宇宙结构的形成

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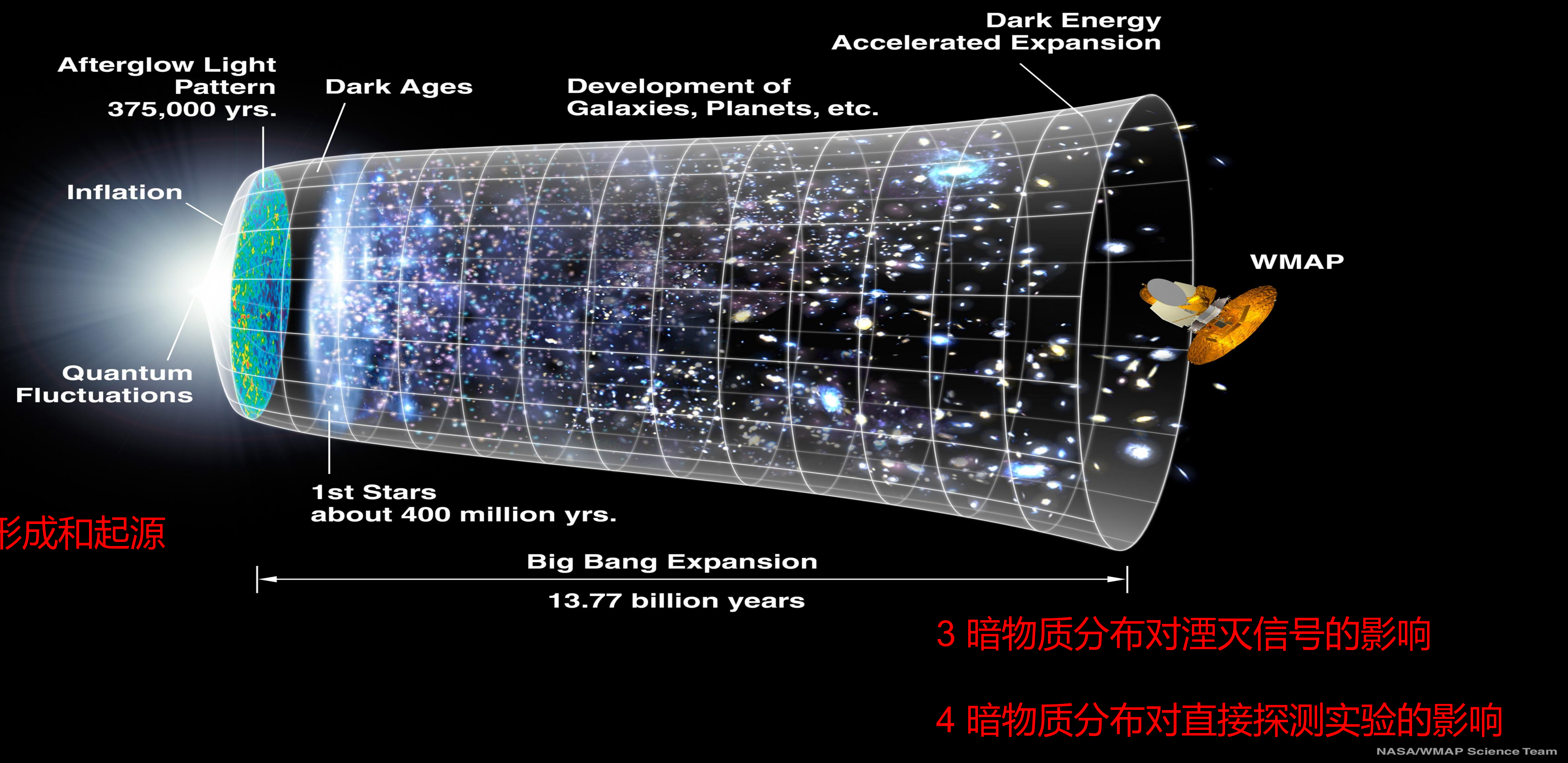
暗物质： 粒子物理 Vs 天体物理

2 暗物质对宇宙结构形成的影响



1 暗物质粒子的形成和起源

3 暗物质分布对湮灭信号的影响

4 暗物质分布对直接探测实验的影响

暗物质模型

●加速器探测

14Tev能级依然没有发现暗物质粒子踪迹

●直接探测

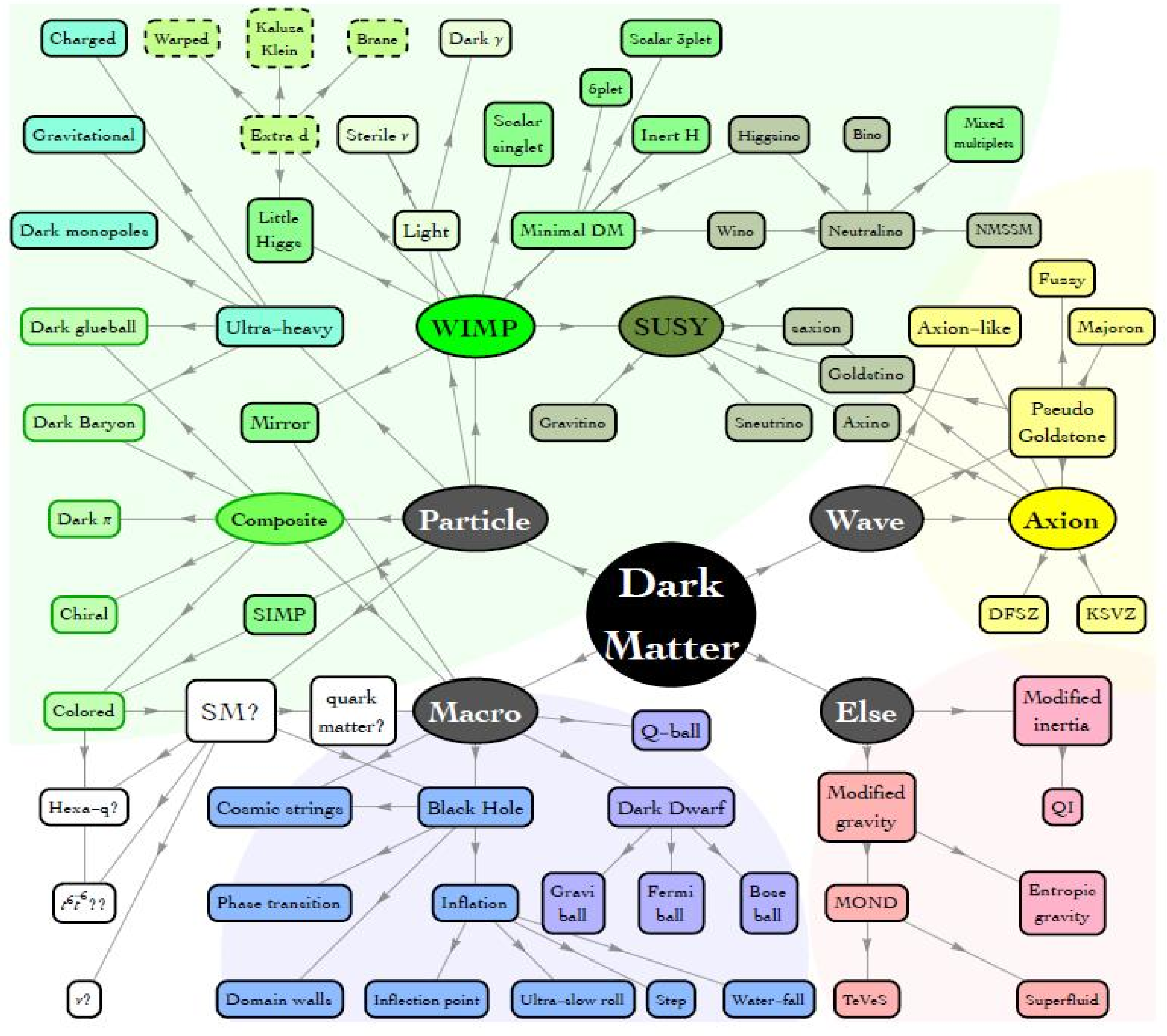
弱相互作用大质量粒子（WIMP）几十年依然没找到，转向轴子等新粒子候选体

●间接探测

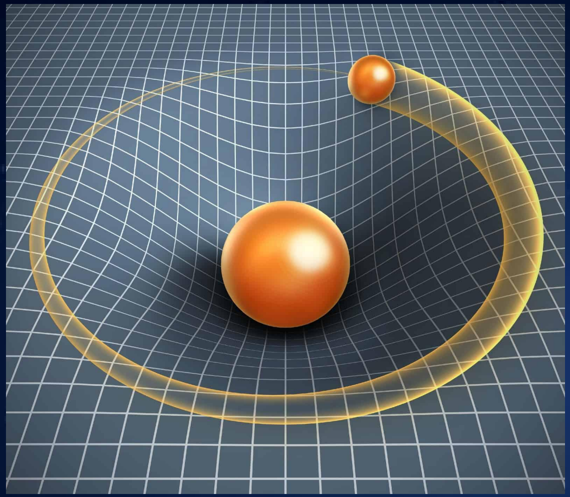
发现了暗物质粒子相互作用的迹象，依然缺乏明确的证据

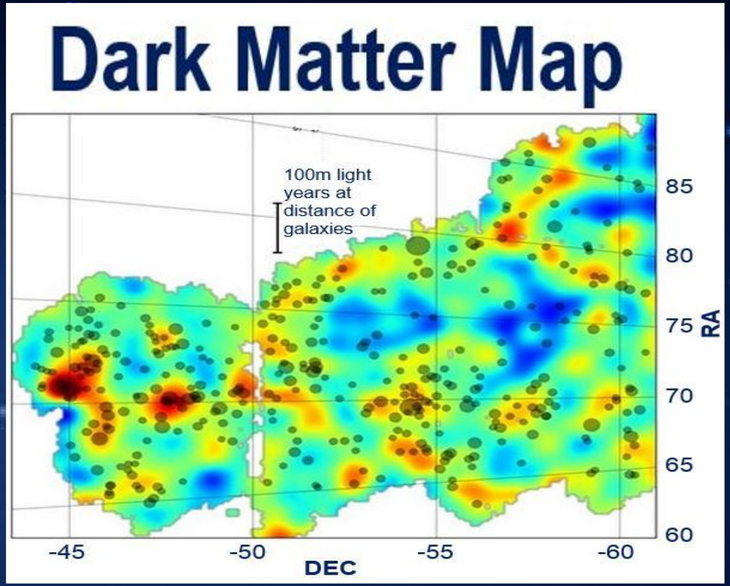
●天体物理手段测量

指出暗物质粒子质量下限>1kev, 无法确定暗物质是冷还是温？



通过测量宇宙暗物质分布限制暗物质属性

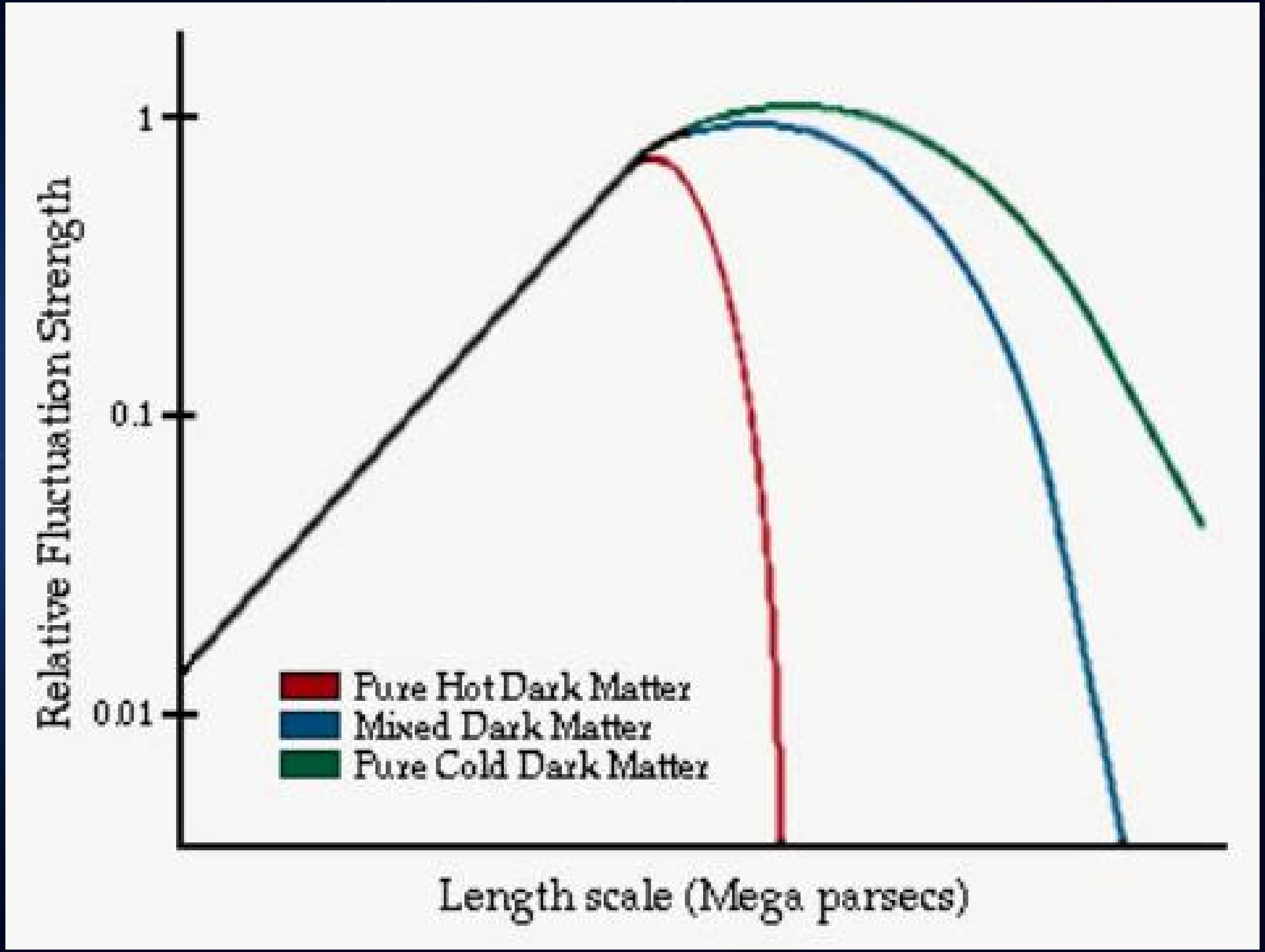


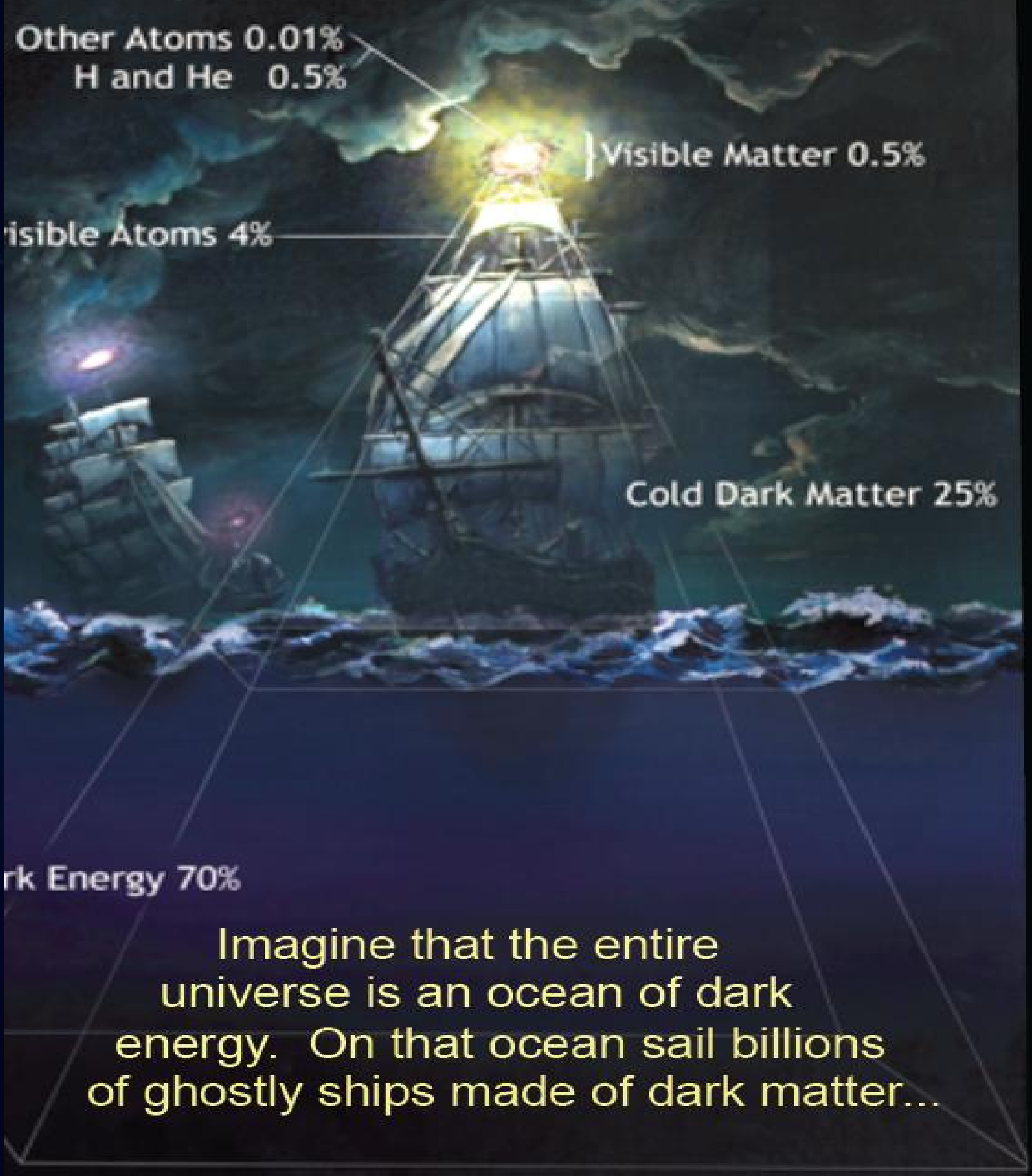


- 通常限制某一类暗物质模型中粒子参数（质量，碰撞截面等）
- 主要通过暗物质引力的宏观效应，统计表现限制暗物质模型
- 需要了解宇宙结构（特别是暗物质晕，星系）的形成演化历史

天文对暗物质粒子质量的限制

- 大尺度物质分布
- 小尺度子结构数目
- 暗晕内部密度轮廓



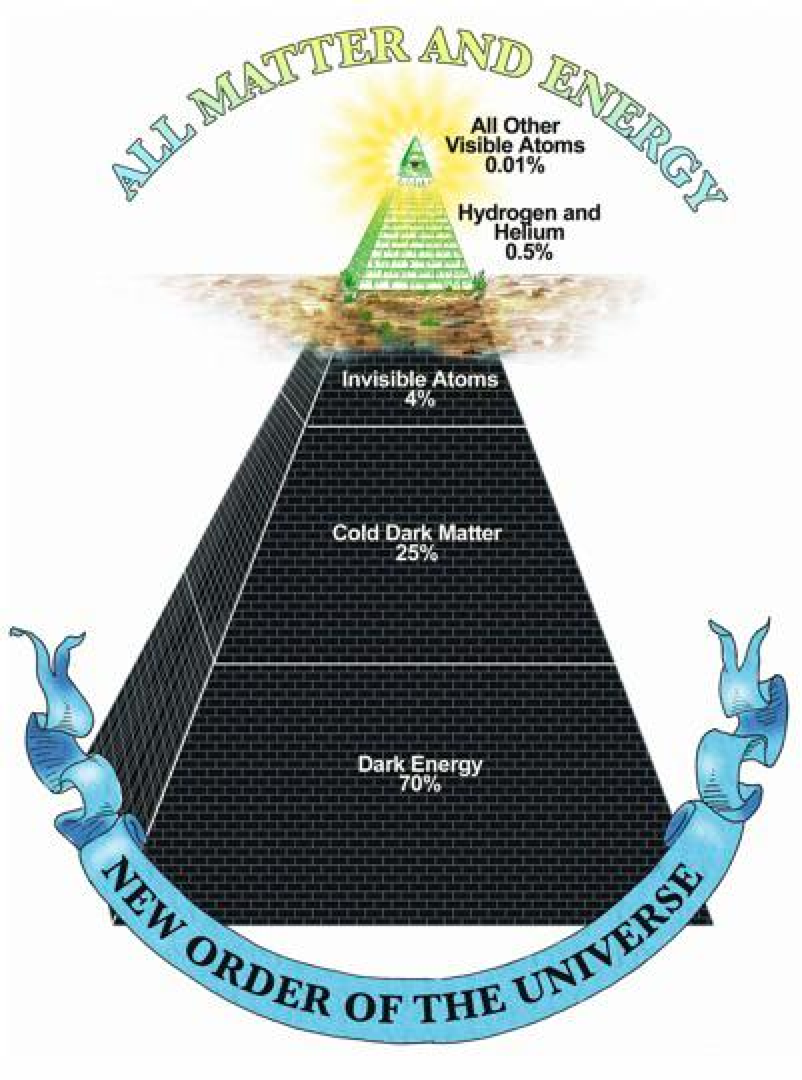


Matter and Energy Content of the Universe

令人惊叹的是通过0.5%的可观测物质，我们还真获得了黑暗世界的知识！

标准宇宙学模型: 双暗模型 (LCDM)

宇宙物质金字塔



重子物质：
✓ 形成恒星，星系，大千世界
✓ 过程复杂

暗物质：
✓ 暗晕，形成宇宙大尺度结构，
✓ 只受引力作用，并主导宇宙的引力势场

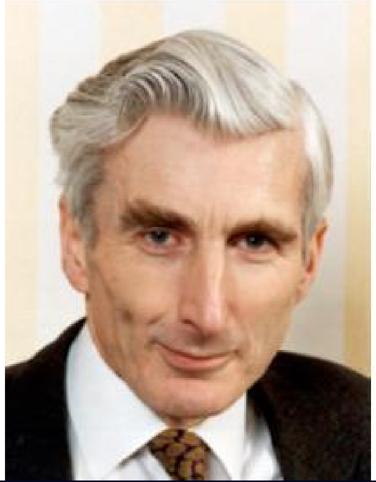
暗能量：
✓ 密度为常数，各项同性均匀分布
✓ 随着宇宙膨胀，占比越来越大
✓ 主导（宇宙晚期）宇宙空间曲率

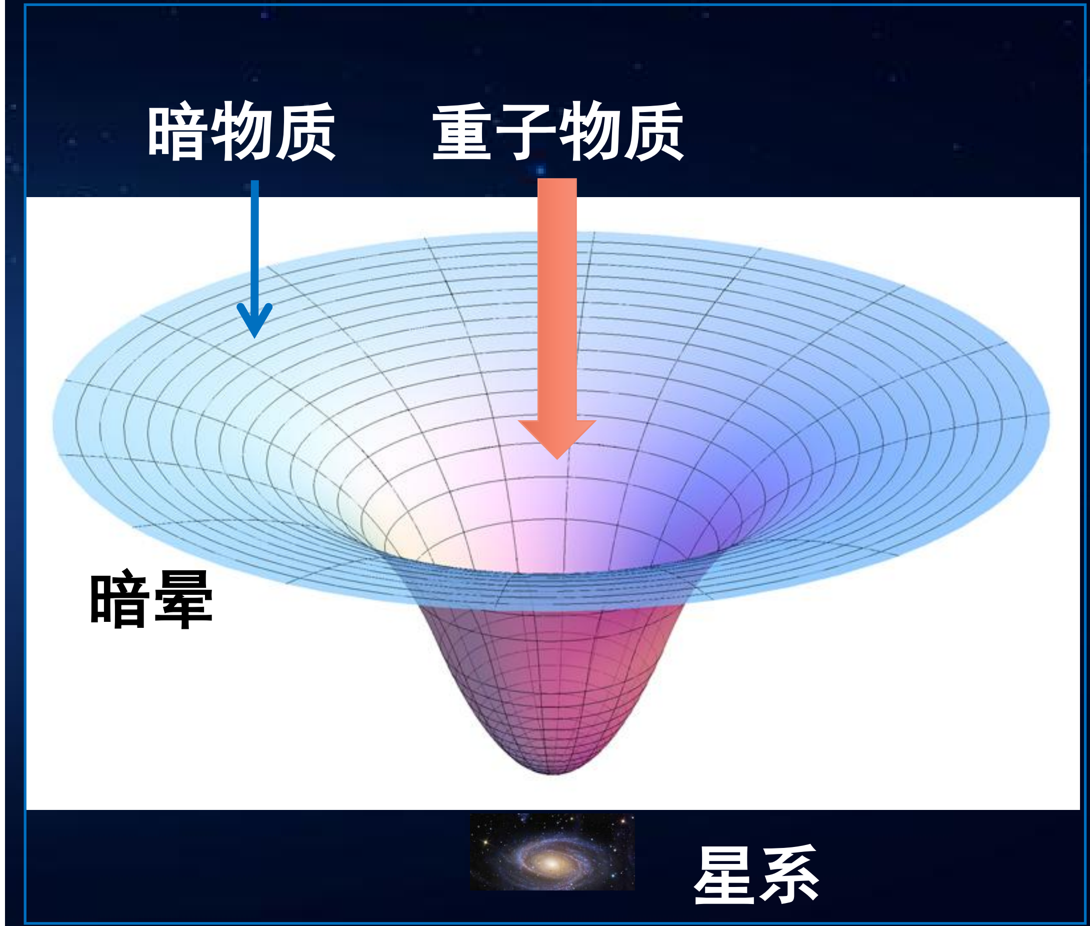
模拟宇宙中的结构形成

Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering 1978

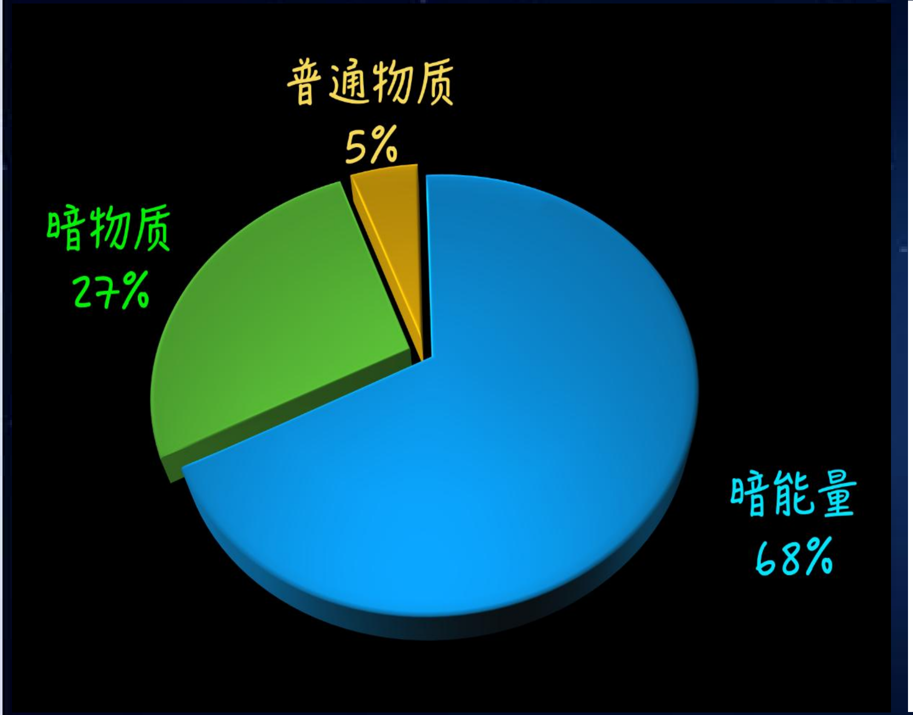
S. D. M. White and M. J. Rees *Institute of Astronomy, Madingley Road, Cambridge*

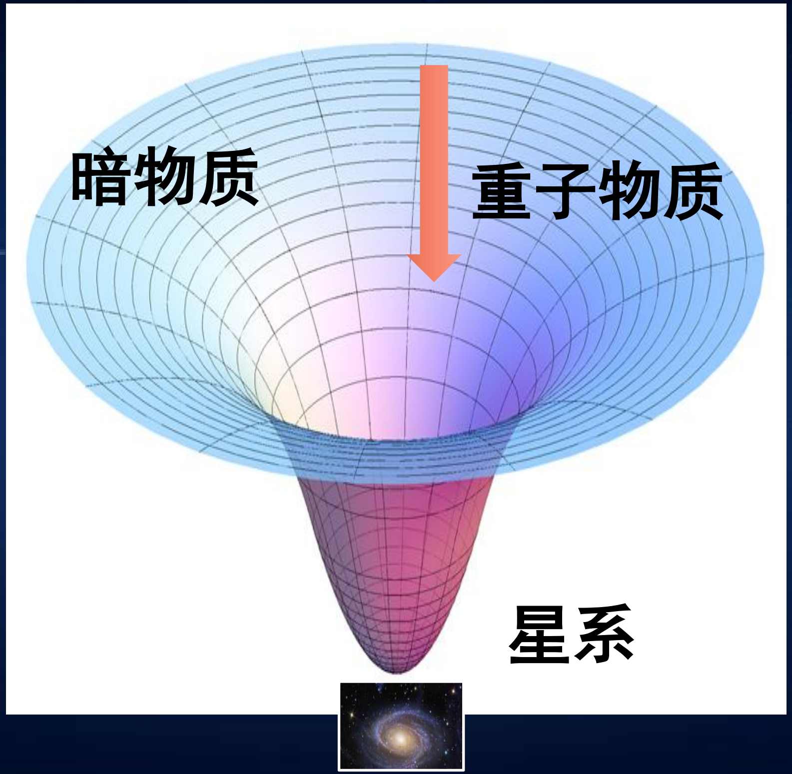
Summary. We suggest that most of the material in the Universe condensed at an early epoch into small 'dark' objects. Irrespective of their nature, these objects must subsequently have undergone hierarchical clustering, whose present scale we infer from the large-scale distribution of galaxies. As each stage of the hierarchy forms and collapses, relaxation effects wipe out its substructure, leading to a self-similar distribution of bound masses of the type discussed by Press & Schechter. The entire luminous content of galaxies, however, results from the cooling and fragmentation of residual gas within the transient potential wells provided by the dark matter. Every galaxy thus forms as a concentrated luminous core embedded in an extensive dark halo. The observed sizes of galaxies and their survival through later stages of the hierarchy seem inexplicable without invoking substantial dissipation; this dissipation allows the galaxies to become sufficiently concentrated to survive the disruption of their halos in groups and clusters of galaxies. We propose a specific model in which $\Omega \simeq 0.2$, the dark matter makes up 80 per cent of the total mass, and half the residual gas has been converted into luminous galaxies by the present time. This model is consistent with the inferred proportions of dark matter, luminous matter and gas in rich clusters, with the observed luminosity density of the Universe and with the observed radii of galaxies; further, it predicts the characteristic luminosities of bright galaxies and can give a luminosity function of the observed shape.

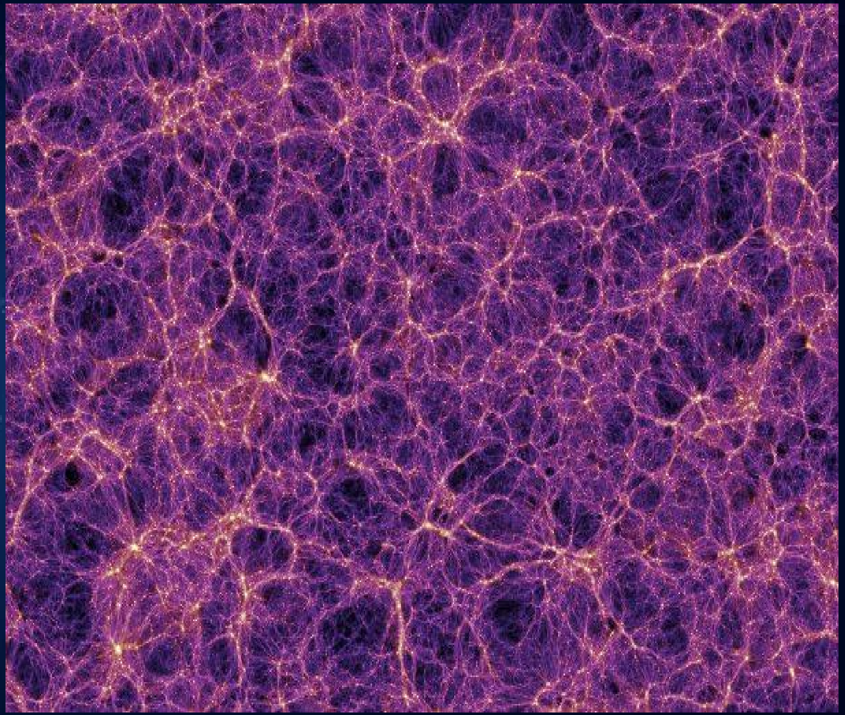




宇宙结构的形成、演化和分布





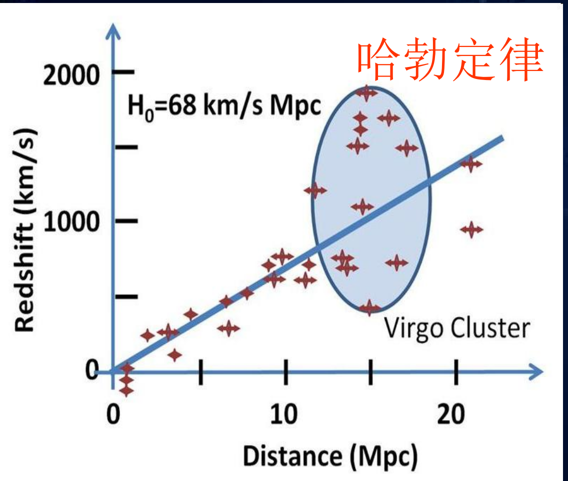


- 暗物质形成暗晕，重子物质在暗晕中聚集，形成恒星、星系
- 暗晕/星系在宇宙中的分布组成大尺度结构

结构形成

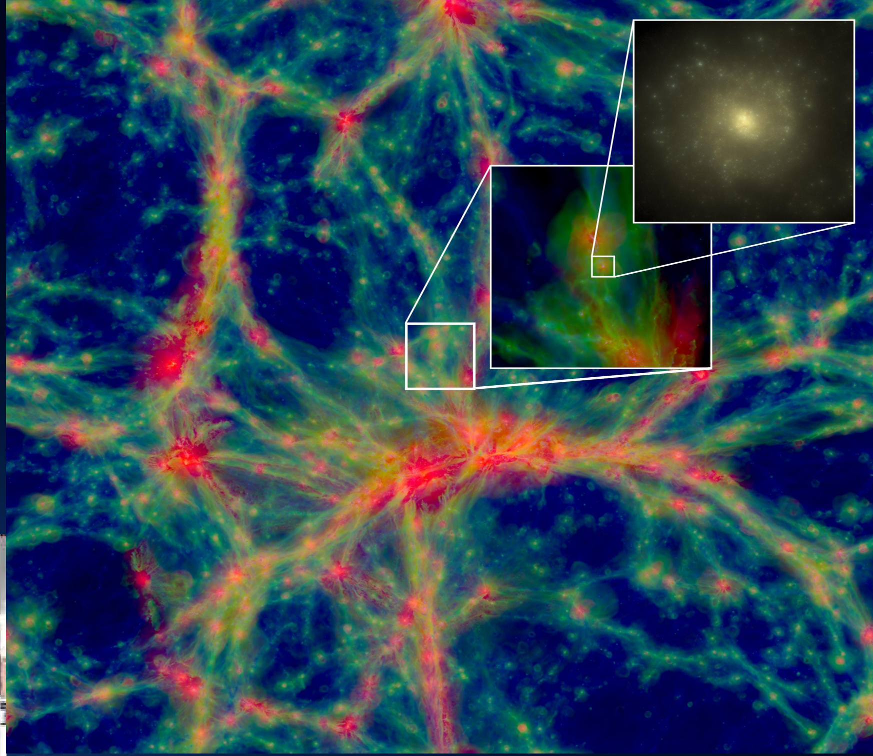
天文学研究范式

理论模型
（线性过程）



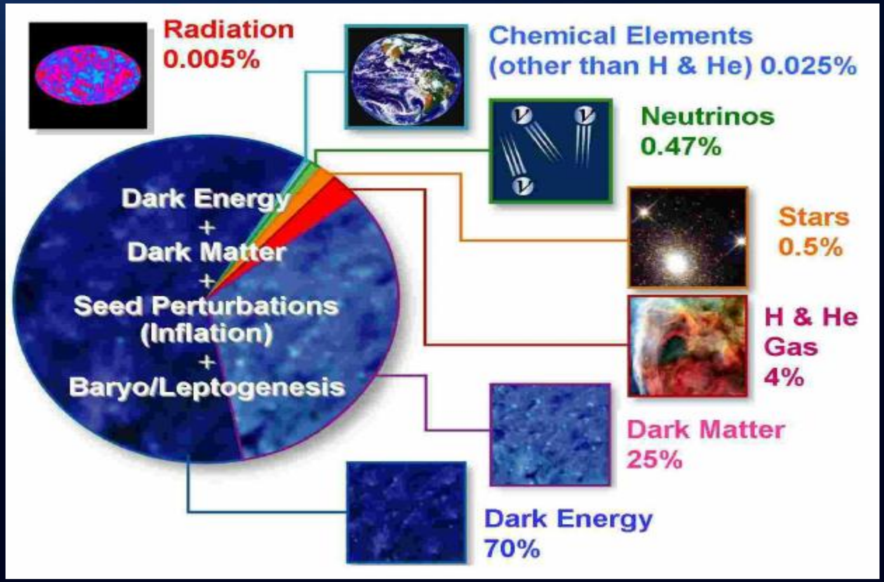
1980s 后

数值模拟
（非线性过程）



观测数据
（线性过程）

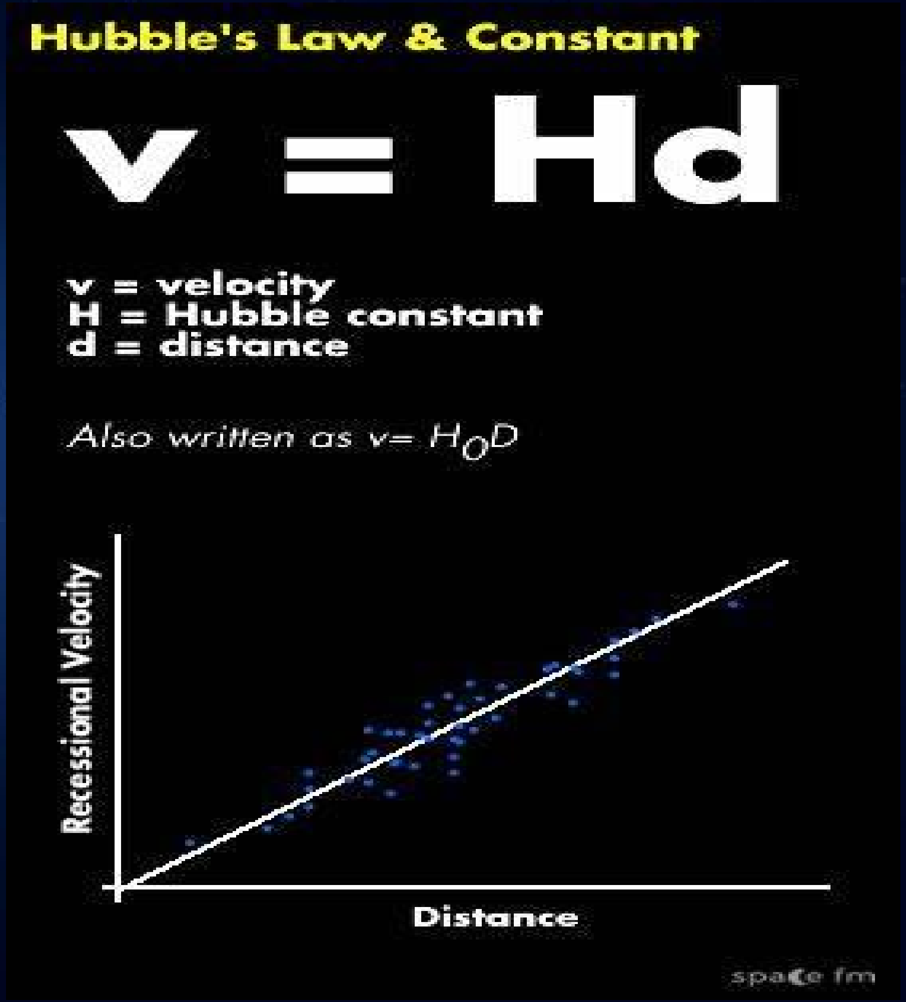
Observation



观测与理论

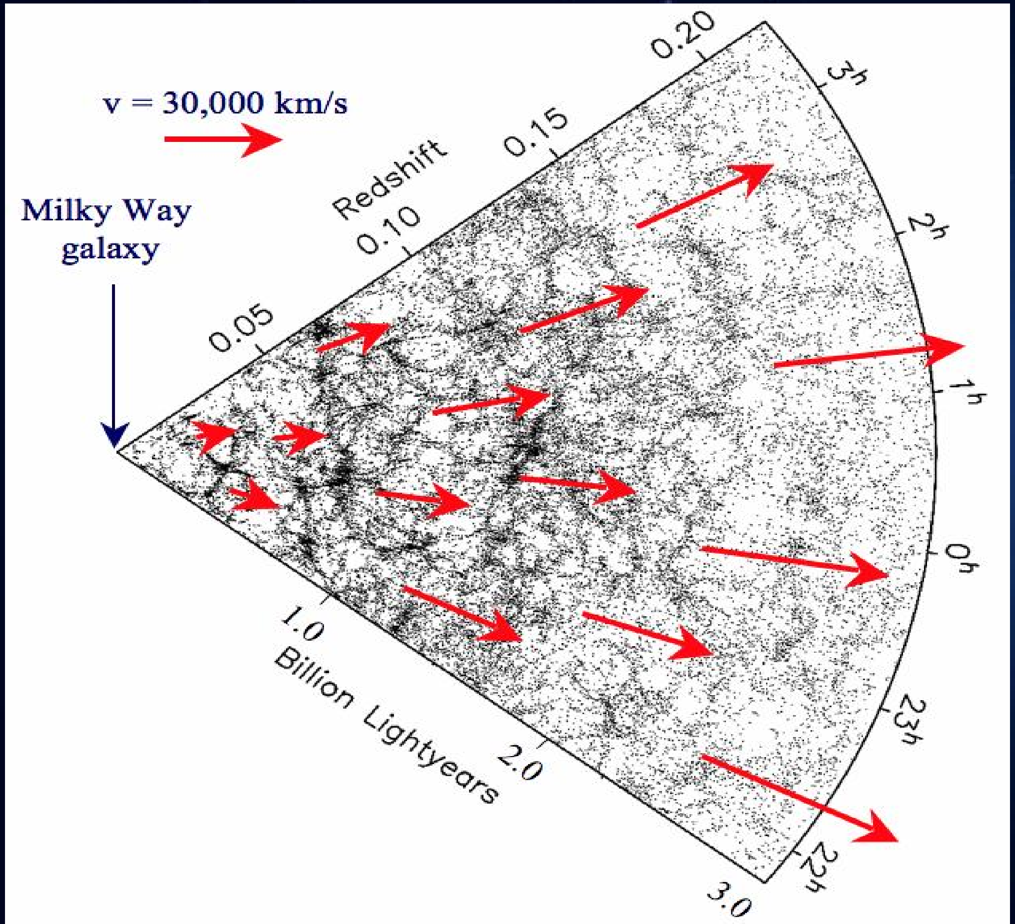
观测数据

理论计算

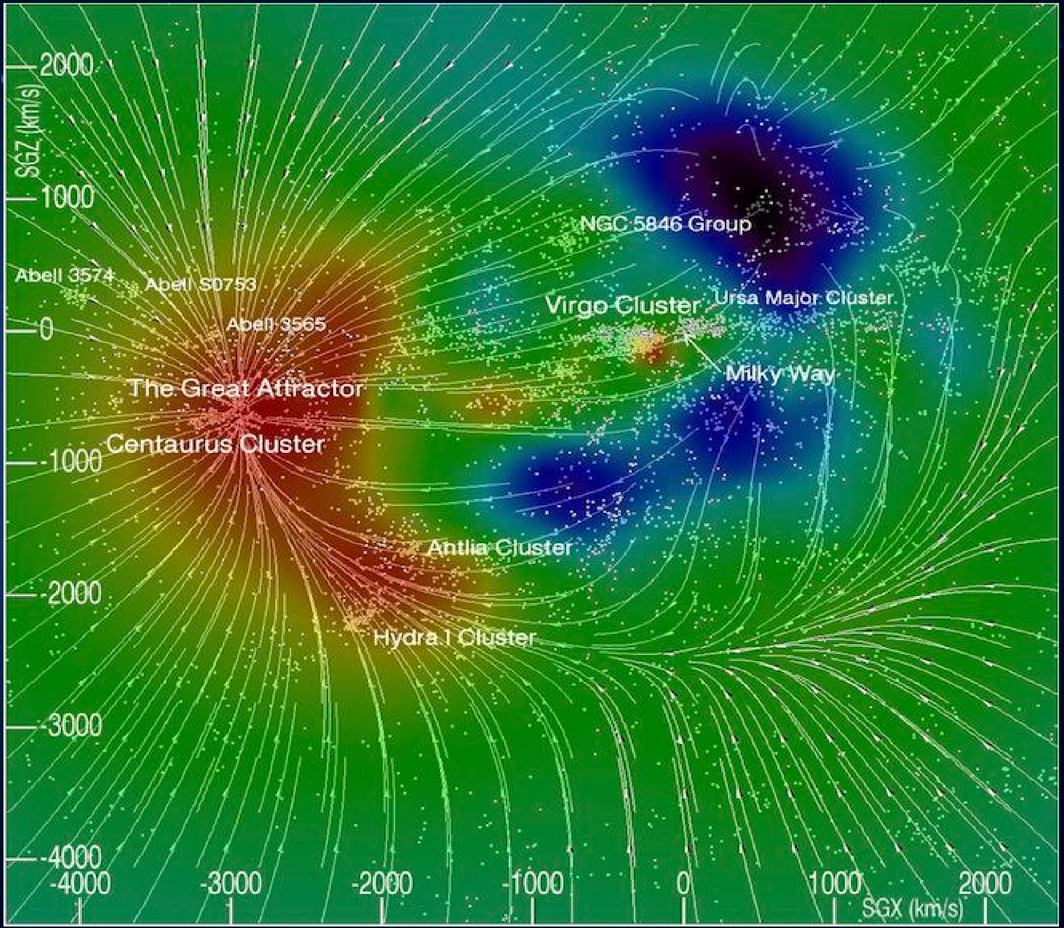


自然规律

宇宙学与数值模拟



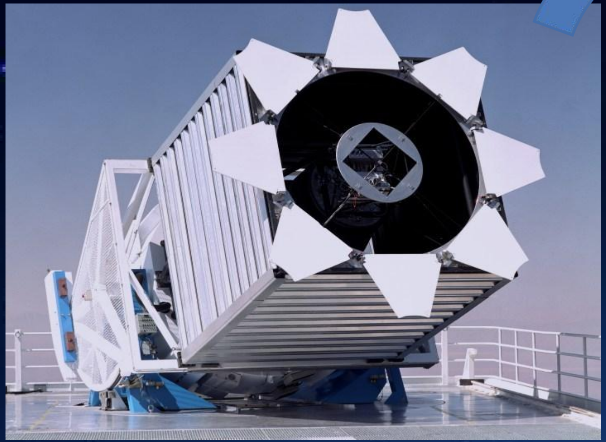
简单，线性



复杂，非线性

宇宙学与数值模拟

观测数据

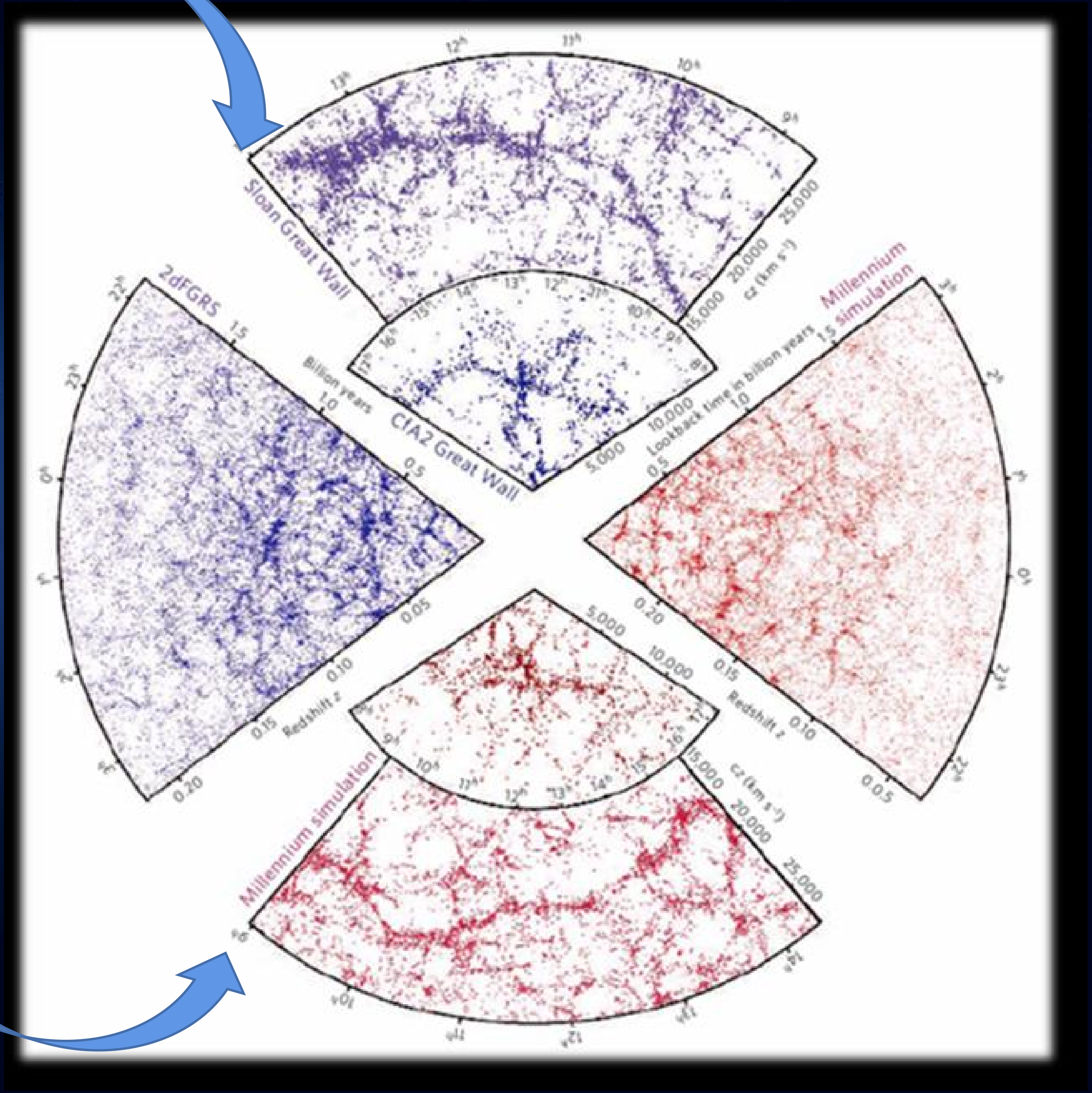


原初条件
（粒子系统）

边界条件

特定物理规律
（宇宙学模型，引力作用规律）

数值模拟



N体模拟

暗物质粒子为无碰撞粒子，只有引力作用
利用蒙特卡洛方法，其演化可用N体系统描述

Poisson-Vlasov System

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \mathbf{v} + \frac{\partial f}{\partial \mathbf{v}} \cdot \left(-\frac{\partial \Phi}{\partial \mathbf{x}} \right) = 0$$

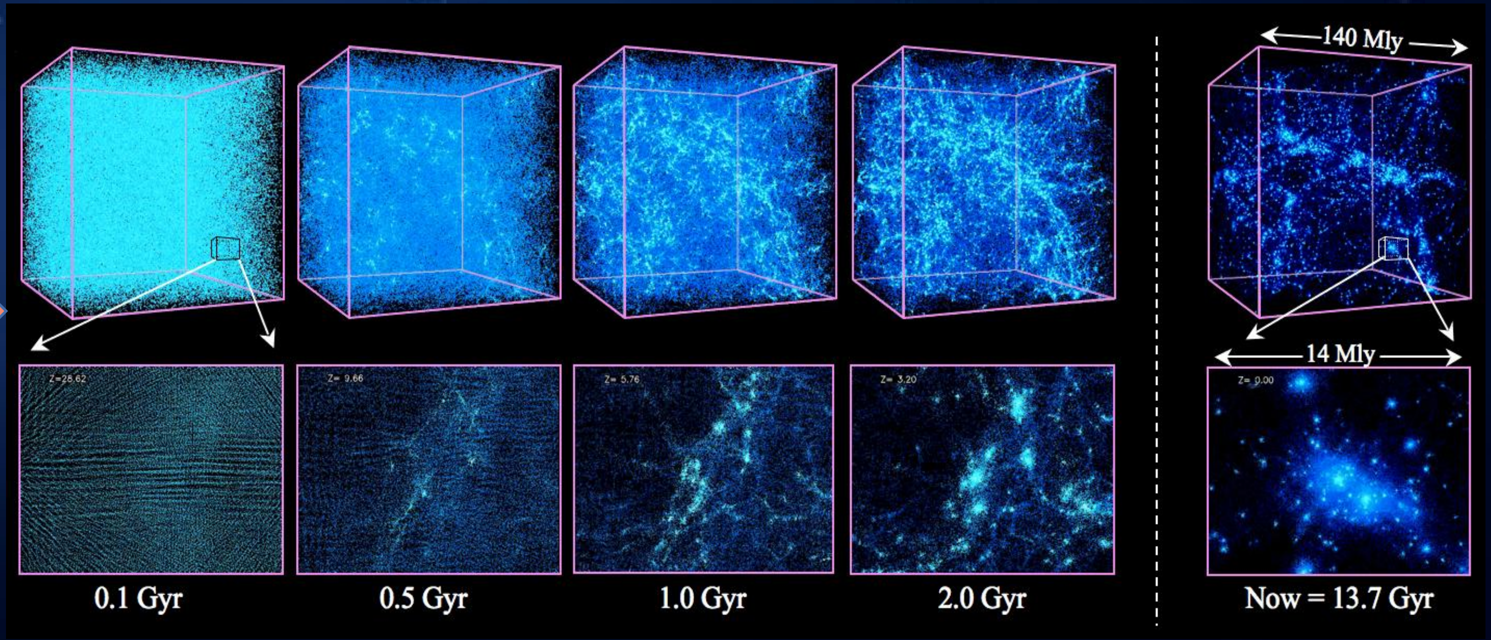
$$\nabla^2 \Phi(\mathbf{x}, t) = 4\pi G \int f(\mathbf{x}, \mathbf{v}, t)\, \mathrm{d}\mathbf{v}$$

N-body System

$$\ddot{\mathbf{x}}_i = -\nabla_i \Phi(\mathbf{x}_i)$$

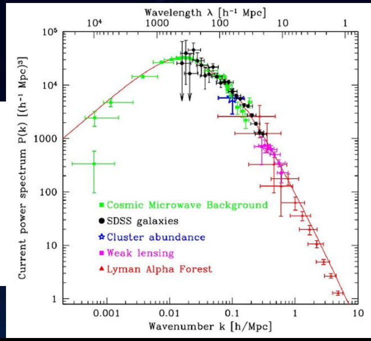
$$\Phi(\mathbf{x}) = -G \sum_{j=1}^{N} \frac{m_j}{[(\mathbf{x} - \mathbf{x}_j)^2 + \epsilon^2]^{1/2}}$$

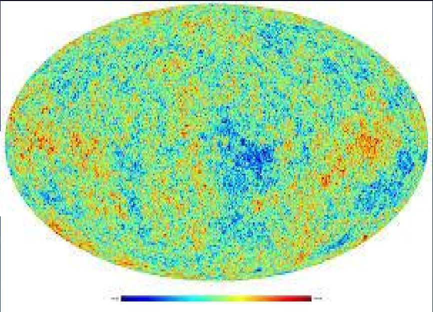
need large *N*

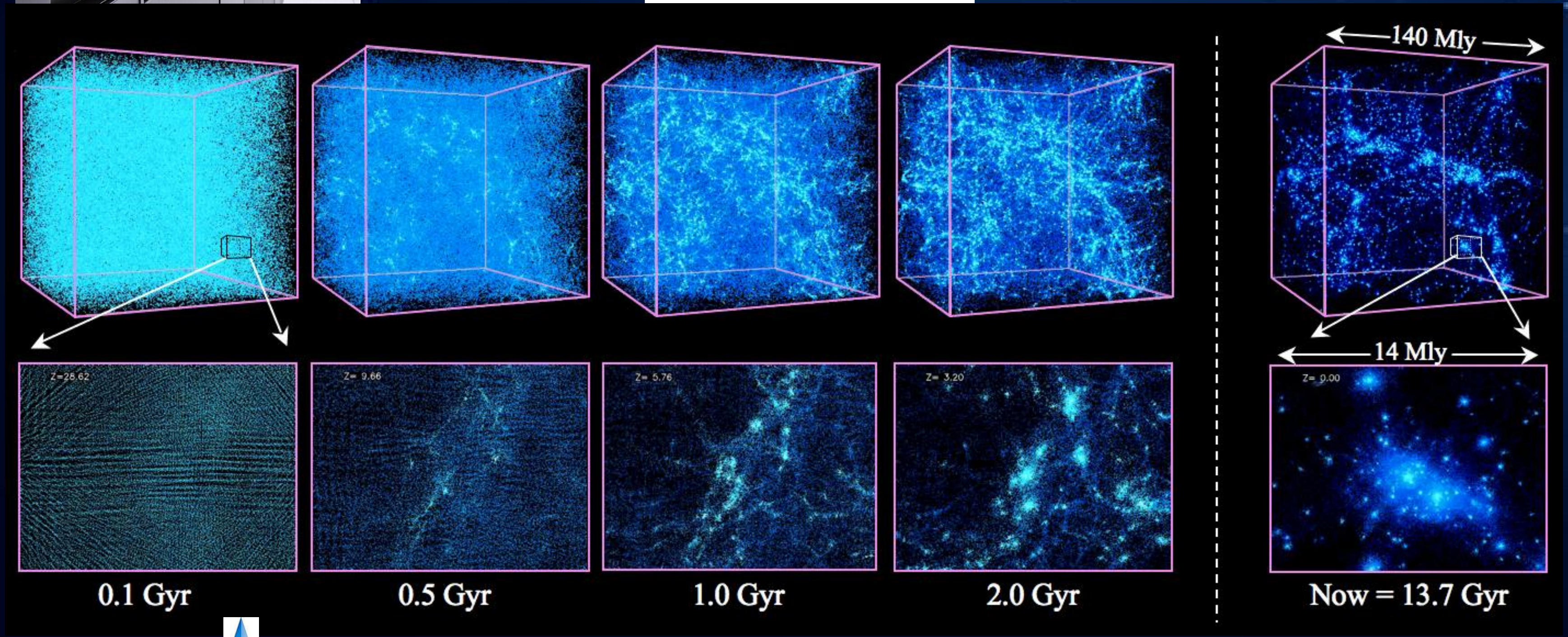


目前N最大可为4×10^{12}

N体模拟技术







- 在一个膨胀的立体区域用离散的粒子分布模拟物质的演化
- 原初条件根据观测到的微波背景的涨落起伏来设定
- 从大爆炸400万年后开始 演化到现在
- 每个粒子的轨迹由N-体引力解决定

N=64^3 ~ 15360^3

$$\frac{d\mathbf{x}}{dt} = \mathbf{u}, \quad \frac{d\mathbf{u}}{dt} = -\nabla\Phi$$

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

宇宙学模型

N体----只有引力

N体的挑战---动态范围

分辨率

需要更小质量的模拟粒子去解析更细微的结构

需要更大的体积去代表宇宙的范围

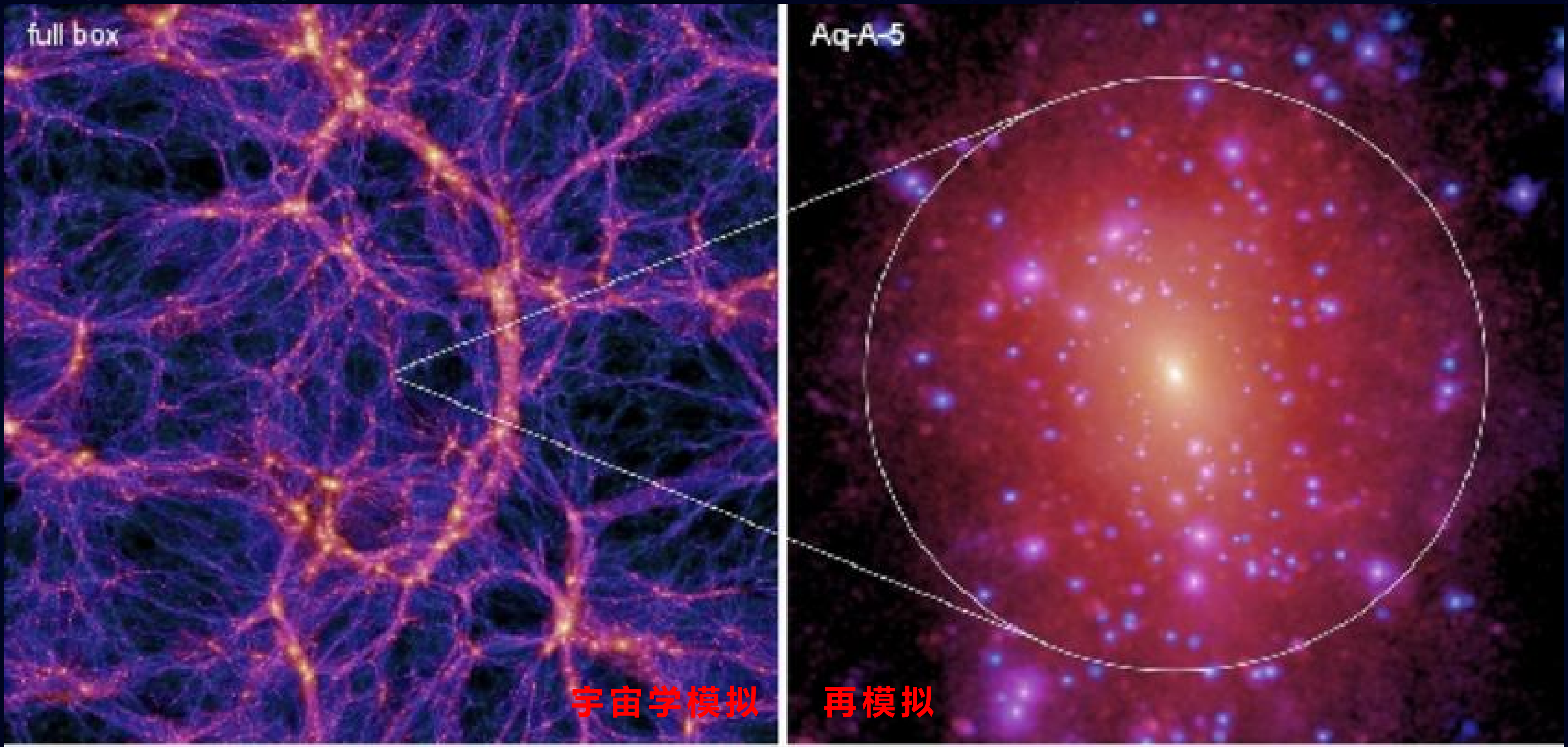
视场

需要更大的 N

（N为模拟的粒子数）

望远镜口径

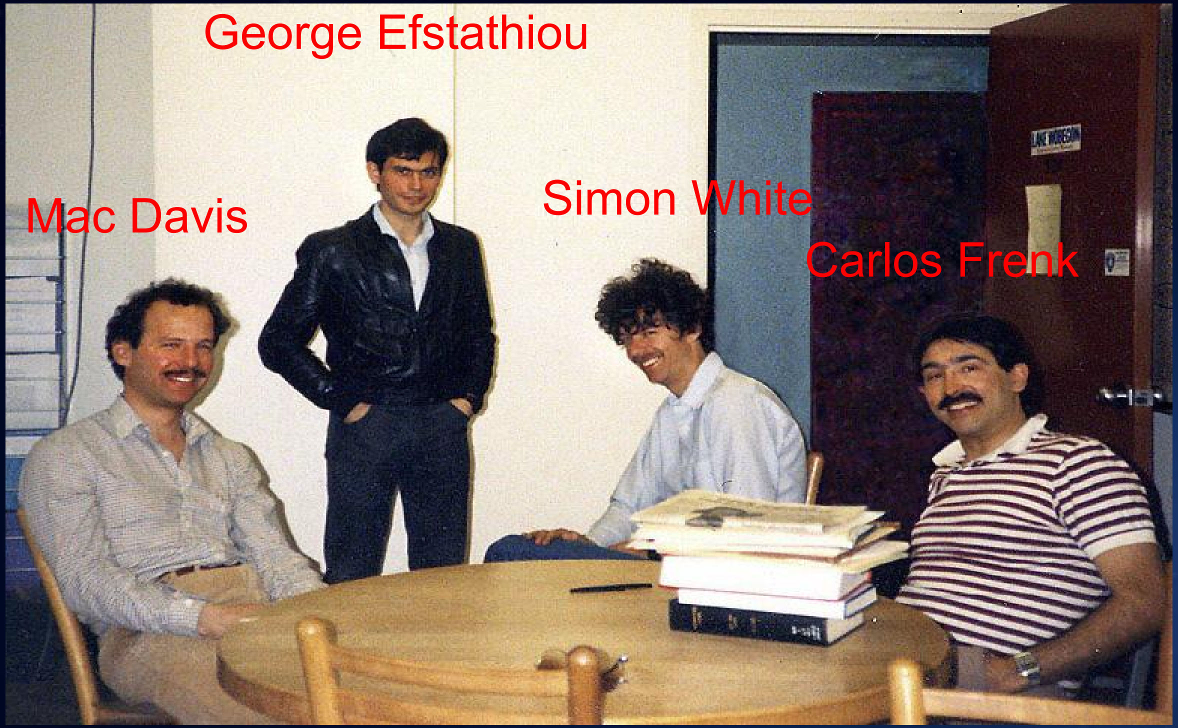
再模拟技术

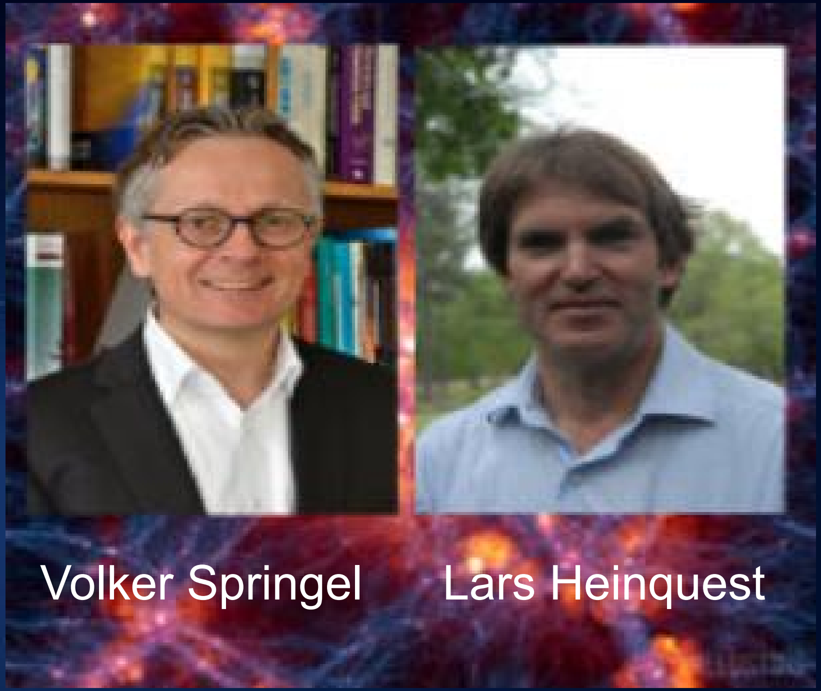


- ➢ 数值模拟的规模由粒子数目决定
- ➢ 体积增大，质量解析度降低
- ➢ 体积减小，质量解析度增高

大质量粒子作为背景引力势井，在一个更小空间内用质量更小的粒子（更多的粒子数目）解析更小的结构

数值模拟深刻改变了宇宙学发展





快速帮助确立了“暗物质暗能量”标准宇宙学模型

极大的帮助理解星系形成中的诸多复杂物理过程

2011 年 Gruber 宇宙学奖:

“ From 1985 to 1988 the DEFW collaboration produced five papers that changed cosmology forever.”

“DEFW合作在1985-1988年完成的五篇文章永远的改变了宇宙学”

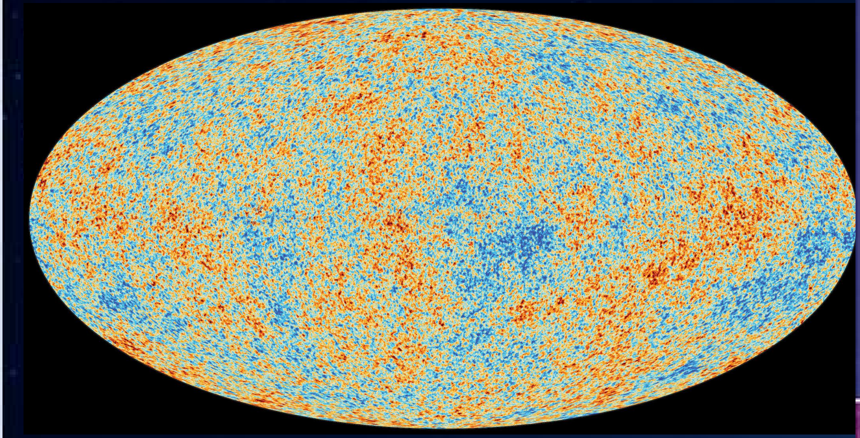
2020 年 Gruber 宇宙学奖:

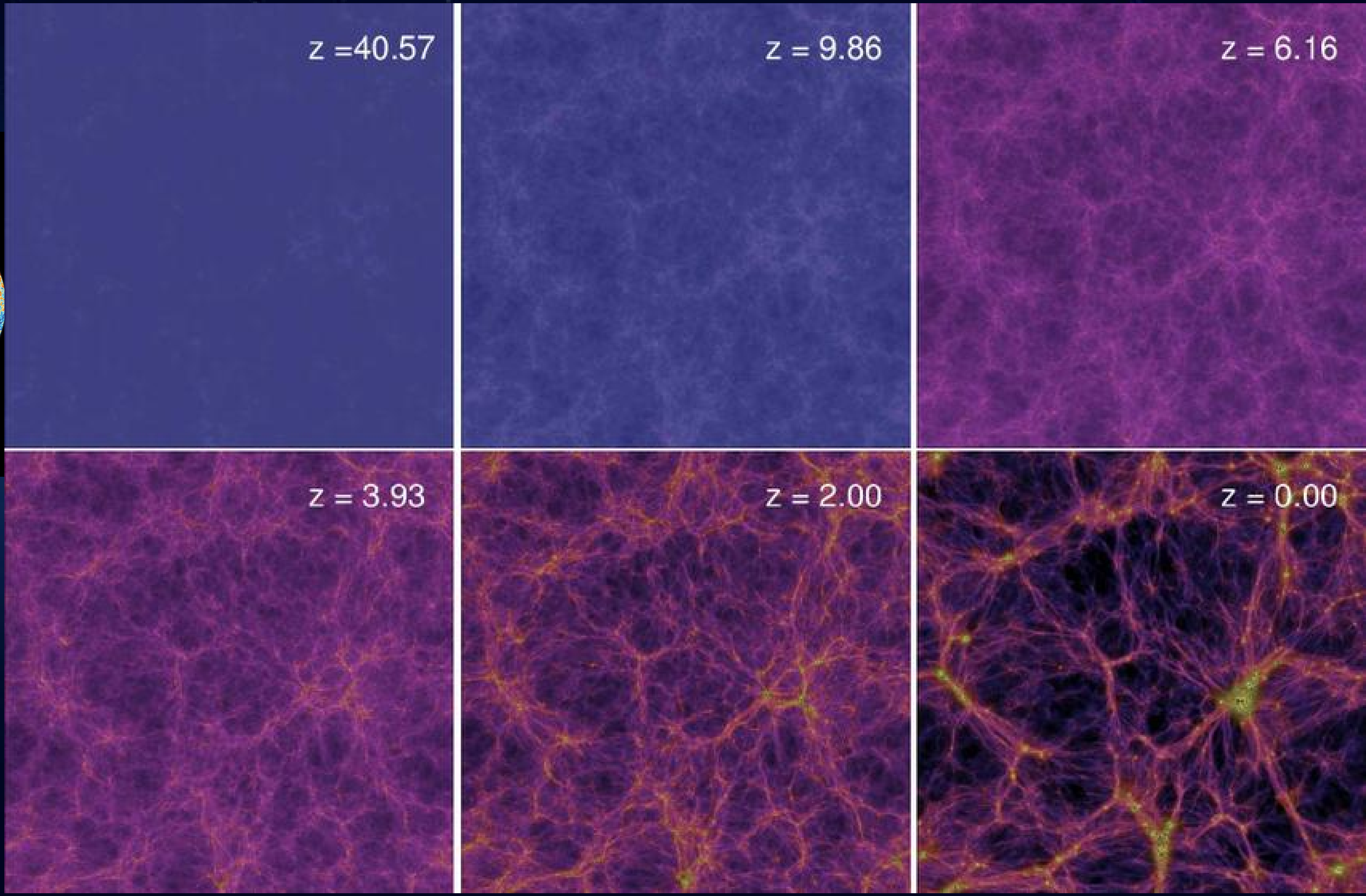
“ ...make computer simulations an indispensable tool for cosmologists, allowing them to test theories and locate fertile areas for further research.”

“...数值模拟成了宇宙学家必不可少的工具，用来检测理论，寻找新的突破点 “

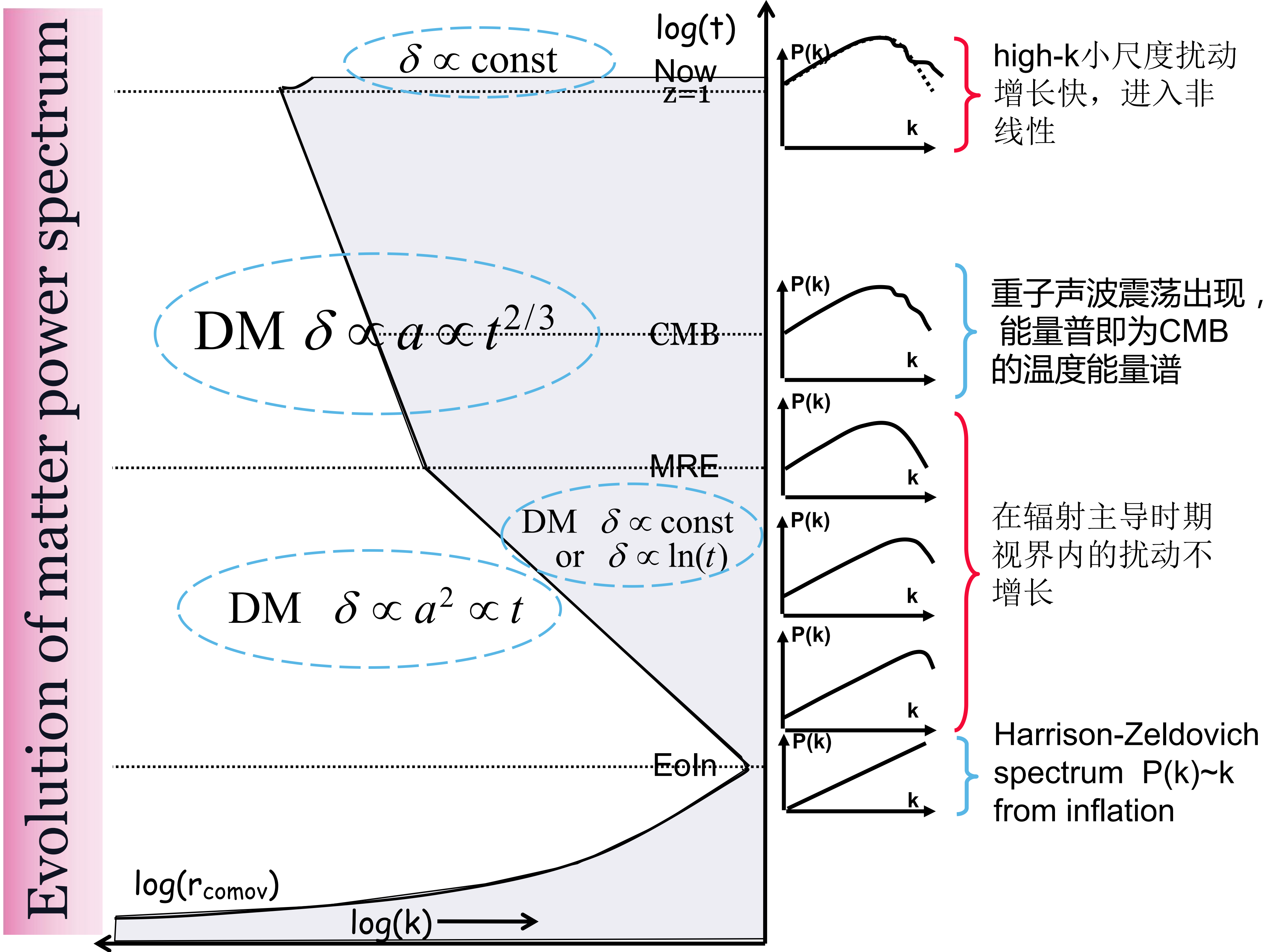
大尺度结构

大尺度结构的形成





宇宙微波背景辐射显示了
宇宙早期的密度涨落



Evolution of matter power spectrum
log(t)
δ ∝ const
Now
Z=1
DM δ ∝ a ∝ t^{2/3}
CMB
MRE
DM δ ∝ const
or δ ∝ ln(t)
DM δ ∝ a² ∝ t
EoIn
log(r_comov)
log(k)
P(k)
k
high-k小尺度扰动增长快，进入非线性
重子声波震荡出现，能量普即为CMB的温度能量谱
在辐射主导时期视界内的扰动不增长
Harrison-Zeldovich spectrum P(k)~k from inflation

Transfer Functions

Transfer function is defined by this relation:

$$P_{\mathrm{MRE}}(k) = T_k^{\ 2} \cdot P_{\inf}(k)$$

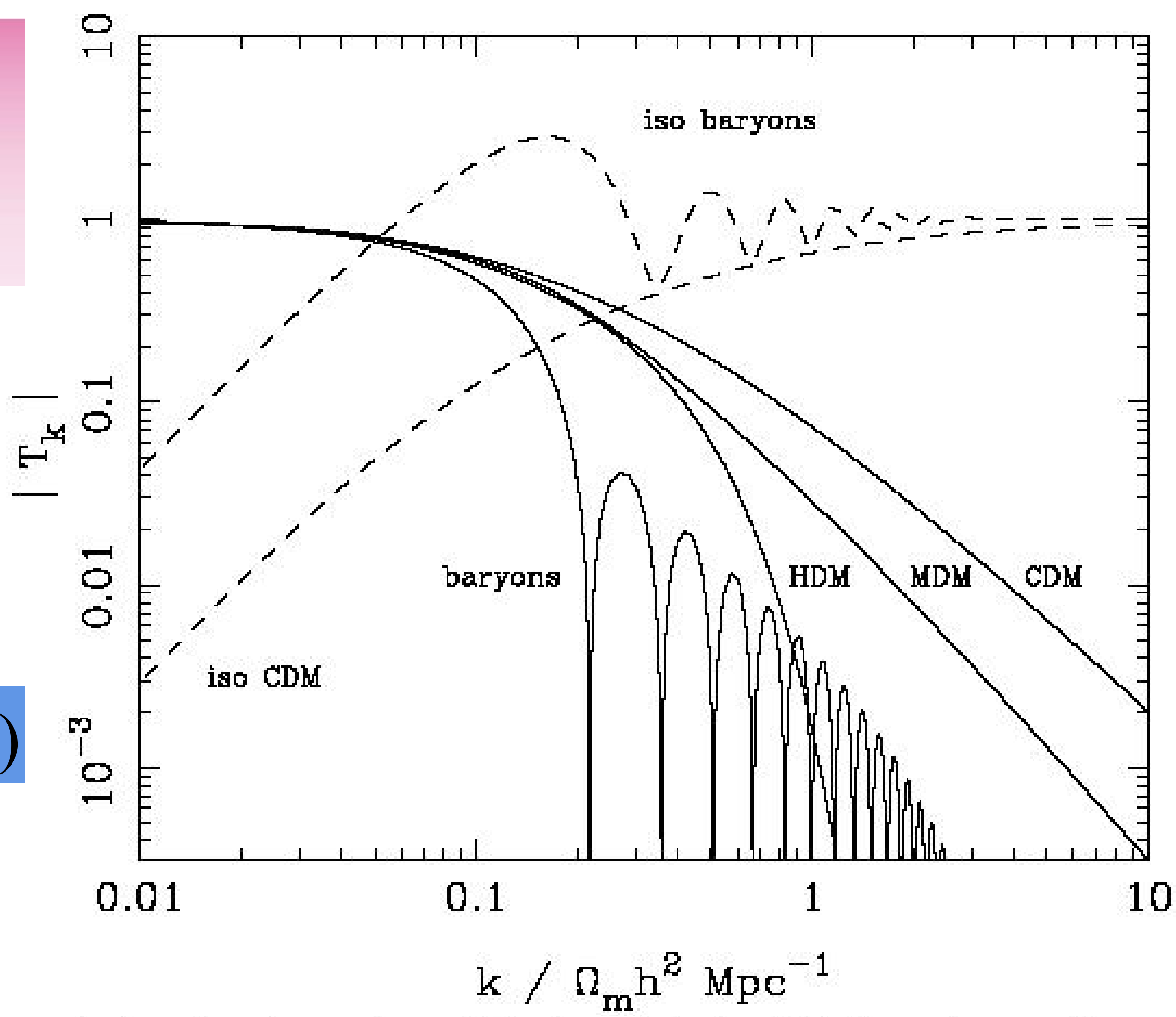


FIGURE 2. A plot of transfer functions for various adiabatic models, in which $T_k \to 1$ at small k. A number of possible matter contents are illustrated: pure baryons; pure CDM; pure HDM. For dark-matter models, the characteristic wavenumber scales proportional to $\Omega_m h^2$, marking the break scale corresponding to the horizon length at matter-radiation equality. The scaling for baryonic models does not obey this exactly; the plotted case corresponds to $\Omega_m = 1$, $h = 0.5$.

Peacock; astro-ph/0309240

Zel'dovich 近似

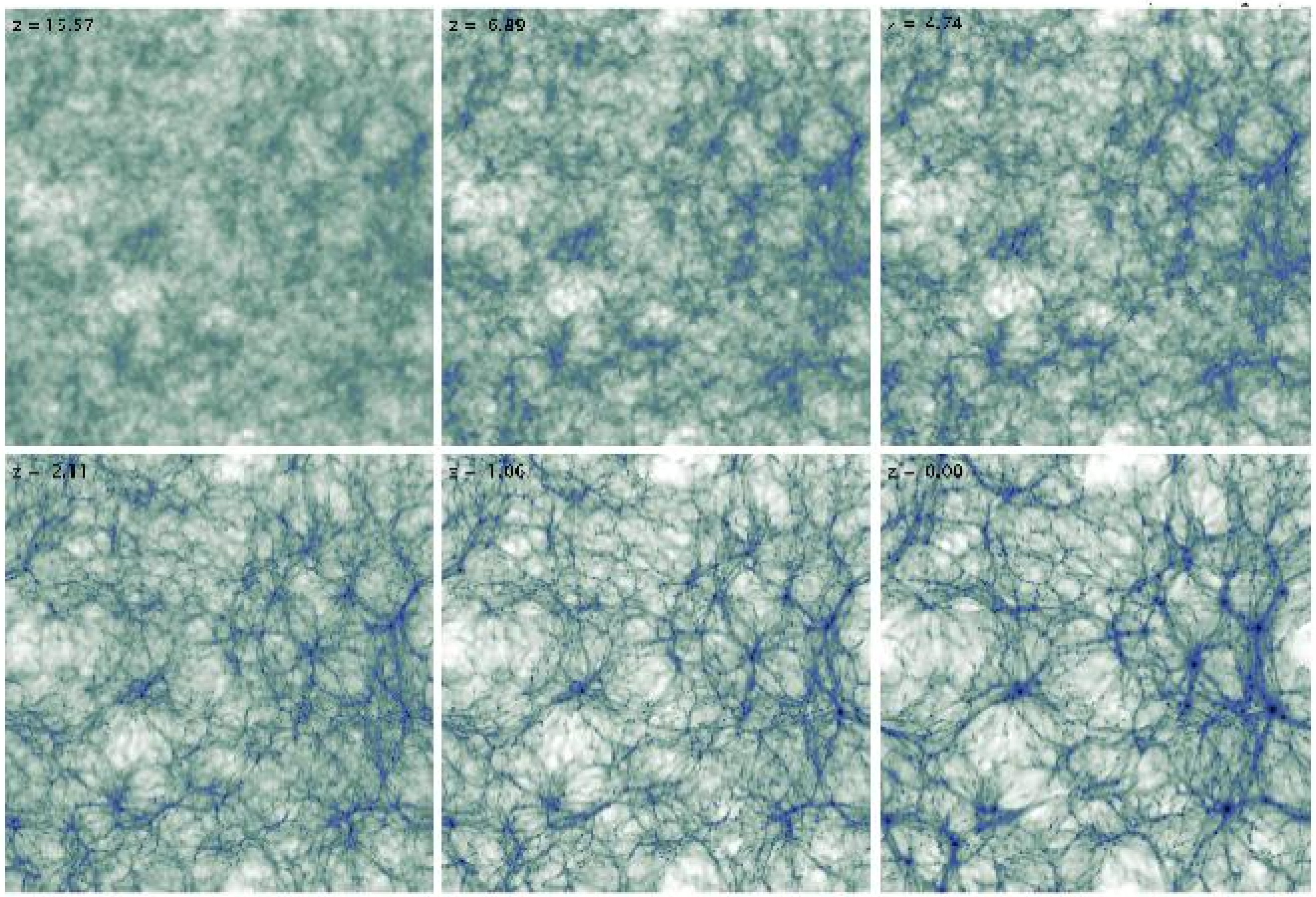
- 假设宇宙中所有的质量粒子都是沿着直线运动，而其速度都按照其线性扰动理论预测的值来运动,即使移动很远的距离，依然近似适用。
- 我们可以对所有粒子的运动得到其运动方程---从远处的位置q到最后的位置x

  - $x=q+\Psi$ with $\Psi(q,t)=D(t)\Psi(q)$ and $\Psi_i=d\Phi/dq_i$
  - $\Psi_k = -ik/k^2\,\delta_k$
- 如果这个原初的物质分布是非常均匀的，则最后的物质分布将是原处物质场的Jacobian转换

  - $\rho\sim[(1-D\alpha)(1-D\beta)(1-D\gamma)]^{-1}$
  - α,β,γ e-values of $-d^2\Phi/dq_idq_j$
-
- 最后形成的结构将首先沿着最大的本征值方向塌缩，形成盘状结构（pancake/sheet），然后沿着另外两个相互垂直的方向塌缩(filaments)，形成丝状结构，和暗晕(halo)

The cosmic web

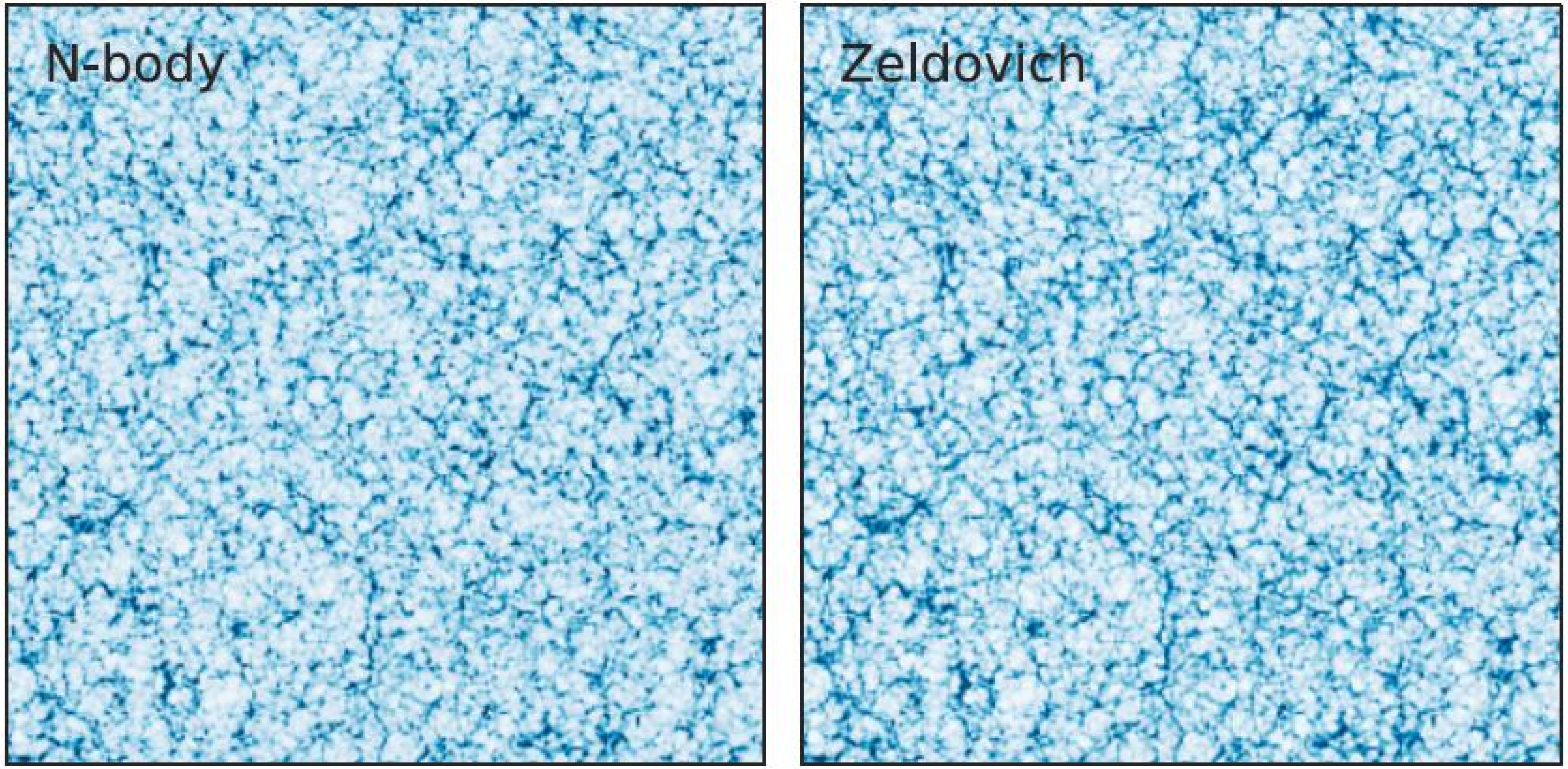
The Zel'dovich approximation, plus the statistics of Gaussian fields, qualitatively describes large-scale structure.



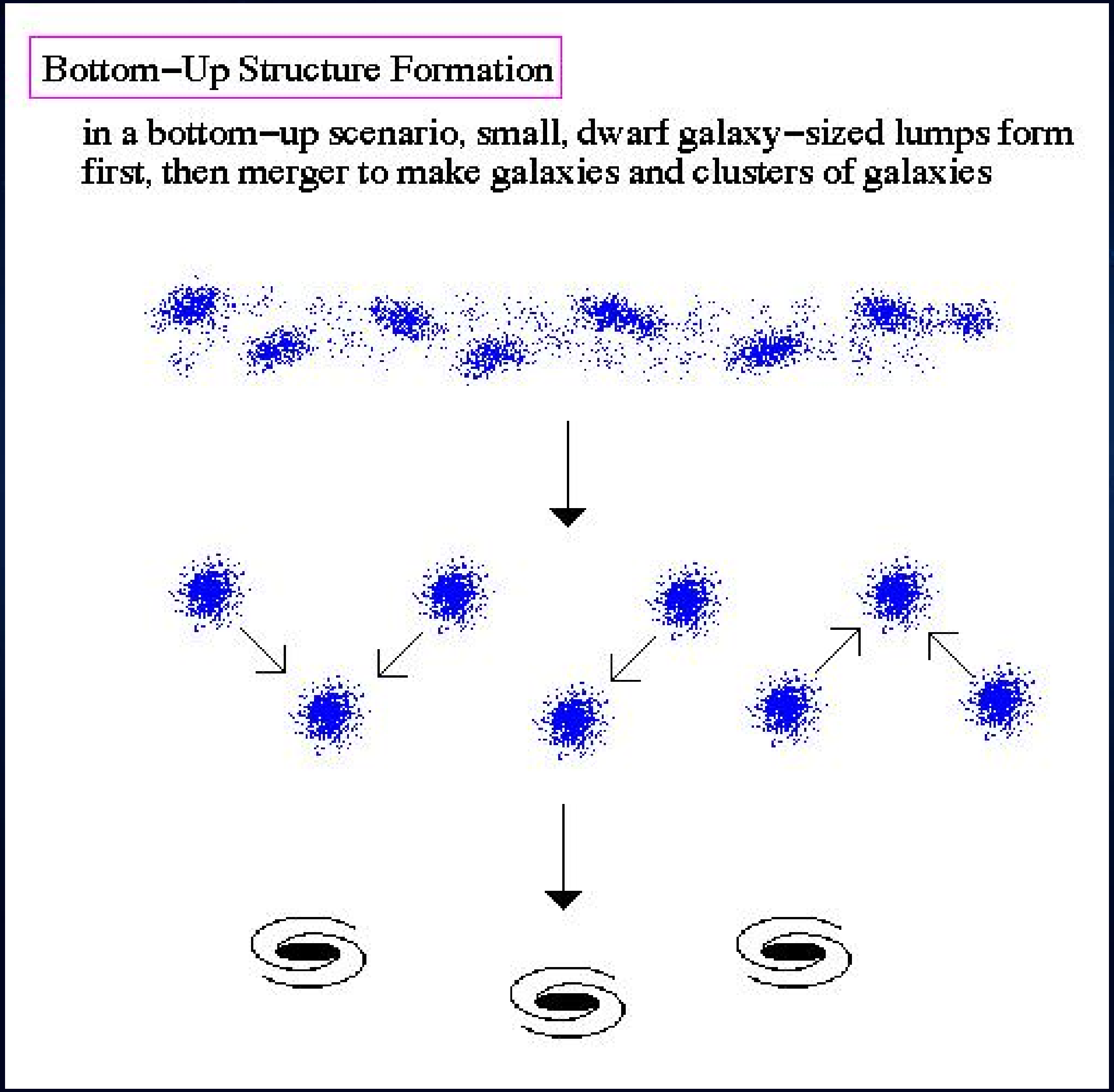
Springel, Hernquist & White (2000)

Sheets, filaments & voids

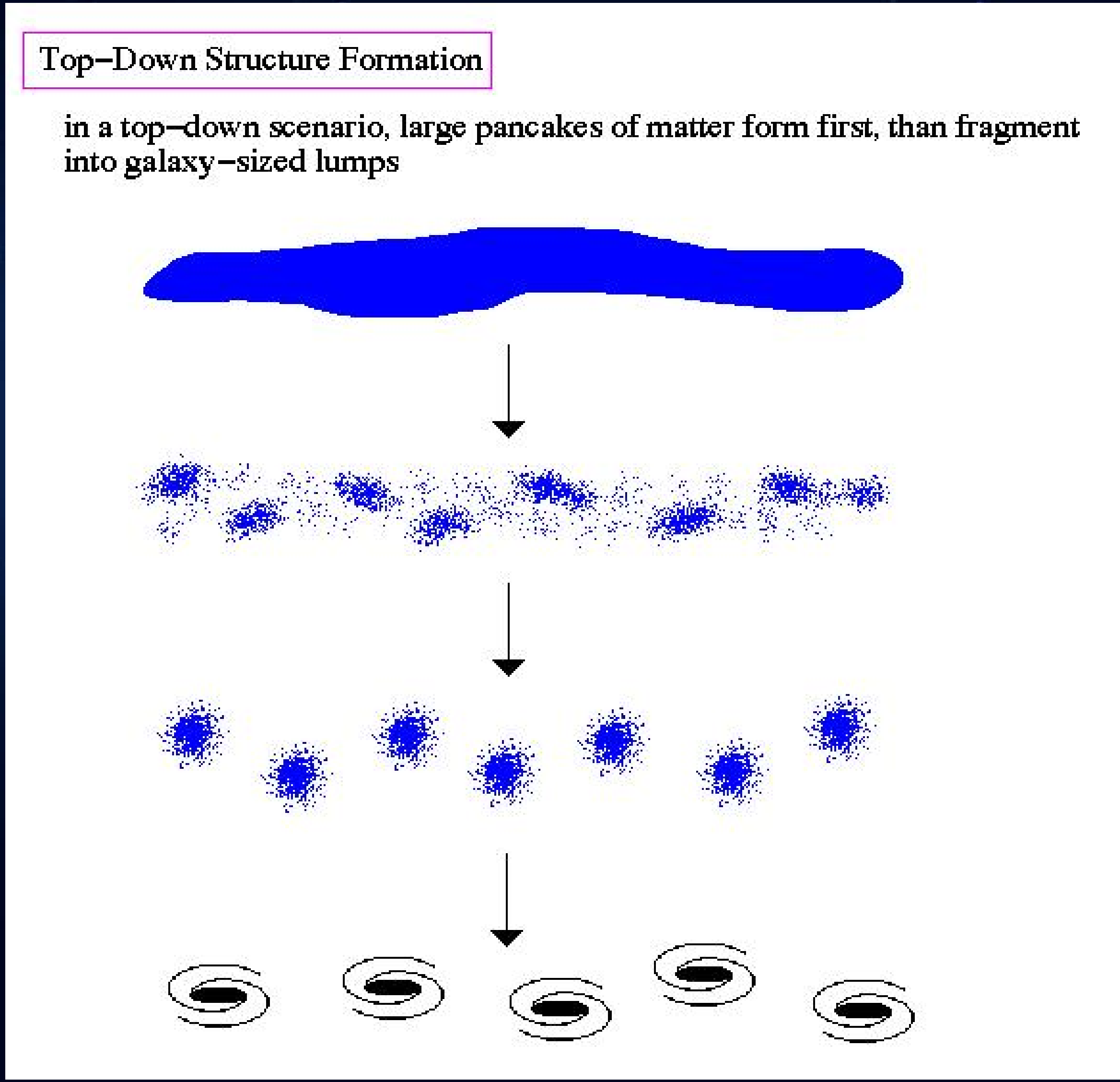
The "cosmic web" of sheets, filaments and voids is the same in N-body simulations and Zel'dovich simulations …



CDM模型:等级成团

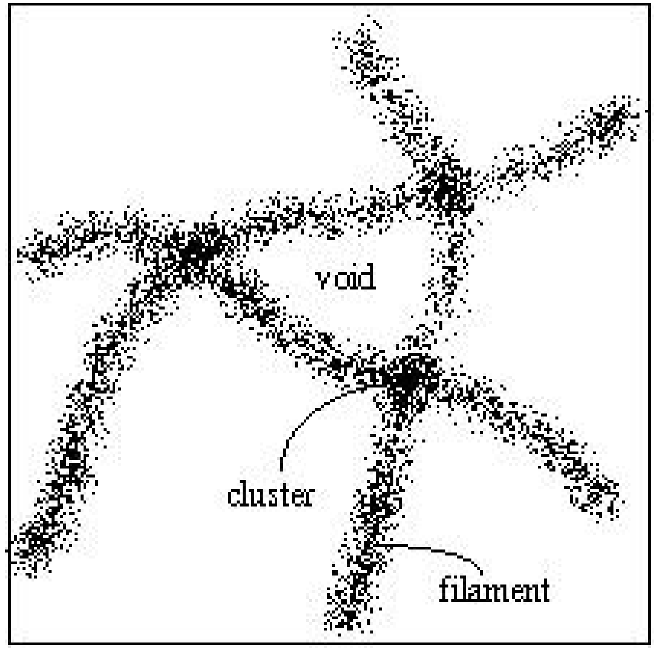

Bottom–Up Structure Formation
in a bottom–up scenario, small, dwarf galaxy–sized lumps form
first, then merger to make galaxies and clusters of galaxies

HDM模型：top-down

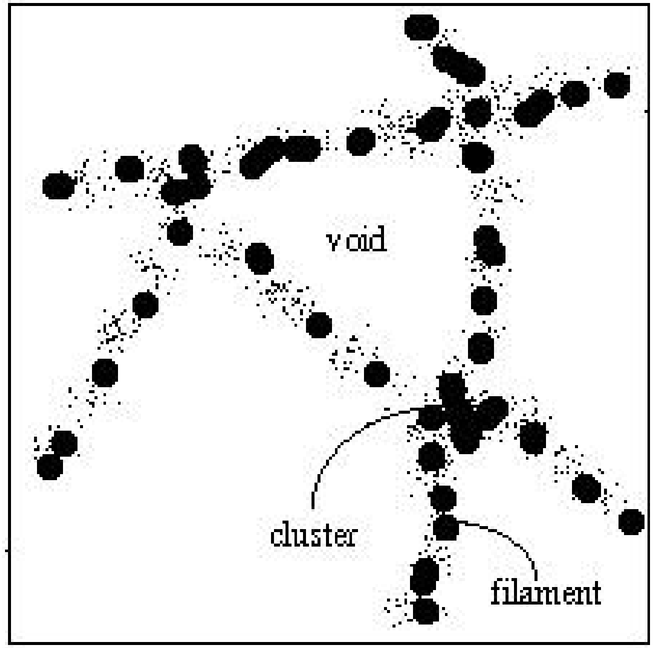


Large Scale Structure

HDM and the top–down scenario predict smooth, weak features in the large scale distribution of galaxies



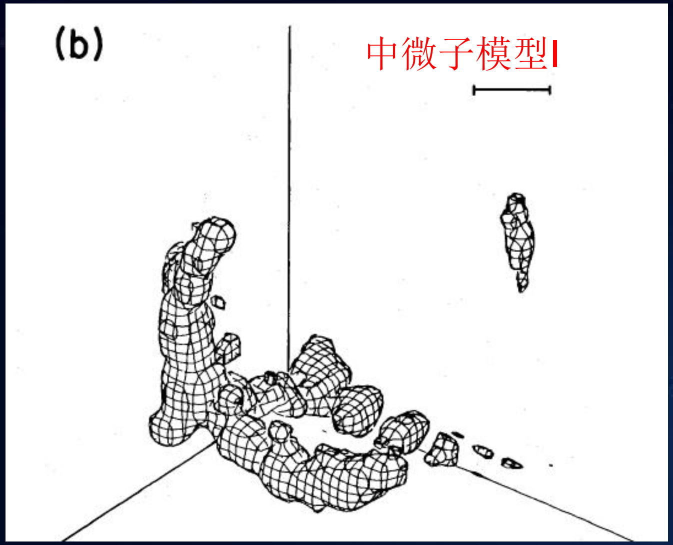
HDM

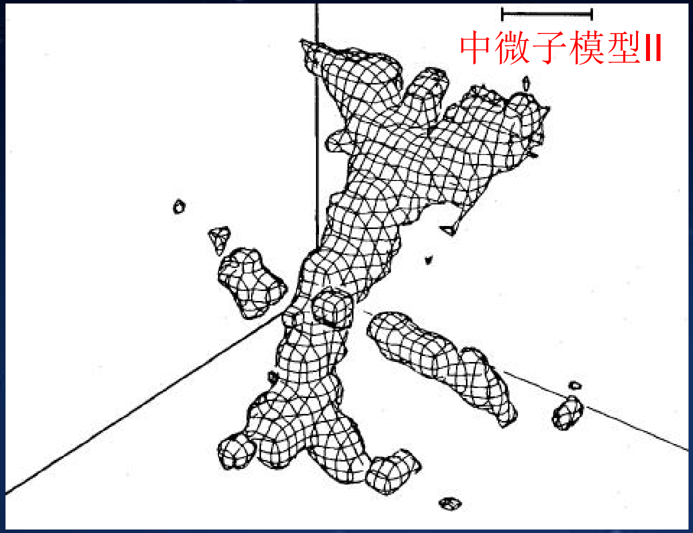


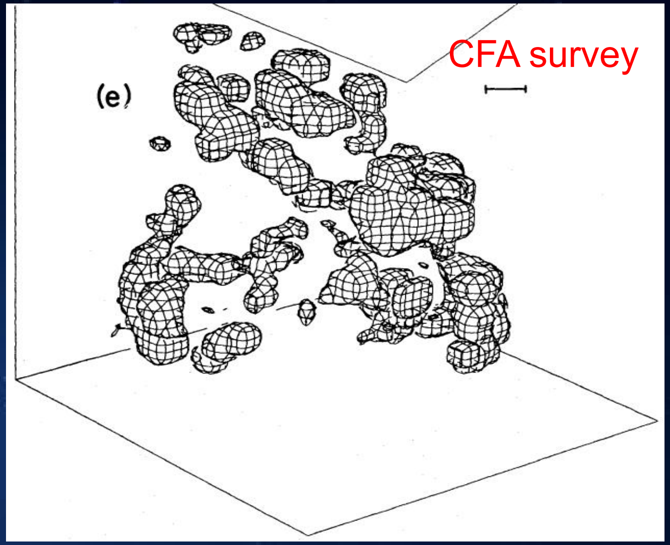
CDM

CDM and the bottom–up scenario predict sharp features with weak connecting filaments

模拟大尺度结构







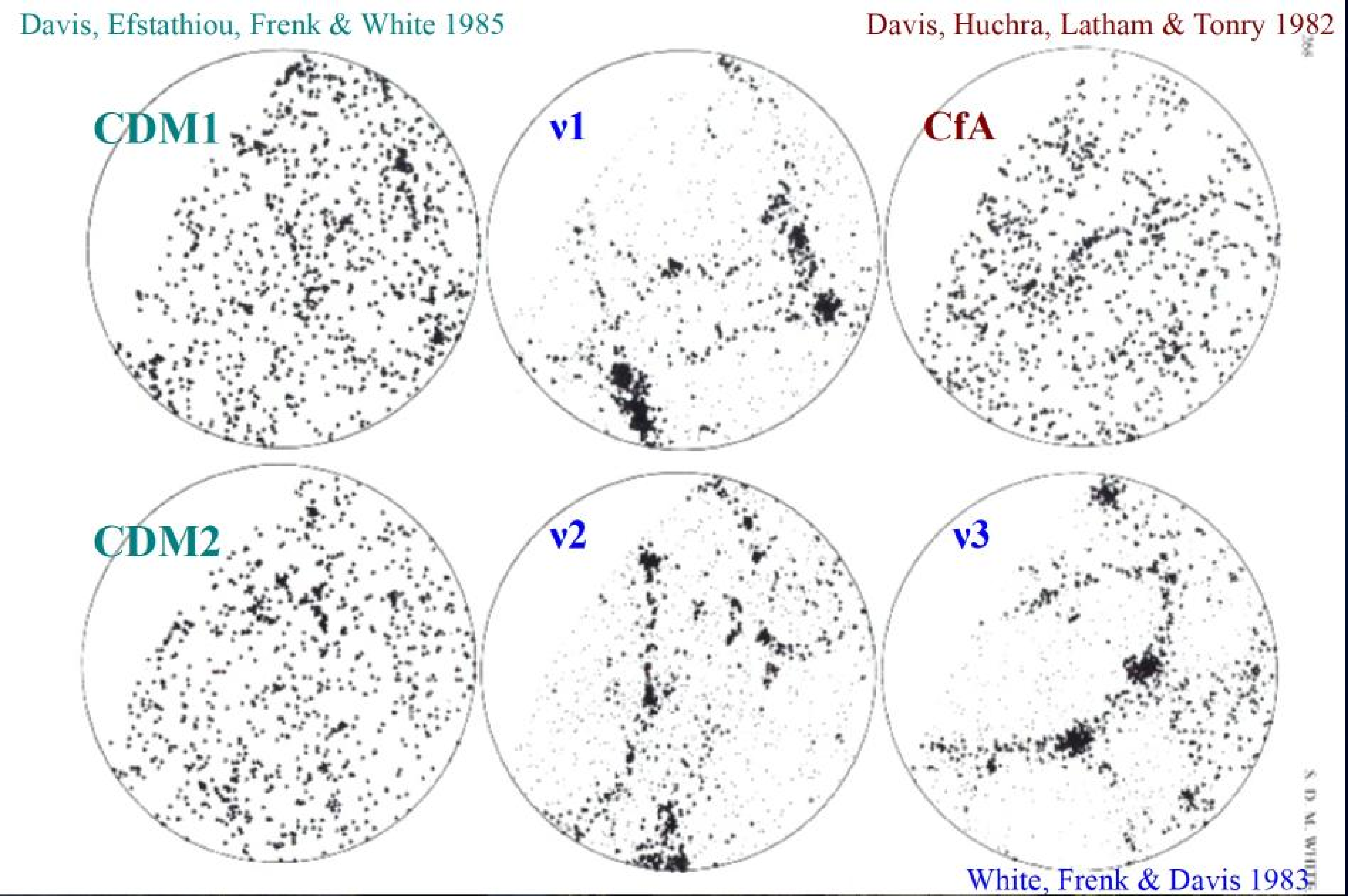
排除了中微子作为暗物质候选对象

White et al 1983

2011 年 Gruber 宇宙学奖:

"From 1985 to 1988 the DEFW collaboration produced five papers that changed cosmology forever."

（DEFW合作在1985-1988年完成的五篇文章永远的改变了宇宙学）

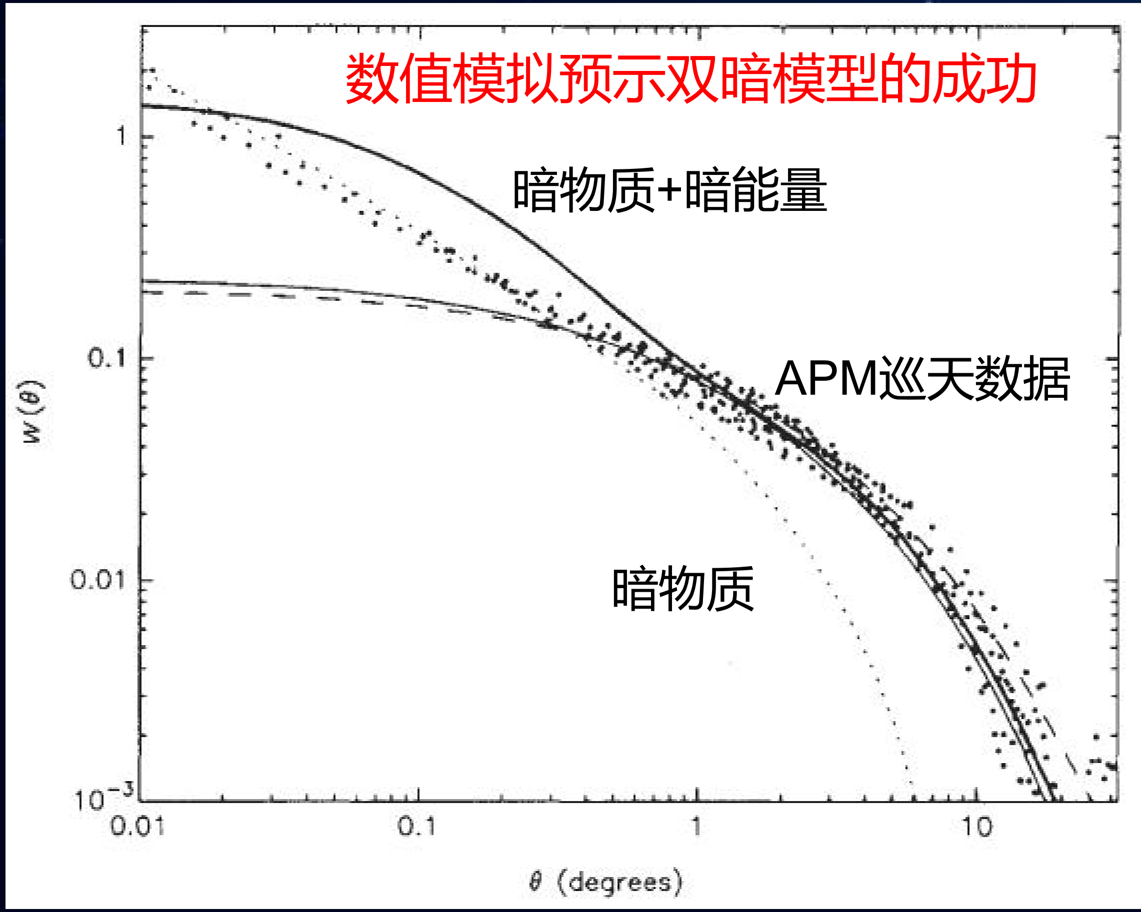


DEFW的系列工作表明暗物质是冷的

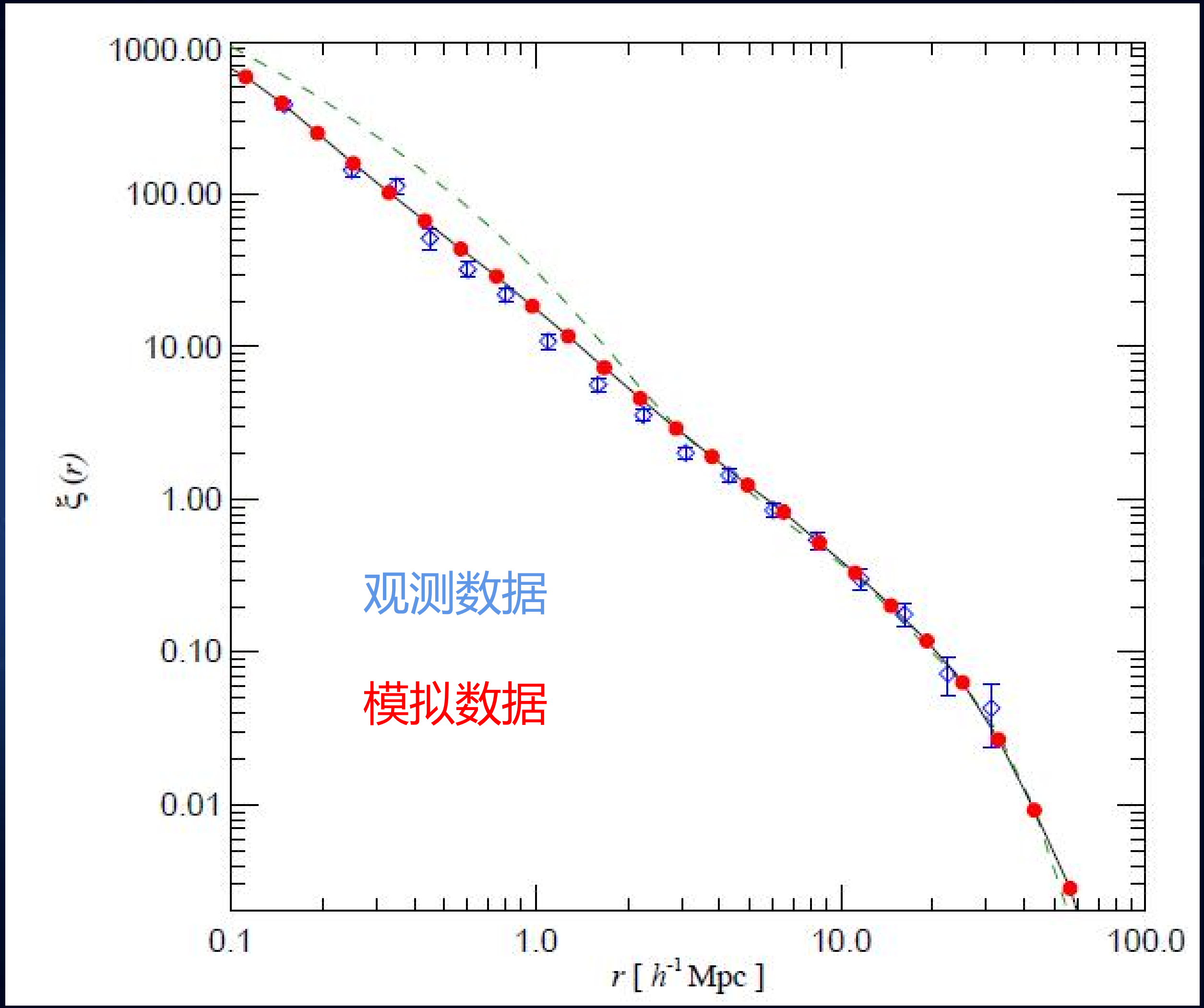
The cosmological constant and cold dark matter

G. Efstathiou, W. J. Sutherland & S. J. Maddox

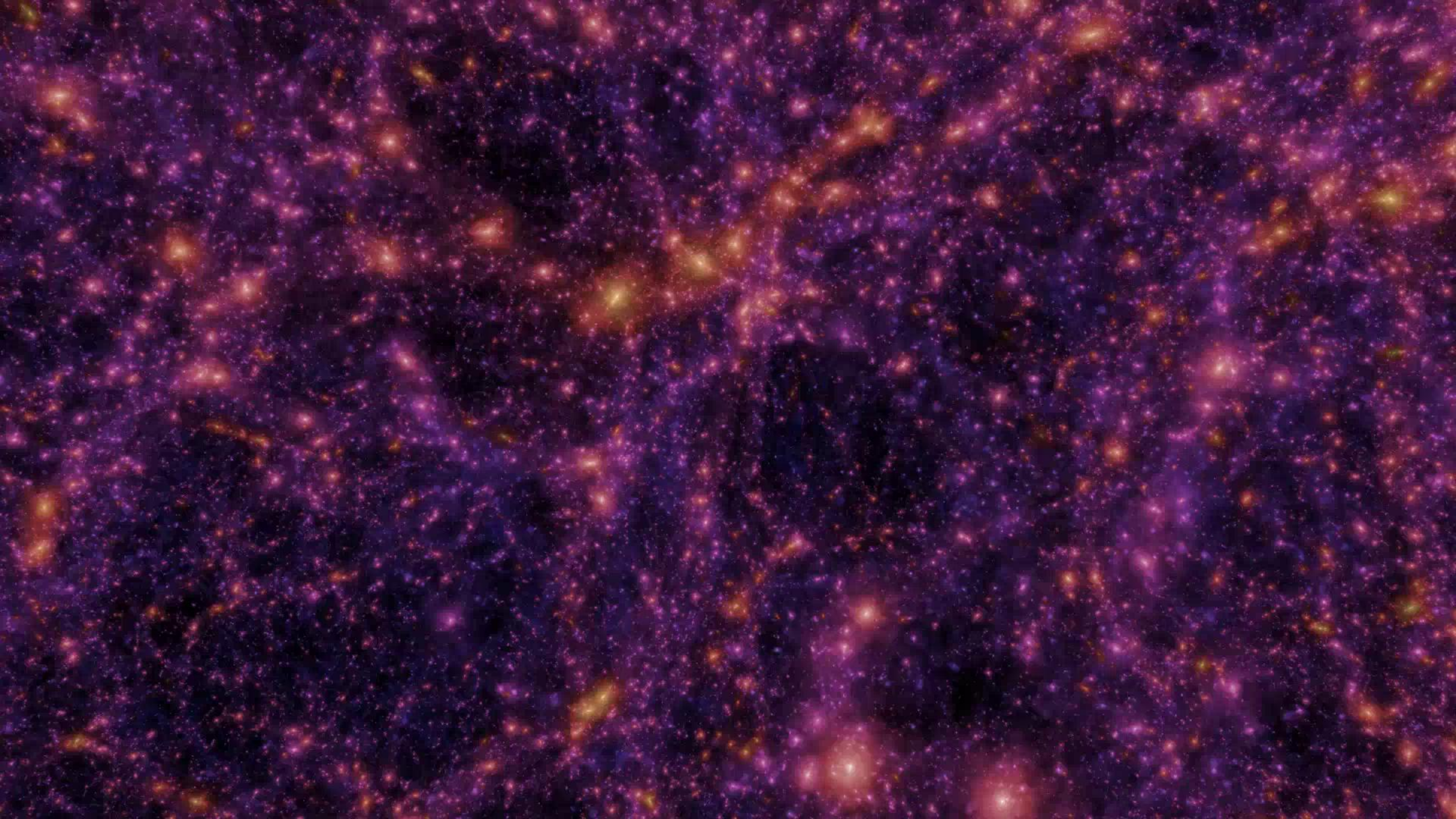
Department of Physics, University of Oxford, Oxford OX1 3RH, UK



Efstathiou et al 1990

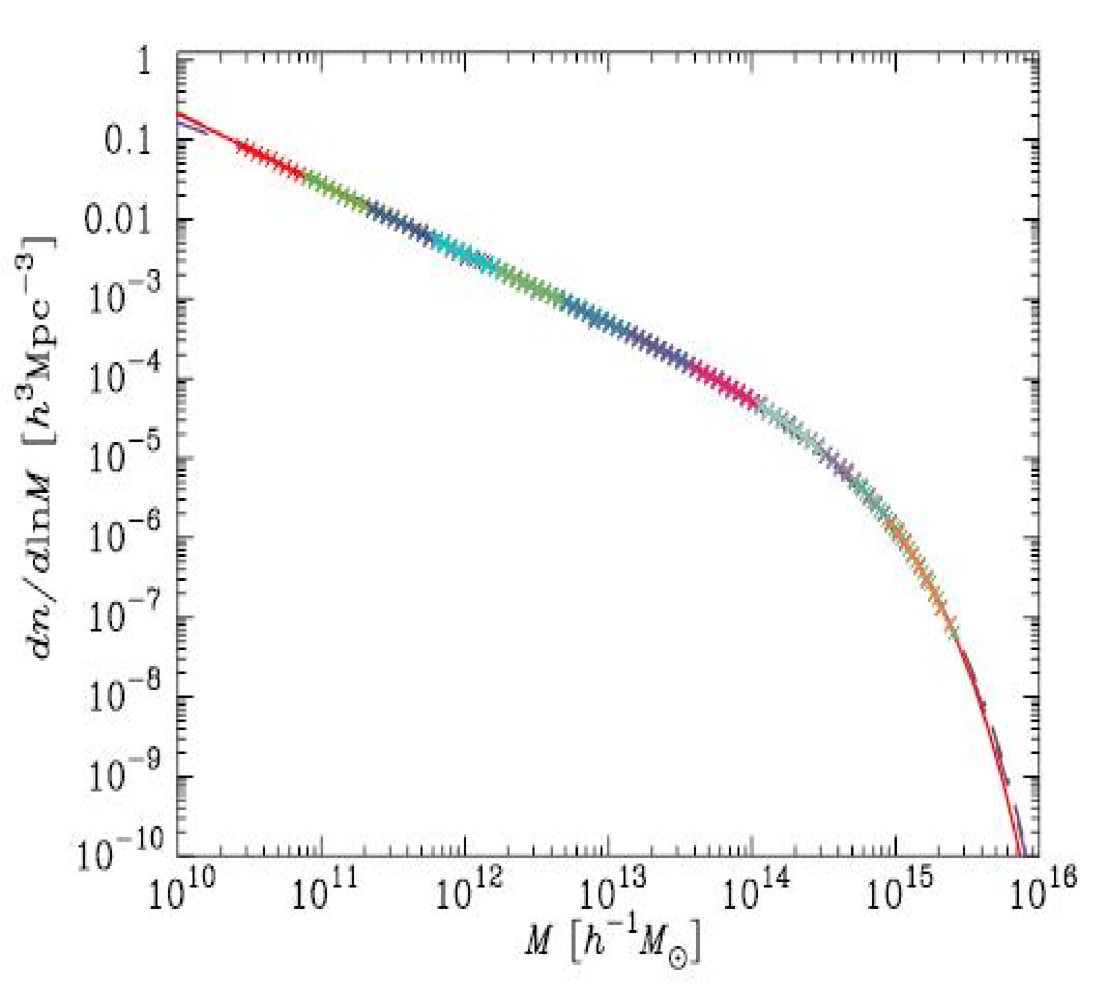


Springel et al 2005

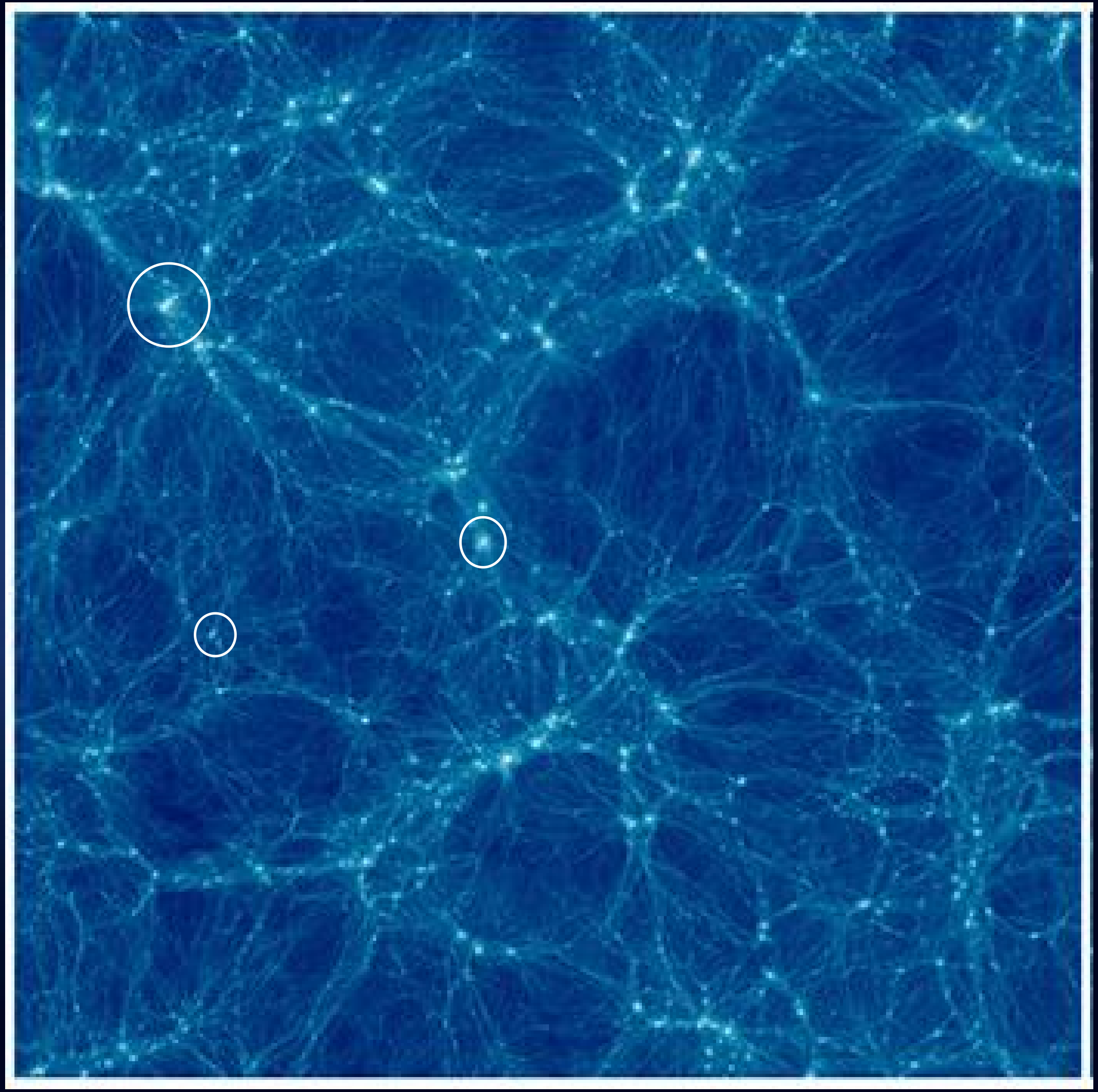


暗晕

暗晕的质量函数

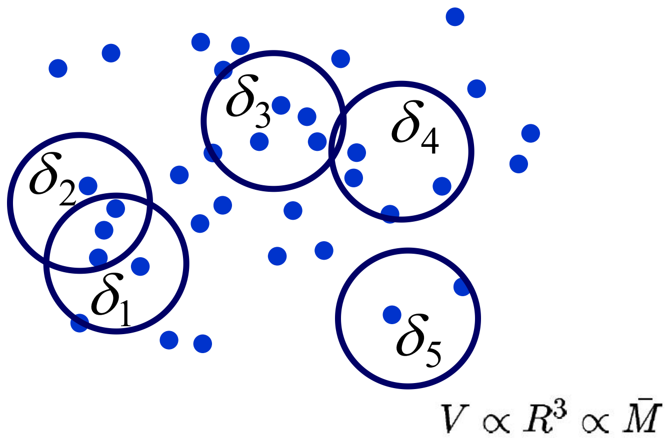


Warren et al 2006



Mass function of collapsed halos: Press-Schechter

Smoothly fluctuating density field; randomly scattered equal volume spheres, each has some overdensity δ. Some of these volumes will have a large enough overdensity (δ_c>1.69) that they will eventually collapse and form gravitationally bound objects.
What is the mass function of these objects at any given cosmic epoch?



rms dispersion in mass, or, equivalently, overdensity δ, in spheres of radius R

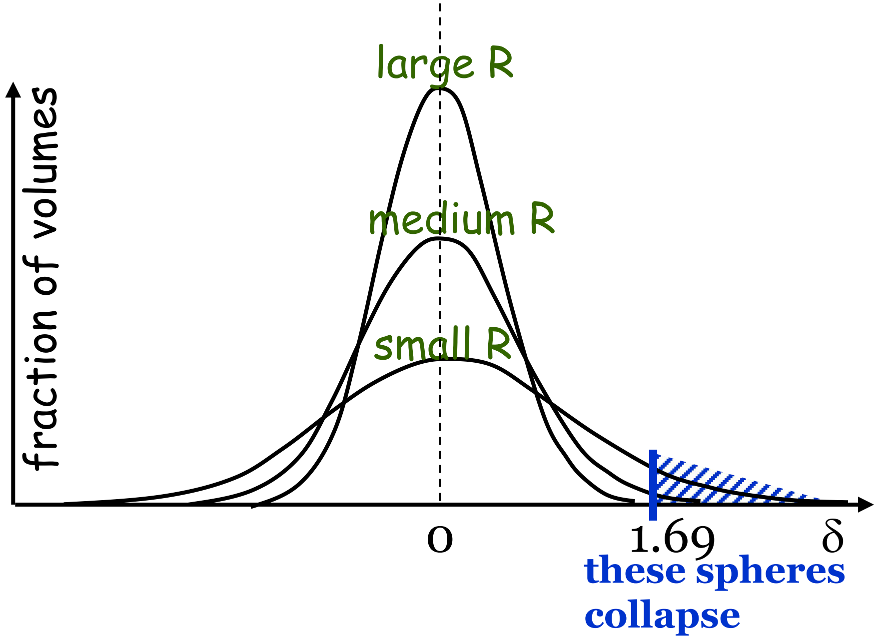
$$\sigma_M{}^2 = \frac{\left\langle \left(M - \overline{M}\right)^2 \right\rangle}{\overline{M}^2} = (\sqrt{A} \cdot \overline{M}^{-\alpha})^2 \qquad \alpha = n/6 + 1/2, \quad P(k) \propto k^n$$

$$\text{time dependence: } \sigma_M \propto a \propto t^{2/3}$$

Press-Schechter (1974) main assumption: the fraction of spheres with volume V having overdensity δ is Gaussian distributed

$$p(\delta, V) = \frac{1}{(2\pi\sigma_M^2)^{1/2}} e^{-\delta^2/2\sigma_M^2} = \frac{1}{(2\pi\sigma_M^2)^{1/2}} e^{-x^2}$$

$$x = \frac{\delta}{\sqrt{2}\sigma_M} \qquad \frac{dx}{dM} = \frac{\delta}{\sqrt{2A}} \alpha \overline{M}^{\alpha - 1}$$



Mass function of collapsed halos: Press-Schechter

The fraction of spheres that will eventually collapse is

$$P(\delta, V) = \int_{\delta_c}^{\infty} p(\delta, V) d\delta = \frac{1}{\pi^{1/2}} \int_{x_c}^{\infty} e^{-x^2} dx$$

The fraction of spheres that have just collapsed (of all possible M, but same δ_C)

$$P(M) - P(M + dM) = \frac{dP}{dM} dM = \frac{dP}{dx}\frac{dx}{dM} dM = \frac{1}{\pi^{1/2}} e^{-x_c^2} \alpha \frac{M^{\alpha-1}}{M_\star{}^{\alpha}} dM$$

$$x_c{}^2 = \frac{\delta_c{}^2}{2AM^{-2\alpha}} = \frac{2AM_\star{}^{-2\alpha}}{2AM^{-2\alpha}} = \left(\frac{M}{M_\star}\right)^{2\alpha}$$

define $M_* : \ \delta_c{}^2 = 2AM_*{}^{-2\alpha}$

How much mass in every unit of volume is contained in these objects?

$$M_{\text{per vol}} = \frac{dP}{dM} dM \times \bar{\rho}$$

How many of the collapsed objects are there?

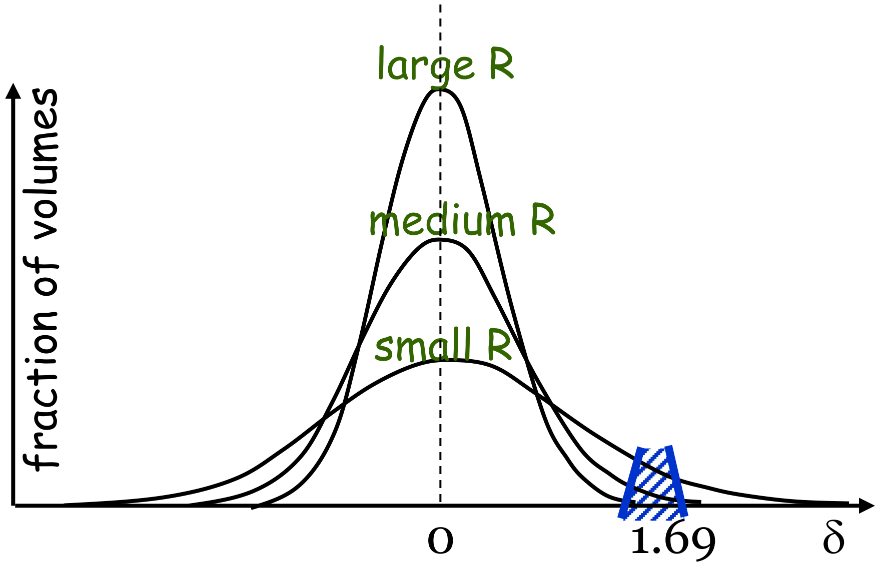
$$n(M)\, dM = \frac{dP}{dM} dM \frac{\bar{\rho}}{M} = \frac{\alpha\bar{\rho}}{\pi^{1/2}} \frac{1}{M^2} \left(\frac{M}{M_\star}\right)^{\alpha} e^{-x_c^2} dM$$

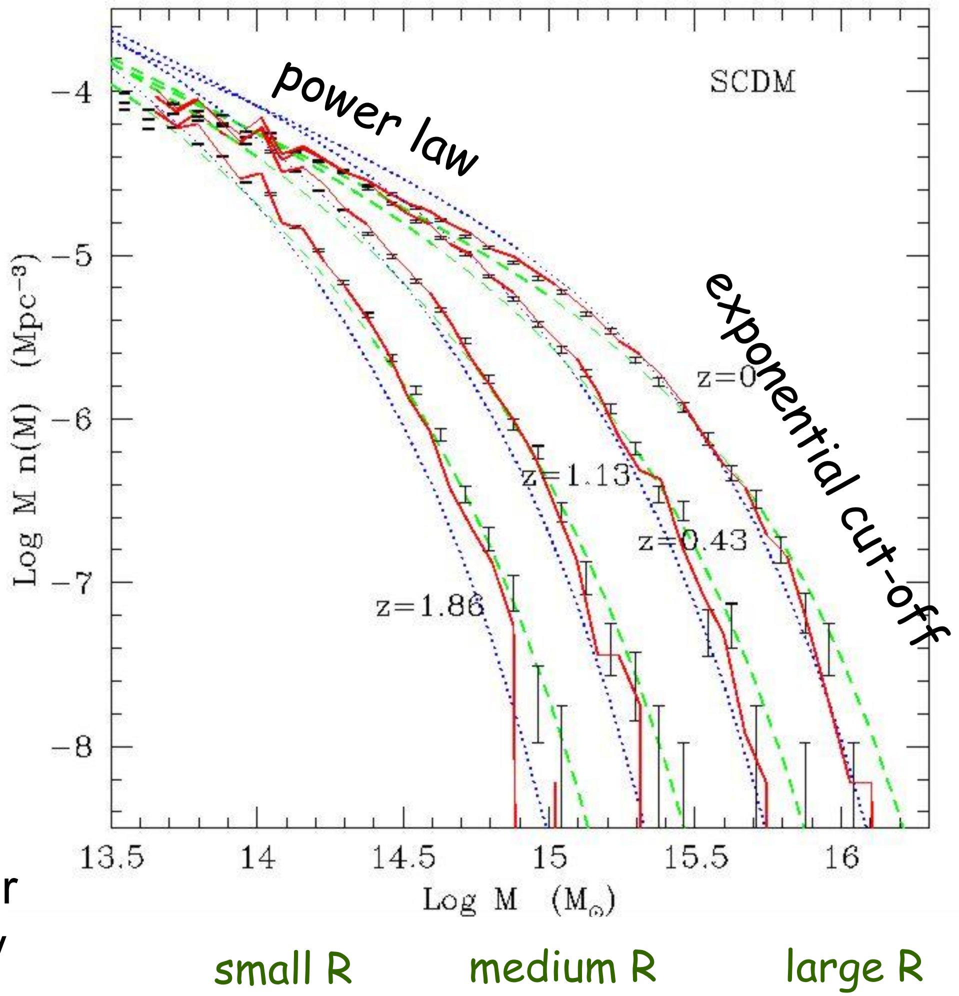
$$\boxed{n(M)\, dM} = \frac{\alpha\bar{\rho}}{\pi^{1/2}} \frac{1}{M_\star{}^2} \left(\frac{M}{M_\star}\right)^{\alpha-2} e^{-(M/M_\star)^{2\alpha}} dM$$

power law — exponential

Note: characteristic mass M_* is time dependent, through A:
$M_* \propto A^{1/(2\alpha)} \propto t^{2/(3\alpha)} \propto a^{1/\alpha}$

Press-Schechter halo mass function

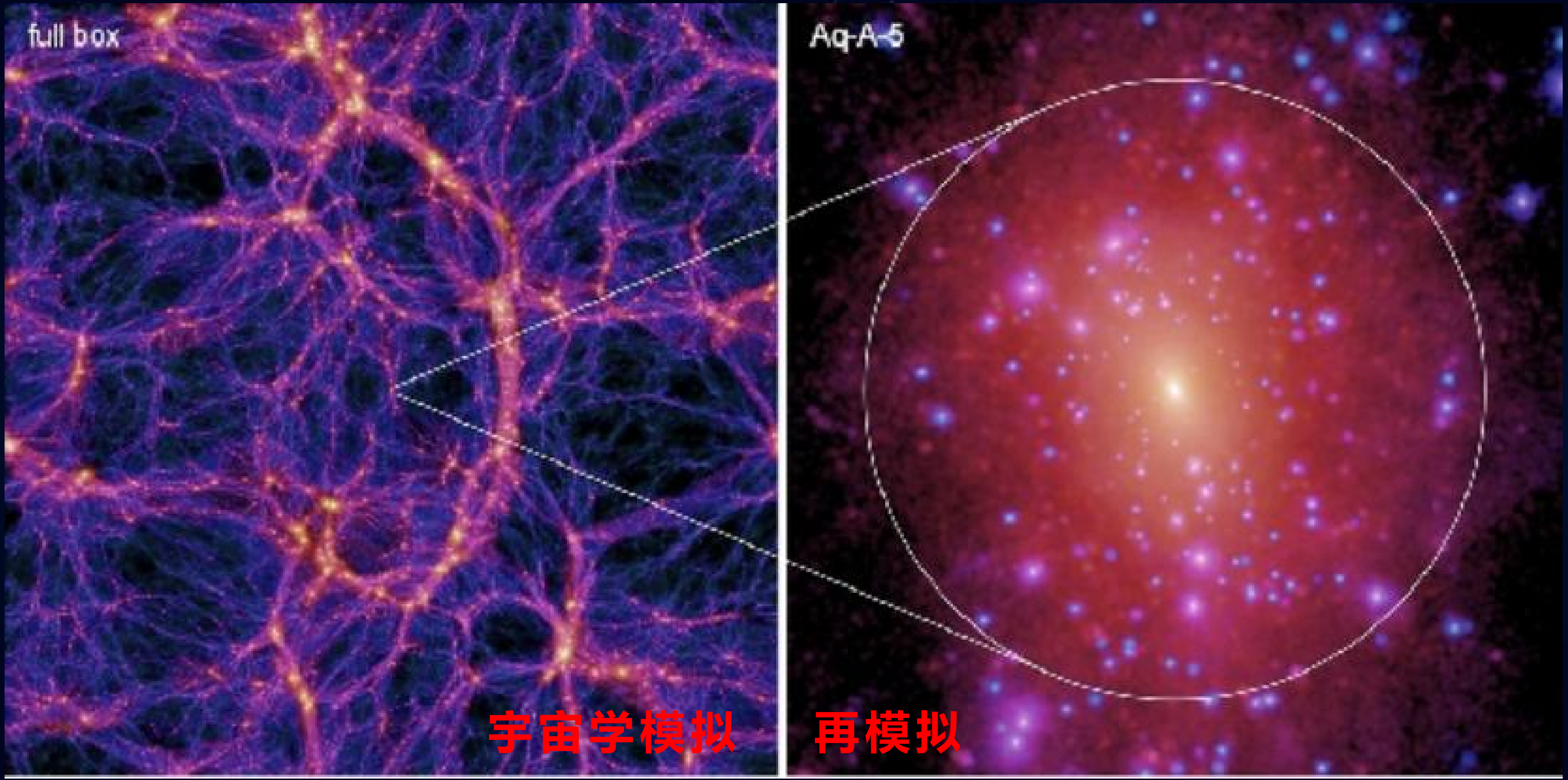




Press-Schechter vs. numerical simulations:

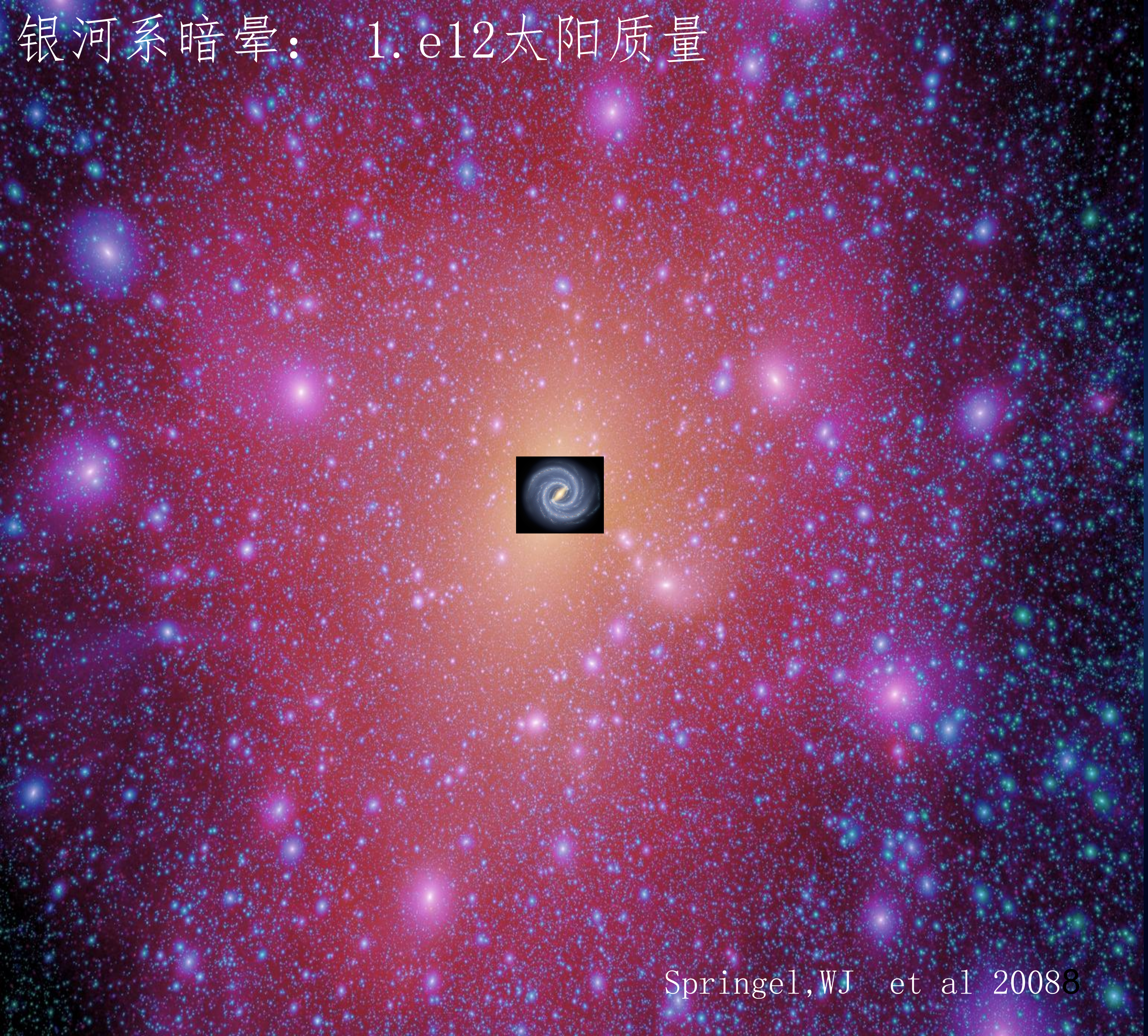
solid red lines: simulations
blue dotted: Press-Schechter
green dashed: extended Press-Schechter
(takes into account non-sphericity of proto halos.)

再模拟技术



数值模拟的规模由粒子数目决定
体积增大，质量解析度降低
体积减小，质量解析度增高

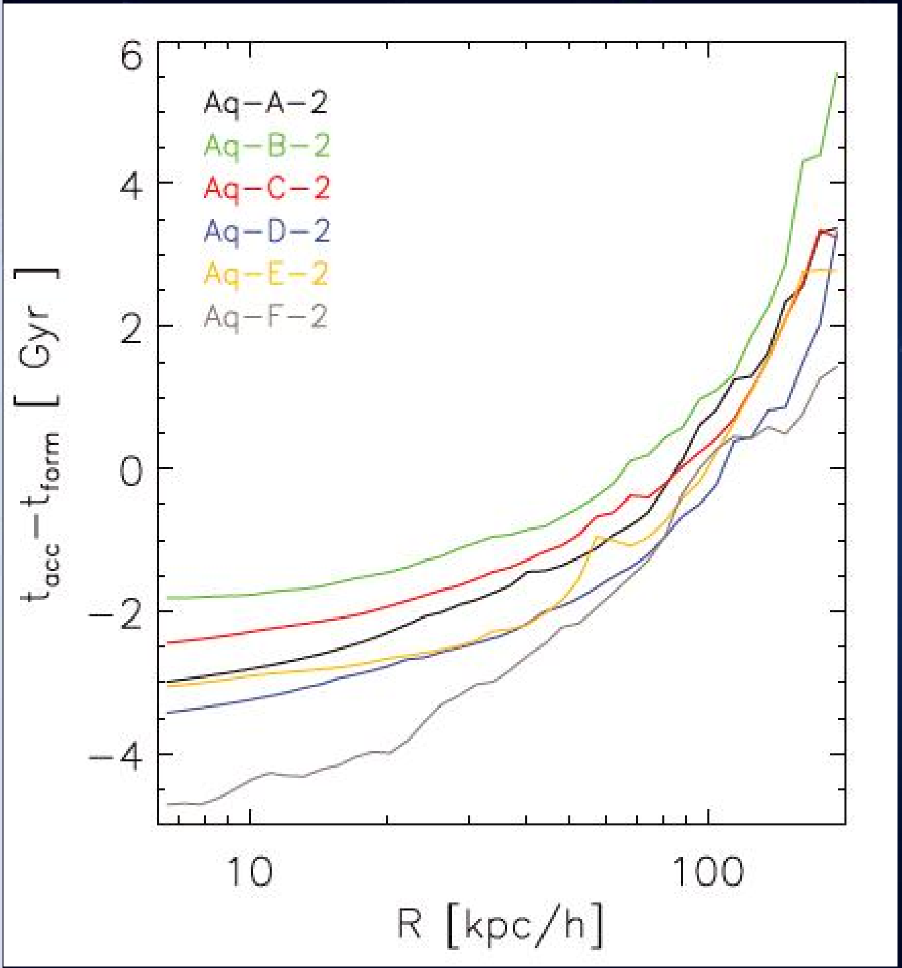
大质量粒子作为背景引力势井，在一个更小空间内用质量更小的粒子（更多的粒子数目）解析更小的结构



可以测量的暗晕属性：

- 暗晕的径向密度轮廓
- 暗晕的形状
- 暗晕演化历史
- 子结构的数目，分布
- 暗晕内角动量分布以及形成历史
- 暗物质湮灭信号的准确预测

暗晕的增长历史



JW et al 2011

Spherical collapse and density profile: a simple model

Gunn & Gott (1972)

Given the mean density within a collapse shell

$$\overline{\rho}(r) = \frac{3M}{4\pi r^3(M)},$$

$$r(M) \propto r_{\rm ta}(M)$$

for de sitter case:

$$\delta_{\rm i} \propto r_{\rm i}^{-3\varepsilon} \propto M^{-\varepsilon}$$

$$r_{\rm ta} \propto r_{\rm i}/\delta_{\rm i} \propto M^{(\varepsilon+1/3)}$$

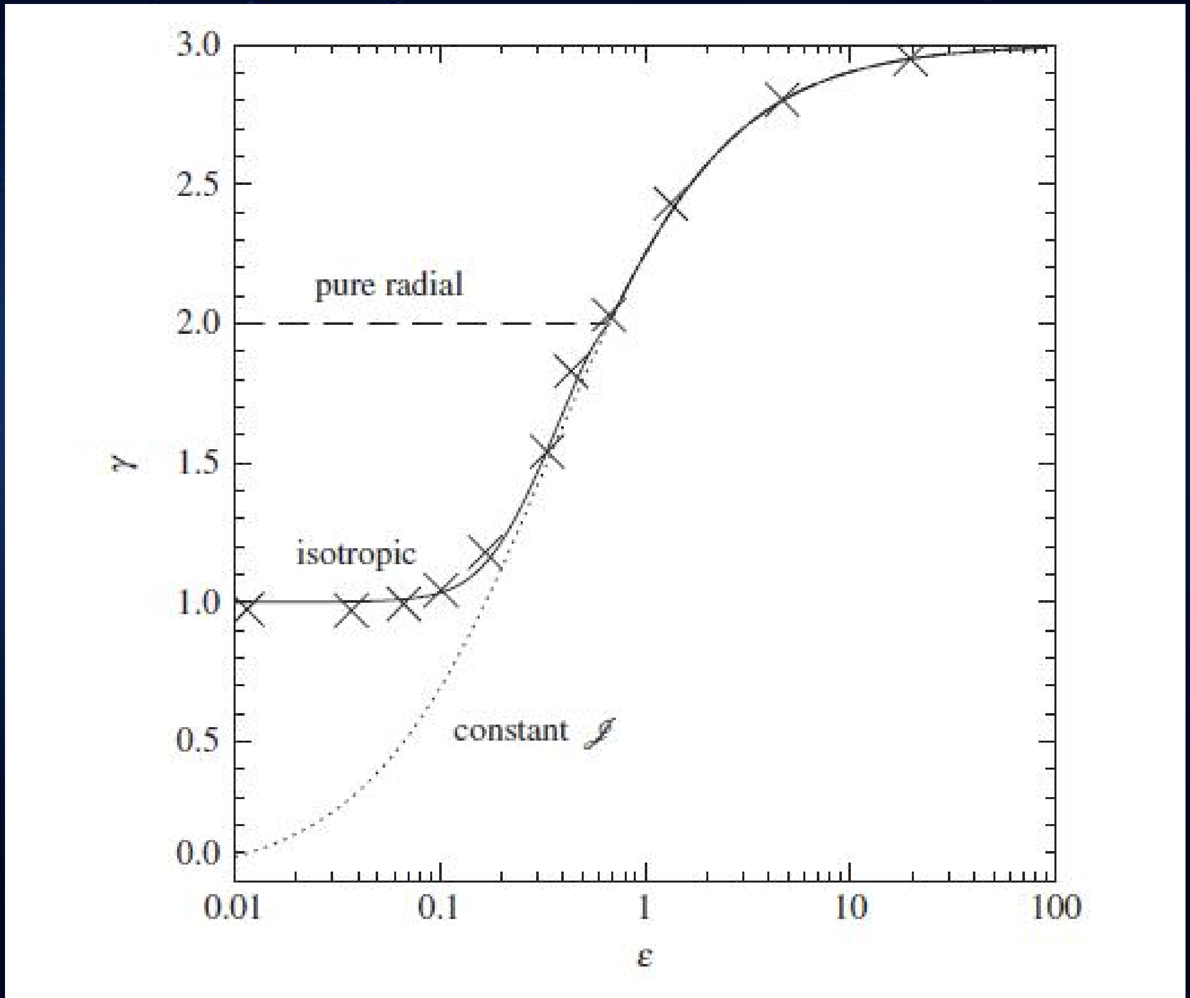
$$\rho(r) \propto r^{-\gamma} \quad \text{with} \quad \gamma = 9\varepsilon/(1+3\varepsilon).$$

$$\varepsilon = 1 \text{ and } \rho(r) \propto r^{-9/4}.$$

Similarity solutions: Fillmore & Goldreich 1984 Bertschinger , 1985
White & Zaritsky 1992

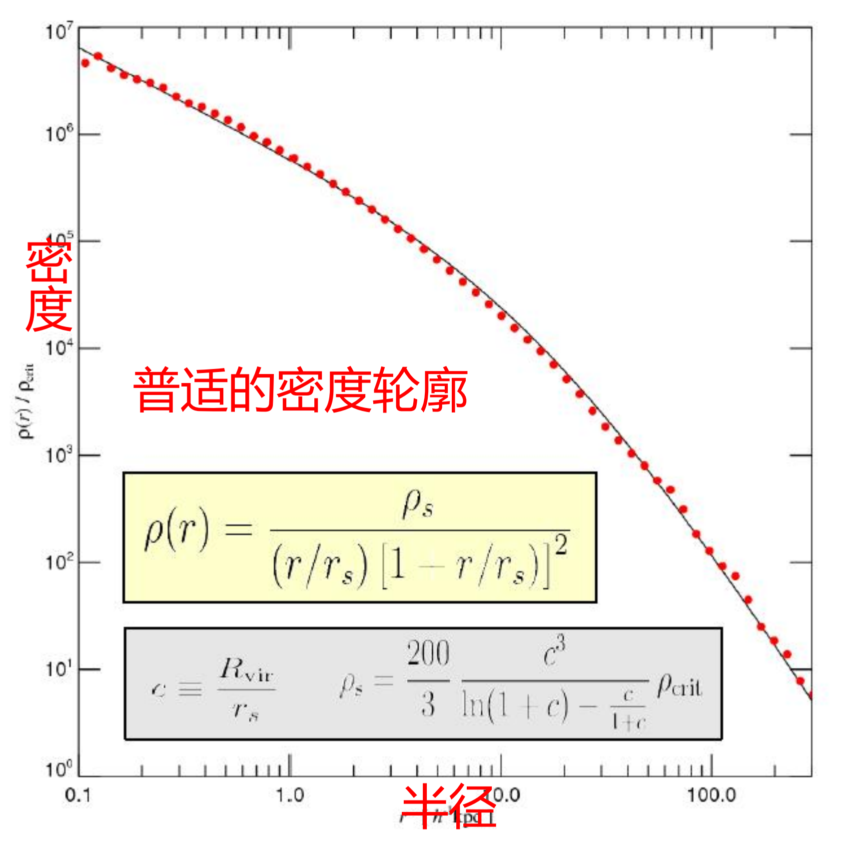
1-D simulation test

$$\gamma \equiv -\mathrm{d}\ln\rho / \mathrm{d}\ln r = 3 - \alpha,$$



Lu et al, 2006

暗晕的内部结构 -- NFW轮廓



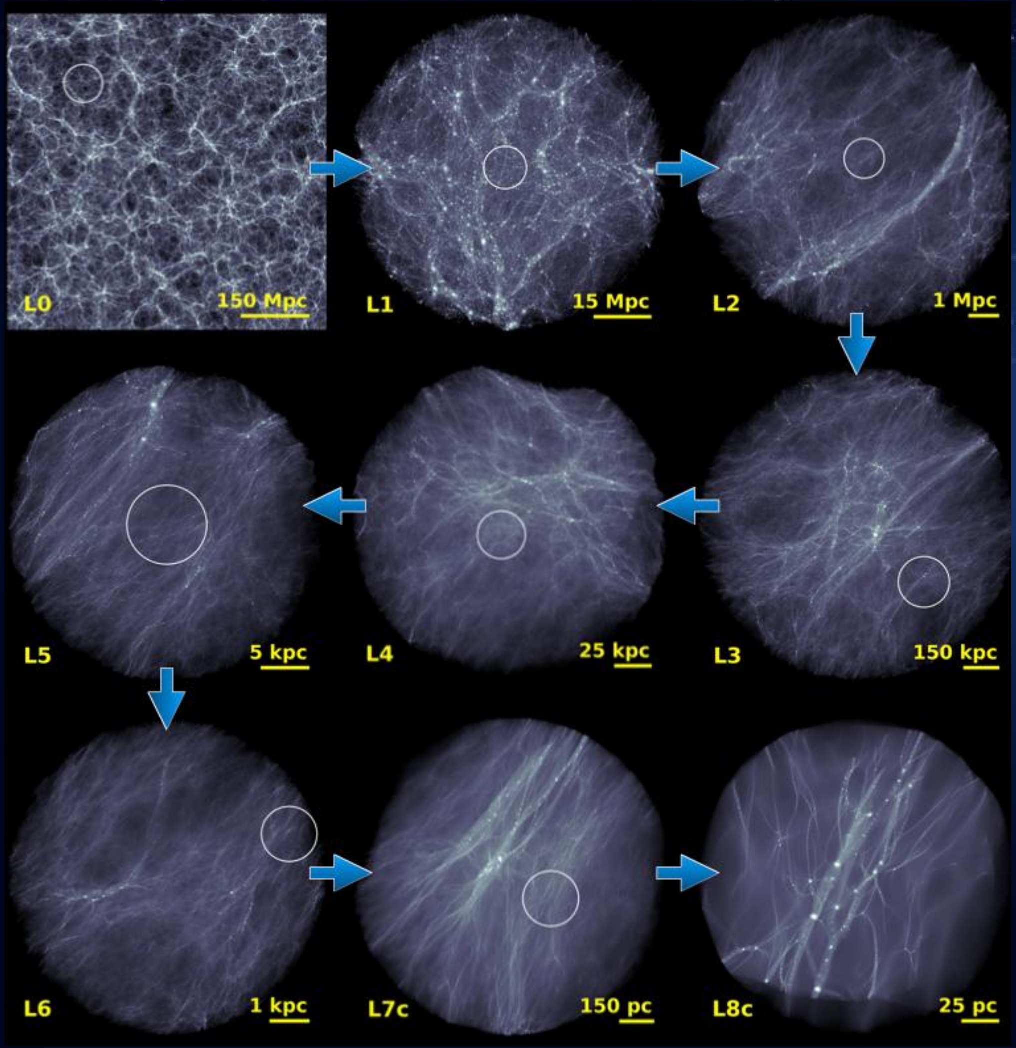
concentration
紧致因子

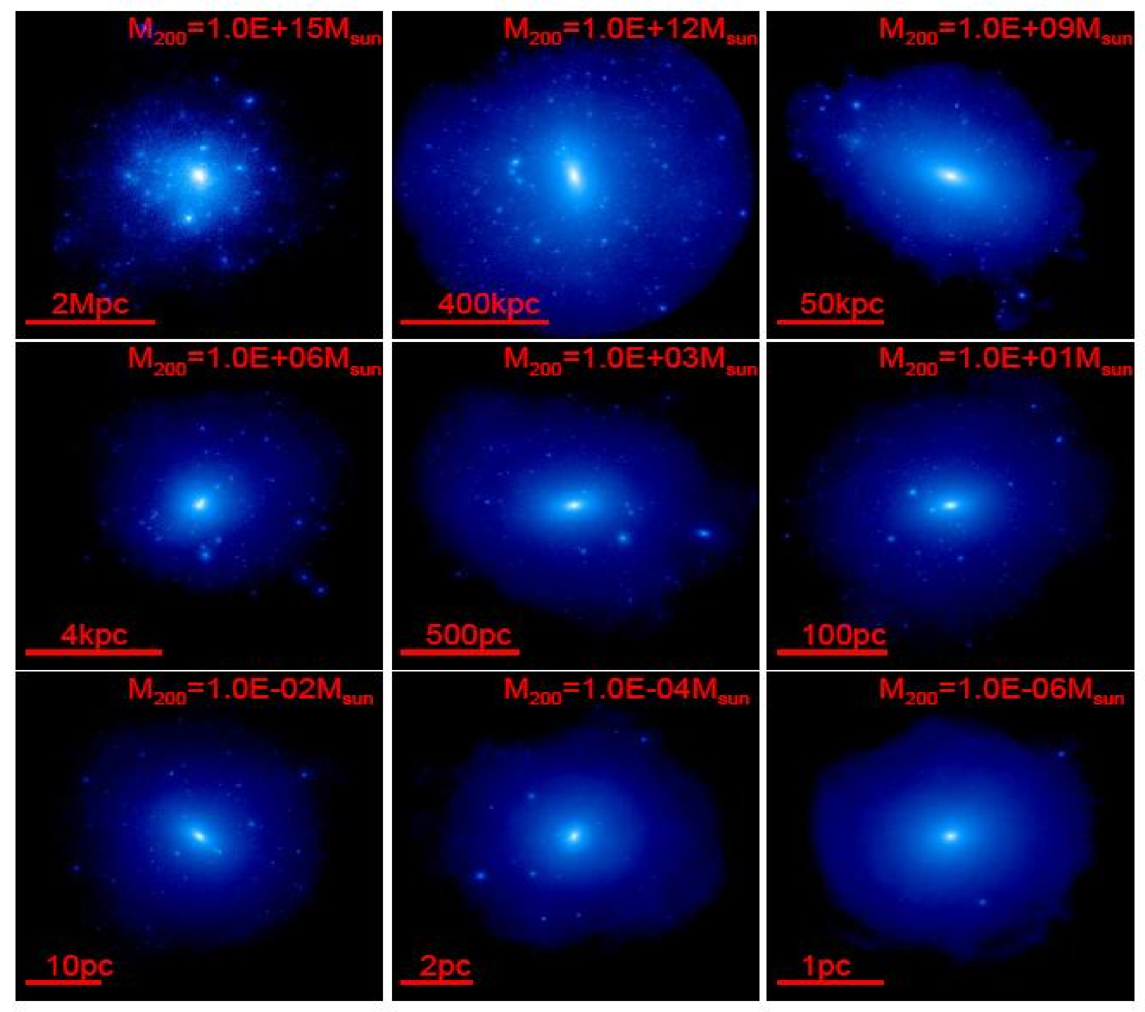
$$c = r_{200} / r_s$$

Navarro, Frenk, & White 1996, 1997

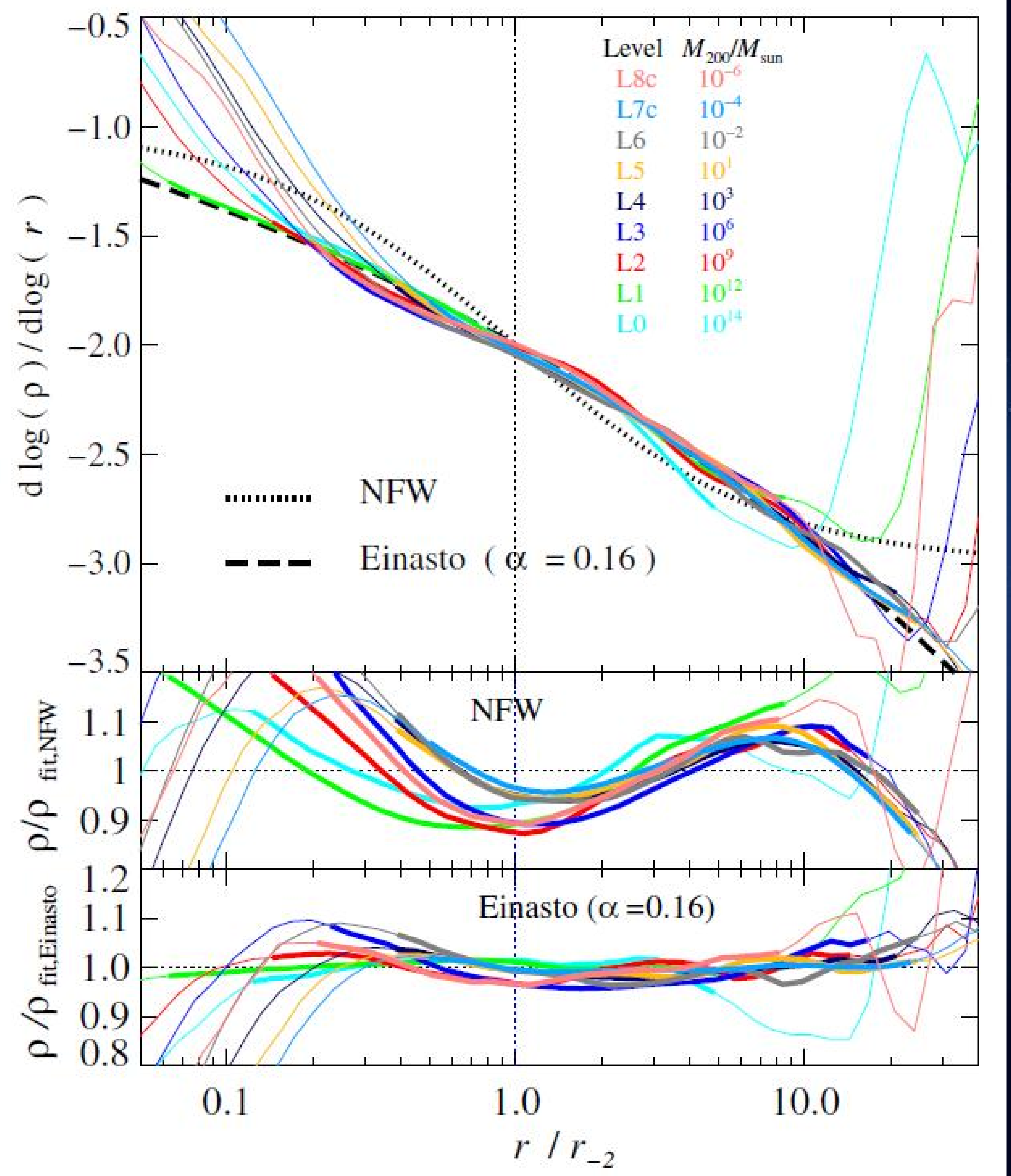
模拟全部质量暗晕的形成和演化

经过八次逐步放大，完成最大挑战





Wang et al 2020



$$\rho(r) = \rho_s r_s^3 / r(r + r_s)^2,$$

NFW

$$\rho(r) = \rho_{-2} \exp[-2\alpha^{-1}((r/r_{-2})^{\alpha} - 1)],$$

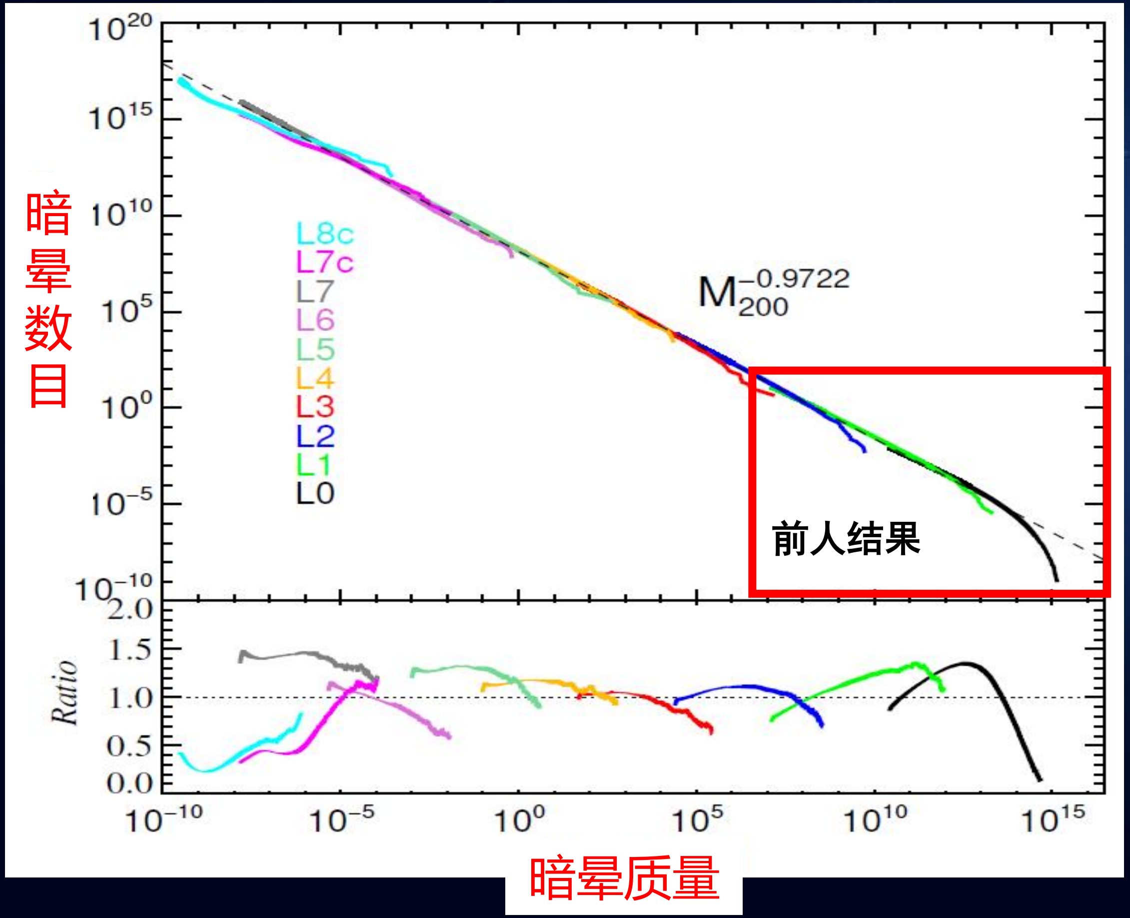
Einasto

在20个质量量级上，暗晕的密度轮廓可以在20%的精确度内用NFW拟合

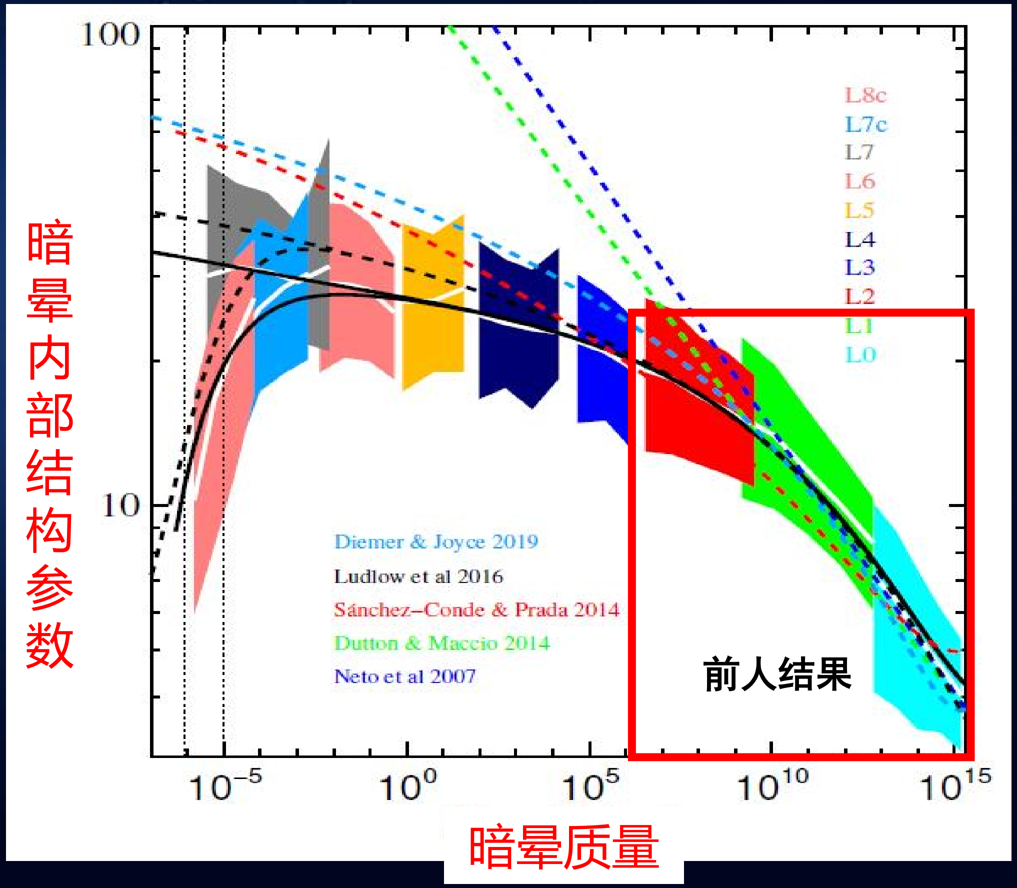
在7%的精度内用Einasto轮廓拟合（ α = 0.16 ）

模拟全部质量暗晕的形成和演化

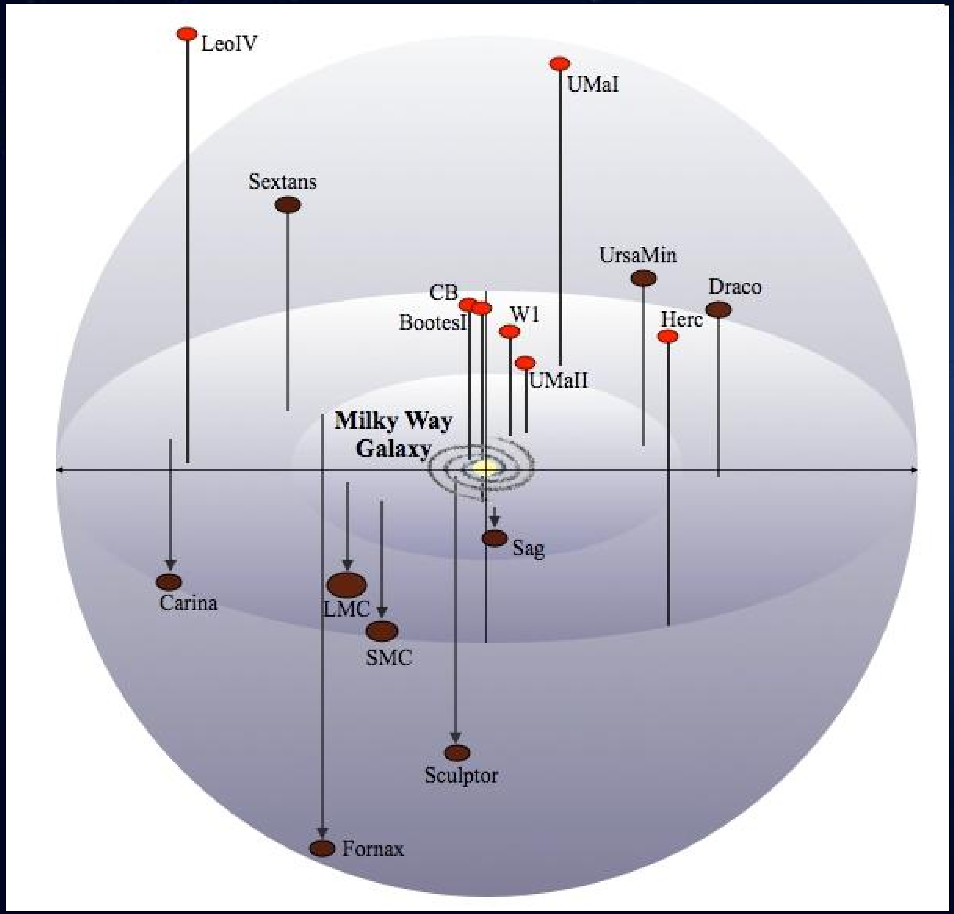
全部质量暗晕数目

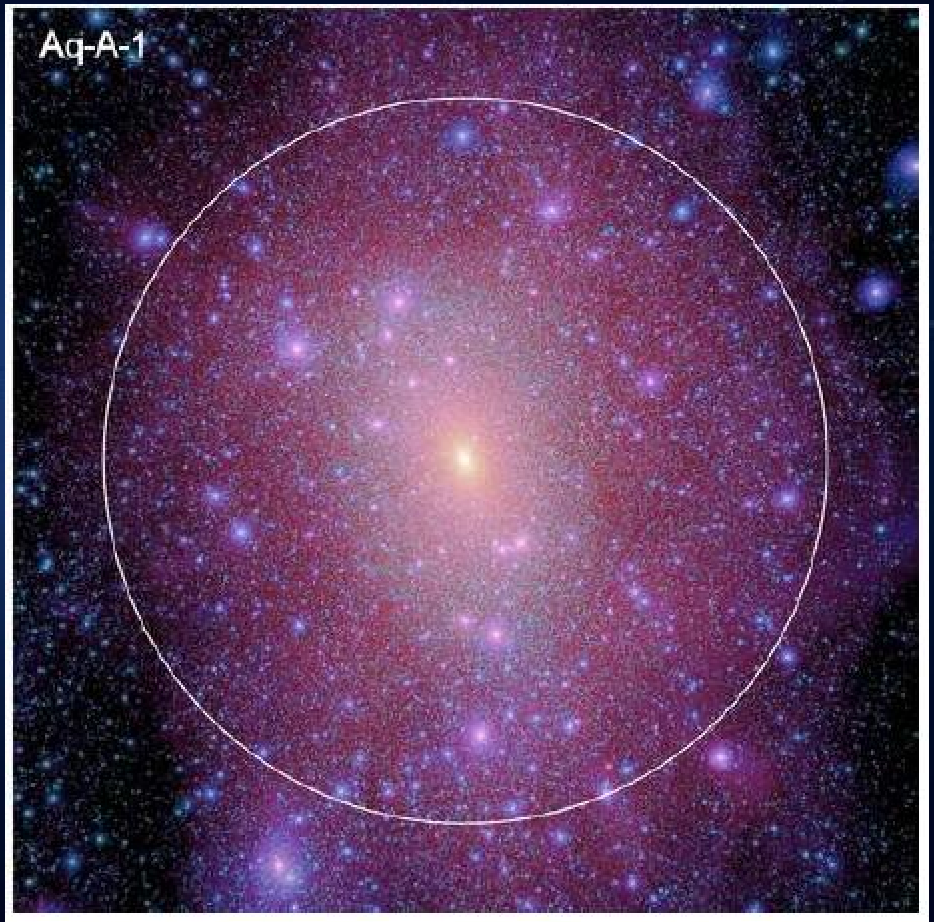


全部质量暗晕内部结构参数

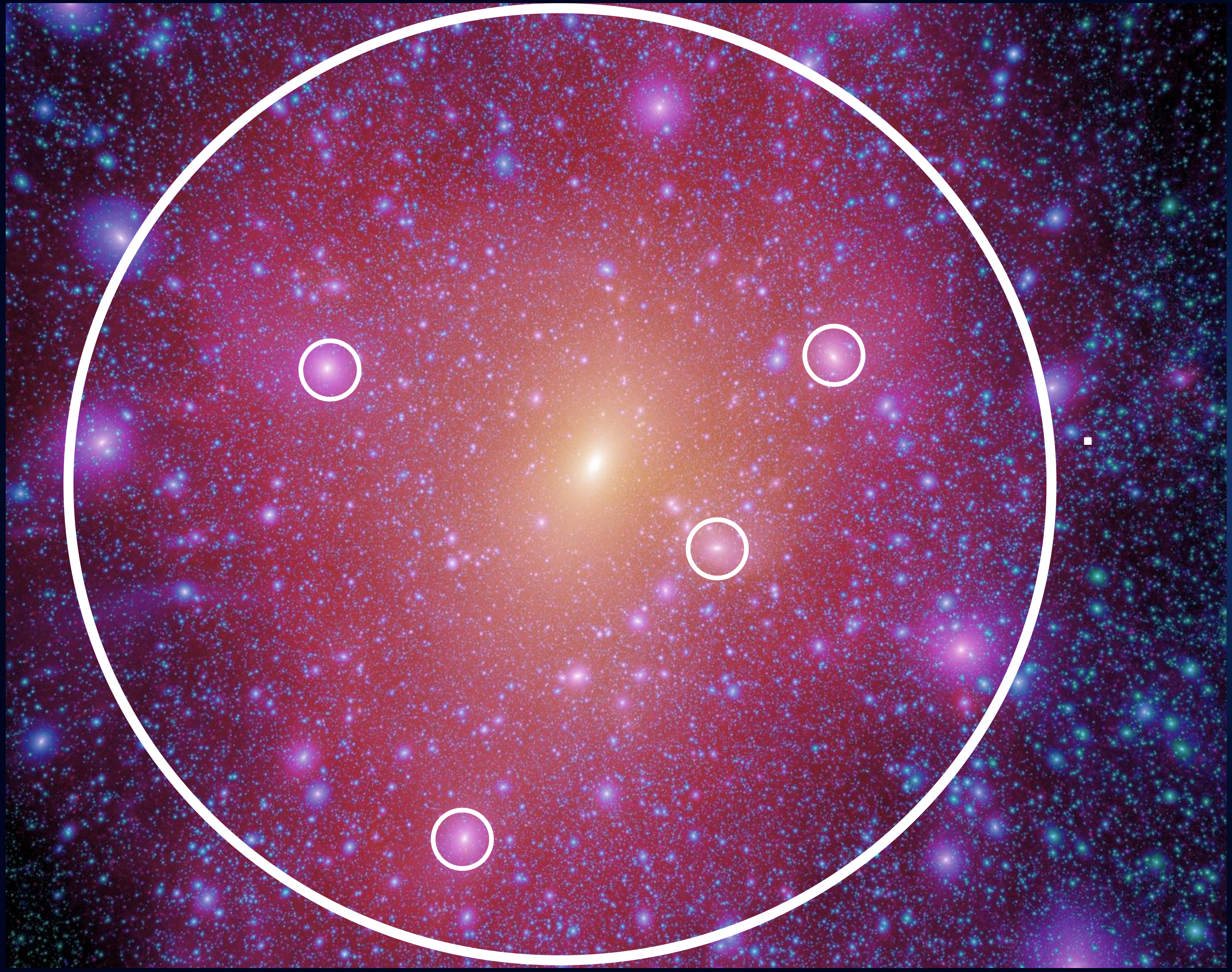


银河系的子结构

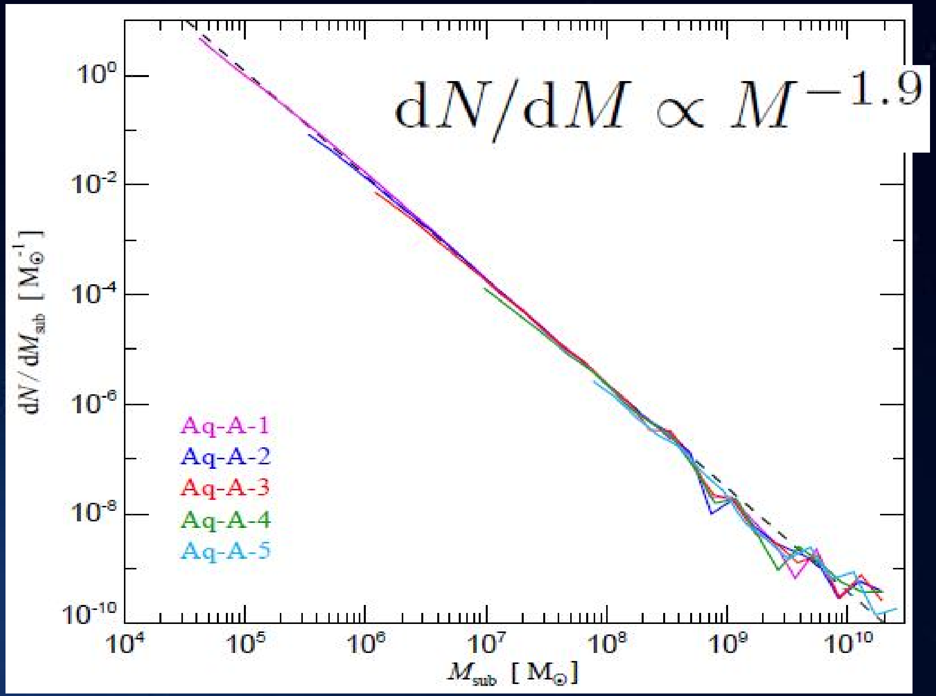

LeoIV
UMaI
Sextans
UrsaMin
Draco
CB
BootesI
W1
Herc
UMaII
Milky Way
Galaxy
Sag
Carina
LMC
SMC
Sculptor
Fornax

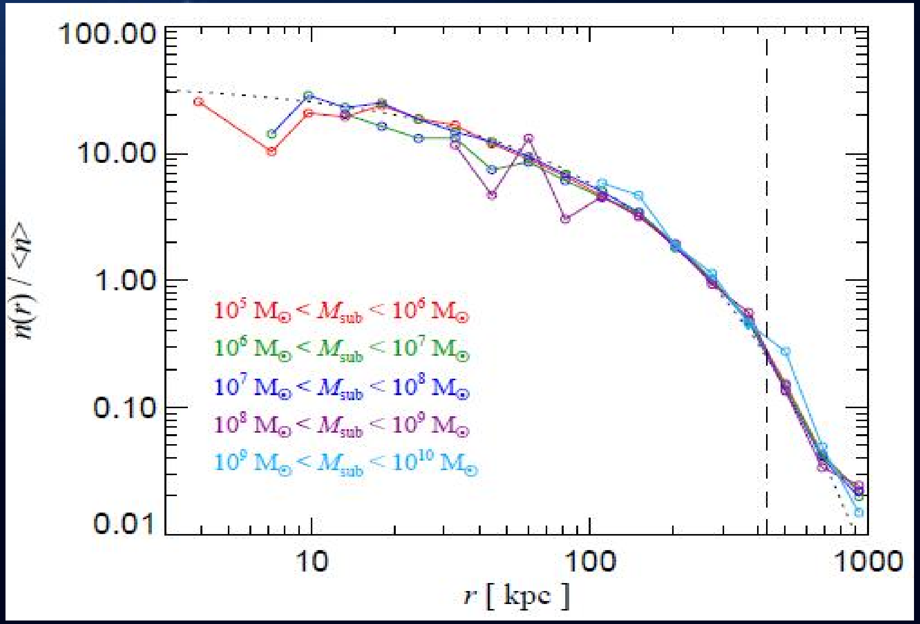

Aq-A-1

子结构质量函数以及空间分布

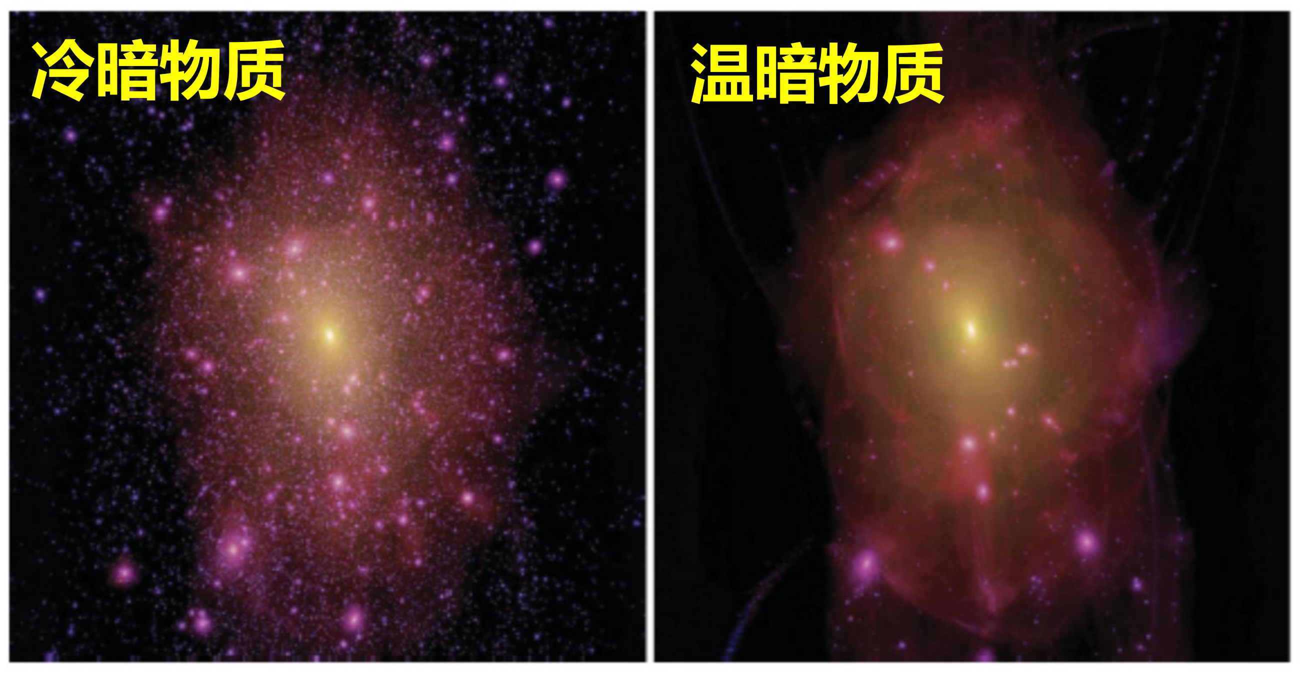


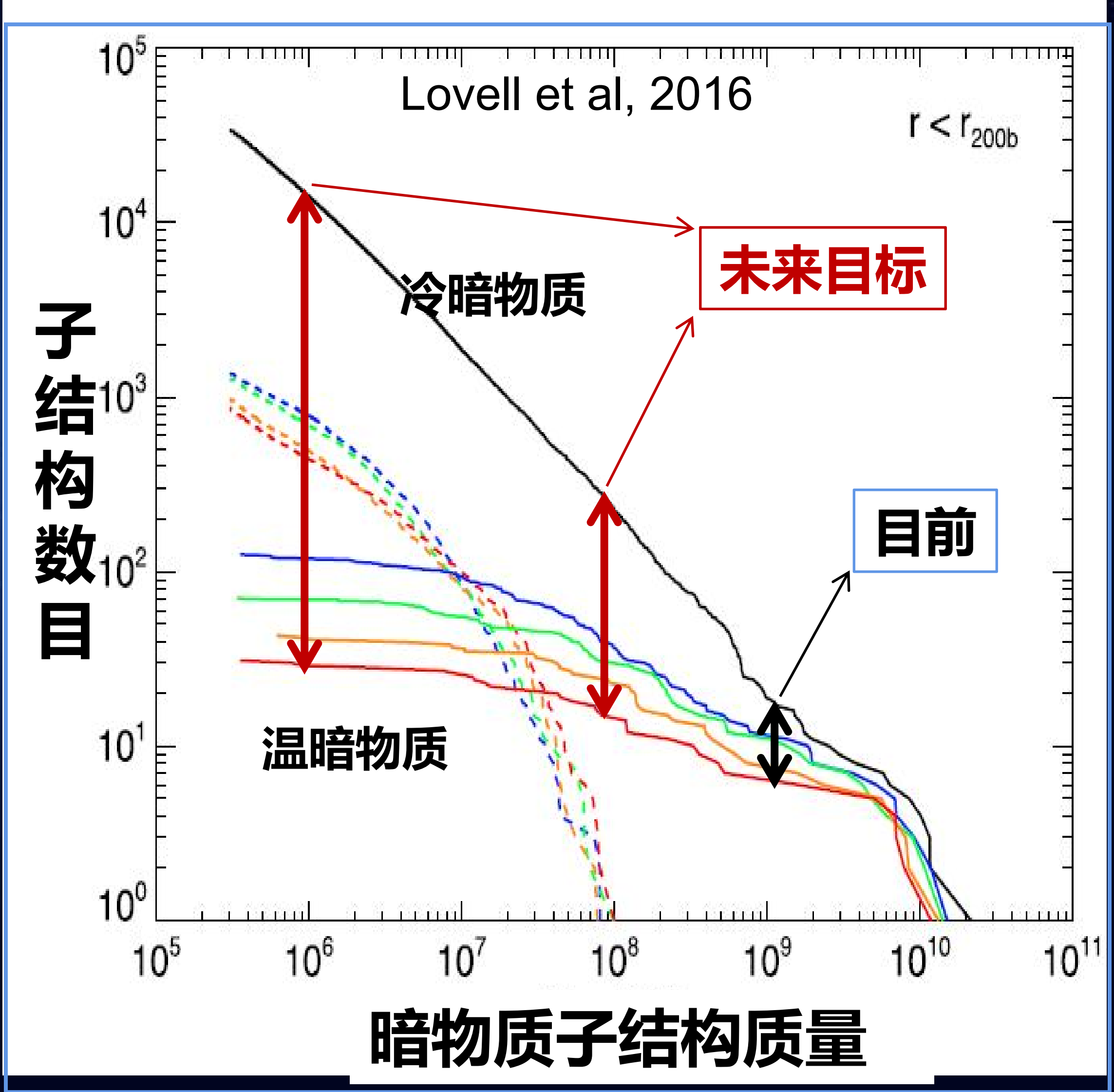
Springel , JW, et al 2008





暗物质粒子属性与子结构数目



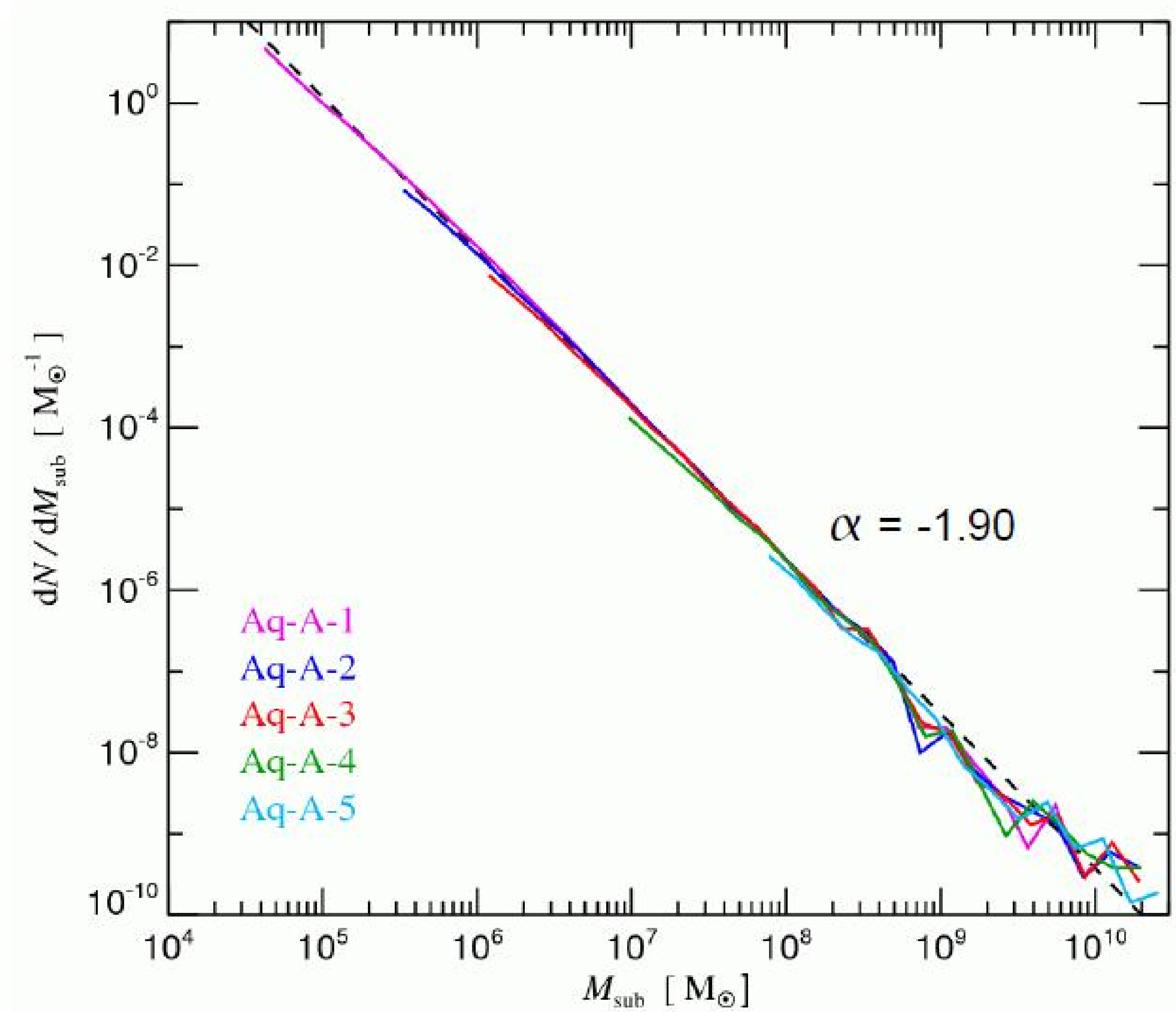


目前只能限定到$10^9 M_\odot$，但是不能有效区分冷/温暗物质

The differential subhalo mass function converges quite well to a power-law

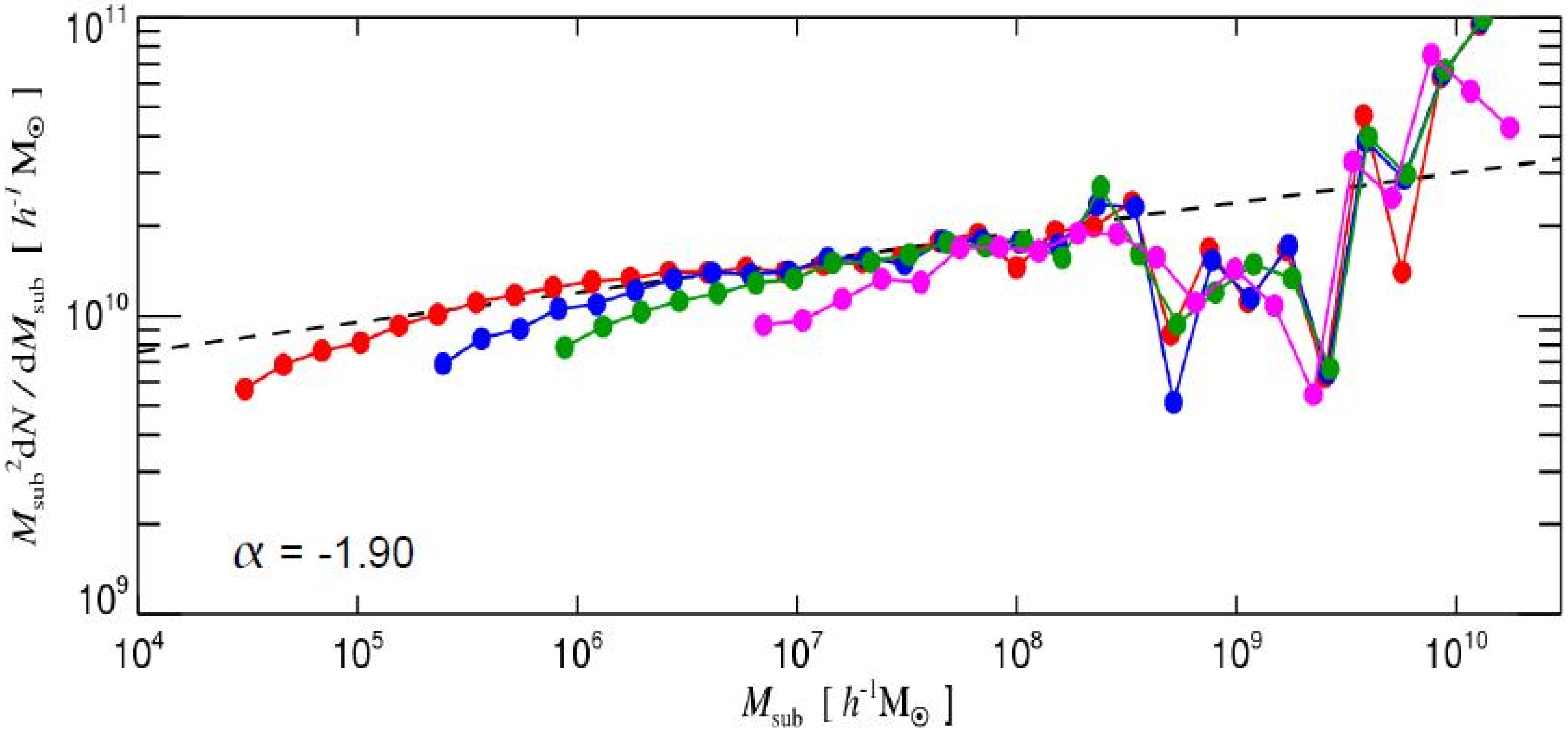
RESULTS FROM A RESOLUTION STUDY OF AQUARIUS HALO AQ-A

Springel et al 2008



The subcritical slope of the differential subhalo mass function implies that the total mass in substructures converges at the faint end

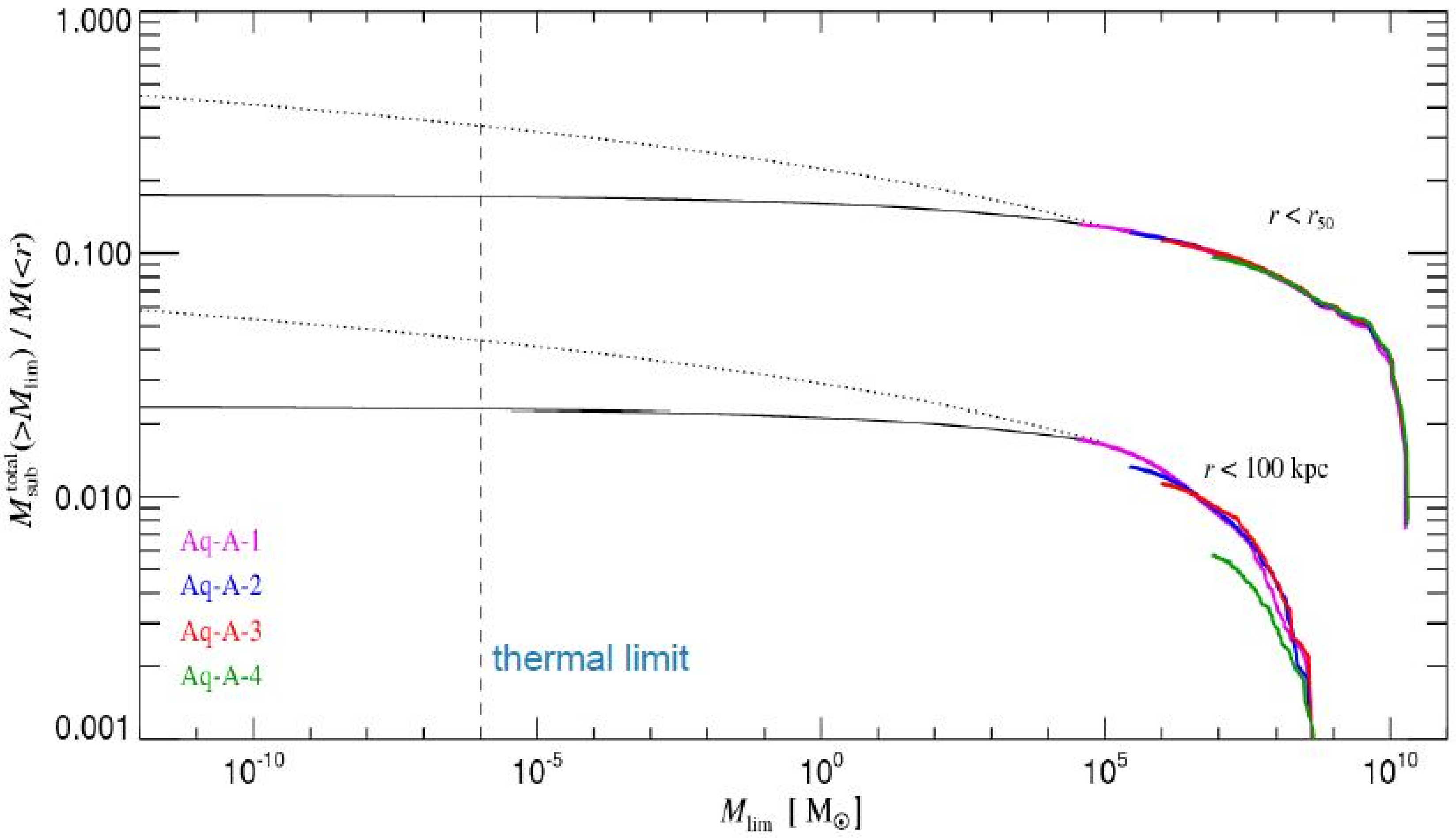
THE DIFFERENTIAL SUBHALO MASS FUNCTION



Springel et al 2008

The cumulative mass fraction in **resolved substructures** reaches about 12-13%, we expect up to ~18% down to the thermal limit

FRACTION OF MASS IN SUBSTRUCTURES AS A FUNCTION OF MASS LIMIT



Springel et al 2008

The radial distribution of substructures is strongly antibiased relative to all dark matter, and independent of subhalo mass

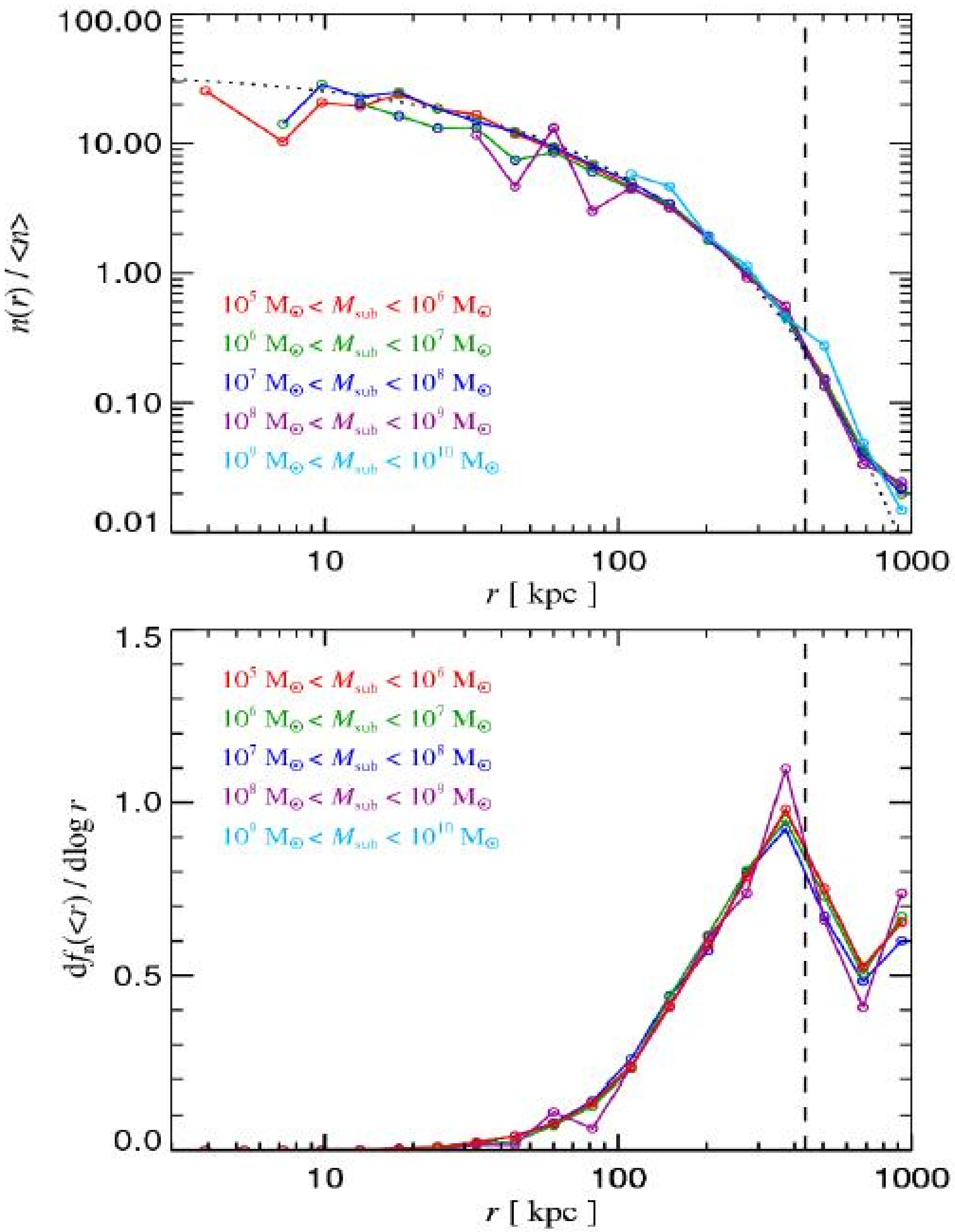
RADIAL SUBSTRUCTURE DISTRIBUTION IN Aq-A-1

Most subhalos are at large radii, subhalos are more effectively destroyed near the centre

Subhalos are far from the Sun

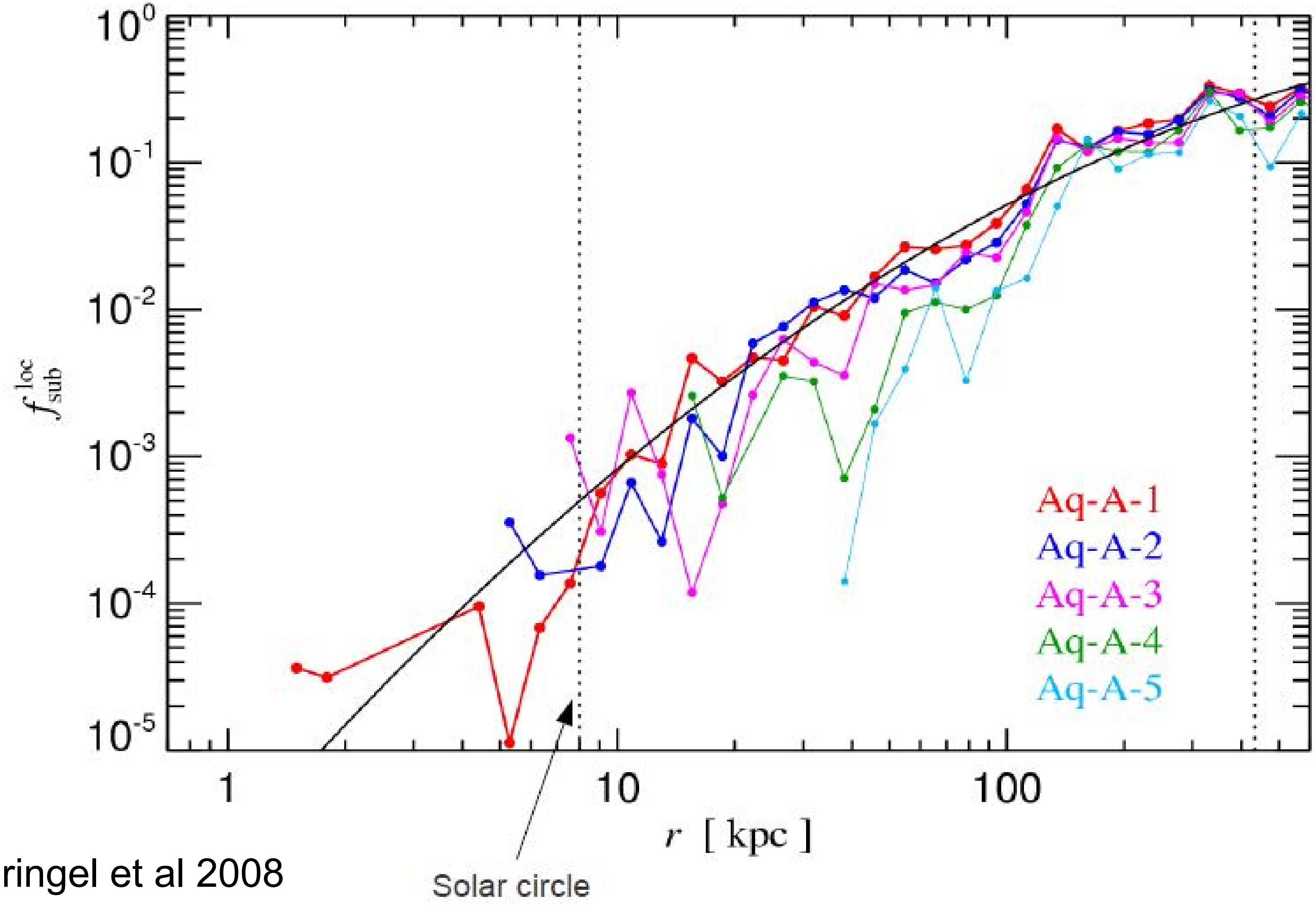
Springel et al
2008

see also Diemand et al. (2007, 2008)



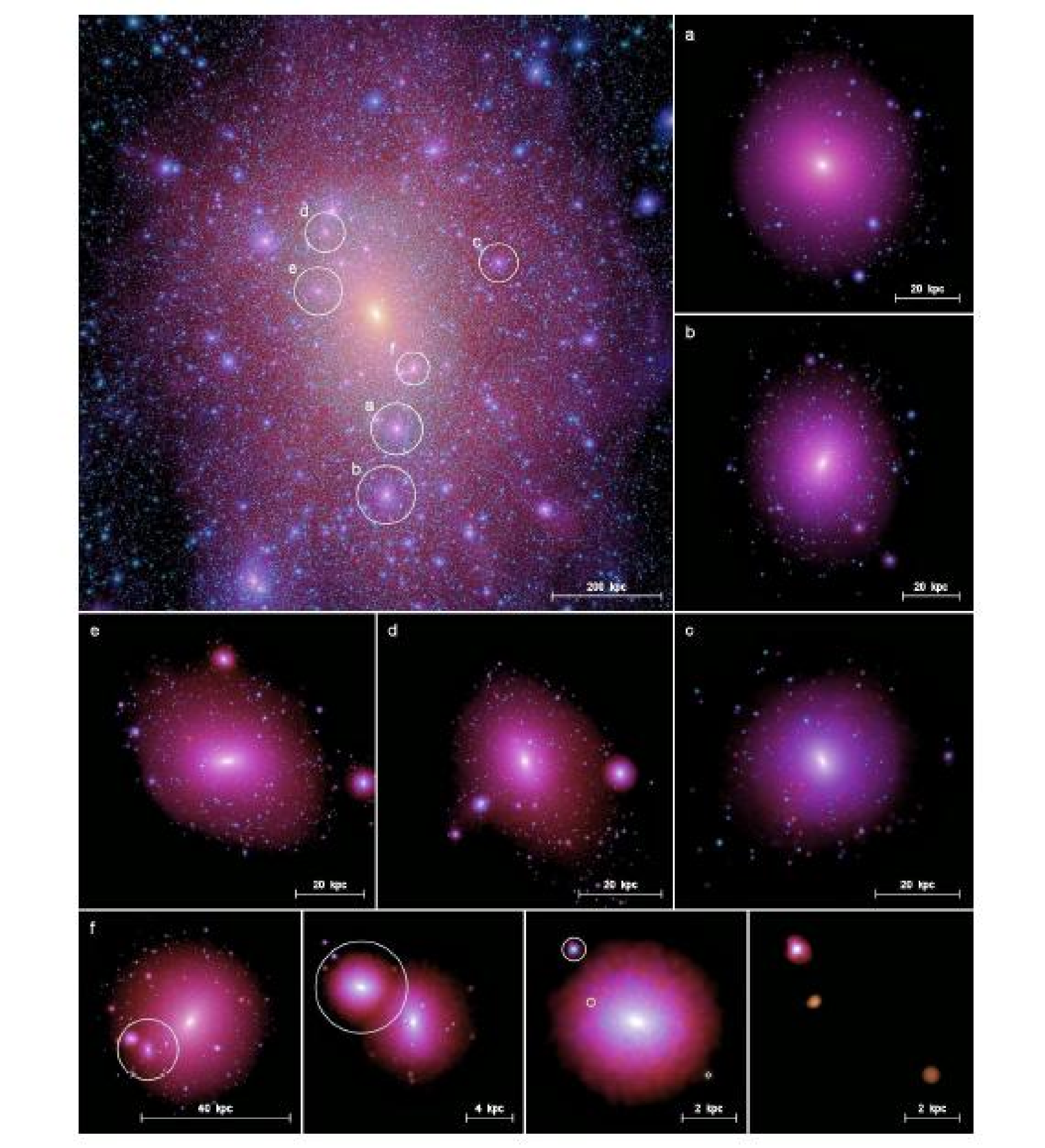
The local mass fraction in substructures is a strong function of radius

MASS FRACTION IN SUBSTRUCTURES AS A FUNCTION OF RADIUS IN HALO AQ-A

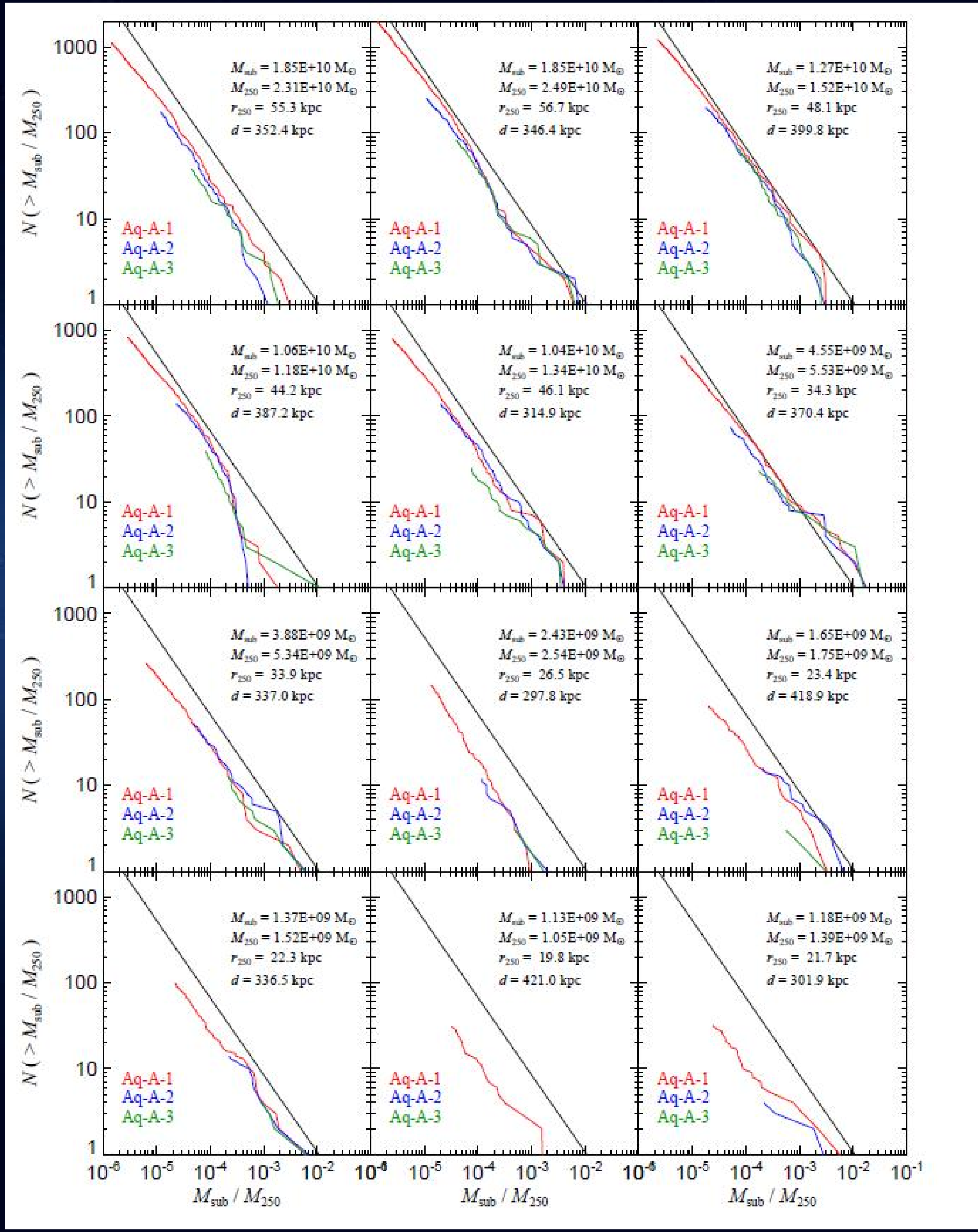


Springel et al 2008

Subhalos in subhalos

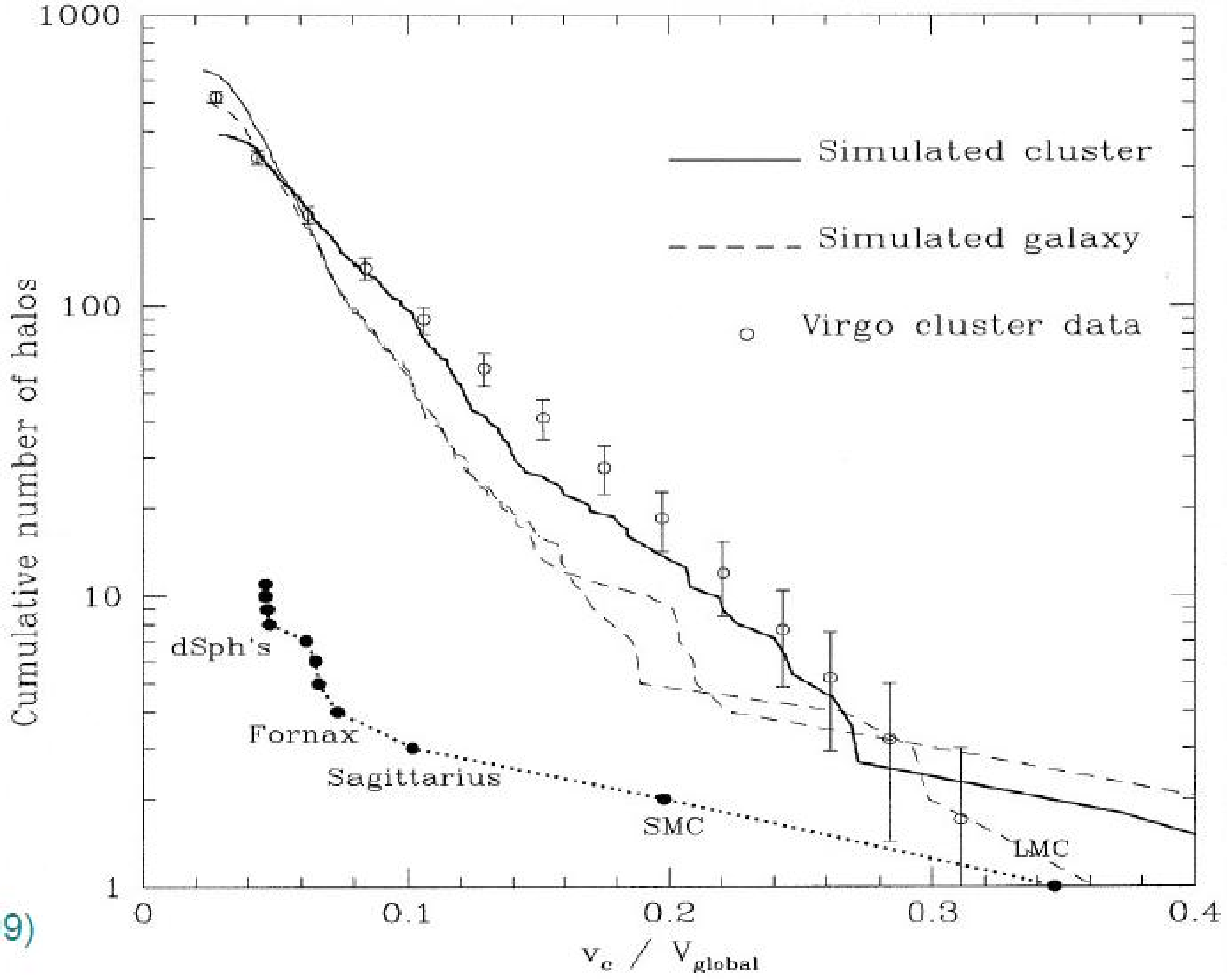


Springel et al 2008

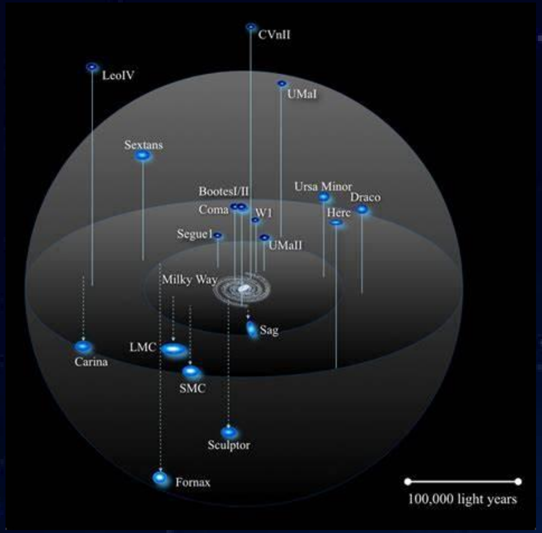


Taken at face value, the number of luminous satellites in the Milky Way is much smaller than the number of dark matter lumps

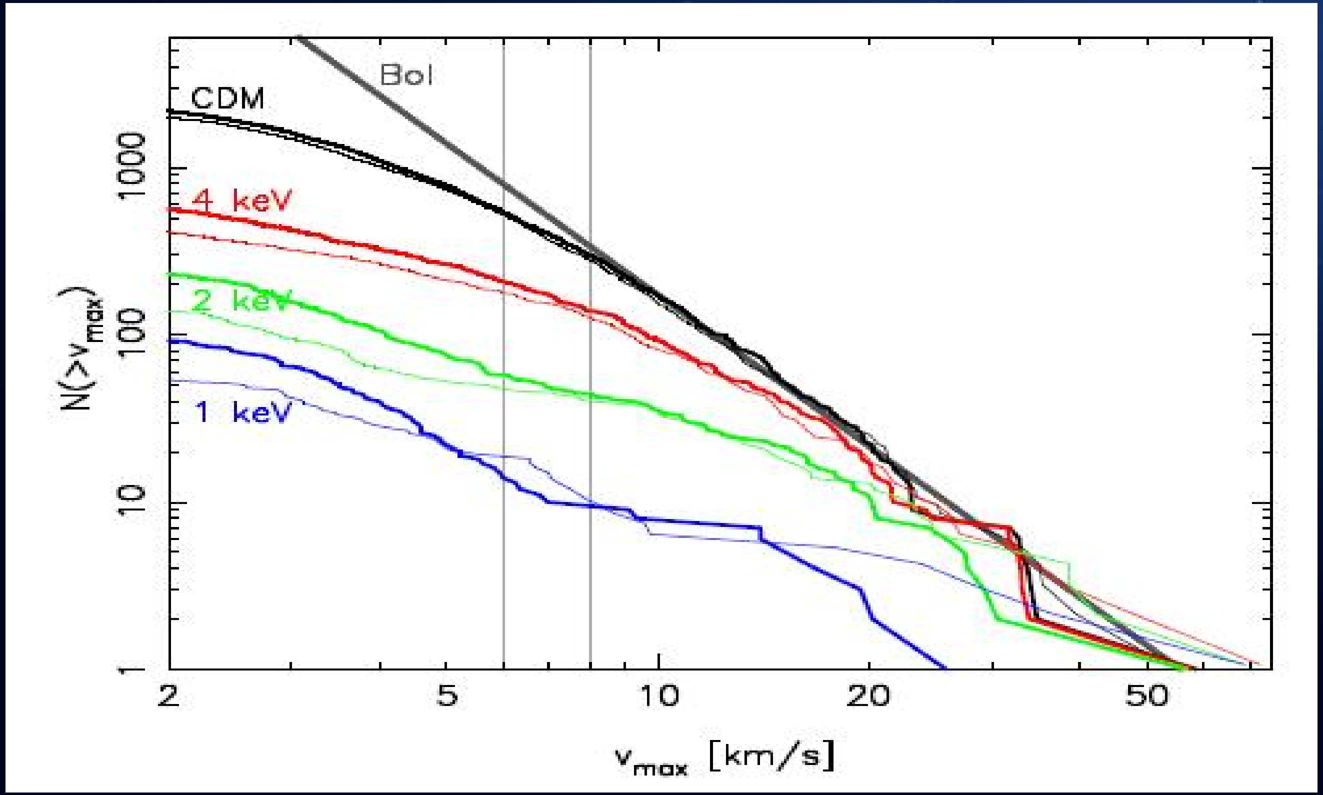
THE SATELLITE PROBLEM

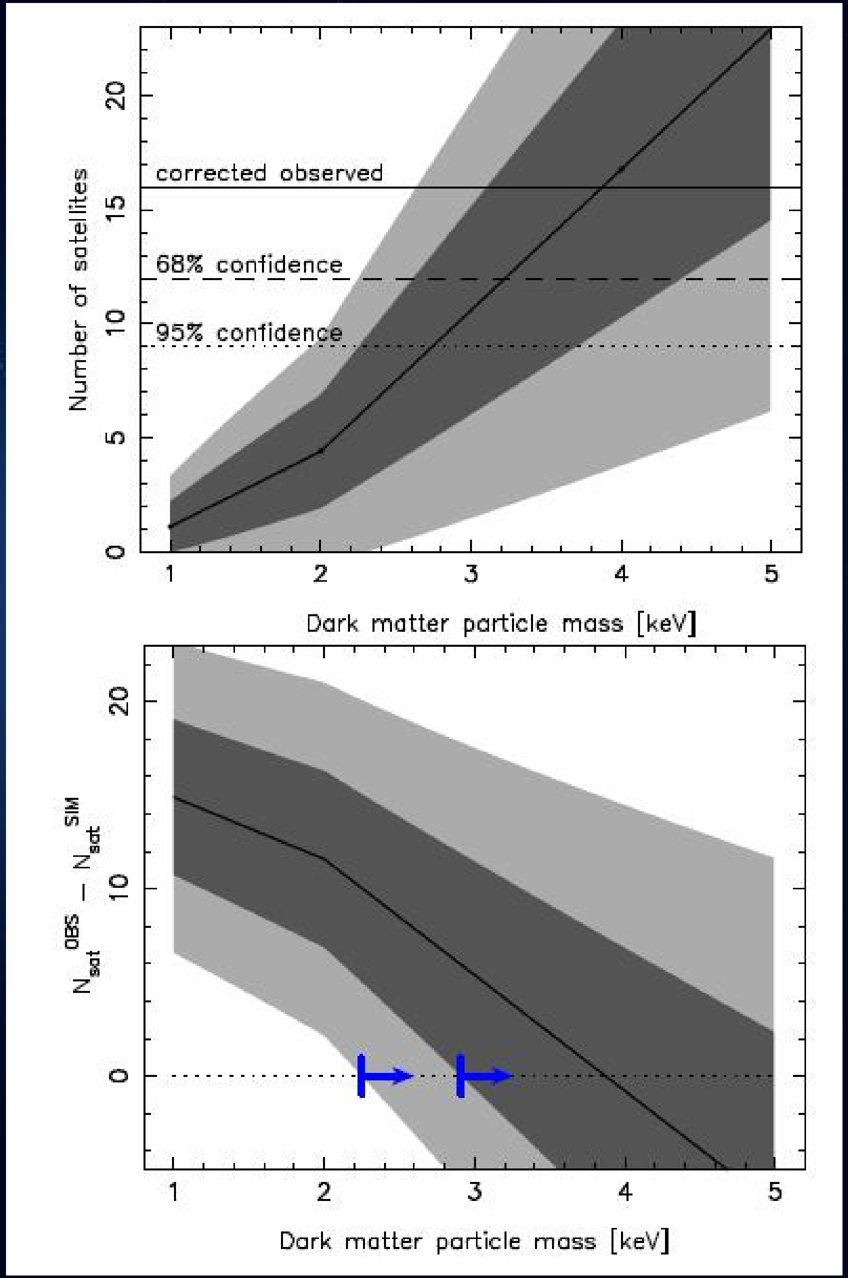


Moore et al. (1999)

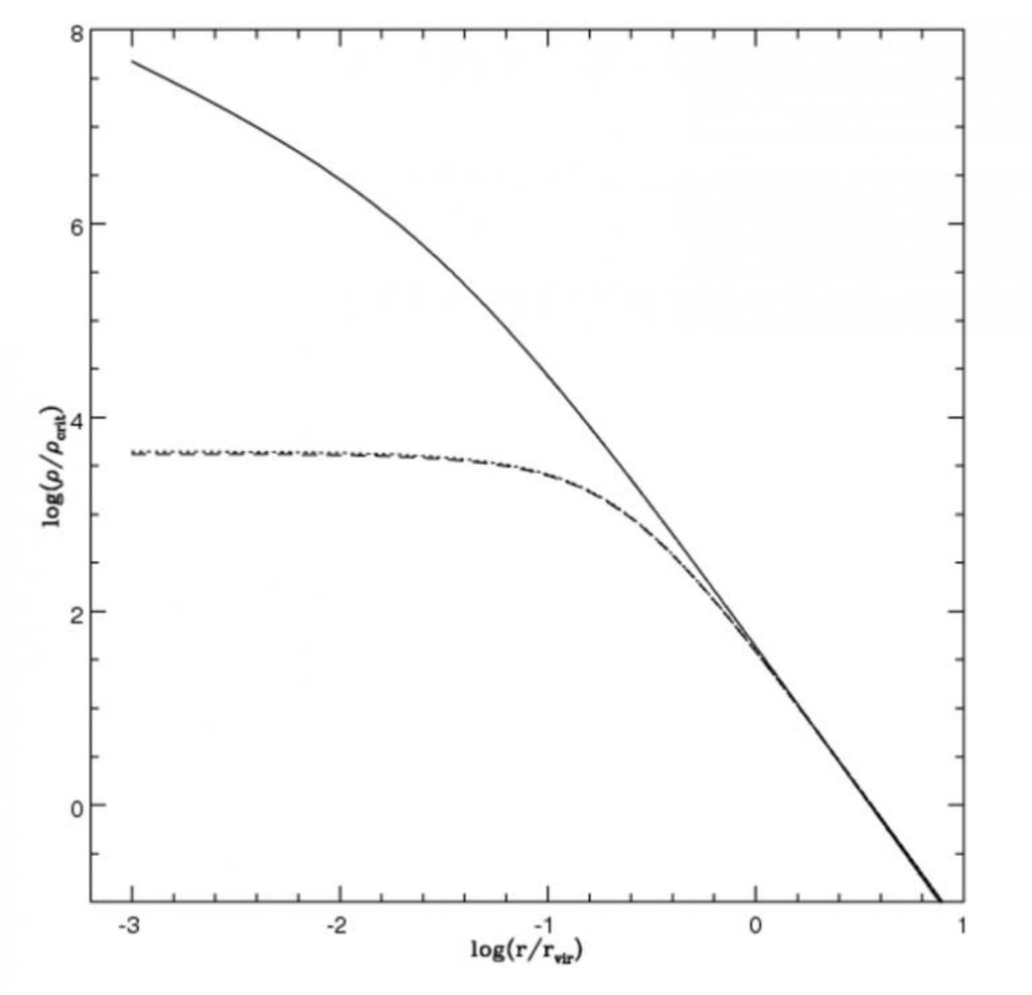


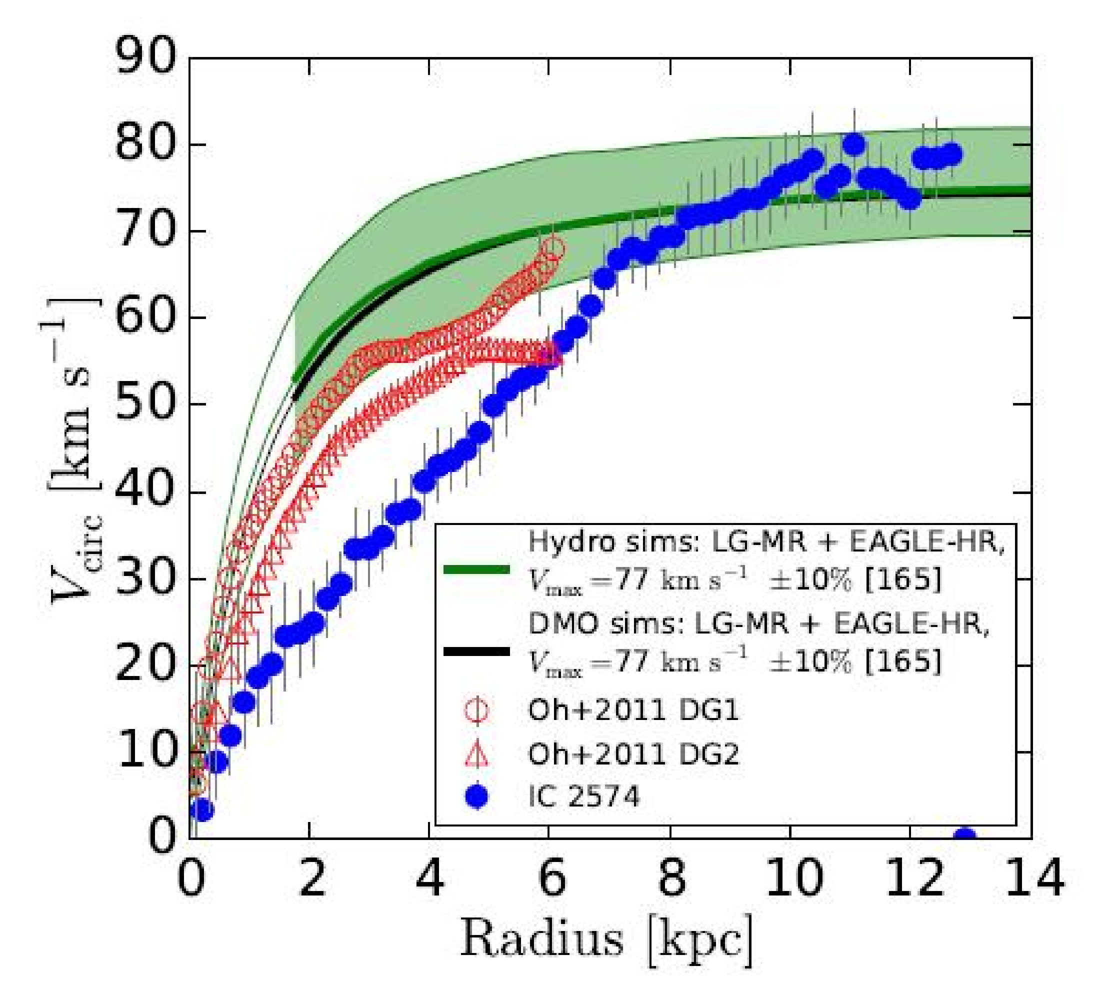
暗物质粒子属性与银河系卫星星系数目





矮星系里的core Vs Cusp问题

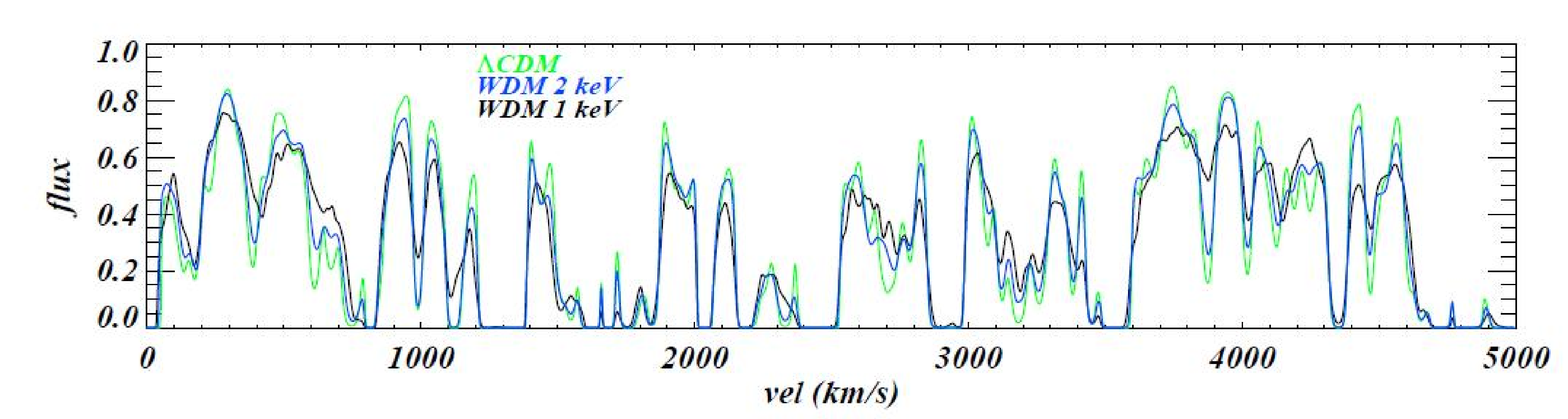


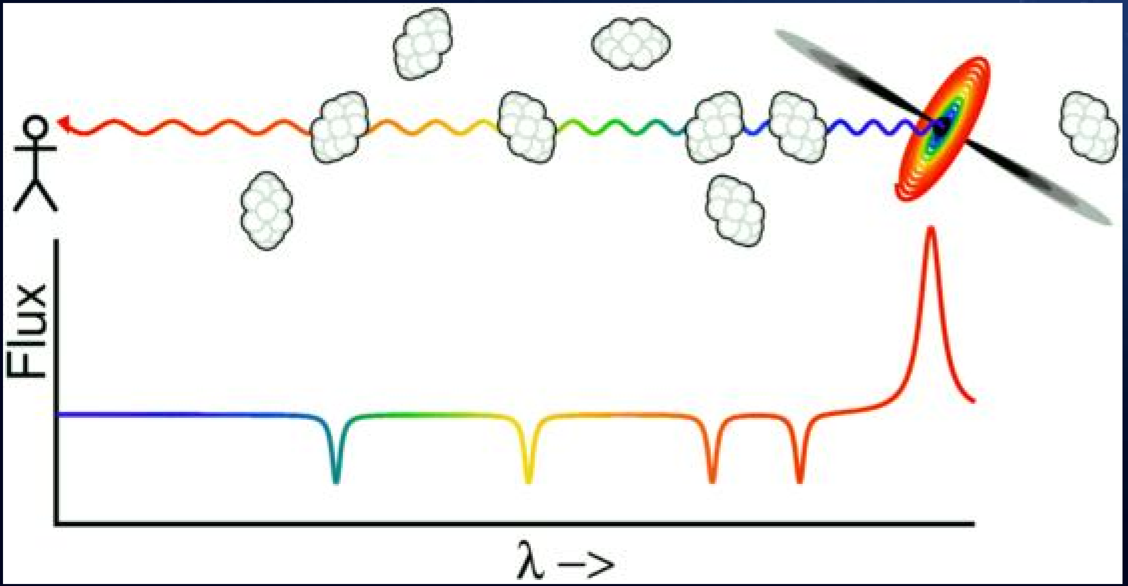


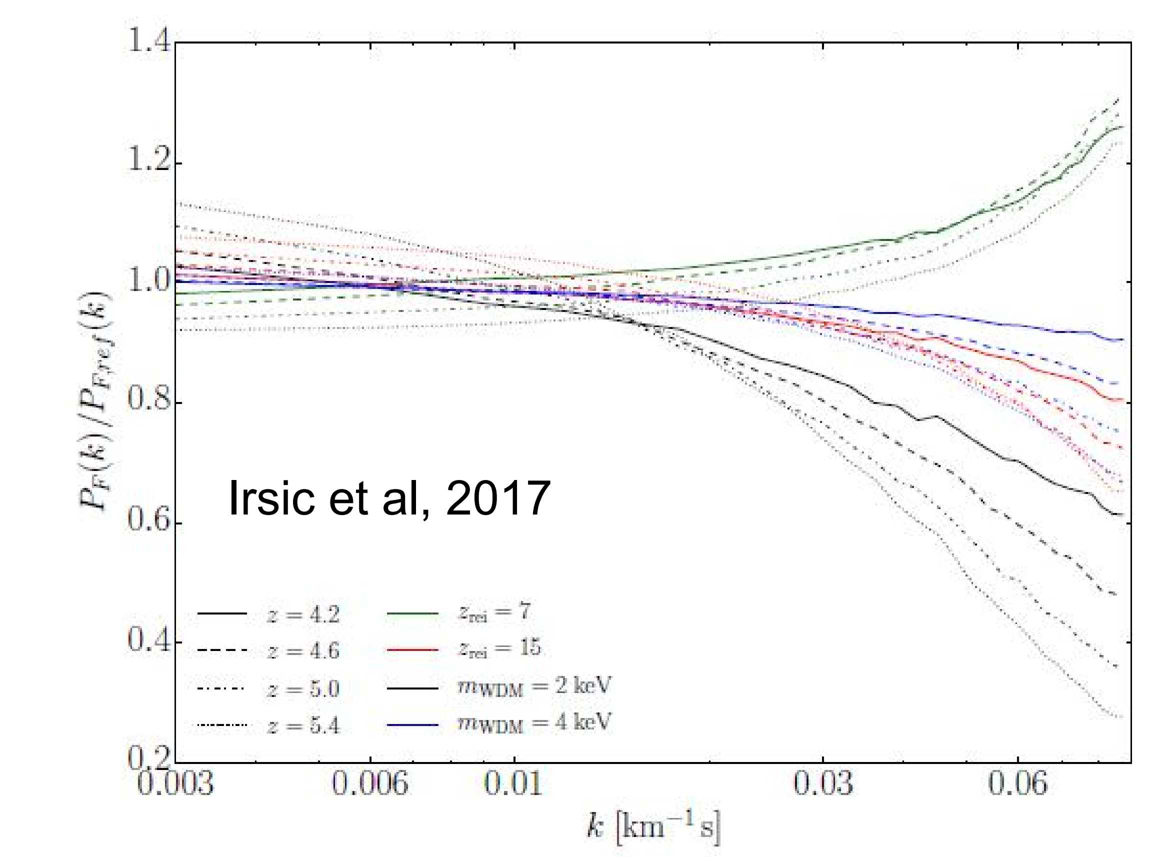
Oman et al 2019

暗物质粒子属性

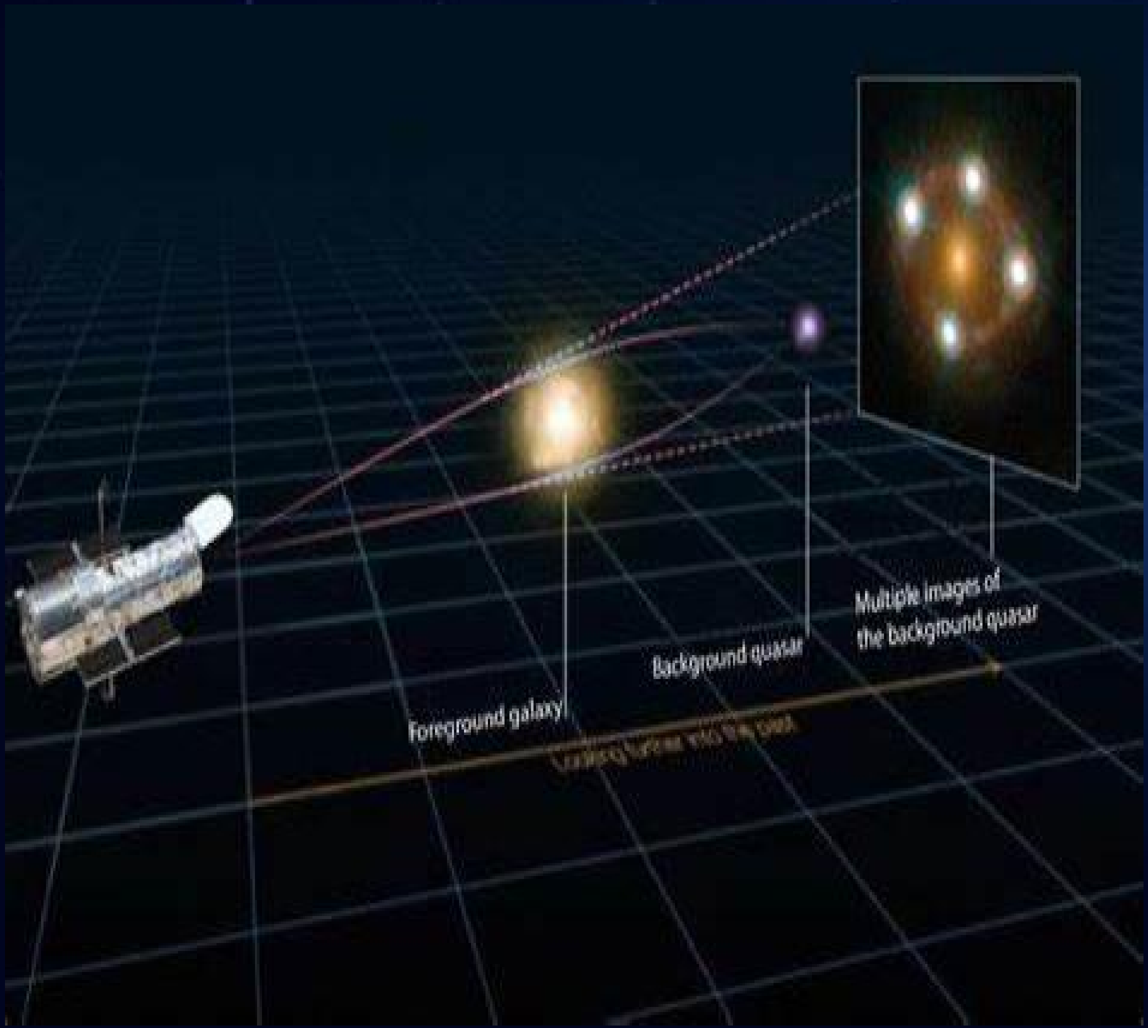
与Ly-a Forest

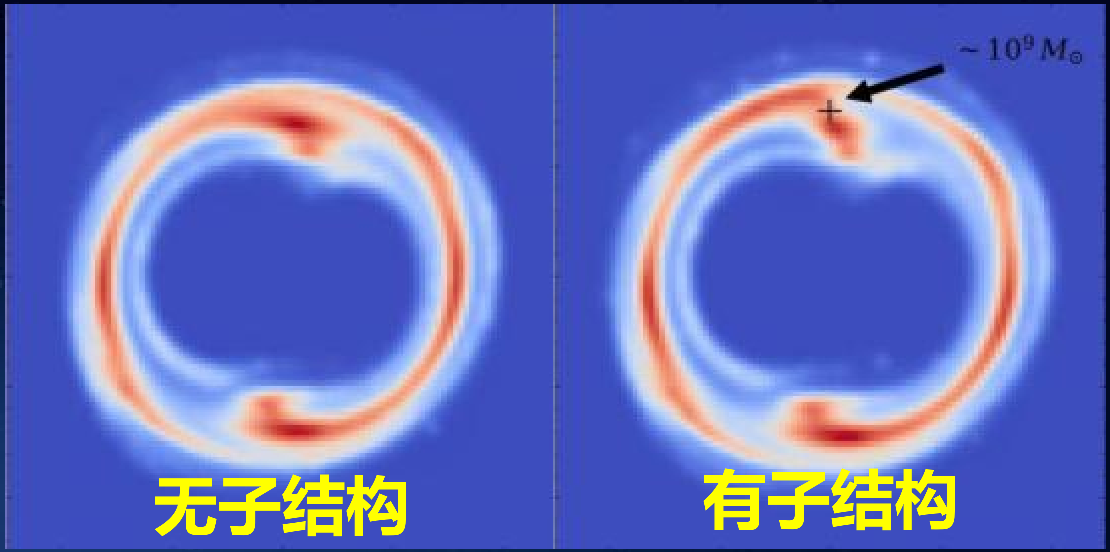


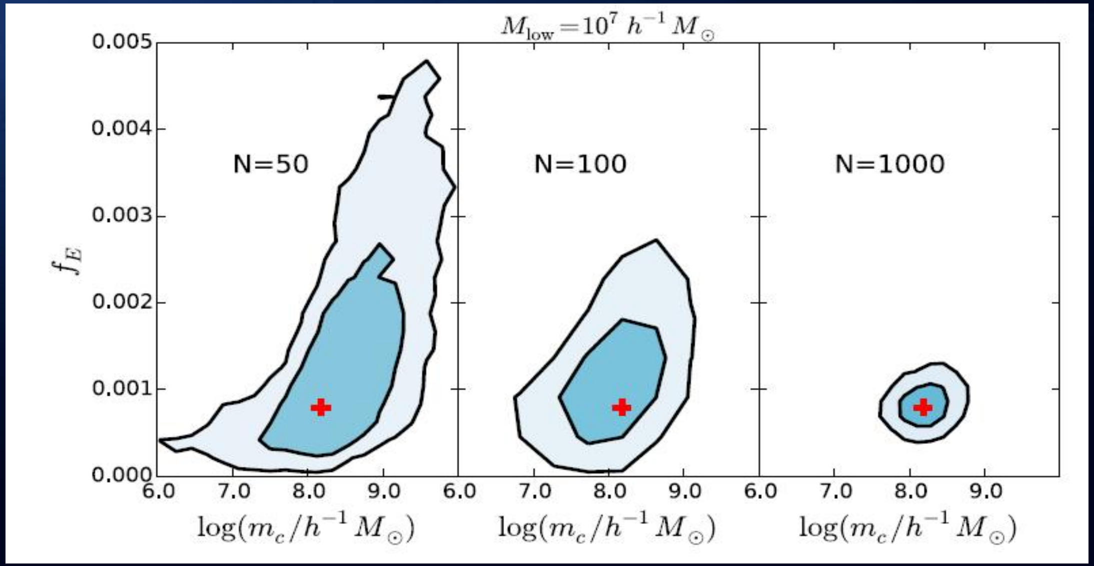




暗物质粒子属性与强引力透镜







Li et al, 2016

Reference	Probe	$\frac{m_{th}}{keV}$ 95% c.l.
This work	See Section 3	6.048
Birrer et al. (2017)	Grav. Imaging	2.0
V18 (Original)	Grav. Imaging	0.3
R19 (Original)	Grav. Imaging	0.26
Gilman et al. (2019a)	Flux Ratios	3.1, 4.4
Gilman et al. (2019b)	Flux Ratios	5.2
Hsueh et al. (2019)	Flux Ratios	5.6
Banik et al. (2018, 2019)	Stellar streams	4.6, 6.3
Alvey et al. (2021)	Dwarf spheroidals	0.59, 0.41
Viel et al. (2005)	Ly α	0.55
Viel et al. (2006)	Ly α	2.0
Seljak et al. (2006)	Ly α	2.5
Iršič et al. (2017)	Ly α	3.5, 5.3
M18 (Original)	Ly α	2.7, 3.6
Polisensky & Ricotti (2011)	MW satellites	2.3
Kennedy et al. (2014)	MW satellites	1.3, 5.0
Jethwa et al. (2017)	MW satellites	2.9
Nadler et al. (2019b)	MW satellites	3.26
Nadler et al. (2021a)	MW satellites	6.5
Nadler et al. (2021b)	MW satellites & Flux Ratios	9.7
N20 (Original)	MW satellites	2.02, 3.99

$m_p > 3$kev

Enzi, et al, 2020

精确测量太阳邻域内暗物质密度

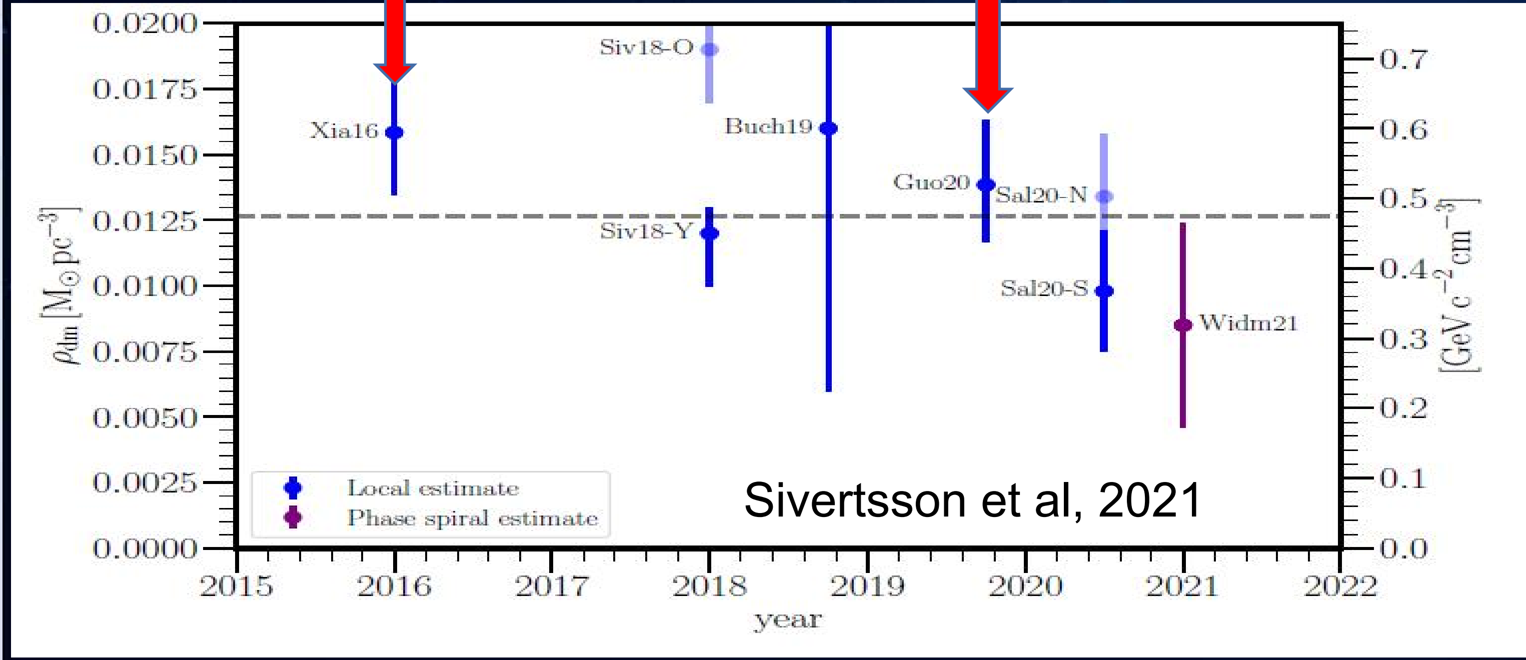
- 对银河系内暗物质分布进行整体（统计）测量，内插太阳邻域处暗物质密度

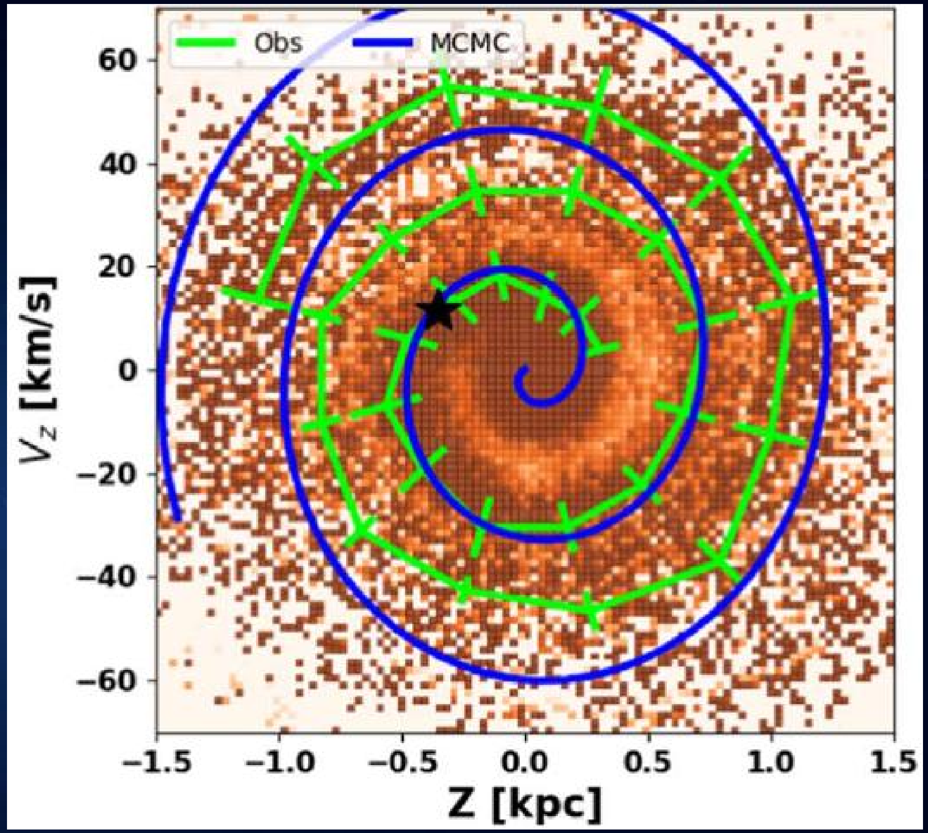
- 对太阳系附近几百pc左右体积内恒星进行动力学建模，直接测量本地密度

精确测量太阳邻域内暗物质密度

DR-2
约一千样本

DR-5
约十万样本



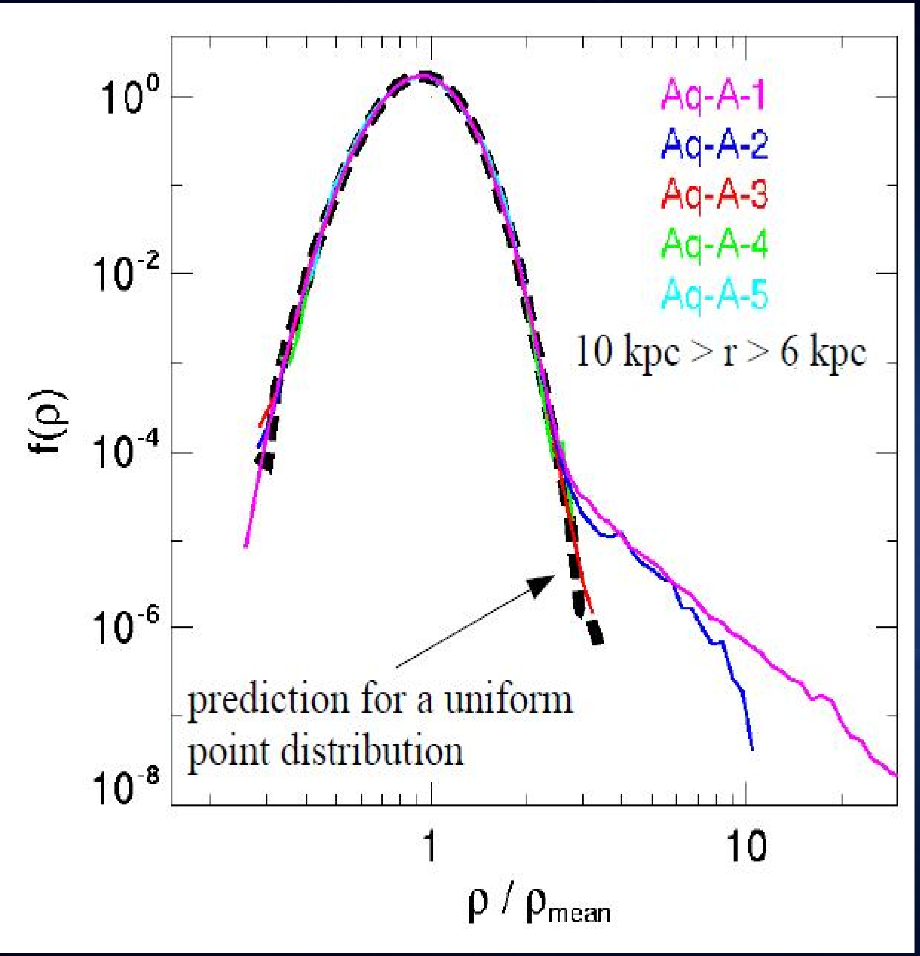


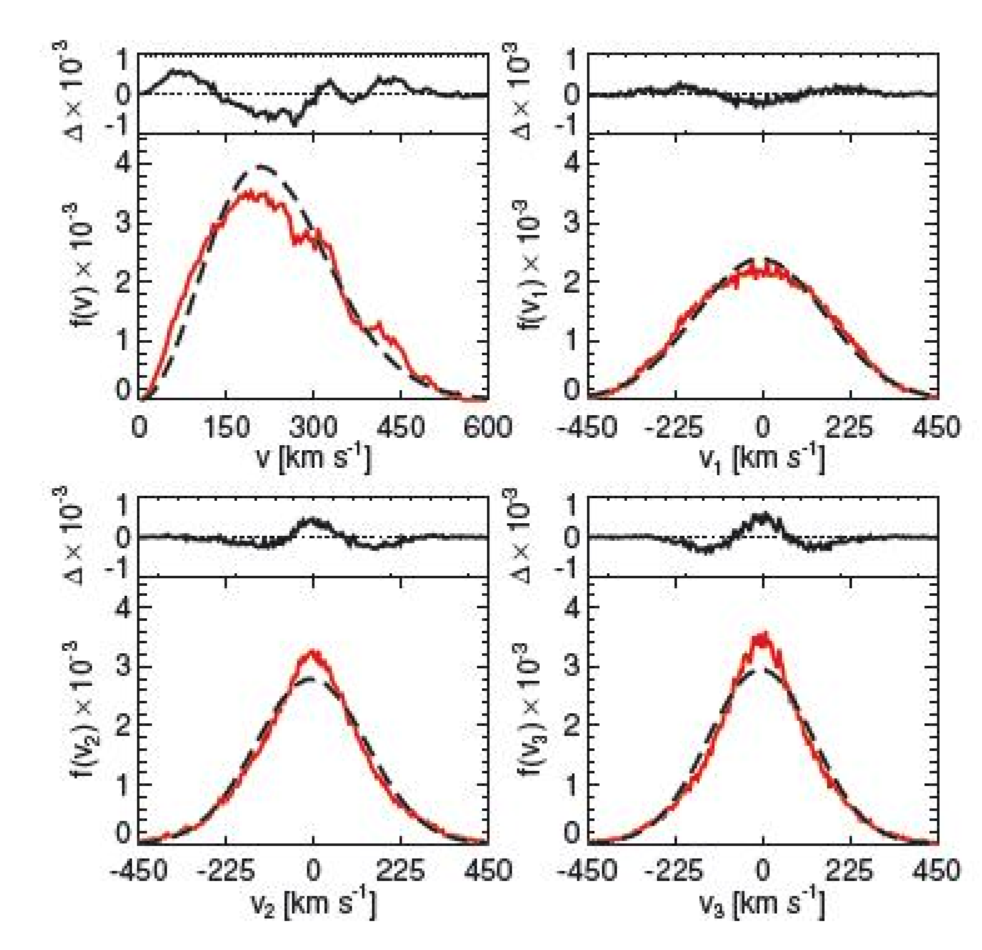
太阳附近暗物质密度测量精度将决定地面暗物质直接探测实验的成败！

系统噪音：

- 盘上/下区间不对称
- 动力学不平衡态
- 样本均匀度与完备性（较高距离处）

太阳领域暗物质密度和速度分布



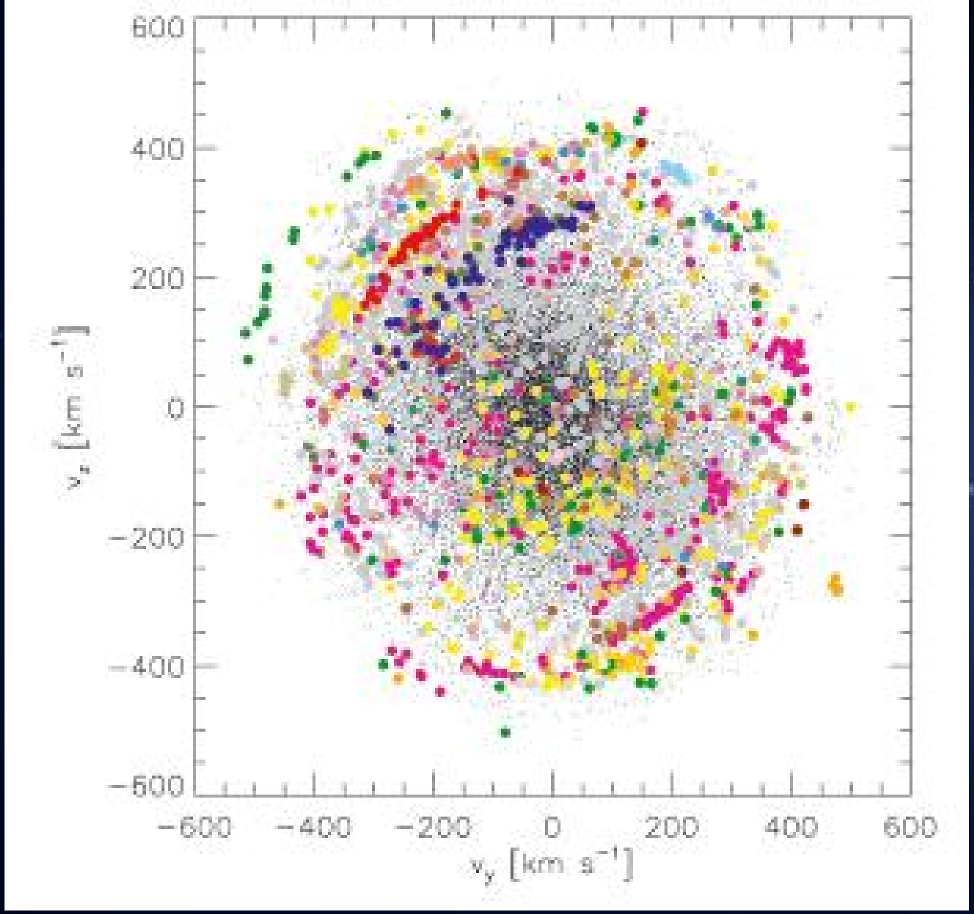


平滑, 子结构 <10^{-4}

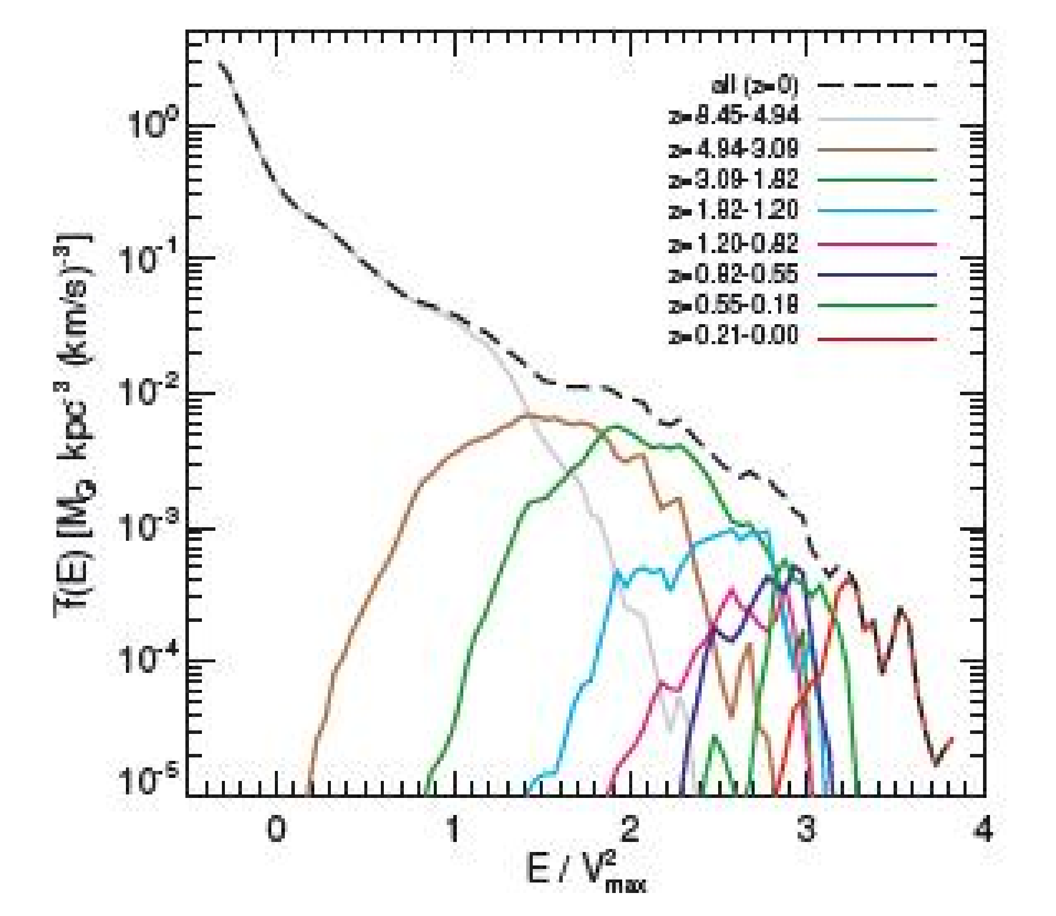
各向异性,平滑,无子结构,但幅度分布有子结构

Vogelberger et al 2009

太阳领域暗物质密度和速度分布



速度空间的结构



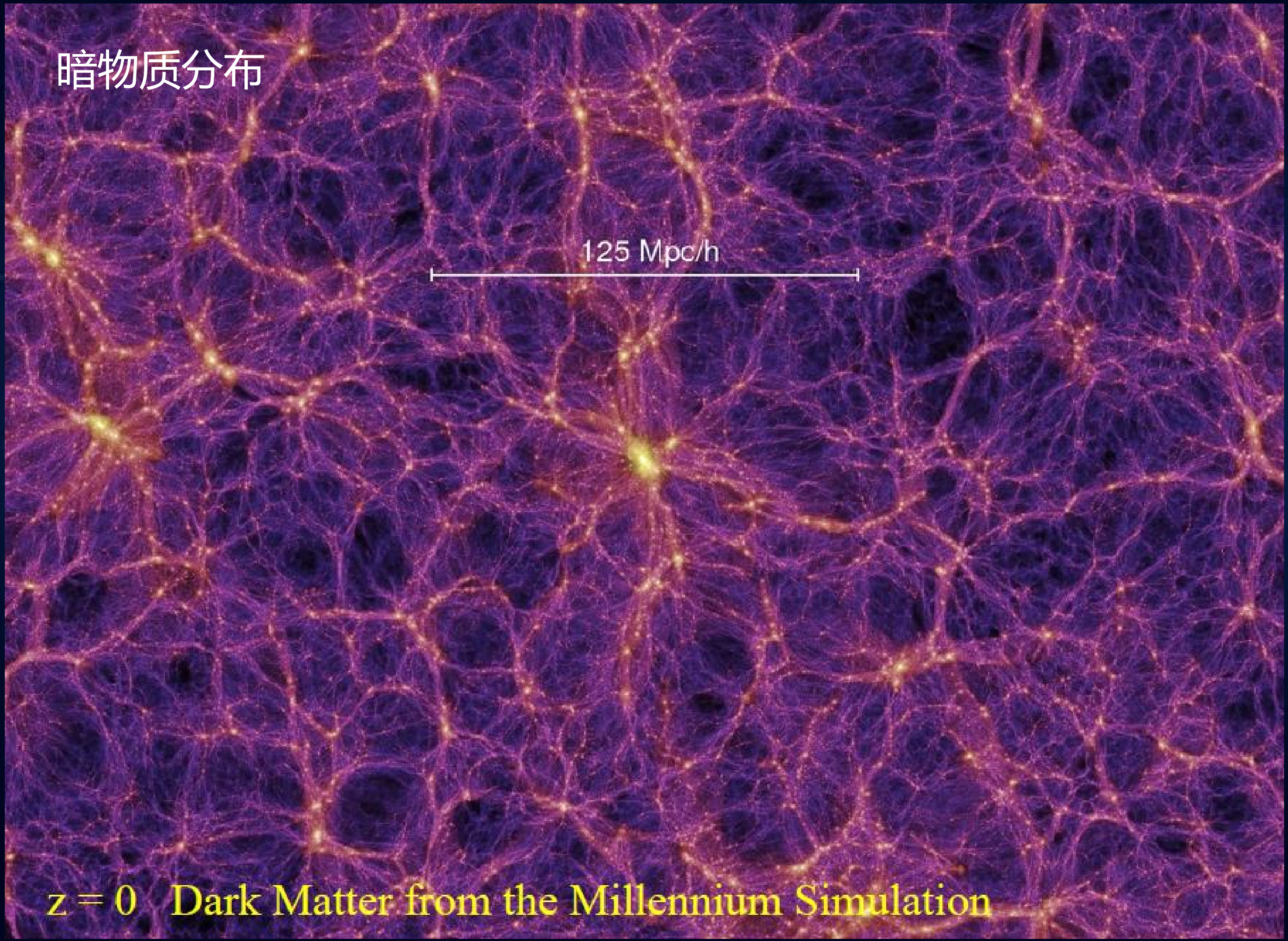
能量空间结构

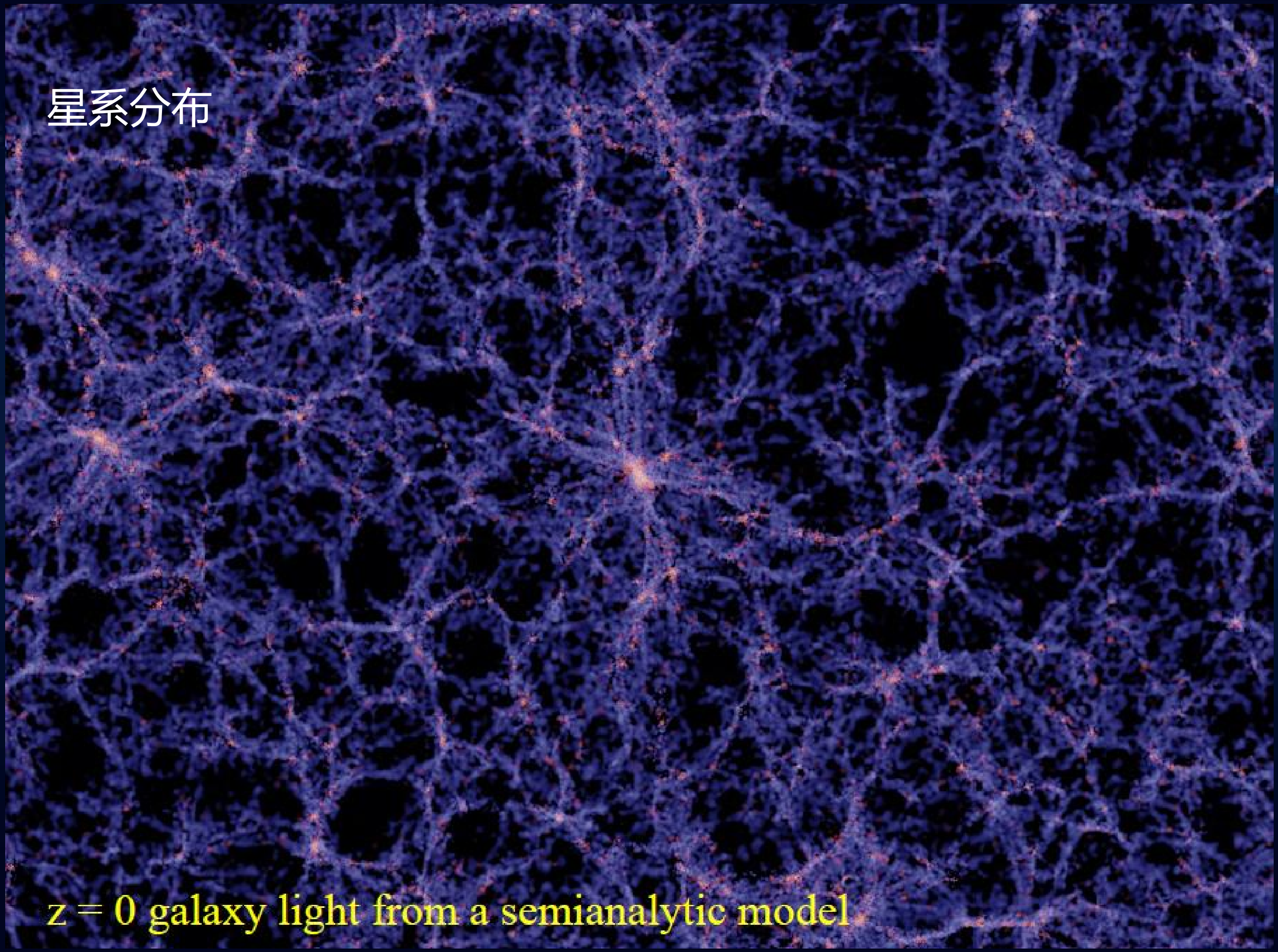
都比较明显 → 暗物质天文学

Vogelberger et al 2009

星系

宇宙中的星系


暗物质分布
125 Mpc/h
z = 0 Dark Matter from the Millennium Simulation


星系分布
z = 0 galaxy light from a semianalytic model

主要星系类型

涡旋

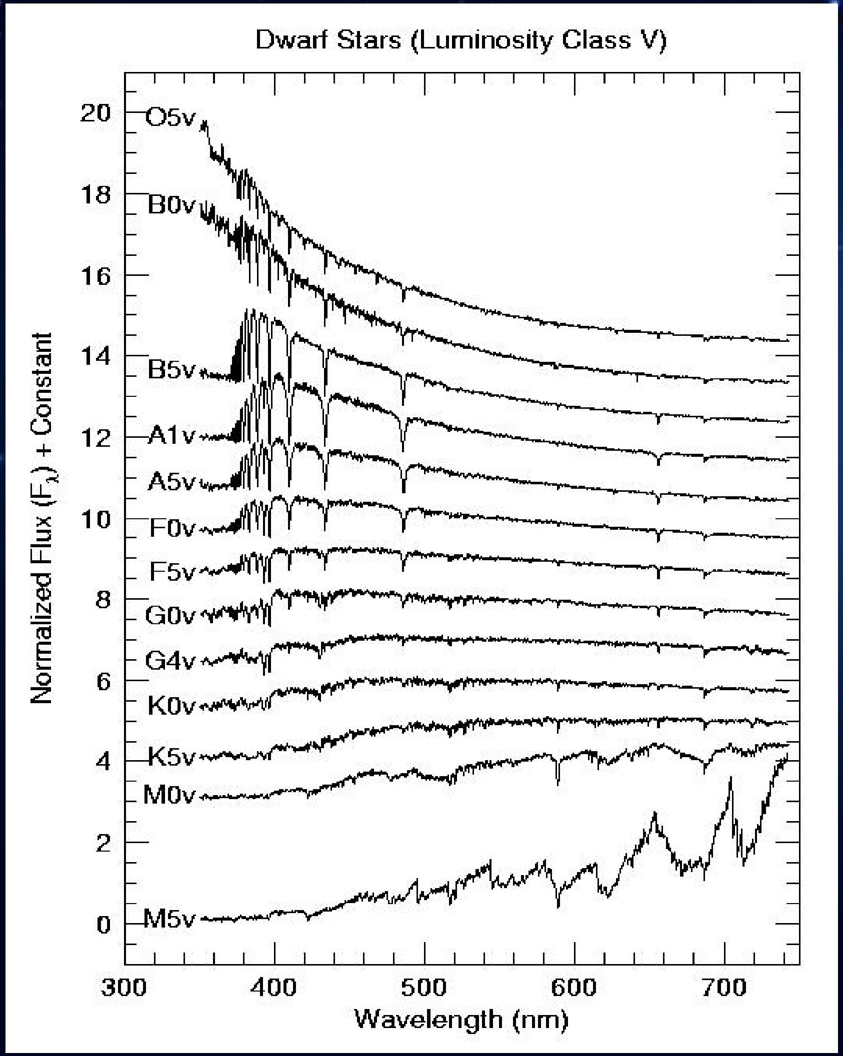
（Spiral）

椭球

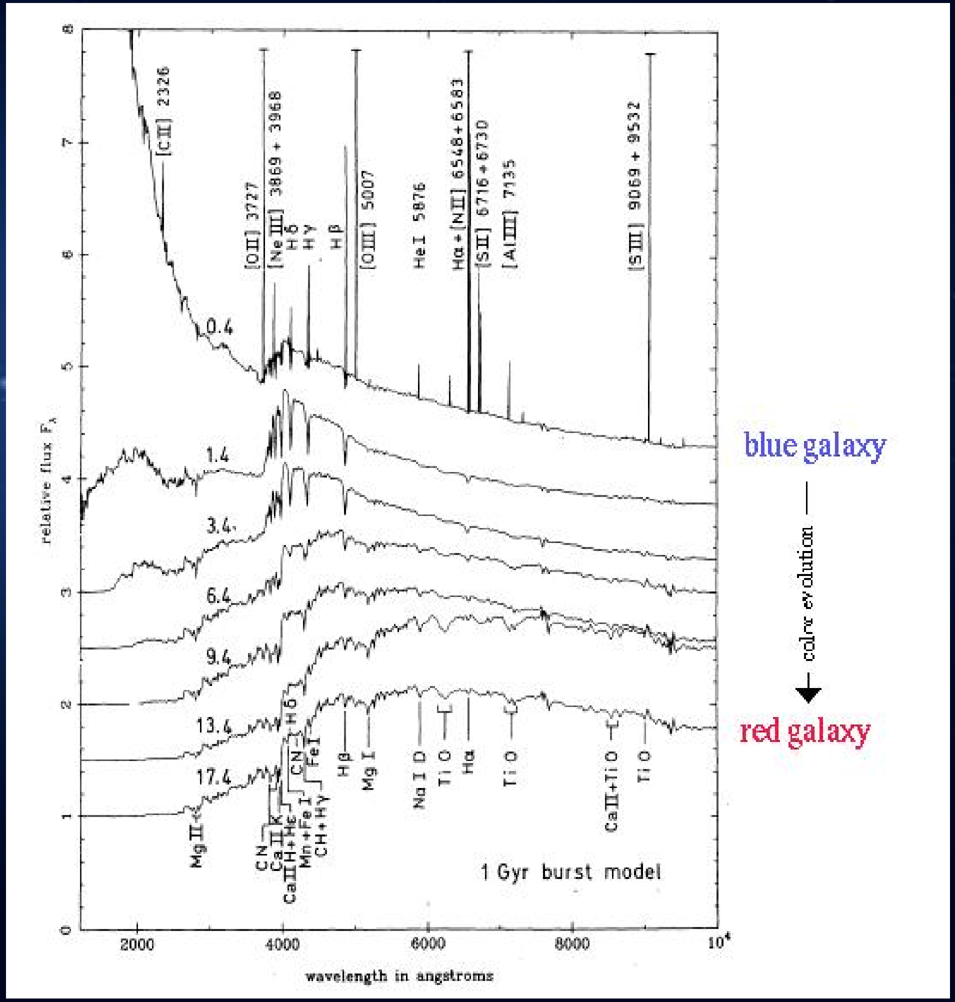
Elliptical

不规则（Irregular）

光谱



Dwarf Stars (Luminosity Class V)
Normalized Flux (Fλ) + Constant
Wavelength (nm)
O5v
B0v
B5v
A1v
A5v
F0v
F5v
G0v
G4v
K0v
K5v
M0v
M5v
300
400
500
600
700
0
2
4
6
8
10
12
14
16
18
20

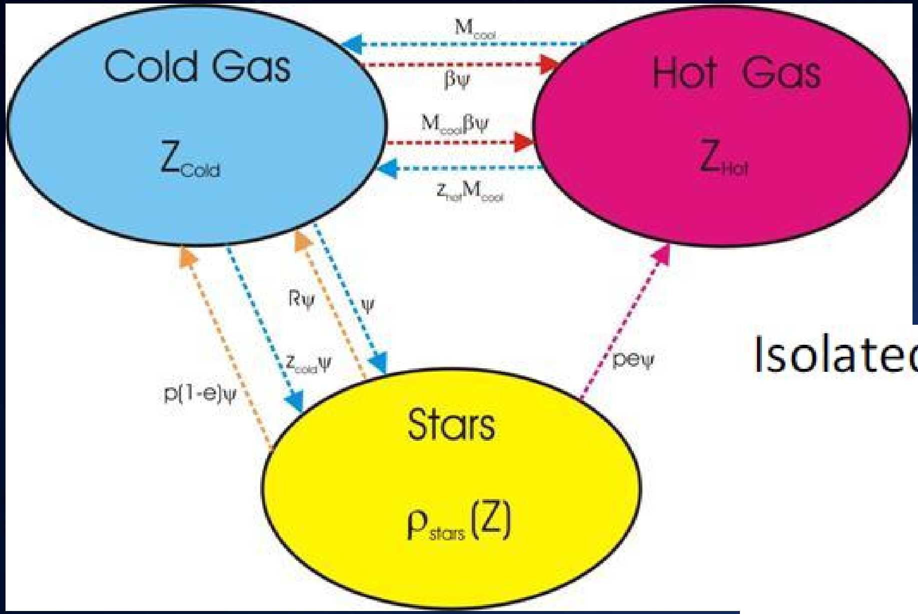


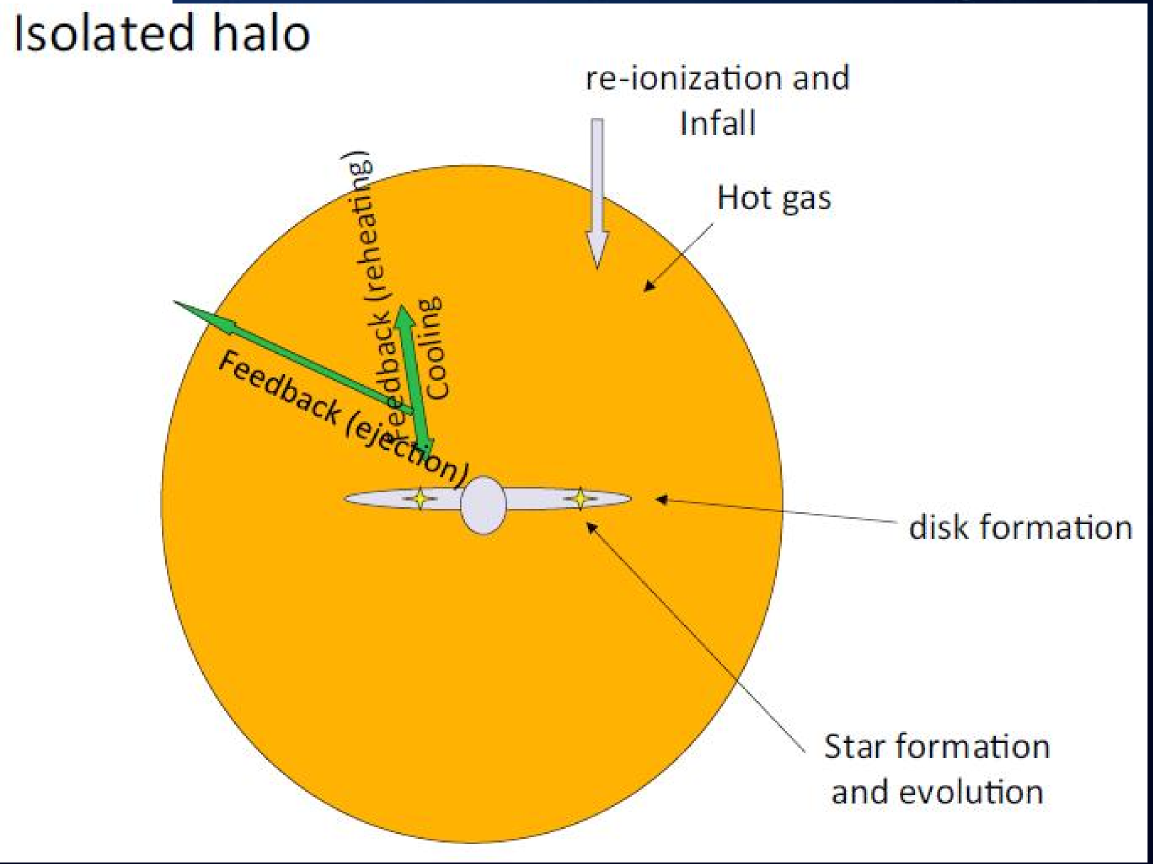
relative flux Fλ
wavelength in angstroms
2000
4000
6000
8000
10⁴
[CII] 2326
[OII] 3727
[Ne III] 3869 + 3968
Hδ
Hγ
Hβ
[OIII] 5007
HeI 5876
Hα+[NII] 6548+6583
[SII] 6716+6730
[AIIII] 7135
[SIII] 9069 + 9532
0.4
1.4
3.4
6.4
9.4
13.4
17.4
Mg II
CN
Ca II K
Ca II H+Hε
CN
Mn+Fe I
CH+Hγ
Fe I
Hδ
Hβ
Mg I
Na I D
Ti O
Hα
Ti O
Ca II+Ti O
Ti O
1 Gyr burst model
blue galaxy
color evolution
red galaxy





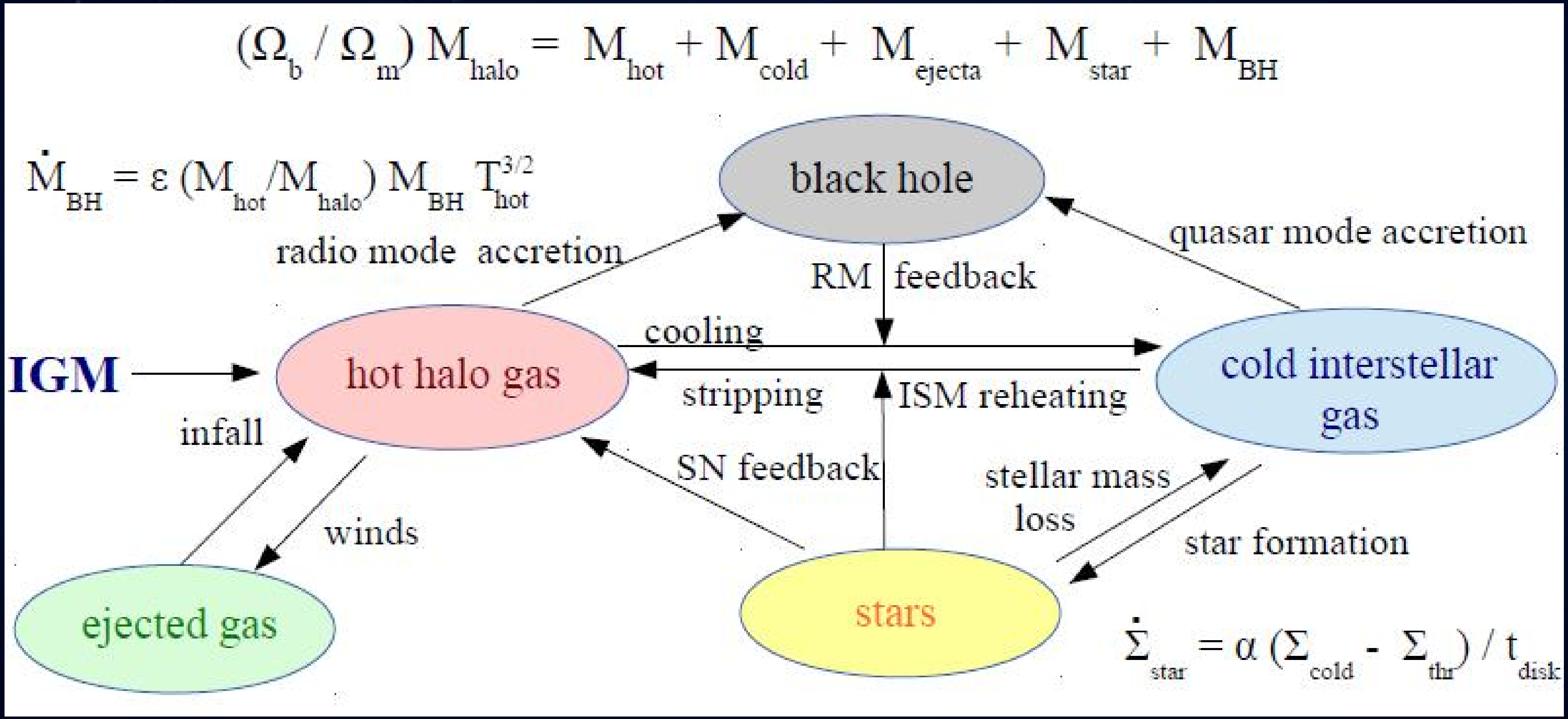
星系形成





- ✓ 引力势井由暗物质主导
- ✓ 不同重子物质之间的相互作用以及物质交换的物理非常复杂

星系形成

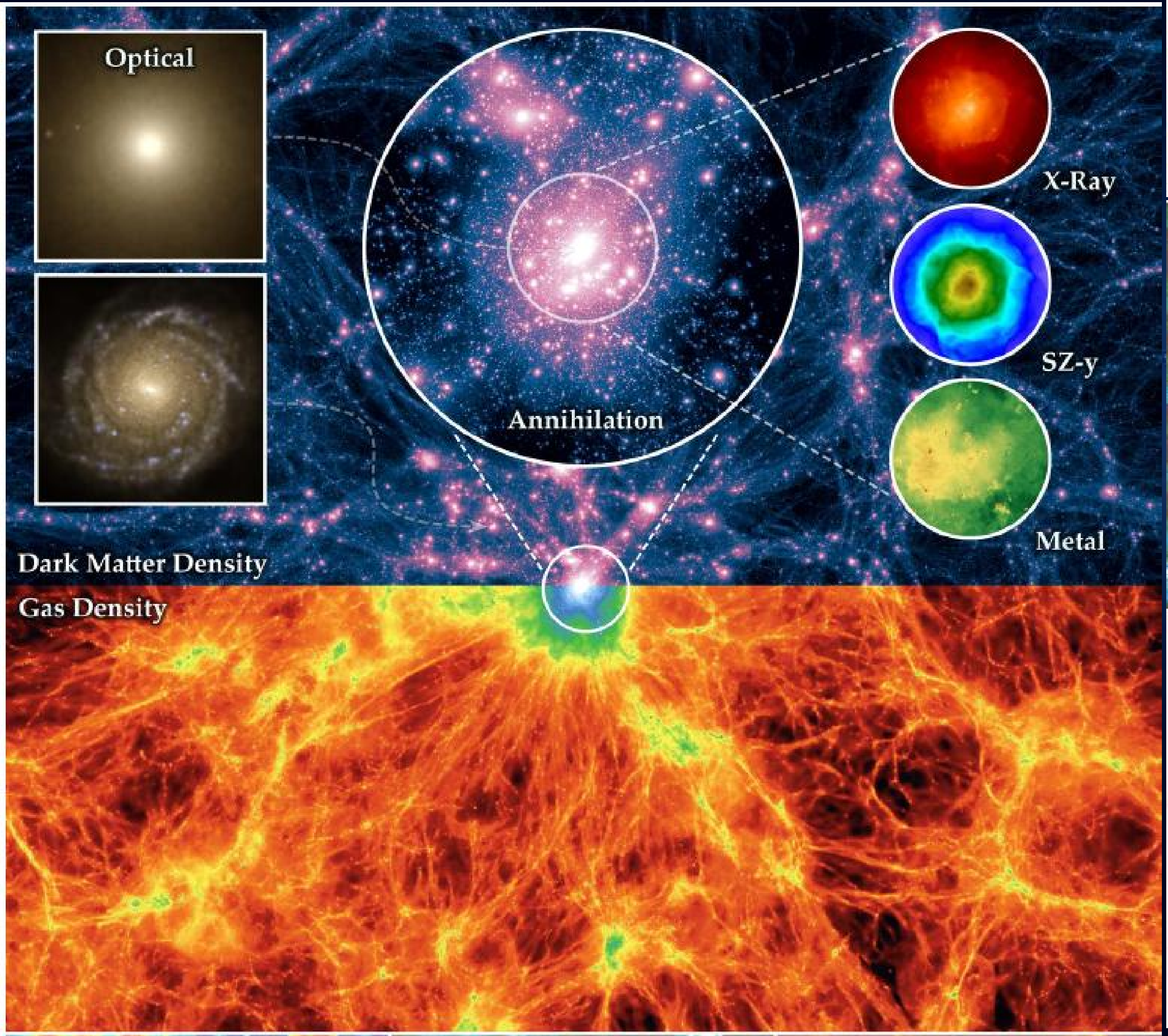

$(\Omega_b / \Omega_m) M_{halo} = M_{hot} + M_{cold} + M_{ejecta} + M_{star} + M_{BH}$
$\dot{M}_{BH} = \varepsilon (M_{hot}/M_{halo}) M_{BH} T_{hot}^{3/2}$
black hole
radio mode accretion
RM feedback
quasar mode accretion
IGM
hot halo gas
cooling
stripping
ISM reheating
cold interstellar gas
infall
SN feedback
stellar mass loss
winds
star formation
ejected gas
stars
$\dot{\Sigma}_{star} = \alpha (\Sigma_{cold} - \Sigma_{thr}) / t_{disk}$

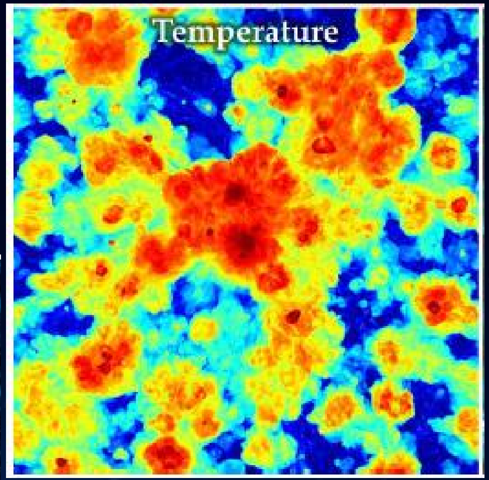
基本方程

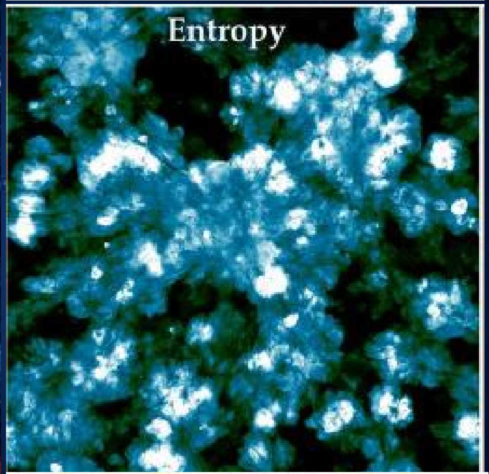
Euler equation:	$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi$$
Continuity equation:	$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\nabla\cdot\mathbf{v} = 0$$
First law of thermodynamics:	$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla\cdot\mathbf{v} - \frac{\Lambda(u,\rho)}{\rho}$$
Equation of state of ideal monoatomic gas:	$$P = (\gamma-1)\rho u\,, \qquad \gamma = 5/3$$

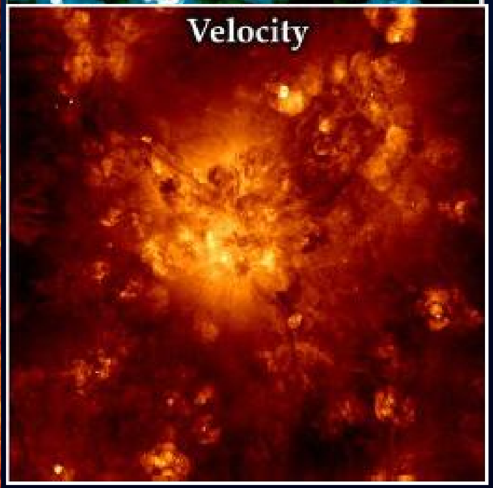
Properties of the most massive haloes

M_200≈2.3e14 solar mass

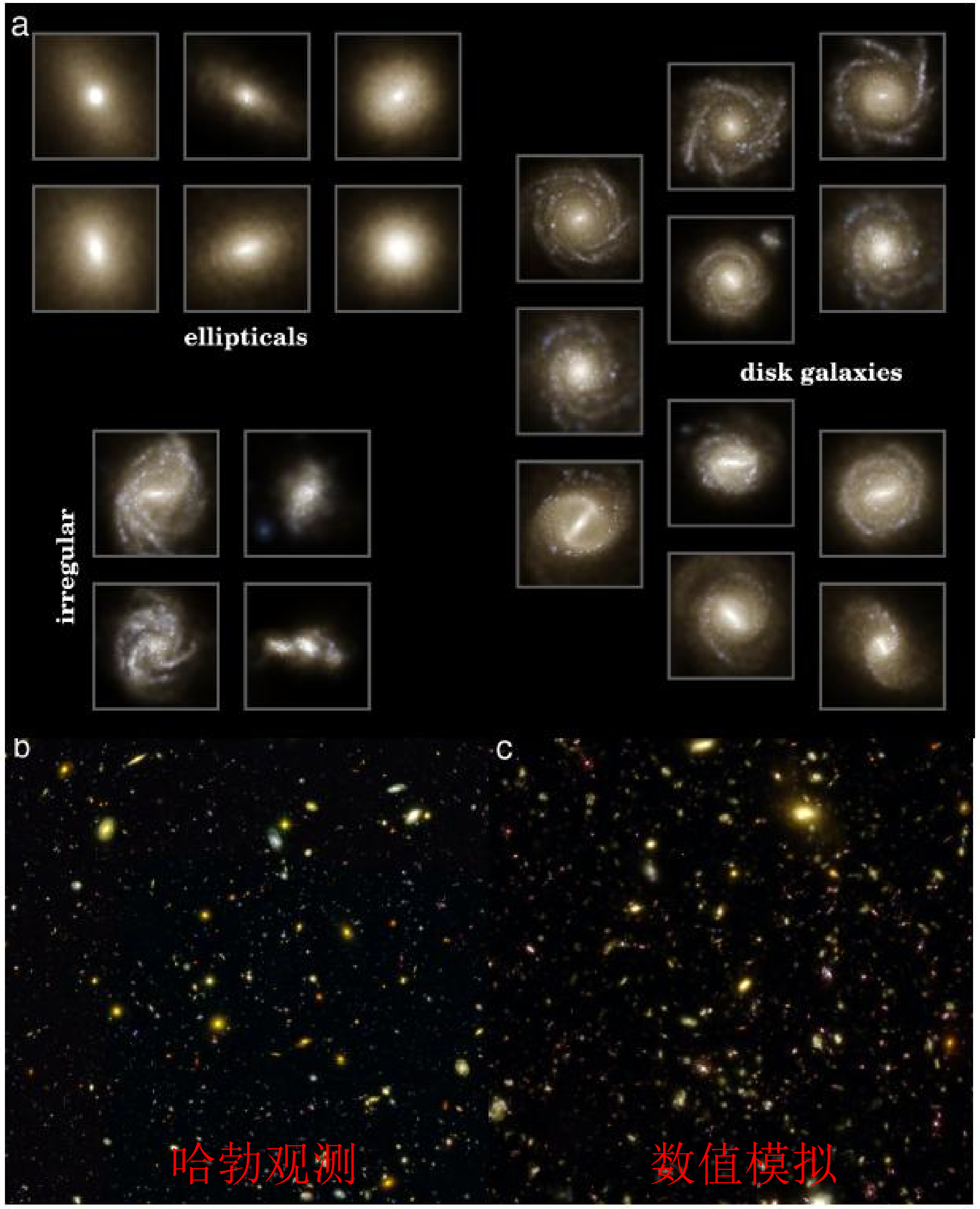


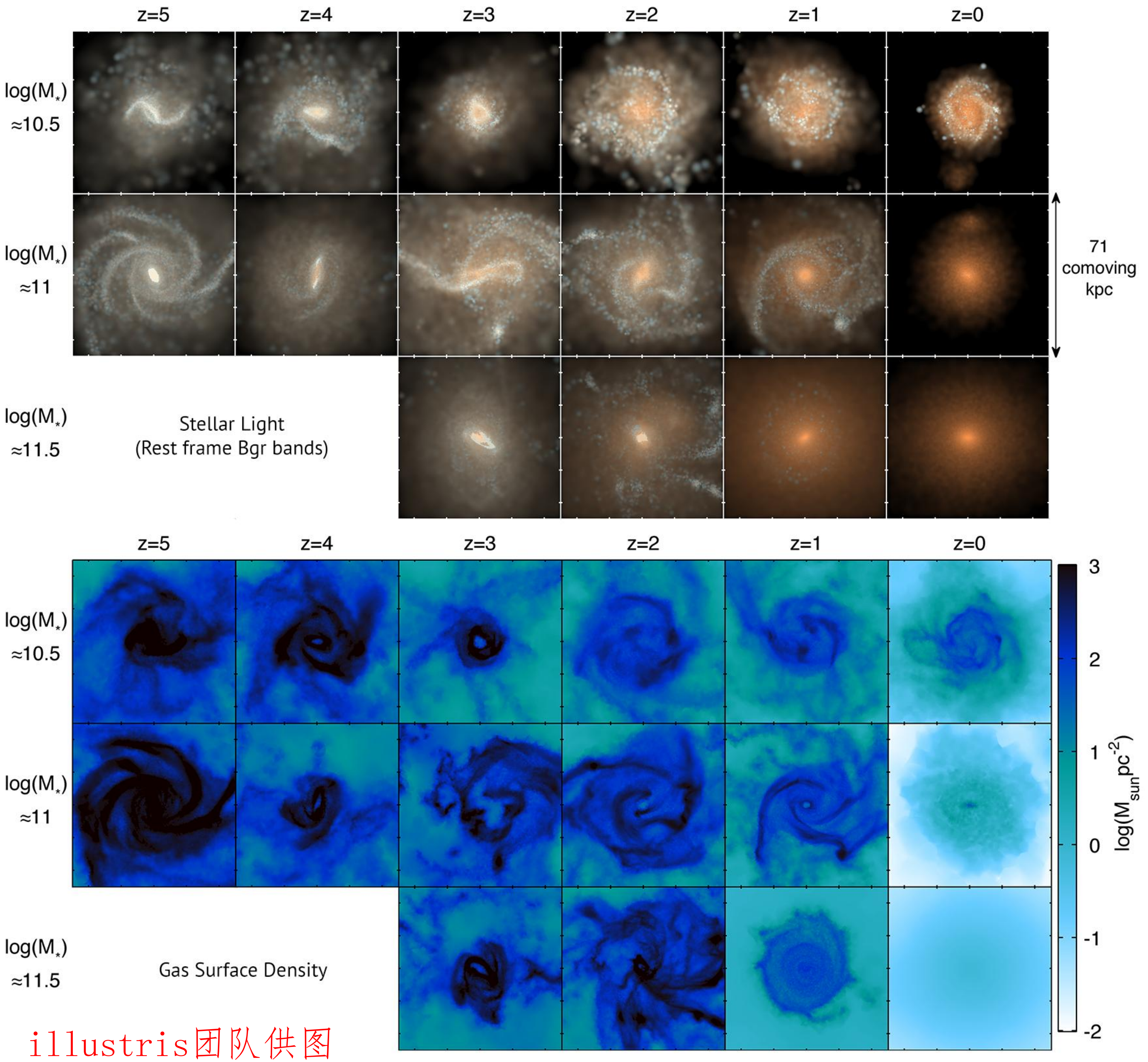






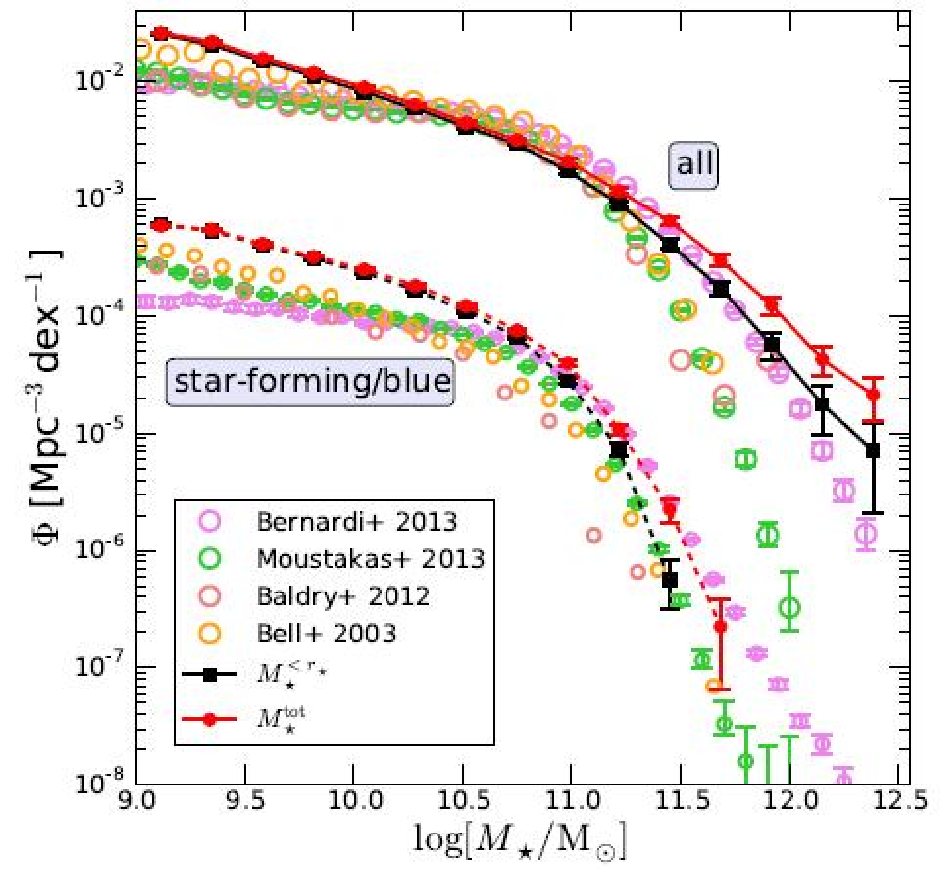
模拟星系形成与演化

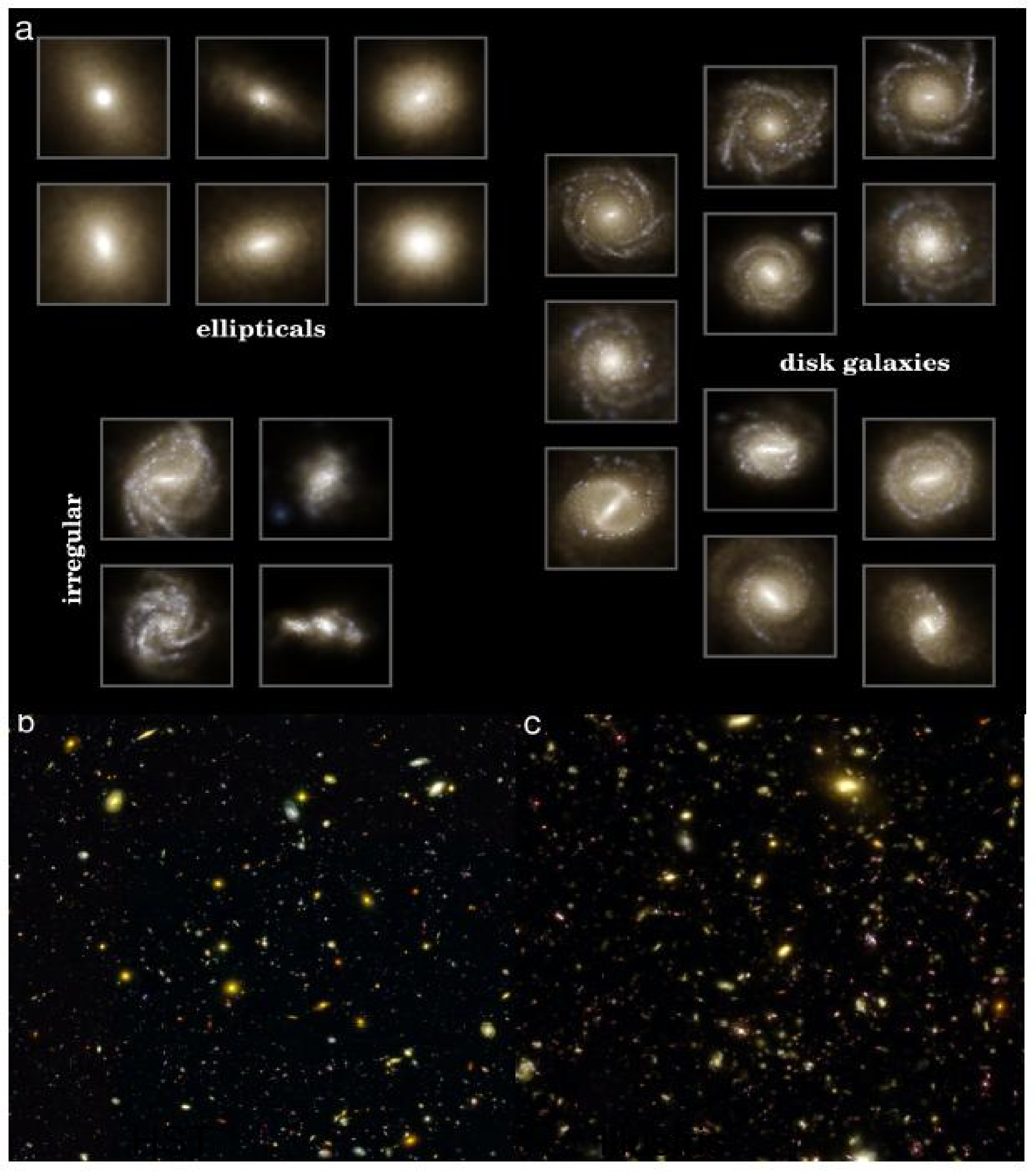




illustris团队供图

Simulated realistic galaxies

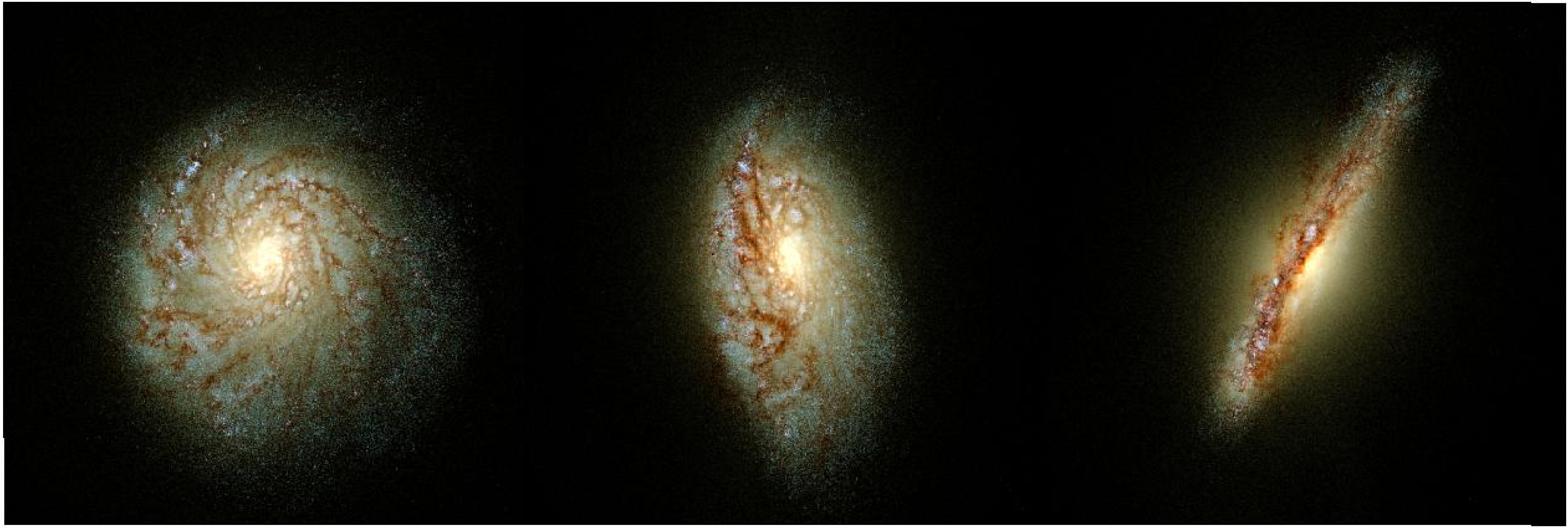


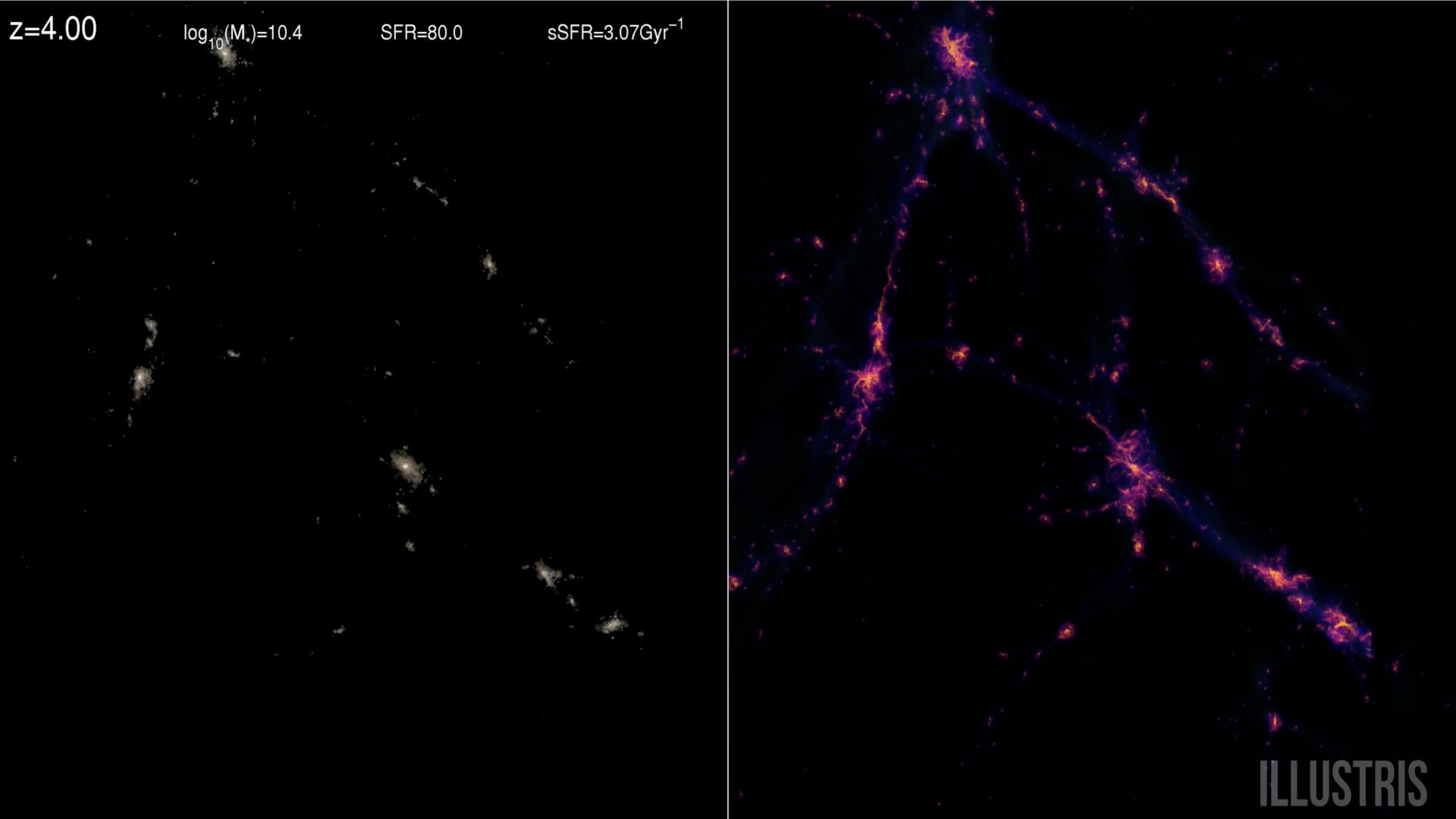


40000 well resolved galaxies

4000 Milky Way like galaxies

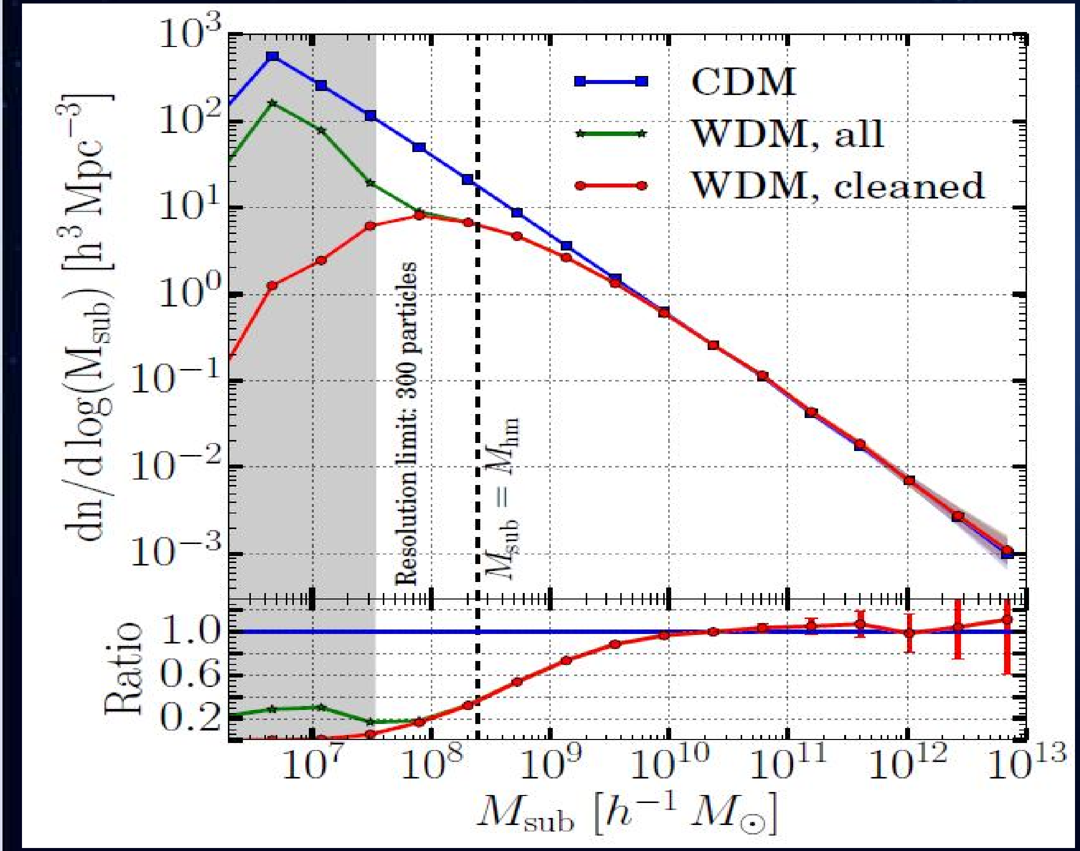
M200=10^(11.5~12.5)




z=4.00
log10(M*)=10.4
SFR=80.0
sSFR=3.07Gyr−1
ILLUSTRIS

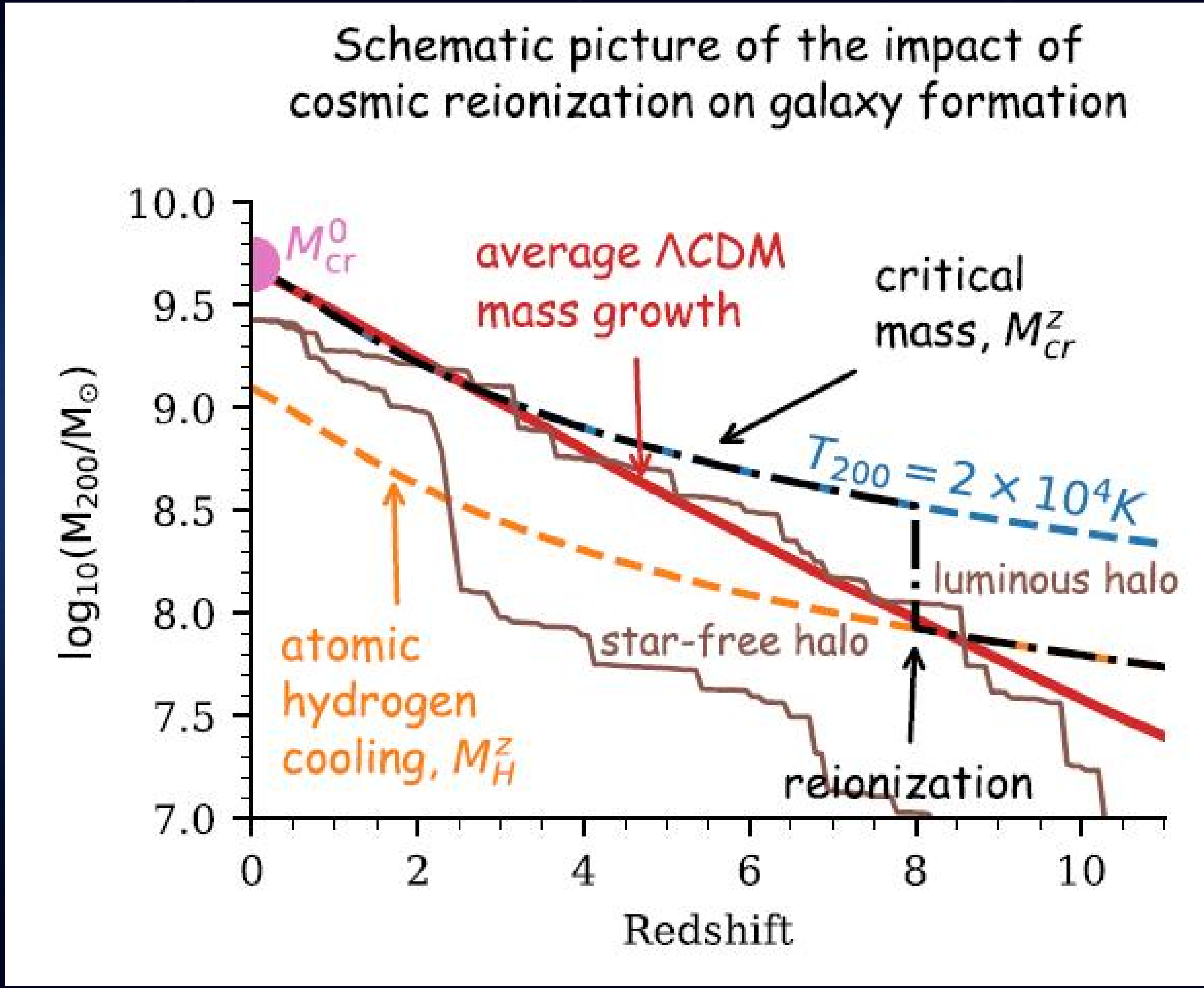
暗物质的属性：RELHICs

REionization-Limited HI Clouds

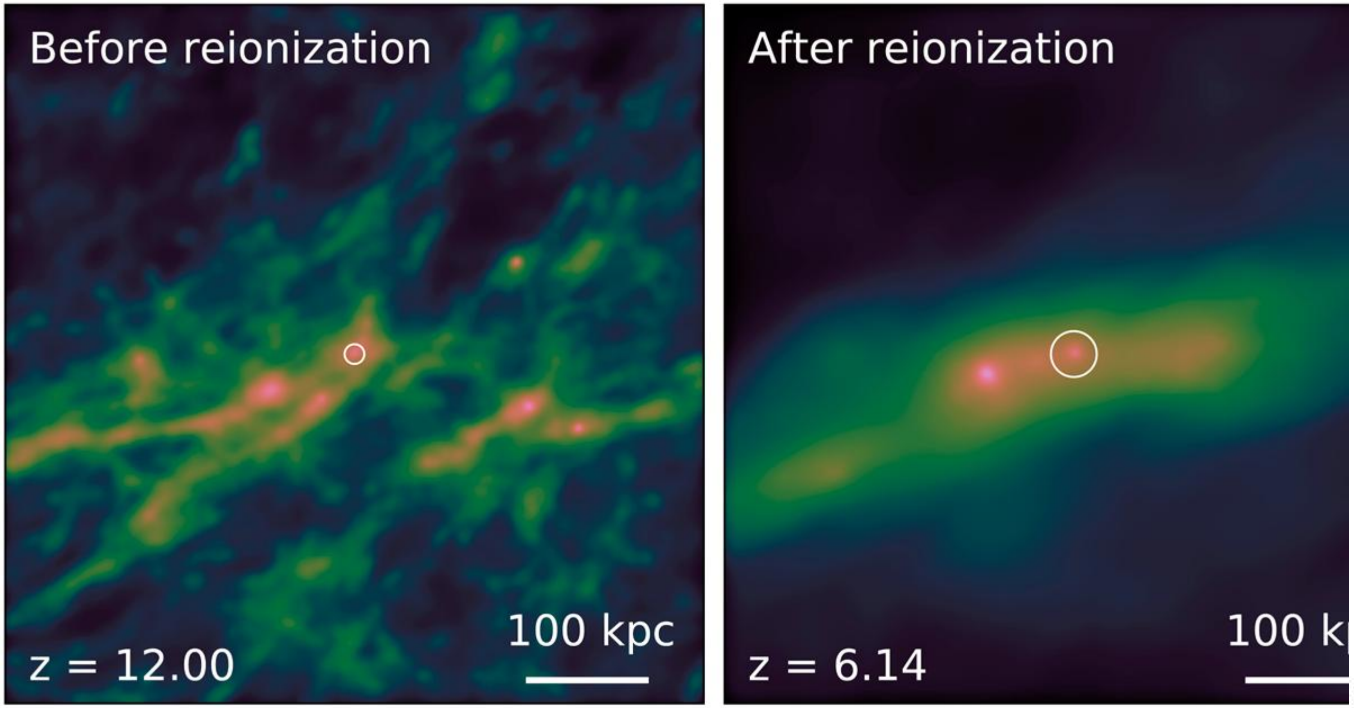


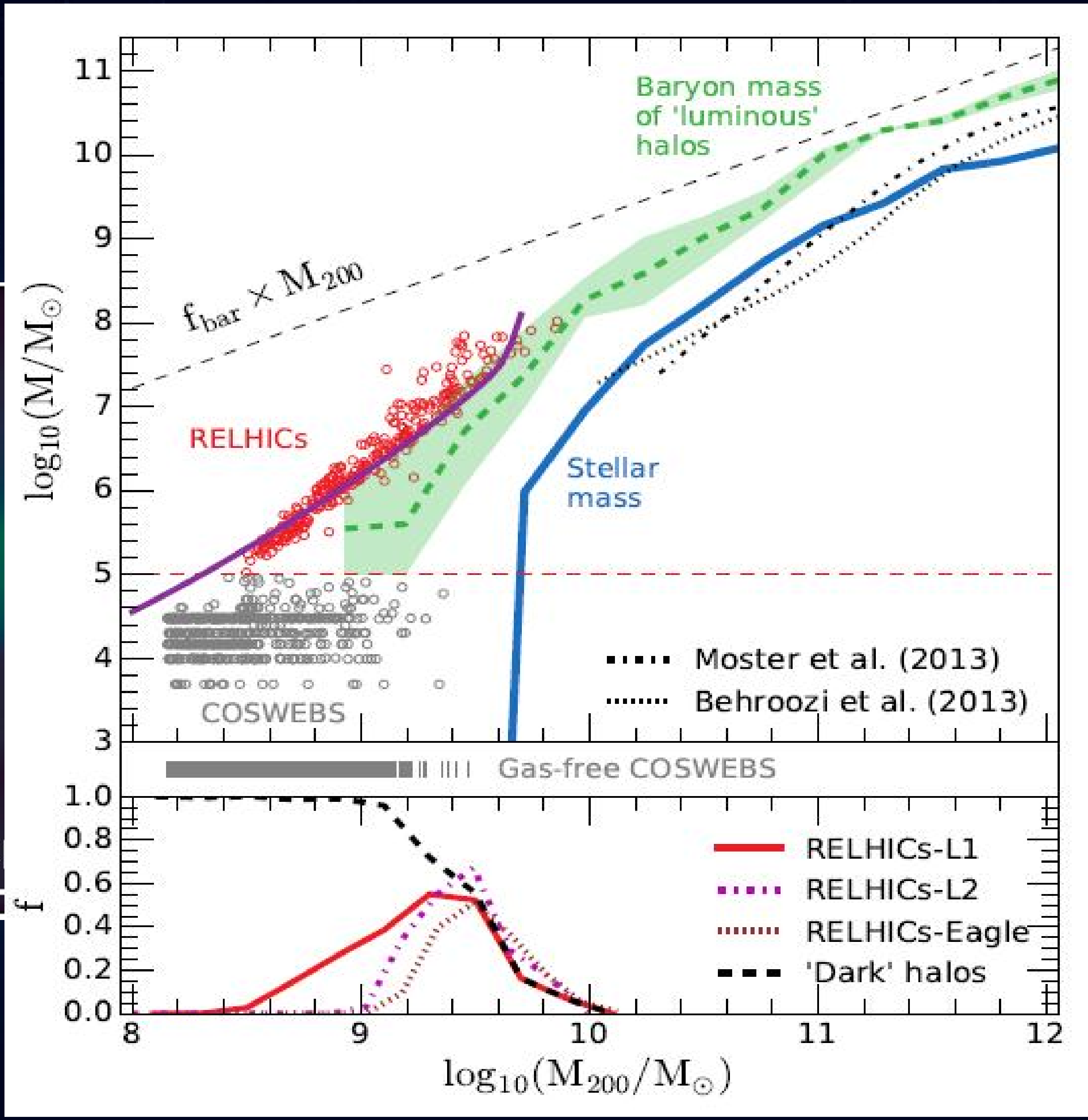
Subhaloes in CDM Vs. WDM

Lovell et al 2010



Benítez-Llambay et al 2020


Before reionization
100 kpc
z = 12.00
After reionization
100 k
z = 6.14


Baryon mass of 'luminous' halos
$f_{bar} \times M_{200}$
RELHICs
Stellar mass
COSWEBS
Moster et al. (2013)
Behroozi et al. (2013)
Gas-free COSWEBS
RELHICs-L1
RELHICs-L2
RELHICs-Eagle
'Dark' halos
$\log_{10}(M/M_{\odot})$
f
$\log_{10}(M_{200}/M_{\odot})$

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Letter to the Editor

A RELHIC Twin Candidate near the Galaxy M51

Qingze Chen[1,2★], Jie Wang[1,2,3★★], Yingjie Jing[1], Chen Xu[1,2], Tiantian Liang[4,5], Zerui Liu[1,2], Zhipeng Hou[1,2], Yiwei Xu[1,2], Cheng Cheng[1], and Wei Du[1]

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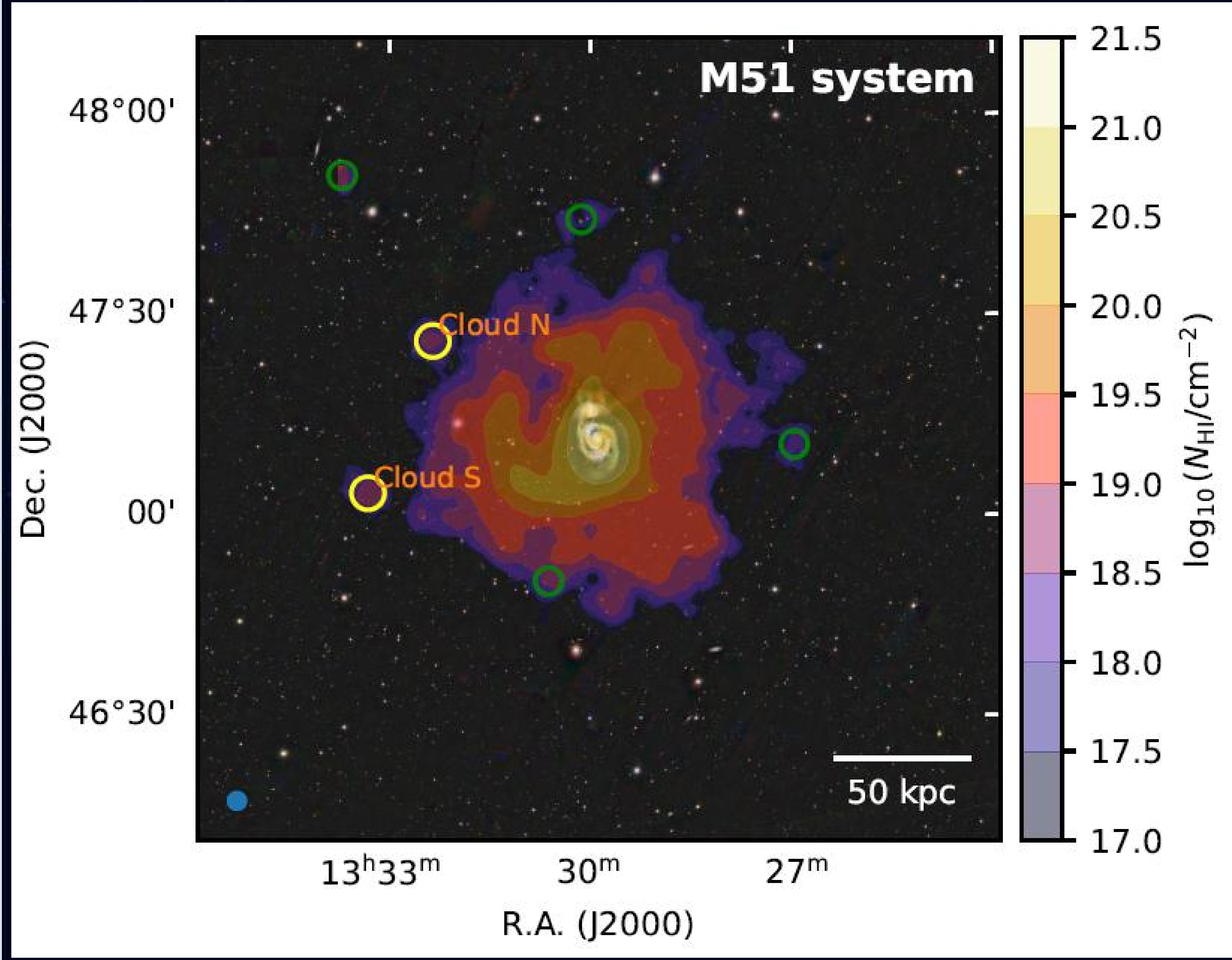
[4] Department of Mathematics and Physics, North China Electric Power University, Baoding 071003, China
[5] Hebei Key Laboratory of Physics and Energy Technology, North China Electric Power University, Baoding 071003, China

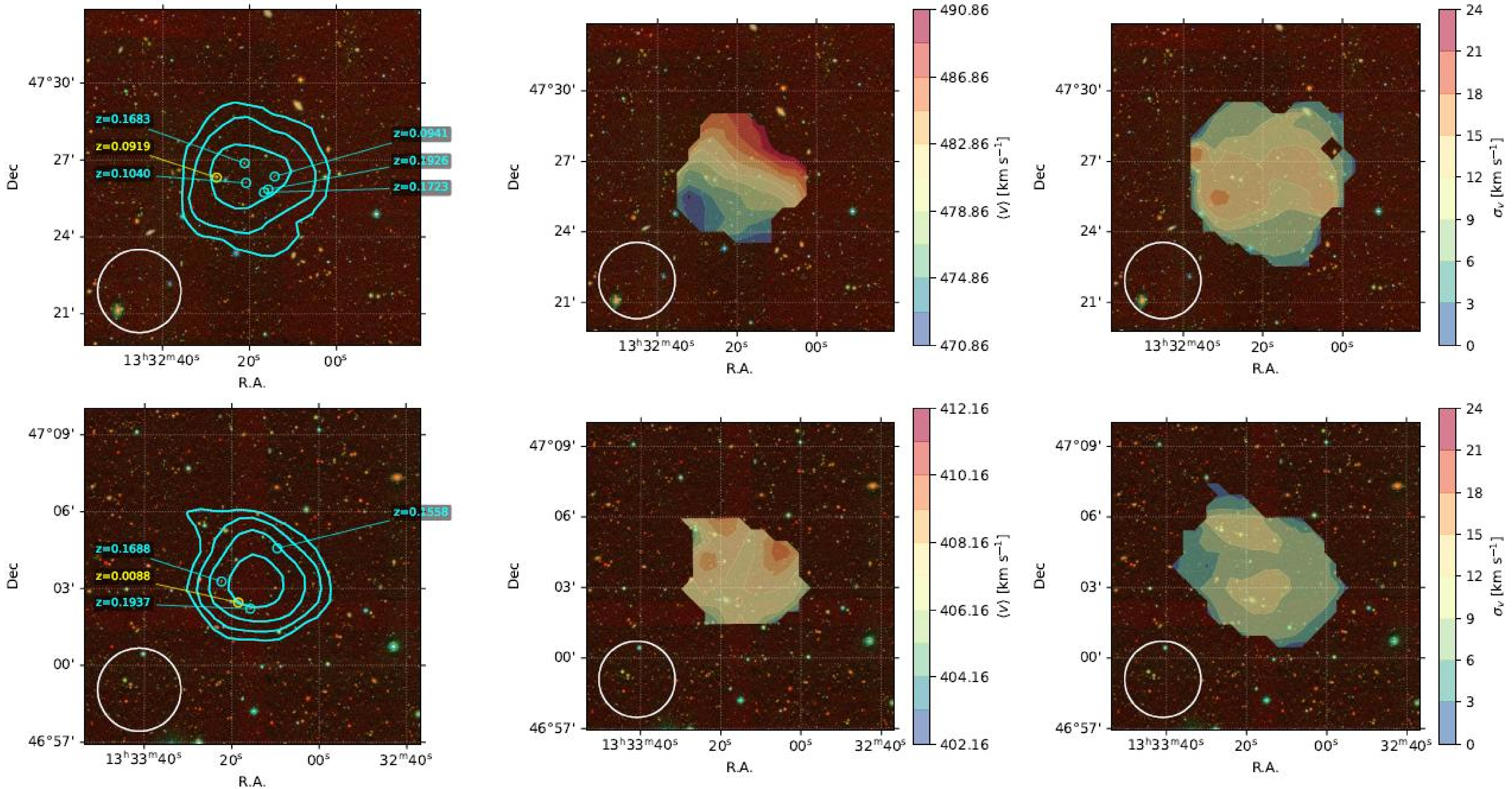


物理尺度： 1kpc

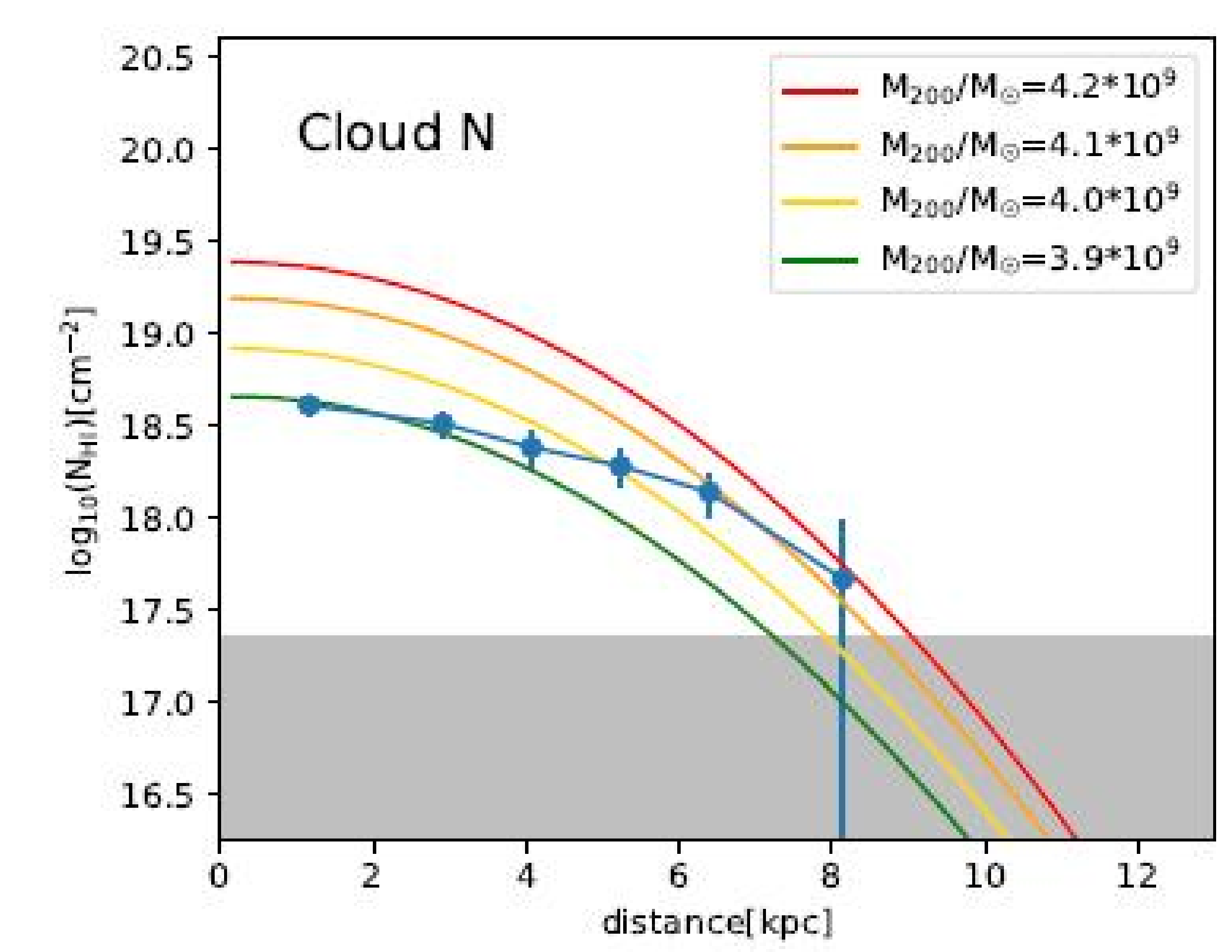
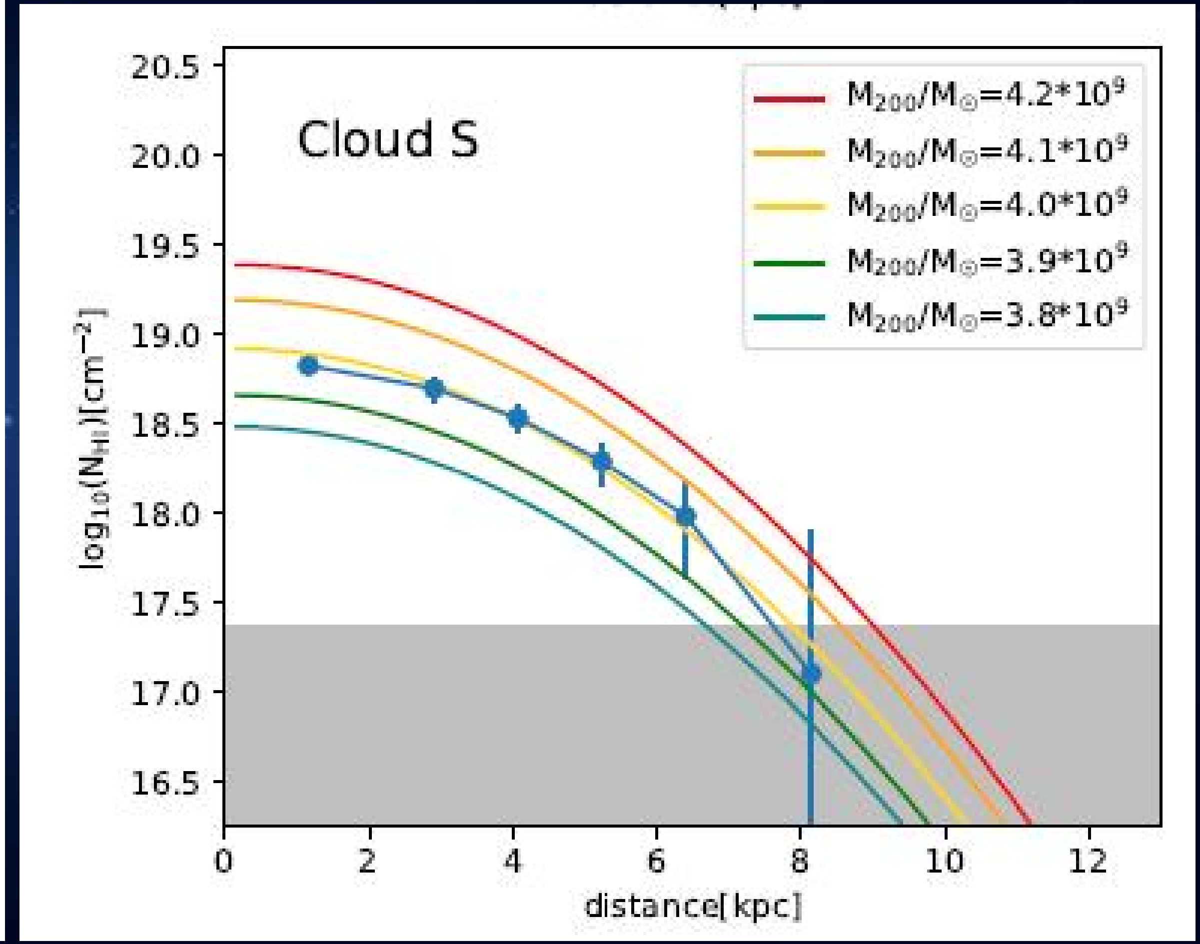
速度弥散： 20 km/s

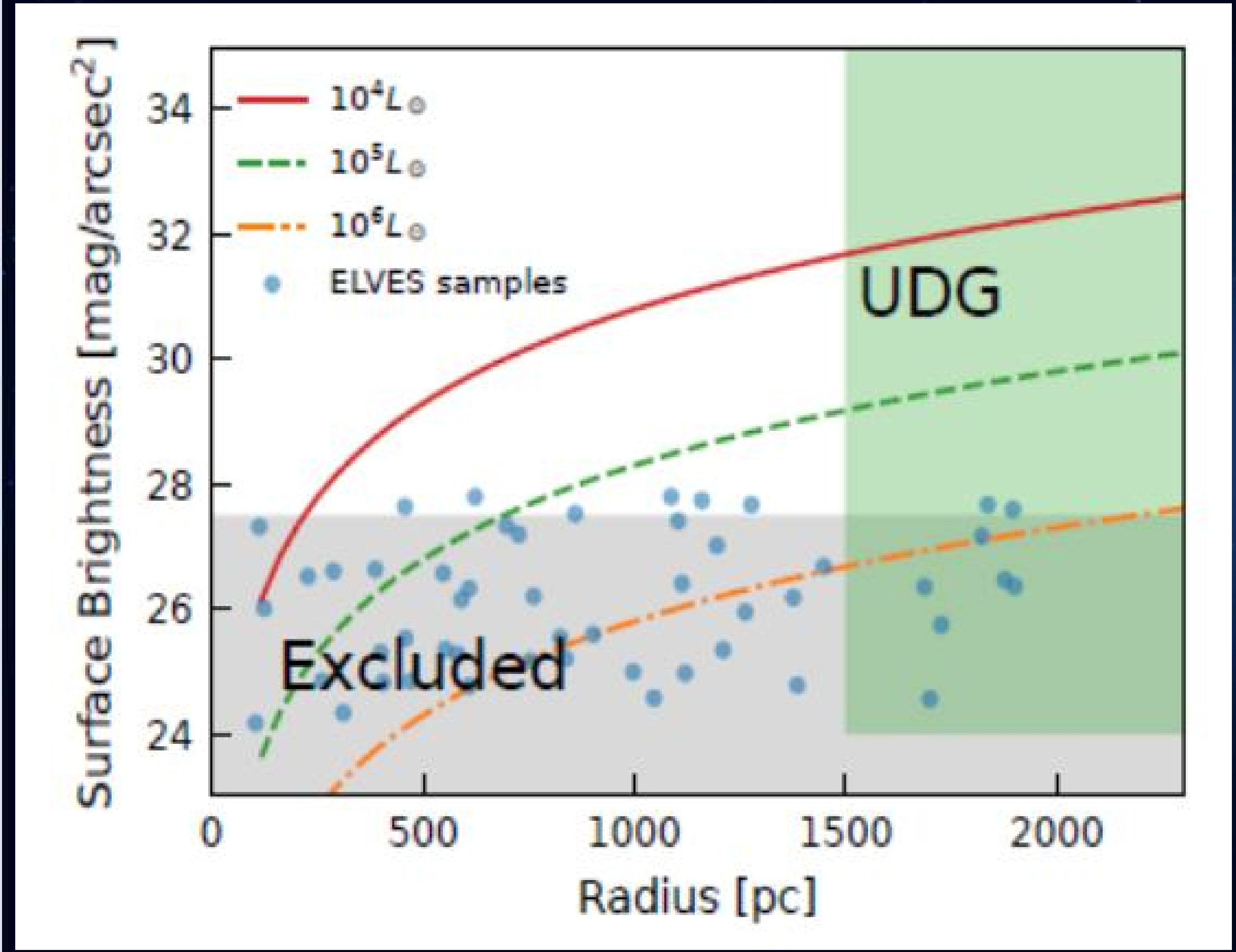
没有光学对应体

	Cloud S	Cloud N
R.A.	13h33m15.16s	13h32m19.22s
Dec.	47d03m29.2s	47d26m19.4s
$\log(M_{HI}/M_\odot)$	6.60	6.53
Barycentric velocity	407.2 km s^{-1}	486.2 km s^{-1}
W_{50}	21.63 km s^{-1}	29.33 km s^{-1}



z=0.1683
z=0.0919
z=0.1040
z=0.0941
z=0.1926
z=0.1723
47°30'
27'
24'
21'
Dec
13h32m40s
20s
00s
R.A.
490.86
486.86
482.86
478.86
474.86
470.86
⟨V⟩ [km s−1]
24
21
18
15
12
9
6
3
0
σv [km s−1]
z=0.1558
z=0.1688
z=0.0088
z=0.1937
47°09'
06'
03'
00'
46°57'
13h33m40s
32m40s
412.16
410.16
408.16
406.16
404.16
402.16


Cloud N
M200/M⊙=4.2*10^9
M200/M⊙=4.1*10^9
M200/M⊙=4.0*10^9
M200/M⊙=3.9*10^9
log10(NHI)[cm^-2]
distance[kpc]
20.5
20.0
19.5
19.0
18.5
18.0
17.5
17.0
16.5
0
2
4
6
8
10
12

Cloud S
M200/M⊙=4.2*10^9
M200/M⊙=4.1*10^9
M200/M⊙=4.0*10^9
M200/M⊙=3.9*10^9
M200/M⊙=3.8*10^9
log10(NHI)[cm^-2]
distance[kpc]
20.5
20.0
19.5
19.0
18.5
18.0
17.5
17.0
16.5
0
2
4
6
8
10
12

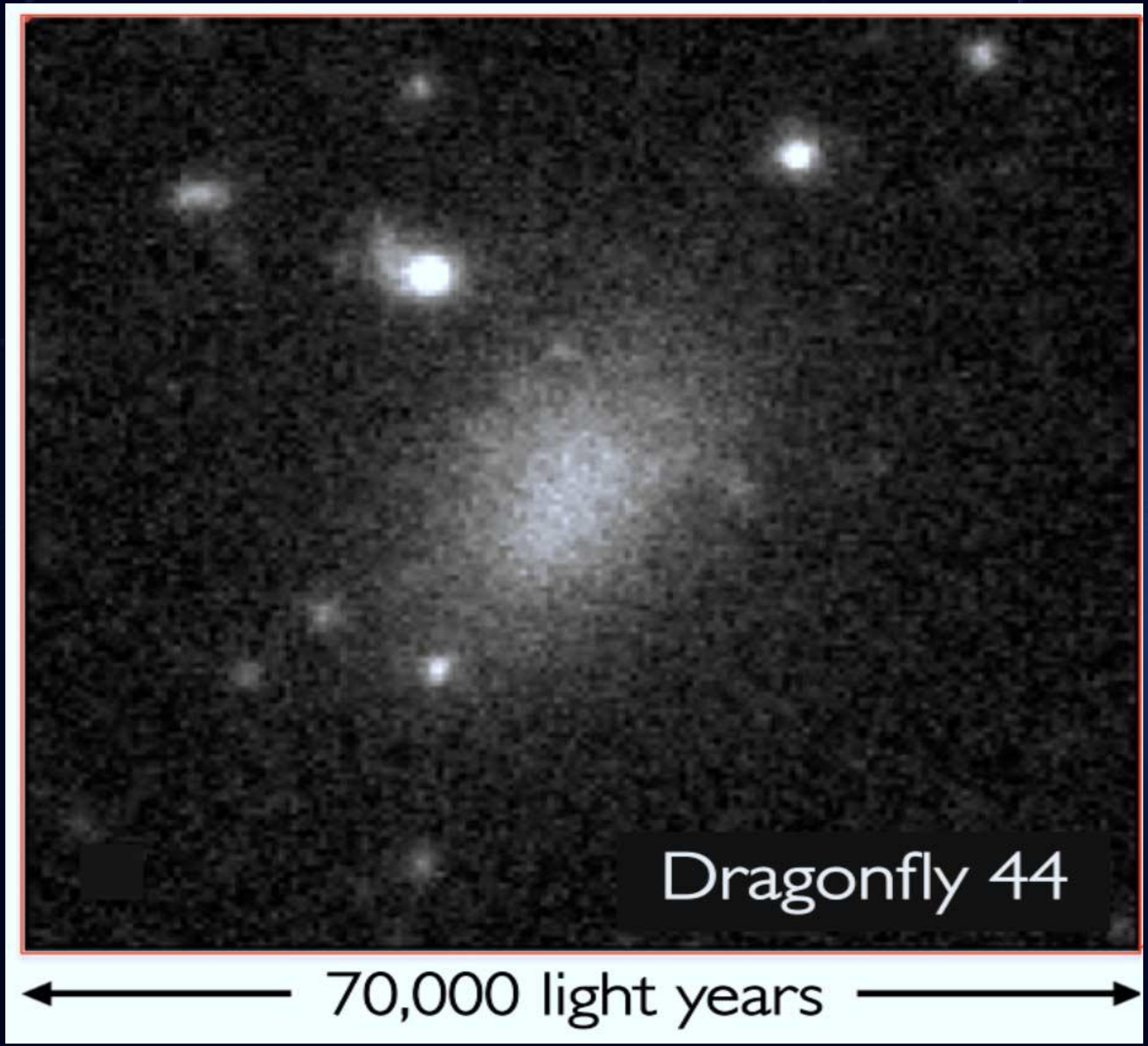


M_{HI} ~$10^{6.5}$ M_{sun}

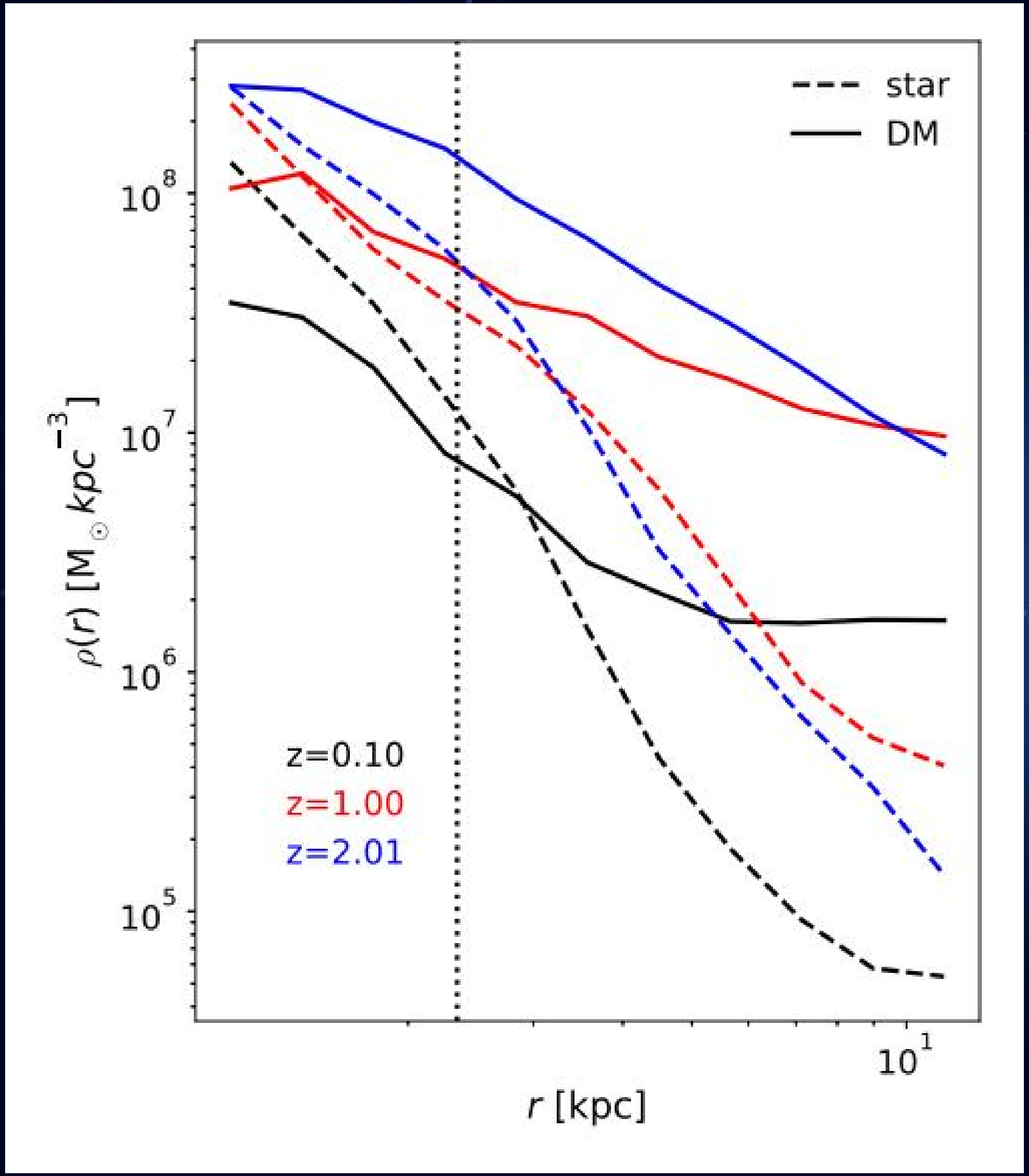
M_{star} < 10^5 M_{sun}

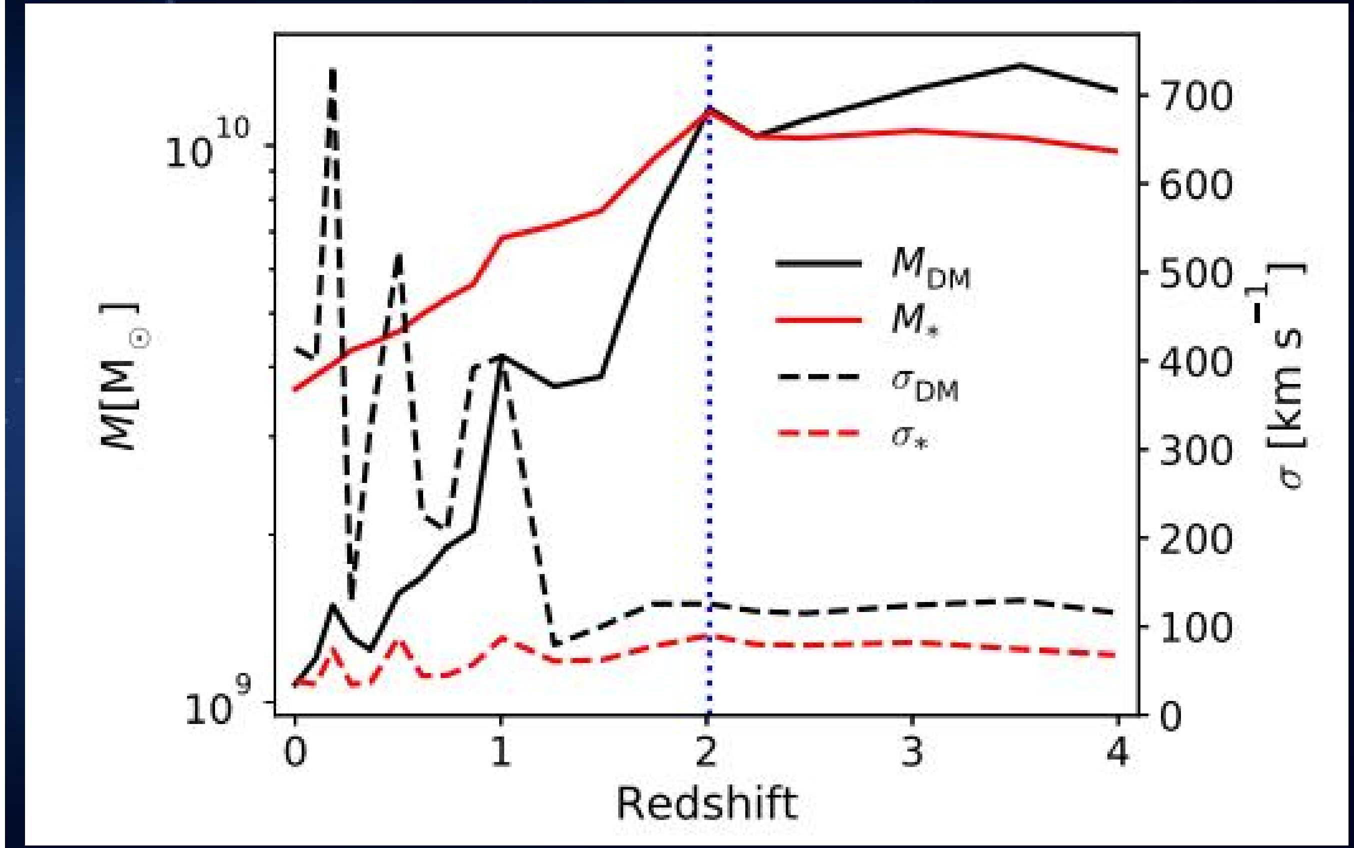
M_{DM} ~4×10^9 M_{sun}

超弥散星系（UDG）



暗物质缺失星系（DMDG）





Jing et al 2019

天体物理主要通过暗物质的引力效应精确测量其分布，从而限制其属性

天文观测数据 → 暗物质分布 → 结构形成理论

- 暗物质属性
- 宇宙学模型
- 星系形成模型

更好的探测手段

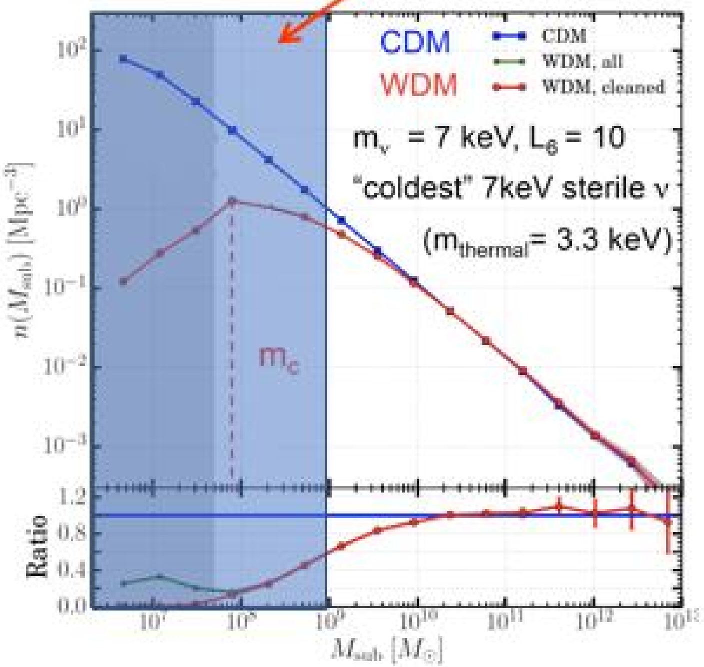
中性氢暗星系

星系强透镜

银河系星流

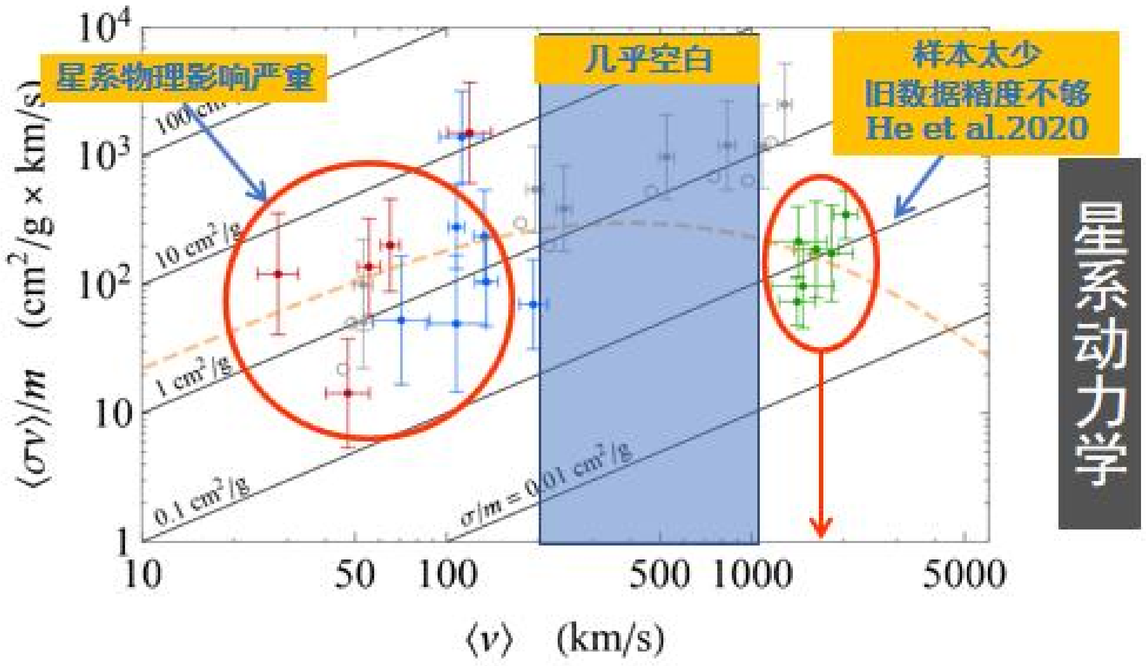
21cm森林

冷VS温：
找到一批低于$10^9 M_{sun}$的小暗晕



确认/排除keV质量的暗物质

自相互作用：
测量星系团/群暗晕有没有密度核



星系动力学

引力透镜

确认/排除暗物质粒子自相互作用
测量自相互作用的速度依赖

天文对于暗物质粒子碰撞截面的限制

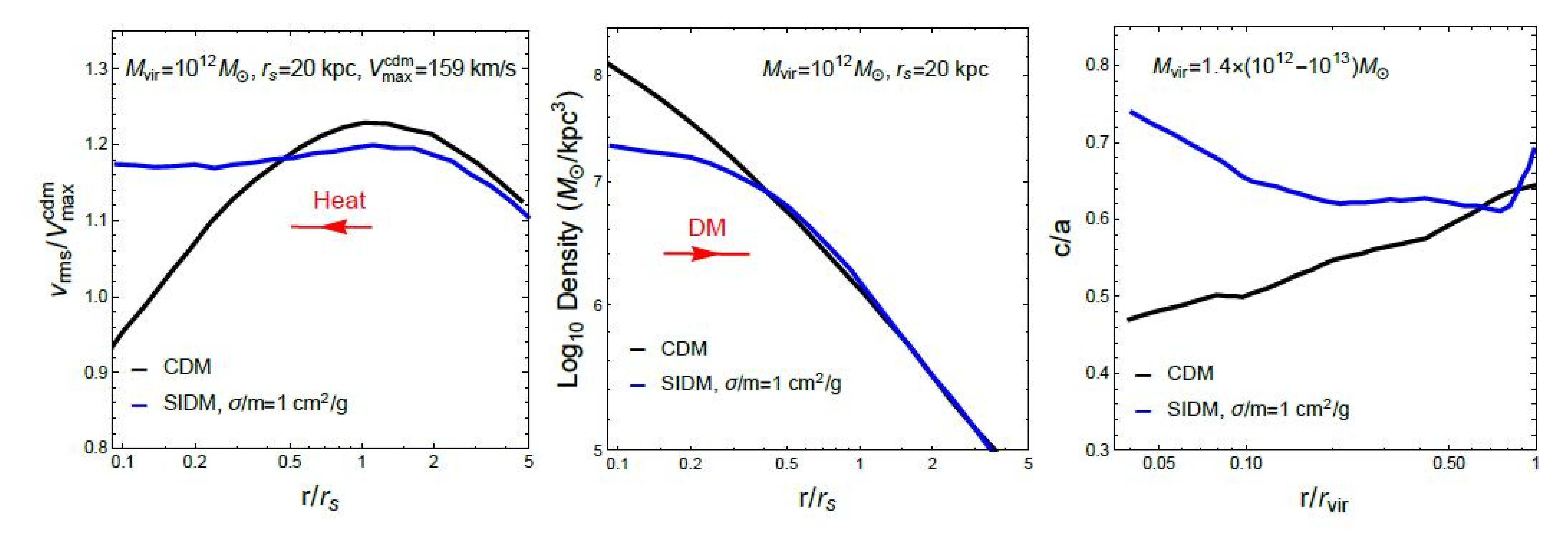
- 暗物质粒子如果有相互作用---湮灭

$$R_{\rm scat} = \sigma v_{\rm rel}\rho_{\rm dm}/m \approx 0.1\ {\rm Gyr}^{-1} \times \left(\frac{\rho_{\rm dm}}{0.1\ {\rm M}_\odot/{\rm pc}^3}\right)\left(\frac{v_{\rm rel}}{50\ {\rm km/s}}\right)\left(\frac{\sigma/m}{1\ {\rm cm}^2/{\rm g}}\right),$$

$$\sigma/m \sim (0.1 - 10)\,{\rm cm}^2{\rm g}^{-1}$$

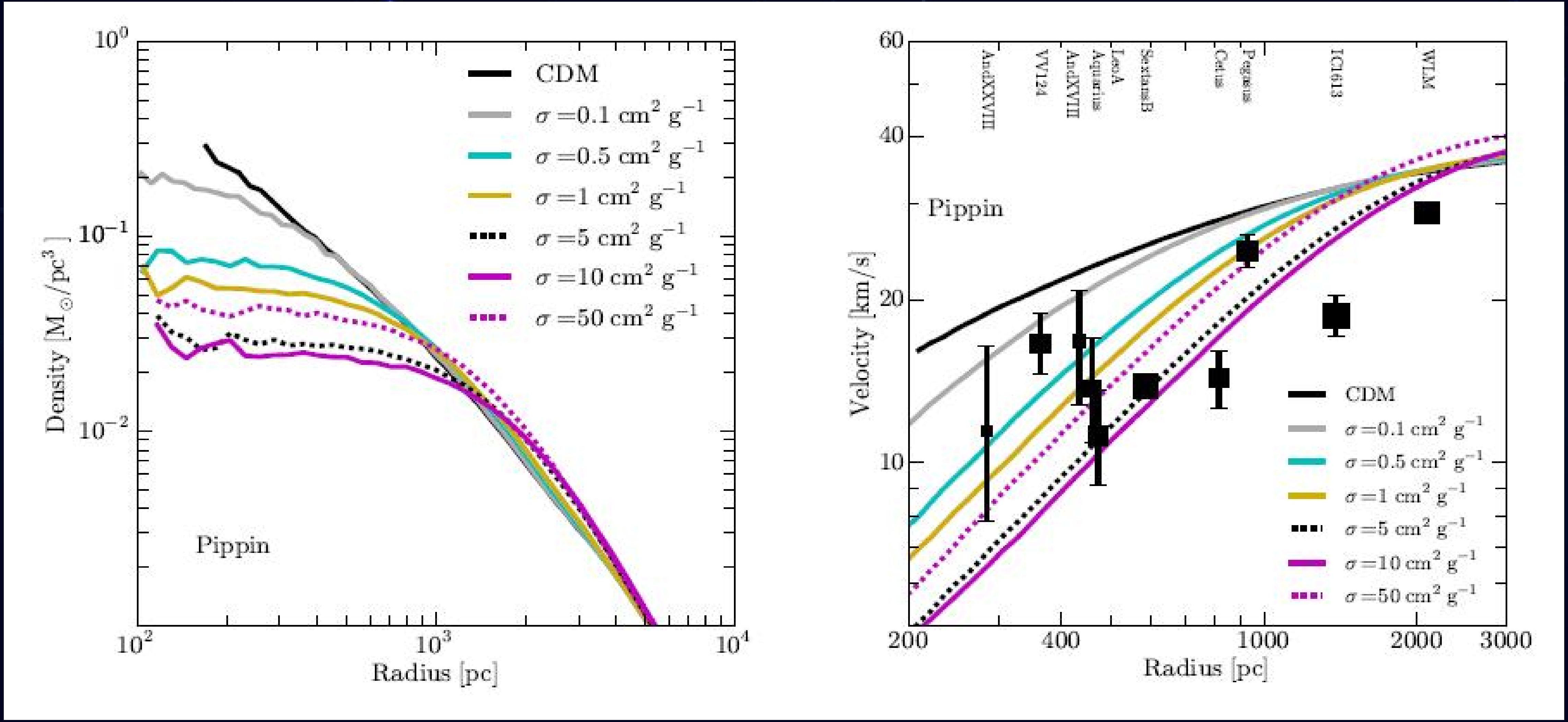
$$1\ {\rm cm}^2/{\rm g} \approx 2 \times 10^{-24}\ {\rm cm}^2/{\rm GeV}$$

暗物质粒子作用截面与暗物质晕内部结构

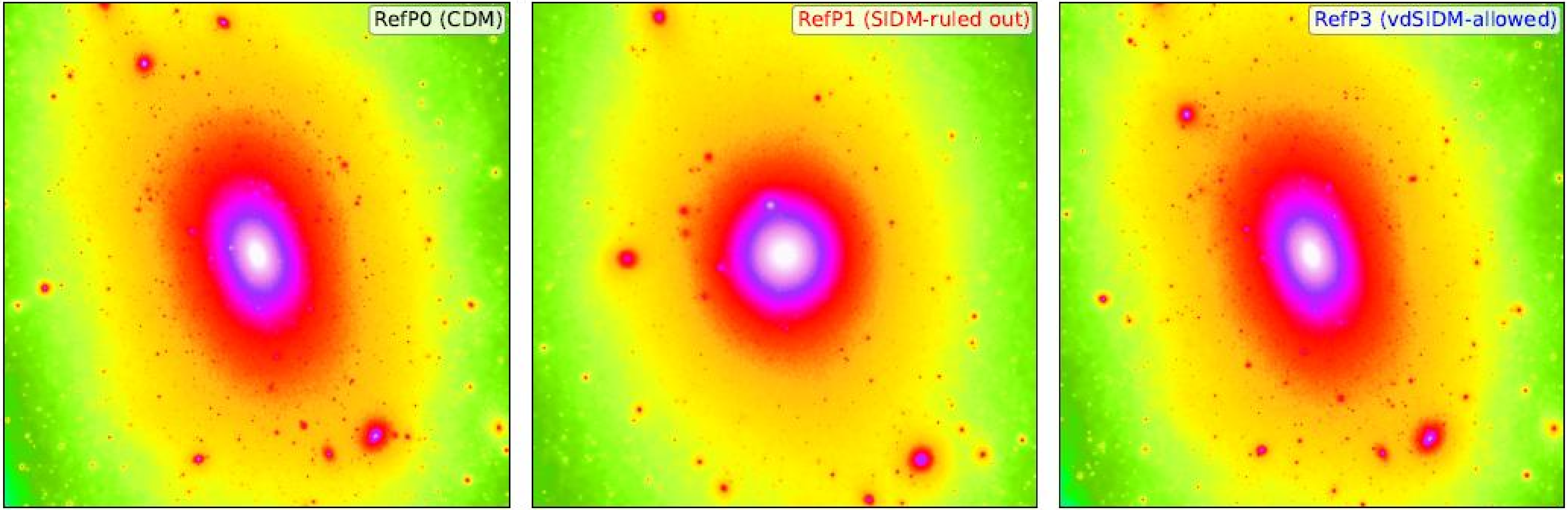


Tulin & Yu，2018

暗物质粒子作用截面与暗物质晕内部结构



Elbert, et al , 2015



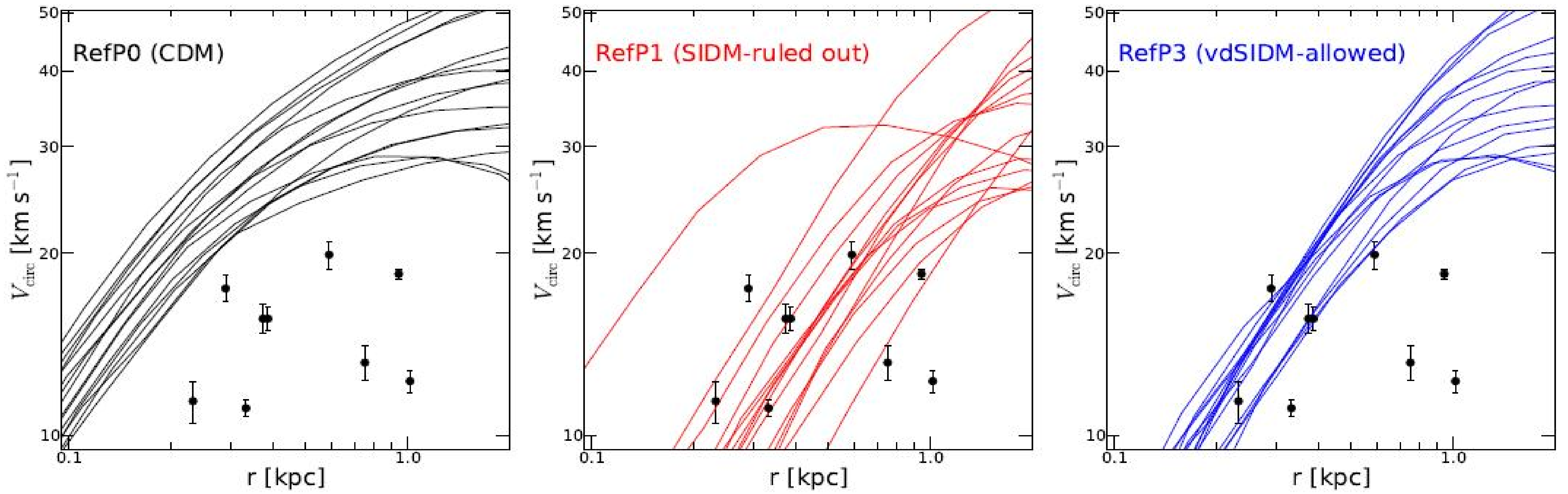
$\sigma/m = 10 \text{ cm}^2/\text{g}$

$\sigma/m = 35 \text{ cm}^2/\text{g}$ *at* $v = 10 \text{ km/s}$

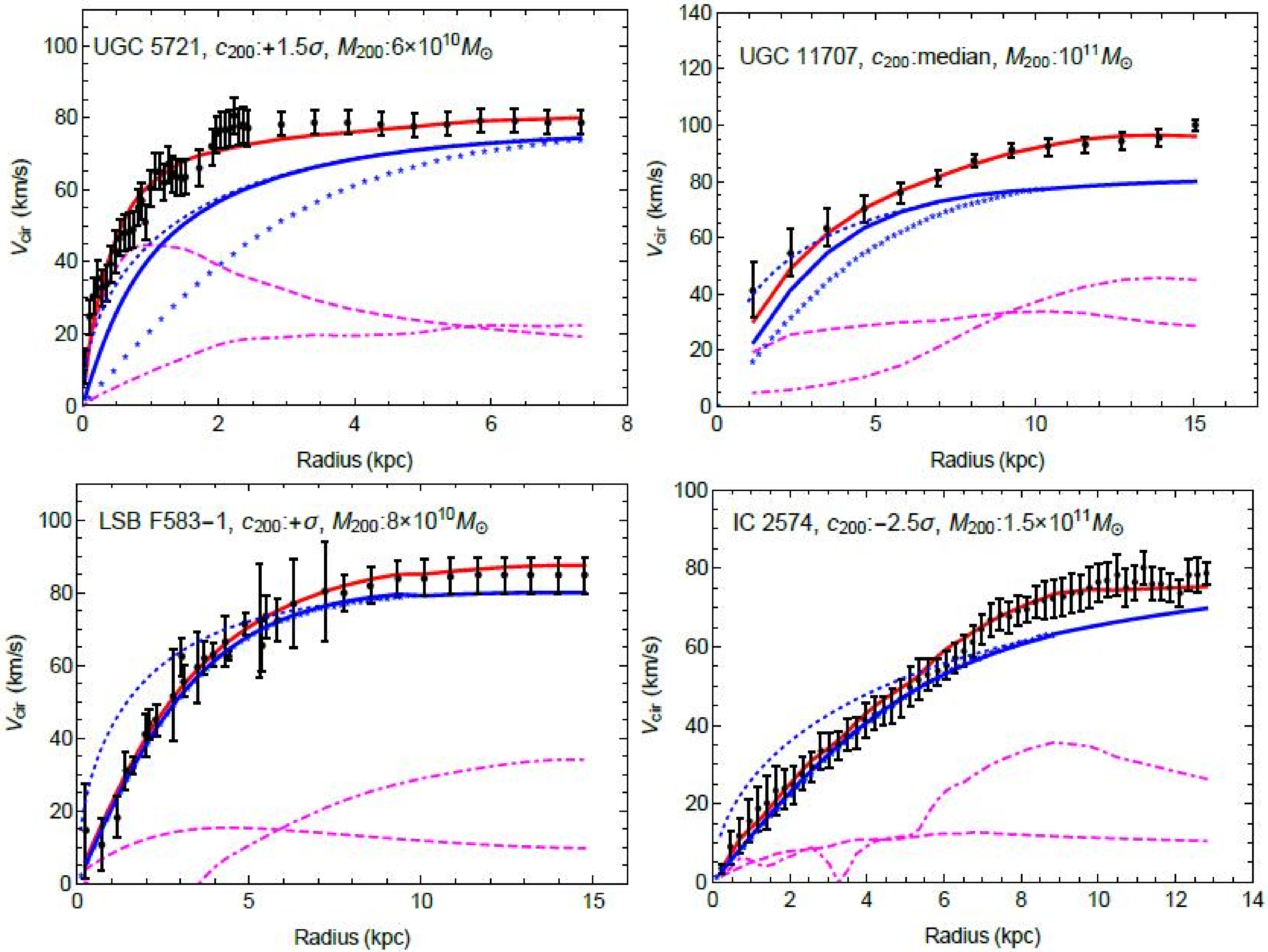
$\sigma/m \lesssim 10^{-2} \text{ cm}^2/\text{g}$ *for* $v \gtrsim 200 \text{ km/s}$

Vogelsberger et al, 2012

暗物质粒子作用截面与矮星系旋转曲线



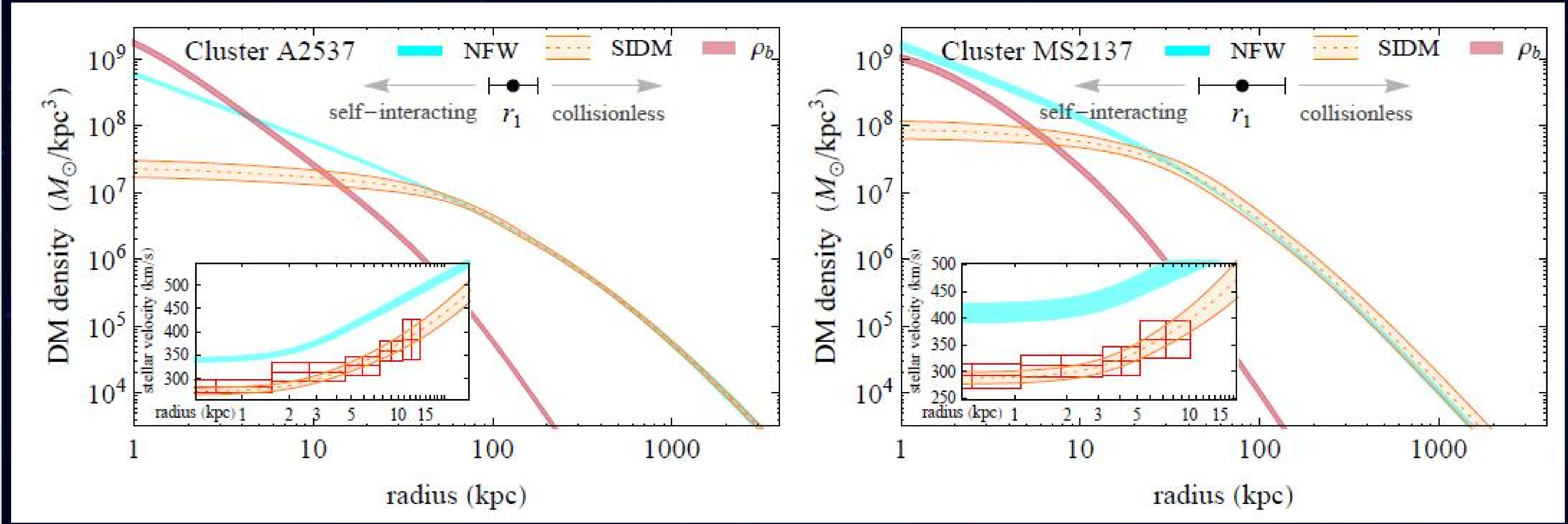
Vogelsberger et al, 2012



$$\sigma/m = 3\ \mathrm{cm}^2/\mathrm{g},$$

Kamada et al 2016

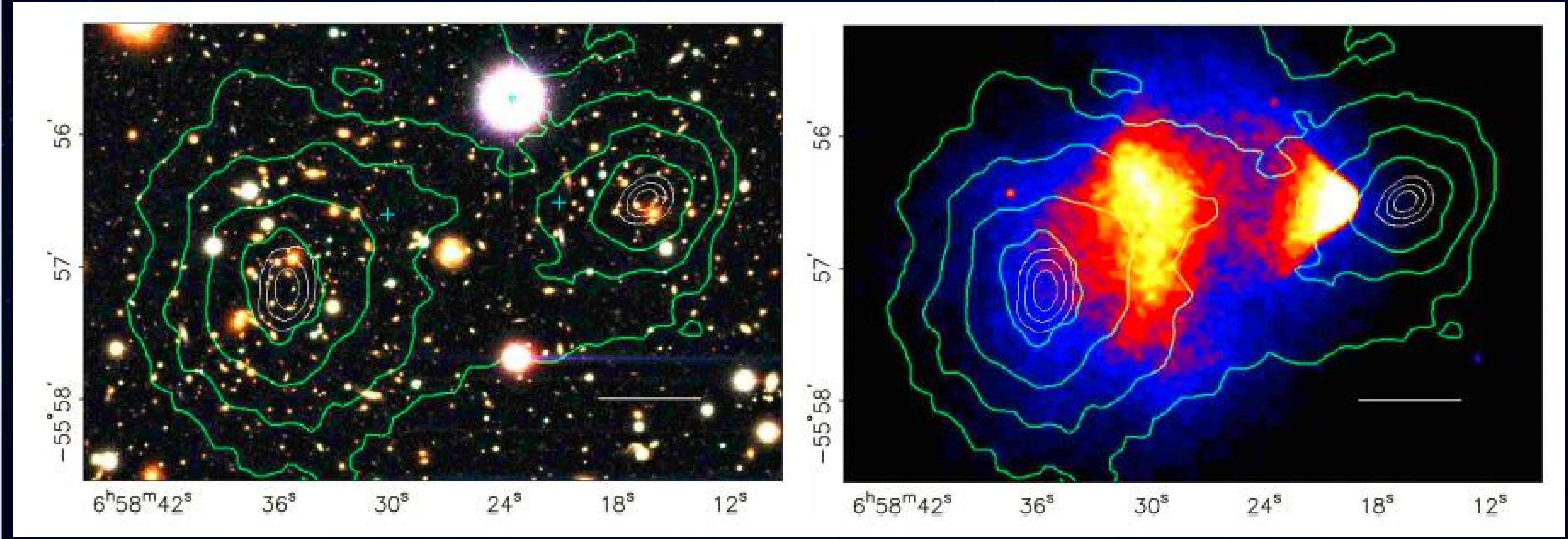
暗物质粒子作用截面与矮星系旋转曲线



$$\sigma/m \approx 0.1\ \mathrm{cm}^2/\mathrm{g}.$$

Kaplinghat et al, 2016

暗物质粒子作用截面与暗晕的并合



Clowe et al. 2006

Cluster	σ/m	Method used	Ref.
Bullet Cluster (1E 0657-558)	$< 3\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.3\ \mathrm{cm^2/g}$)	[298]
	$< 0.7\ \mathrm{cm^2/g}$	Mass loss $< 23\%$	[106]
	$< 1.25\ \mathrm{cm^2/g}$	DM-galaxy offset 25 ± 29 kpc	[106]
Abell 520	$3.8 \pm 1.1\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.07\ \mathrm{cm^2/g}$)	[326]
	$0.94 \pm 0.06\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.14\ \mathrm{cm^2/g}$)	[128]
Abell 2744	$< 1.28\ \mathrm{cm^2/g}$	Offset	[340]
	$< 3\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.3\ \mathrm{cm^2/g}$)	[329]
Musket Ball Cluster (DLSCL J0916.2+2951)	$< 7\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.15\ \mathrm{cm^2/g}$)	[316]
Baby Bullet (MACS J0025.4-1222)	$< 4\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.25\ \mathrm{cm^2/g}$)	[318]
Abell 3827	$\sim 1.5\ \mathrm{cm^2/g}$	Offset	[127]

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Positive observations	σ/m	$v_{\rm rel}$	Observation	Refs.
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1\ \mathrm{cm^2/g}$	$30 - 200\ \mathrm{km/s}$	Rotation curves	[102, 116]
Too-big-to-fail problem				
Milky Way	$\gtrsim 0.6\ \mathrm{cm^2/g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[110]
Local Group	$\gtrsim 0.5\ \mathrm{cm^2/g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[111]
Cores in clusters	$\sim 0.1\ \mathrm{cm^2/g}$	$1500\ \mathrm{km/s}$	Stellar dispersion, lensing	[116, 126]
Abell 3827 subhalo merger	$\sim 1.5\ \mathrm{cm^2/g}$	$1500\ \mathrm{km/s}$	DM-galaxy offset	[127]
Abell 520 cluster merger	$\sim 1\ \mathrm{cm^2/g}$	$2000 - 3000\ \mathrm{km/s}$	DM-galaxy offset	[128, 129, 130]
Constraints				
Halo shapes/ellipticity	$\lesssim 1\ \mathrm{cm^2/g}$	$1300\ \mathrm{km/s}$	Cluster lensing surveys	[95]
Substructure mergers	$\lesssim 2\ \mathrm{cm^2/g}$	$\sim 500 - 4000\ \mathrm{km/s}$	DM-galaxy offset	[115, 131]
Merging clusters	$\lesssim$ few $\mathrm{cm^2/g}$	$2000 - 4000\ \mathrm{km/s}$	Post-merger halo survival (Scattering depth $\tau < 1$)	Table II
Bullet Cluster	$\lesssim 0.7\ \mathrm{cm^2/g}$	$4000\ \mathrm{km/s}$	Mass-to-light ratio	[106]

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谢谢！