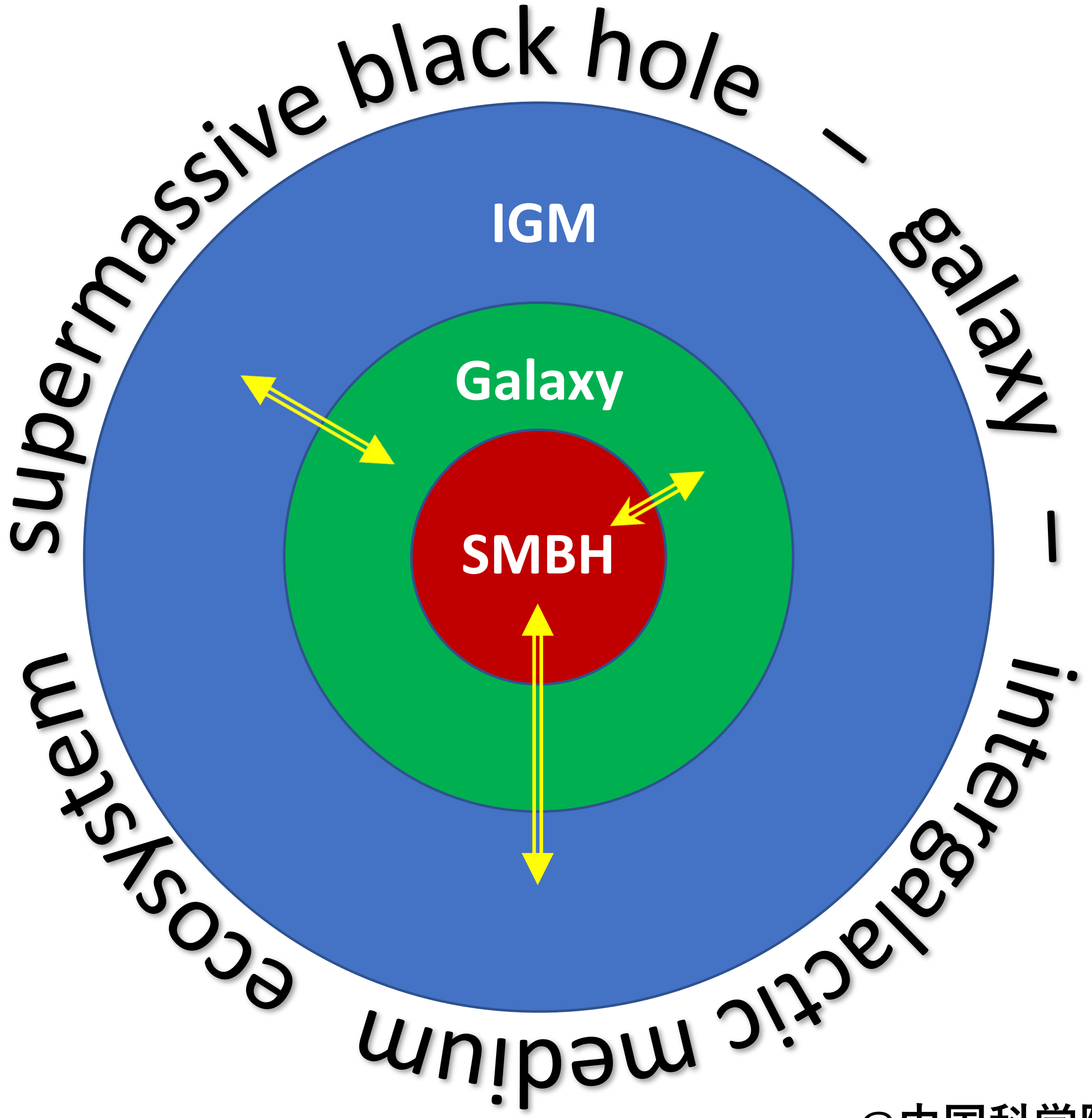
Physical Mechanisms Regulating Gas Supply to Galaxies



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&

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School of Physics

Zhejiang University

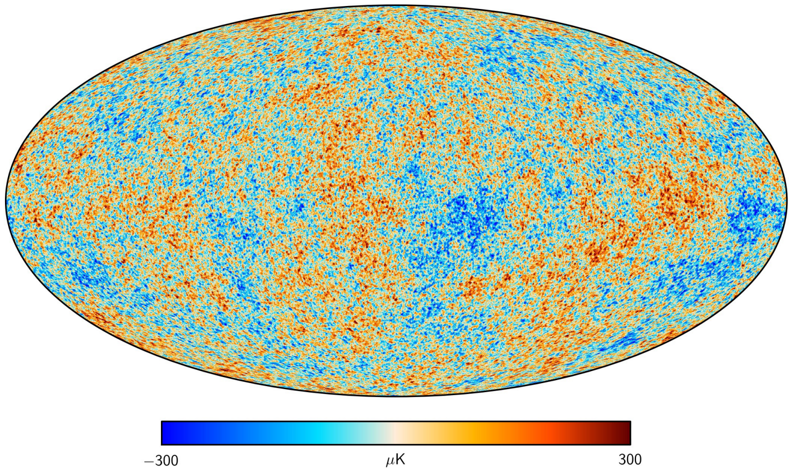
@中国科学院国家天文台, May 17, 2023

Outline

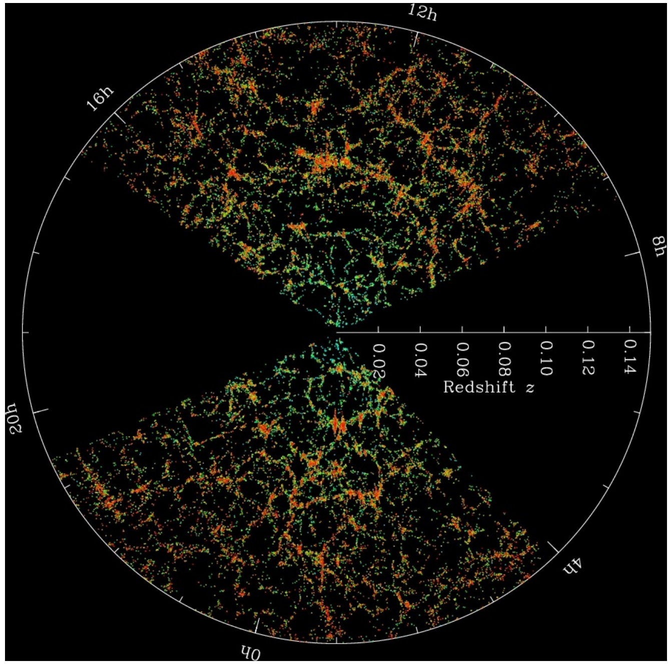
- The core astrophysical problem
- A multi-scale computational problem
- A multi-physics problem: cosmology, dark energy, dark matter, gravity, gas dynamics, microphysics, chemistry, stellar feedback, supermassive black hole feedback
- Conclusions

The core astrophysical problem ：how are galaxies formed?

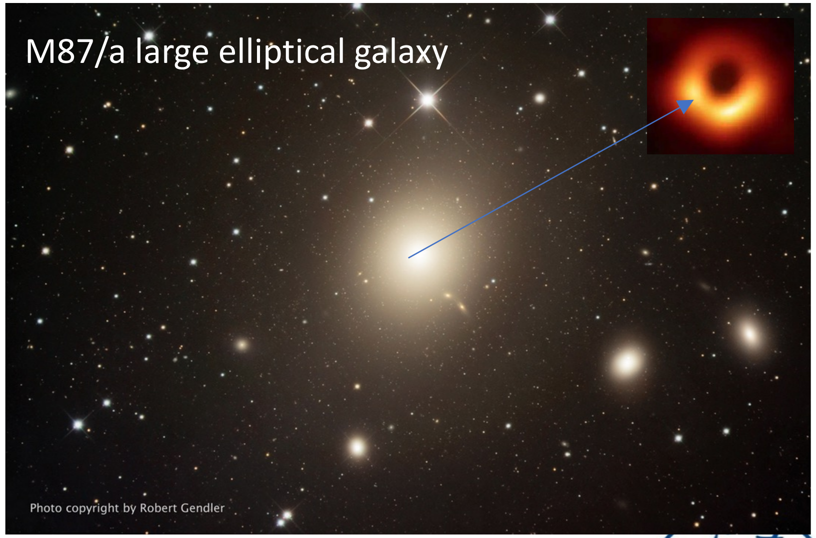
➢ goal: learn physics of galaxy formation



Planck cosmic microwave background surveyor



SDSS local universe



Outline

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The core astrophysical problem ：A hard computational problem

Multi scales

- star forming clouds: 0.1pc
- galaxies: 100kpc
- intergalactic medium: 100 Mpc
- universe: 10^4 Mpc

Scales are dynamically coupled

- gravity is of long range
- structure seed fluctuation energy peaks at 180Mpc
- radiation and cosmic rays act over very large scales
- atomic scale processes influence how galaxies form
- galactic feedback reaches beyond galactic scales

11 dex computational symphony

Five pianos worth of dynamic range that are coupled,

Outline

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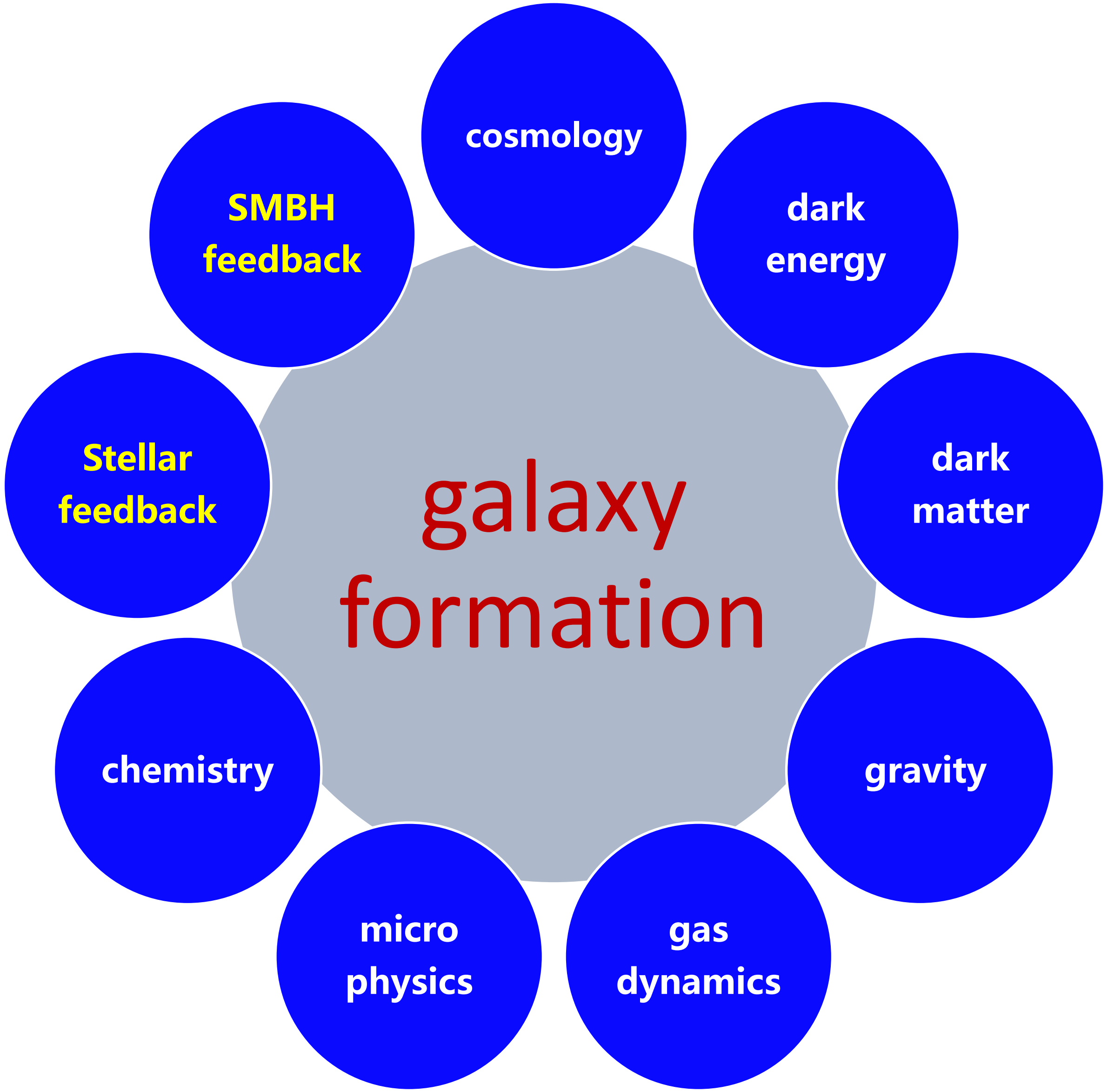
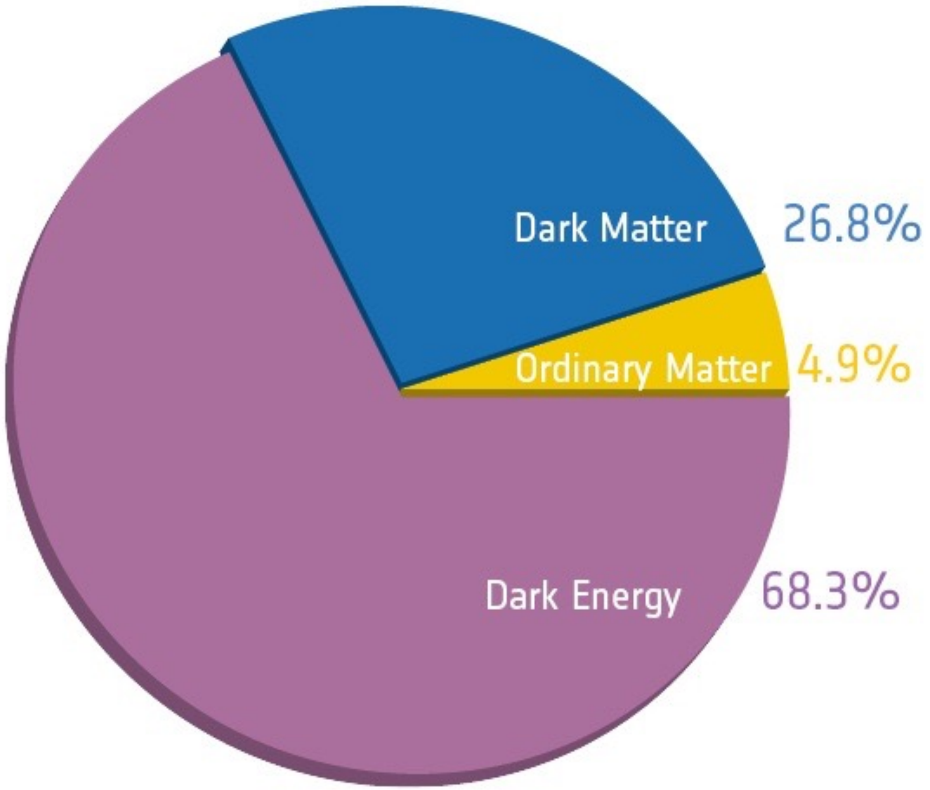
The core astrophysical problem ：A multi-physics problem



cosmology

A flat Λ–dominated cold dark matter universe:

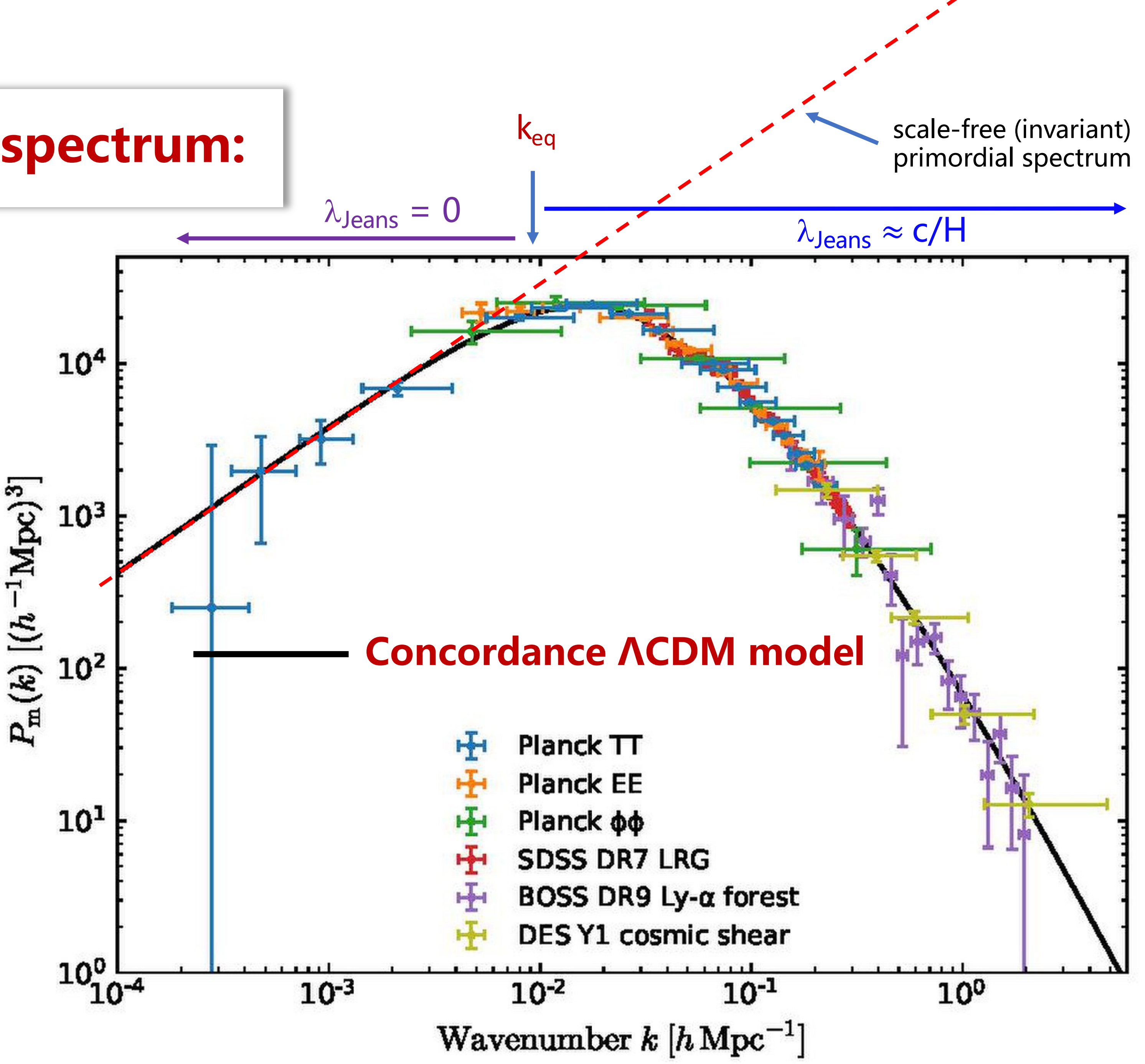


Take-away message: consistent with inflation
Puzzle: partitioning of energy density is mystery

Planck Collaboration 2020, A&A, 641, A6; arXiv:1807.06209

Matter power spectrum:

- Baryon-photon is dynamically coupled to cold dark matter (CDM) by gravity prior to recombination, so CMB power spectrum yields CDM power spectrum, $P_m(k)$
- The scale-free primordial cold dark matter power spectrum, generated by quantum fluctuations prior to inflation, is later modified by the transfer function, i.e. Jeans suppression
- In radiation dominated (redshift>3400) era, total matter is relativistic and Jeans length is equal to the horizon scale, while in matter dominated era, Jeans length drops to zero
- Fourier modes that enter the horizon after radiation-matter equality (eq) redshift are unchanged, while earlier, shorter modes are suppressed



Planck Collaboration 2020, A&A, 641, A6; arXiv:1807.06209 cosmology

Hubble constant crisis (?) : 67.4 vs 73.3 km/s/Mpc

Figure 2

68% confidence-level constraints on H0 from different cosmological probes. From Ref. (12) (based on Refs. [49, 50]).

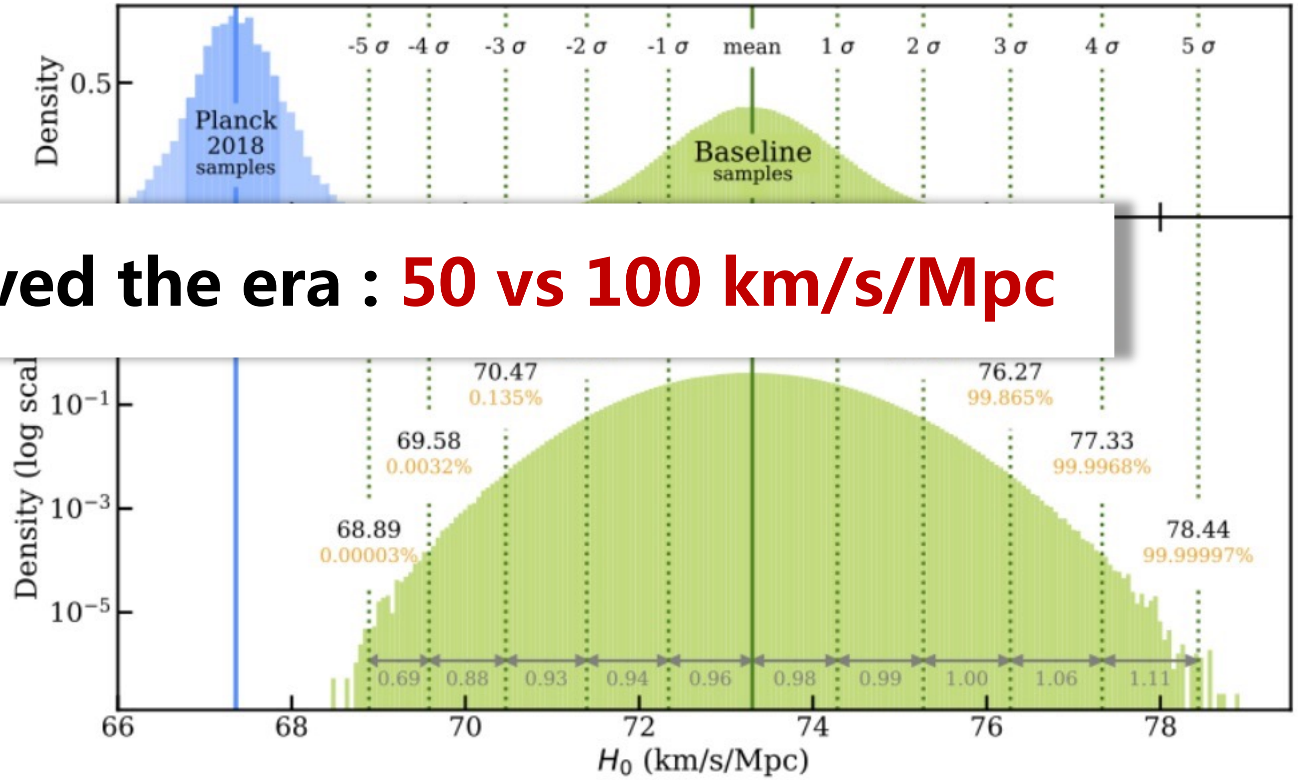


Figure 1

Extended MCMC sampling of the posterior for H_0 to measure out to the 5σ confidence level. The upper panel shows the probability density for the baseline from SH0ES and from the Planck Collaboration et al. (2020) chains. The bottom panel shows the log of the probability density to improve the ability to see the tails.

For those of you who lived the era : 50 vs 100 km/s/Mpc

Kamionkowski & Riess 2022

dark energy

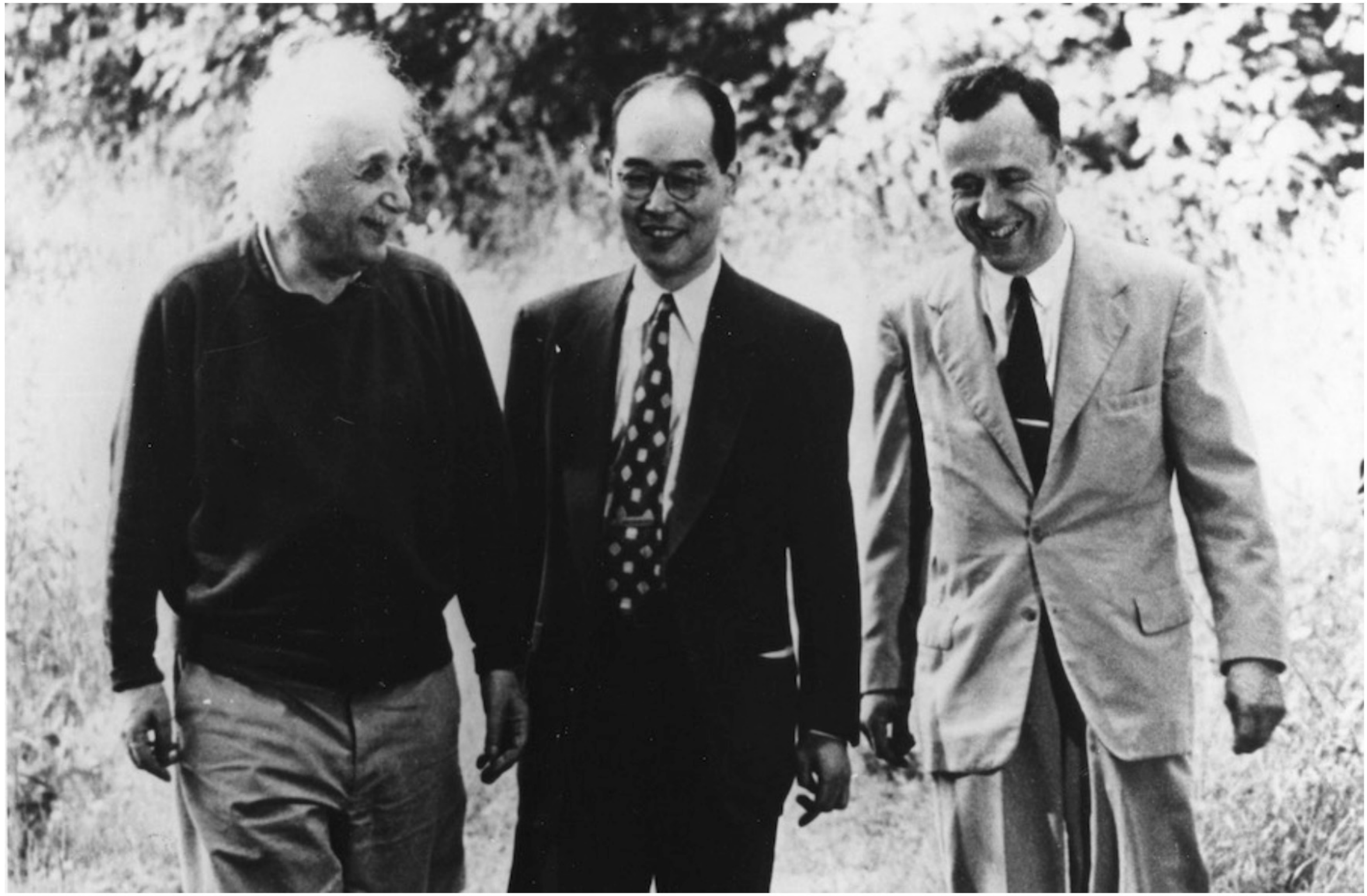
In 1915, Einstein gave the world his General Theory of Relativity

Einstein tensor:
curvature of spacetime

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein added the cosmological constant, Λ, **the anti-gravity.**

It was the biggest blunder of his life, said he (according to Gamow).



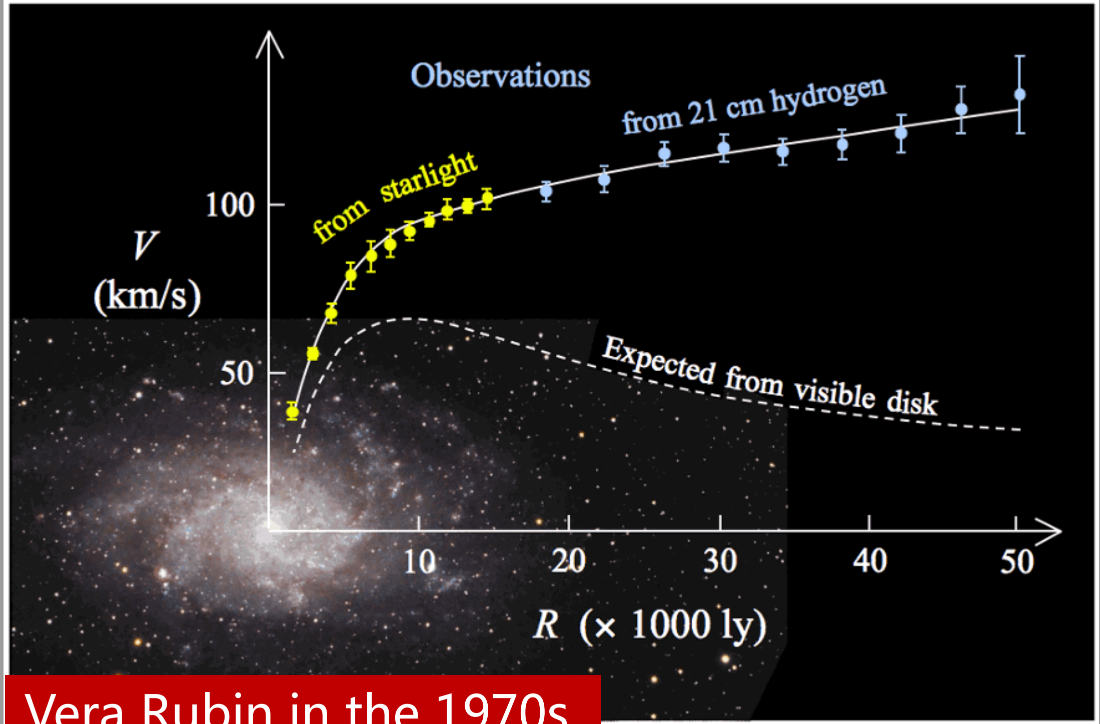
Albert Einstein, Hideki Yukawa, and John Archibald Wheeler walk through Marquand Park in Princeton, New Jersey, in 1954.

or was it?

Understanding origin of Λ may shed light on new physics to the standard particle physics model dark matter

Two-fold evidence (implied, earlier)

Present-day galaxies, clusters:
- Rotation curves of stars and gas



Vera Rubin in the 1970s

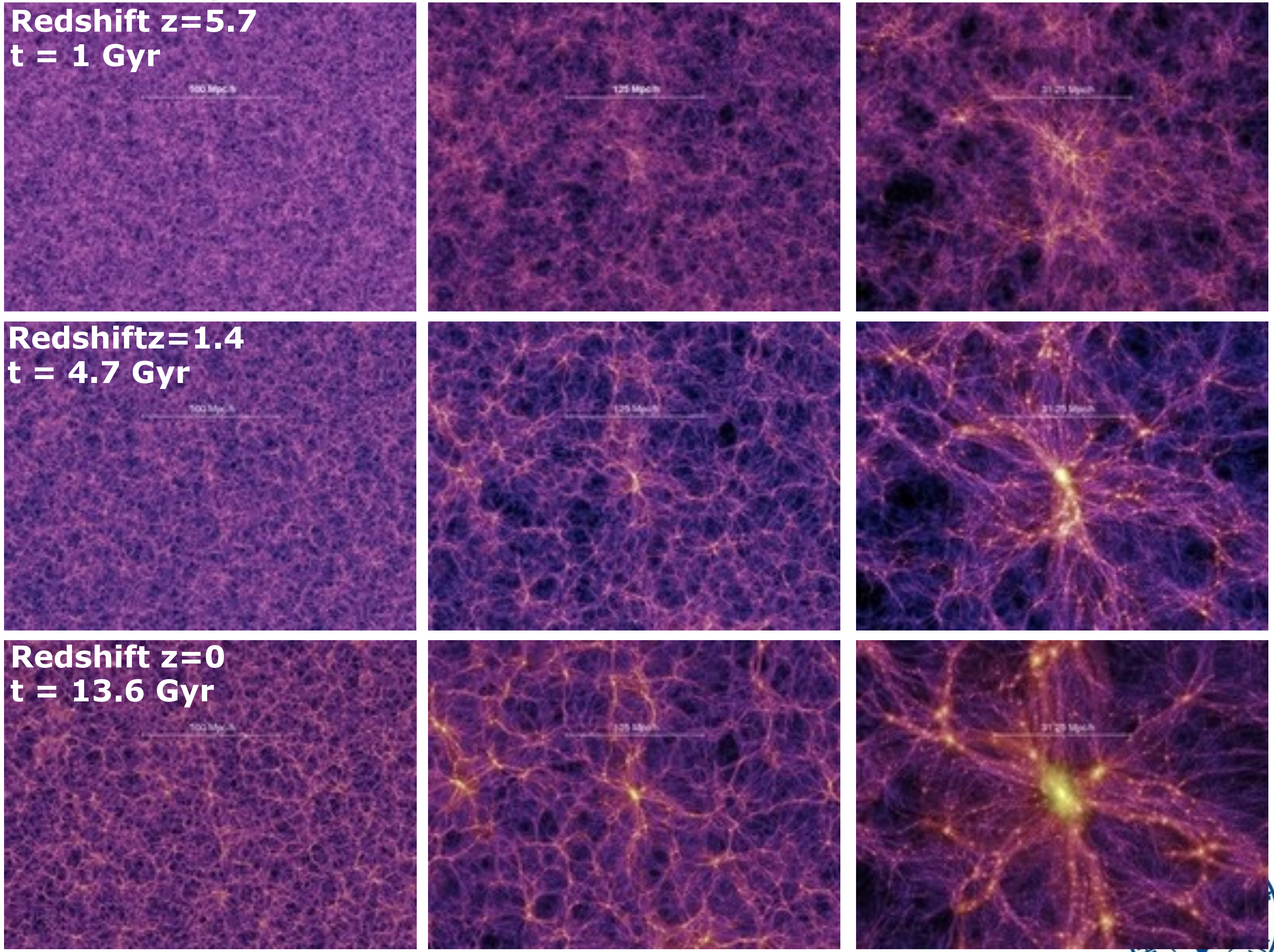
Galaxy formation:
- DM to seed galaxy formation

- z>1100 the photon-baryon fluid is only **nearly perfect**
- **On small scales,** the coupling is **not perfect** and baryons and photons can past one another (Silk 1968) at z>1100, i.e., **adiabatic** perturbations with wavelengths shorter than photon mean free path are damped
- It implies that dark matter is needed to **seed** galaxy formation after recombination
- Otherwise, galaxies **less massive than $10^{11}M^{\odot}$ will not exist** in most places, but we see them everywhere

gravity

Dynamics of dark matter after 40 years of effort

- We understand the gravitational growth of dark matter from recombination to the present
- We understand the growth, abundance and clustering of dark matter halos
- We understand that the density profile of virialized dark matter halos decreases monotonically towards larger radii from center, although exact slope at the very center is not universally agreed upon and variations exist



Millennium Simulations (Springel et al 2005) gravity

Basic structure formation picture:

- Structure formation proceeds **in a hierarchical fashion**: small scales become nonlinear and collapse first
- Earliest structures of mass **$10^5 M_\odot$** form at redshift 20-30
- Mergers and accretion of smaller structures → ever larger structures with time
- Cycle has gone on, will cease soon due to increasingly dominant positive Λ energy
- The largest gravitationally bound systems are **clusters of galaxies** of size 10 million light years across (probing the 2σ tail of the Gaussian distribution, i.e., σ_8, Ω_M)
- Looking ahead, the Milky Way and the Andromeda may collide in about **6 billion years**, and Λ cannot stop it, if you were counting on Λ

What about galaxies ?

It is mainly about cold gas supply, we need to understand both

internal and external

physical processes that ultimately affect the cold gas supply to galaxies

+ gas dynamics + radiative processes + chemistry

gas processes linked to gravity

Two robust results from cosmological hydrodynamic simulations mark outer boundary conditions of galaxies mainly influenced by gravity

- Warm-hot intergalactic medium
- hot-cold accretion dichotomy

Warm-hot intergalactic medium : cosmic baryon budget

TABLE 3

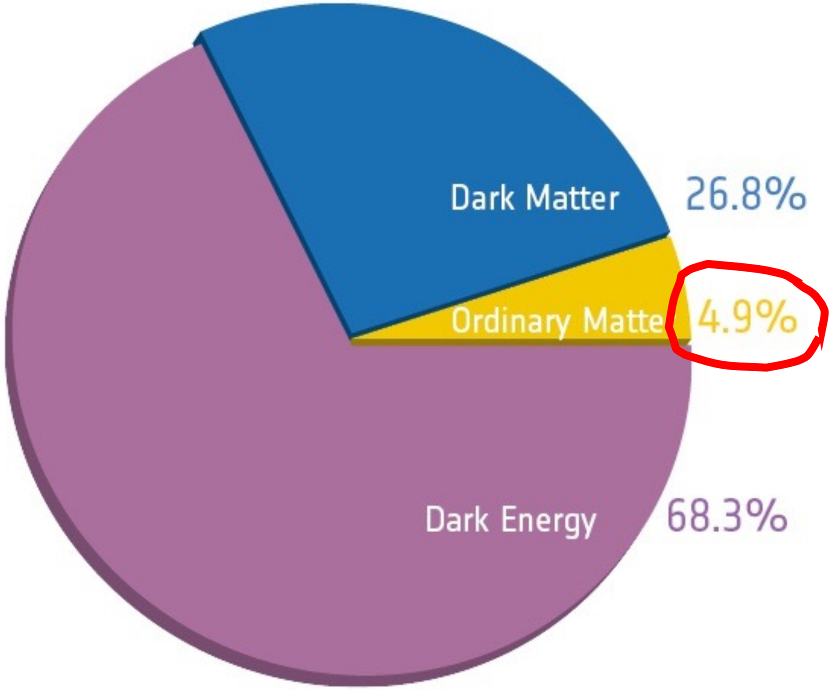
THE BARYON BUDGET

Component	Central	Maximum	Minimum	Grade[a]
Observed at $z \approx 0$				
1. Stars in spheroids	$0.0026\ h_{70}^{-1}$	$0.0043\ h_{70}^{-1}$	$0.0014\ h_{70}^{-1}$	A
2. Stars in disks	$0.00086\ h_{70}^{-1}$	$0.00129\ h_{70}^{-1}$	$0.00051\ h_{70}^{-1}$	A−
3. Stars in irregulars	$0.000069\ h_{70}^{-1}$	$0.000116\ h_{70}^{-1}$	$0.000033\ h_{70}^{-1}$	B
4. Neutral atomic gas	$0.00033\ h_{70}^{-1}$	$0.00041\ h_{70}^{-1}$	$0.00025\ h_{70}^{-1}$	A
5. Molecular gas....................	$0.00030\ h_{70}^{-1}$	$0.00037\ h_{70}^{-1}$	$0.00023\ h_{70}^{-1}$	A−
6. Plasma in clusters	$0.0026\ h_{70}^{-1.5}$	$0.0044\ h_{70}^{-1.5}$	$0.0014\ h_{70}^{-1.5}$	A
7a. Warm plasma in groups	$0.0056\ h_{70}^{-1.5}$	$0.0115\ h_{70}^{-1.5}$	$0.0029\ h_{70}^{-1.5}$	B
7b. Cool plasma	$0.002\ h_{70}^{-1}$	$0.003\ h_{70}^{-1}$	$0.0007\ h_{70}^{-1}$	C
7′. Plasma in groups	$0.014\ h_{70}^{-1}$	$0.030\ h_{70}^{-1}$	$0.0072\ h_{70}^{-1}$	B
8. Sum (at $h = 70$ and $z \simeq 0$)......	0.021	0.041	0.007	...
Gas components at $z \approx 3$				
9. Damped absorbers	$0.0015\ h_{70}^{-1}$	$0.0027\ h_{70}^{-1}$	$0.0007\ h_{70}^{-1}$	A−
10. Lyα forest clouds	$0.04\ h_{70}^{-1.5}$	$0.05\ h_{70}^{-1.5}$	$0.01\ h_{70}^{-1.5}$	B
11. Intercloud gas (He II)	...	$0.01\ h_{70}^{-1.5}$	$0.0001\ h_{70}^{-1}$	B
Abundances of:				
12. Deuterium	$0.04\ h_{70}^{-2}$	$0.054\ h_{70}^{-2}$	$0.013\ h_{70}^{-2}$	A
13. Helium	$0.010\ h_{70}^{-2}$	$0.027\ h_{70}^{-2}$	...	A
14. Nucleosynthesis	$0.020\ h_{70}^{-2}$	$0.027\ h_{70}^{-2}$	$0.013\ h_{70}^{-2}$	...

[a] Confidence of evaluation, from A (robust) to C (highly uncertain).

Fukugita, Hogan & Peebles 1998, ApJ, 503, 518

from CMB



Where are (the other half of) the cosmic baryons ?

Warm-hot intergalactic medium : solution to the missing baryons

Physics

redshift 1100 20 6 3 0

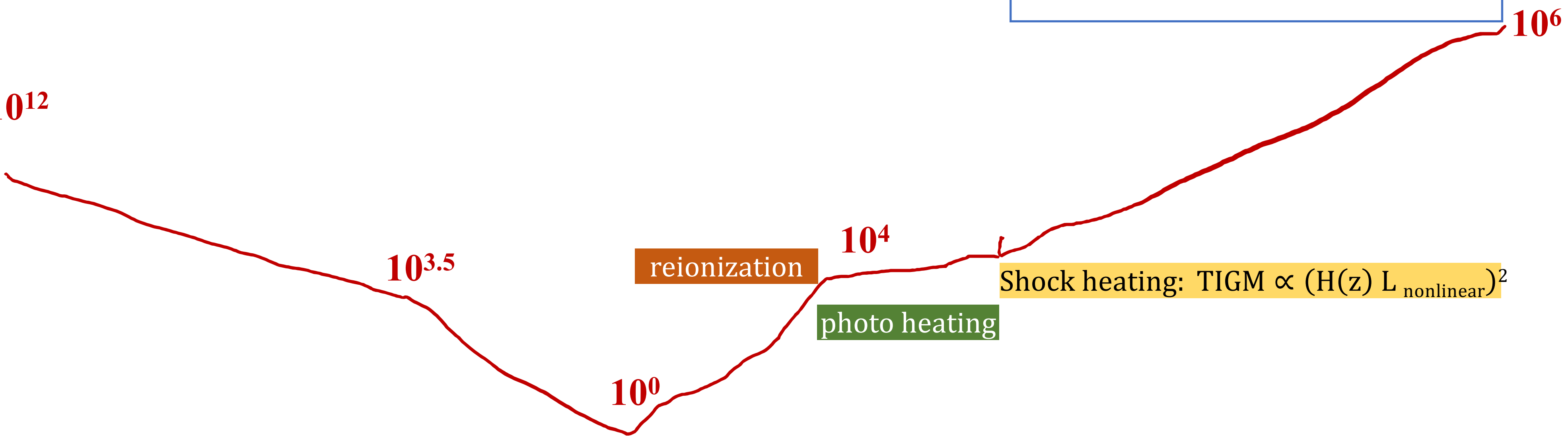
Cold dark matter model — hierarchical structure formation

Gravity — increasingly large scales turn nonlinear with time

Hydrodynamics — Nonlinear gas waves break and heat up IGM to higher temperatures with time

time forward

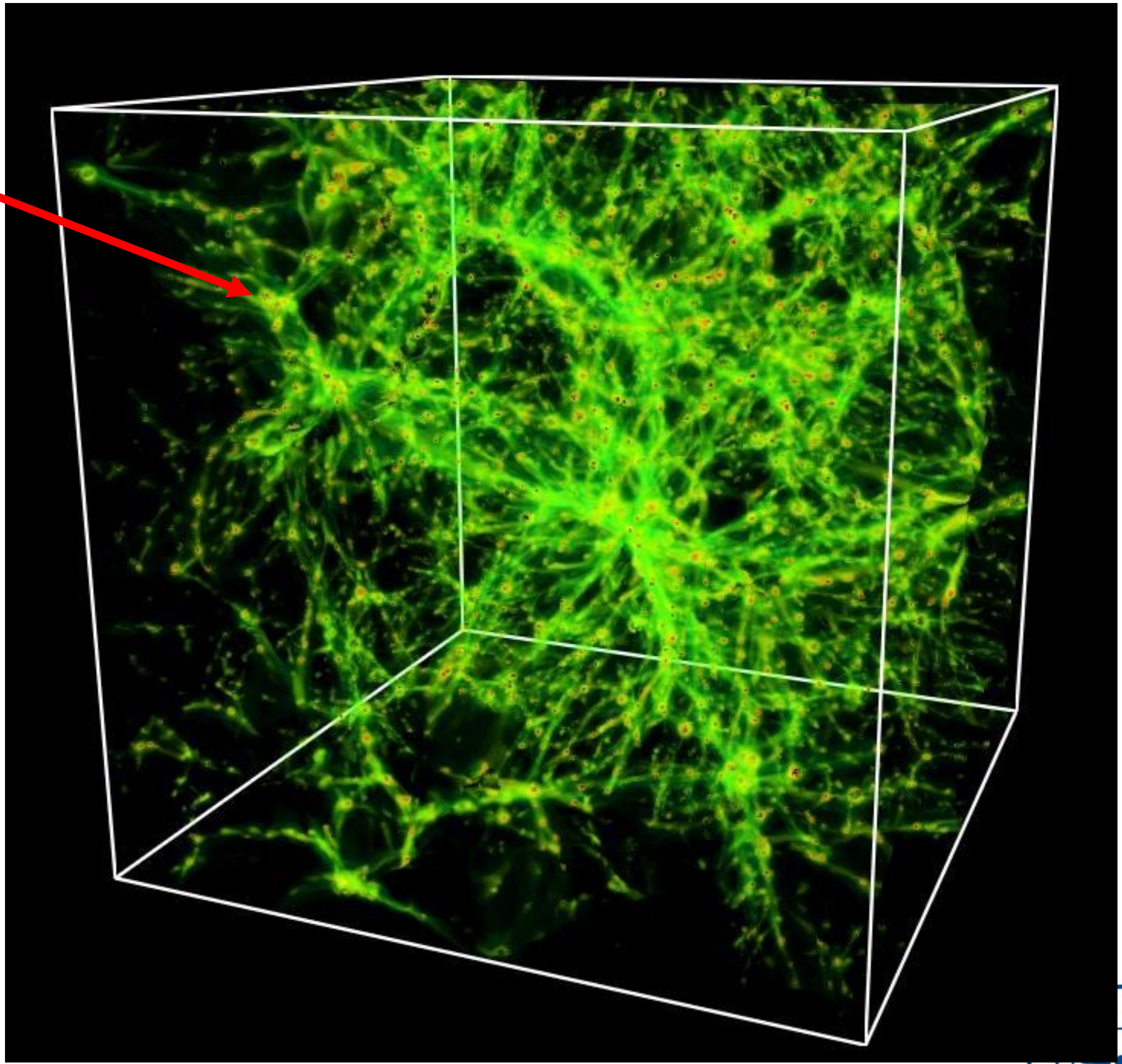
temperature of intergalactic medium [Kelvin]



Warm-hot intergalactic medium : missing baryons and physics

Predictions

- 50% of cosmic baryons in the universe @z=0 exist in a filamentary network with temperature of 10^5-10^7 K:
  the warm-hot intergalactic medium (WHIM)
  (Cen & Ostriker 1999, ApJ, 514, 1) :



Confirmation

- Warm component with T= 10^5-10^6K was unambiguously confirmed by the Hubble Space Telescope COS far UV absorption line observations

on galaxy formation

- WHIM at z=0-3 poses as an important boundary condition for galaxies accreting from it

Warm-hot intergalactic medium : further confirmation imperative

Further confirmation in X-ray is needed to complete the checking

X棱镜

Launch time：2023

XRISM：jointly developed by JAXA/NASA (日本宇宙航空研究开发机构和NASA)

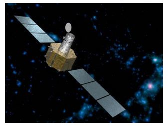
XRISM major science subjects include:
The missing baryons in the intergalactic medium

3.1 Missing Baryons and the WHIM

Current observations of hot gas in galaxy clusters, the Local Group, and the warm intergalactic medium (IGM) indicate that 20-40% of the baryons seen in the high-z Universe are missing from our observations at z=0[73,74]. The missing baryons are suspected to occupy the filaments of gas

清华大学正开展的项目

HUBS: 热宇宙重子测量员

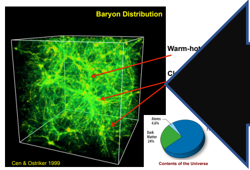


HUBS: Hot Universe Baryon Surveyor

Wei Cui, for the HUBS Collaboration
Department of Astronomy, Tsinghua University

INTRODUCTION

Based on the measured abundances of primordial isotopes the theory of Big Bang Nucleosynthesis (BBN) tells us how many baryons were produced nearly at the birth of the universe. As the universe evolved, it cooled and, in a matter of minutes after the Big Bang, it could no longer sustain fusion, so the production of heavier isotopes ends. As it cooled further, neutral atoms began to form about 370,000 years after the Big Bang, locking up the electrons that had tied photons and matter together via scattering and allowing the photons to fill the entire universe, which produced what is now known as the cosmic microwave background (CMB). Precise measurements on the anisotropy of the CMB have allowed us to derive the values of key cosmological parameters, including the energy density of baryonic matter. The result implies that all of the BBN baryons were still there at the redshift of about 1100. Going down in redshifts, first stars and galaxies formed and evolved, when the baryons seem to go "missing" in optical surveys. In the present-day universe, only about half of the baryons are seen optically. This is the long-standing "missing baryon problem"



Theoretically, cosmological hydrodynamical simulations show a significant fraction of cosmic baryons were heated to temperatures of 10^{5-6} K by shocks that had been produced during the formation of large-scale structures. Radiation from such low-density, hot baryons lies mainly between far UV and soft X-ray wavelengths, making it difficult to detect observationally. Such a solution to the "missing baryon problem" has found significant support from indirect observations, through the absorption of radiation from distant quasars by the missing baryons or their distortion of the CMB spectrum.

The primary scientific objectives of HUBS include: (1) to directly detect X-ray emission from the hot baryons in the IGM or CGM, and characterize their physical and chemical properties; and (2) to study, based on the observations, the accretion and feedback processes that are thought to be highly relevant to the heating and chemical enrichment of the baryons in the CGM (and perhaps also IGM). The results are expected to help advance our understanding of galaxy formation and evolution significantly. Secondary objectives are many, including hot interstellar medium, diffuse X-ray background, supernova remnants, as well as charge exchange processes in the solar system.

PRELIMINARY DESIGN

The most effective approach is to carry out high-throughput, high-resolution imaging spectroscopy in the soft X-ray band (< 2 keV), where the hot baryons are expected to manifest themselves in emission and absorption lines. The best spectral lines to focus on are associated with helium-like and hydrogen-like ions (especially oxygen lines at ~0.6 keV).

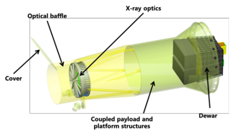
The HUBS imaging spectrometer will be based on the transition-edge sensor (TES) technology that is optimized for the softest X-ray band (0.1-2 keV), where the oxygen lines are located. The design aims at maximizing the product of grasp (A_{eff} Ω) and spectral resolution (E/ΔE), for detecting extended X-ray emission,[2] and achieving moderate angular resolution at the same time.

清华大学主持HUBS项目，拟用X发射线来绘制出这宇宙网络，来检测预言的**热星系际介质**，由中国国家航天局资助，现处关键技术开发开发阶段

Launch time：2030

The grasp of HUBS is, therefore, over an order of magnitude larger than Athena X-IFU, and is, by design, complementary in primary scientific objectives.

HUBS adopts an integrated design of the scientific payload and the satellite platform.



ENABLING TECHNOLOGIES

The enabling technologies of HUBS include: TES array with large X-ray absorbers, SQUID-based multiplexing readout, cryocooler and ADR, and X-ray optics.

A 2-stage cryocooler design is baselined for providing a pre-cooled stage for the ADR. Two prototypes have been developed [3-5], with one referred to as Vuilleumier hybrid pulse tube cryocooler (VM-PTC), and the other High-frequency pulse tube cryocooler (HPTC). VM-PTC consists of a VM stage and a PT stage, and is able to reach 2.17 K, providing about 10 mW of cooling power. The HPTC consists of two PT stages, and is able to reach 3.5 K, providing about 6 mW of cooling power.

As for X-ray optics, the slumped glass technique is used to form light-weight, thin glass mirror shells, and the shells are then nested to to realize Wolter-I optics with a large

…TION

HUBS intends to sustain the scientific community's quest for a dedicated X-ray mission to detect the missing baryons over the past nearly two decades. At present, science definition and technology R&D are mainly being carried out by collaborating universities and research institutes in China, but international collaboration is strongly encouraged, by CNSA, at all levels, including observing strategies and target selection through the Science Working Groups, technology R&D, and auxiliary payloads (which enhance and/or broaden the scientific capabilities and objectives of HUBS).

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1. R. Cen, & J.P. Ostriker, Astrophys. J., 519, L109 (1999)
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3. J. Wang, C. Pan, T. Zhang, et al., Sci. Bull., 64, 219 (2019)
4. C. Pan, J. Wang, K. Luo, et al., Cryogenics, 98, 71 (2019)
5. L. Chen, X. Wu, J. Wang, et al., Cryogenics, 94, 103 (2018)

For more information, please visit the HUBS web site: *http://hubs.phys.tsinghua.edu.cn/en/*

Athena: ESA's Big X-ray Telescope

By Elizabeth Howell

雅典娜: 欧洲航天局的大X射线望远镜

Launch time：2035

Artist's conception of the proposed Advanced Telescope for High-Energy Astrophysics (Athena+). (Image credit: Athena+ Team)

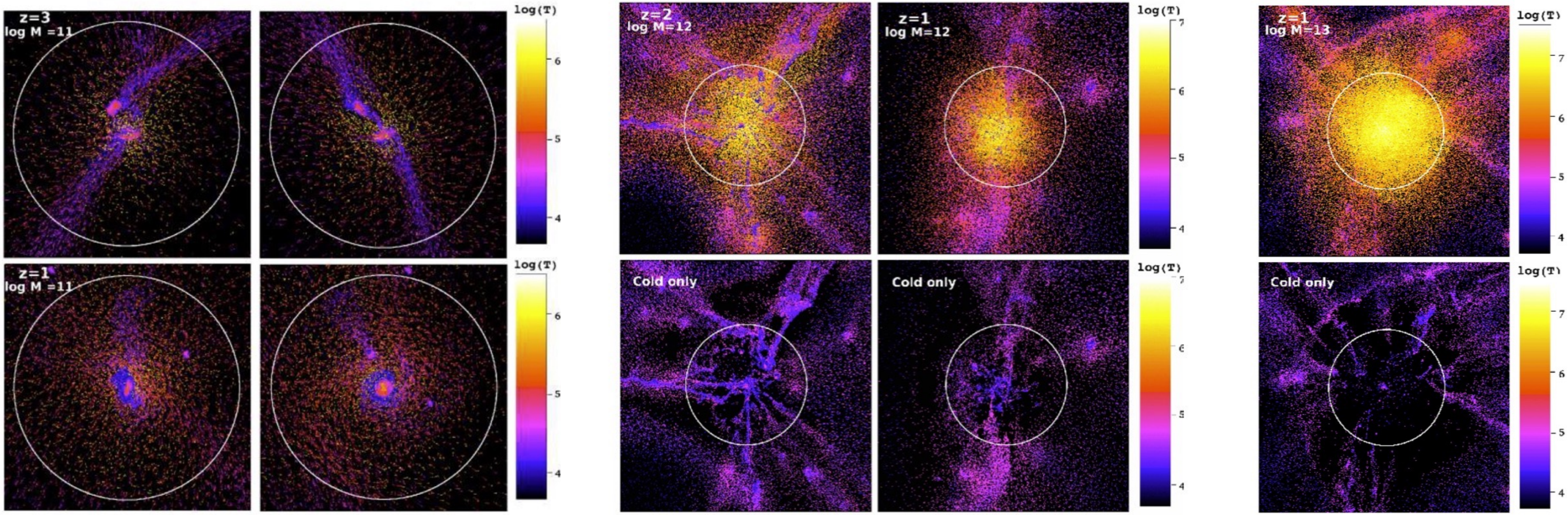
The spacecraft is an X-ray observatory expected to answer questions about the hot and energetic universe. The two main questions include "How does ordinary matter assemble into the large-scale structures that we see today" (such as galaxy groups and clusters) and "How do black holes grow and influence the environment around them." A black hole's environment is best seen in X-rays, and hot gases, which are visible in X-rays, can give clues about galactic structure

One of the main science subjects:
The missing baryons in the intergalactic medium

- missing baryons in the intergalactic medium, or plasma between galaxies;
- how black holes and supermassive black holes grow over time;

hot-cold accretion dichotomy : new insight on gas inflows

$M_h=10^{11}M_\odot$ $M_h=10^{12}M_\odot$ $M_h=10^{13}M_\odot$

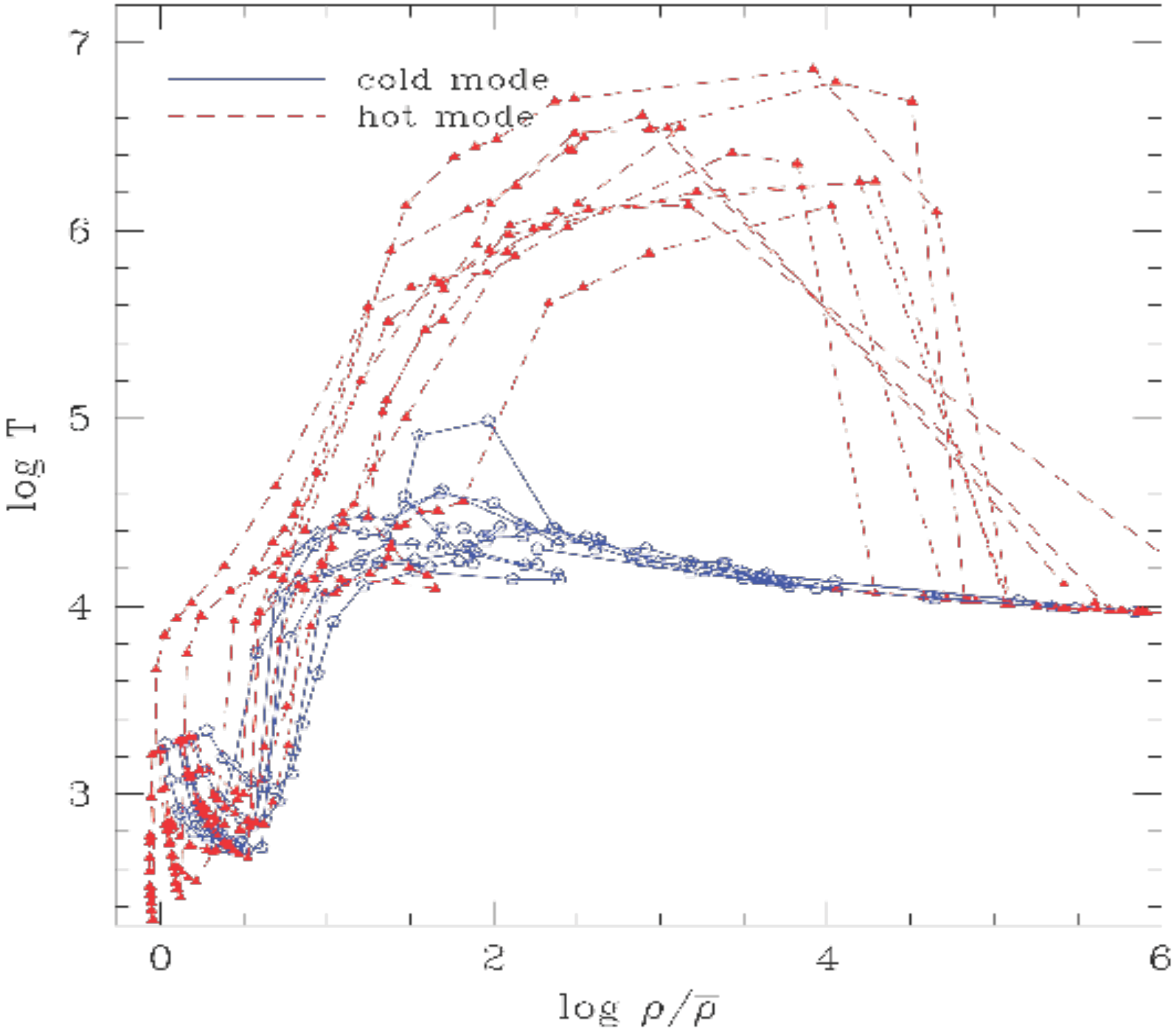


Keres et al 2009, MNRAS, 395, 160

hot-cold accretion dichotomy ： part of gravitational heating

Significance

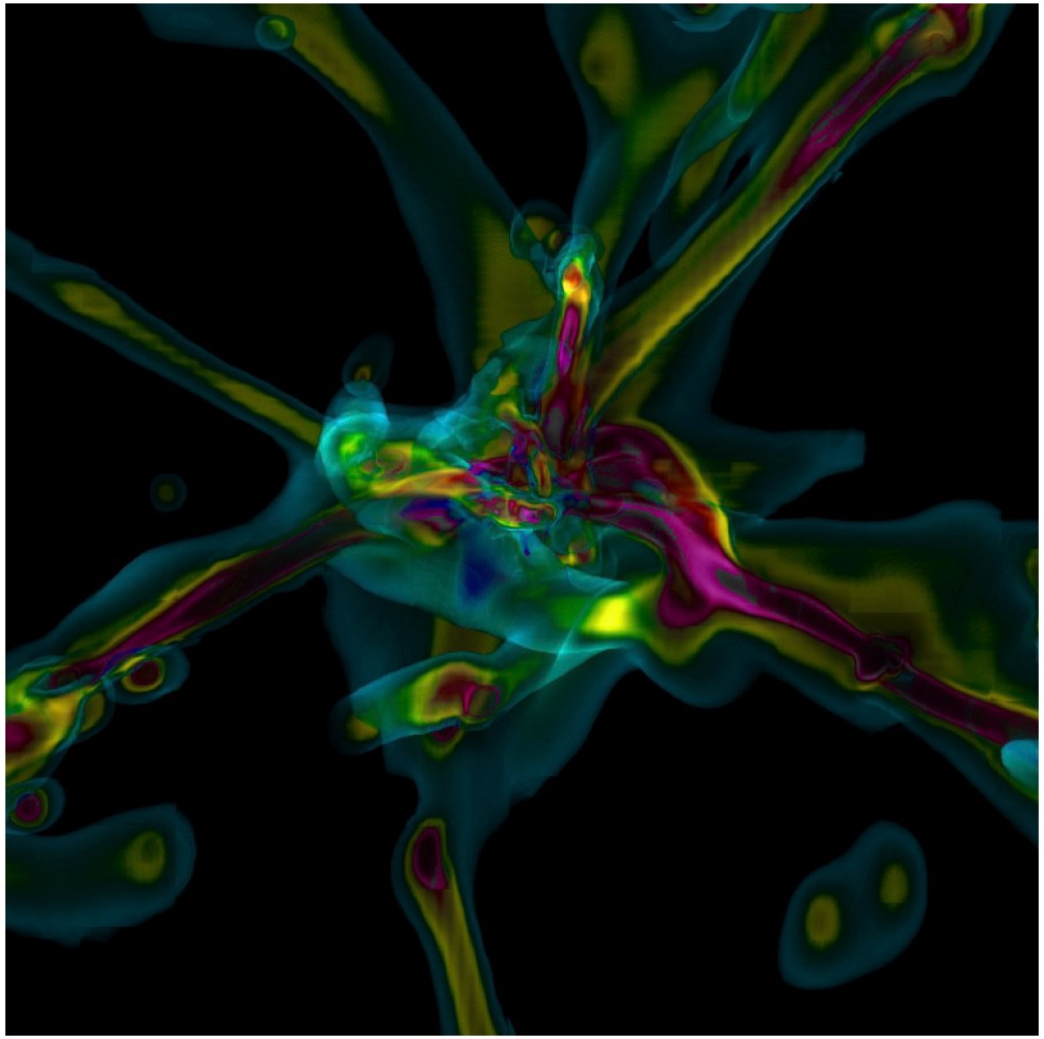
- Classic picture: all gas entering halo is shocked heated to virial temperature
- New insight: not all accreted gas is shock heated to virial temperature entering halo
- There are **two distinct modes**: **cold and hot accretion modes**
- Halo mass dependent accretion mode has major implications for galaxy formation



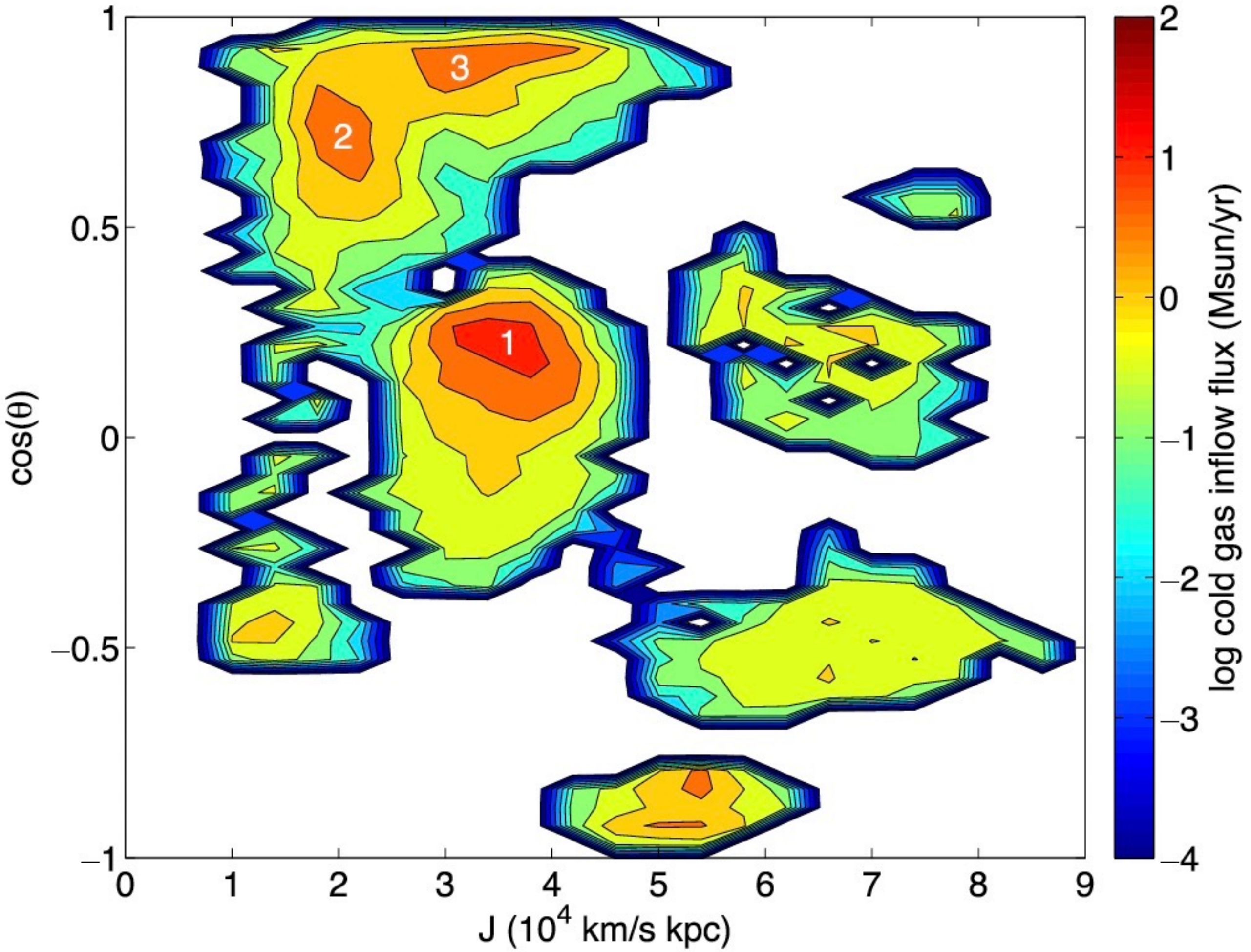
Keres et al 2005, MNRAS, 363, 2

hot-cold accretion dichotomy : quantifying cold streams

cold streams are readily identifiable in cosmological hydrodynamic simulations



Cen 2014



Stream interactions：SMBH mass to bulge mass ratio

$mass_{gas}$(J) of episodic inflow could lead to M_{BH}-M_{bulge} relation

- Simulations (Hopkins & Quataert 2010,2011) show that from 0.01-1000pc inflow gas ends with a Mestel disk of surface density $\Sigma(r) \propto r^{-1}$ (r is radius)
- $$r_0 = 0.42(\alpha/0.1)^{2/5}(l_E/0.1)^{-2/5}\left(M_{BH}/10^8 M_\odot\right)^{3/25} \times (\mathrm{Ma}/0.1)^{14/25}(\kappa/\kappa_e)^{4/25}\ \mathrm{pc} \quad (7)$$

Toomre Q<1 for $r > r_0$

Q>1 for $r < r_0$

(Goodman 2003, Equation (42)), where α is radiative efficiency, l_E is luminosity in Eddington units, Ma is Mach number of the viscous disk at r_0, and κ and κ_e opacity, and electron-scattering opacity, respectively. Hence, the feeding rate to the accretion disk

- we combine the above two ingredients with 100pc resolution cosmological simulations to show that the observed M_{BH}-M_{bulge} relation can be produced (Cen 2015)

M_{BH}-M_{bulge} relation : reproduced from inflow gas J distribution

Blue: log10 (accretion rate Mdot)
Red: log10 (500Mdot/SFR)

THE ASTROPHYSICAL JOURNAL LETTERS, 805:L9 (6pp), 2015 May 20 CEN

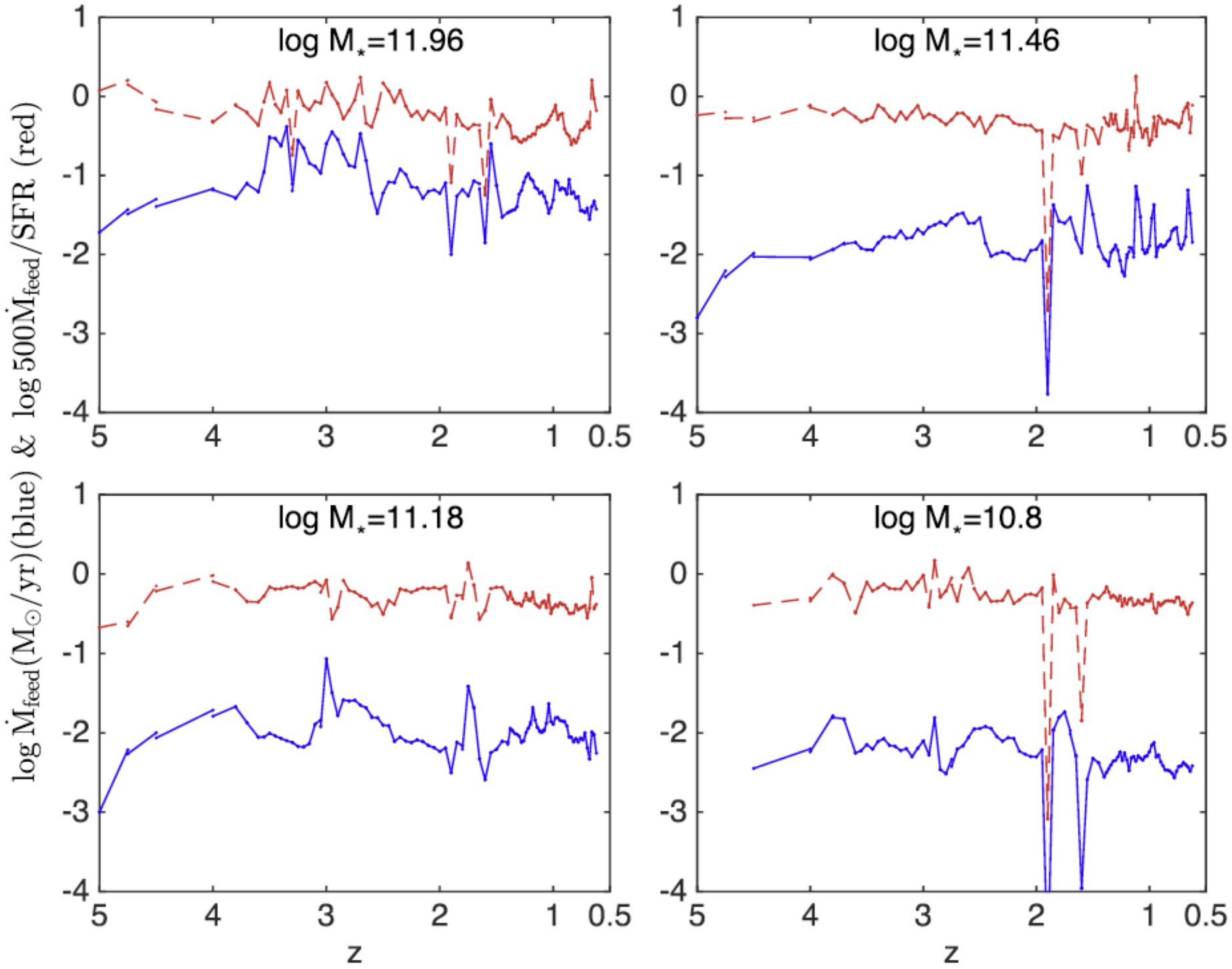
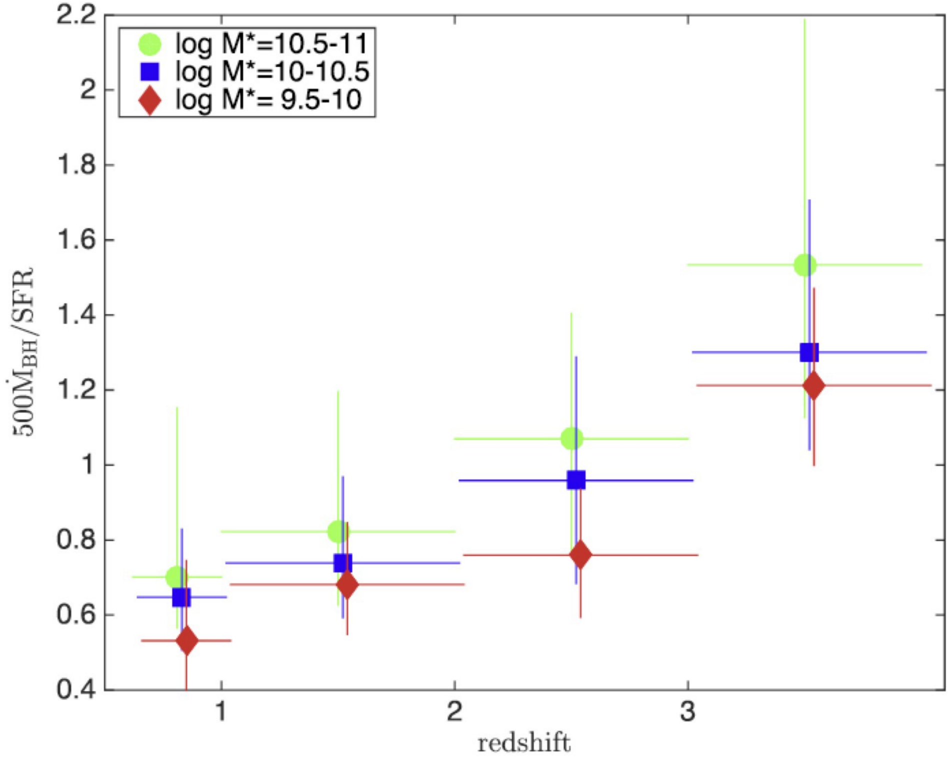


Figure 1. Shows histories of the feeding rate $\dot{M}_{\rm feed}$ (blue) and $R \equiv 500\,\dot{M}_{\rm feed}/{\rm SFR}$ (red) for four random galaxies. The logarithm of the stellar mass for each galaxy at $z = 0.62$ is indicated at the top of each panel.

Cen 2015

M_{BH}-M_{bulge} due to inflow **regulation** : M_{BH}/M_{bulge} increases with redshift



2. Median of R as a function of redshift, separately for three stellar mass ranges $10^{9.5-10}\,M_\odot$ (red), $10^{10-10.5}\,M_\odot$ (blue), and $10^{10.5-11}\,M_\odot$
measured at the redshift in question. The vertical error bars indicate the interquartile range, whereas the horizontal error bars represent th
red and blue points are horizontally slightly right-shifted for clarity of display. There are (659, 2214) galaxies with stellar mass in the r
– 4, 0.62 – 1), respectively.

Cen 2015

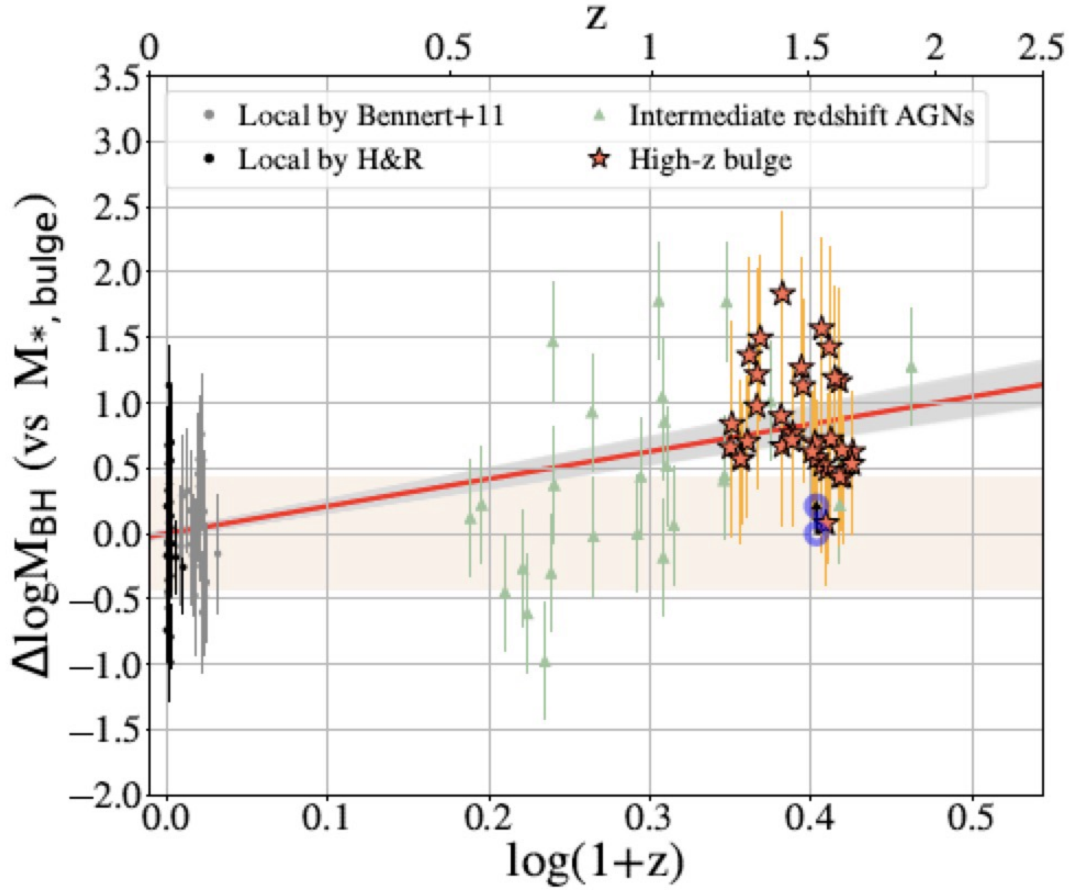


FIG. 13.— Same as Figure 8, but for $\mathcal{M}_{\rm BH}$-$M_{*,\rm bulge}$ relations. The intermedia
Silverman (2013), listed in Table 7. Cisternas et al. (2011) do not provide informati

Ding, Silverman et al 2020

M_{BH}-M_{bulge} due to inflow regulation: enhanced central SF in QSOs

Latest detailed observation shows significant central star formation enhancements in PG quasars,
not the way around

THE ASTROPHYSICAL JOURNAL, 944:30 (21pp), 2023 February 10 Molina et al.

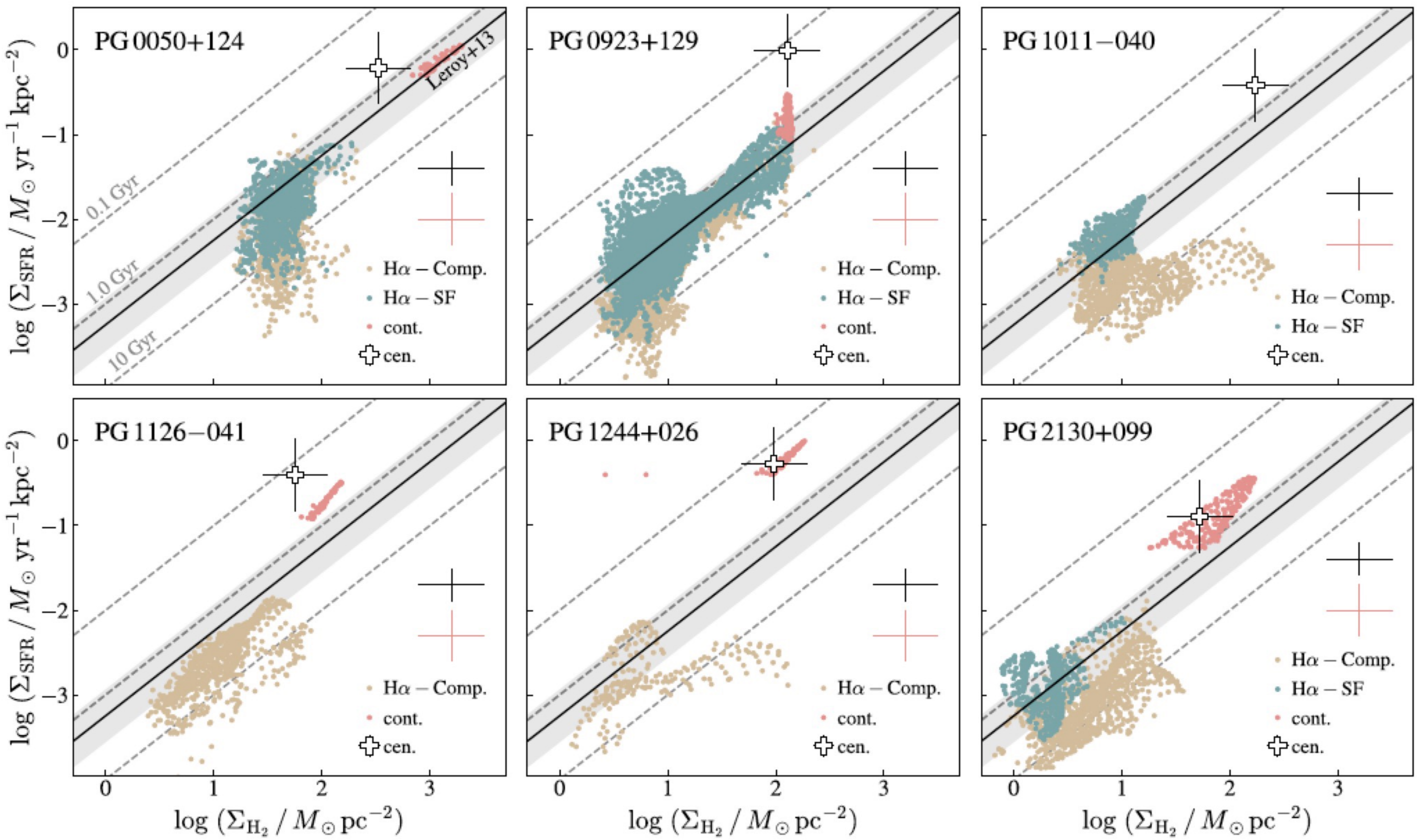


Figure 6. The PG quasar host galaxies in the Kennicutt–Schmidt diagram (Kennicutt 1998a). The red points show the Σ_{SFR} values estimated from the rest-frame 230 GHz continuum data. We show with green circles the MUSE pixels classified as star-forming, while the other pixels are represented by brown circles. The plus sign presents the average host galaxy central value computed over the host galaxy area where we miss the optical light emission owing to AGN deblending flux oversubtraction. The solid line shows the best-fit values of t_{dep} derived by Leroy et al. (2013) for local inactive galaxies, with the shaded region corresponding to the 1σ uncertainty. The dashed lines represent values of constant t_{dep}, as labeled in the top left panel. The regions with obscured and unobscured star formation activity are characterized by t_{dep} values similar to or slightly higher than those measured from the inactive systems, indicating starburst-like activity. The black and red colored error bars located above the legend correspond to the typical 1σ uncertainty of the Hα- and continuum-based pixel-wise data.

Molina, Ho, et al 2023

+ gas dynamics + radiative processes + chemistry

gas process linked to stellar radiation

One robust result from cosmological hydrodynamic simulations marks

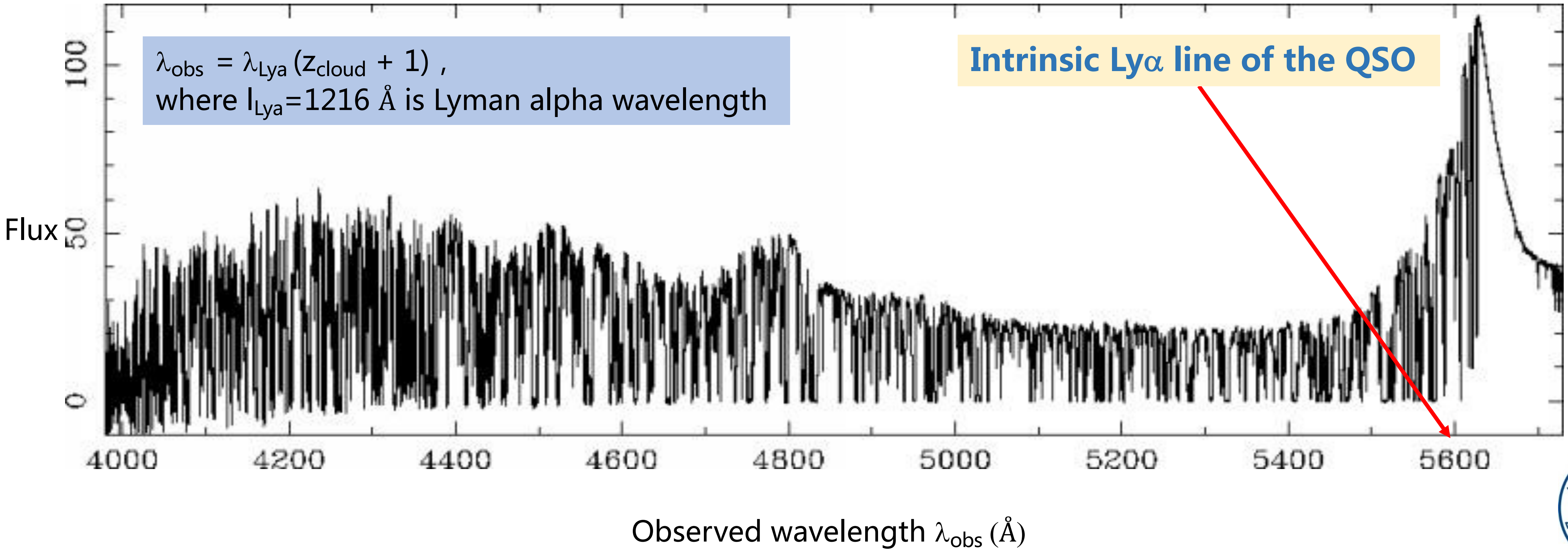
outer gas boundary conditions due to photo-heating by stars & QSOs

Lyman alpha forest

Lyman alpha forest : discovered in 1970

Numerous absorption lines were seen in the spectra of high-z quasars, hence the (Lyman alpha) forest

QSO at z=3.6



Lyman alpha forest : significance and theoretical speculation

Cosmological significance

@z≥3 the Lyman alpha forest contains
>95% of the baryons in the universe

Heuristic theoretical models

- Galactic outflows (Fransson & Epstein 1982)
- Confined by intergalactic hot gas (Sargent 1980; Ostriker & Ikeuchi 1983)
- Minihalos (Rees 1986; Ikeuchi 1986)
- Infalling gas to dark matter halos (Bond, Szalay & Silk 1988)
- Outer galactic disks (Charlton, Salpeter & Hogan 1993)
- Debris from merging satellites (Wang 1993; Morris & van den Bergh)
- Primordial linear density fluctuations (Bi 1993)
- Confined by hot gas in halos (Mo 1994)

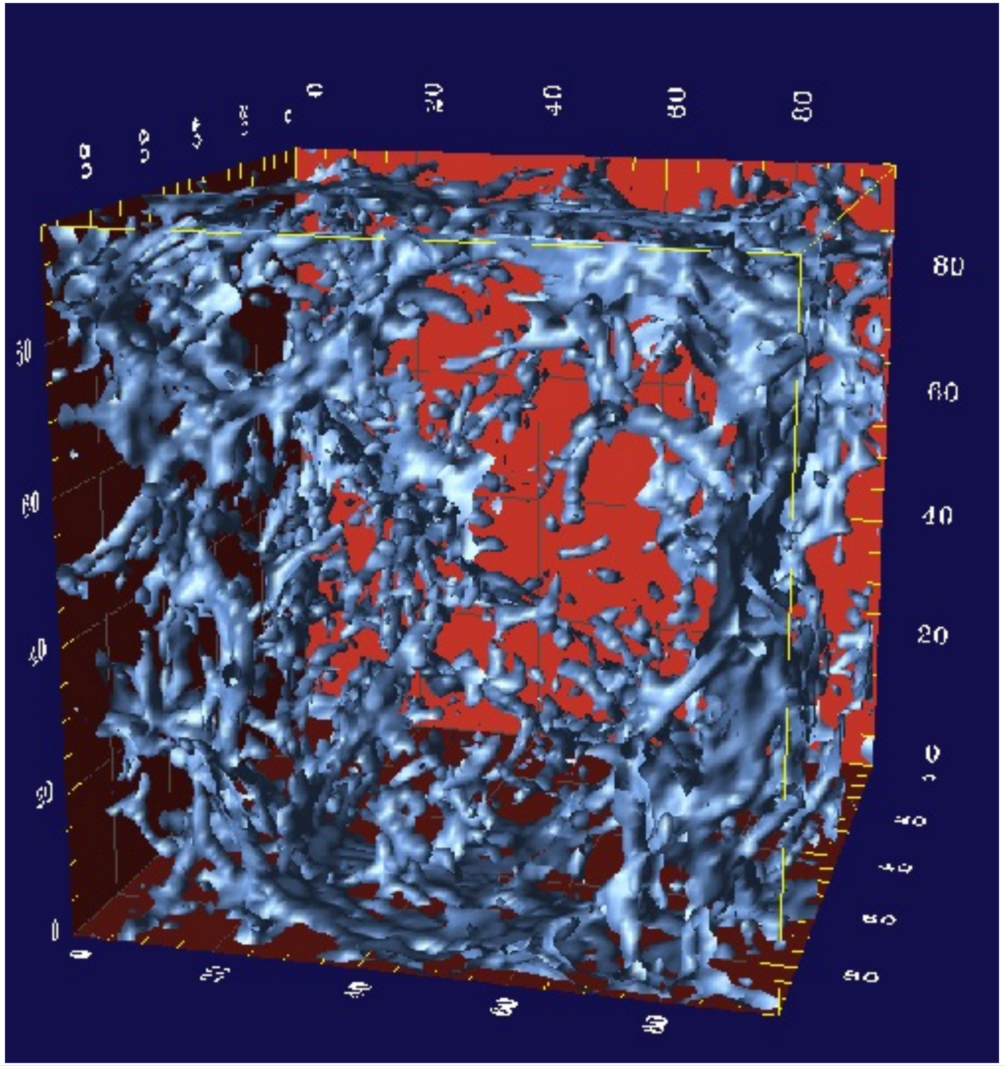
Lyman alpha forest : an ab initio model

Significance

- Lyman alpha forest absorption is the **fluctuating Gunn-Peterson optical depth field,** stemming from photo-ionized, nonlinear, large-scale baryonic structure of the universe at moderate redshift
  (Cen et al. 1994, ApJ, 437, L9)

- This theory quantitatively and systematically explains a whole array of the Lyman alpha forest observables (dn/dz, dn/dN_{HI},b,T, ...)

- It is a **parameter-free theory** based solely on the ΛCDM cosmological model itself and little affected by uncertainties due to feedback processes



Isodensity surfaces@3×mean density @z=3

Cen & Simcoe 1997, ApJ, 483, 8

Lyman alpha forest : cosmological applications

One major contemporary method for measuring cosmological parameters

- **the parameter-free Lyman alpha forest theory depends only on cosmological model parameters**
- **laid foundation for measurements of Lyman alpha forest flux distribution as one of pillar methods for determination of cosmological parameters, neutrino mass, …**

Examples: cosmological parameters and dark energy equation of state constraints

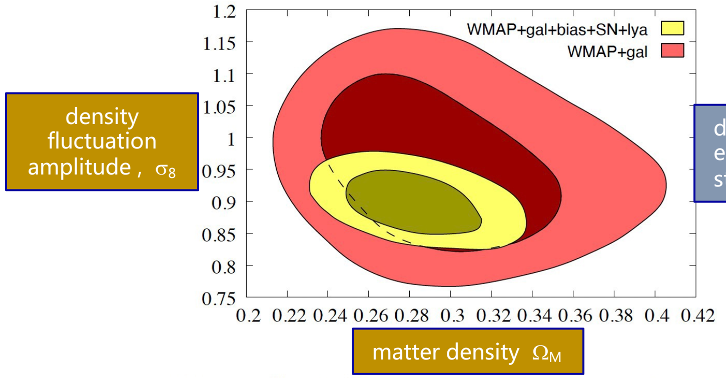


FIG. 5: 68% and 95% contours in the (Ω_m, σ_8) plane showing previous constraints from WMAP and galaxy clustering with the new data.

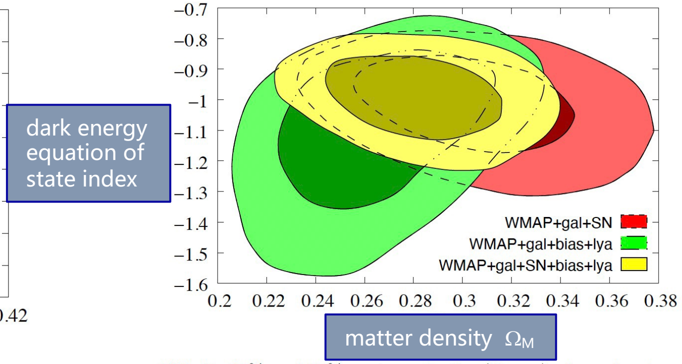


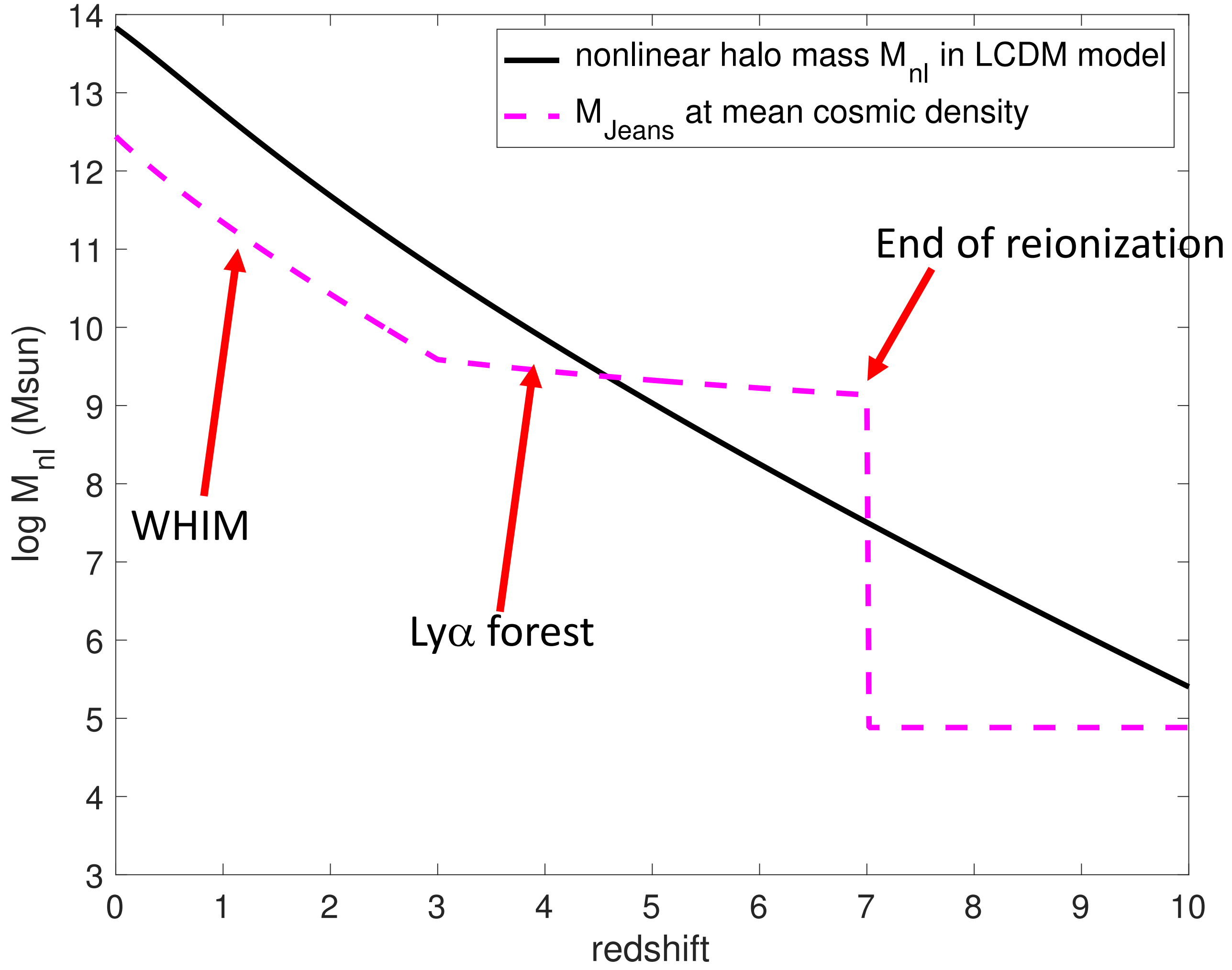
FIG. 7: 68% and 95% contours in the (Ω_m, w) plane showing previous constraints without SDSS-lya and bias, constraints without SNIa, and combined constraints. In all cases the data are consistent with a cosmological constant model ($w = -1$).

Seljak et al. 2005, PRD, 71, 103515;
see also Dawson et al. 2012, AJ, 145, 10
and Palanque-Delabrouille et al. 2020, JCAP, 04, 038

Reionization+Lyα forest+WHIM : outer boundary of galaxies @z=0-6

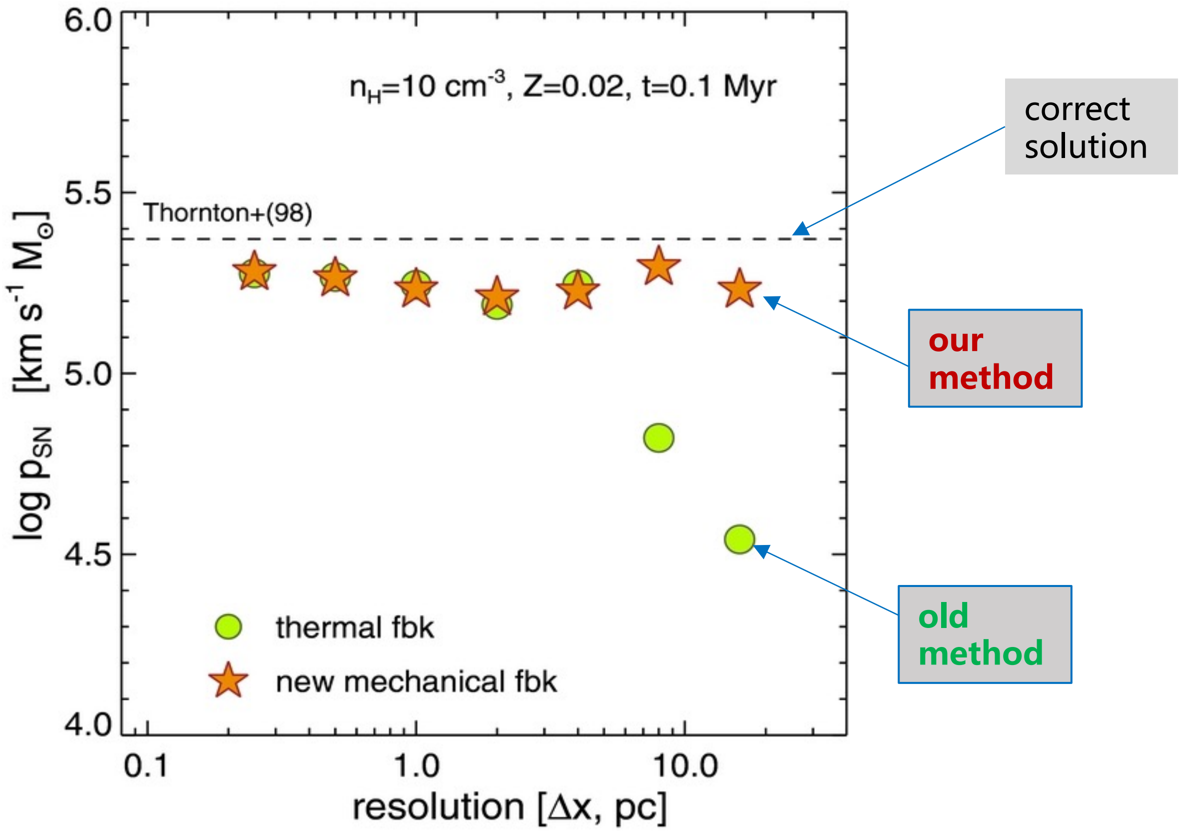
cosmological origin of Lyα forest & discovery of warm-hot IGM

- Completion of reionzation of the universe at z~7
- photo-heated intergalactic medium imposes the Jeans mass scale for galaxy formation at z=3-7
- gravitational shock heated intergalactic medium sets the Jeans mass scale for galaxy formation at z<3



supernova feedback

a well known physical process, but an effective implementation with minimum # of free parameters was illusive until recently



Kimm & Cen 2014

From 1988, supernova feedback was added to simulations (Katz, Hernquist, Cen, …) but ineffective

Kimm & Cen (2014) put forth a method to model supernova feedback, realizing that the Sedov-Taylor blastwave with cooling has in practice two distinct phases:

- **energy conserving phase: $v = (2\ E/m_{shell})^{1/2}$**
- **momentum conserving phase: $v = p_{term}/m_{shell}$**
- **E conserving → p conserving has a rapid transition with a brief duration**
- **transition time is expressible by shell mass, which is a very weak function of (density, metallicity), $m_{shell} \sim 100 m_{ejecta}$**

Internal vs external feedback ：Why external feedback is easier?

External feedback energetically more economical

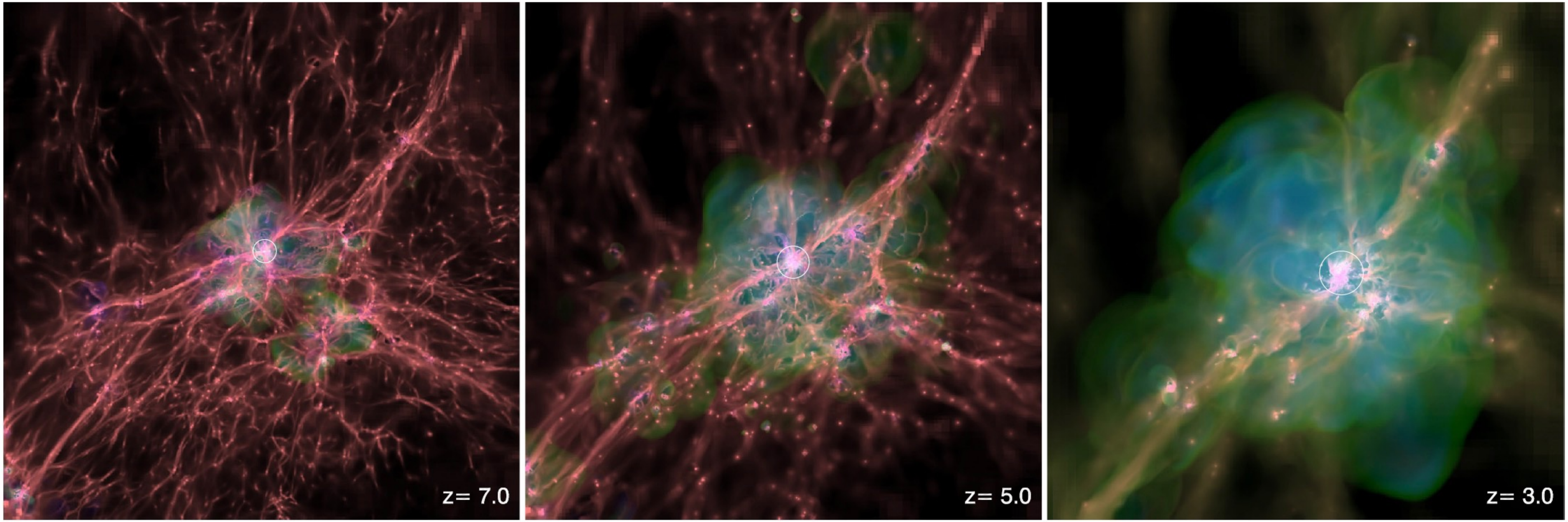
- to blow away a baryon from inside a halo, you need about $\varepsilon_{int}=m_p\sigma^2$ energy (σ is the velocity dispersion of the halo)
- to prevent a baryon from ever entering the same halo, you need $\varepsilon_{ext}=\delta^{-2/3}\ \varepsilon_{int} \approx 3\%\ \varepsilon_{int}$ energy (δ is halo over-density) by heating it up at the mean cosmic density

External SN feedback ：how important?

It depends on how well, how much and how far supernova feedback energy can escape from galaxy

- SNe II feedback energy is tightly coupled to ISM; external feedback depends critically on the depth of gravitational potential well of the halo
- From dwarf galaxies, external SN feedback is likely very important, probably responsible for enriching IGM
- SNe Ia feedback energy is likely easier to escape due to weaker ISM coupling

External SN feedback ：demonstration



Evolution of a galaxy of halo mass **$10^{11.7}M_\odot$** at z=0, with correct implementation of supernova feedback

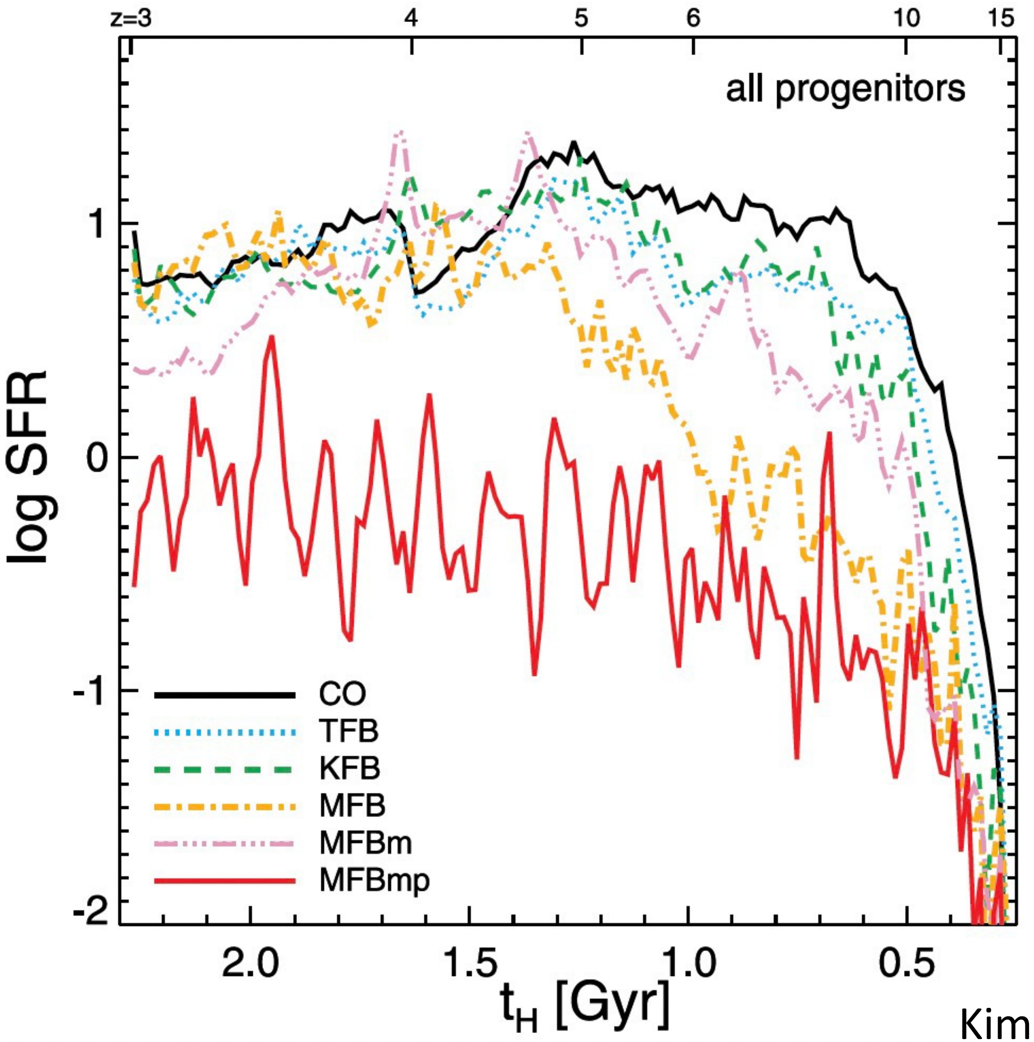
Red: density

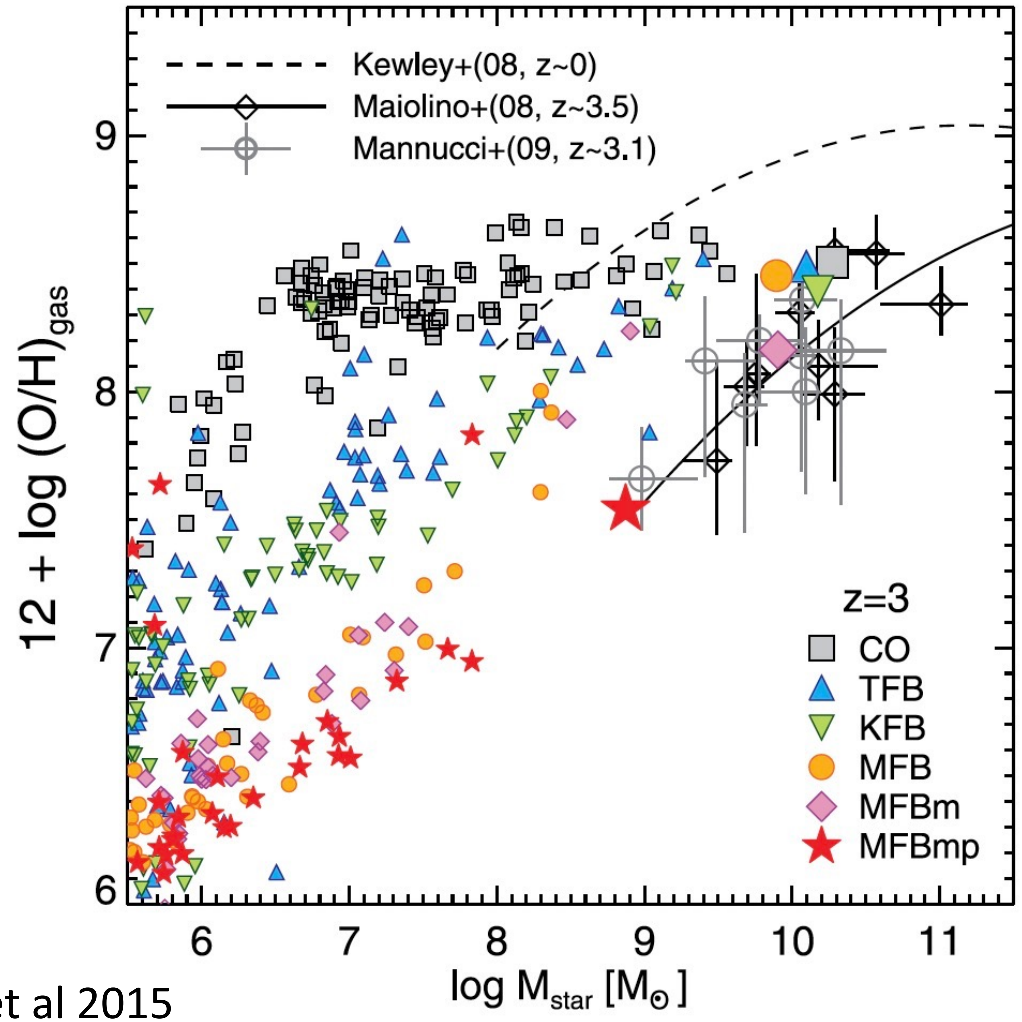
Green: metallicity

Kimm, Cen et al 2015

supernova feedback

Galaxy formation outcomes depend critically on supernova feedback implementations





Kimm, Cen et al 2015

supernova feedback v SMBH feedback

comparisons of energetics

THE ASTROPHYSICAL JOURNAL, 755:28 (14pp), 2012 August 10

Table 1
Comparison of SF and SMBH Energetics

No.	Form	SF	SMBH
(1)	Total radiation	$\epsilon_*(\mathrm{rad}) = 7 \times 10^{-3}$	$\epsilon_{\mathrm{BH}}(\mathrm{rad}) = 2 \times 10^{-4}$
(2)	Ionizing radiation ($\gtrsim$13.6 eV)	$\epsilon_*(\mathrm{LL}) = 1.4 \times 10^{-4}$	$\epsilon_{\mathrm{BH}}(\mathrm{LL}) = 3 \times 10^{-5}$
(3)	X-ray (2–10 keV)	$\epsilon_*(2\text{–}10\,\mathrm{keV}) = 9 \times 10^{-8}$	$\epsilon_{\mathrm{BH}}(2\text{–}10\,\mathrm{keV}) = 5 \times 10^{-6}$
(4)	Mechanical	$\epsilon_*(\mathrm{SN}) = 1 \times 10^{-5}$	$\epsilon_{\mathrm{BH}}(\mathrm{BAL}) = (0.2\text{–}2.8) \times 10^{-5}$
(5)	Radio jets	$\epsilon_*(\mathrm{jet}) = 0$	$\epsilon_{\mathrm{BH}}(\mathrm{jet}) = 4 \times 10^{-5}$

Notes. Under the assumption that $M_{\mathrm{BH}}: M_{\mathrm{BG}} = 2{:}1000$, a Salpeter IMF for stars and a radiative efficiency of SMBH accretion of 10% (Yu & Tremaine 2002), and energy output from both SF and SMBH in various forms are listed: (1) total radiation energy, (2) ionizing radiation, (3) X-ray radiation in the 2–10 keV band, (4) mechanical energy, and (5) radio jets.

Cen 2012

External feedback : the critical entropy

gas cooling time exceeds Hubble time, if S>S_{crit}

$$t_{\rm cool} = \frac{(3/2)nk_BT}{n_e^2\Lambda(T)} = S^{3/2}\left[\frac{3}{2}\left(\frac{\mu_e}{\mu}\right)^2\frac{k_B}{T^{1/2}\Lambda(T)}\right]$$

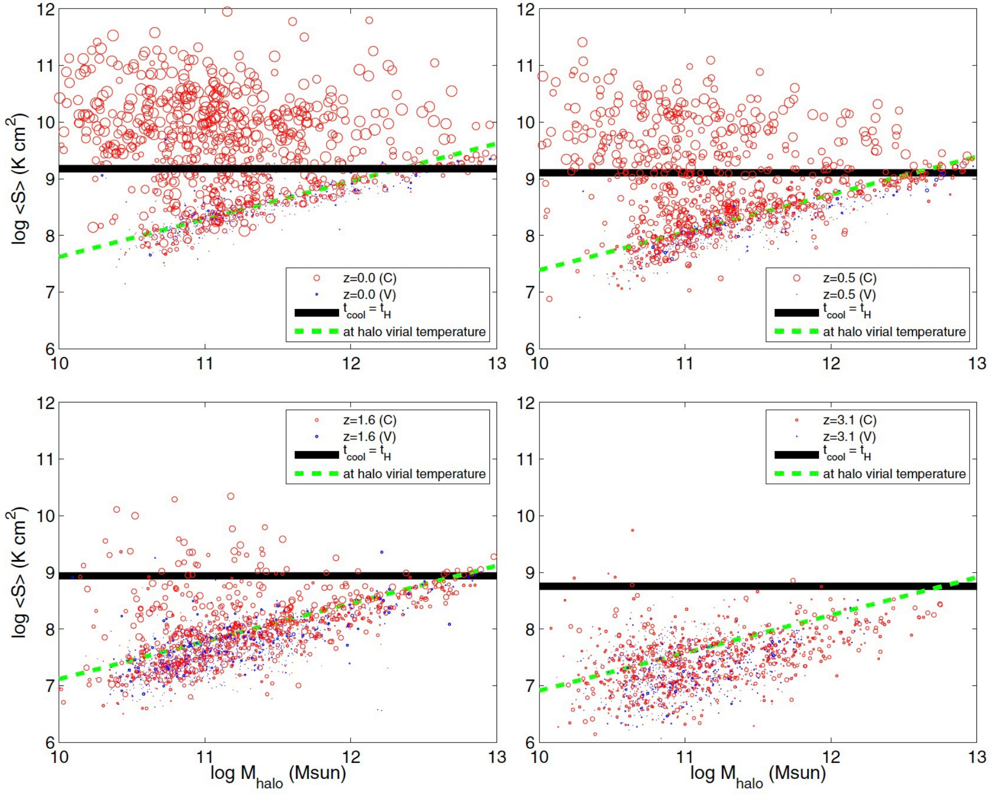
$$\log[S_{\rm crit}/({\rm K\,cm^2})] = 9.183 - 0.167z + 0.0092z^2$$

Cen 2011

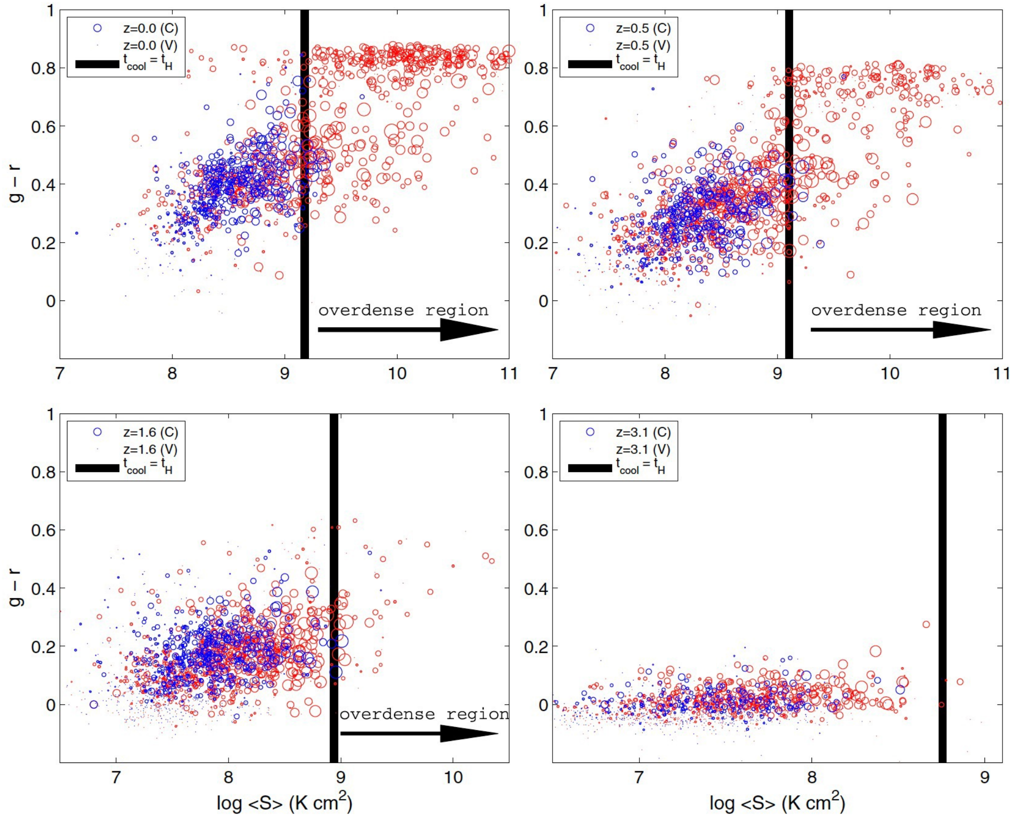
External feedback ：the critical entropy

When environmental $S>S_{crit}$, galaxies turn red

THE ASTROPHYSICAL JOURNAL, 741:99 (15pp), 2011 November 10



THE ASTROPHYSICAL JOURNAL, 741:99 (15pp), 2011 November 10 CEN



Cen 2011

SMBH feedback

The current state

[Submitted on 4 Apr 2023]

The CAMELS project: Expanding the galaxy formation model space with new ASTRID and 28-parameter TNG and SIMBA suites

Yueying Ni, Shy Genel, Daniel Anglés-Alcázar, Francisco Villaescusa-Navarro, Yongseok Jo, Simeon Bird, Tiziana Di Matteo, Rupert Croft, Nianyi Chen, Natalí S. M. de Santi, Matthew Gebhardt, Helen Shao, Shivam Pandey, Lars Hernquist, Romeel Dave

We present CAMELS-ASTRID, the third suite of hydrodynamical simulations in the Cosmology and Astrophysics with MachinE Learning (CAMELS)

Current State of Affairs

- **Most simulations are focused on internal feedback from AGN**
- **AGN feedback have presently modelled with two modes**

  (1) QSO mode (e.g., high energy flux isotropic winds)

  (2) jets mode (e.g., low energy flux, long duration)
- **What is missing is external feedback from AGN, e.g., high energy FRI/FRII radio jets**
- **Inclusion of this key external feedback physics may alleviate the need of too many free parameters**

SMBH feedback

need to re-establish simulations as first-principle based

three significant challenges

- We need to cull an unbiased set of observational data on AGN that is impervious to personal amplifications, in
  (1) winds in all forms
  (2) radio jets (small and large)
- We then need to understand and extract tangible and implementable physics from such a data set
- We then need to combine focused simulations/theoretical works on AGN scales and make connecting simulations (e.g., between radio jets scale and galactic to extragalactic) to devise physics-based implementation schemes
- This is a difficult and major challenge, i.e., a great opportunity for students who are interested

Conclusions

- Through collective efforts from 1970s to 2010s, dark matter gravitational dynamics is essentially well understood, i.e., we understand properties of dark matter halos in space and time via simulations
- Through collective efforts from 1990 to now, we have made significant breakthroughs in understanding the thermodynamic properties of the intergalactic gas in the cosmic web at low and high redshift
- The core problem of galaxy formation has one last major hurdle: feedback processes from the growth of supermassive black holes
- Efforts to meet this challenge will be richly rewarded physically and will have the opportunity to have a say in the construction of the final theory of galaxy formation