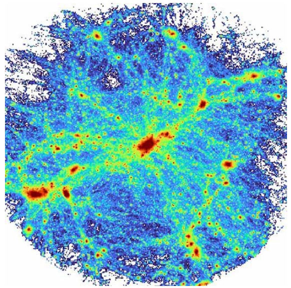
中国科学技术大学
University of Science and Technology of China



Cosmology Simulation

From N-body to Hydrodynamical

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Weitian Wang *PB24511938*

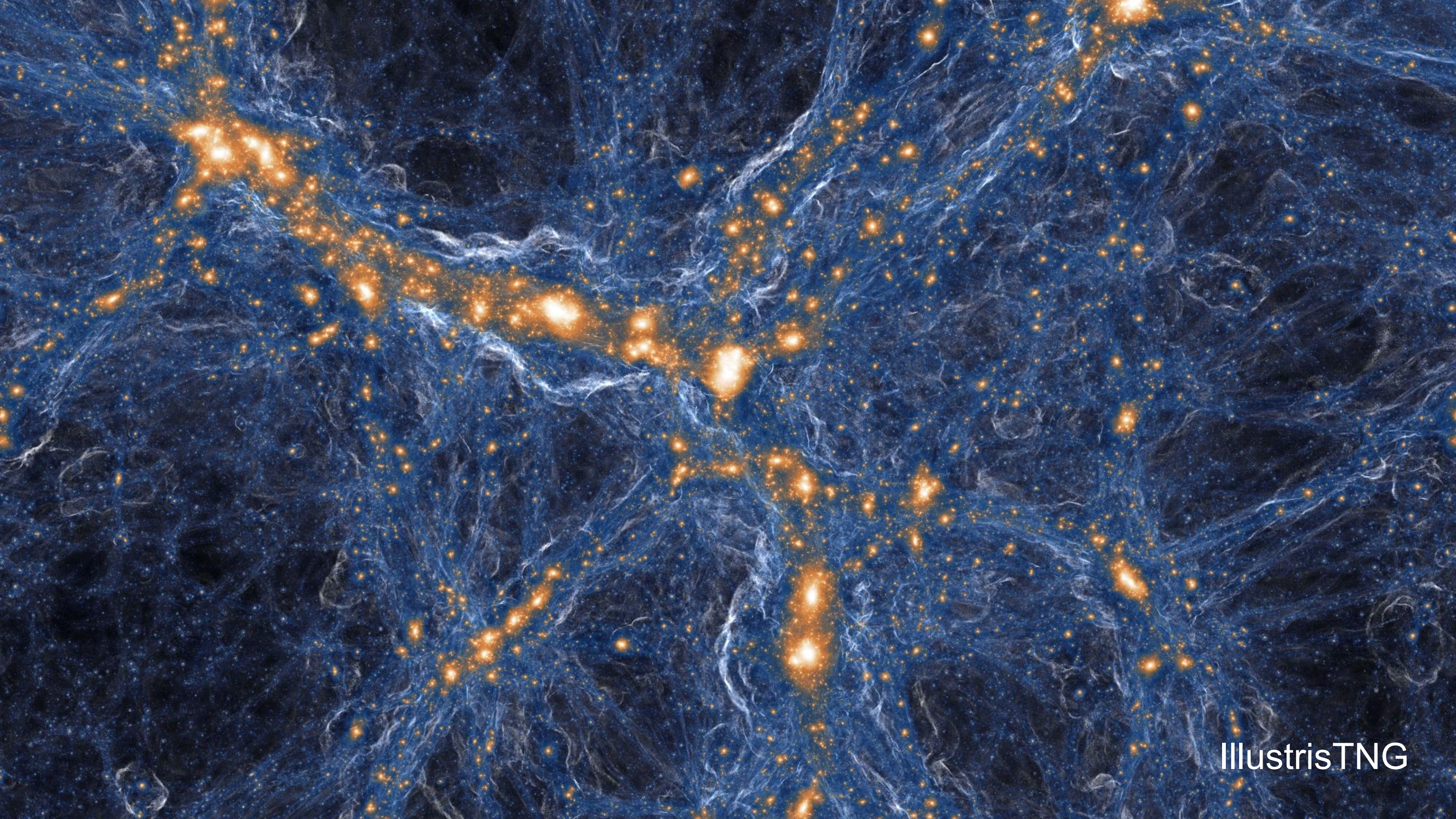
天体物理前沿讲座
06/01/2026

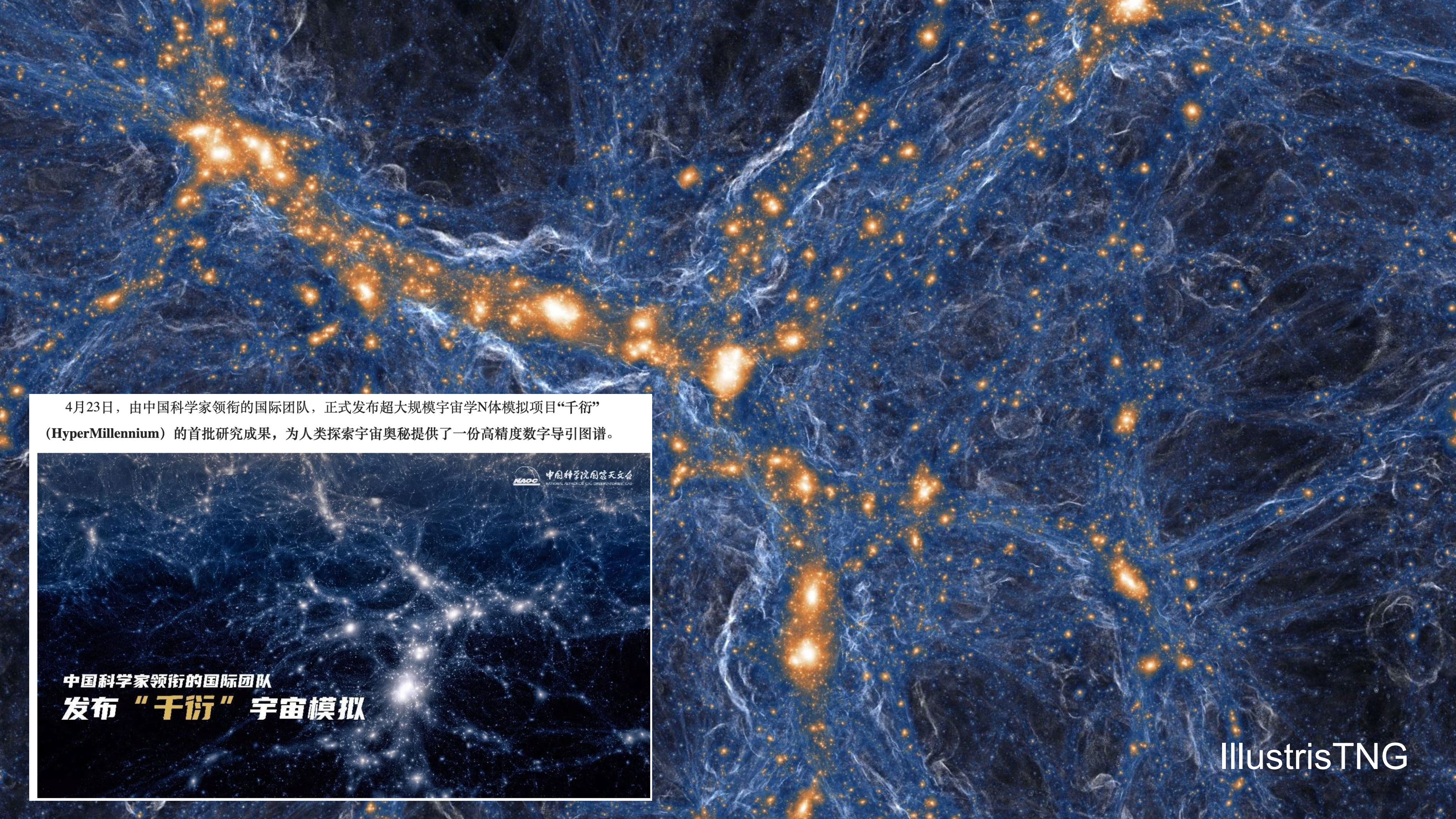
What we will talk about:

- What cosmology simulation do
- Why cosmology simulation
- How to perform N-body simulation
- About hydrodynamical simulation
- Adding AGN feedback
- Further Work

Hongfei

Weitian


IllustrisTNG



4月23日，由中国科学家领衔的国际团队，正式发布超大规模宇宙学N体模拟项目“千衍”（HyperMillennium）的首批研究成果，为人类探索宇宙奥秘提供了一份高精度数字导引图谱。

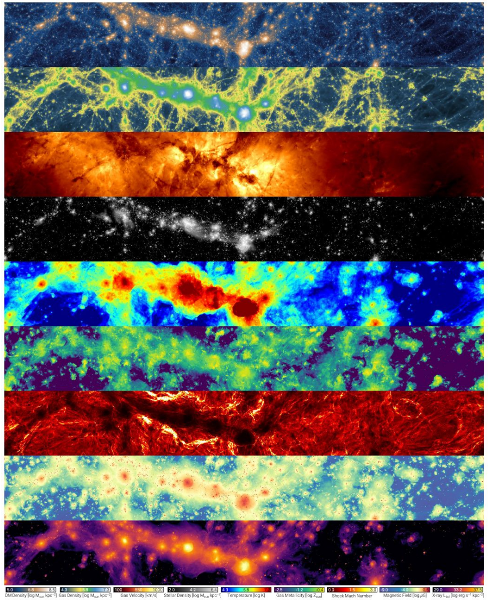
Cosmology Simulation

Input Parameters → **Evolution** → **Output Data**

Run	Volume [cMpc^3]	$L_{\rm box}$ [cMpc/h]	$N_{\rm GAS,DM}$ -	$N_{\rm TRACER}$ -	$m_{\rm baryon}$ [M$_\odot$/h]	$m_{\rm DM}$ [M$_\odot$/h]	$m_{\rm baryon}$ [10^6 M$_\odot$]	$m_{\rm DM}$ [10^6 M$_\odot$]
TNG50-1	51.7^3	35	2160^3	1×2160^3	5.7×10^4	3.1×10^5	0.08	0.45
TNG50-2	51.7^3	35	1080^3	1×1080^3	4.6×10^5	2.5×10^6	0.68	3.63
TNG50-3	51.7^3	35	540^3	1×540^3	3.7×10^6	2.0×10^7	5.4	29.0
TNG50-4	51.7^3	35	270^3	1×270^3	2.9×10^7	1.6×10^8	43.4	232
TNG100-1	106.5^3	75	1820^3	2×1820^3	9.4×10^5	5.1×10^6	1.4	7.5
TNG100-2	106.5^3	75	910^3	2×910^3	7.6×10^6	4.0×10^7	11.2	59.7
TNG100-3	106.5^3	75	455^3	2×455^3	6.0×10^7	3.2×10^8	89.2	478
TNG300-1	302.6^3	205	2500^3	1×2500^3	7.6×10^6	4.0×10^7	11	59
TNG300-2	302.6^3	205	1250^3	1×1250^3	5.9×10^7	3.2×10^8	88	470
TNG300-3	302.6^3	205	625^3	1×625^3	4.8×10^8	2.5×10^9	703	3760
TNG50-1-Dark	51.7^3	35	2160^3	-	-	3.7×10^5	-	0.55
TNG50-2-Dark	51.7^3	35	1080^3	-	-	2.9×10^6	-	4.31
TNG50-3-Dark	51.7^3	35	540^3	-	-	2.3×10^7	-	34.5
TNG50-4-Dark	51.7^3	35	270^3	-	-	1.9×10^8	-	275
TNG100-1-Dark	106.5^3	75	1820^3	-	-	6.0×10^6	-	8.9
TNG100-2-Dark	106.5^3	75	910^3	-	-	4.8×10^7	-	70.1
TNG100-3-Dark	106.5^3	75	455^3	-	-	3.8×10^8	-	567
TNG300-1-Dark	302.6^3	205	2500^3	-	-	7.0×10^7	-	47
TNG300-2-Dark	302.6^3	205	1250^3	-	-	3.8×10^8	-	588
TNG300-3-Dark	302.6^3	205	625^3	-	-	3.0×10^9	-	4470

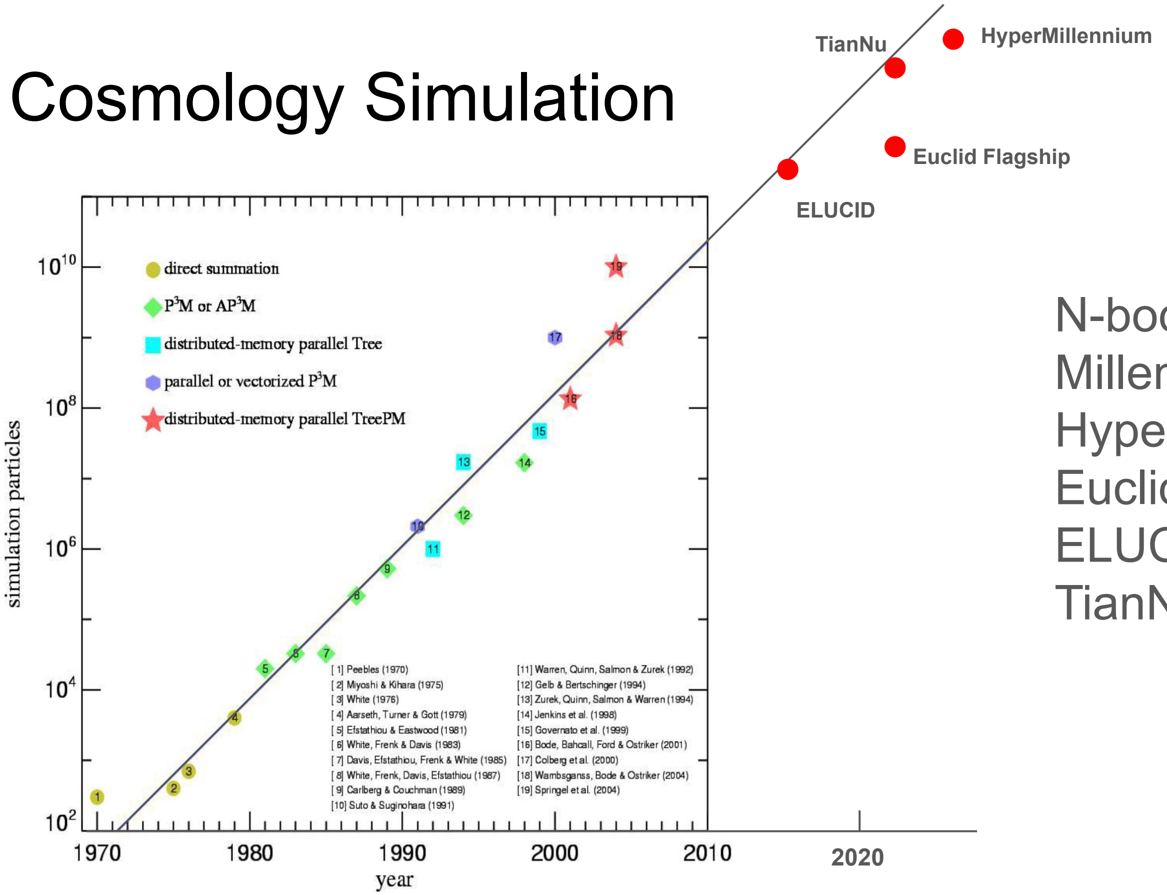
Run	$\epsilon_{\rm DM,\star}^{z=0}$ [kpc]	$\epsilon_{\rm DM,\star}$ [ckpc/h]	$\epsilon_{\rm gas,min}$ [ckpc/h]	$r_{\rm cell,min}$ [pc]	$\bar{r}_{\rm cell}$ [kpc]	$\bar{r}_{\rm cell,SF}$ [pc]	$\bar{n}_{\rm H,SF}$ [cm^{-3}]	$n_{\rm H,max}$ [cm^{-3}]
TNG50-1	0.29	$0.39 \rightarrow 0.195$	0.05	8	5.8	138	0.8	650
TNG50-2	0.58	$0.78 \rightarrow 0.39$	0.1	19	12.9	282	0.7	620
TNG50-3	1.15	$1.56 \rightarrow 0.78$	0.2	65	25.0	562	0.6	80
TNG50-4	2.30	$3.12 \rightarrow 1.56$	0.4	170	50.1	1080	0.5	35
TNG100-1	0.74	$1.0 \rightarrow 0.5$	0.125	14	15.8	355	1.0	3040
TNG100-2	1.48	$2.0 \rightarrow 1.0$	0.25	74	31.2	720	0.6	185
TNG100-3	2.95	$4.0 \rightarrow 2.0$	0.5	260	63.8	1410	0.5	30
TNG300-1	1.48	$2.0 \rightarrow 1.0$	0.25	47	31.2	715	0.6	490
TNG300-2	2.95	$4.0 \rightarrow 2.0$	0.5	120	63.8	1420	0.5	235
TNG300-3	5.90	$8.0 \rightarrow 4.0$	1.0	519	153	3070	0.4	30

Snap	a	z	Snap	a	z
2	0.0769	12	33	0.3333	2
3	0.0833	11	40	0.4	1.5
4	0.0909	10	50	0.5	1
6	0.1	9	59	0.5882	0.7
8	0.1111	8	67	0.6667	0.5
11	0.125	7	72	0.7143	0.4
13	0.1429	6	78	0.7692	0.3
17	0.1667	5	84	0.8333	0.2
21	0.2	4	91	0.9091	0.1
25	0.25	3	99	1	0



Nelson+ (2019) (IllustrisTNG)

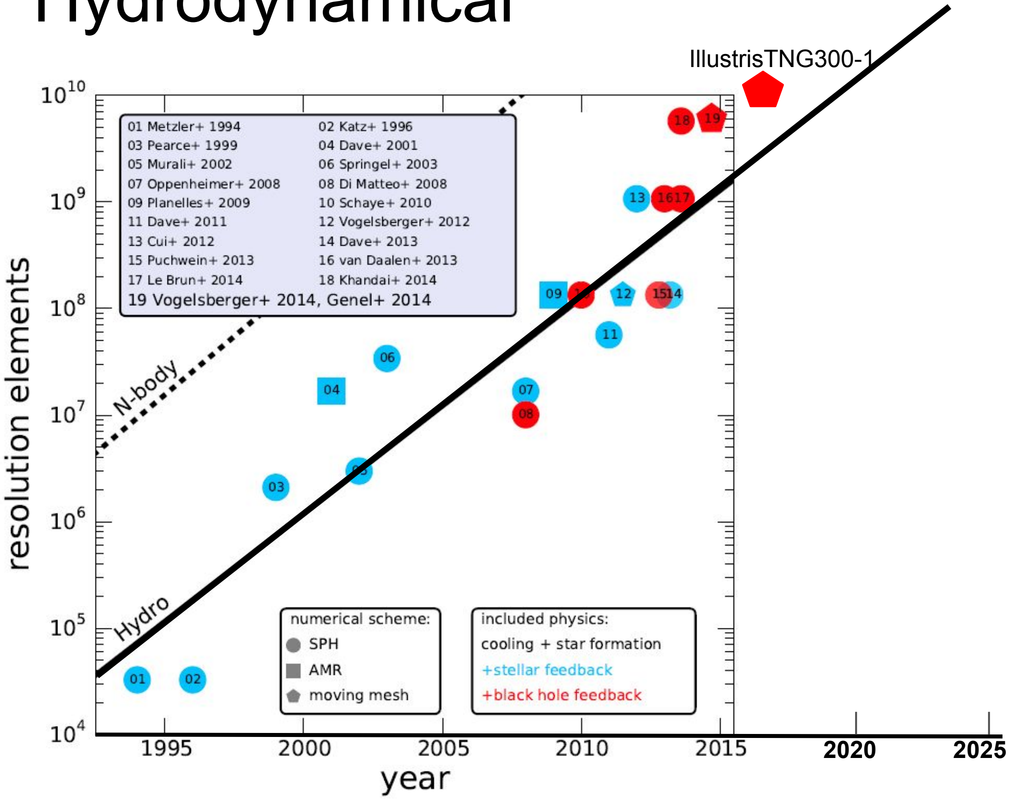
Cosmology Simulation



Springel+ (2004)

N-body simulation:
Millennium
HyperMillennium (@NAOC & @SHAO)
Euclid Flagship
ELUCID (@USTC & @SJTU)
TianNu (@CITA & @NAOC)

Hydrodynamical



Hydrodynamical simulation:
EAGLE
IllustrisTNG
NIHAO
FIRE
ELUCID-hydro

Sijacki+ (2015)

Why cosmology simulation?

Growth history of the Universe

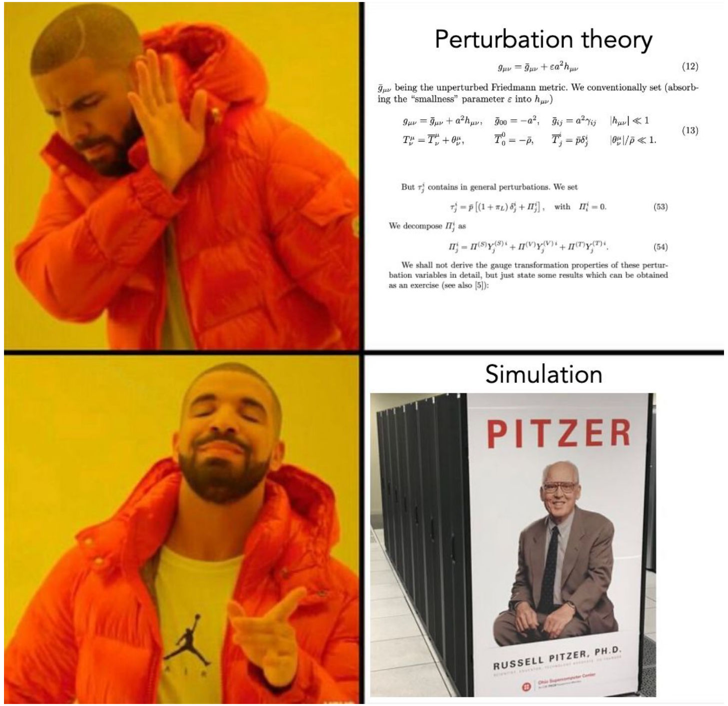
Nature of DARK ENERGY

Nature of DARK MATTER

INFLATION theory

GENERAL RELATIVITY

Simulation Based Inference (SBI) !



Credit: Annika Peter

Why cosmology simulation?

Precision Cosmology

Prob the universe:
BAO (Boxsize > 2Gpc/h)
Weak Lensing
RSD
and etc.

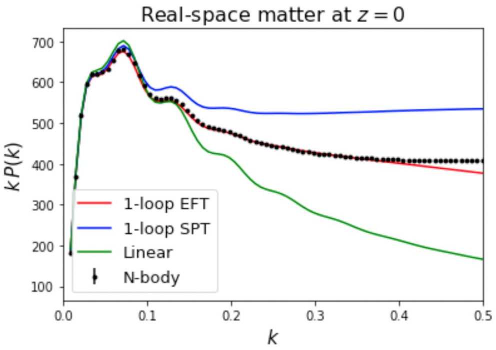
Credit: DESI

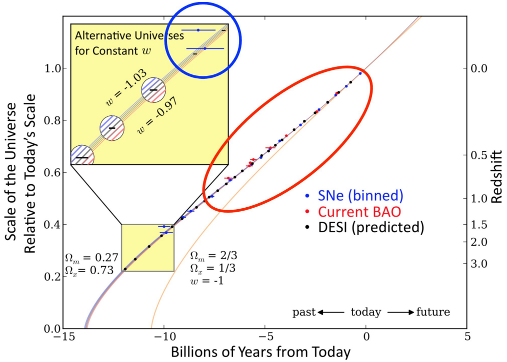
Why cosmology simulation?

Theory — Computing — Observation

Computing → Simulation

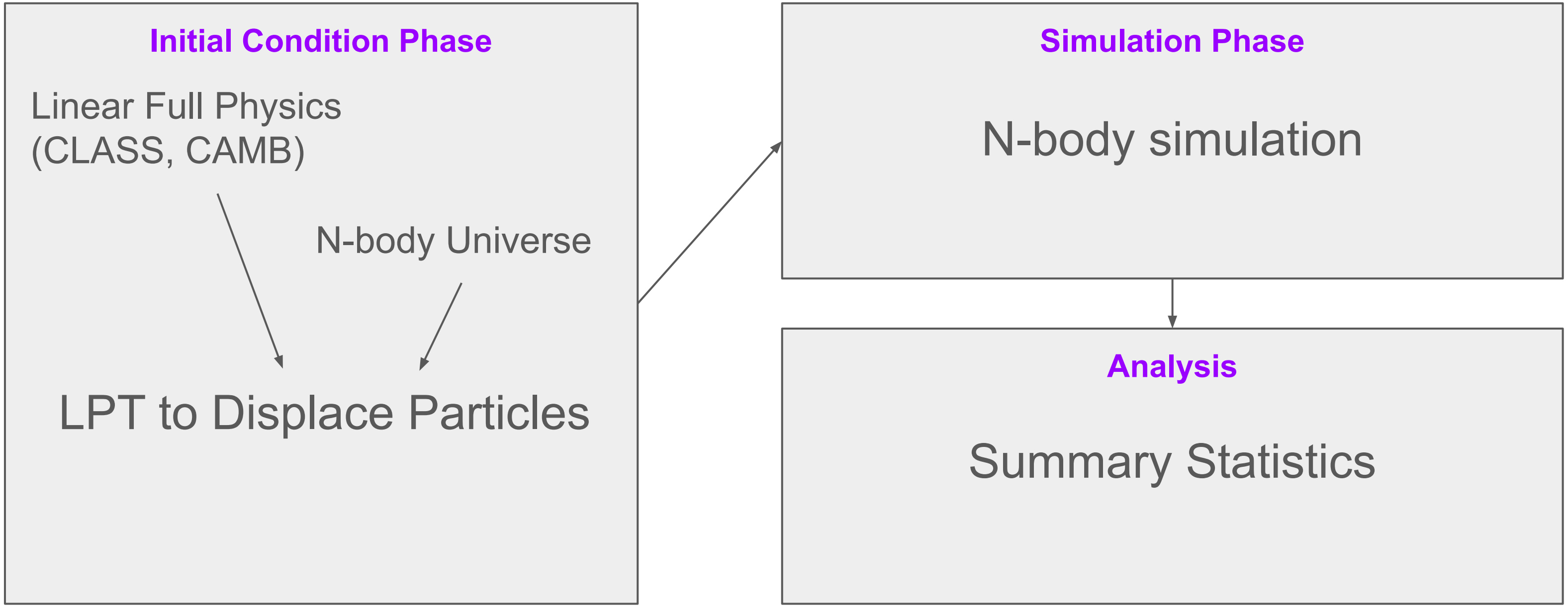
Computing → Emulation





Credit: (Left fig.) Oliver Philcox
(Right fig.) Ofer Lahav

N-body Simulation



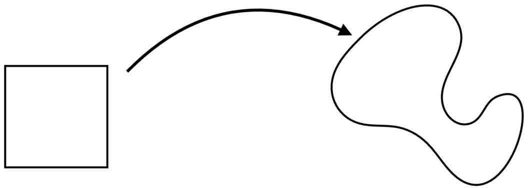
Credit: Atelier (2020)

N-body Simulation — Initial Condition

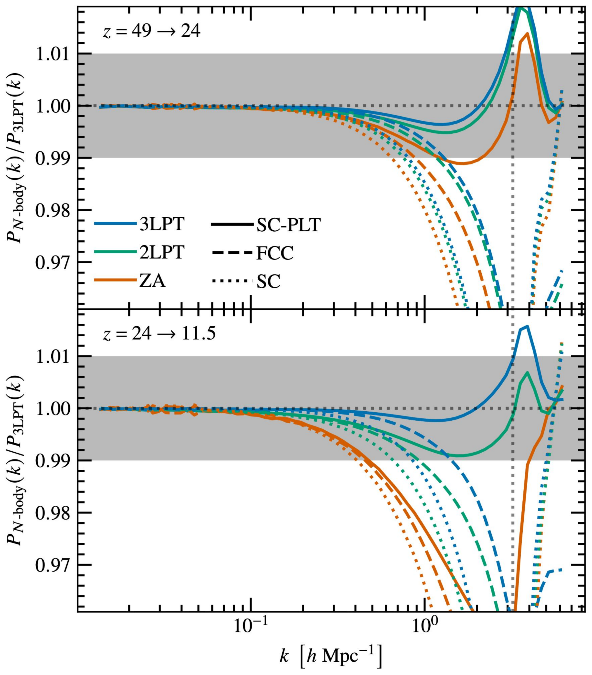
Lagrangian Perturbation Theory (LPT)

$$\boldsymbol{x}(\tau) = \boldsymbol{q} + \boldsymbol{\Psi}(\boldsymbol{q}, \tau).$$

$$\mathbb{Q} \subset \mathbb{R}^3 \to \mathbb{R}^6 \; : \; \mathbf{q} \mapsto (\mathbf{x_q}(t), \mathbf{v_q}(t))$$



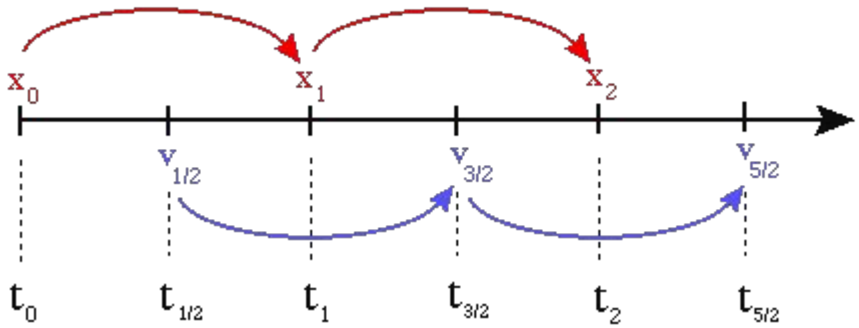
$$\left\langle |\delta(\boldsymbol{k}, z)|^2 \right\rangle = \frac{(2\pi)^3}{k_F^3} P(k, z) = V P(k, z),$$



Credit: Atelier (2020), Michaux+ (2020)

N-body Simulation — Evolution

Leapfrog Method（drift-kick-drift as an example）:



$$\{\boldsymbol{x}(t_n), \boldsymbol{p}(t_n)\}$$

$$\text{Drift: } \mathbf{D}\left(\frac{\Delta t}{2}\right)\Big\downarrow \quad \boldsymbol{x}\left(t_{n+\frac{1}{2}}\right) = \boldsymbol{x}(t_n) + \boldsymbol{v}(t_n)\frac{\Delta t}{2}$$

$$\{\boldsymbol{x}\left(t_{n+\frac{1}{2}}\right), \boldsymbol{p}(t_n)\}$$

$$\text{Kick: } \mathbf{K}(\Delta t)\Big\downarrow \quad \boldsymbol{v}(t_{n+1}) = \boldsymbol{v}(t_n) + \boldsymbol{F}\left(t_{n+\frac{1}{2}}\right)\Delta t$$

$$\{\boldsymbol{x}\left(t_{n+\frac{1}{2}}\right), \boldsymbol{p}(t_{n+1})\}$$

$$\text{Drift: } \mathbf{D}\left(\frac{\Delta t}{2}\right)\Big\downarrow \quad \boldsymbol{x}(t_{n+1}) = \boldsymbol{x}\left(t_{n+\frac{1}{2}}\right) + \boldsymbol{v}(t_{n+1})\frac{\Delta t}{2}$$

$$\{\boldsymbol{x}(t_{n+1}), \boldsymbol{p}(t_{n+1})\}$$

Credit: Shuyan's Note

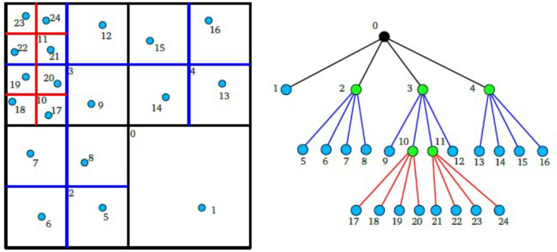
N-body Simulation — Gravity Solving

$$\frac{d\mathbf{r}_i}{dt} = \mathbf{u}_i,$$

$$\frac{d\mathbf{u}_i}{dt} = \mathbf{F}_i = -\nabla\phi|_i,$$

PP (particle-particle) $\mathbf{F}_i = -\sum_{j\neq i} Gm \frac{\mathbf{r}_i - \mathbf{r}_j}{|\mathbf{r}_i - \mathbf{r}_j|^3}.$

Tree



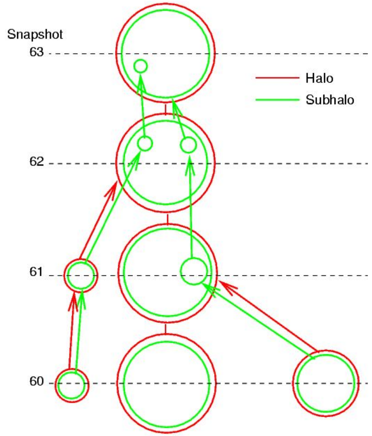
PM (particle-mesh) $\nabla^2\phi = 4\pi G\rho(\mathbf{r},t).$

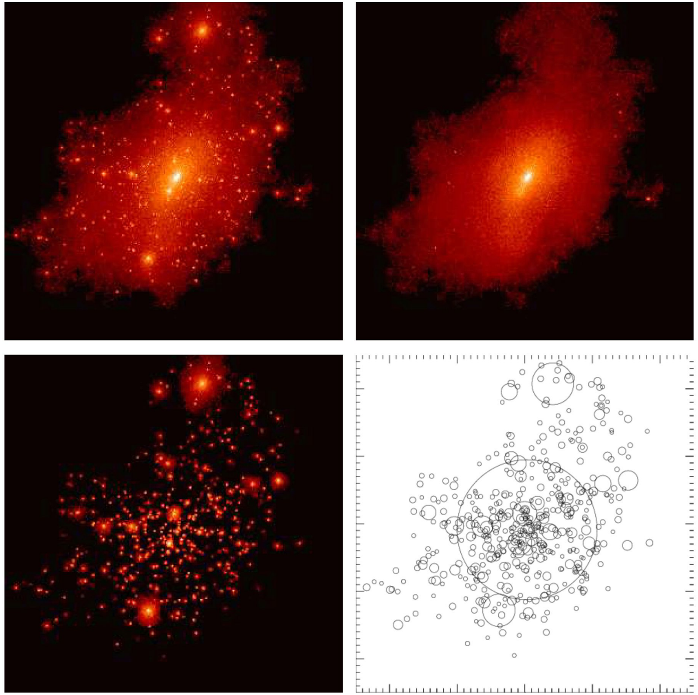
FMM, PP-PM (P3M), Tree-PM, FMM-PM……

N-body Simulation — Post-processing

Substructure Find Method:
Friend of Friend (FOF)
ROCKSTAR

Merge Tree





FOF: Springel+ (2000)
Merge Tree: Millennium Merger Trees

N-body Simulation

To fully access a simulation, you should know:

- Simulation Details (parameters and configs)
- Snapshot
- Initial Conditions
- Merge Trees
- (optional) Supplementary Data Catalogs

Simulation Details:

Parameter Description	Value
simulation name	TNG300-1
alternative simulation name	L205n2500TNG
short description of run	Main high-resolution IllustrisTNG300 run including the full TNG physics model.
side length of simulation box [ckpc/h]	205000.0
average gas cell mass [10^10 msun/h] (0=no gas)	0.000743736
dark matter particle mass [10^10 msun/h]	0.00398342749867548
number of dark matter particles	15625000000
number of gas tracer particles	15625000000
starting redshift (e.g. z=99)	127.0
ending redshift (e.g. z=0)	0.0
short description of cosmological parameters (e.g. 'WMAP-7')	Planck2015
total matter density (e.g. 0.27)	0.3089
dark energy density (e.g. 0.73)	0.6911
baryonic matter density (e.g. 0.04)	0.0486
hubble constant 'little h' in units of [100 km/s/Mpc]	0.6774

Snapshot List:

TNG300-1 has [100] snapshots available, with 201.5 TB total data volume.

Over all snapshots, have 1,696,057,751 FoF groups, 1,478,735,255 Subfind groups, and 3,092,931,362,649 particles.

Snapshot [#]	Redshift	Age [Gyr]	Lookback [Gyr]	Gas Cells [#]	Stars [#]	BHs [#]	FoF Groups [#]	Subfind Groups [#]	Download Snapshot	Download FoF & Subfind	Download Offsets
0	20.05	0.179	13.624	15624999994	4	0	10	10	[Snapshot] (1.5 TB)	[Groupcat] (15.2 MB)	
1	14.99	0.271	13.532	15624991902	4119	0	12167	12218	[Snapshot] (1.5 TB)	[Groupcat] (34.8 MB)	
2	11.98	0.370	13.433	15624633413	124698	7	265002	266304	[Snapshot] (4.1 TB)	[Groupcat] (262.5 MB)	
3	10.98	0.418	13.385	15623835834	343298	74	621780	624732	[Snapshot] (4.1 TB)	[Groupcat] (572.2 MB)	
4	10.00	0.475	13.328	15621625376	821487	381	1318085	1321052	[Snapshot] (4.1 TB)	[Groupcat] (1.1 GB)	
5	9.39	0.517	13.286	15618656262	1365221	635	2016524	2017659	[Snapshot] (1.5 TB)	[Groupcat] (1.7 GB)	

Initial Conditions:

TNG300-1 has its initial conditions available.

- Download Initial Conditions (465.7 GB in one HDF5 file)

Merger Trees:

TNG300-1 has the SubLink merger trees available: they contain the progenitor/descendant connectivity, and essentially all Subhalo properties.

- Download SubLink Tree (1.4 TB across 125 files)

TNG300-1 has the LHaloTree merger trees available: they contain the progenitor/descendant connectivity, and the most important Subhalo properties.

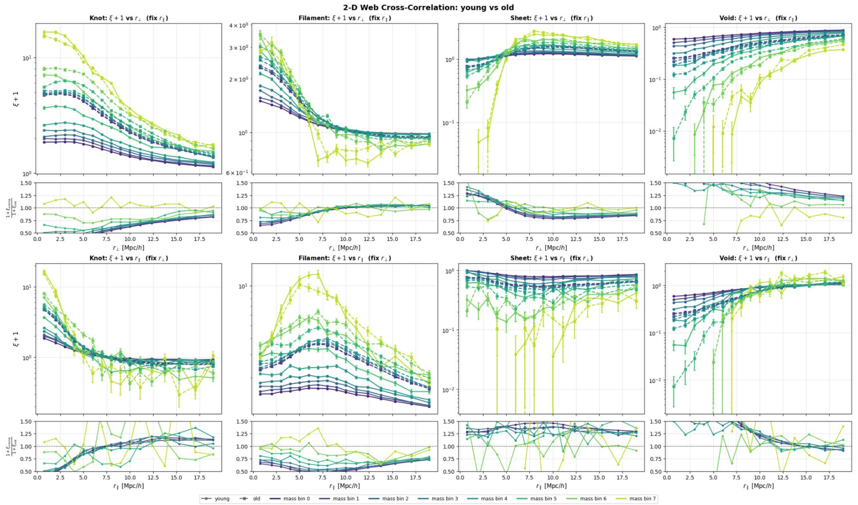
- Download LHaloTree (775.5 GB across 320 files)

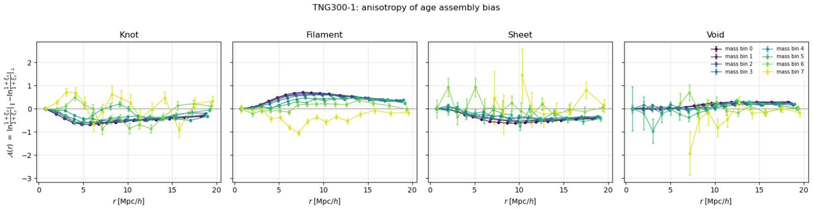
Credit: IllustrisTNG300-1

N-body Simulation

Analysis:

- Correlation function (assembly bias)
- Power spectrum
- Dark matter (halo/subhalo)
- Cosmic web
- ……





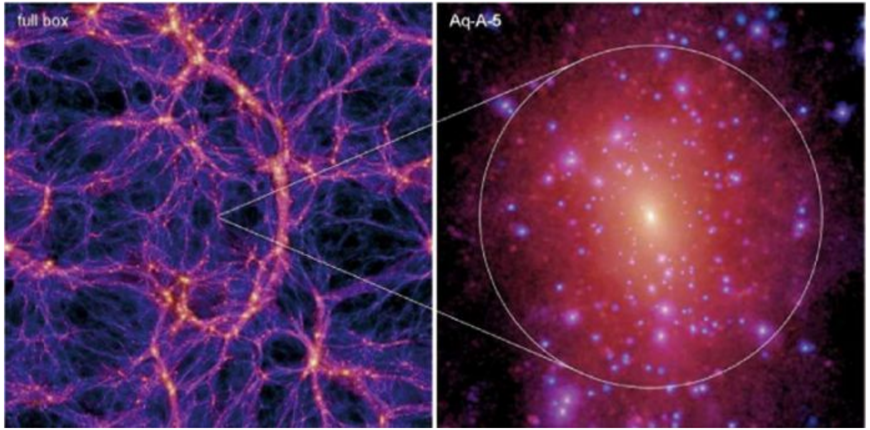
Yu+ (2026, in preparation)

Hydrodynamical Simulation

Key processes happen below the resolution of Cosmology simulation

Add gas dynamics and baryonic physics

Subgrid models for unresolved process



Consider:
Gravity, Hydrodynamics, Cooling and Heating, Star Formation, AGN feedback*…

Hydrodynamical Simulation

Gravity

$$\nabla^2\Phi = 4\pi G\rho_{\rm tot}$$

Hydrodynamics

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0$$

$$\frac{\partial(\rho\mathbf{v})}{\partial t} + \nabla\cdot(\rho\mathbf{v}\mathbf{v} + P\mathbf{I}) = -\rho\nabla\Phi$$

$$\frac{\partial E}{\partial t} + \nabla\cdot[(E+P)\mathbf{v}] = -\rho\mathbf{v}\cdot\nabla\Phi + \mathcal{H} - \mathcal{C}$$

Cooling and Heating

Star Formation

AGN Feedback*

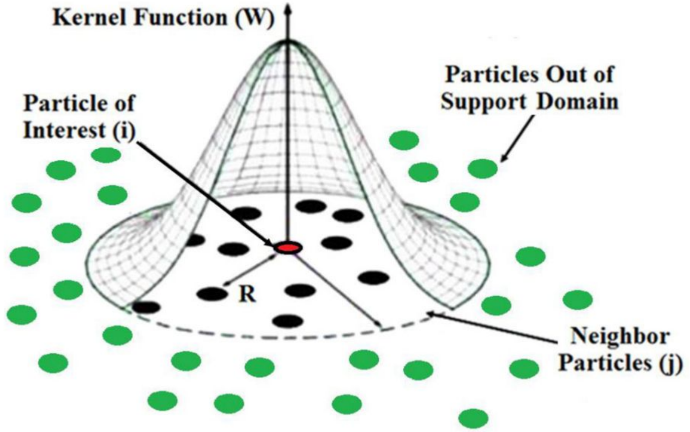
$$\dot{E}_{\rm feed} = \epsilon_f\epsilon_r\dot{M}_{\rm BH}c^2$$

Numerical Methods

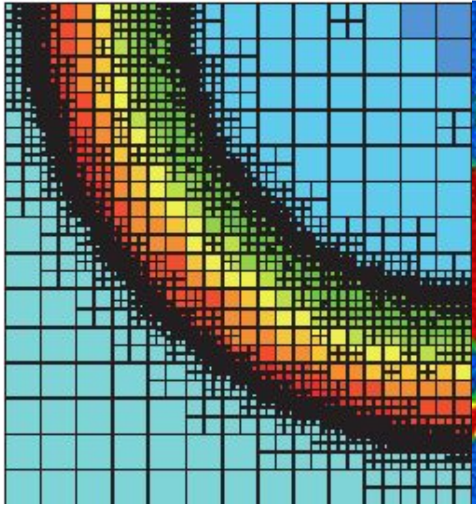
a) Smoothed Particle Hydrodynamics (SPH)

b) Adaptive Mesh Refinement (AMR)

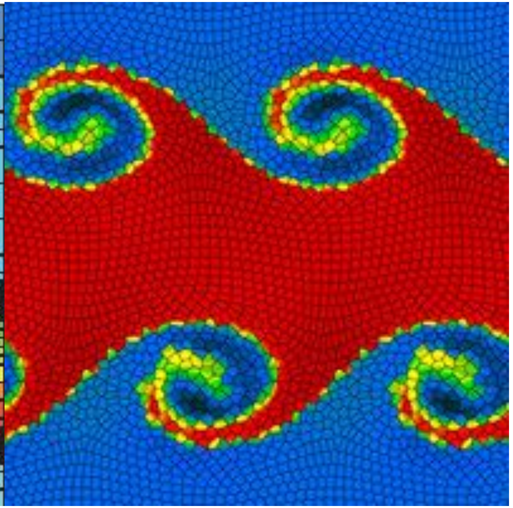
c) Moving Mesh (IllustrisTNG)



Bagheri et al. 2024

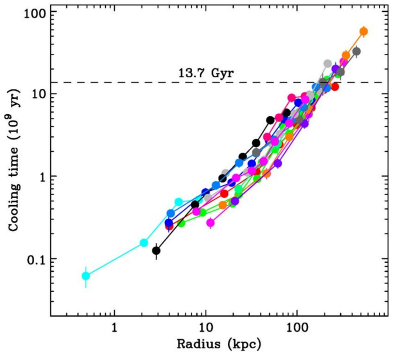


Tumblin et al. 2015



Springel 2010

AGN Feedback



Cooling Flow Problem:

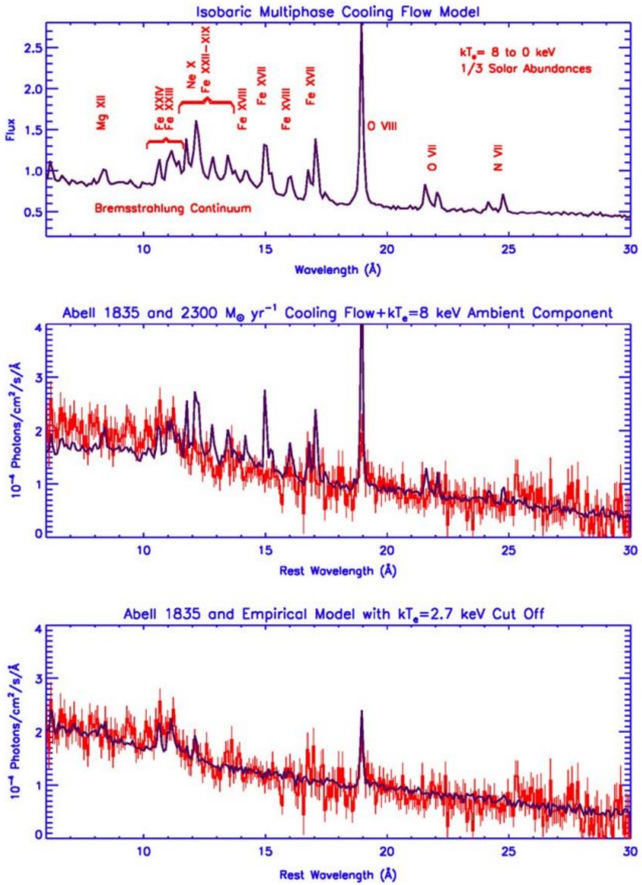
X-ray observation ⟶ Short cooling time

⟶ Cooling flow

Observed: No cooling gas (missing line)

Need heating! ⟶ AGN feedback

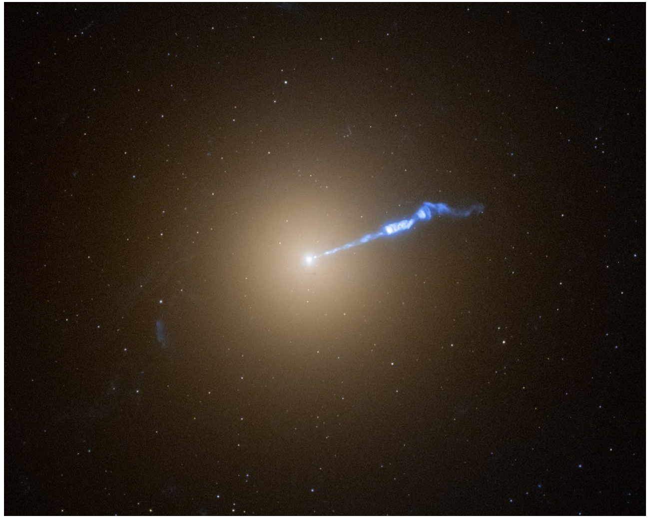
Radio/ Jet and Radiative/ Quasar Mode



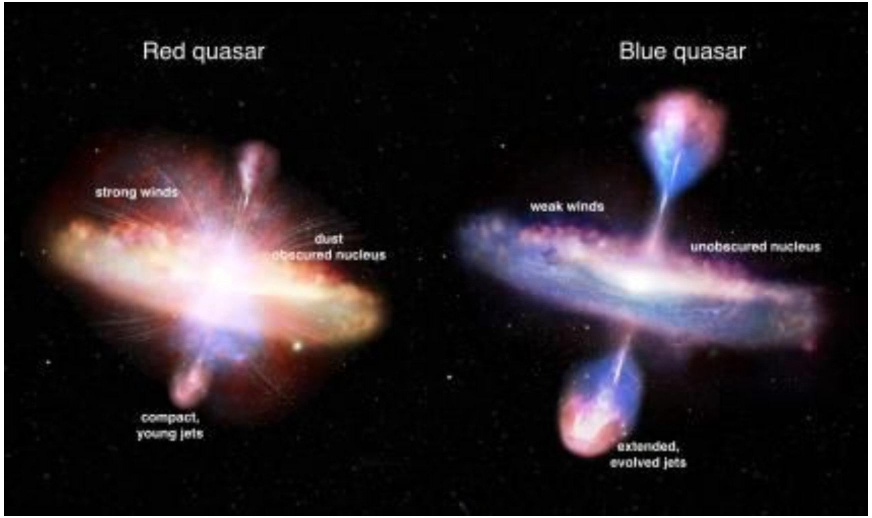
Peterson & Fabian 2006

Two Modes of AGN Feedback

Radio/ Jet Mode



Radiative/ Quasar Mode



Add AGN Feedback in Simulations

Basic procedure:

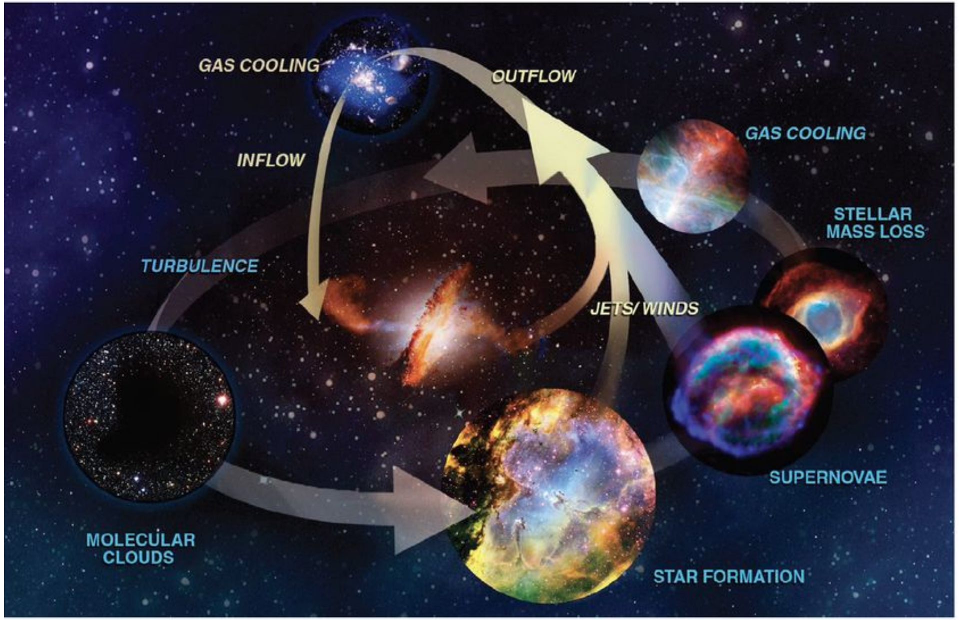
1. Seed black holes in massive halos

2. Grow BHs by gas accretion and mergers

3. Estimate accretion rate

4. Convert accreted mass into feedback energy

5. Inject energy into gas: thermal heating / kinetic winds



Lulu Zhang et al. 2025

Example: IllustrisTNG

AREPO moving-mesh MHD simulation

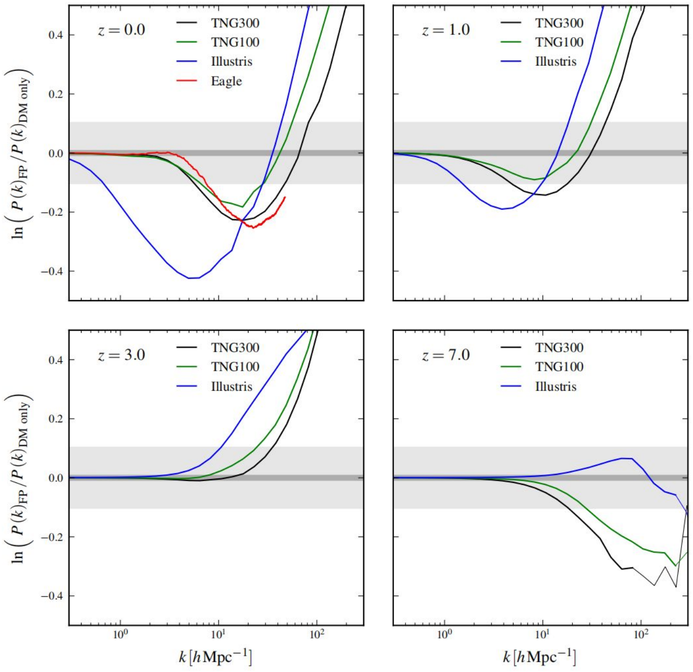
Updated galaxy formation model

New low-accretion radio AGN feedback

TNG300: 302.6 Mpc, 2×2500³

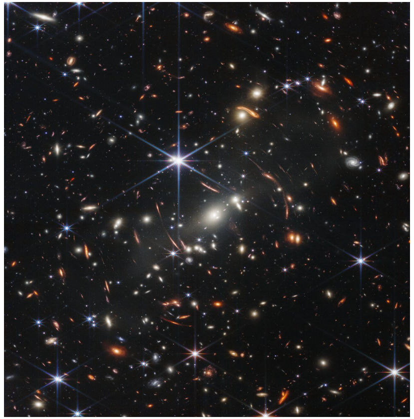
TNG100: 110.7 Mpc, 2×1820³

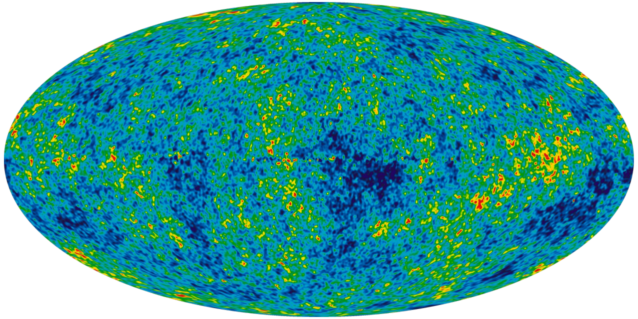
Full-physics + DM-only counterparts

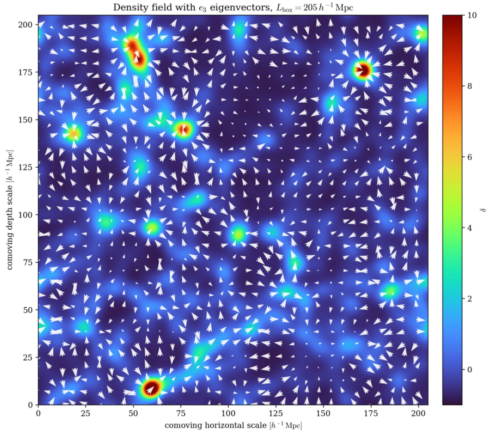


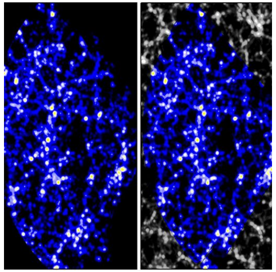
Springel et al. 2017

Further Work









Reconstruction of…

- Density field (scalar)
- Velocity field (vector)
- Tidal field (tensor)

Credit: NASA, ELUCID, Planck

Further Work

SBI

Simulation Based Inference:
Field level?
Effective Field Theory of Large-scale Structure (EFT of LSS) ?

Initial Conditions:
Quijote
and etc.

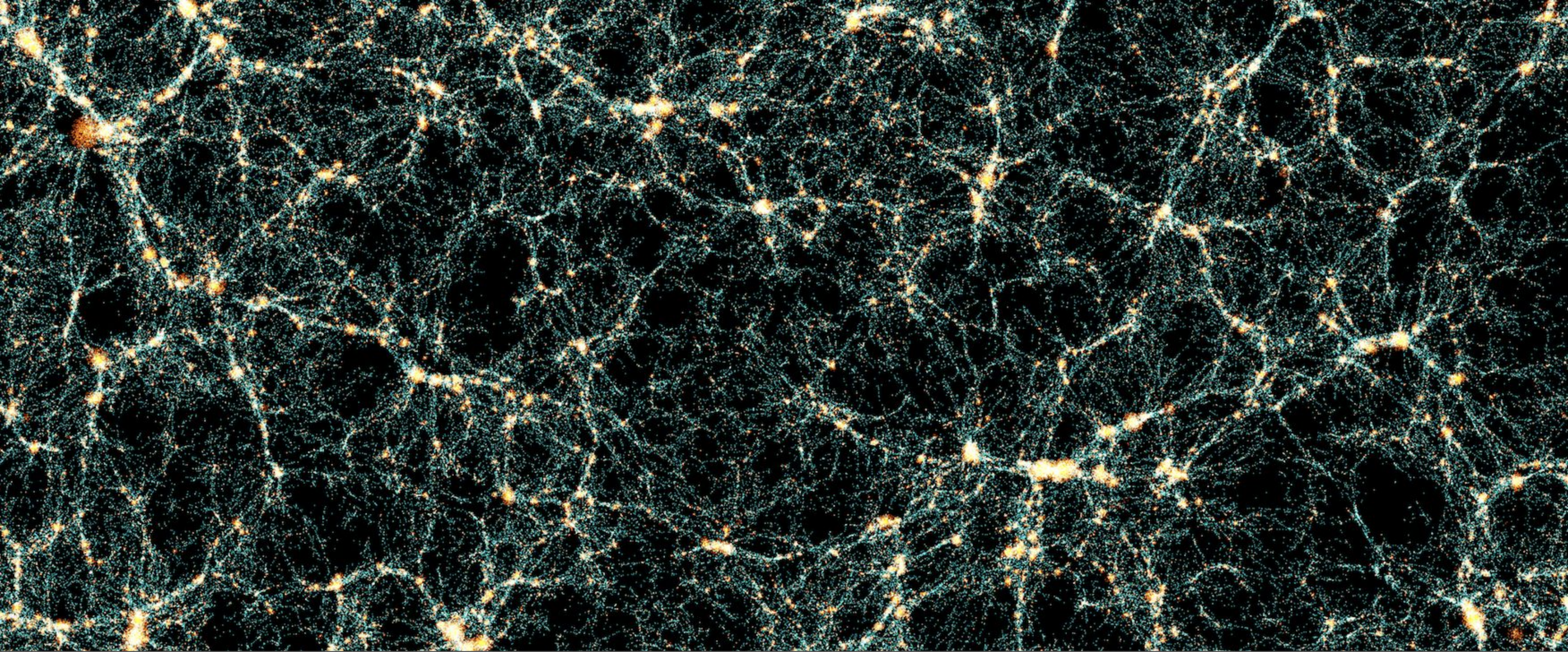
Clustering Dark Energy:
Linda+ (2026)
GINKAKU (2026)

Neutrinos:
TianNu (2023)
GINKAKU (2026)

Weak Lensing:
Stefan+ (2019)
Ulagam (2023)

Alternative DM Model:
AIDA-TNG (2025)

……



Thanks For Your Listening!