

面向下一代巡天的宇宙学数值模拟

—— 超级计算在现代宇宙学中的应用



中国科学院国家天文台
NATIONAL ASTRONOMICAL OBSERVATORIES
CHINESE ACADEMY OF SCIENCES

李明 国家天文台

2023年4月21日

内容提要

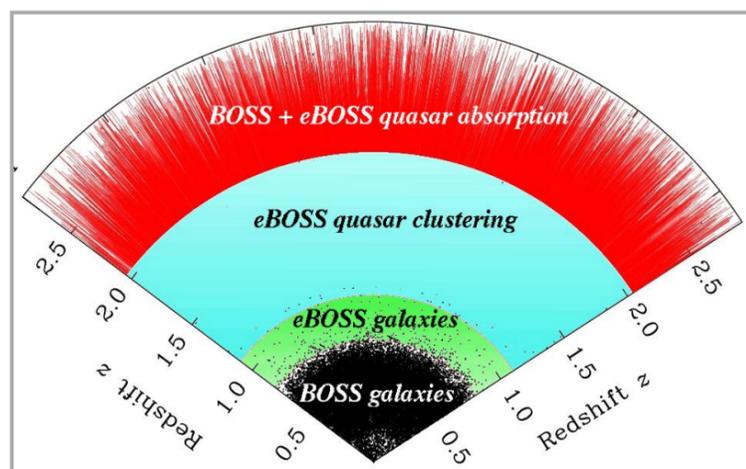
- 天文背景概要
- 基于新一代巡天的宇宙学模拟
- 未来展望



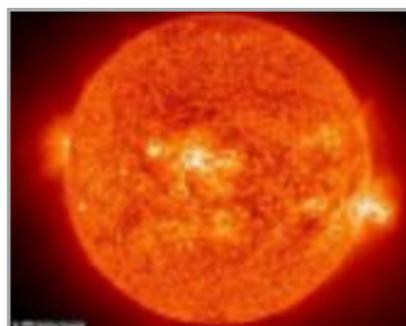
天文背景概要

天文学既是一门古老的学科，又是一门现代的学科。

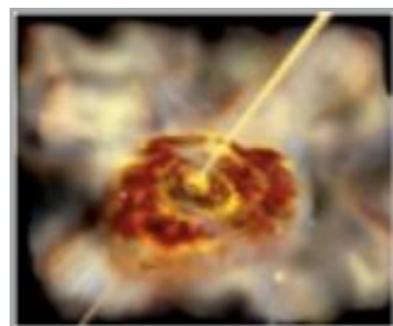
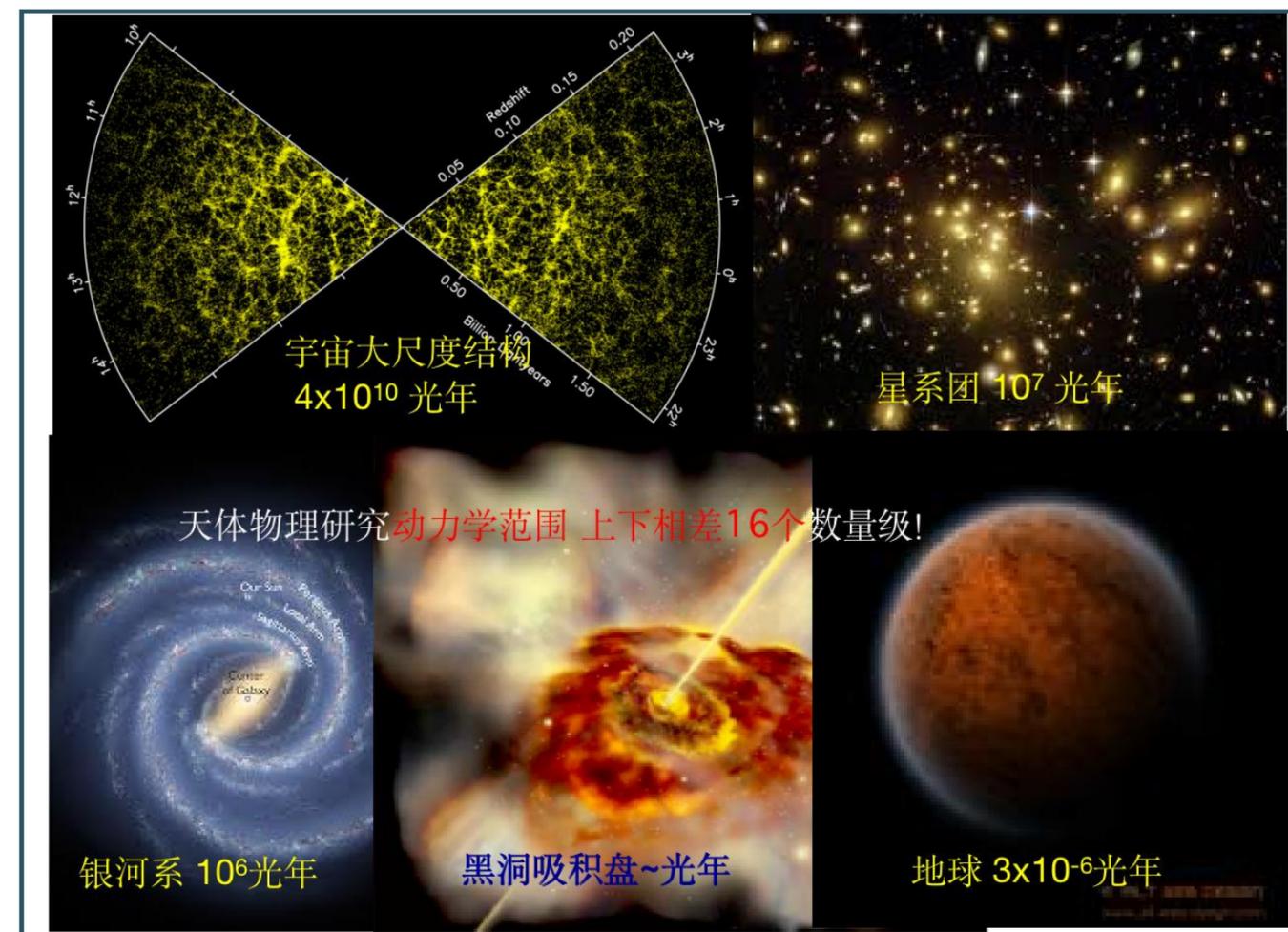
宇宙尺度结构



星系



恒星



黑洞



白矮星



中子星

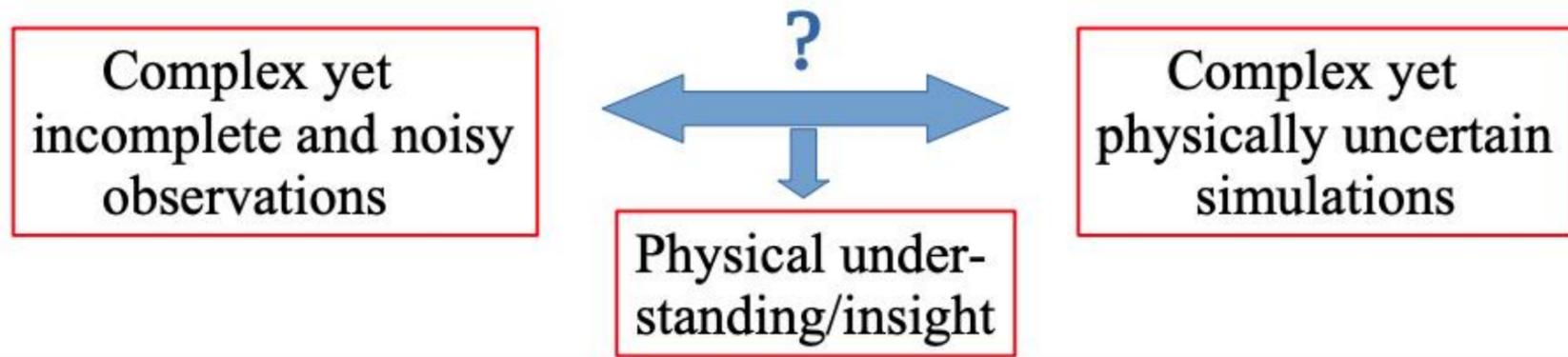


行星

天文学研究范式

If your experiment needs statistics, you ought to have done a better experiment.

Ernest Rutherford



天文观测

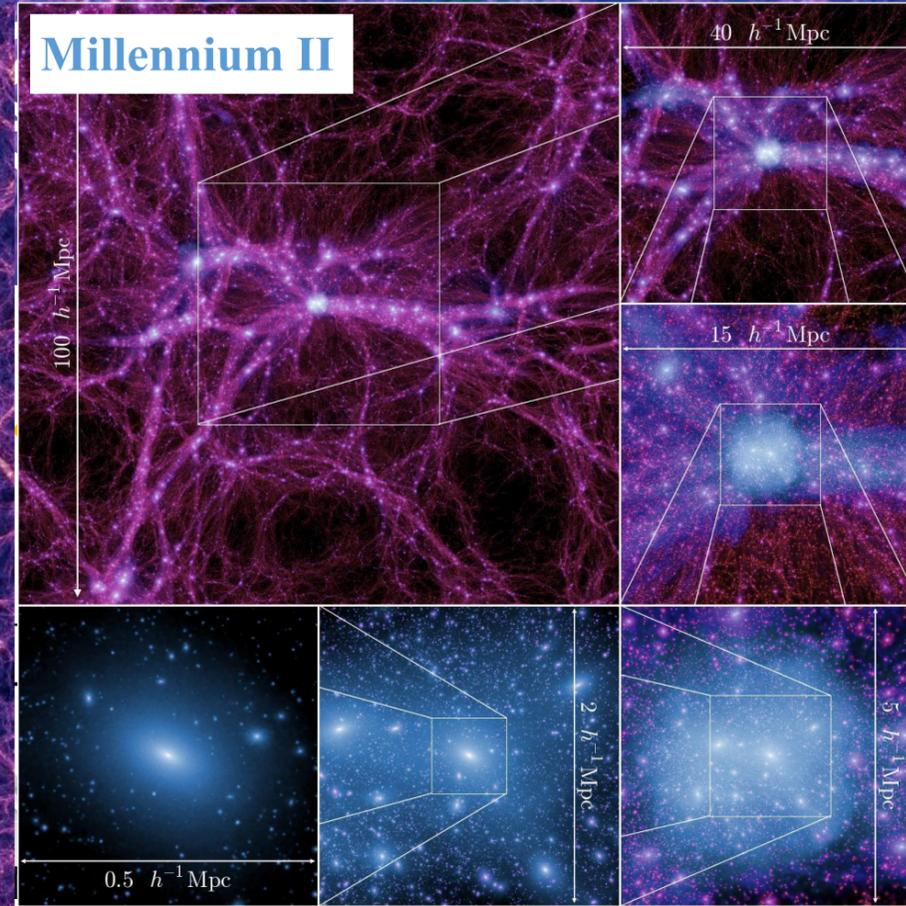
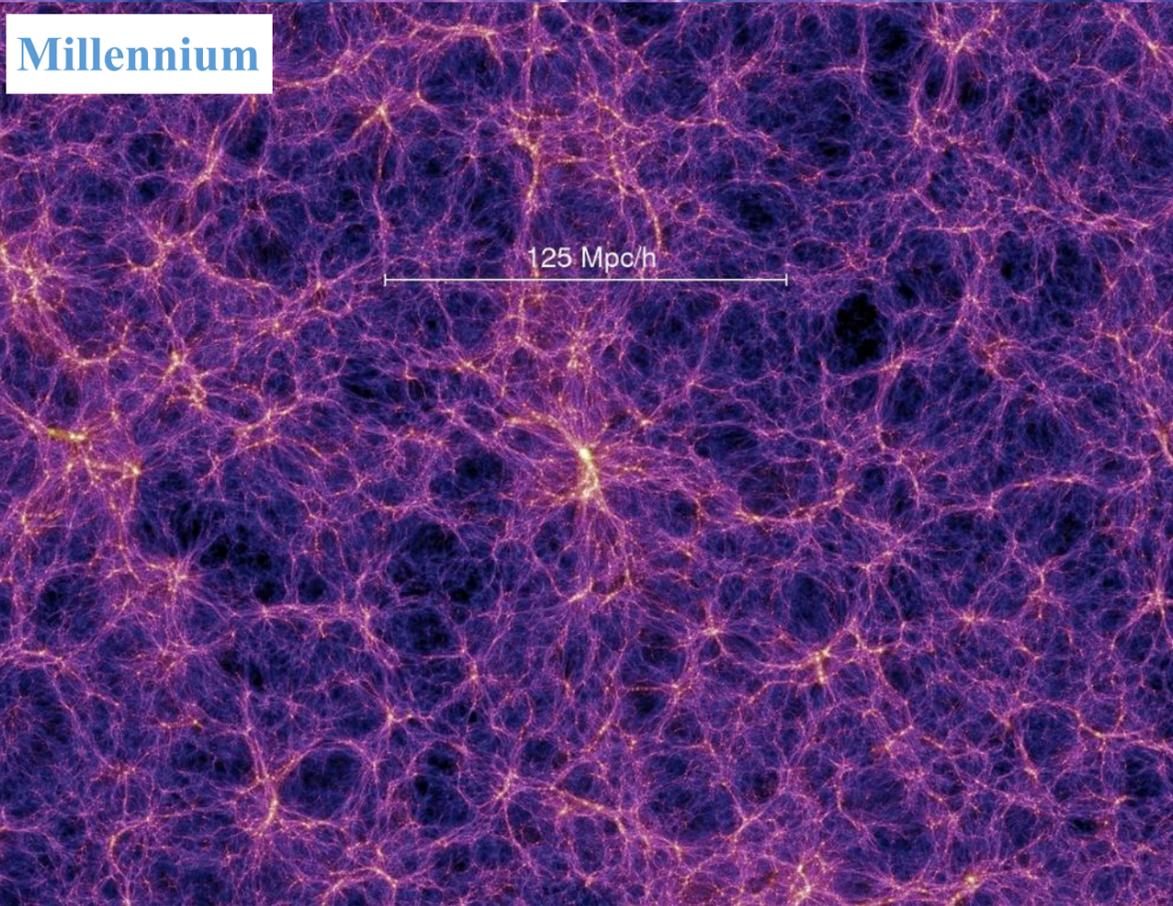


理论模型

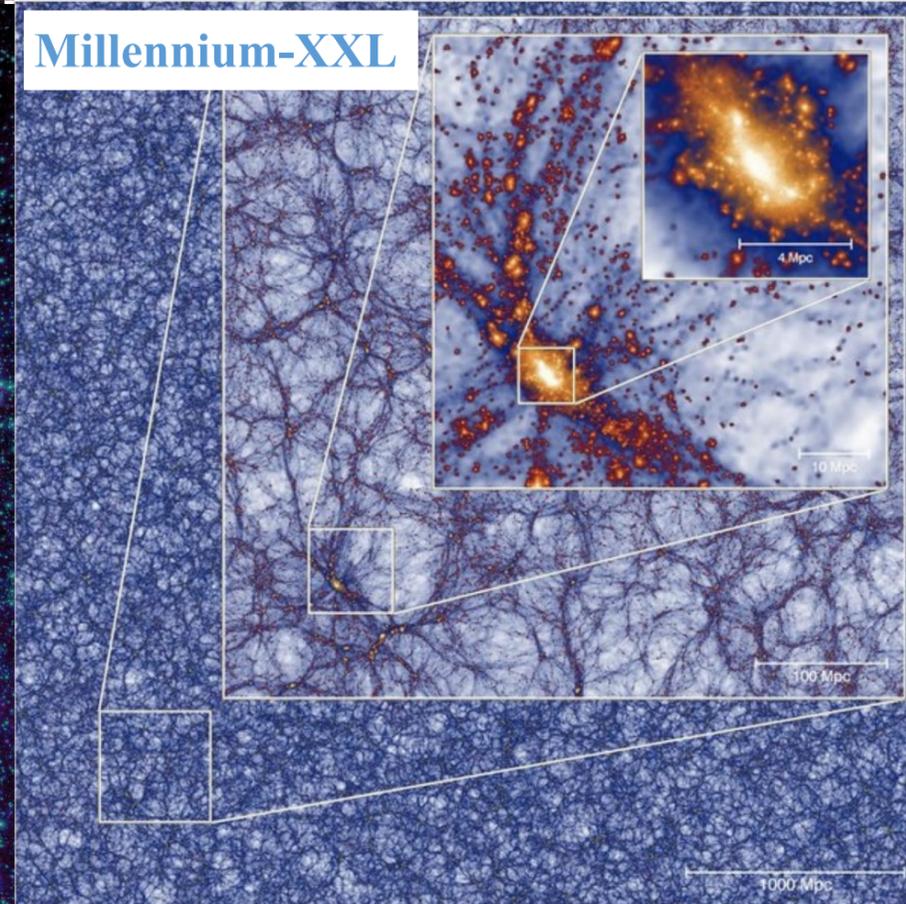


解释、指导天文观测；验证、完善理论

高性能



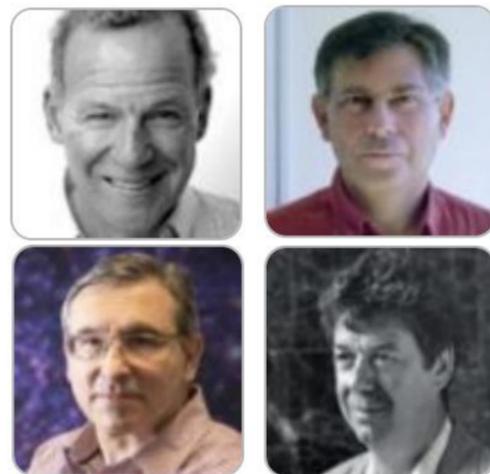
A HISTORICAL



2005

me 2005:

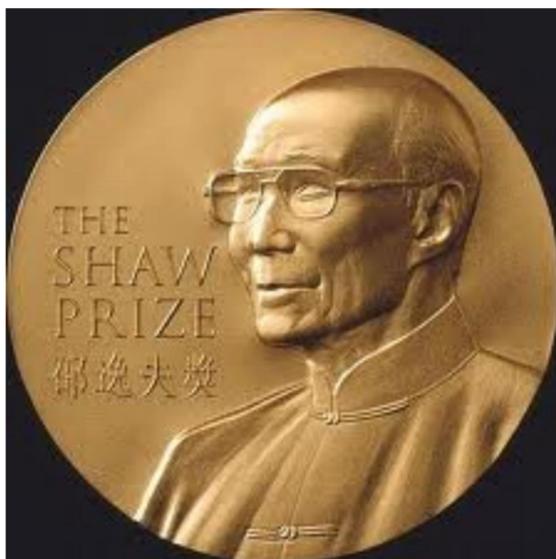




2011年 **Gruber Prize** 宇宙学最大奖
计算宇宙学开拓者们，确定目前标准
冷暗物质宇宙学模型



2020年 **Gruber Prize** 宇宙学最大奖
编写的程序 and 发展的算法在星系宇宙
学中得到广泛应用，推动了星系宇宙
学的发展



Simon D M White

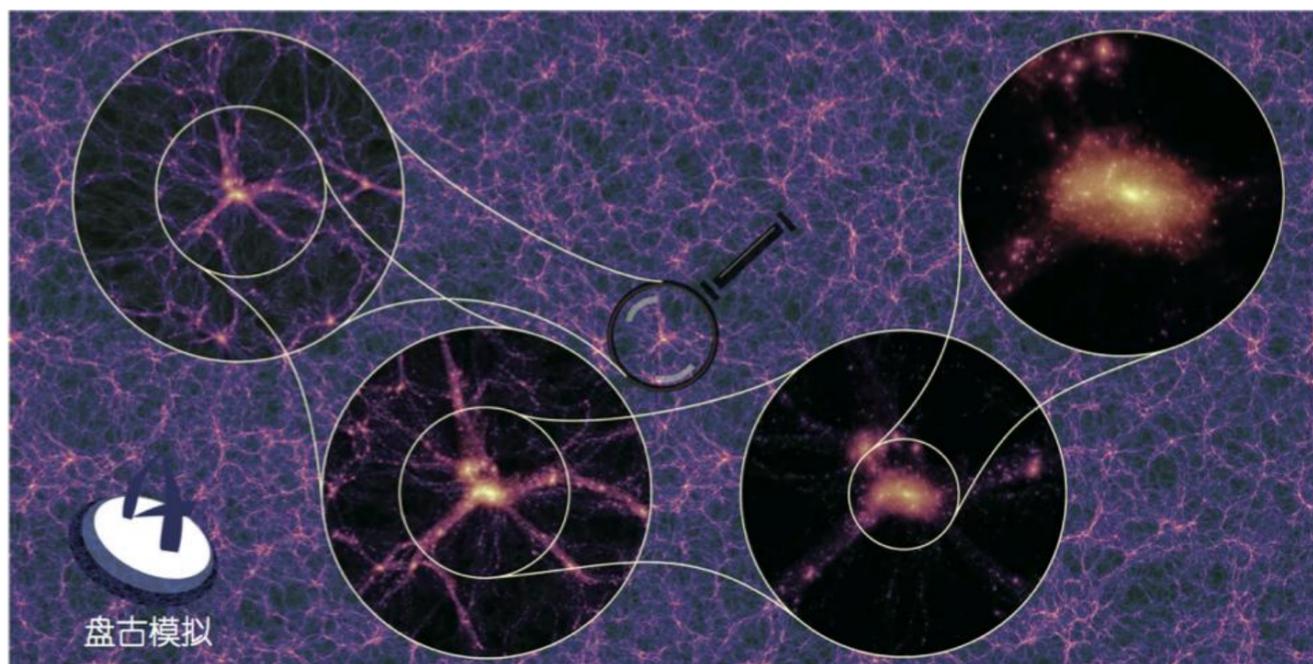
for his contributions to understanding structure formation in the Universe. With powerful numerical simulations he has shown how small density fluctuations in the early Universe develop into galaxies and other nonlinear structures, strongly supporting a cosmology with a flat geometry, and dominated by dark matter and a cosmological constant.

2017

[Read More >](#)

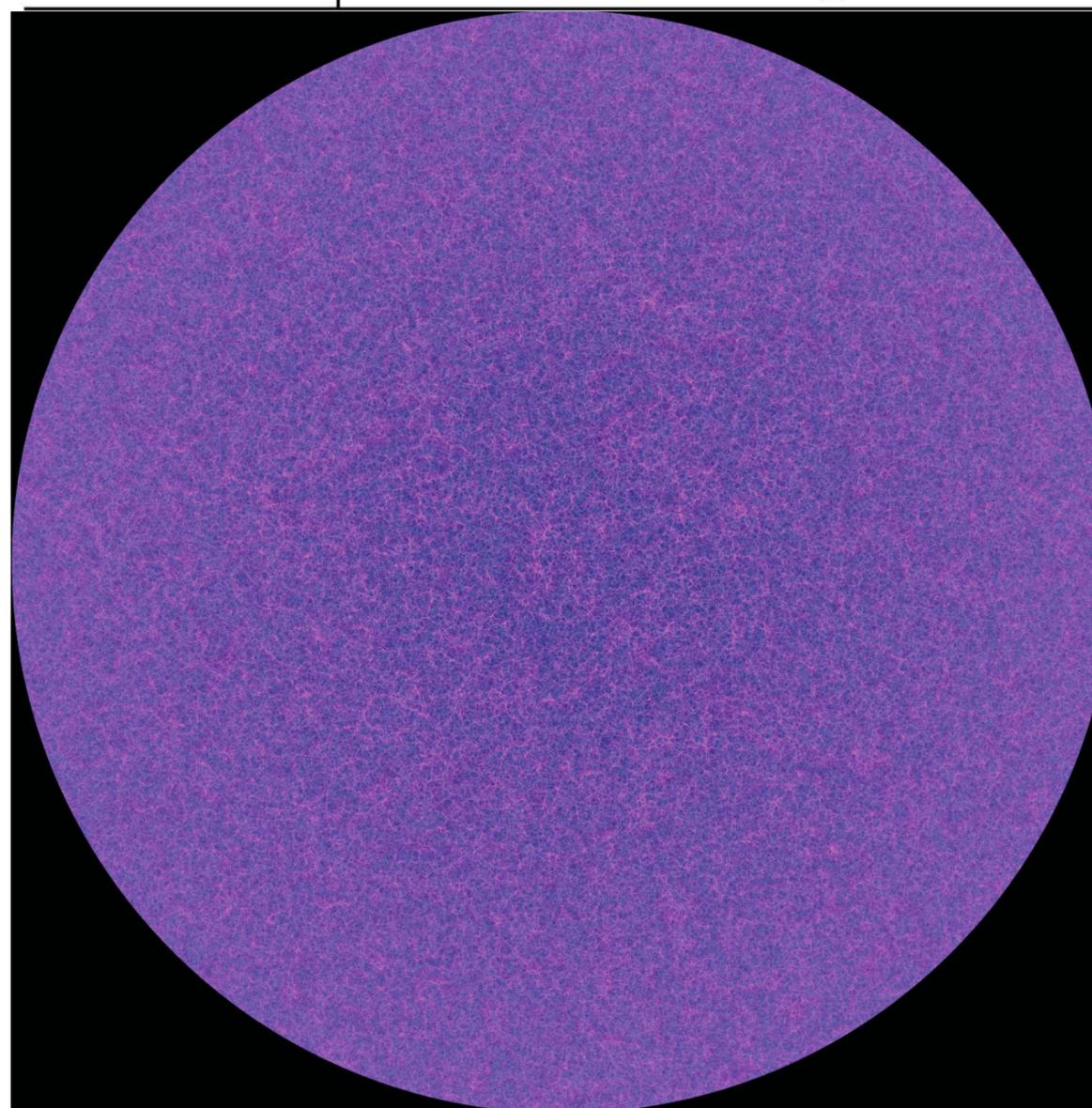
~2010

模拟名称	Pangu-I	Millennium-XXL
完成年份	2011	2010
完成机构	C4 Consortium	Virgo Consortium
超级计算机	DeepComp 7000	JuRoPa
模拟类型	纯暗物质	纯暗物质
软件	L-GADGET2	L-GADGET3
模拟尺度 (L_{Box}) [$h^{-1}\text{Gpc}$]	1	3
粒子数 (N_{part})	3072^3	6720^3
质量分辨率 (m_{part}) [$\times 10^{10} h^{-1} M_{\odot}$]	0.25	0.62
软化因子 [$h^{-1}\text{kpc}$]	7	10



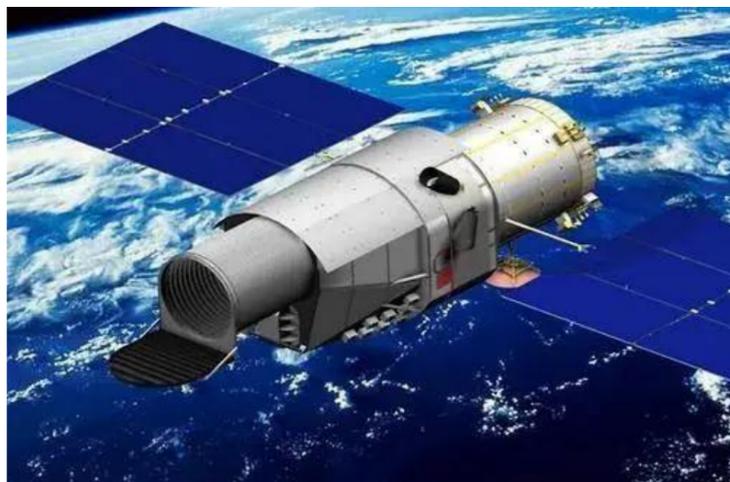
~2022

L_{box}	$2500 h^{-1}\text{Mpc}$
N_{particle}	$16128^3 \sim 4.195 \times 10^{12}$
m_{particle}	$3.21 \times 10^8 h^{-1} M_{\odot}$
ϵ	$3.0 h^{-1} \text{kpc}$



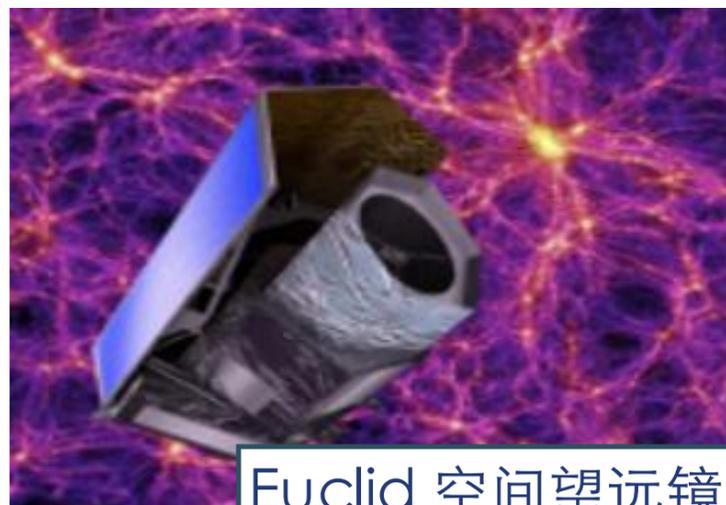
面向新一代巡天的挑战

更深 宇宙早期结构



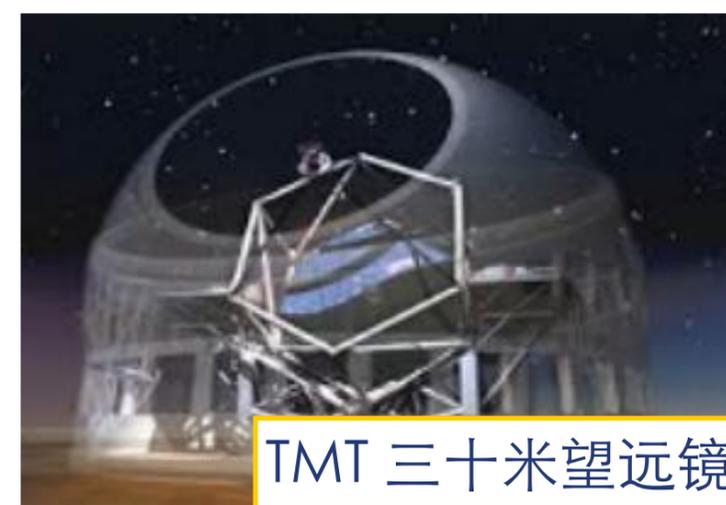
詹姆斯-韦伯空间望远镜

更广 宇宙增长历史



Euclid 空间望远镜

更精 精细天体物理过程



TMT 三十米望远镜



SKA 平方公里天线阵



Vera Rubin (LSST)



ELT 欧洲甚大望远镜

面向新一代巡天的挑战

精确宇宙学时代：宇宙学的研究极度依赖数值模拟的支撑

- 宇宙学是巡天空间望远镜（CSST）的驱动性研究方向
- 观测任务：17500平方度多色成像与无缝光谱巡天+深场
- 重大科学问题：暗能量本质、暗物质属性、检验引力理论、中微子质量序、早期暴胀物理机制等
- CSST宇宙学探针：强、弱引力透镜，大尺度结构，星系团等

巨大体积、高精度数值模拟

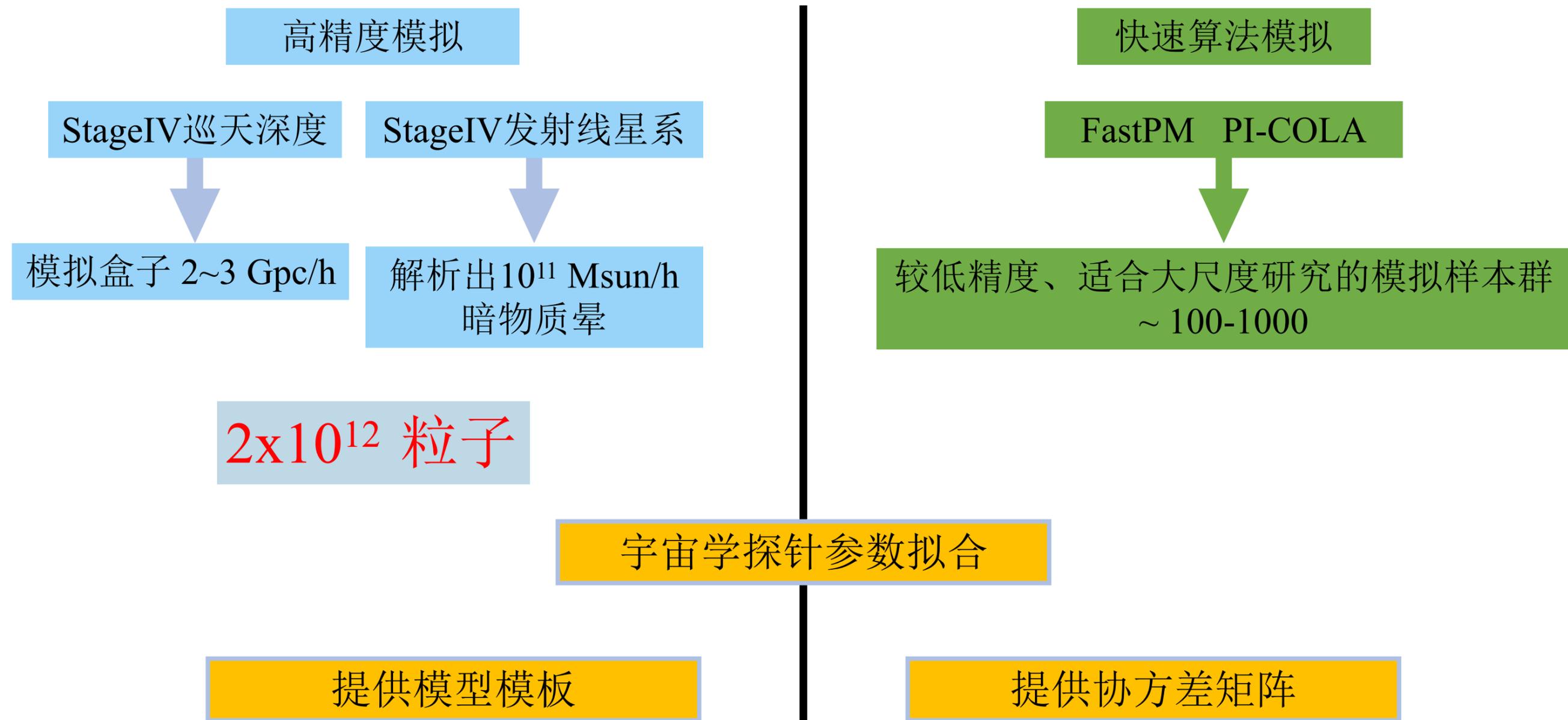
制备模拟星表

- 检验高精度测量方法和数据处理管线
- 详尽的系统误差分析和控制

- 理解观测的选择效应
- 制定最佳的巡天策略

面向新一代巡天的挑战

精确宇宙学时代：宇宙学的研究极度依赖数值模拟的支撑



面向新一代巡天的数值模拟

CSST宇宙学数值模拟方法与仿真器研究

子课题一：负责完成标准LCDM宇宙模型的数值模拟

JT₃₀₀ : $L = 300 h^{-1} \text{ Mpc}$, $N_p = 6144^3$
JT_{1G} : $L = 1000 h^{-1} \text{ Mpc}$, $N_p = 6144^3$
JT_{2G} : $L = 2000 h^{-1} \text{ Mpc}$, $N_p = 6144^3$
 $z_{\text{init}} = 127$, $N_{\text{snap}} = 128$
宇宙学参数: Planck 2018

曙光先进计算 华东中心（昆山）

九天(JT)模拟系列：主模拟

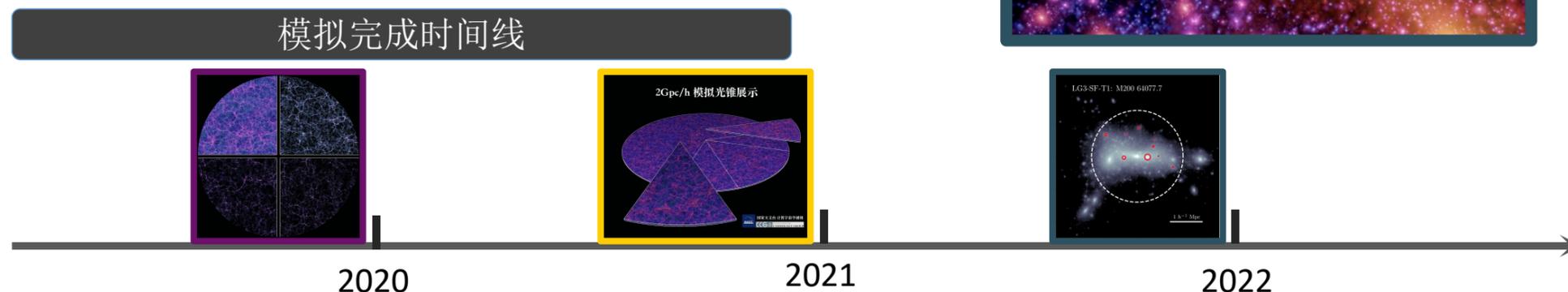
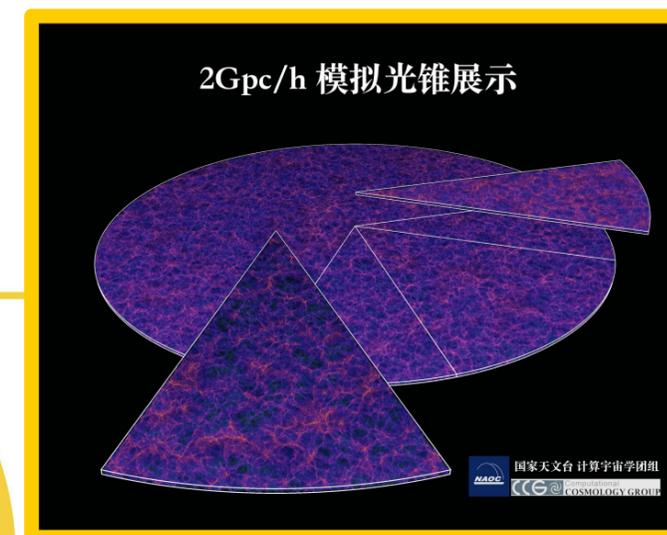
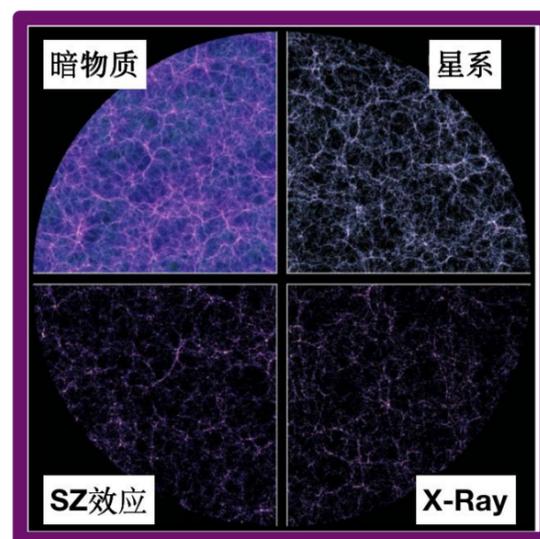
模拟规模: 300Mpc/h, 1Gpc/h, 2Gpc/h, 粒子数 2000亿, 1套 (3组) 已完成;
消耗机时 约3000 万核时。

目前国内精度高、规模大、数据产出齐全的模拟系列。

3组模拟总数据量超过3PB

数据类型包括:

- 时间切片
- 暗物质晕/子结构表
- 并和树
- 连续光锥 (全天、pencil-beam、disk-like、mass-shell天图等)

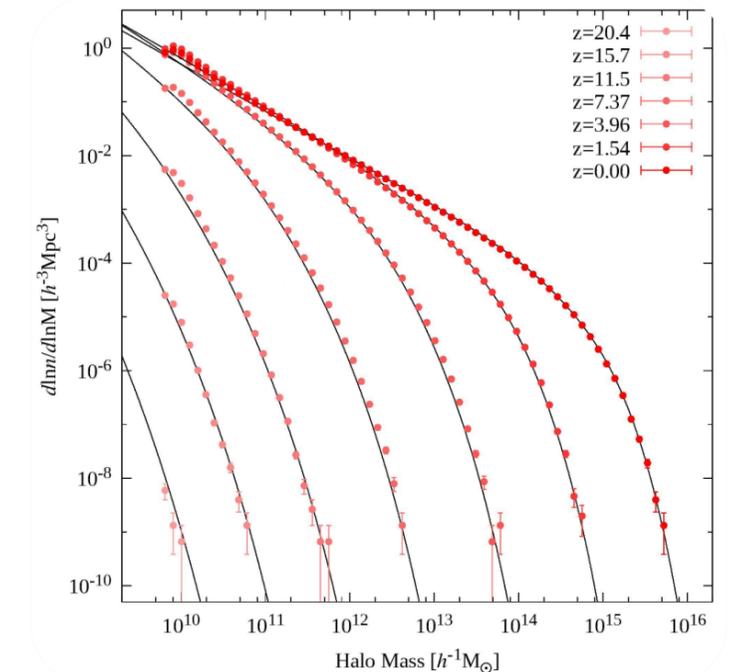
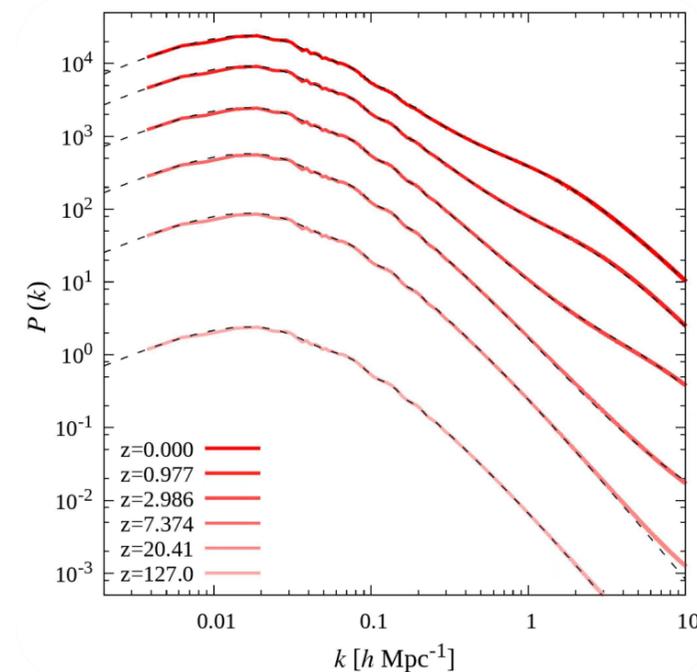


PhotoNs3与Hyper-Millennium 模拟

- PhotoNs是一款快速多极子 (FMM) +谱方法 (PM) 的混杂引力算法的宇宙N体数值模拟软件
- 在GPU等加速芯片上实现了加速, 整体速度有数量级的提升
- 目前的版本在国产超算系统上实现了百万核心以上的运行能力 [Wang, Gao & Meng, 2022, MNRAS]

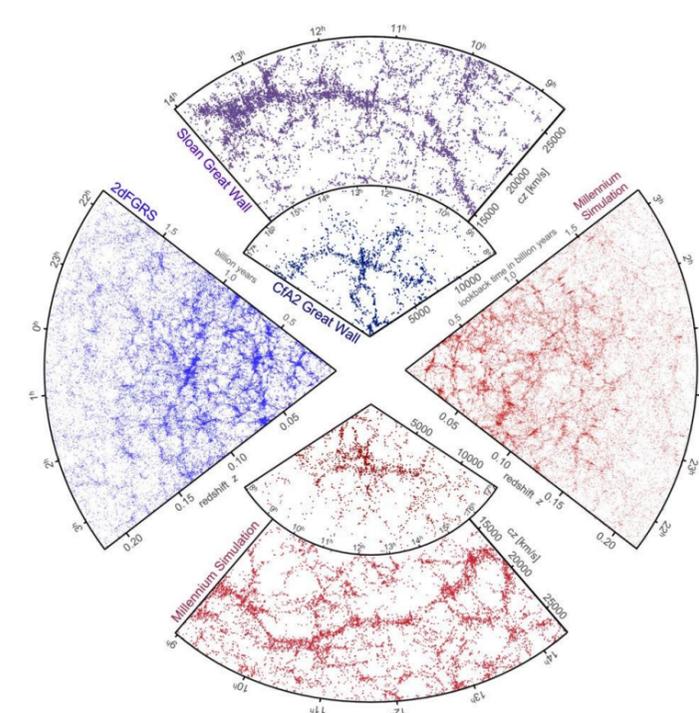
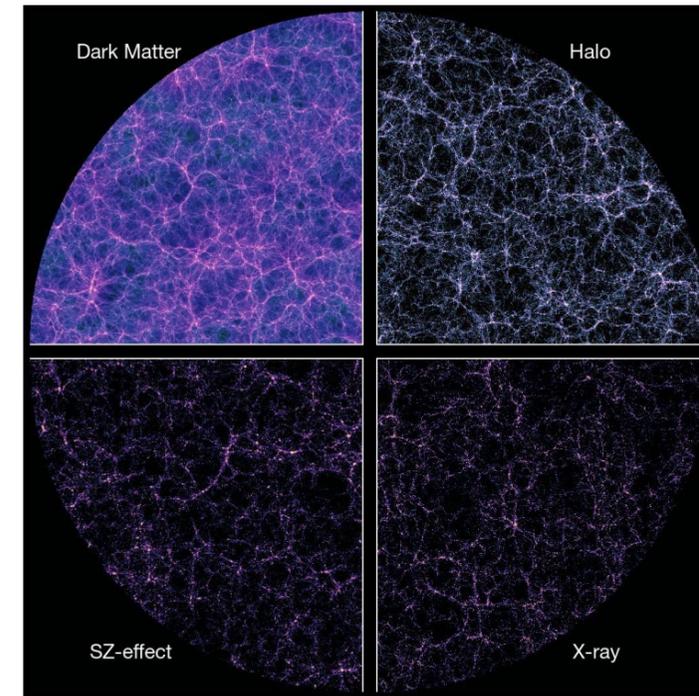
在东方一号 (中科院超算) 完成里4万亿粒子规模的数值模拟, 墙钟时间约17.5天, 输出了100个full snapshots

- 尺度边长 2.5 Gpc/h , 质量分辨率 $\sim 3.2e8 M_{\odot}/h$
- 计划释放暗晕、子暗晕、模拟星表等数据

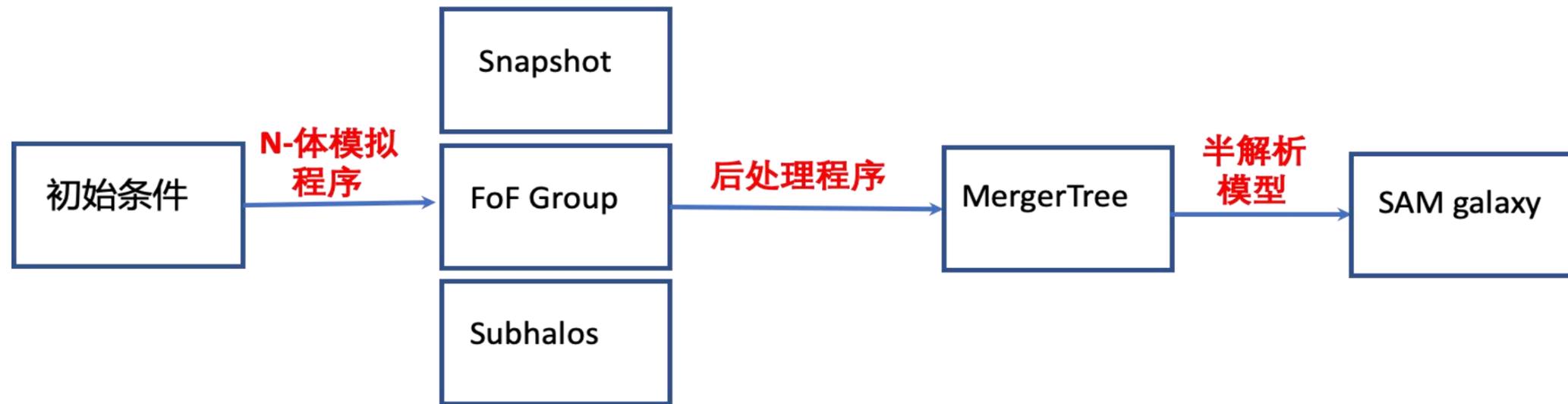


模拟数据的后处理

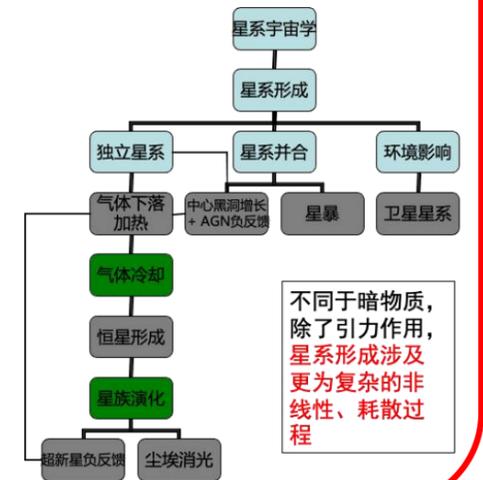
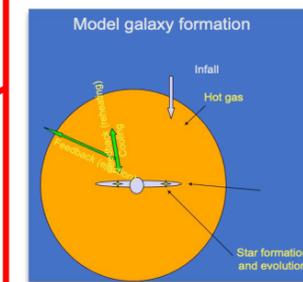
6.8T anapdir_000	6.8T anapdir_049	6.8T anapdir_081
6.8T anapdir_001	6.8T anapdir_050	6.8T anapdir_082
6.8T anapdir_002	6.8T anapdir_051	6.8T anapdir_083
6.8T anapdir_003	6.8T anapdir_052	6.8T anapdir_084
6.8T anapdir_004	6.8T anapdir_053	6.8T anapdir_085
6.8T anapdir_005	6.8T anapdir_054	6.8T anapdir_086
6.8T anapdir_006	6.8T anapdir_055	14T anapdir_087
6.8T anapdir_007	6.8T anapdir_056	14T anapdir_088
6.8T anapdir_008	6.8T anapdir_057	14T anapdir_089
6.8T anapdir_009	6.8T anapdir_058	14T anapdir_090
6.8T anapdir_010	6.8T anapdir_059	14T anapdir_091
6.8T anapdir_011	6.8T anapdir_060	14T anapdir_092
6.8T anapdir_012	6.8T anapdir_061	14T anapdir_093
6.8T anapdir_013	6.8T anapdir_062	14T anapdir_094
6.8T anapdir_014	6.8T anapdir_063	14T anapdir_095
6.8T anapdir_015	6.8T anapdir_064	14T anapdir_096
6.8T anapdir_016	6.8T anapdir_064_extra	14T anapdir_097
6.8T anapdir_017	6.8T anapdir_065	14T anapdir_098
6.8T anapdir_018	6.8T anapdir_066	14T anapdir_099
6.8T anapdir_019	6.8T anapdir_067	14T anapdir_100
6.8T anapdir_020	6.8T anapdir_068	14T anapdir_101
6.8T anapdir_021	6.8T anapdir_068_extra	14T anapdir_102
6.8T anapdir_022	6.8T anapdir_069	14T anapdir_103
6.8T anapdir_023	6.8T anapdir_070	14T anapdir_104
6.8T anapdir_024	6.8T anapdir_071	14T anapdir_105
6.8T anapdir_025	6.8T anapdir_072	14T anapdir_106
6.8T anapdir_026	6.8T anapdir_073	14T anapdir_107
6.8T anapdir_027	6.8T anapdir_074	14T anapdir_108
6.8T anapdir_028	6.8T anapdir_075	14T anapdir_109
6.8T anapdir_029	6.8T anapdir_076	14T anapdir_110
6.8T anapdir_030	6.8T anapdir_077	14T anapdir_111
6.8T anapdir_031	6.8T anapdir_078	14T anapdir_112
6.8T anapdir_032	6.8T anapdir_078_extra	14T anapdir_113
6.8T anapdir_033	6.8T anapdir_079	14T anapdir_114
6.8T anapdir_034	6.8T anapdir_080	14T anapdir_115
6.8T anapdir_035	6.8T anapdir_081	14T anapdir_116
6.8T anapdir_035_extra	6.8T anapdir_082	14T anapdir_117
6.8T anapdir_036	6.8T anapdir_083	14T anapdir_118
6.8T anapdir_037	6.8T anapdir_084	14T anapdir_119
6.8T anapdir_038	6.8T anapdir_085	14T anapdir_120
6.8T anapdir_039	6.8T anapdir_086	14T anapdir_121
6.8T anapdir_040	14T anapdir_087	14T anapdir_122
6.8T anapdir_041	14T anapdir_088	14T anapdir_123
6.8T anapdir_042	14T anapdir_089	14T anapdir_124
6.8T anapdir_043	14T anapdir_090	14T anapdir_125
6.8T anapdir_044	14T anapdir_091	14T anapdir_126
6.8T anapdir_045	14T anapdir_092	14T anapdir_127
6.8T anapdir_046	14T anapdir_093	6.8T anapdir_128_extra
6.8T anapdir_047	14T anapdir_094	1.2T total
18M groups_000	146G groups_047	463G groups_082_extra
18M groups_001	138G groups_048	468G groups_083
18M groups_002	149G groups_049	474G groups_084
18M groups_003	161G groups_050	480G groups_085
18M groups_004	173G groups_051	485G groups_086
18M groups_005	185G groups_052	490G groups_087
18M groups_006	197G groups_053	495G groups_088
18M groups_007	209G groups_054	500G groups_089
18M groups_008	221G groups_055	506G groups_090
18M groups_009	233G groups_056	511G groups_091
18M groups_010	244G groups_057	515G groups_092
18M groups_011	255G groups_058	520G groups_093
18M groups_012	266G groups_059	524G groups_094
18M groups_013	277G groups_060	528G groups_095
18M groups_014	288G groups_061	532G groups_096
18M groups_015	288G groups_061_extra	537G groups_097
18M groups_016	298G groups_062	540G groups_098
18M groups_017	309G groups_063	544G groups_099
19M groups_018	319G groups_064	547G groups_100
24M groups_019	329G groups_065	551G groups_101
35M groups_020	338G groups_066	554G groups_102
59M groups_021	347G groups_067	557G groups_103
104M groups_022	356G groups_068	560G groups_104
187M groups_023	365G groups_069	563G groups_105
339M groups_024	374G groups_070	566G groups_106
333M groups_024_extra	382G groups_071	569G groups_107
568M groups_025	390G groups_072	571G groups_108
939M groups_026	398G groups_073	573G groups_109
1.5G groups_027	416G groups_074	576G groups_110
2.3G groups_028	416G groups_075	578G groups_111
3.4G groups_029	422G groups_076	581G groups_112
4.4G groups_030	429G groups_077	583G groups_113
4.9G groups_030_extra	437G groups_078	585G groups_114
6.8G groups_031	444G groups_079	587G groups_115
9.2G groups_032	450G groups_080	590G groups_116
13G groups_033	456G groups_081	592G groups_117
16G groups_034	462G groups_082	594G groups_118
21G groups_035	463G groups_082_extra	596G groups_119
26G groups_036	468G groups_083	597G groups_120
32G groups_037	474G groups_084	599G groups_121
38G groups_038	480G groups_085	601G groups_122
38G groups_038_extra	485G groups_086	603G groups_123
46G groups_039	490G groups_087	605G groups_124
54G groups_040	495G groups_088	606G groups_125
63G groups_041	500G groups_089	608G groups_126
72G groups_042	506G groups_090	610G groups_127
82G groups_043	511G groups_091	610G groups_128_extra
92G groups_044	515G groups_092	38T total



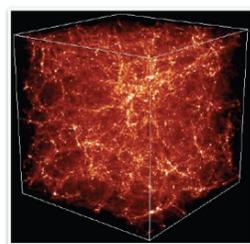
模拟数据的后处理



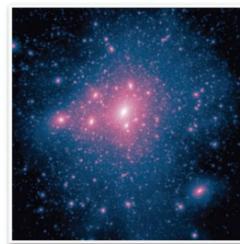
半解析模型 Semi Analytical Model (SAM)



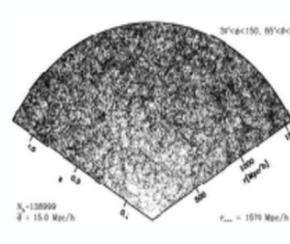
不同于暗物质，除了引力作用，星系形成涉及更为复杂的非线性、耗散过程



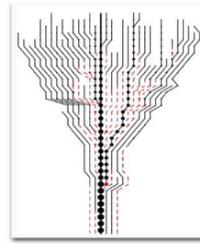
时间切片



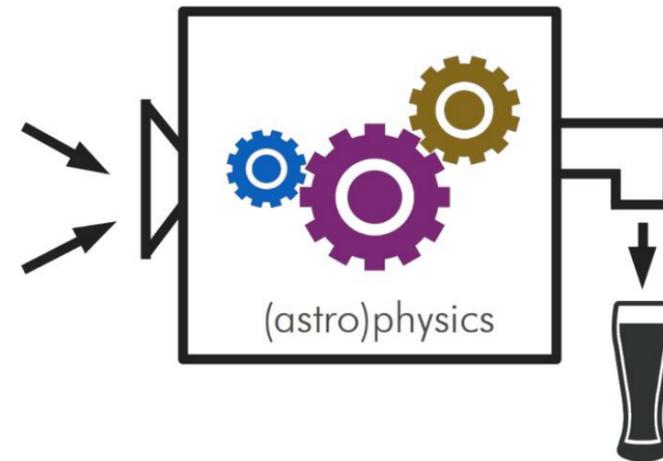
暗物质晕表



连续光锥



并合树



虚拟天空



The Millennium Run Observatory, Overzier, R. Et al. 2013, M

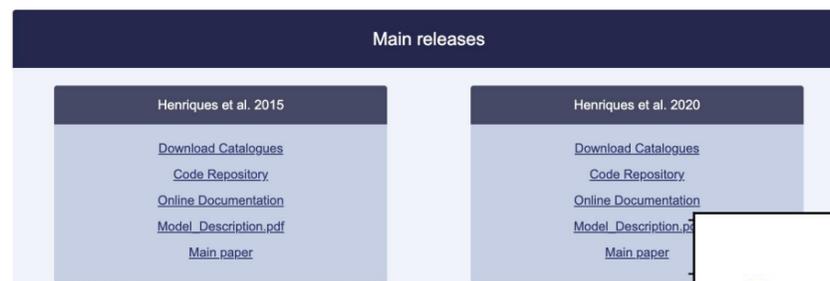
模拟数据的后处理：星表

模拟星表的建立

L - GALAXIES

国家天文台 博士生 裴文祥

基于 JT-1G 模拟数据

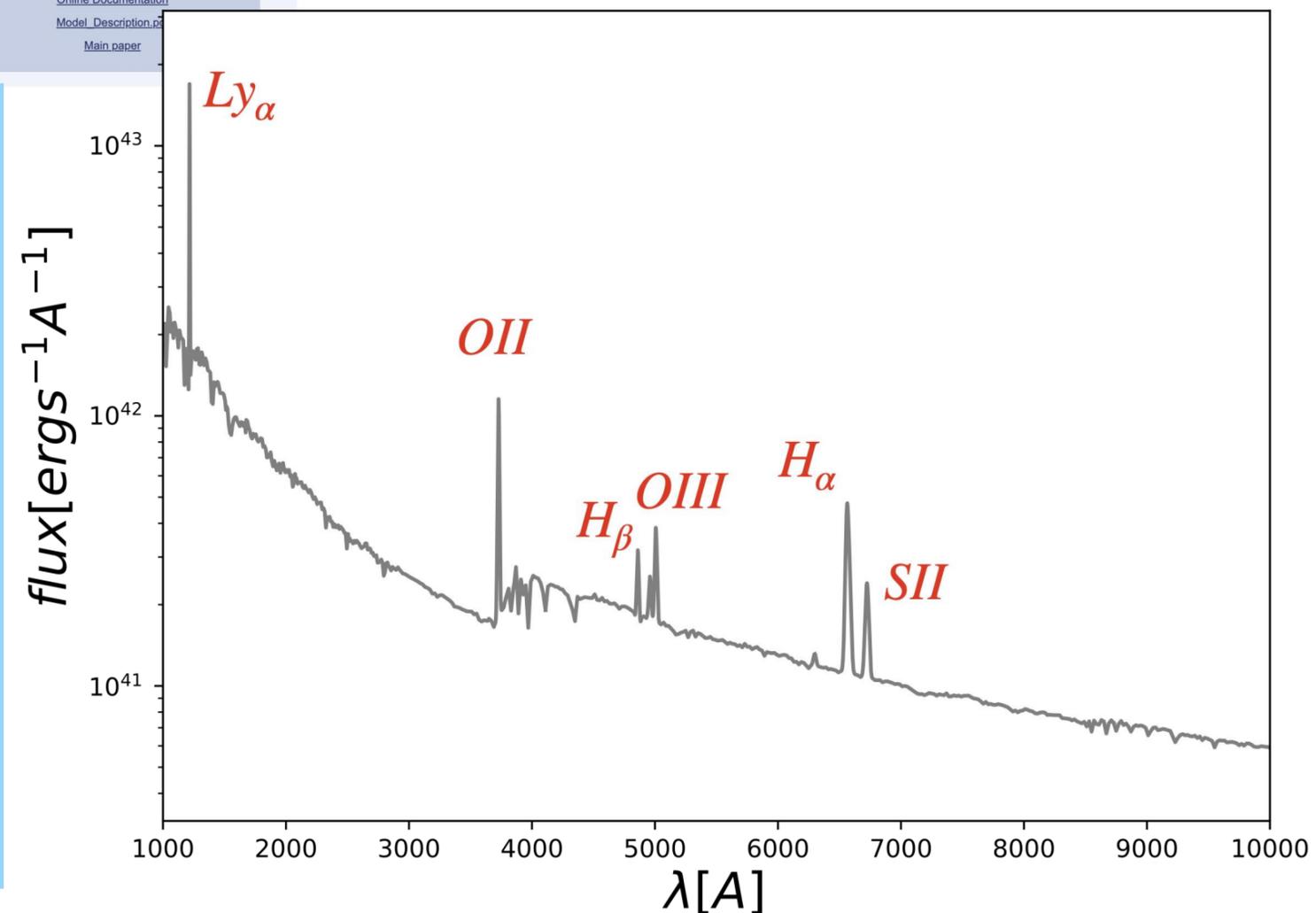


star forming galaxies at $z \sim 0$

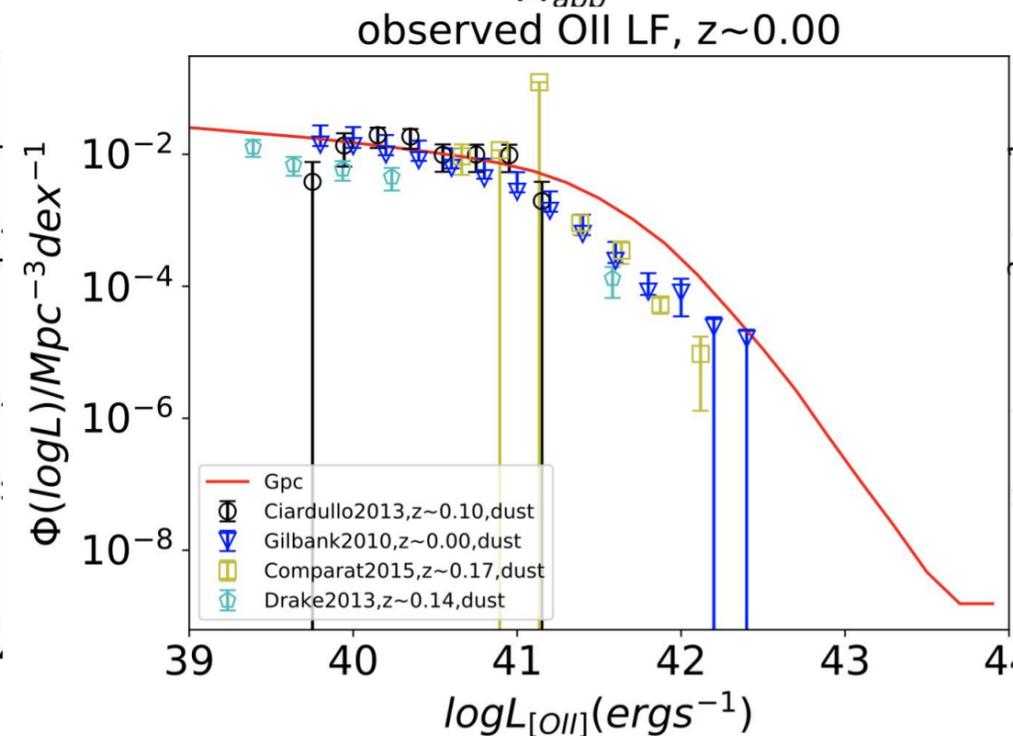
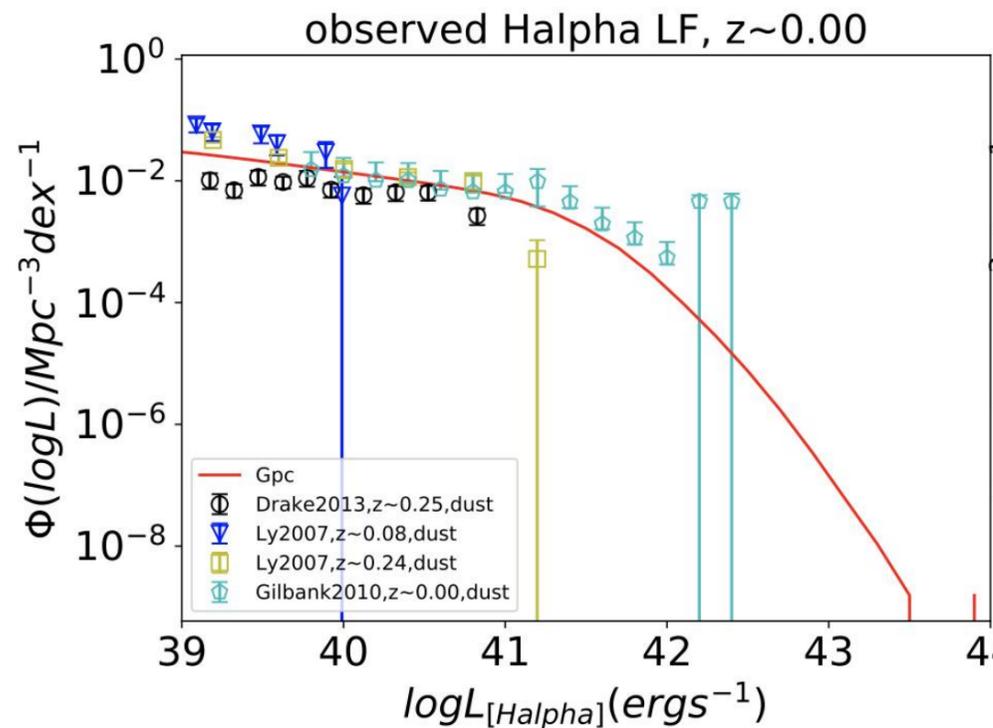
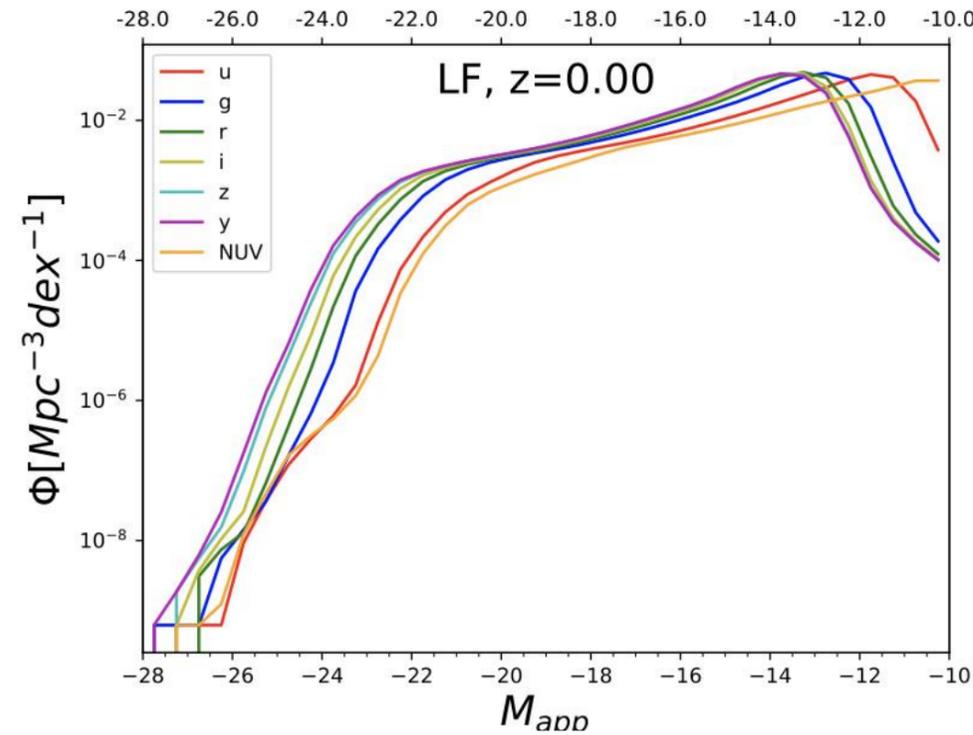
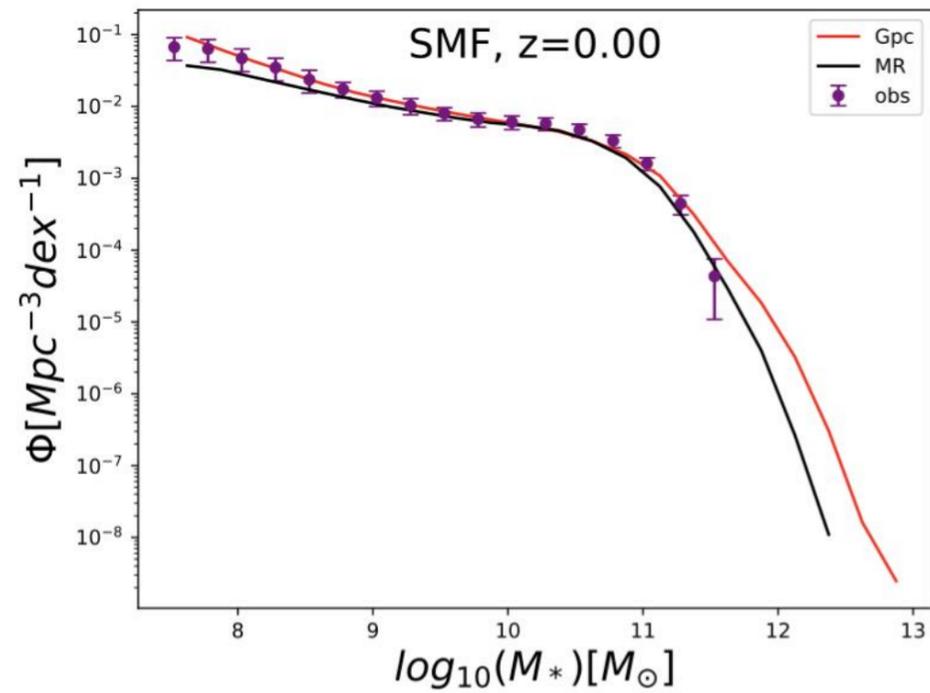
The Munich galaxy formation model: L-Galaxies

LGalaxies 2015 + new parameters + CSST

- Solving the time convergence problem with a New disruption models
- Emission Line Galaxies
 - Line ratios - CLOUDY13.03
 - Geometry hemical contents ionizing spectrum metallicity (Z)
 - ionizing parameter (U) Hydrogen density (n_H)
- AGN Luminosities



模拟数据的后处理：星表



国家天文台 博士生 裴文祥

Galaxy data $\sim 50T$

total galaxies $\sim 4.6e10$

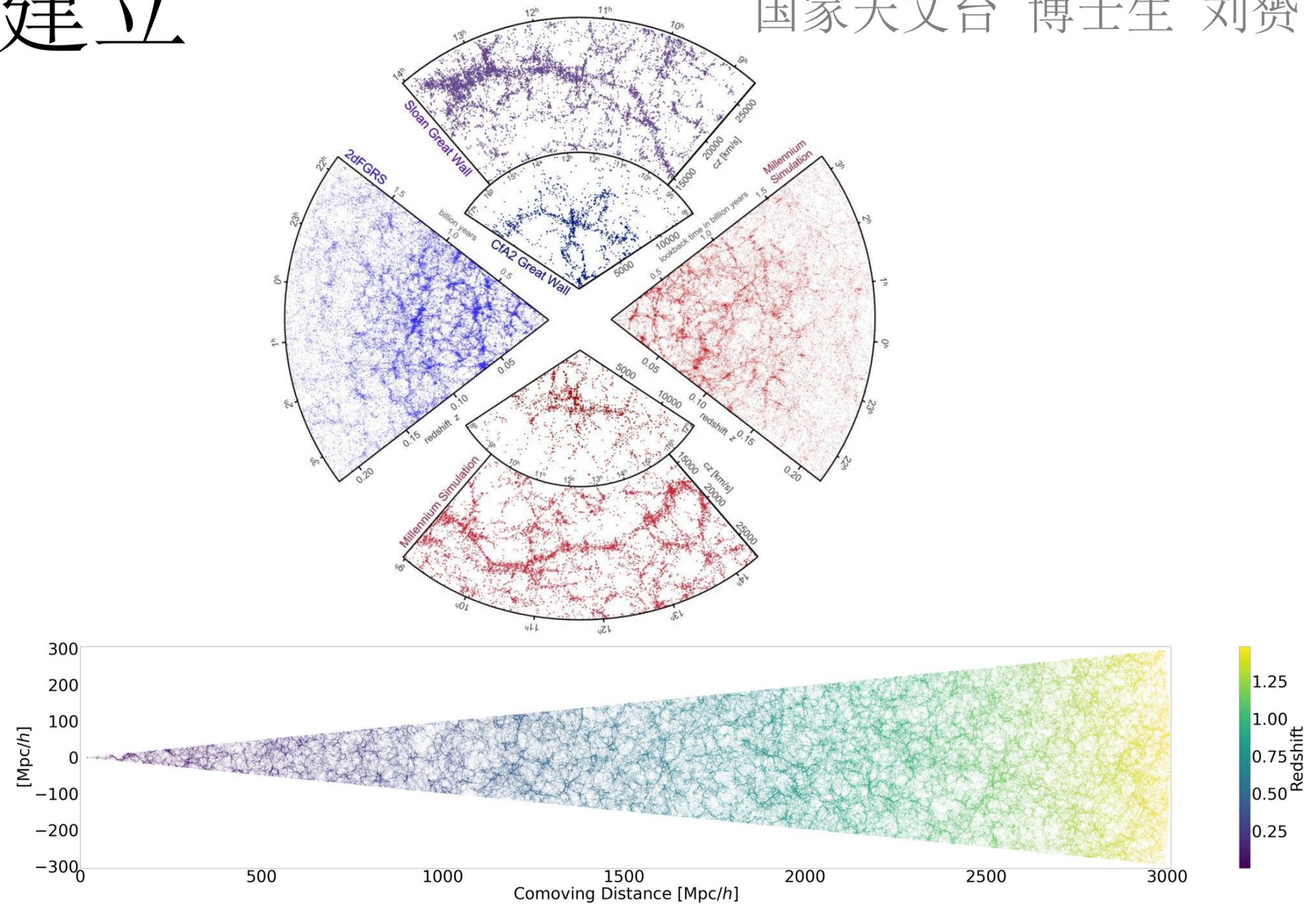
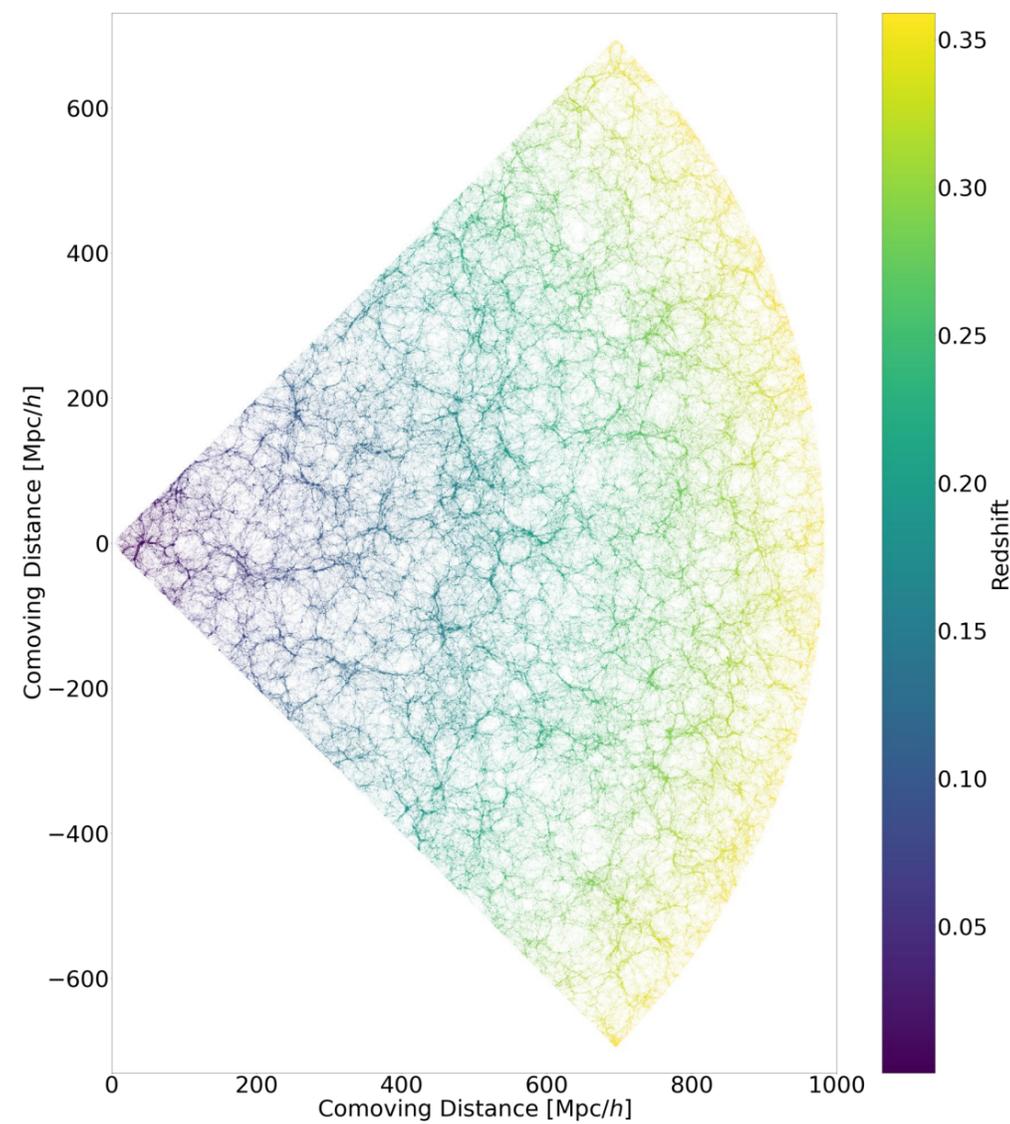
Magnitude of CSST filters

coldGas	real	phys.mass	$10^{10} M_{sun}/h$	Mass in the cold gas disk.
stellarMass	real	phys.mass	$10^{10} M_{sun}/h$	Total mass in stars in the disk and the bulge together.
bulgeMass	real	phys.mass	$10^{10} M_{sun}/h$	Mass of stars in the bulge.
diskMass	real	phys.mass	$10^{10} M_{sun}/h$	Mass of stars in the disk.
hotGas	real	phys.mass	$10^{10} M_{sun}/h$	Mass in hot gas.
ejectedMass	real	phys.mass	$10^{10} M_{sun}/h$	Mass in the ejected gas component.
blackHoleMass	real	phys.mass	$10^{10} M_{sun}/h$	Mass of the central black hole.
icmStellarMass	real	phys.mass	$10^{10} M_{sun}/h$	Mass in intra-cluster stars
metalsColdGas	real	phys.mass	$10^{10} M_{sun}/h$	Mass in metals in the cold gas disk.
metalsStellarMass	real	phys.mass	$10^{10} M_{sun}/h$	Mass in metals in stars in the disk and the bulge together.
metalsBulgeMass	real	phys.mass	$10^{10} M_{sun}/h$	Mass in metals in stars in the bulge.
metalsDiskMass	real	phys.mass	$10^{10} M_{sun}/h$	Mass in metals in stars in the disk.
metalsHotGas	real	phys.mass	$10^{10} M_{sun}/h$	Mass in metals in hot gas.
metalsEjectedMass	real	phys.mass	$10^{10} M_{sun}/h$	Mass in metals in the ejected mass component.
metalsICMStellarMass	real	phys.mass	$10^{10} M_{sun}/h$	Mass in metals in intra-cluster stars
primordialAccretionRate	real	phys.SFR	M_{sun}/yr	Accretion rate of primordial gas.
coolingRadius	real	phys.size.radius	Mpc/h	The radius within which the cooling time scale is shorter than the dynamical timescale
coolingRate	real	phys.SFR	M_{sun}/yr	Cooling rate
coolingRateNoAGN	real	phys.SFR	M_{sun}/yr	Cooling rate if there was no AGN feedback.
quasarAccretionRate	real	phys.SFR	M_{sun}/yr	Rate at which cold gas is accreted into the central black hole in the quasar mode.
radioAccretionRate	real	phys.SFR	M_{sun}/yr	Rate at which hot gas is accreted into the central black hole in the radio mode.
sfr	real	phys.SFR	M_{sun}/yr	Star formation rate
sfrBulge	real	phys.SFR	M_{sun}/yr	Star formation rate in bulge.
xrayLum	real	em.X-Ray	$\log_{10}(erg/sec)$	\log_{10} of X-Ray luminosity in erg/sec
bulgeSize	real	phys.size.radius	Mpc/h	Half mass radius of bulge
stellarDiskRadius	real	phys.size.radius	Mpc/h	Size of the stellar disk, 3x the scale length.

模拟数据的后处理：光锥

模拟星表光锥的建立

国家天文台 博士生 刘赞



模拟数据的后处理：观测

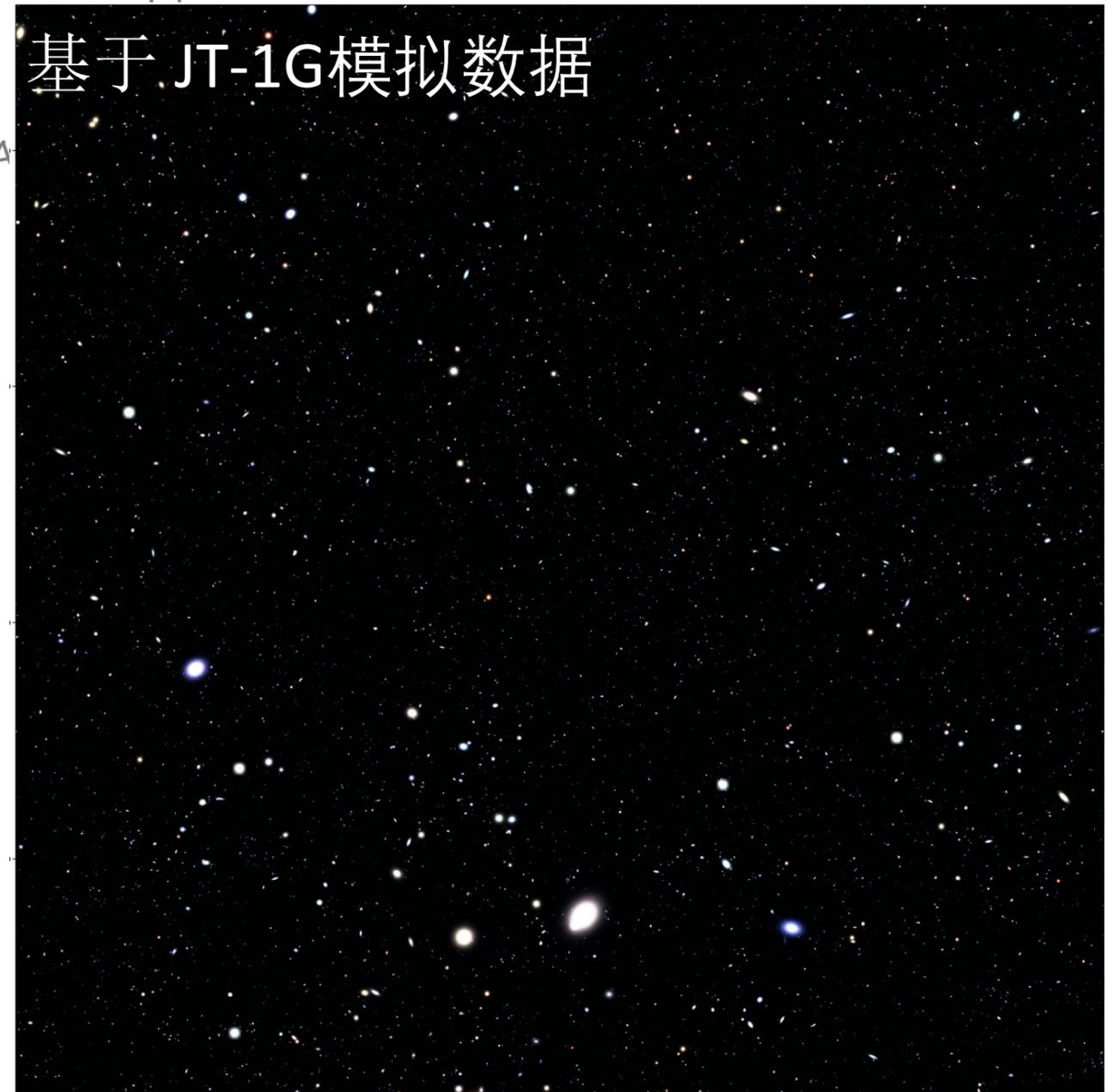
虚拟天空

紫金山天文台 李国亮 韦成

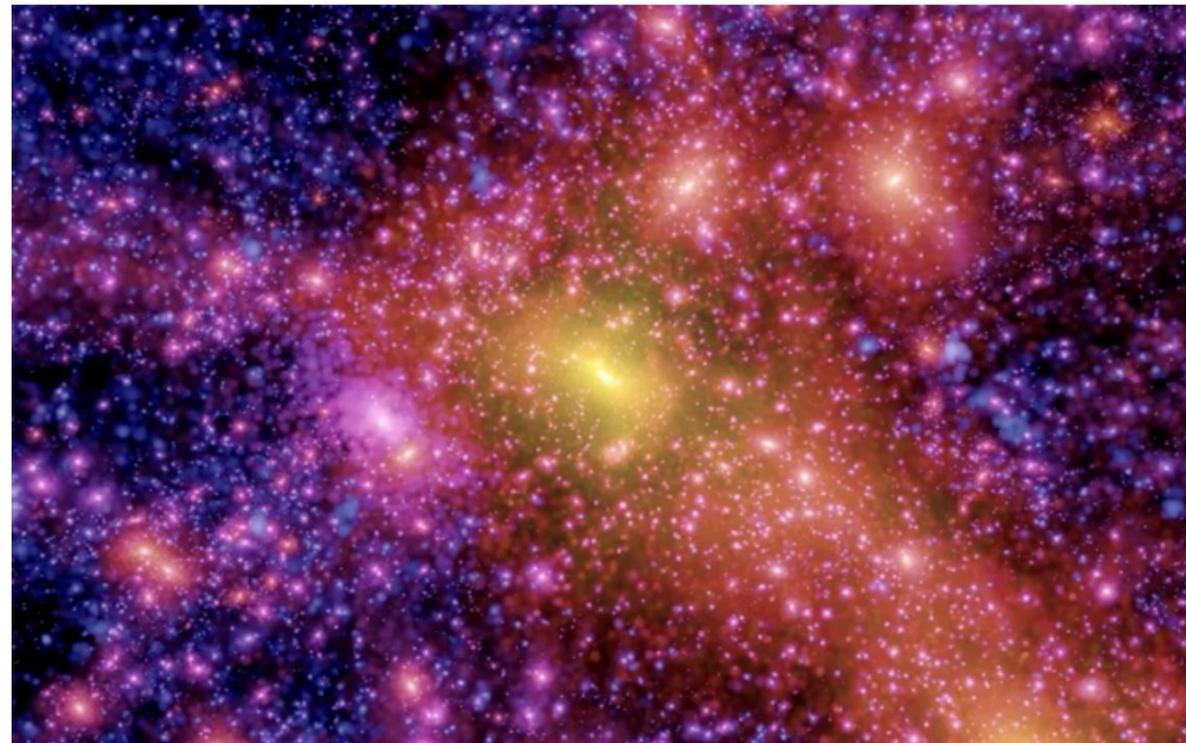
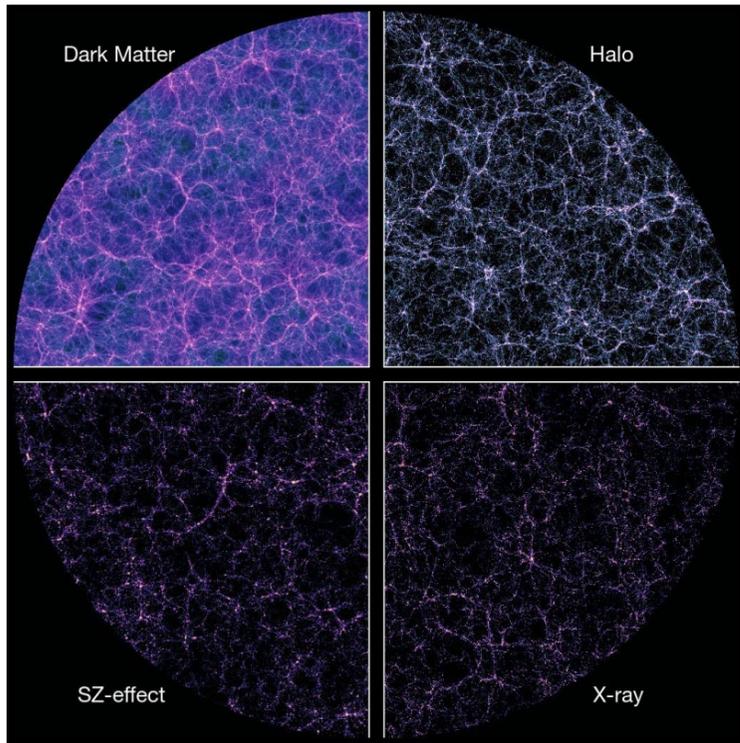
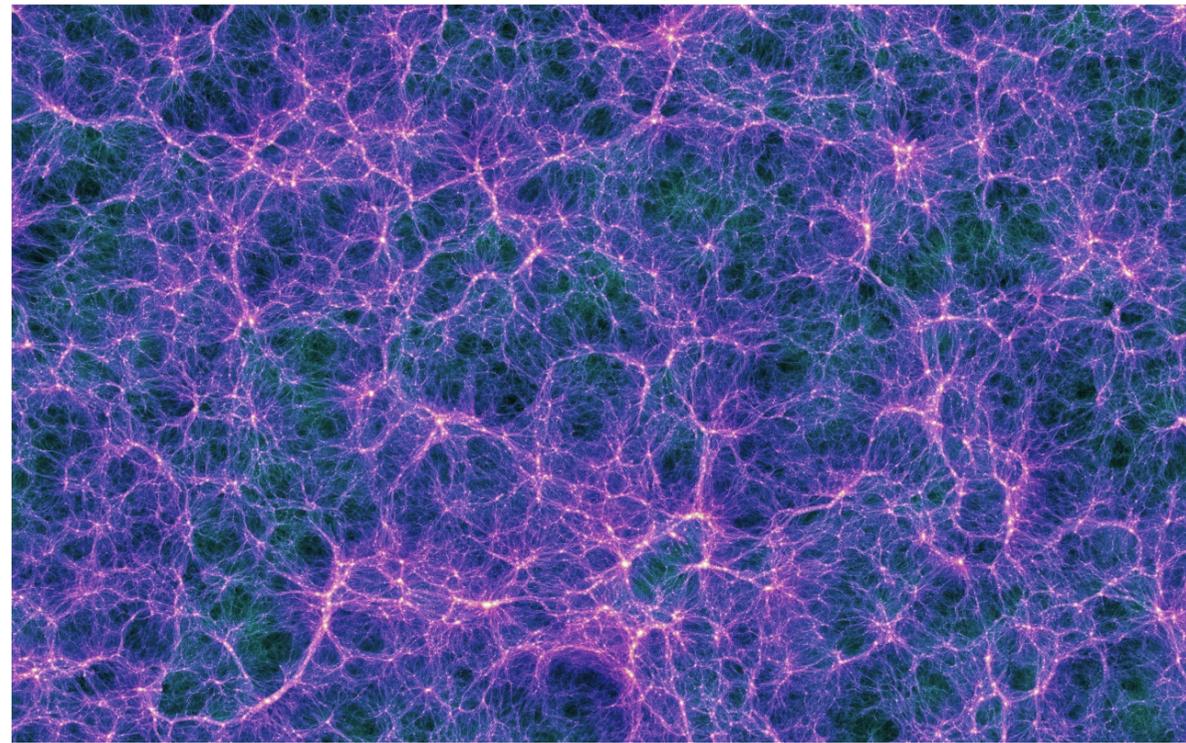
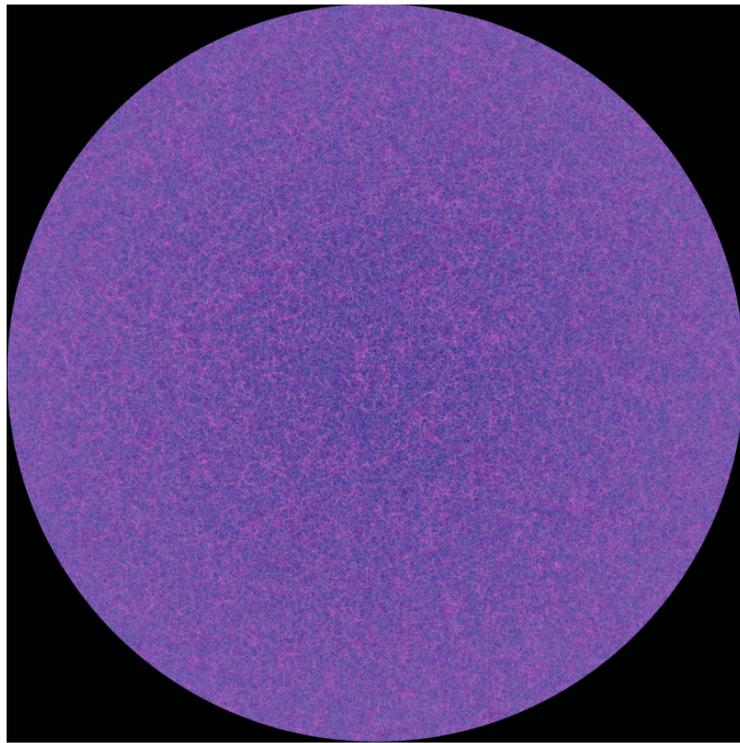
言

基于 JT-1G 模拟数据

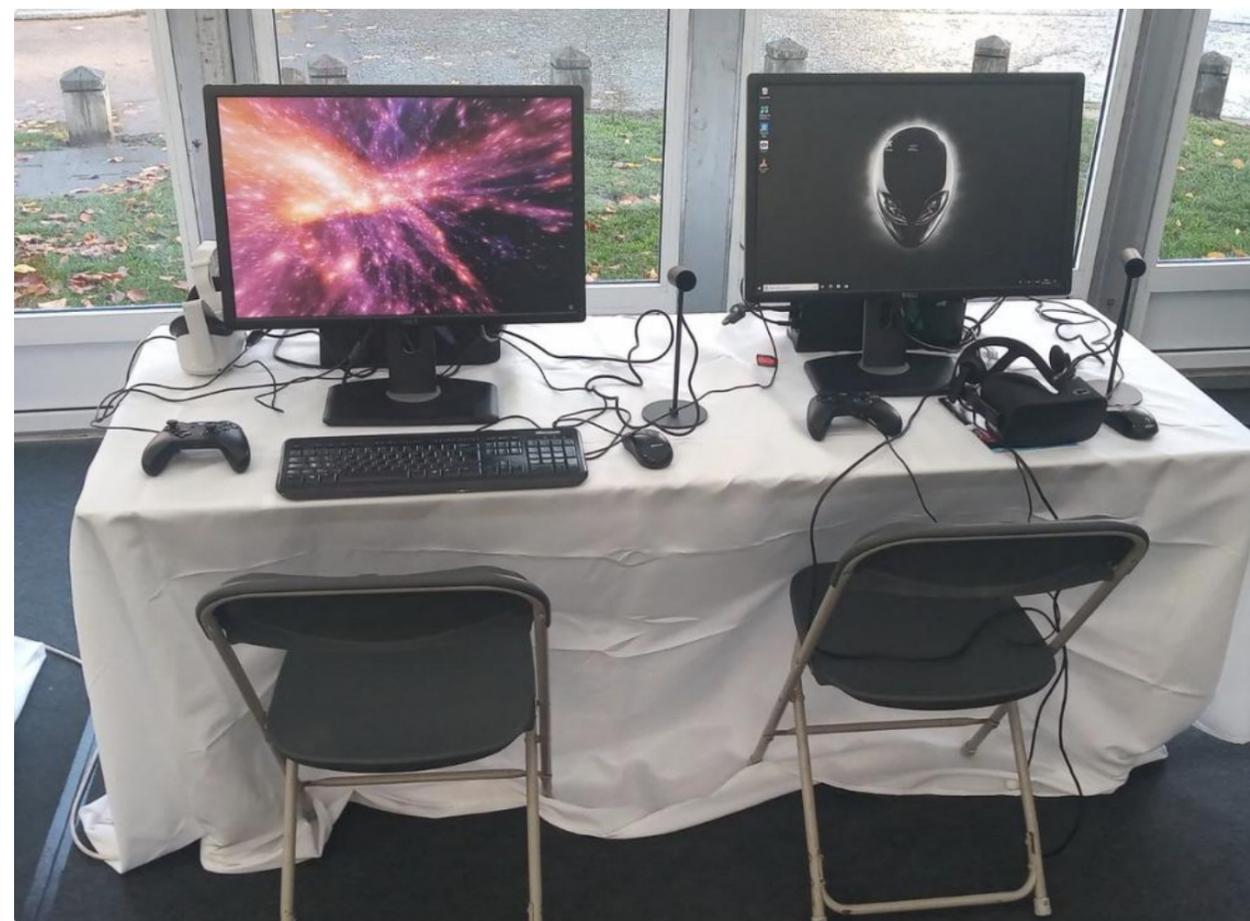
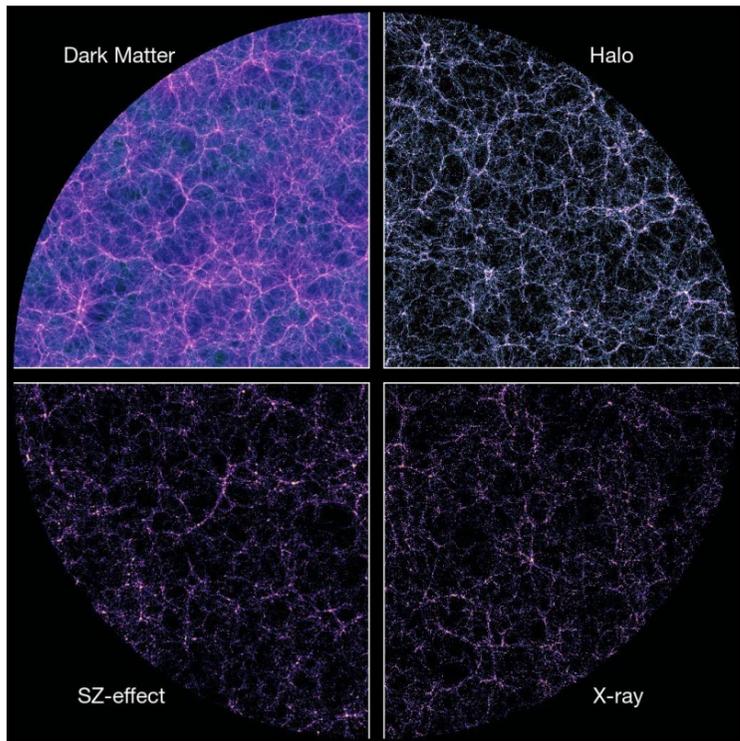
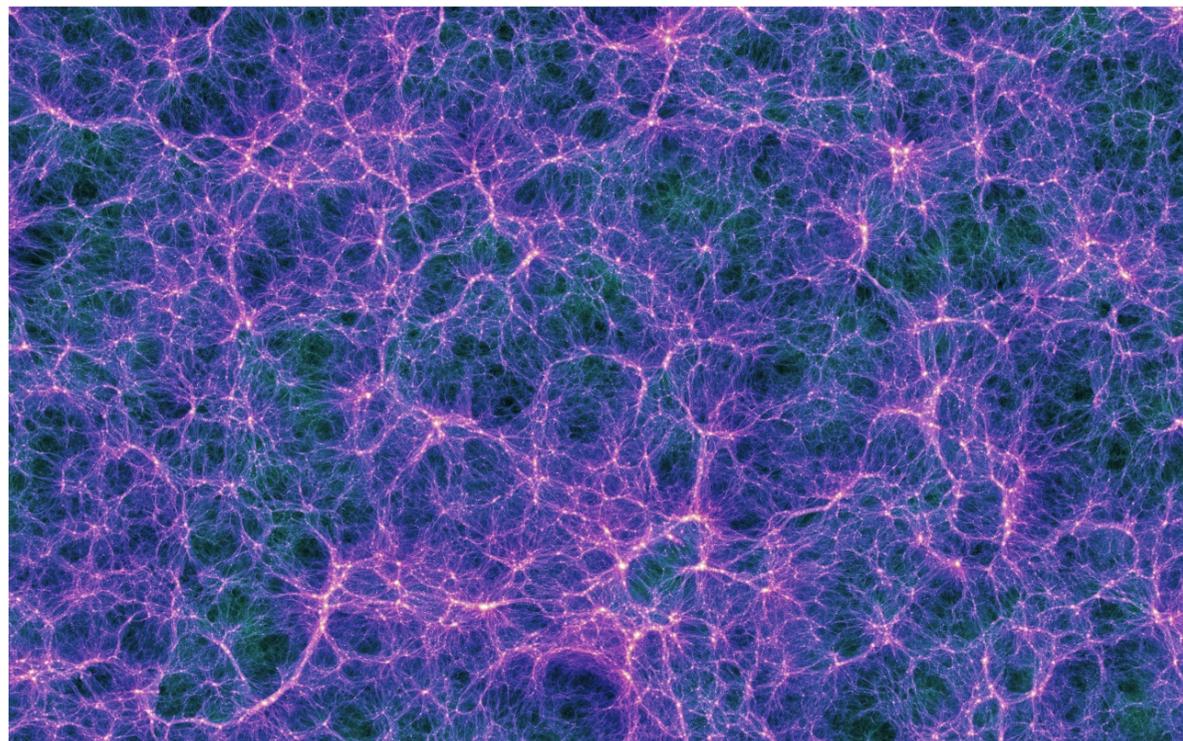
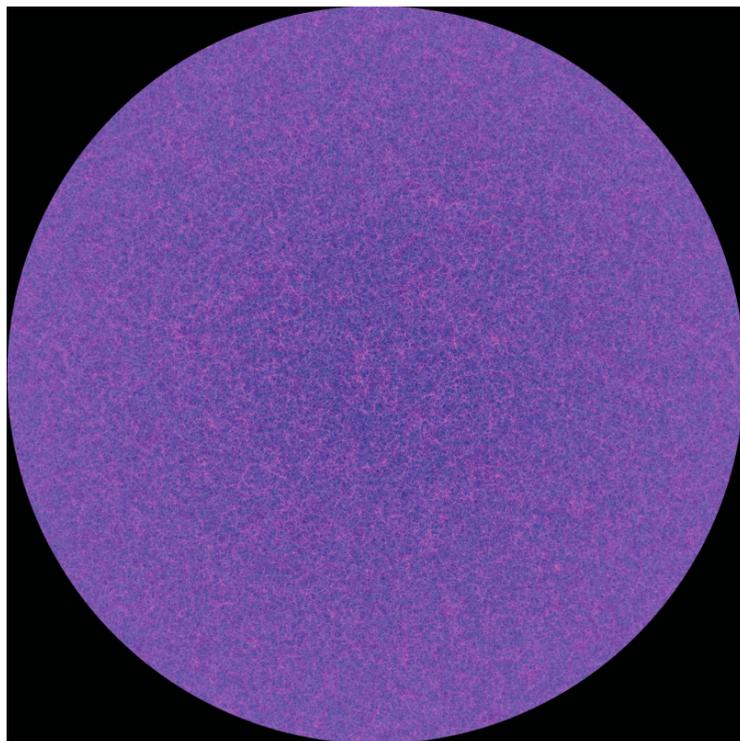
The Millennium Run Observatory, Overzier, R. Et al. 2013, MNRAS



模拟数据的可视化



模拟数据的可视化



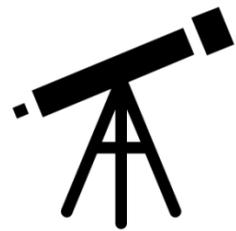
未来展望



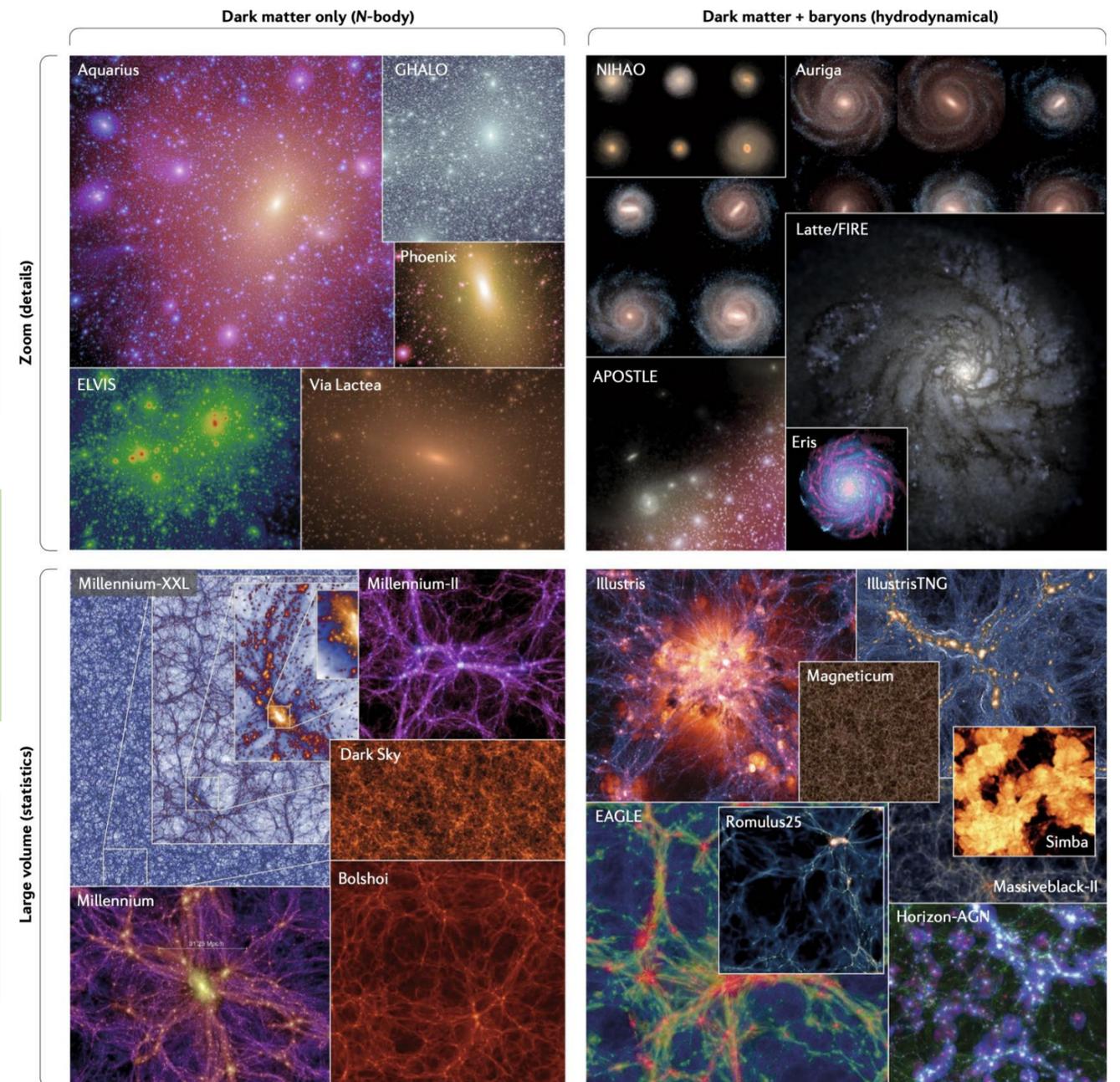
包含流体的宇宙学模拟，追踪复杂的结构形成和天体物理过程

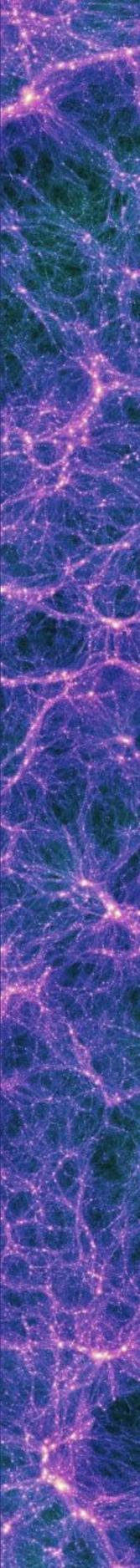


异构并行计算，异构加速部件；自主软件的研发，全流程的自主、可控



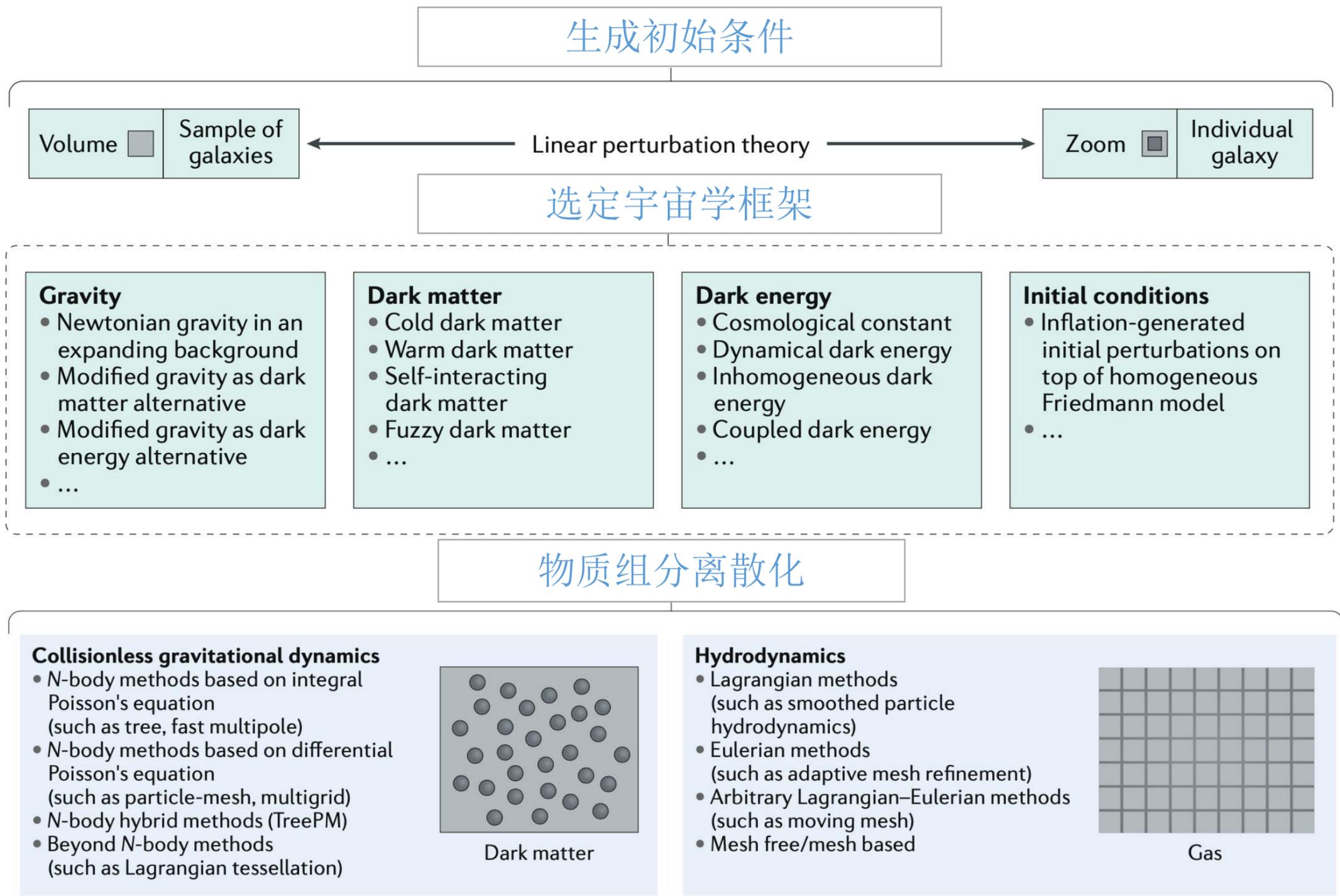
面向我国主导、参与项目的科学需求为我国的大科学装置服务





Huge simulations – State of the art

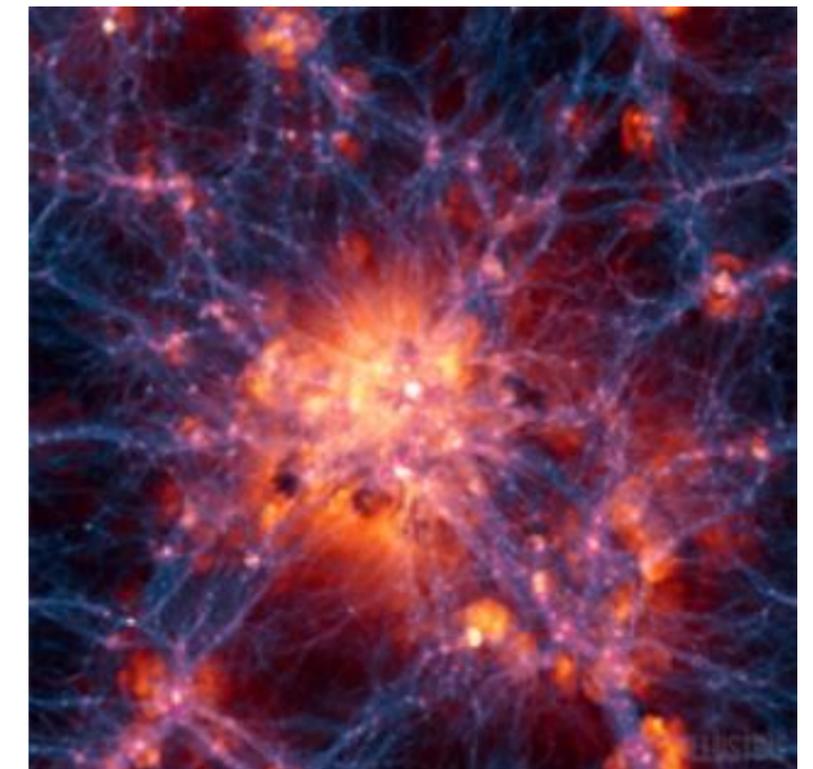
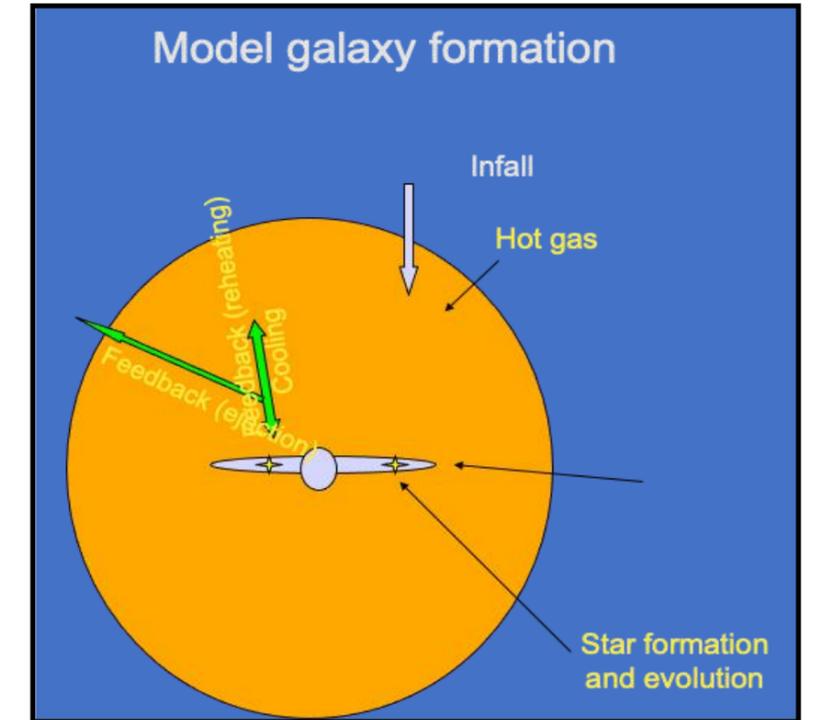
Name	Code	L_{box} [$h^{-1}\text{Mpc}$]	N_{p} [10^9]	m_{p} [$h^{-1}M_{\odot}$]	ϵ_{soft} [$h^{-1}\text{kpc}$]	z range	N_{snap}	Halofinder / Mergertree
Horizon Run 3	GOTPM	10815	370	2.5×10^{11}	150.0	—	—	—
Bolshoi PL	ART	250	8.6	1.6×10^8	1.0 [†]	[0,80]	178	BDM, FOF, Rockstar / Consistent Tree
Small MultiDark PL	GADGET-2	400	57	1.5×10^9	5.0	[0,120]	89	FOF, Rockstar / Consistent Tree
MultiDark PL	GADGET-2	1000	57	1.5×10^9	$30 \sim 10^{\dagger}$	[0,120]	89	BDM, FOF, Rockstar / Consistent Tree
Big MultiDark PL	GADGET-2	2500	57	2.4×10^{10}	$30 \sim 10^{\dagger}$	[0,100]	80	BDM, Rockstar / ?
Huge MultiDark PL	GADGET-2	4000	69	7.9×10^{10}	$50 \sim 25^{\dagger}$	[0,100]	—	BDM, Rockstar / ?
Horizon-4II	RAMSES	2000	69	7.8×10^9	7.6 [†]	—	—	—
DEUS FUR	RAMSES-DEUS	21000	550	1.2×10^{12}	40.0 [†]	[0, 106]	31	PFOF-DEUS / ?
Pangu	L-GADGET-2	1000	29	2.5×10^9	7.0	[0, 127]	64	FOF, SubFind / MPA Tree
Tiangong Pathfinder	L-GADGET-3	1000	232	3.72×10^8	4.0	[0, 63]	128	FOF, SubFind / MPA Tree
$\nu^2\text{GC-L}$	GREEM	1120	550	2.2×10^8	4.3	[0, 127]	51	FOF, Rockstar / Consistent Tree
Shin-Uchuu	GREEM	140	262	8.97×10^5	0.4	[0, 127]	51	FOF, Rockstar / Consistent Tree
Uchuu	GREEM	2000	~ 2000	3.27×10^8	4.27	[0, 127]	51	FOF, Rockstar / Consistent Tree
Euclid Flagship	PKDGRAV3	3780	~ 2000	$\sim 2.398 \times 10^9$	4.8	[0, 49]	—	Rockstar / ?
Euclid Flagship v2.0	PKDGRAV3	3600	~ 4000	$\sim 1 \times 10^9$	—	—	—	—
Q-Continuum	HACC	923	~ 550	1.05×10^8	—	[0, 200]	101	FOF / Rangel, E. et al. 2020
Outer Rim	HACC	3000	~ 1070	1.85×10^9	—	[0, 200]	99	FOF / Rangel, E. et al. 2020
Millennium	L-GADGET-2	500	10	8.6×10^8	5.0	[0, 127]	64	FOF, SubFind / MPA Tree
Millennium-II	P-GADGET-3	100	10	6.9×10^6	1.0	[0, 127]	68	FOF, SubFind / MPA Tree
Millennium-XXL	L-GADGET-3	3000	300	6.2×10^9	10.0	[0, 63]	64	FOF, SubFind / MPA Tree
Hyper-Millennium	GADGET-4	2000	2000	3.4×10^8	3.0	[0, 63]	128	on-the-fly



未来展望

星系形成—要理解宇宙，必须从理解星系开始

Galaxies are strongly coupled, highly nonlinear, multi-scale and multi-physics systems with timescales \ll the Hubble time



Most important astrophysical processes

Gas cooling	Interstellar medium	Star formation	Stellar feedback	Supermassive black holes	Active galactic nuclei	Magnetic fields	Radiation fields	Cosmic rays
Atomic/ molecular/ metals/ tabulated network	Effective equation of state/ multiphase	Initial stellar mass function/ probabilistic sampling/ enrichment	Kinetic/ thermal/ variety of sources from stars, supernovae	Numerical seeding/ growth by accretion prescription/ merging	Kinetic/ thermal/ radiative/ quasar model radio mode	Ideal MHD/ cleaning schemes/ constrained transport	Ray tracing/ Monte Carlo/ moment based	Production/ heating/ anisotropic diffusion/ streaming

Vogelsberger, M., Marinacci, F., Torrey, P. et al. Cosmological simulations of galaxy formation. *Nat Rev Phys* 2, 42–66 (2020). <https://doi.org/10.1038/s42254-019-0127-2>