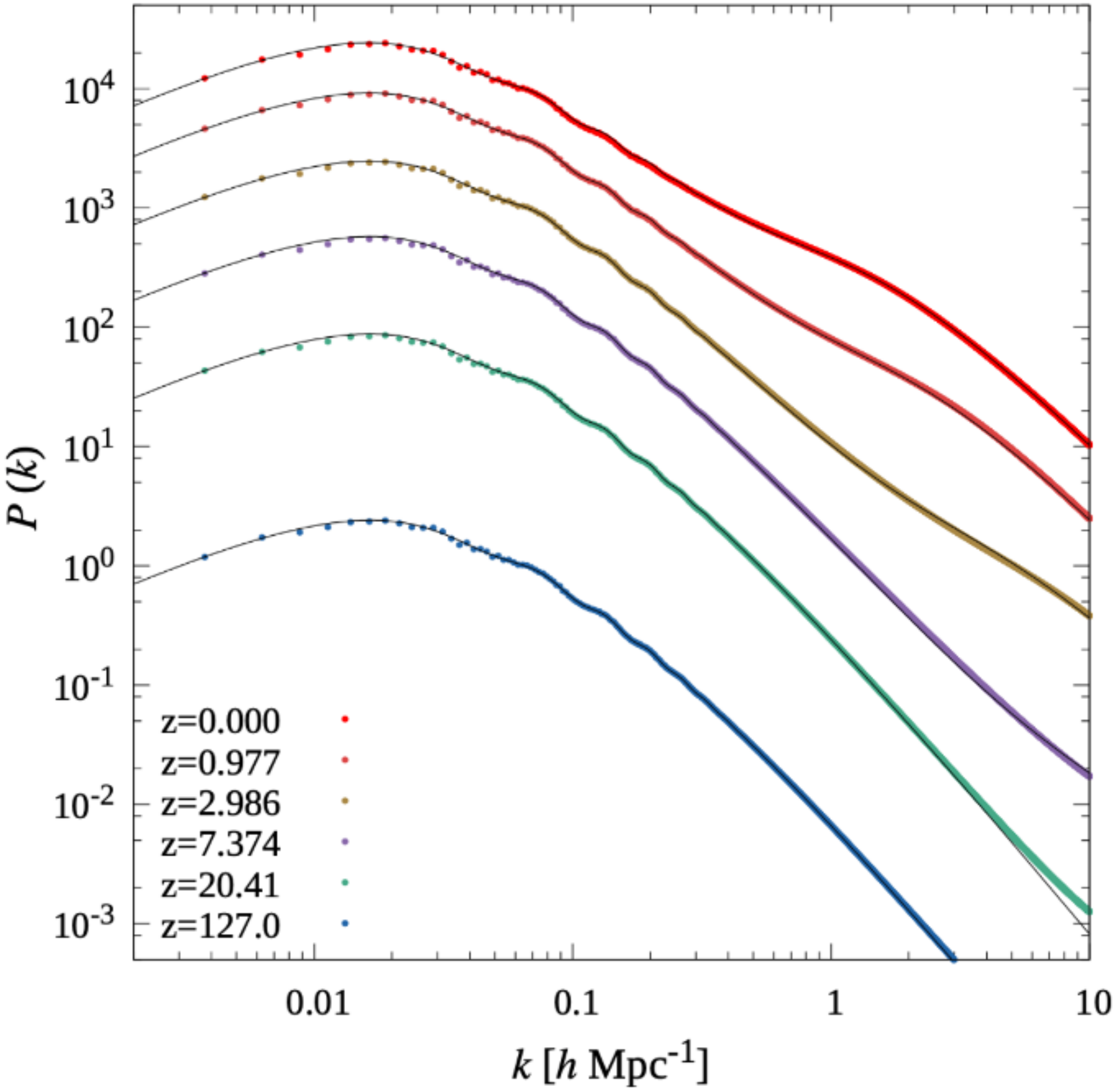
Wang et al. 2019; 2022

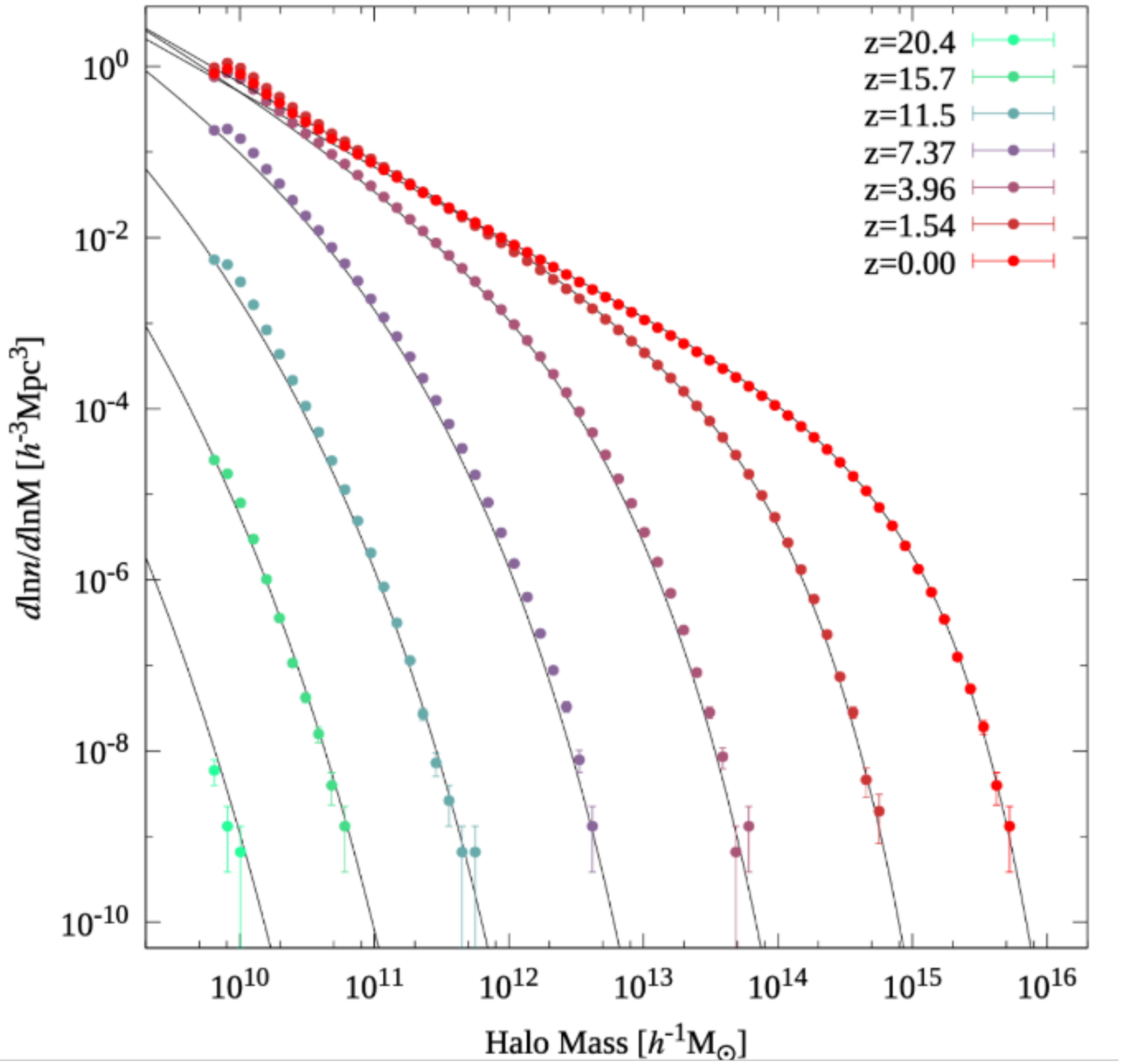
Current status



- **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





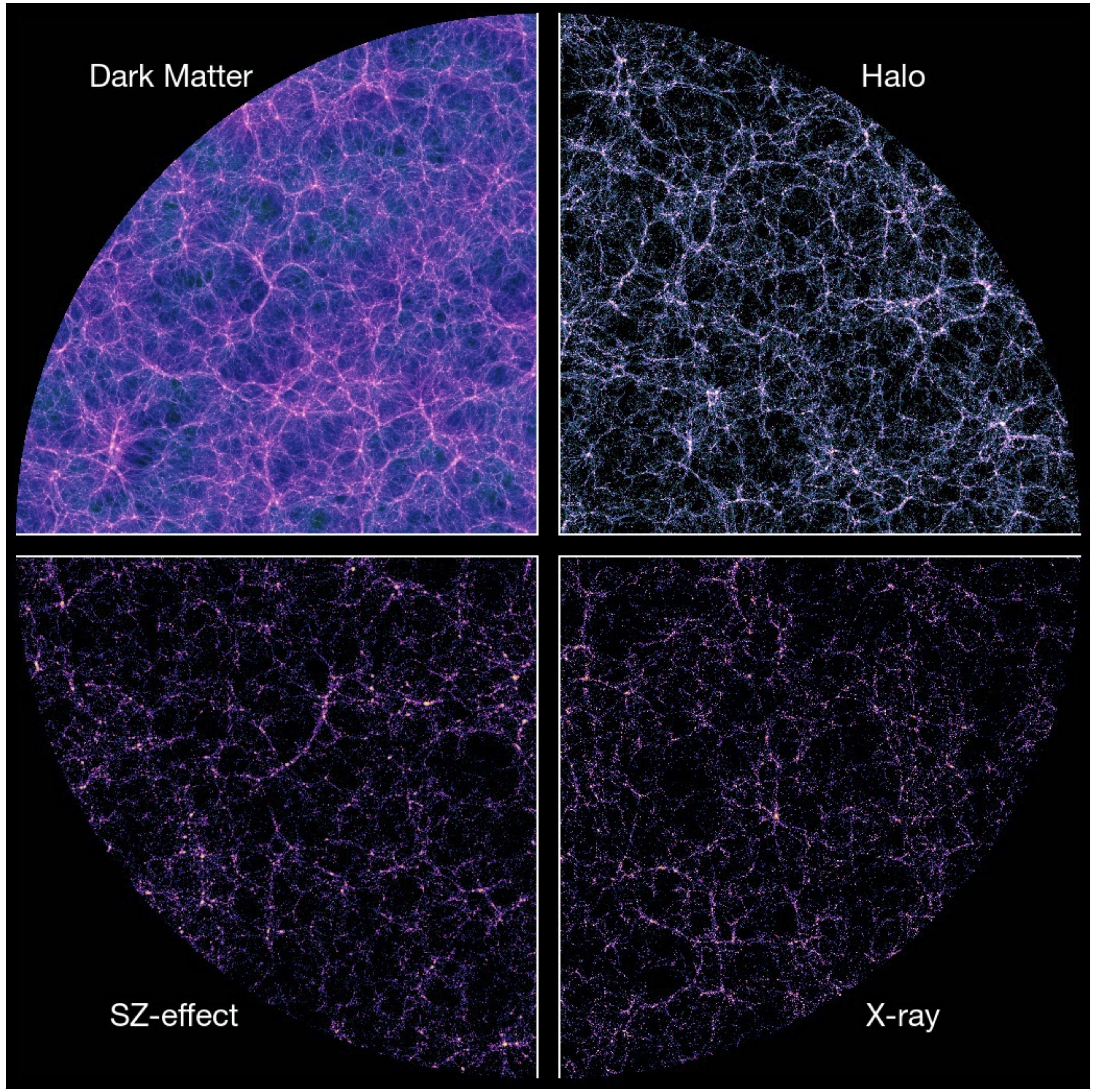
Li et al. in prep

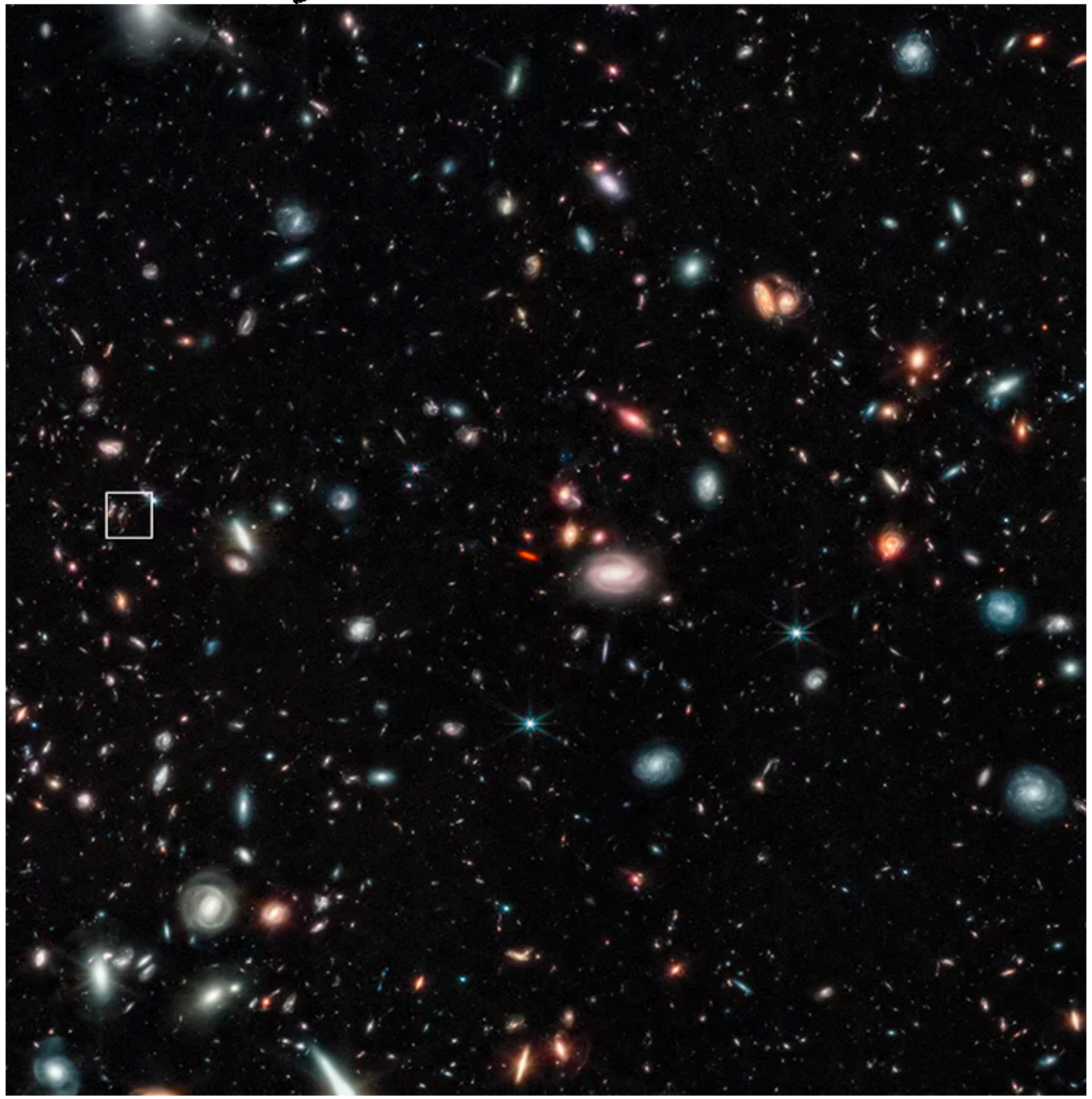
A series of cosmological simulations of LCDM

Planck 2018 Cosmology

Name	Lbox [Mpc/h]	Mp [1d8Msun/h]	np	snapnums	code
Hyper-Millennium	2500	3.2	16128^3	100	PhontoNs
Jiutian-1Gpc	1000	3.7	6144^3	128	Gadget
Jiutian-300M	300	0.1	6144^3	128	Gadget
Hyper-test	125	3.7	768^3	33;65;129; 257;513	Gadget

Mind the gap: from "Dark" to "Bright"

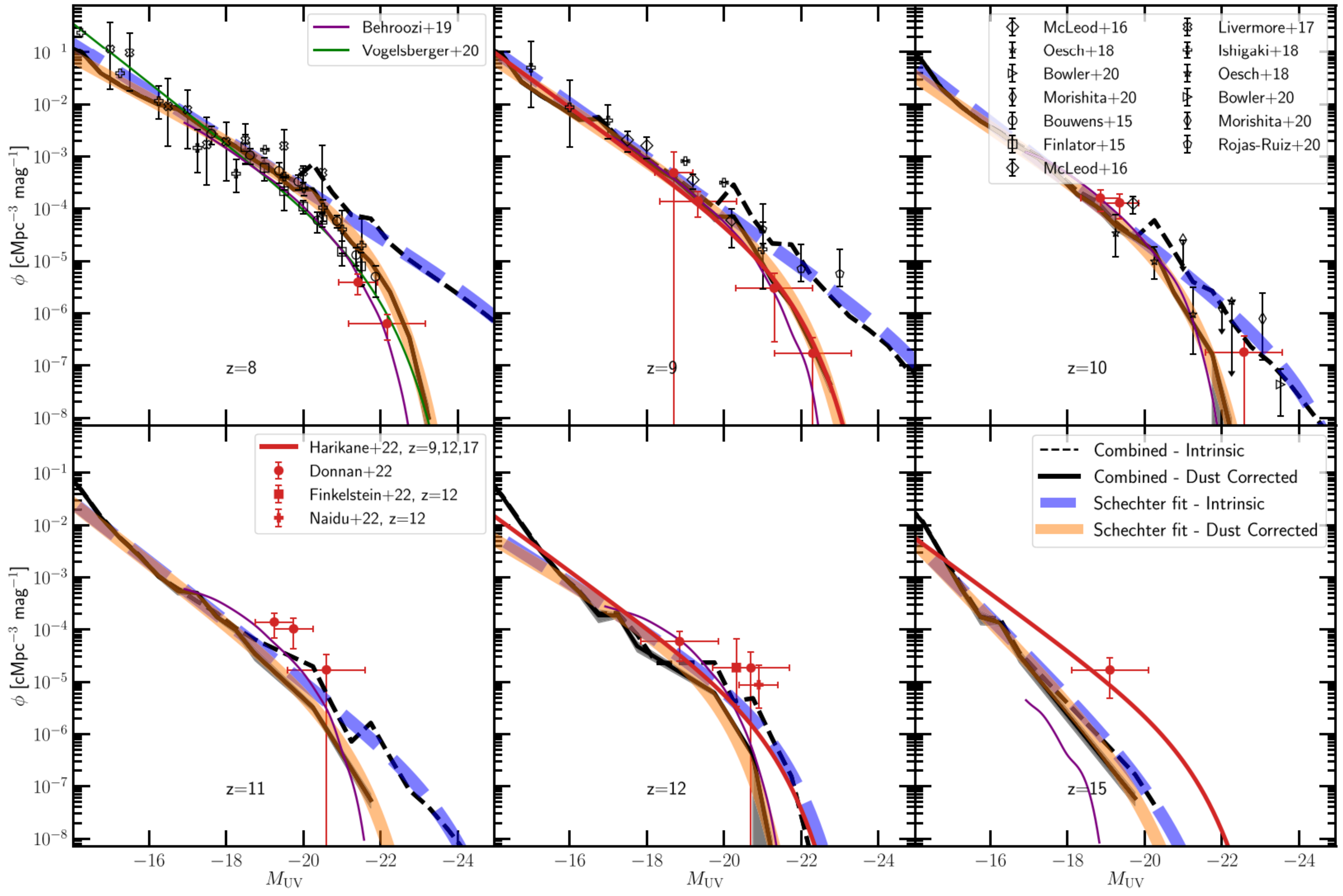




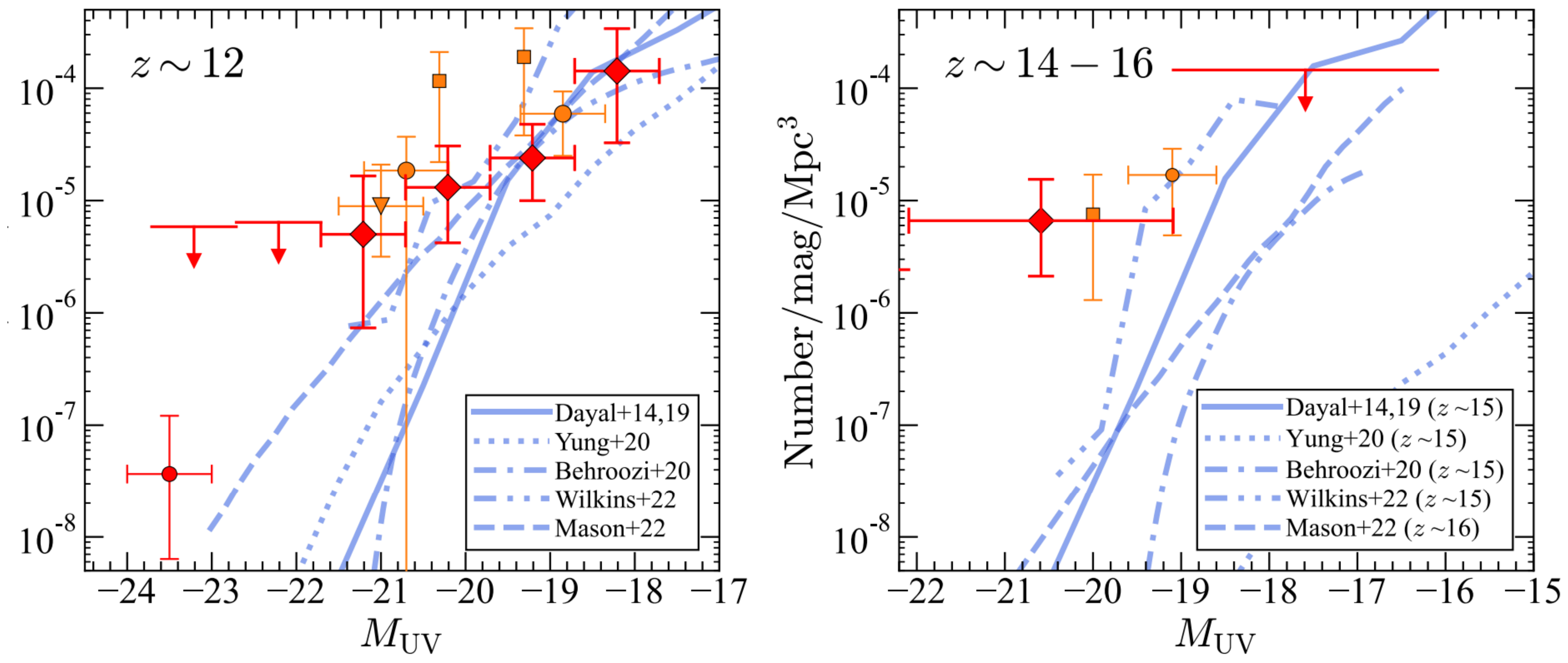
Simple model:

match the halo growth rate to SFR

Abundance of high-z luminous galaxies in the JWST era



MillenniumTNG Kannan+2023



Harikane+2023

Too many luminous galaxies at high-z

Top heavy IMF?

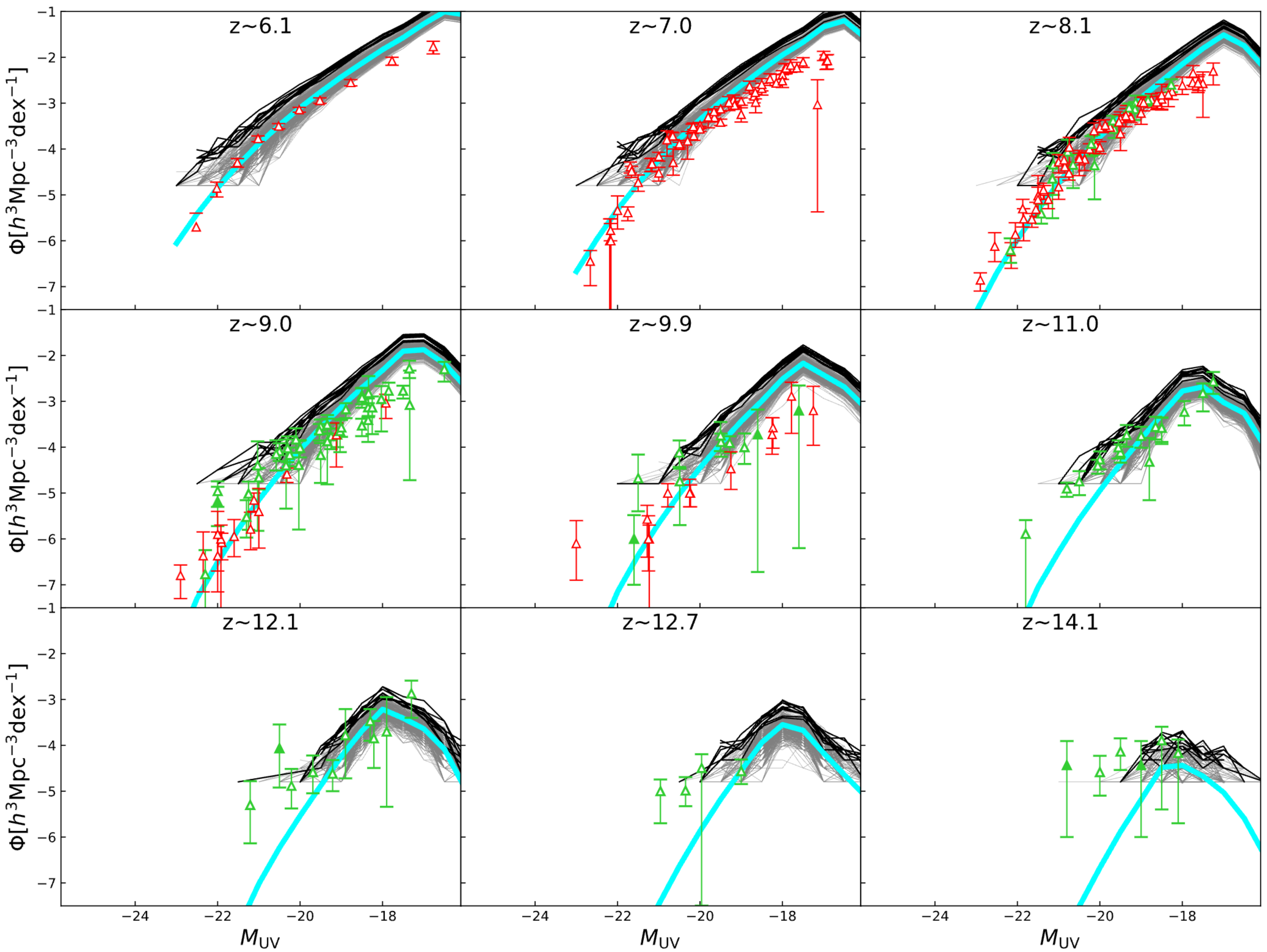
dust?

Feedback?

High star formation efficiency?

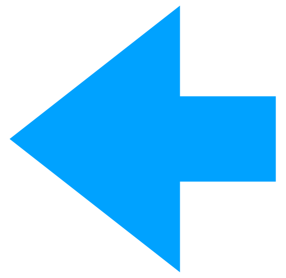
COSMIC VARIANCE

Preliminary



sub box 50Mpc each sided

$$\mathrm{SFR} = \epsilon \dot{\mathrm{M}}_\mathrm{b} = \epsilon \mathrm{f}_\mathrm{b} \dot{\mathrm{M}}_\mathrm{h}$$



$$\epsilon = 0.05$$

Pei et al. in prep

The blue solid line represents the UVLF of the entire box, while the grey solid line corresponds to the UVLF of each individual sub-box. We stress highest 10 sub-boxes UVLF by black lines to show the most extremely case in each redshift.

Semi-analytical galaxy formation models

$$\dot{M}_{\rm BH} = \kappa \left(\frac{f_{\rm hot}}{0.1}\right) \left(\frac{V_{\rm vir}}{200kms^{-1}}\right)^3 \left(\frac{M_{\rm BH}}{10^8/hM_\odot}\right) M_\odot/{\rm yr}.$$

$$\delta M_{\rm reheat} = \epsilon_{\rm disk} \times \delta M_*$$

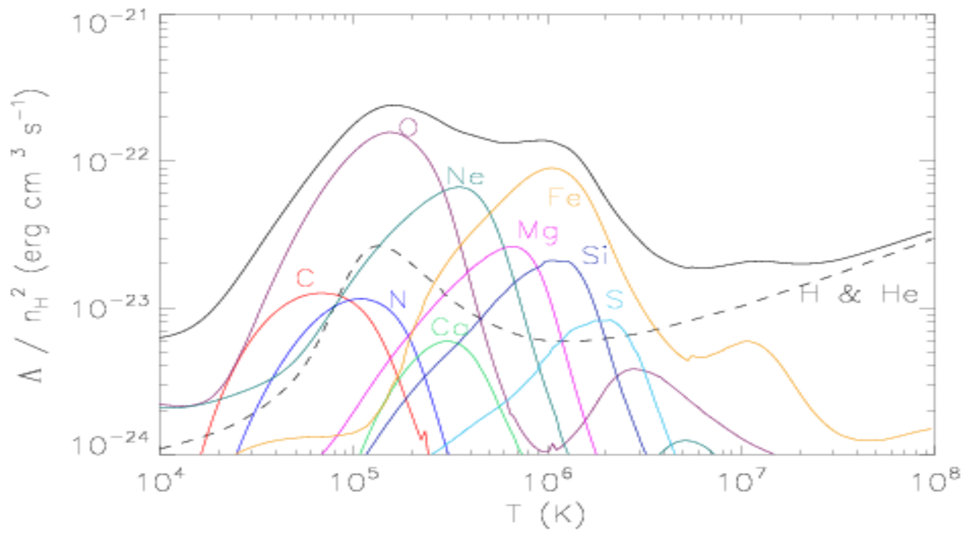
$$\delta E_{\rm SN} = \epsilon_{\rm halo} \times \frac{1}{2}\delta M_* V_{\rm SN}^2$$

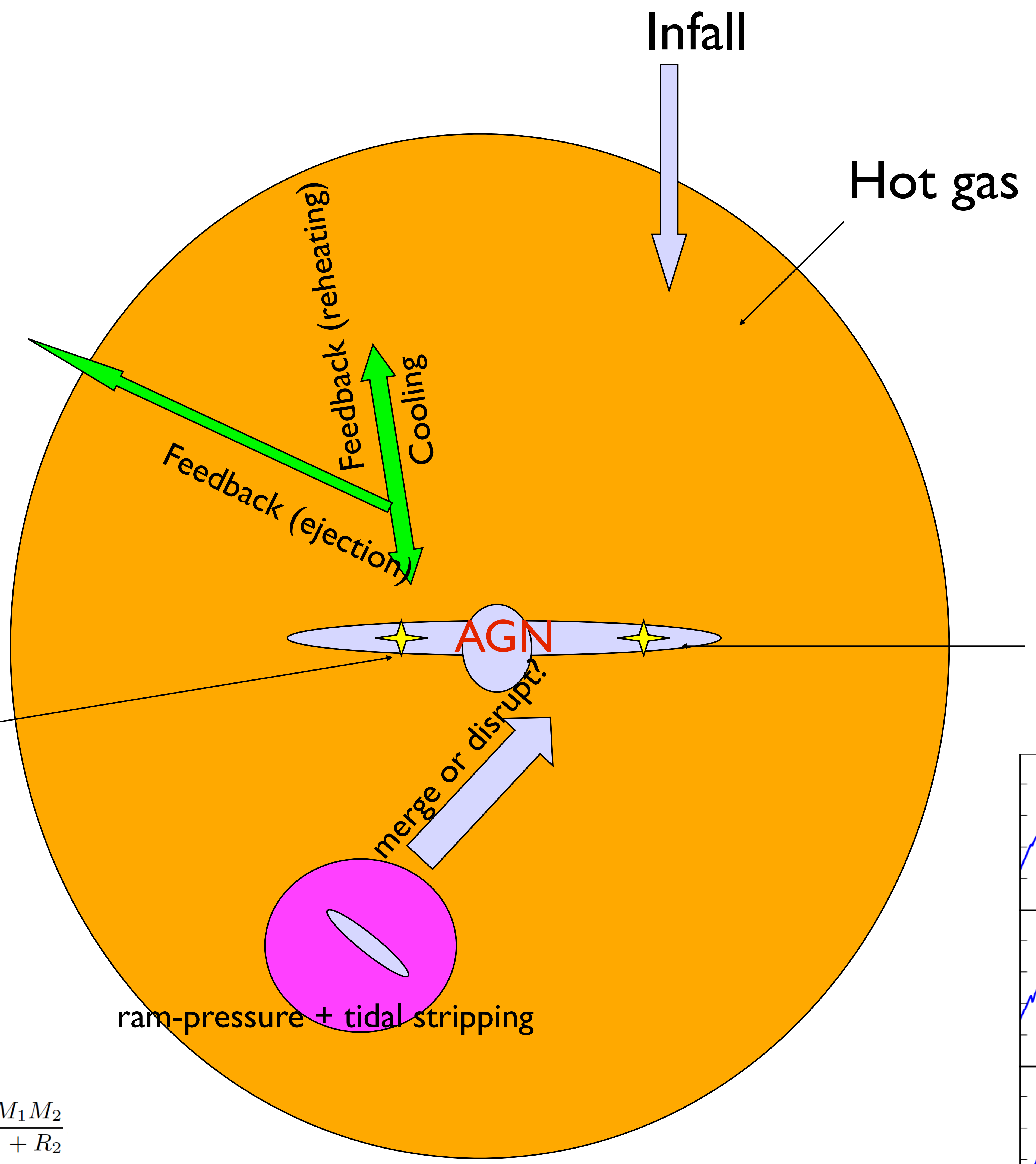
$$\epsilon_{\rm halo} = \eta \times \left[0.5 + \left(\frac{V_{\rm max}}{70{\rm km/s}}\right)^{-\beta_2}\right]$$

$$\delta M_{\rm ejec} = \frac{\delta E_{\rm SN} - \frac{1}{2}\delta M_{\rm reheat} V_{\rm vir}^2}{\frac{1}{2}V_{\rm vir}^2}$$

$$\dot{E}_{\rm radio} = 0.1 \dot{M}_{\rm BH} c^2$$

$$t_{\rm cool}(r) = \frac{3\mu m_{\rm H} k T_{\rm vir}}{2\rho_{\rm hot}(r)\Lambda(T_{\rm hot}, Z_{\rm hot})}$$





$$\dot{M}_* = \alpha(M_{\rm gas} - M_{\rm crit})/t_{\rm dyn}$$

[Z/H]	L_U	L_B	L_V	L_R	L_I	L_J	L_H	L_K	D4000	CaT*	Mg_2	Mgb	⟨Fe⟩	Hβ	$H\delta_A$	$H\gamma_A$	$H\delta_F$	$H\gamma_F$
−0.33	60	38	−8	−30	−41	−52	−56	−55	−21	−8	−6	−17	−19	77	5	2.9	6.4	3.35
0.00	58	38	5	−8	−15	−24	−26	−26	−25	−3	−7	−15	−13	61	4.8	2.4	5.7	2.9
0.35	70	47	12	−4	−12	−26	−31	−32	−25	−2	−12	−18	−14	73	5.7	2.6	6.3	3.1

Star formation and evolution

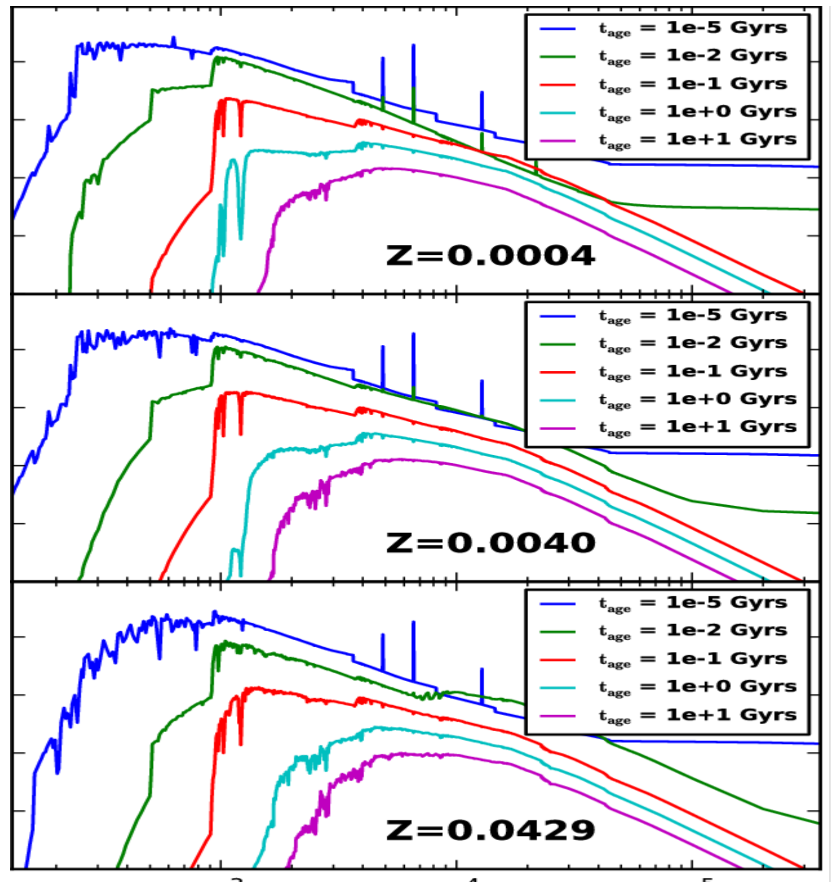
$$\delta\vec{J}_{\rm gas,cooling} = \dot{M}_{\rm cool}\frac{\vec{J}_{\rm DM}}{M_{\rm DM}}\delta t$$

$$\Delta\vec{J}_{\rm gas} = \delta\vec{J}_{\rm gas,cooling} + \delta\vec{J}_{\rm gas,acc} + \delta\vec{J}_{\rm gas,SF}$$

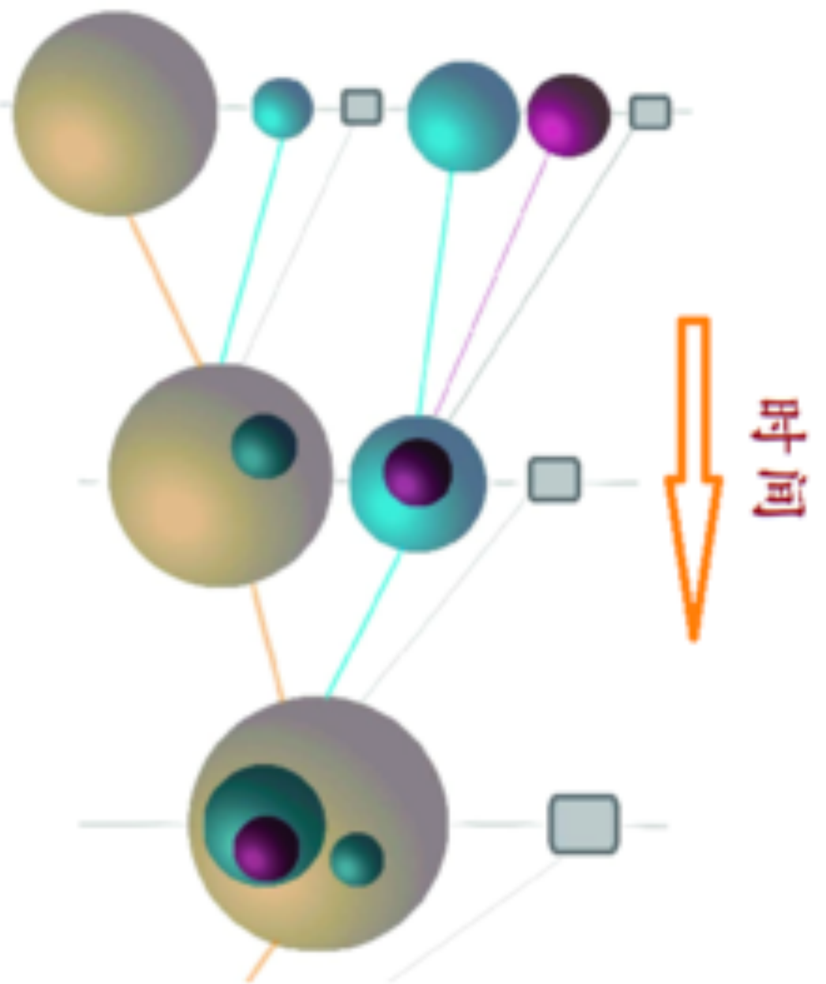
$$R_{\rm gas,d} = \frac{J_{\rm gas}/M_{\rm gas}}{2V_{\rm max}}$$

disk formation

$$\Sigma_{\rm crit}(R) = 12 \times \left(\frac{V_{\rm max}}{200{\rm km/s}}\right)\left(\frac{R}{10{\rm kpc}}\right)^{-1} M_\odot{\rm pc}^{-2}$$



暗物质晕的逐级形成过程



$$e_{\rm burst} = 0.56\left(\frac{M_{\rm minor}}{M_{\rm major}}\right)^{0.7}$$

$$t_{\rm friction} = \alpha_{\rm fric}\frac{V_{\rm vir} r_{\rm sat}^2}{G m_{\rm sat} \ln\Lambda}$$

$$R_{\rm strip} = min(R_{\rm tidal}, R_{\rm r.p.})$$

$$\left(\frac{R}{R_{\rm peri}}\right)^2 = \frac{\ln R/R_{\rm peri} + \frac{1}{2}(V/V_{\rm vir})^2}{\frac{1}{2}(V_t/V_{\rm vir})^2}$$

$$C\frac{GM_{\rm new,bulge}^2}{R_{\rm new,bulge}} = C\frac{GM_1^2}{R_1} + C\frac{GM_2^2}{R_2} + \alpha_{\rm inter}\frac{GM_1M_2}{R_1+R_2}$$

$$\delta M_\star = 2\pi\Sigma_{\star 0}R_{\star,\rm d}[R_{\star,\rm d} - (R_{\rm b} + R_{\star,\rm d})\exp(-R_{\rm b}/R_{\star,\rm d})].$$

物理量	数据类型	单位	说明
GalID	int64		星系ID
HaloID	int64		包含该星系的子暗晕的haloId
FirstProgGal	int64		该星系的首个祖先星系的galaxyId。如果lastProgenitorId > galaxyId，则为galaxyId+1，否则为-1。
NextProgGal	int64		该星系下一个的星系ID
LastProgGal	int64		该星系最后一个祖先星系ID
FOFCentralGal	int64		该星系所在FOF团的中心星系的ID
CentralGal	int64		该星系的并合中心星系的ID
FileTreeNr	int64		包含该星系的星系并合树的唯一编号
DescendantGal	int64		该星系在并合树中的后代星系的ID
MainLeafId	int64		沿主分支可达的最末端星系的ID
TreeRootId	int64		包含该星系的并合树的根节点星系的ID
SubID	int64		包含该星系的子暗晕的ID
MMSubID	int64		包含该星系的FOF团中心的子暗晕的ID
PeanoKey	int32		该星系所在的256^3网格单元的Peano-Hilbert索引。
Redshift	float32		与snapnum对应的红移
Type	int32		标识星系是否为FOF团中心（type=0），非FOF团中心的子暗晕中心（type=1），或已失去子暗晕的卫星（type
SnapNum	int32		该星系被识别时的快照编号。
LookBackTimeToSnap	float32		从z=0到该星系红移的回顾时间
CentralMvir	float32	10^10 Msun/h	该星系所在FOF团的中心星系的维里质量
CentralRvir	float32	Mpc/h	该星系所在FOF团的中心星系的维里半径
DistanceToCentralGal	('<f4', (3,))	Mpc/h	该星系与其FOF团中心星系之间距离
Pos	('<f4', (3,))	Mpc/h	星系的位置
Vel	('<f4', (3,))	km/s	星系的速度
Len	int32		包含该星系的子暗晕的粒子数量
Mvir	float32	10^10 Msun/h	当该星系最后为type=0类型时其所在FOF团的维里质量。
Rvir	float32	Mpc/h	当该星系最后为type=0类型时其所在FOF团的维里半径。
Vvir	float32	km/s	当该星系最后为type=0类型时其所在FOF团的维里速度。
Vmax	float32	km/s	星系子暗晕的最大旋转速度。
GasSpin	('<f4', (3,))	Mpc/h km/s	冷气体盘自旋
StellarSpin	('<f4', (3,))	Mpc/h km/s	恒星盘自旋
InfallVmax	float32	km/s	吸积时母暗晕的最大旋转速度。
InfallVmaxPeak	float32	km/s	星系历史上母暗晕的最大旋转速度。
InfallSnap	int32		星系从type 0转为type 1或2时的最新快照编号
InfallHotGas	float32	10^10 Msun/h	星系吸积时的热气体质量
HotRadius	float32	Mpc/h	热气体延伸的半径
OriMergTime	float32	yr	设置并合时钟时估算的动力学摩擦时间
MergTime	float32	yr	估算的剩余并合时间
ColdGas	float32	10^10 Msun/h	冷气体盘中的气体质量
StellarMass	float32	10^10 Msun/h	星系中恒星的总质量
BulgeMass	float32	10^10 Msun/h	星系核球中恒星的质量
DiskMass	float32	10^10 Msun/h	星系盘中恒星的质量
HotGas	float32	10^10 Msun/h	热气体的质量
EjectedMass	float32	10^10 Msun/h	被喷出的气体质量
BlackHoleMass	float32	10^10 Msun/h	中央黑洞的质量
ICM	float32	10^10 Msun/h	星系团中弥散恒星的质量
MetalsColdGas	float32	10^10 Msun/h	冷气体盘中的金属质量
MetalsStellarMass	float32	10^10 Msun/h	恒星中金属质量总和
MetalsBulgeMass	float32	10^10 Msun/h	核球恒星中的金属质量
MetalsDiskMass	float32	10^10 Msun/h	盘中恒星的金属质量
MetalsHotGas	float32	10^10 Msun/h	热气体中的金属质量
MetalsEjectedMass	float32	10^10 Msun/h	喷出气体中的金属质量
MetalsICM	float32	10^10 Msun/h	星系团弥散恒星中的金属质量
PrimordialAccretionRate	float32	Msun/yr	原初气体的吸积率
CoolingRadius	float32	Mpc/h	冷却半径
CoolingRate	float32	Msun/yr	冷却速率
CoolingRate_beforeAGN	float32	Msun/yr	若无AGN反馈时的冷却速率
QuasarAccretionRate	float32	Msun/yr	quasar mode冷气体吸积进黑洞的速率
RadioAccretionRate	float32	Msun/yr	radio mode热气体吸积进黑洞的速率
Sfr	float32	Msun/yr	恒星形成率
SfrBulge	float32	Msun/yr	核球中的恒星形成率
XrayLum	float32	log10(erg/sec)	X射线波段的光度
BulgeSize	float32	Mpc/h	核球的半质量半径
StellarDiskRadius	float32	Mpc/h	恒星盘的大小
GasDiskRadius	float32	Mpc/h	气体盘的大小
CosInclination	float32		星系的倾角
DisruptOn	int32		潮汐瓦解标识
MergeOn	int32		并合标识
MagDust	('<f4', (10,))		考虑尘埃消光的星等
Mag	('<f4', (10,))		星等
MagBulge	('<f4', (10,))		核球星等
ObsMagDust	('<f4', (10,))		观测者坐标系下考虑尘埃消光的星等
ObsMag	('<f4', (10,))		观测者坐标系下星等
ObsMagBulge	('<f4', (10,))		观测者坐标系下核球星等
MassWeightAge	float32	10^9 yr	星系的质量加权年龄
rbandWeightAge	float32	10^9 yr	星系的r波段光度加权年龄
sfh_ibin	int32		当前使用的最高恒星形成历史区间索引
sfh_numbins	int32		非空的恒星形成历史区间数量
sfh_DiskMass	('<f4', (22,))	10^10 Msun/h	星系盘中恒星形成历史
sfh_BulgeMass	('<f4', (22,))	10^10 Msun/h	星系核球中恒星形成历史
sfh_ICM	('<f4', (22,))	10^10 Msun/h	星系团弥散恒星中恒星形成历史
sfh_MetalsDiskMass	('<f4', (22,))	10^10 Msun/h	星系盘中金属形成历史
sfh_MetalsBulgeMass	('<f4', (22,))	10^10 Msun/h	星系核球中金属形成历史
sfh_MetalsICM	('<f4', (22,))	10^10 Msun/h	星系团弥散恒星中金属形成历史

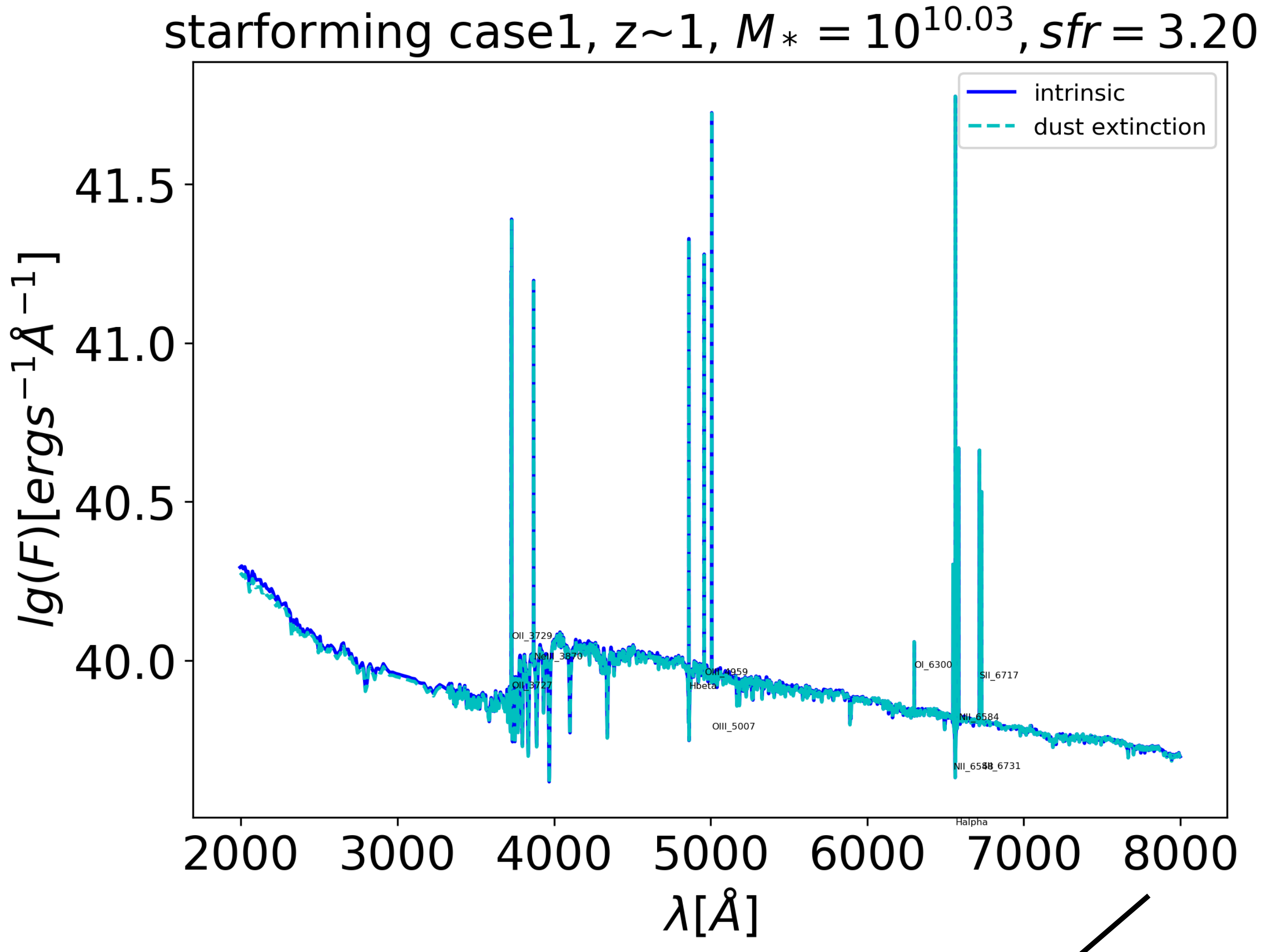
Semi-analytic galaxy catalogs

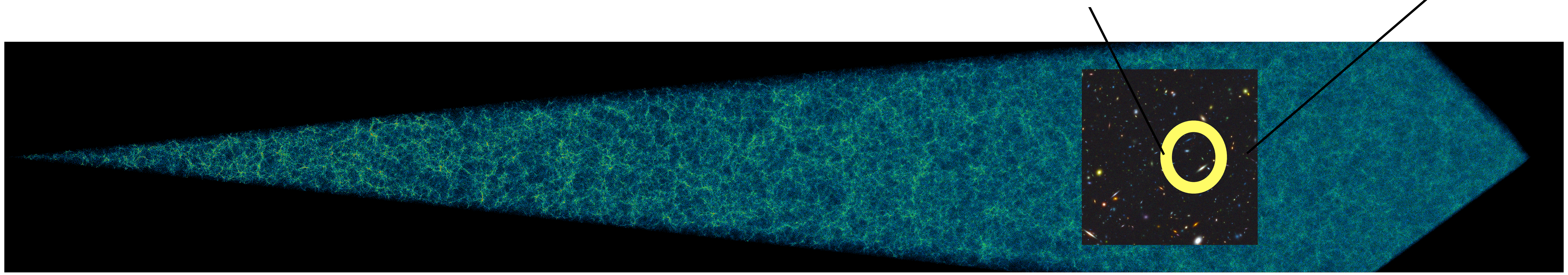
裴文祥

Simulated galaxies properties:

Physical properties, e.g. mass, metallicity, sfr and etc

observables: luminosities in various bands, emission lines…



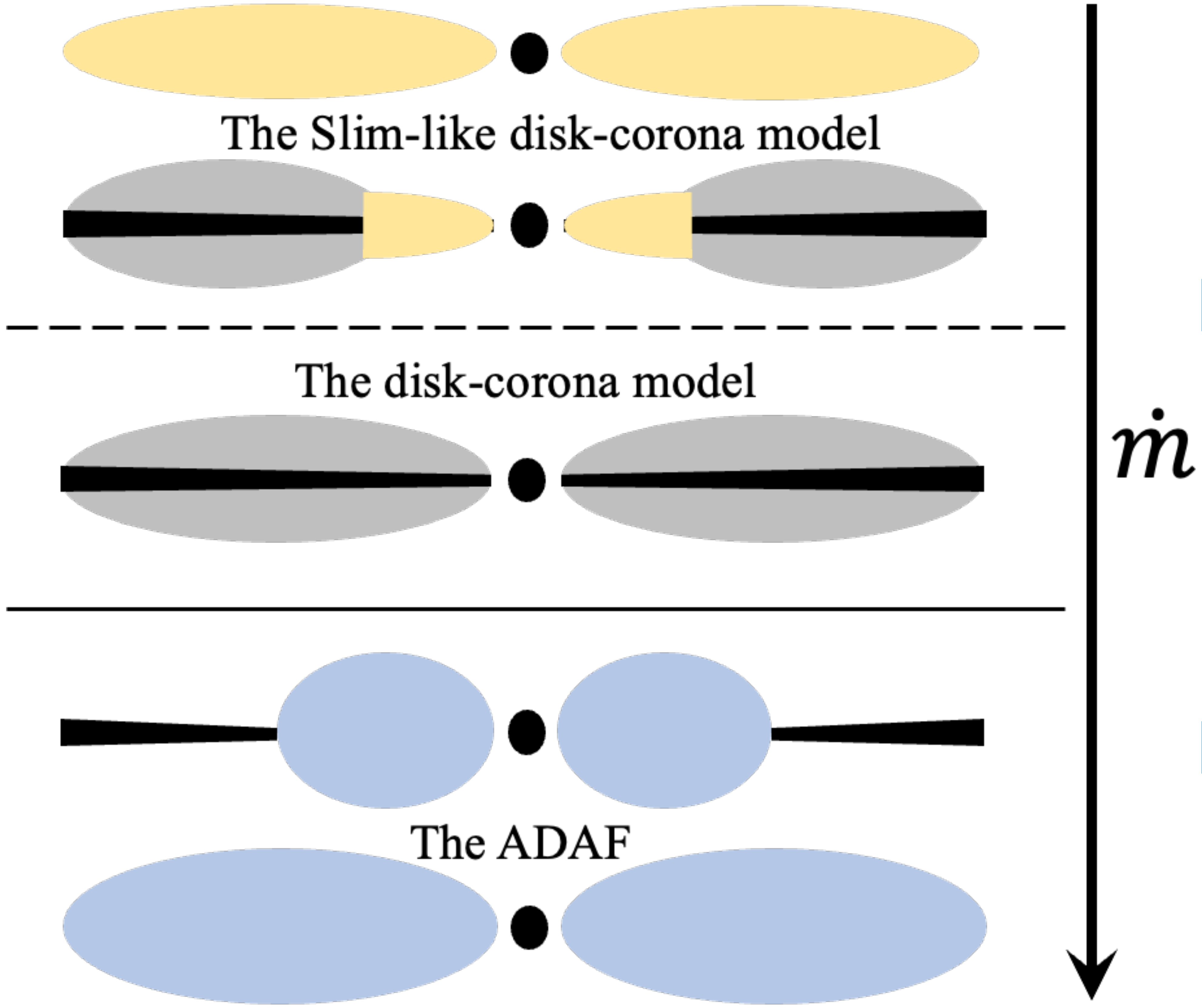


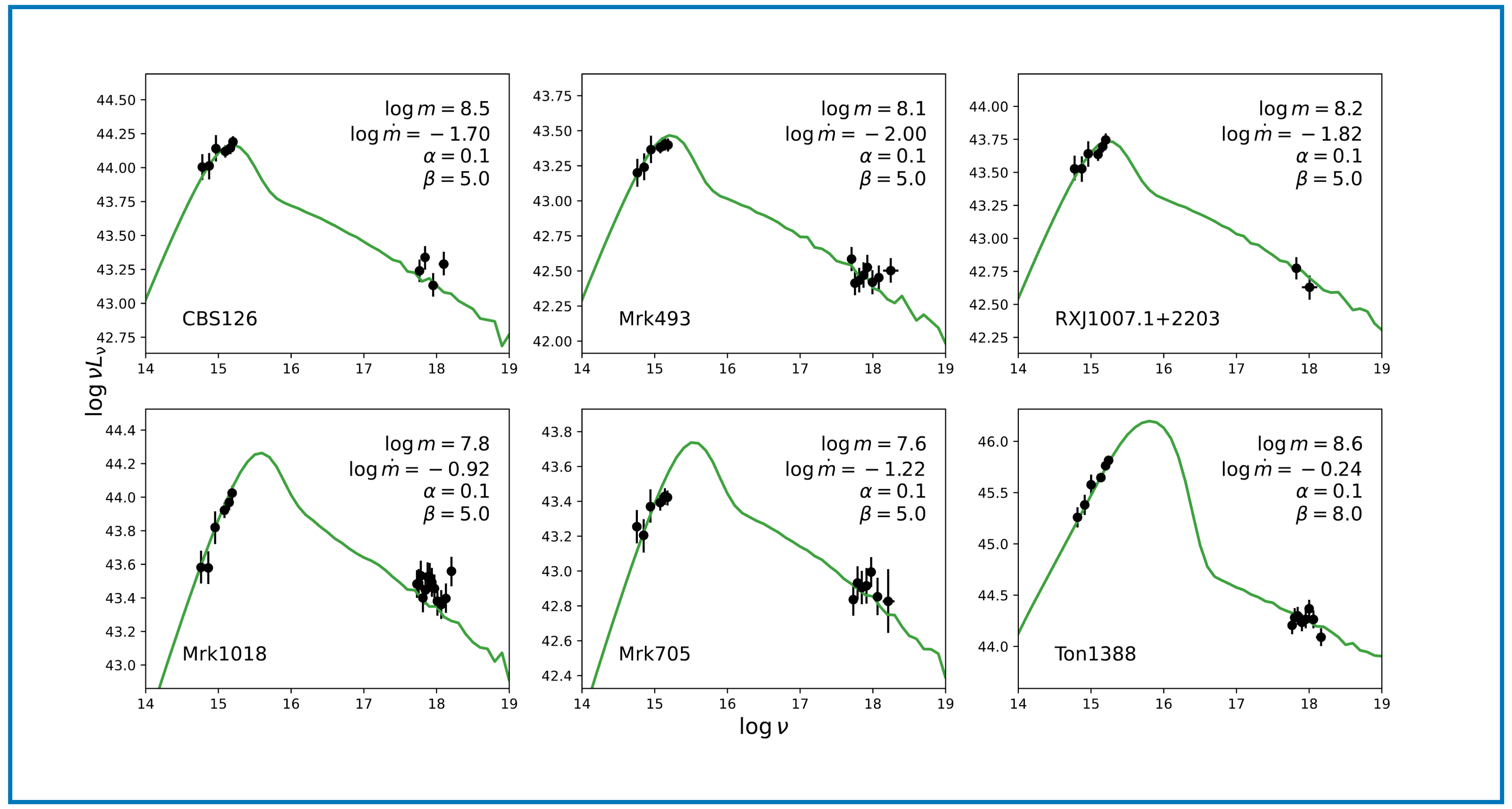
Semi-analytic galaxy catalogue —AGNs

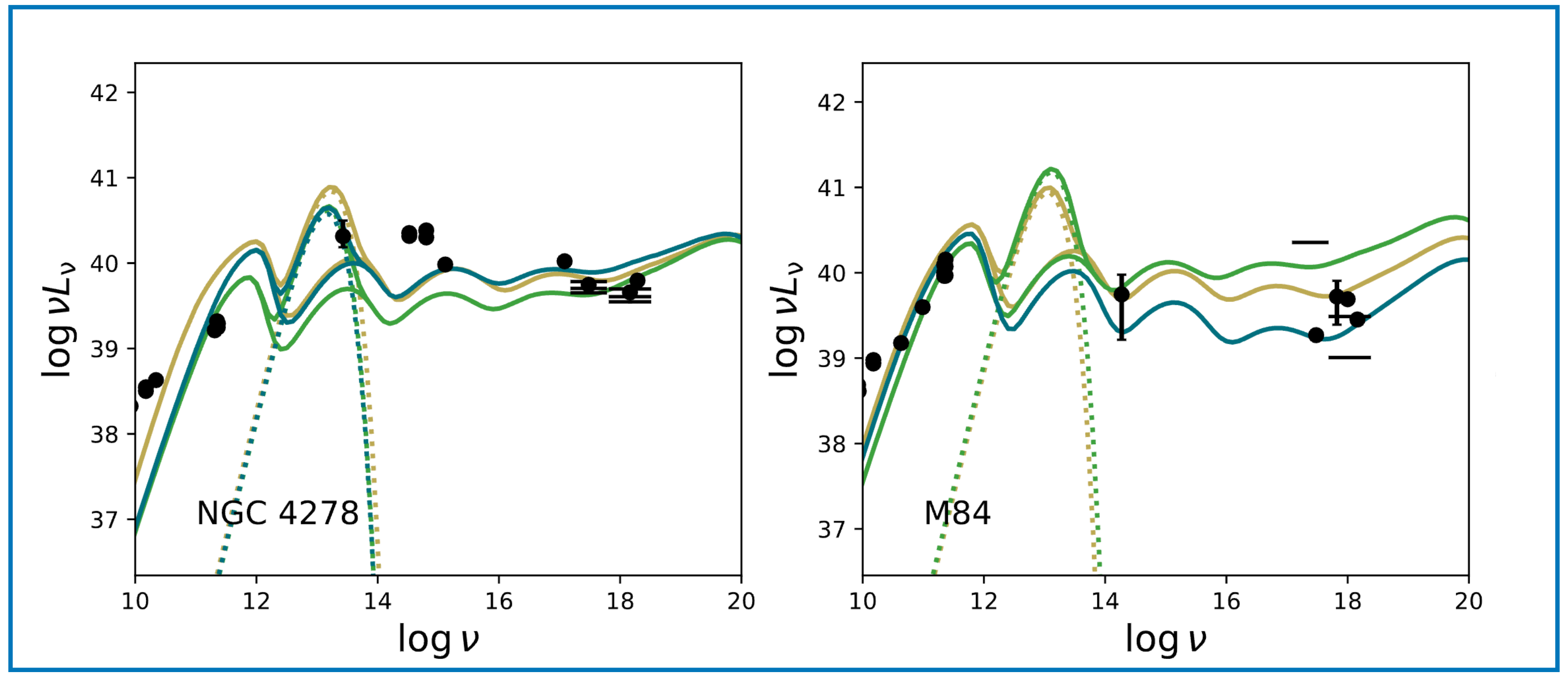
Too simple assumptions in many previous cosmological simulations

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

Su+ in prep

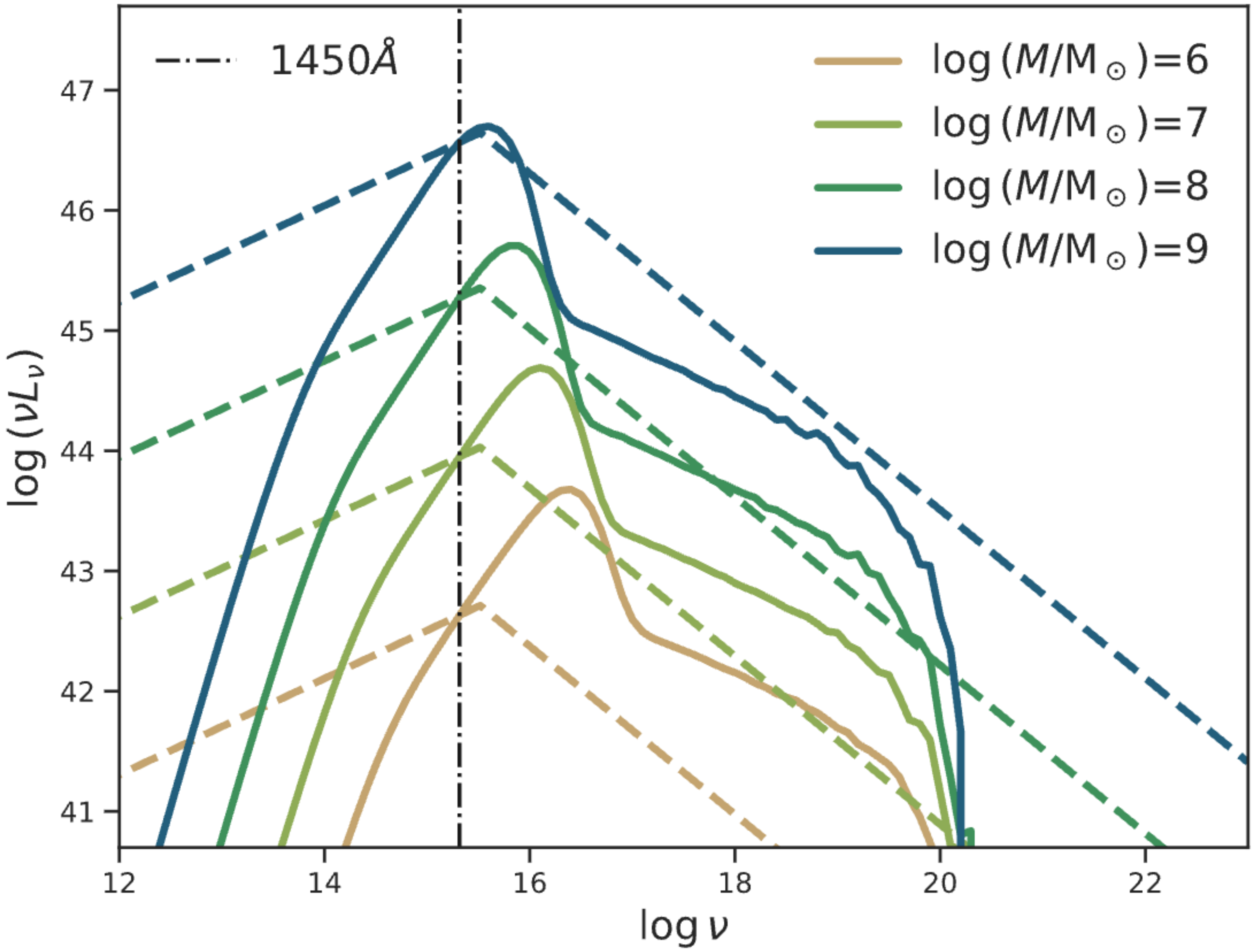




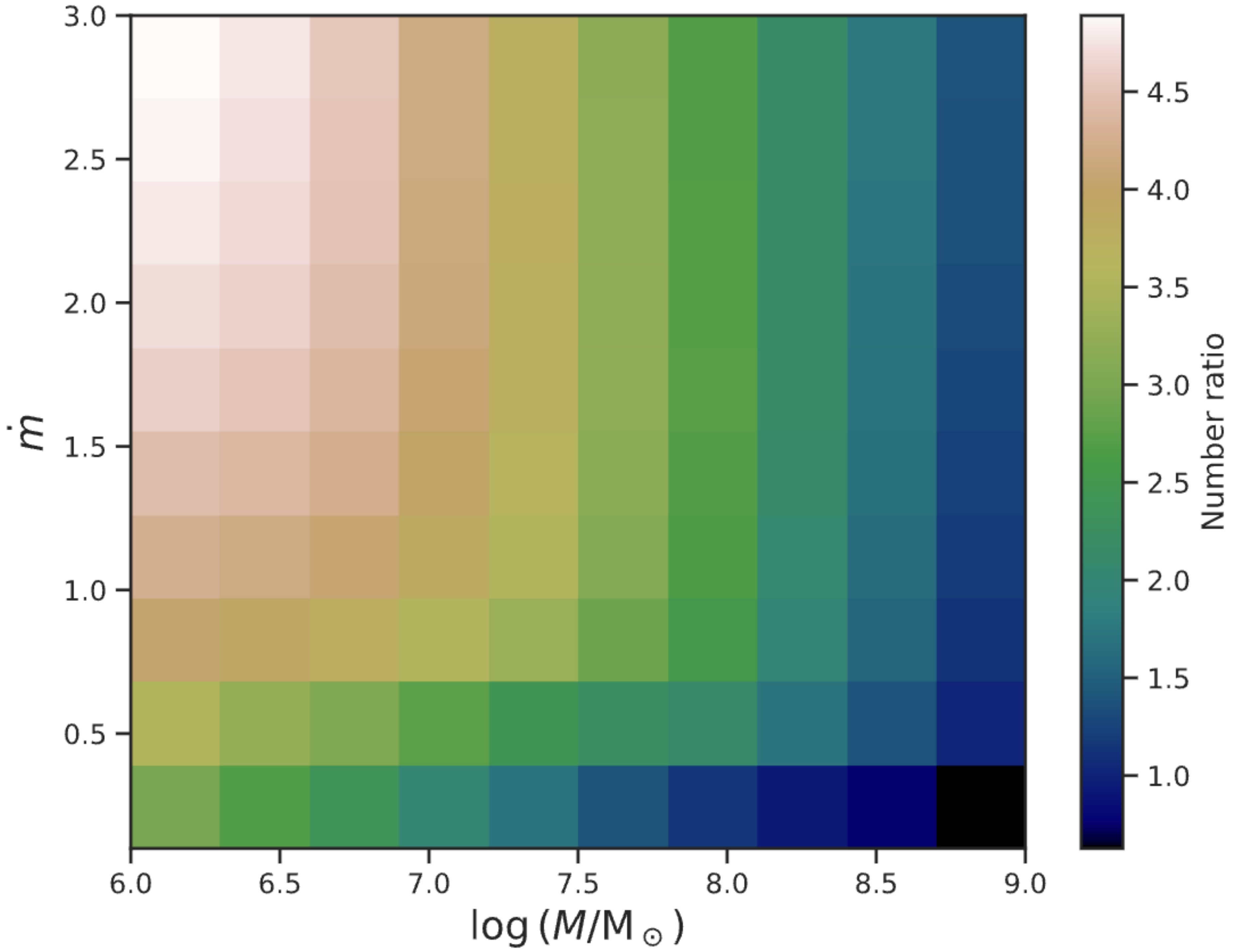


AGN's role in reionization

broken power-law model vs. the disk-corona mode

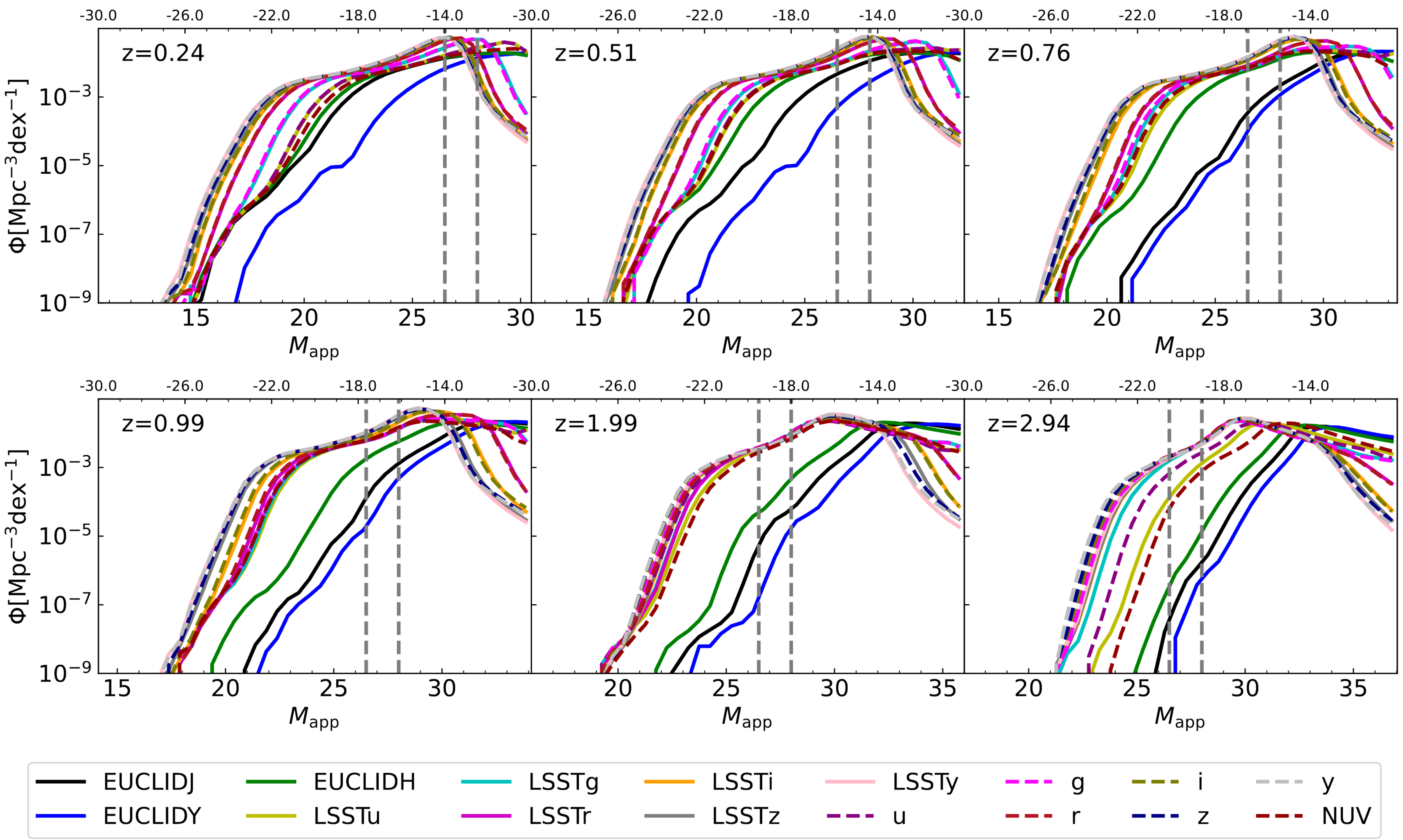


$\dot{n}_{ion,diskcor}/\dot{n}_{ion,PL}$



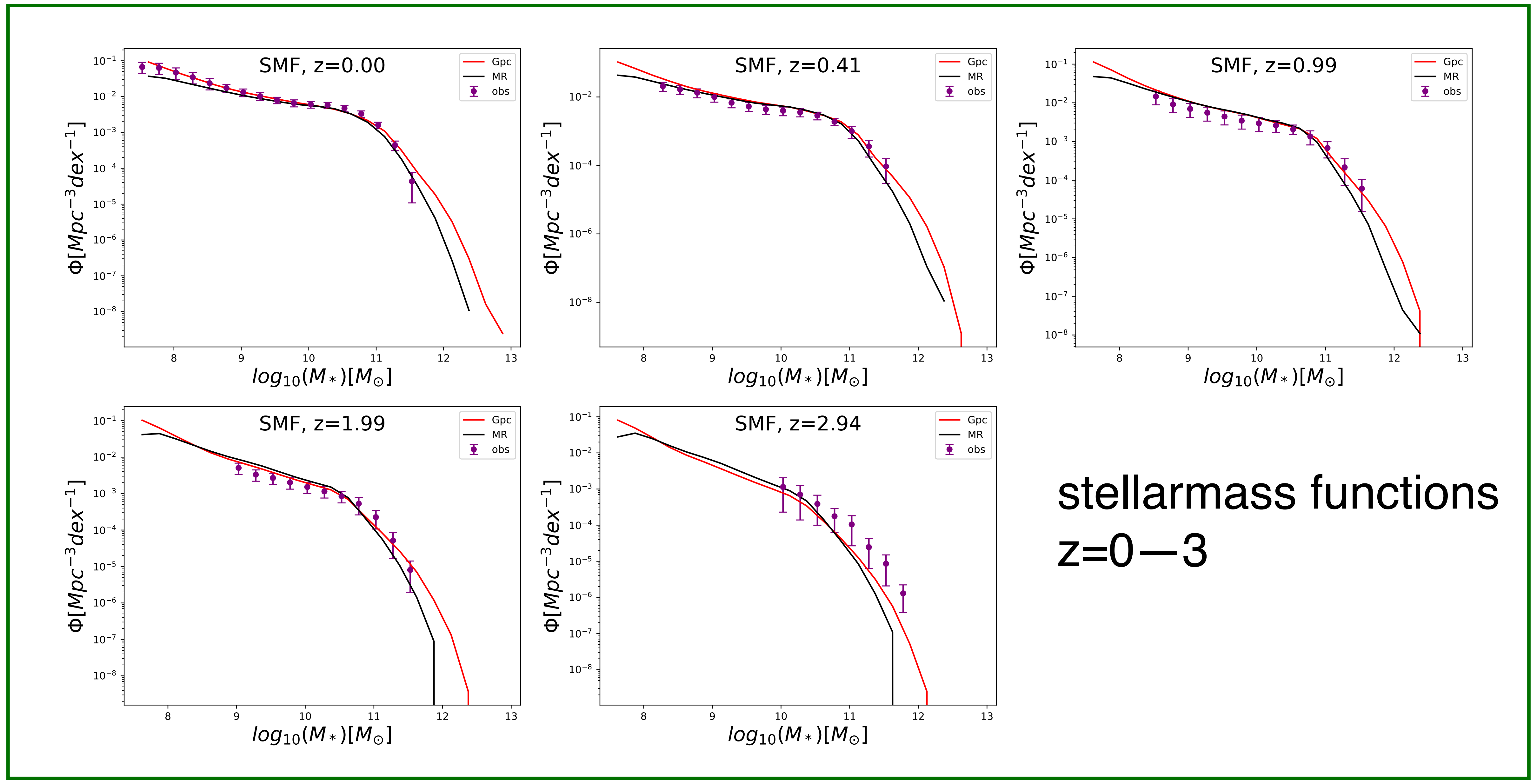
Su, Guo et al. submitted

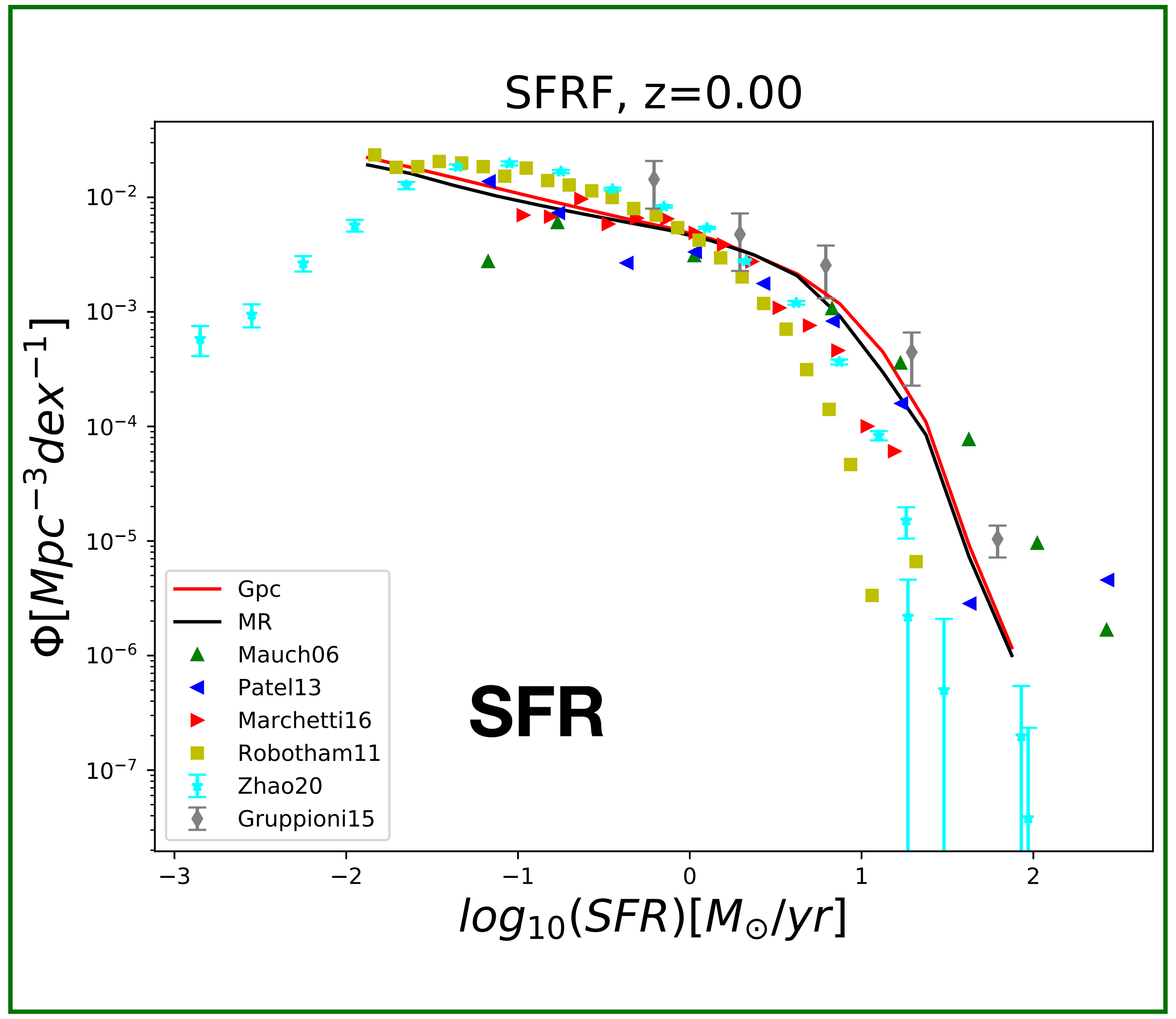
The new catalogue meet the resolution requirement for the next generation of large-scale surveys

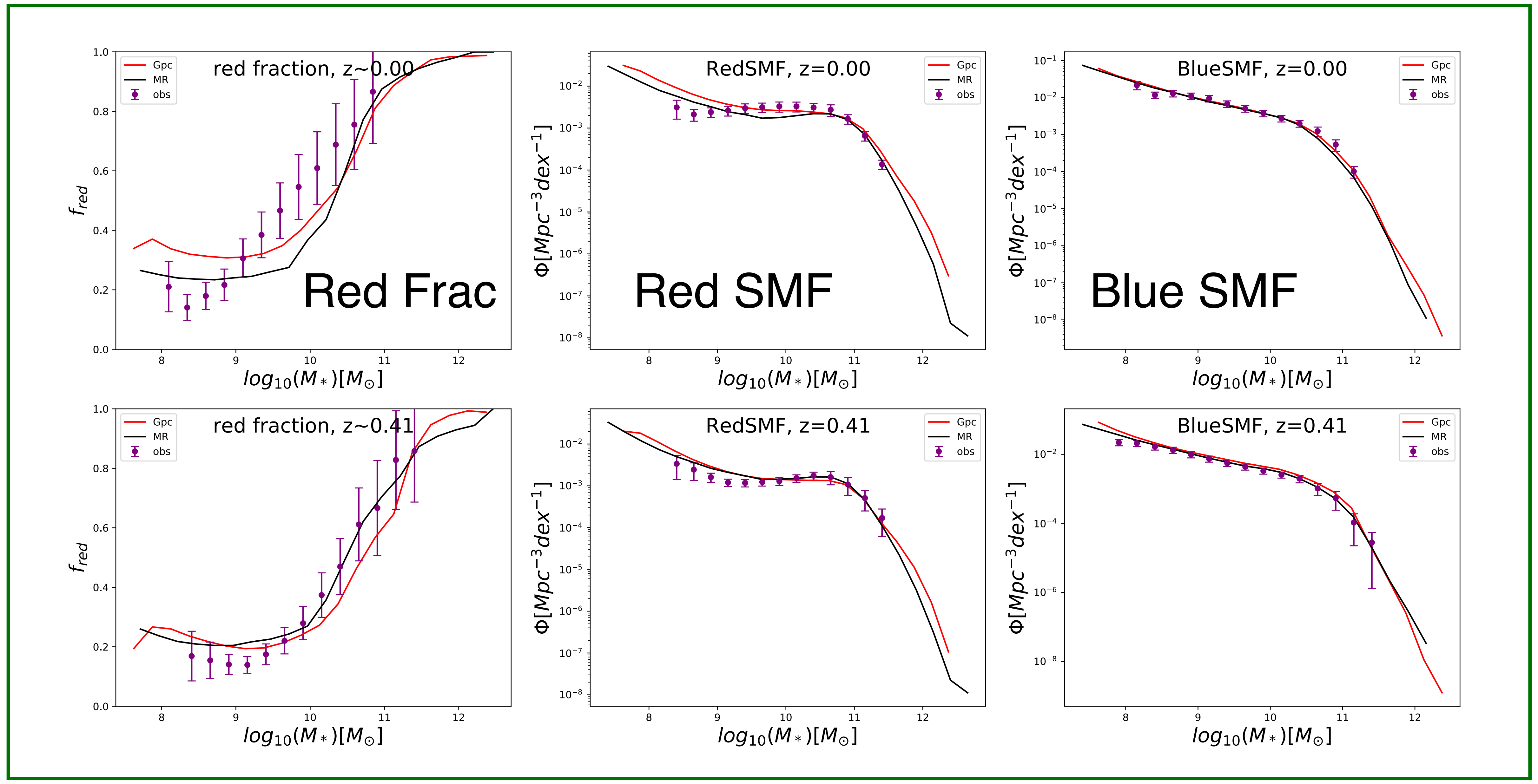


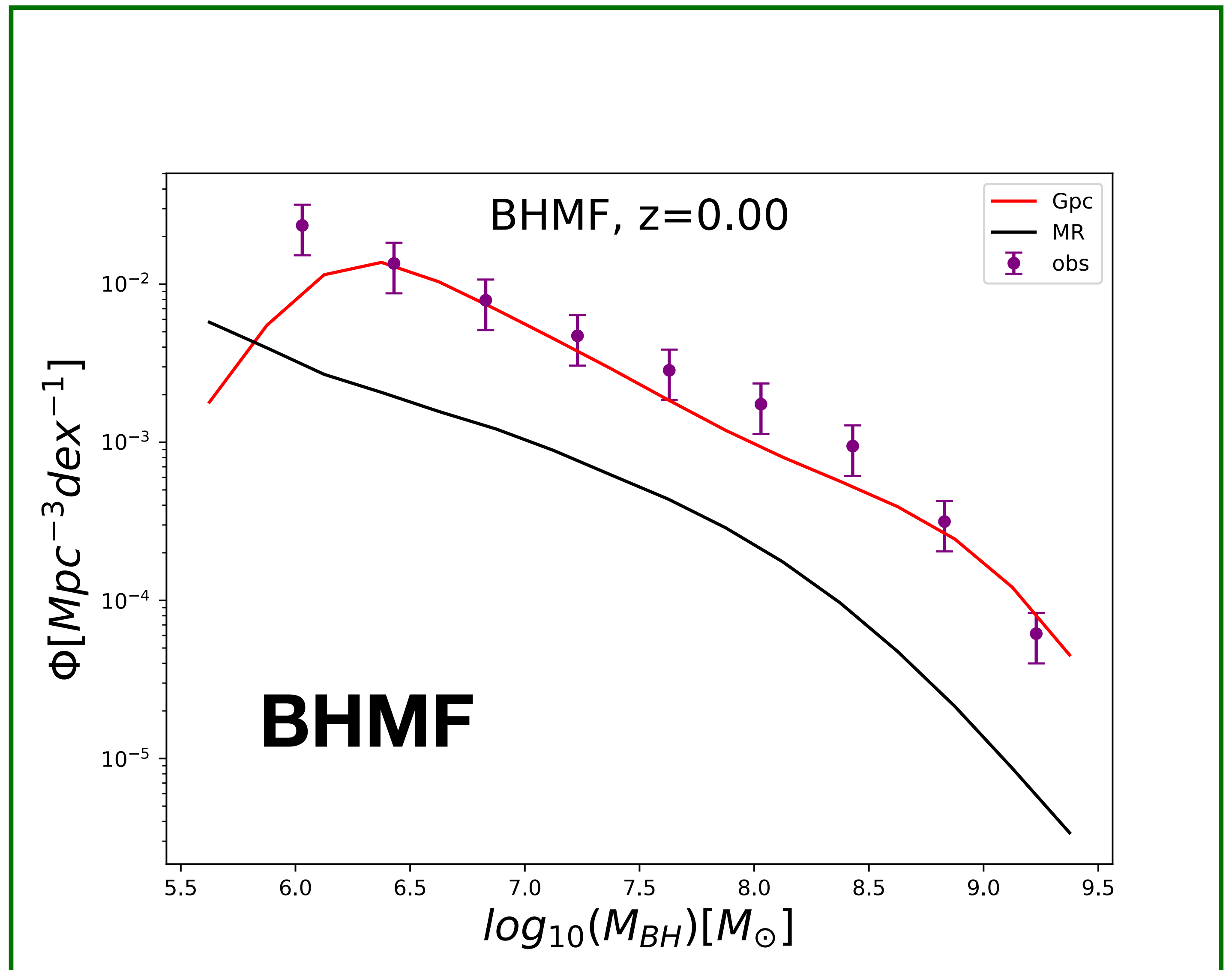
Pei, Guo et al.(2024)

Reproduce many galaxy properties



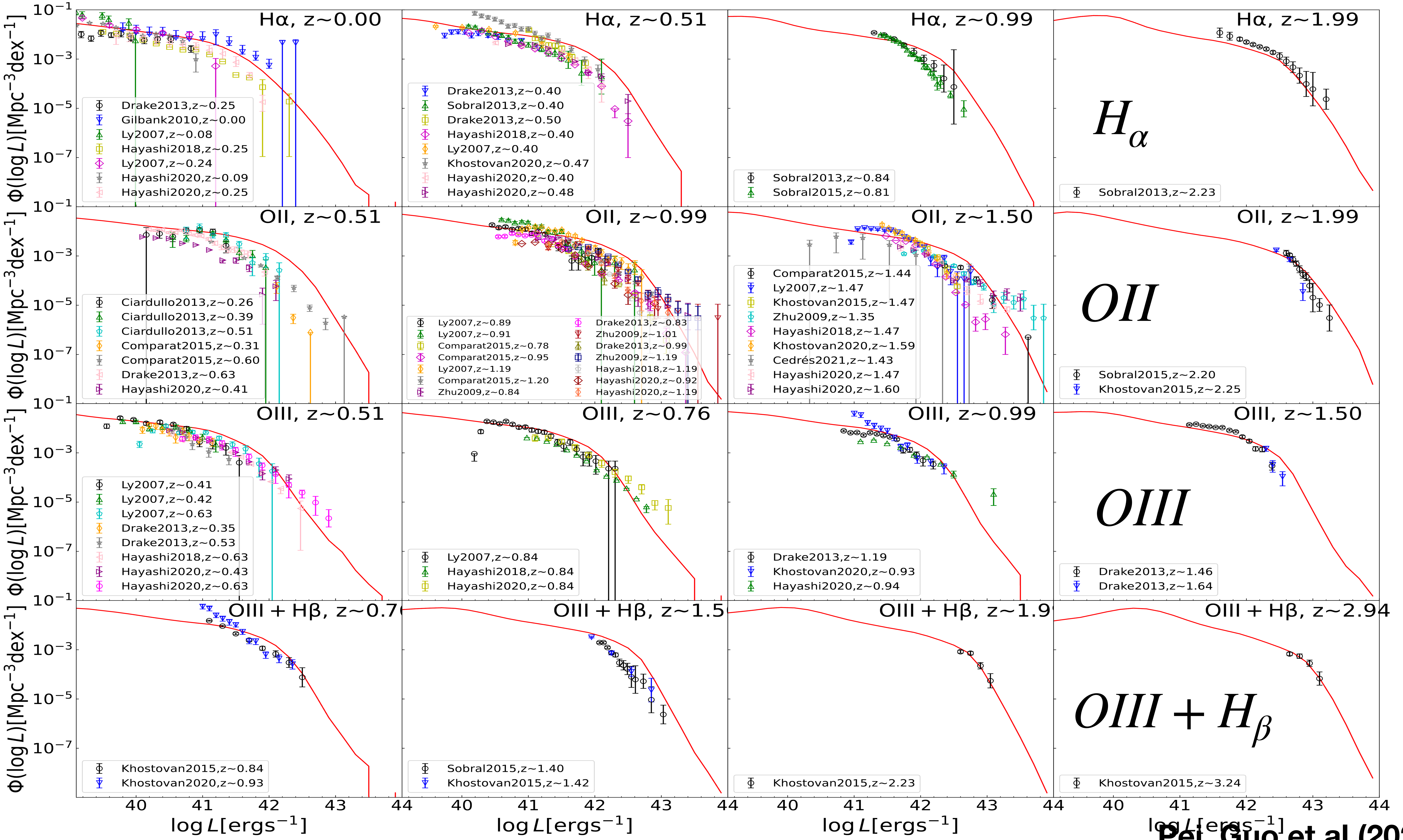






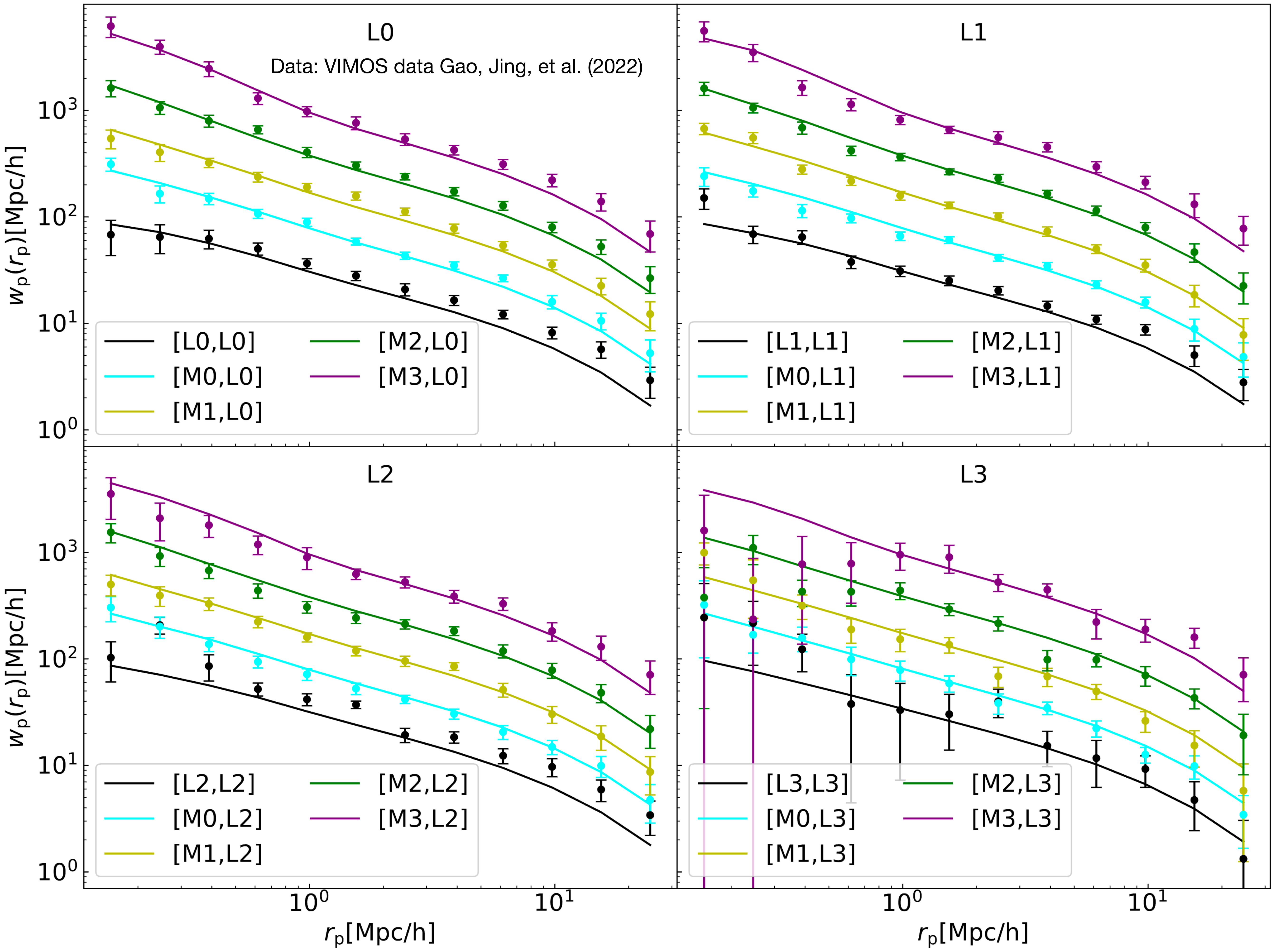
Pei, Guo et al.(2024)

Emission line luminosity functions



Pei, Guo et al.(2024)

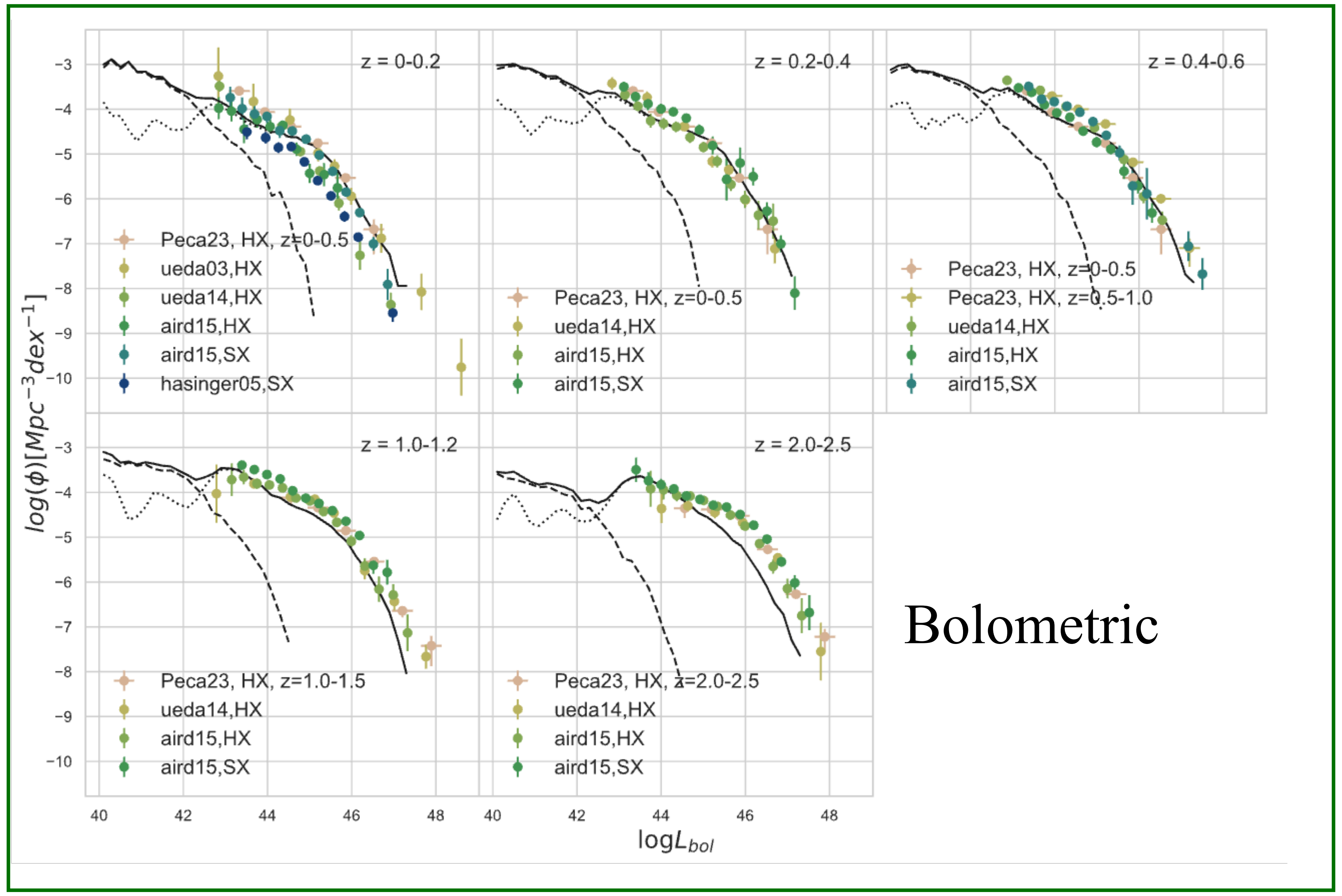
OII-selected Galaxy Correlation functions

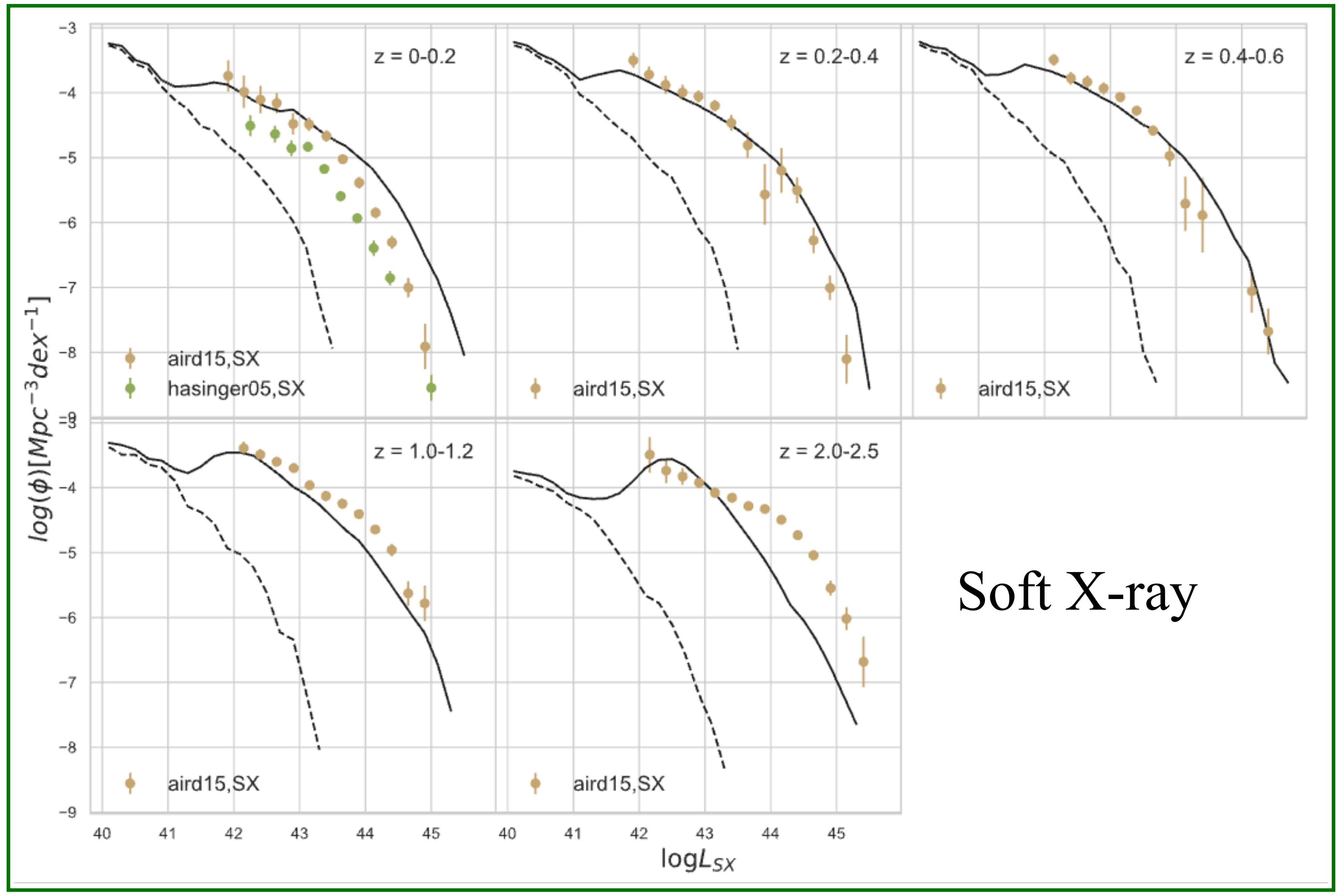


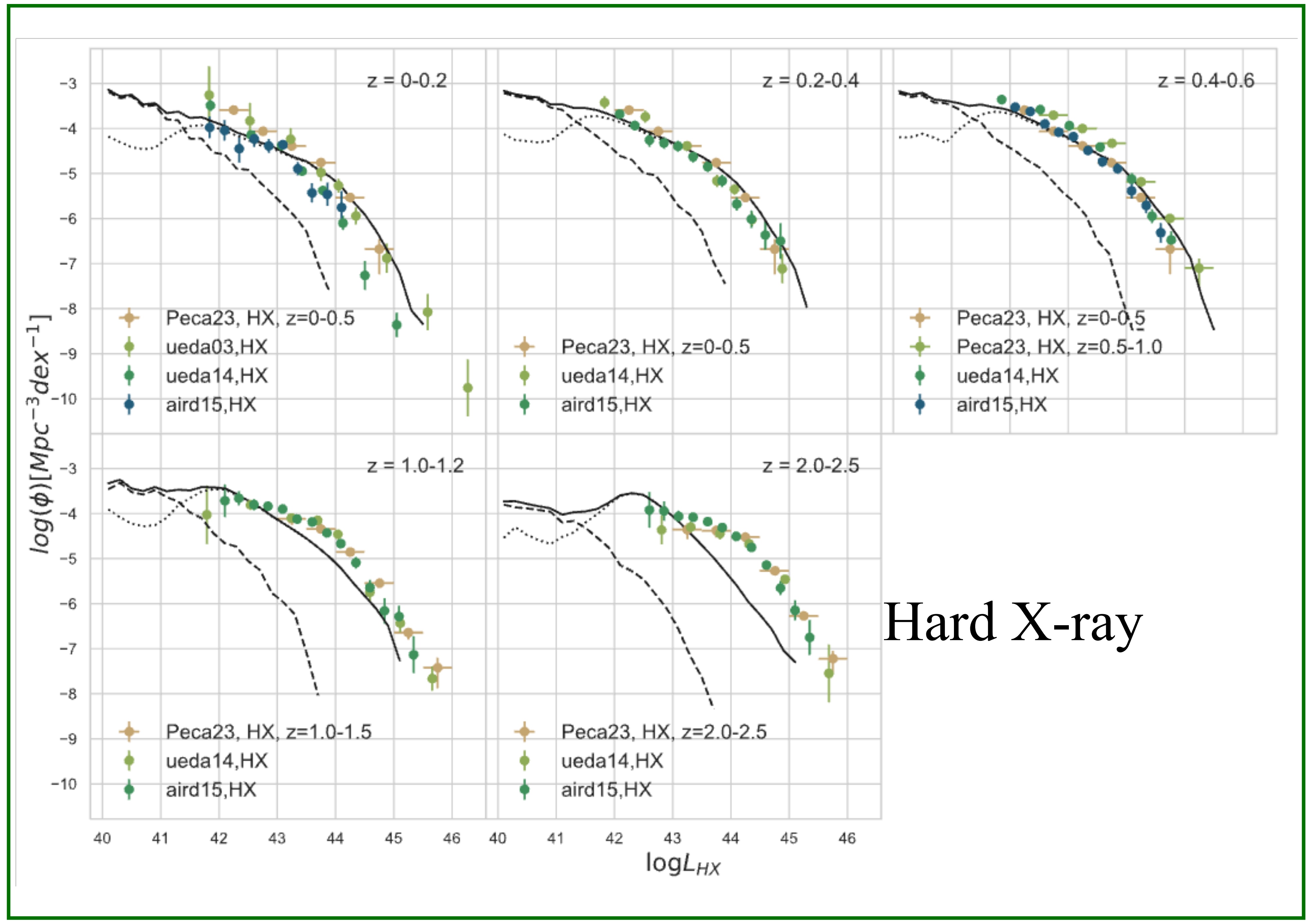
Pei + MNRAS (2024)

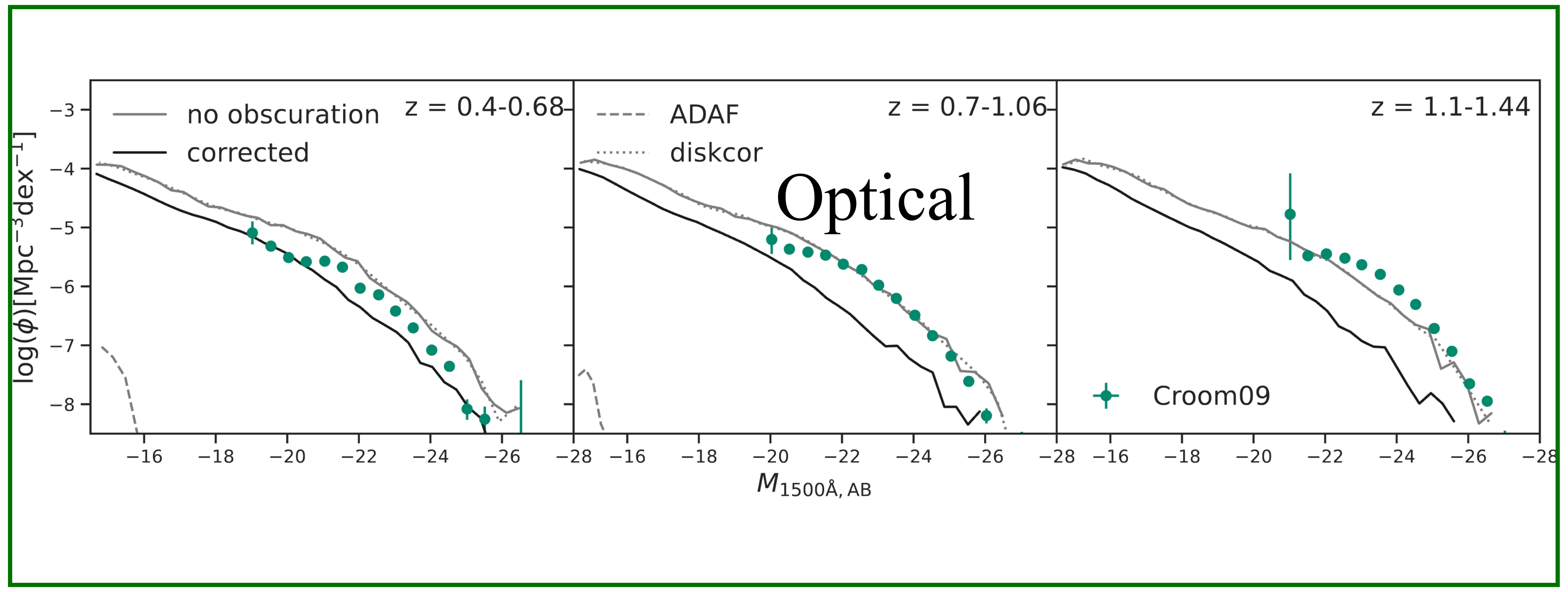
Pei, Guo et al.(2024)

AGN Luminosity functions









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

Su, Guo et al. submitted

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

- Galaxies and AGNs
  - Abundance of high-z luminous galaxies discovered by JWST can be explained by the cosmic variance
  - When more sophisticated AGN SED models are adopted, the contribution of AGN to reionization becomes significant.
  - Catalog: Galaxy + AGN SED, suitable for the next generation of large-scale surveys.

Thank you！