

天文观测对暗物质 粒子属性的限制

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浙江-千岛湖

第二届地下和空间粒子物理与宇宙物理前沿问题研讨会

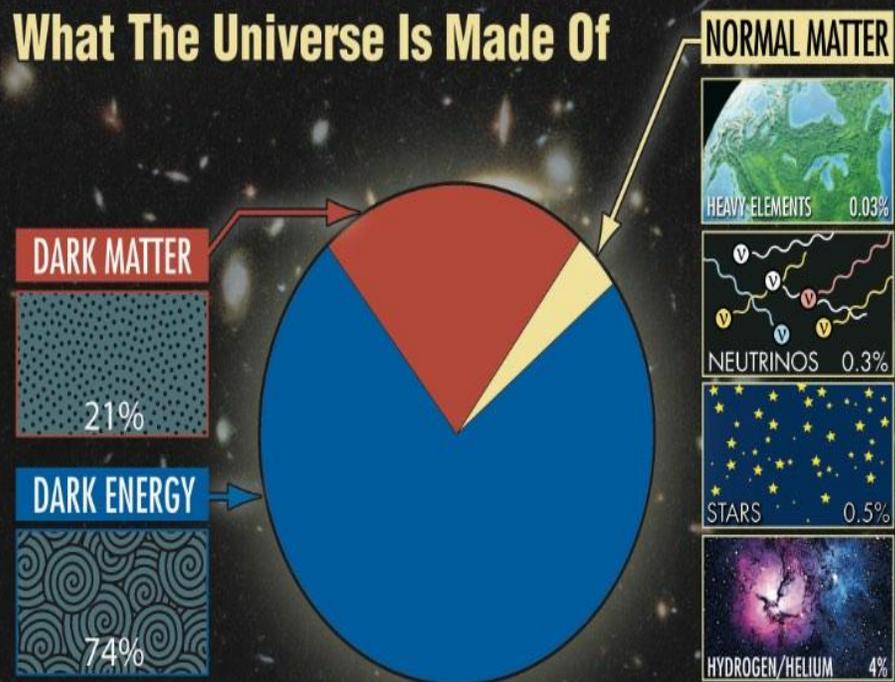
2023.5.7-12

纲要

- 暗物质: 粒子物理与天文的桥梁
- 天文对于暗物质粒子质量的限制
- 天文对于暗物质粒子碰撞截面的限制
- 天文对太阳系暗物质密度的限制

宇宙中的暗物质

What The Universe Is Made Of



All Other Atoms 0.01%
H and He 0.5%

Visible Matter 0.5%

Invisible Atoms 4%

Cold Dark Matter 25%

Dark Energy 70%

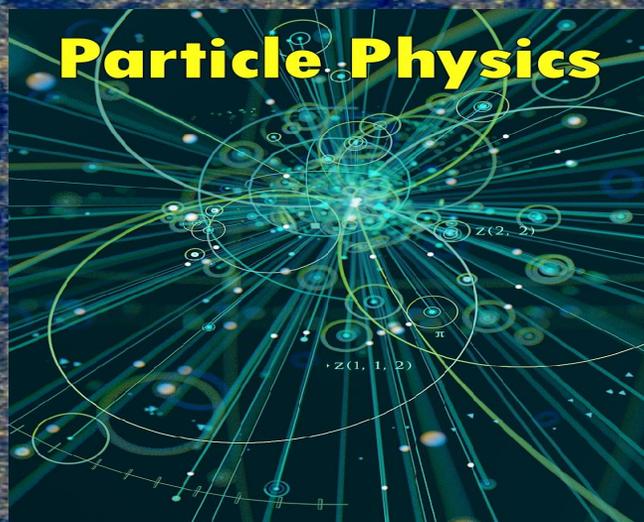
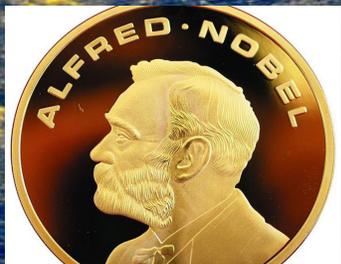
Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

Matter and Energy Content of the Universe

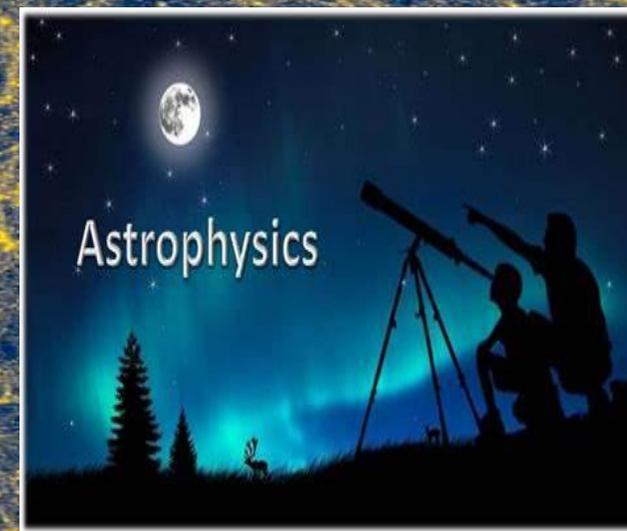
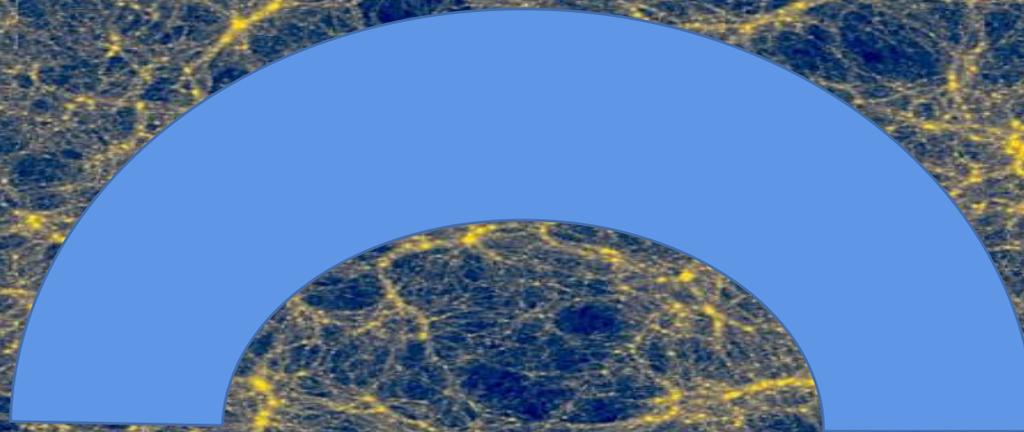
暗物质只有引力作用

我们主要通过0.5%的可观测物质探求黑暗的世界！

暗物质是粒子物理和天文的一个主要桥梁



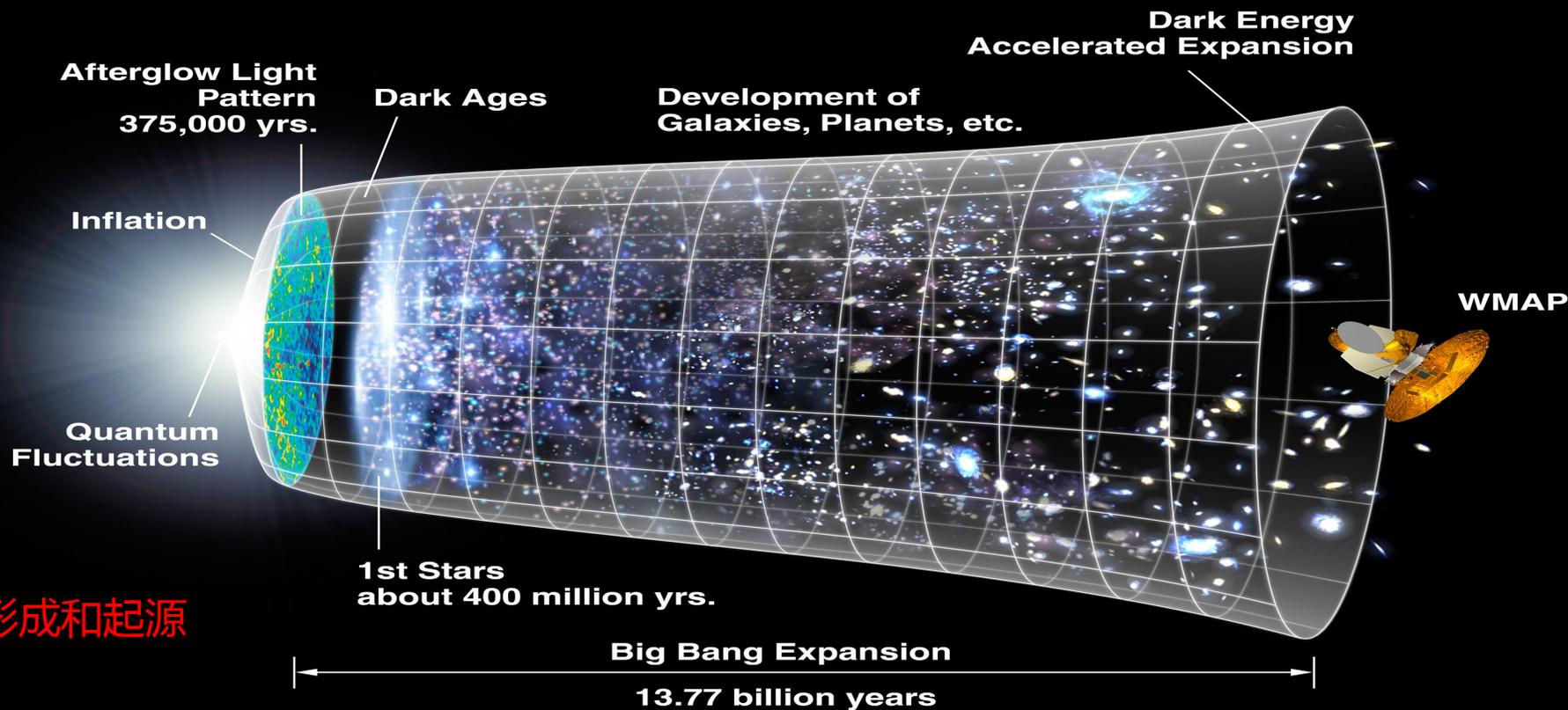
探索物理本质
微观



唯象描述引力效应
宏观

暗物质：粒子物理 Vs 天体物理

2 暗物质粒子对宇宙结构形成的影响

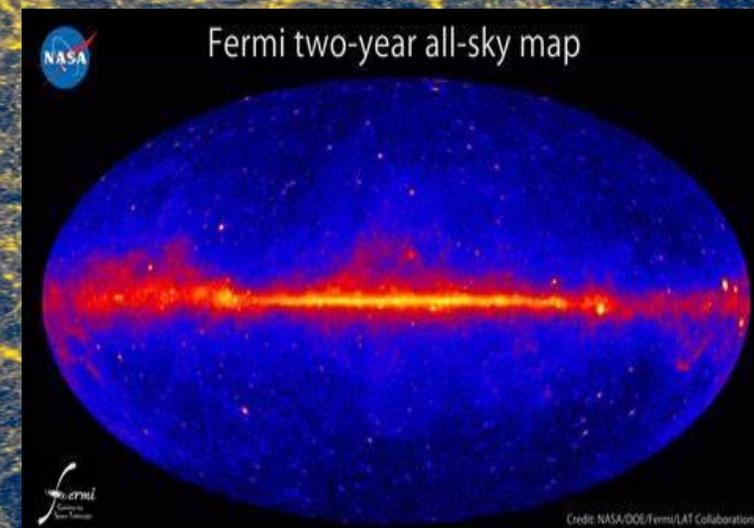
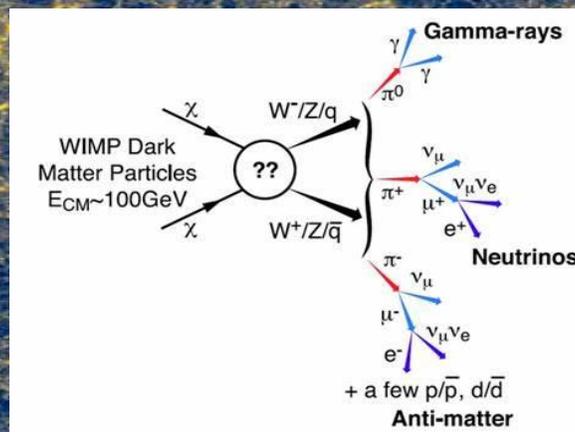
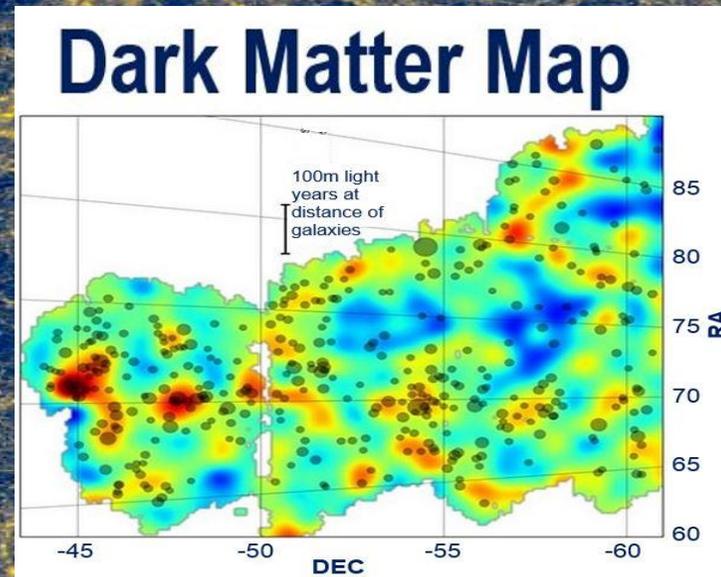
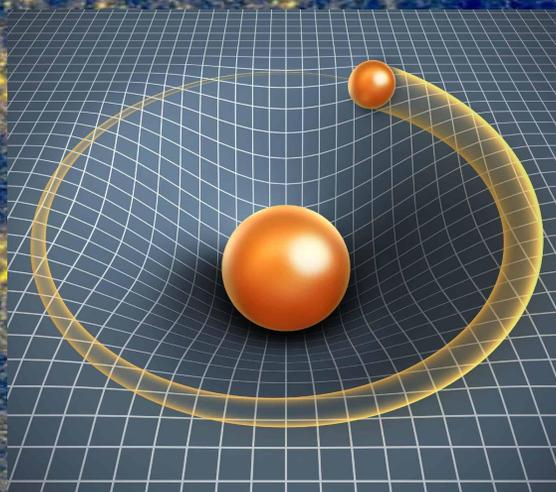


1 暗物质粒子的形成和起源

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

暗物质天文测量途径



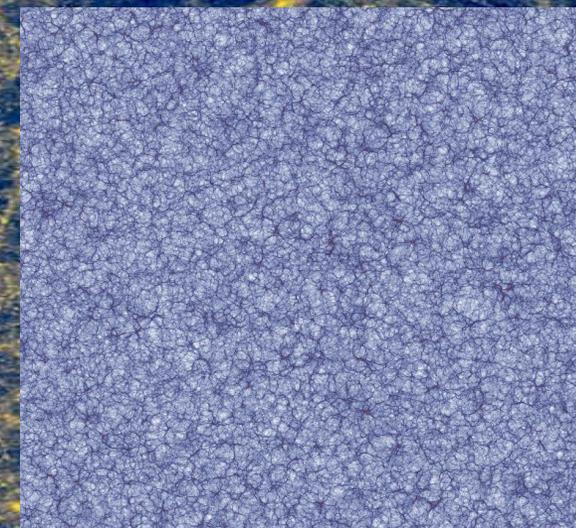
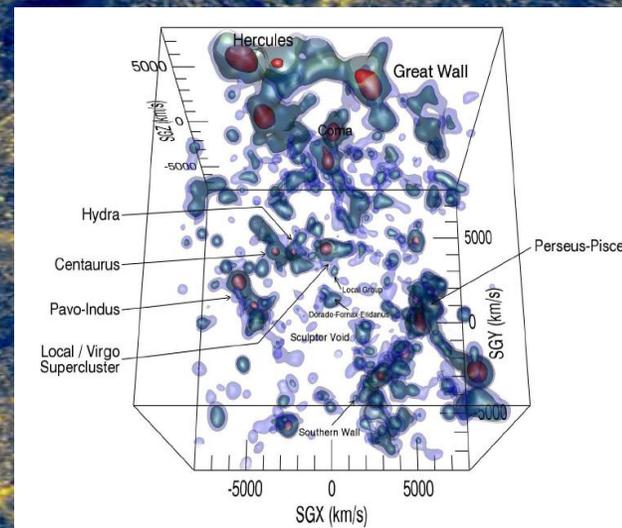
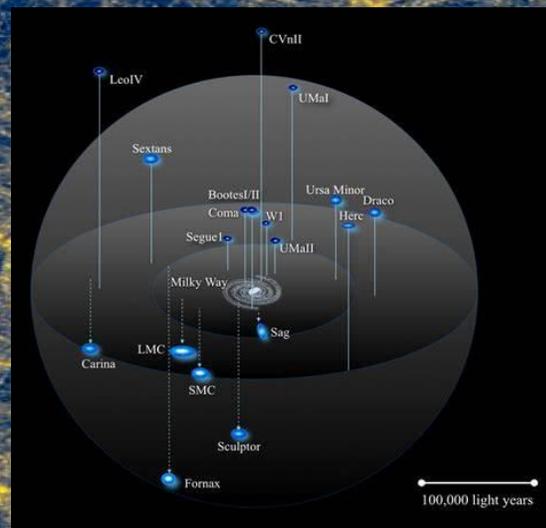
发光物质 ----- 引力作用 ----- 暗物质分布

pc

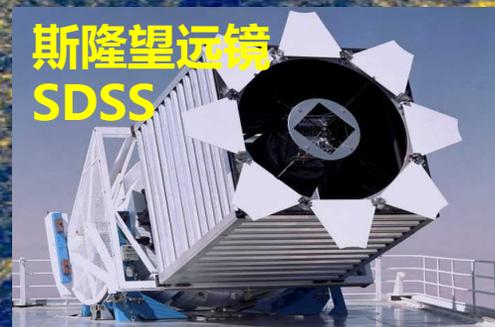
500 Kpc

100 Mpc

10Gpc



郭守敬望远镜
LAMOST



斯隆望远镜
SDSS



盖亚卫星
GAIA

暗物质存在的证据

- 宇宙物质的总的引力效应
- 引力透镜
- 直接可视化 (引力透镜)

Evidence for Dark Matter



Rotation of galaxies

Velocities of galaxies in clusters



Velocities of stars in dwarf galaxies



Hot gas in galaxy clusters



Galaxy interactions



Collisions of galaxy clusters



Gravitational lensing



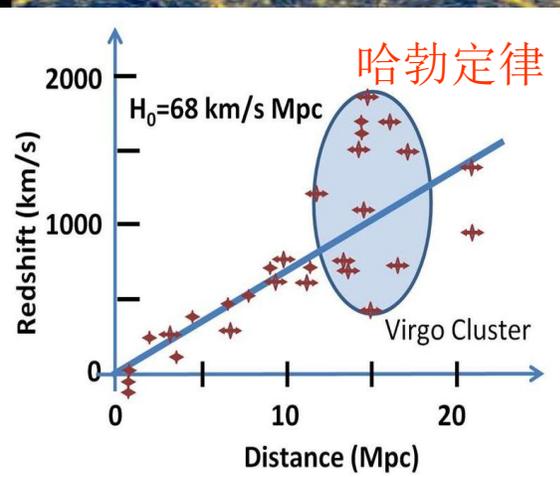
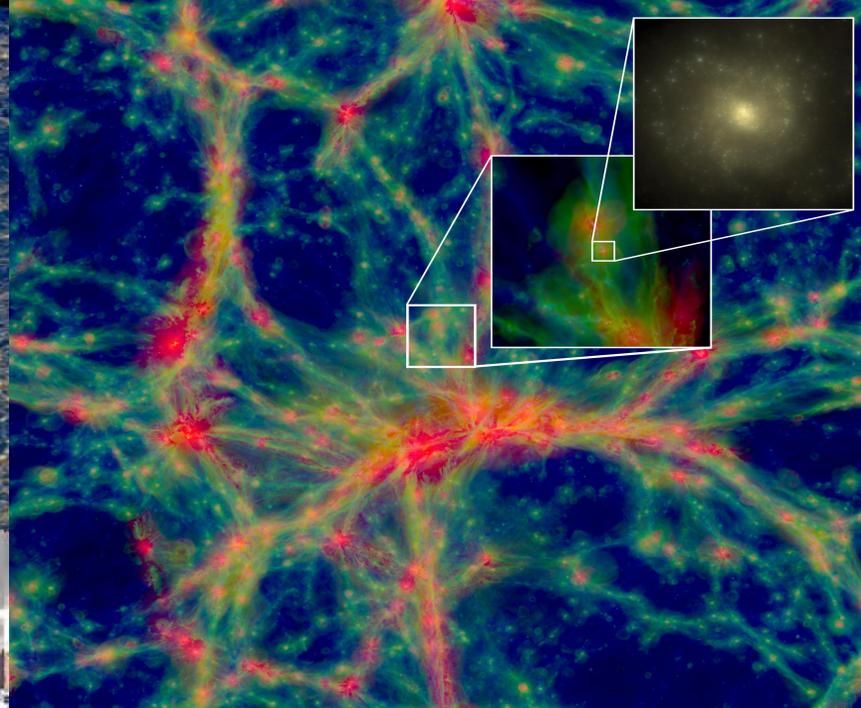
Clowe et al. 2006

天文学研究方法

理论模型
(线性过程)

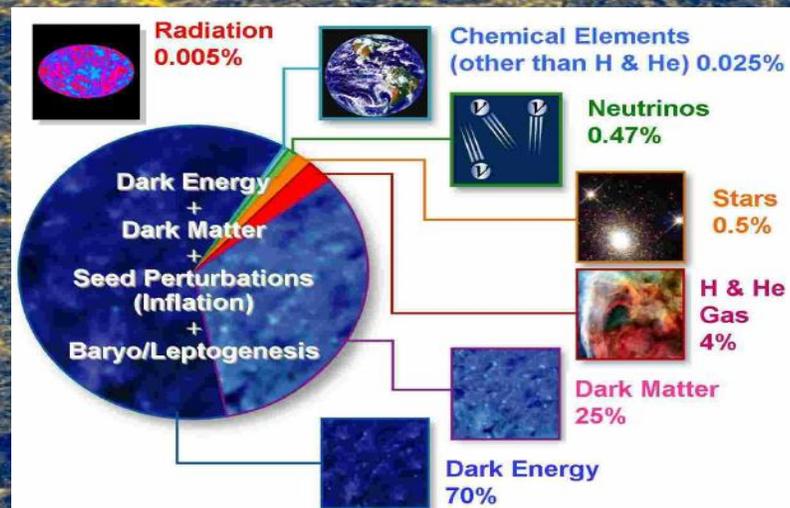


数值模拟
(非线性过程)



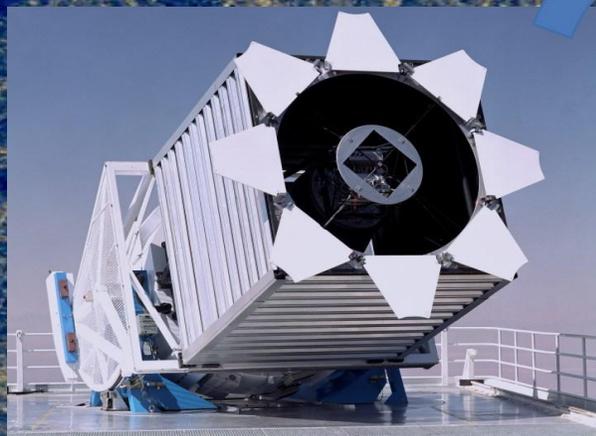
1980s 后

观测数据
(线性过程)



宇宙学与数值模拟

观测数据



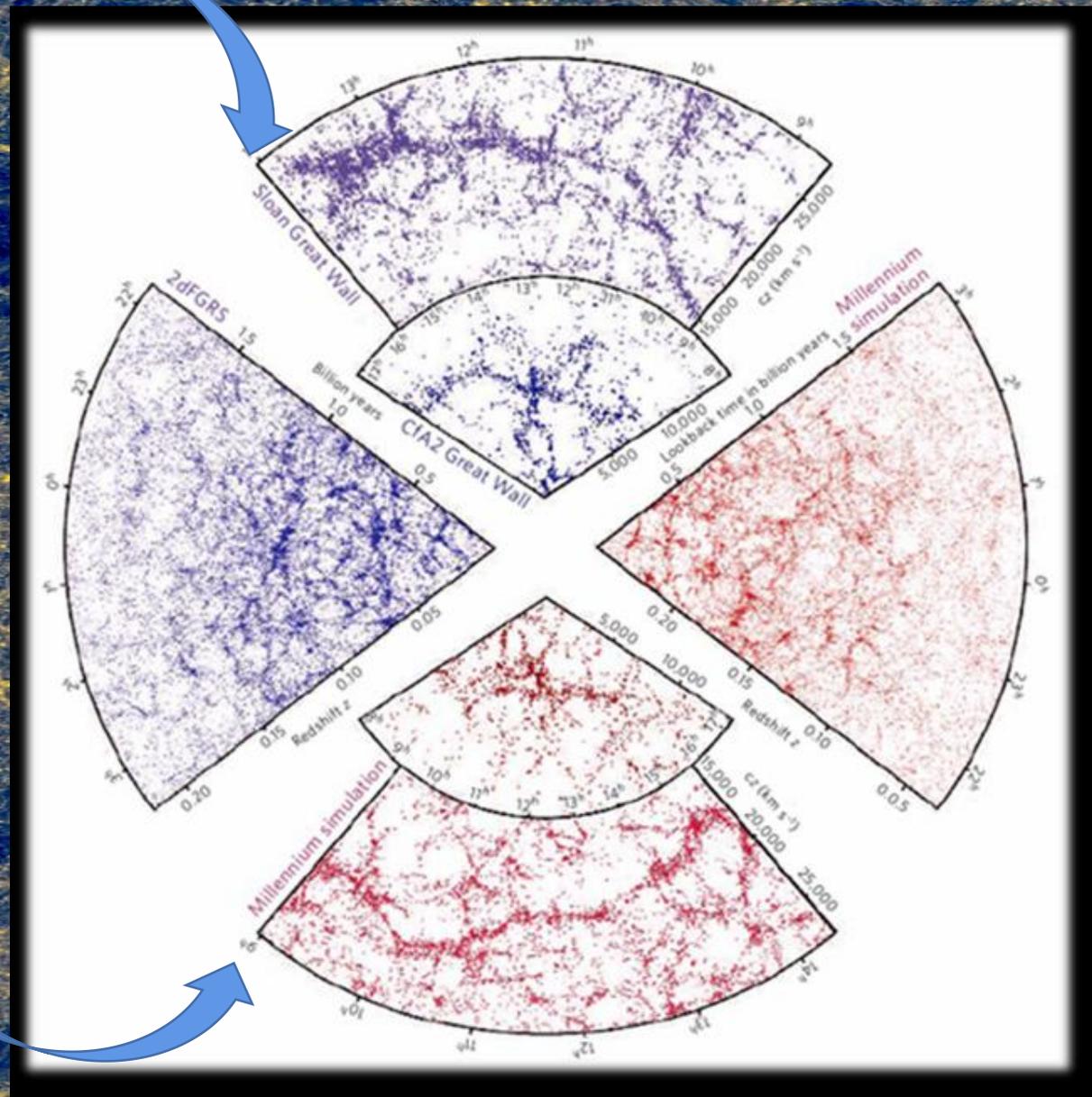
原初条件
(粒子系统)

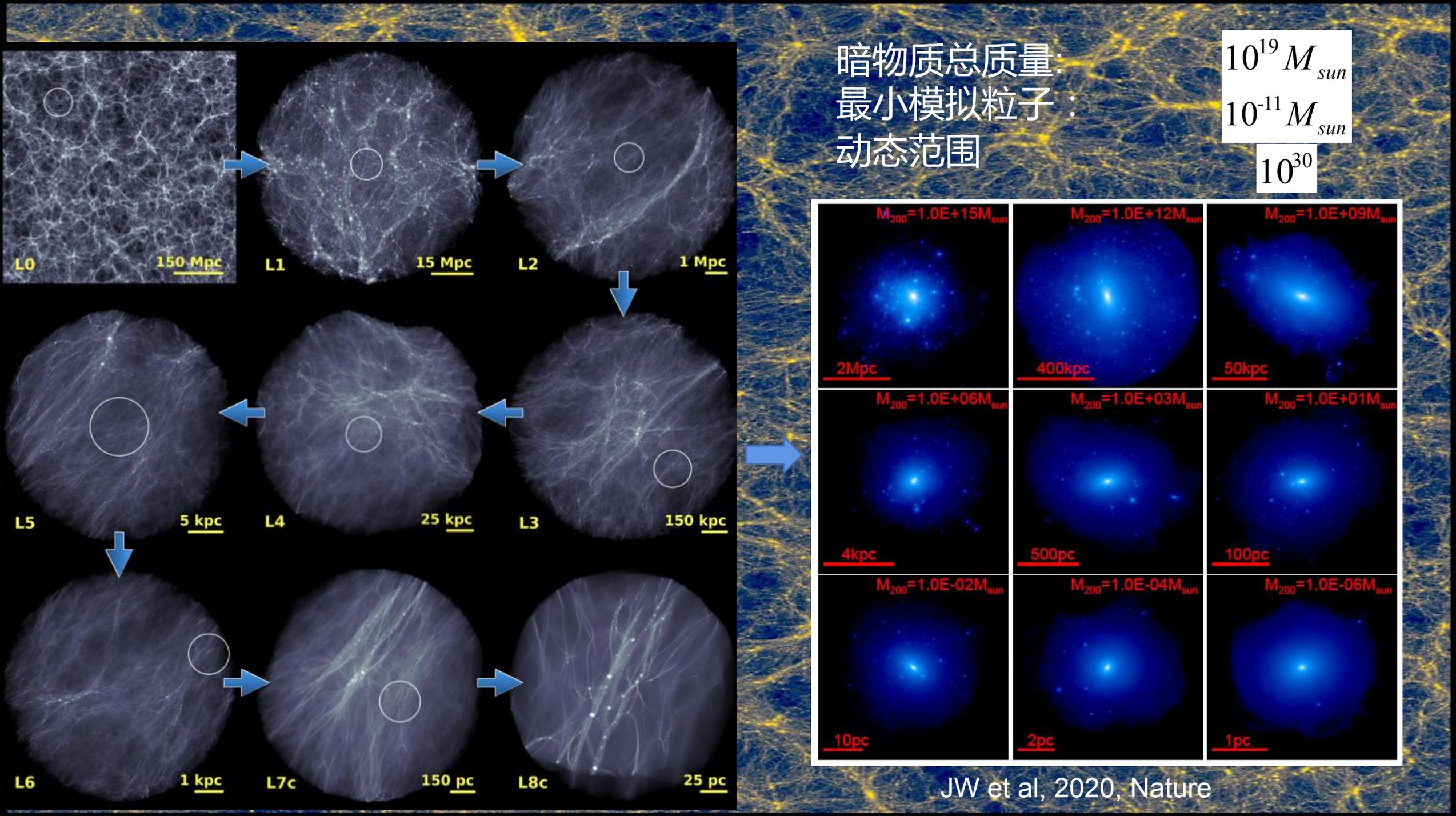
边界条件

特定物理规律
(宇宙学模型, 引力
作用规律)

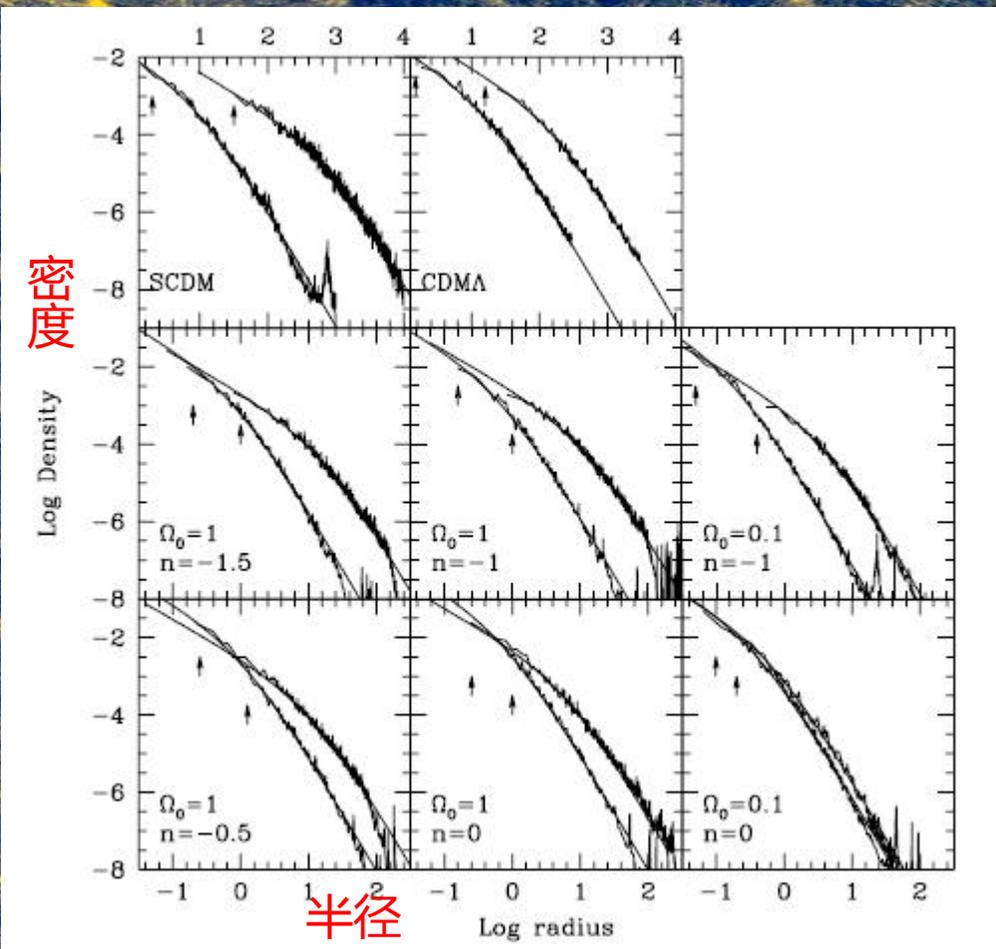


数值模拟





暗晕的内部结构 -- NFW



普适的密度轮廓

$$\frac{\rho(r)}{\rho_{\text{crit}}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

concentration
紧致因子

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

Navarro, Frenk, & White 1996, 1997

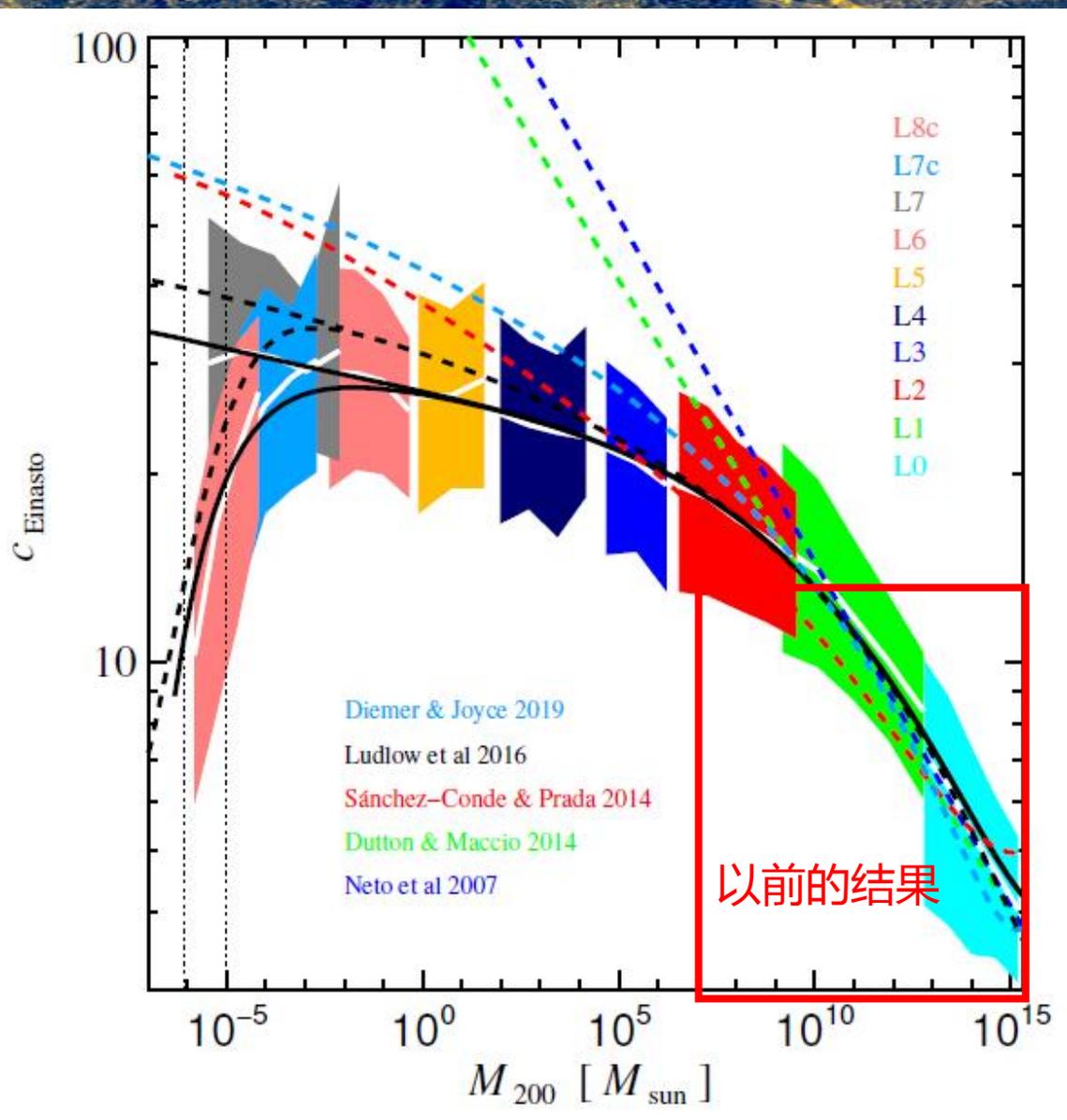


Navarro

Frenk

White

20个质量区间的Concentration-mass关系



- ✓ 在1000个地球质量左右，紧致因子快速下降，因为 free-streaming 效应
- ✓ M-C关系的弥散和质量依赖性不强

幂指数项

多项式项

$$c_{\text{Einasto}}(M_{200}) = \exp \left[c_6 \times \left(\frac{M_{\text{fs}}}{M_{200}} \right)^{\frac{1}{3}} \right] \times \sum_{i=0}^5 c_i \left[\ln \frac{M_{200}}{h^{-1} M_{\odot}} \right]^i$$

$$c_0 = 27.108$$

$$c_1 = 0.381$$

$$c_2 = 1.815 \times 10^{-3}$$

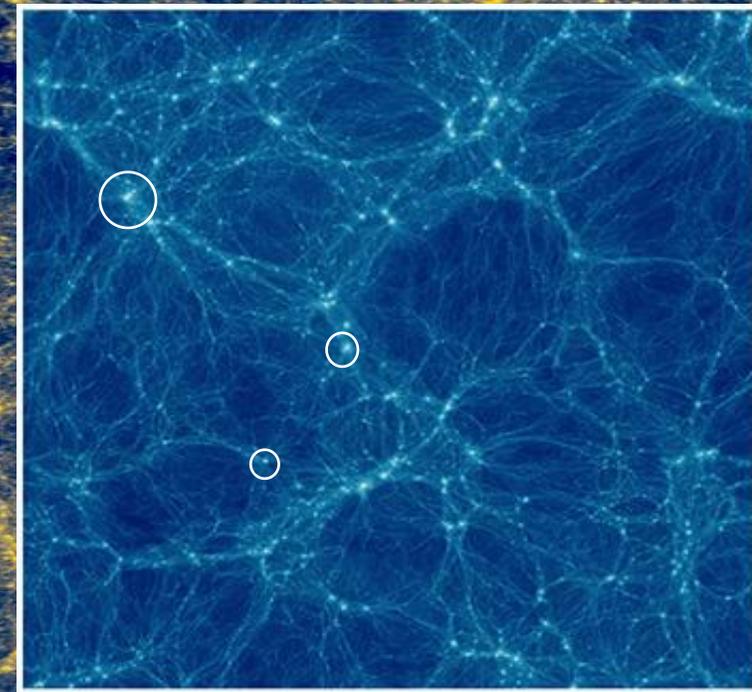
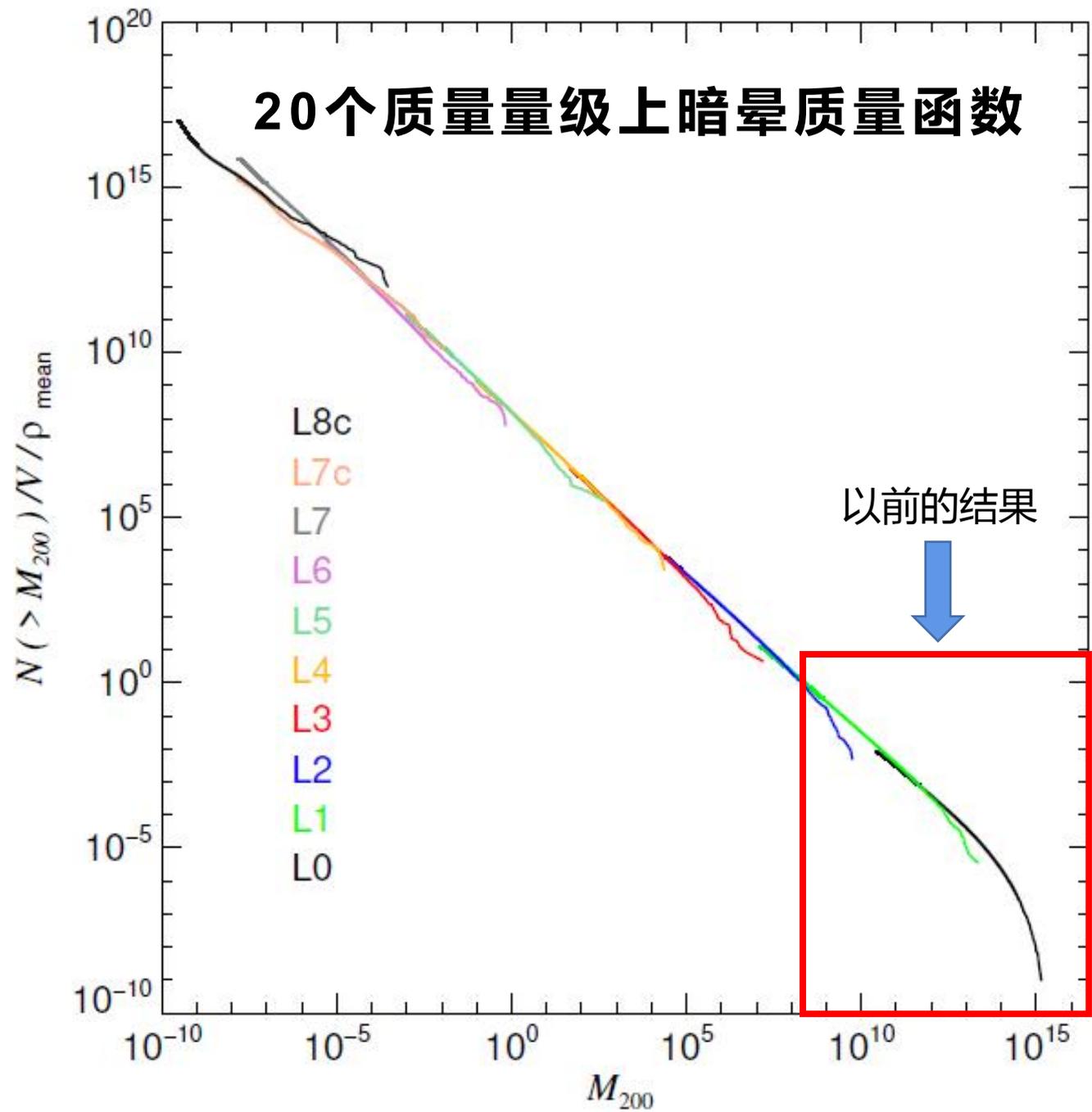
$$c_3 = 4.089 \times 10^{-4}$$

$$c_4 = 4.282 \times 10^{-6}$$

$$c_5 = 3.188 \times 10^{-7}$$

$$c_6 = -0.602$$

20个质量量级上暗晕质量函数

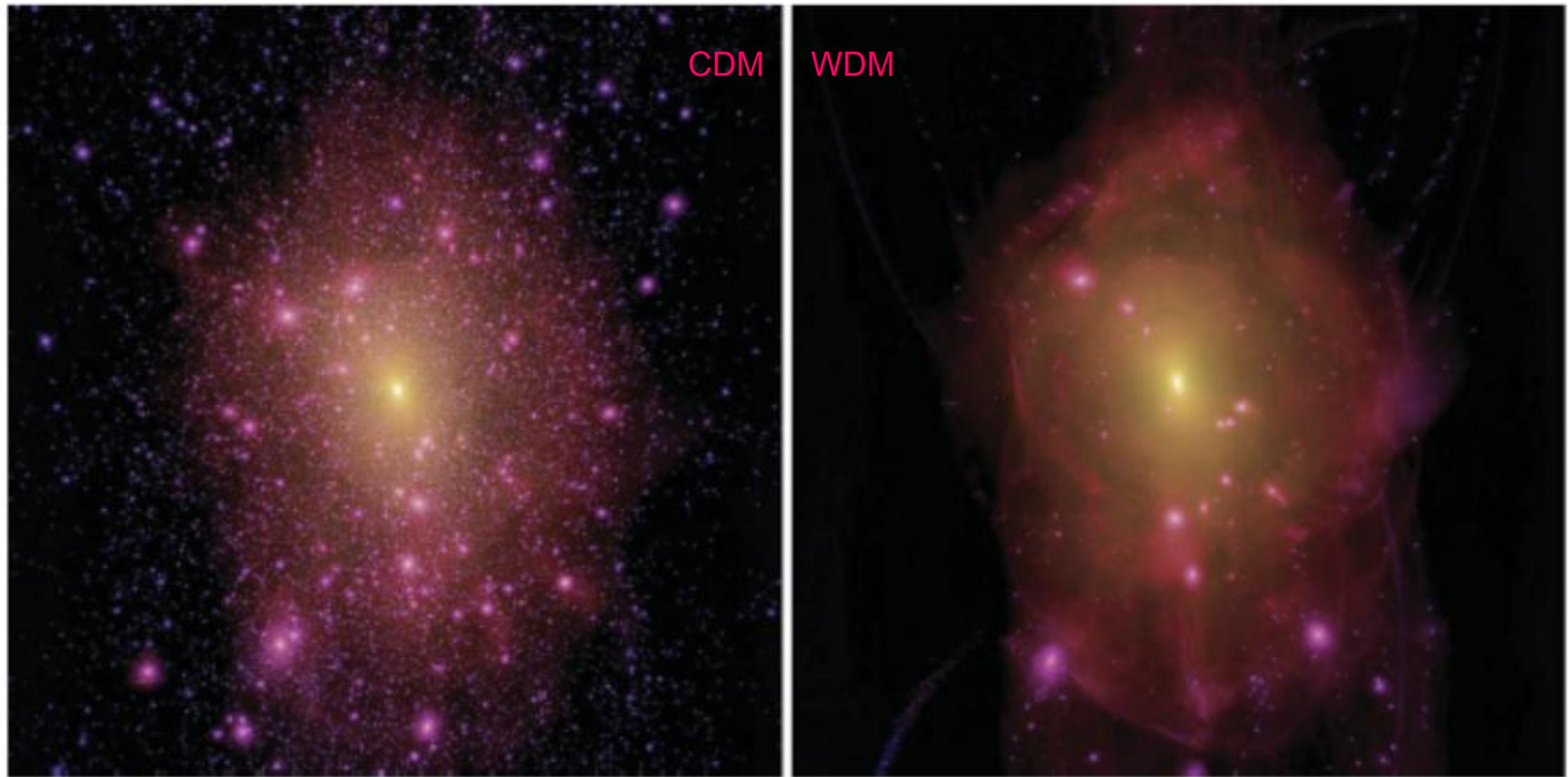


宇宙中所有物质

- 60% 存在于 $M_{200} > 10^8$ Msun 暗晕中
- 95% 存在于 $M_{200} > 10^6$ Msun 暗晕中
- 暗晕数目 $n \sim M^{-1}$:

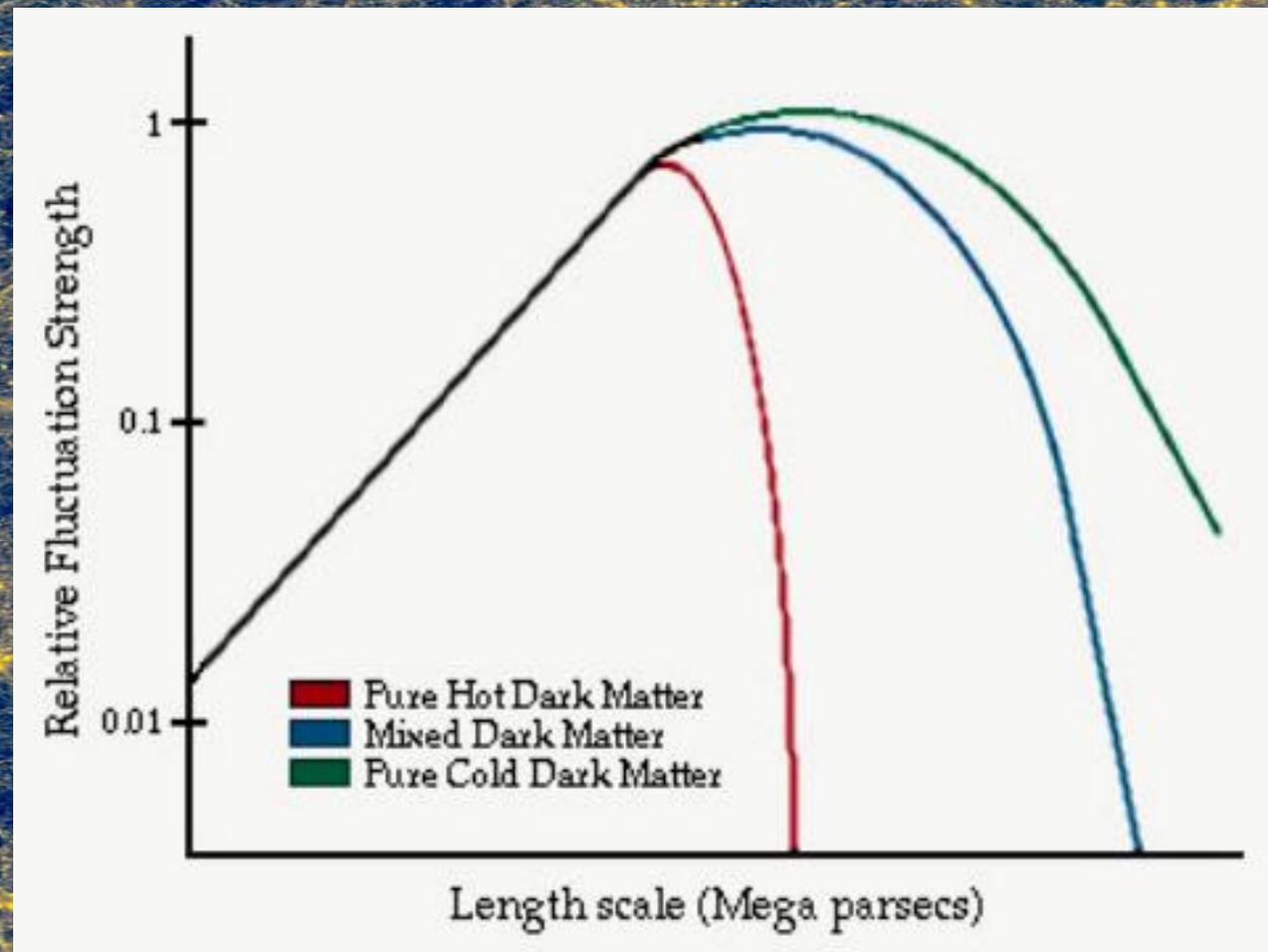
质量下降一个量级，
暗晕数目增加约十倍

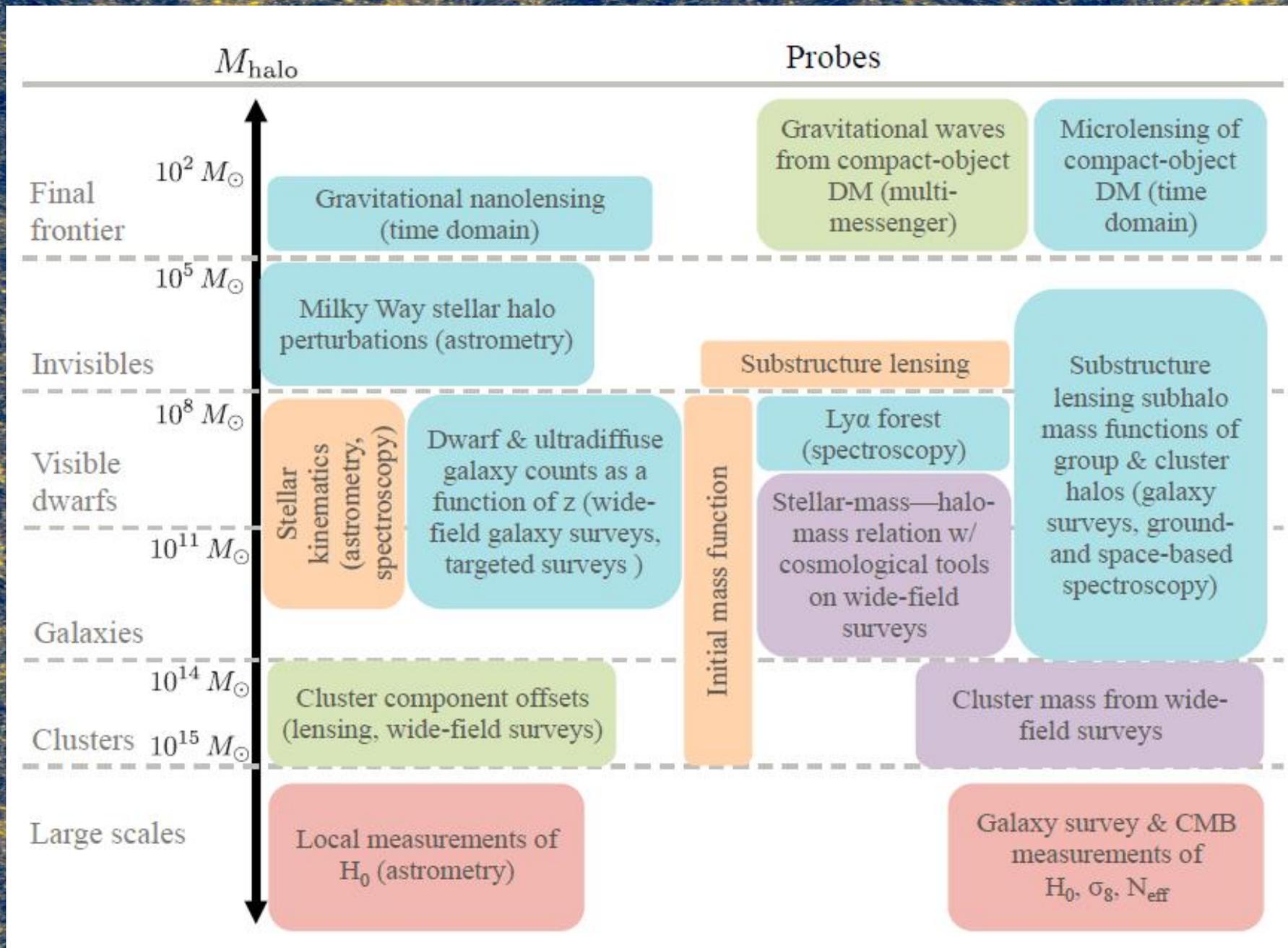
不同暗物质模型里，银河系暗晕里的子结构



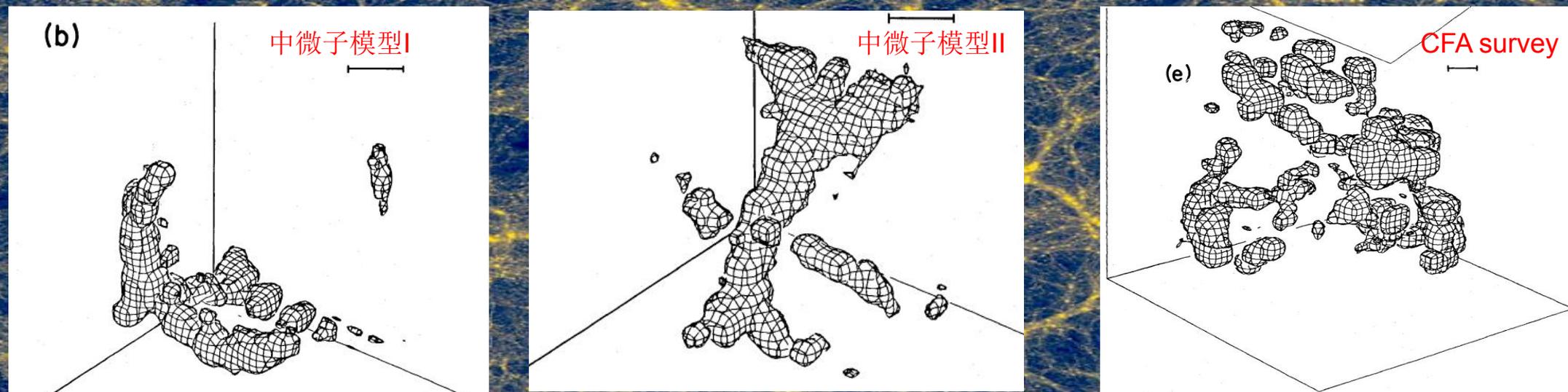
天文对暗物质粒子质量的限制

- 大尺度物质分布
- 小尺度子结构数目
- 暗晕内部密度轮廓





暗物质粒子属性与大尺度结构



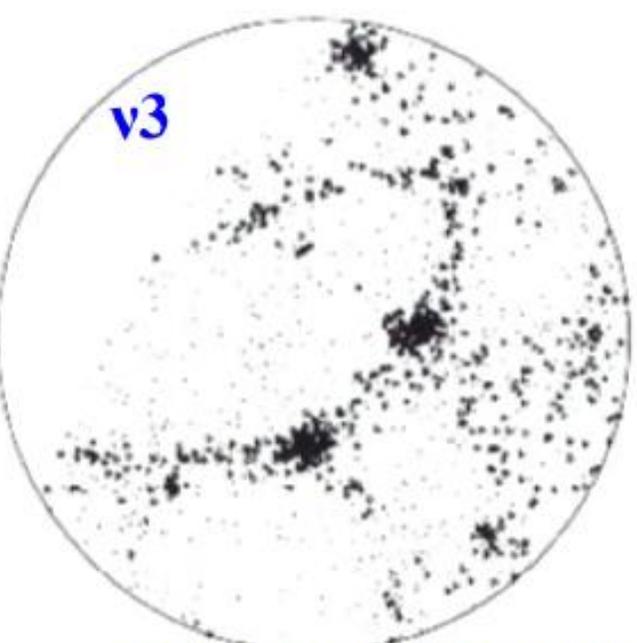
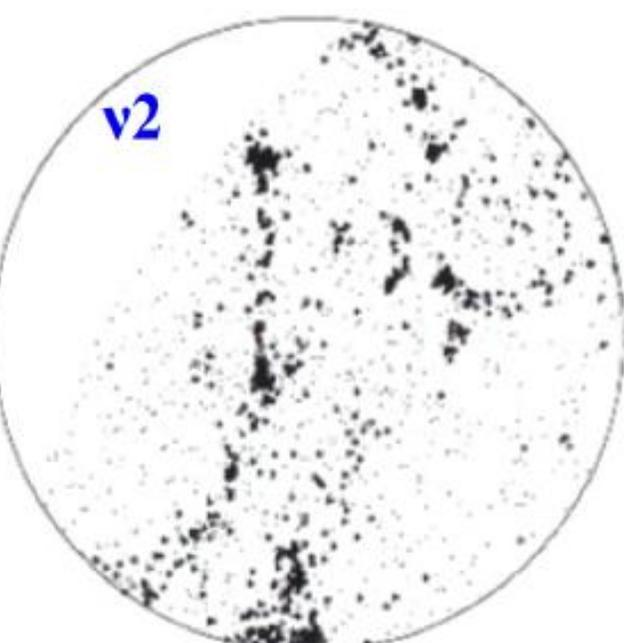
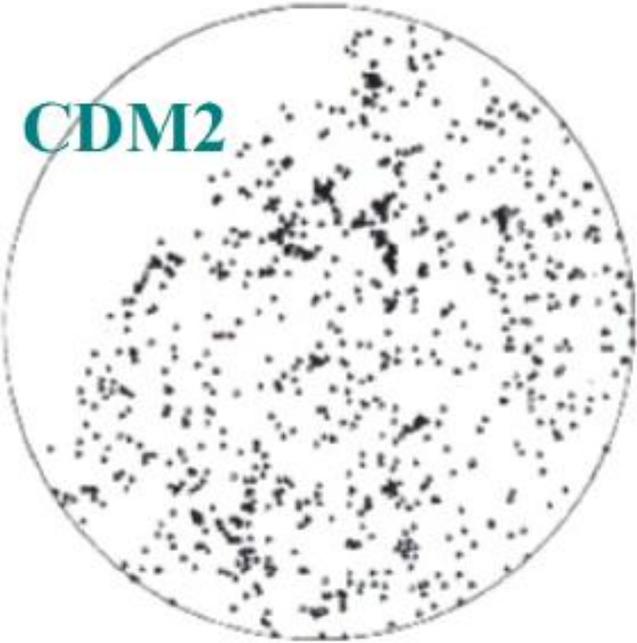
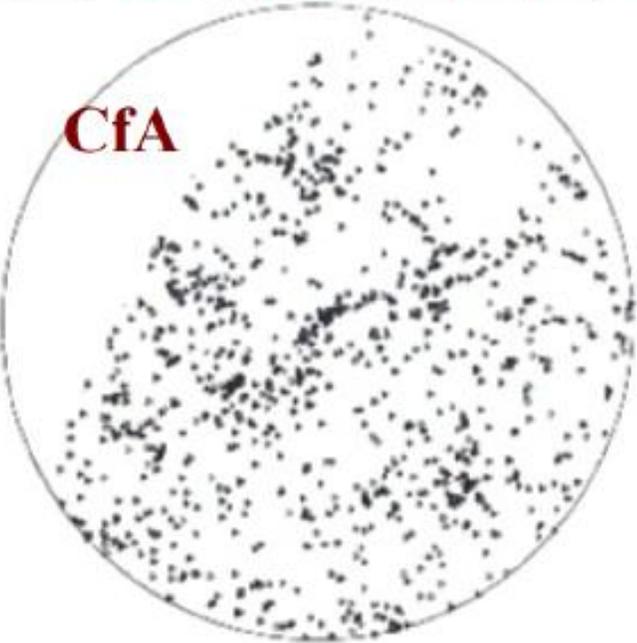
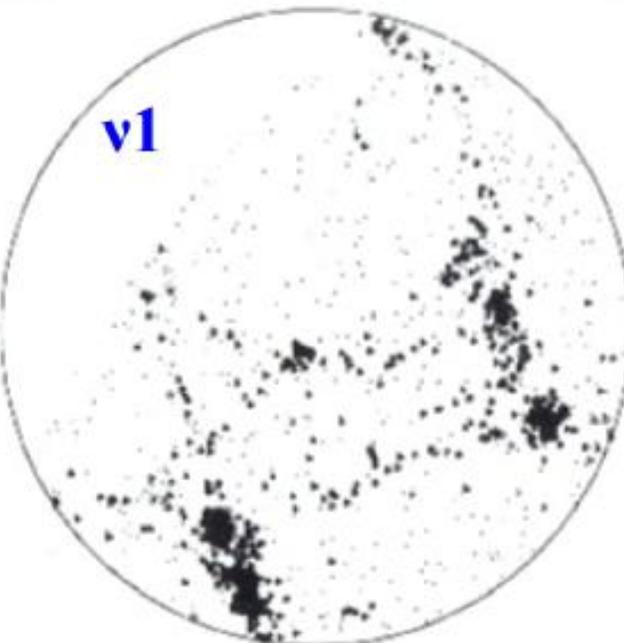
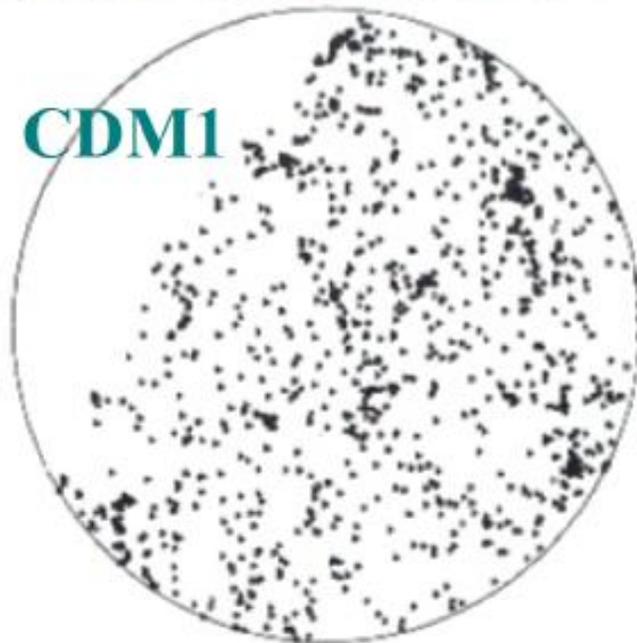
排除了中微子作为暗物质候选对象

White et al 1983

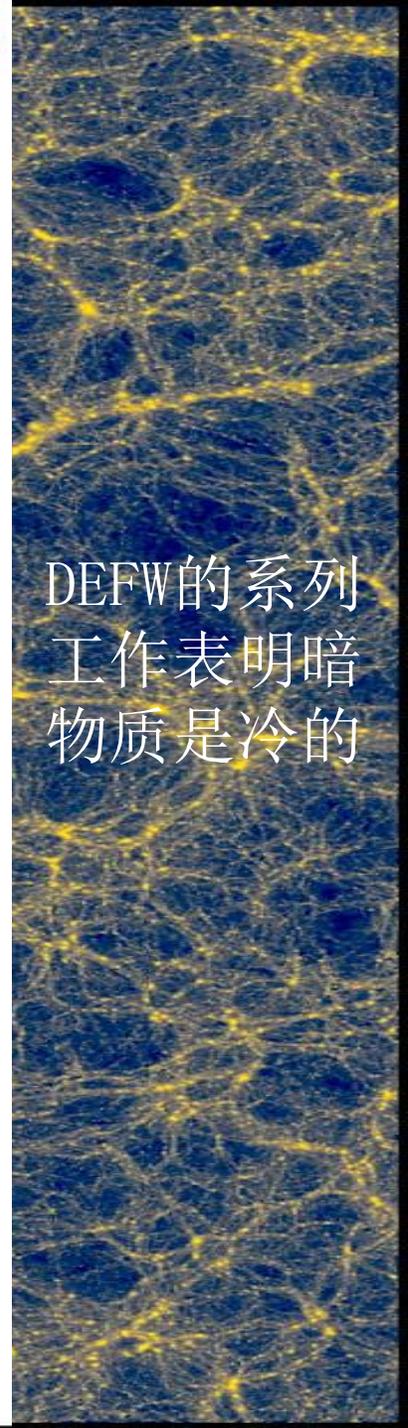
2011 年 Gruber 宇宙学奖:

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

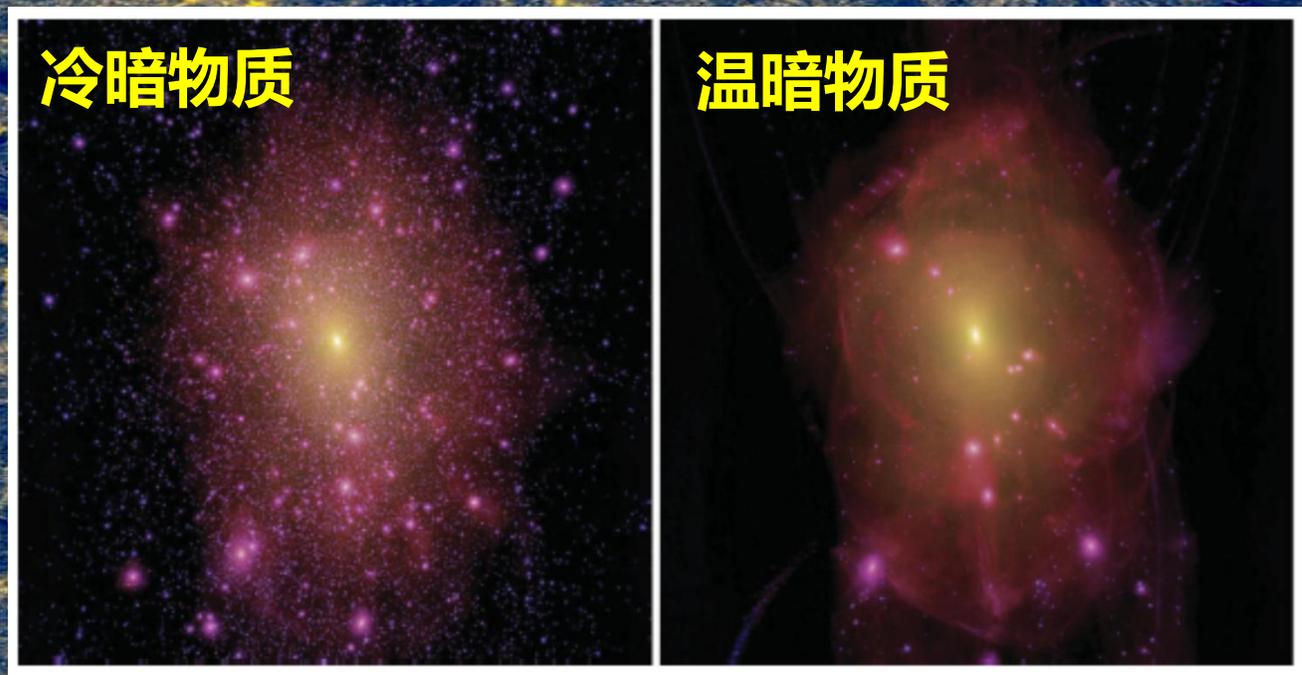
(DEFW合作在1985-1988年完成的五篇文章**永远的改变了宇宙学**)



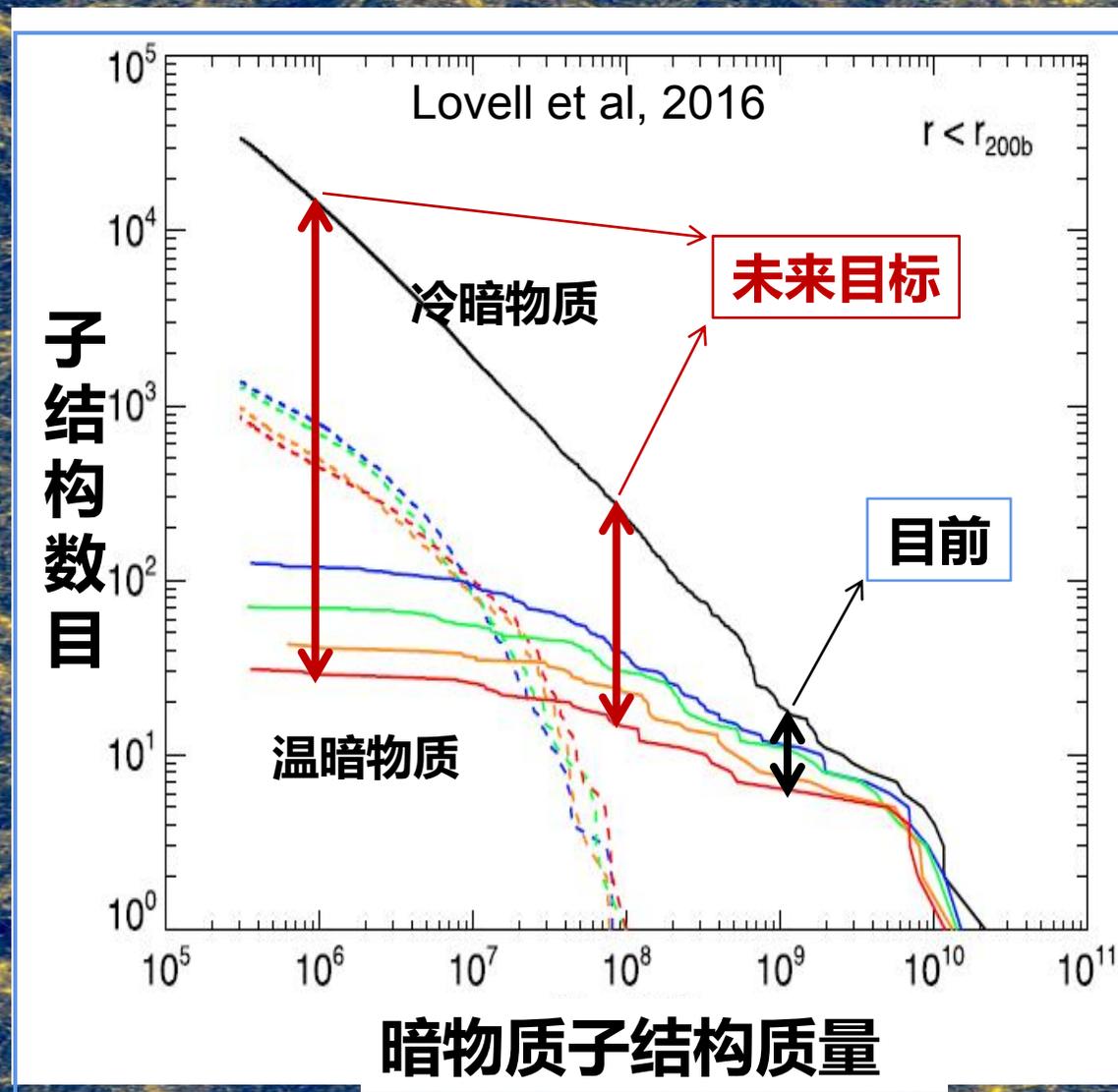
DEFW的系列工作表明暗物质是冷的



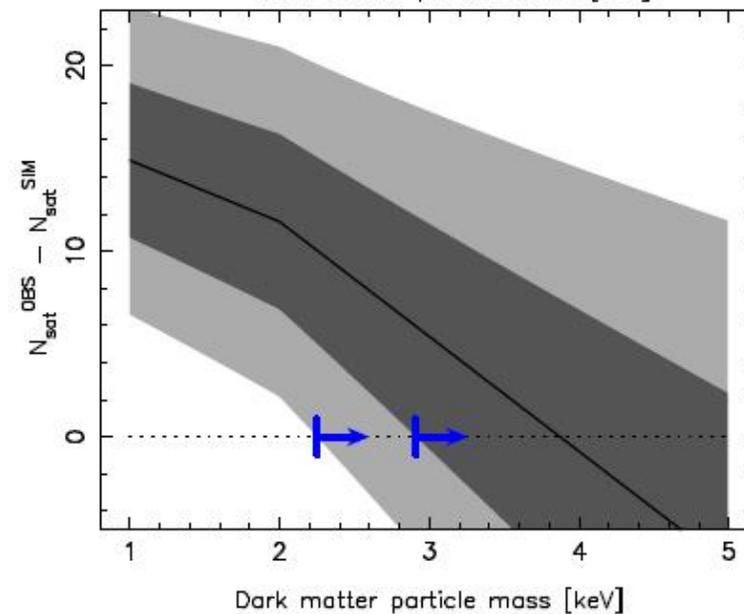
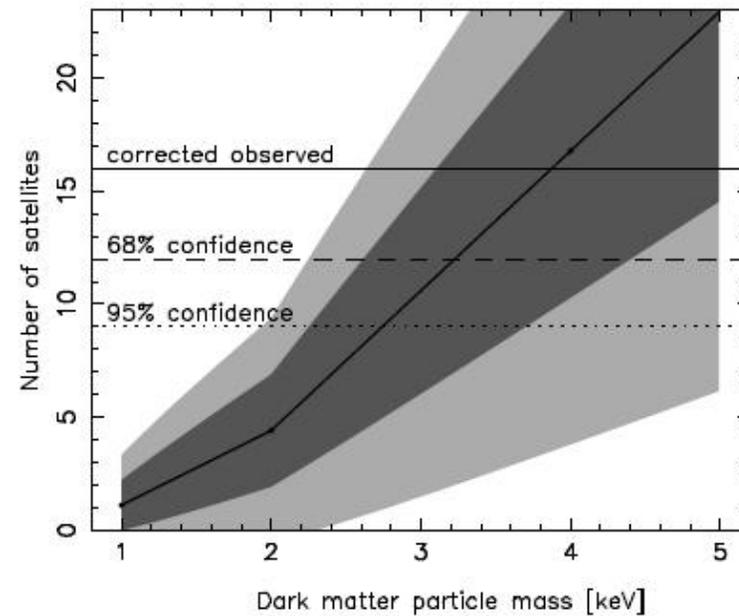
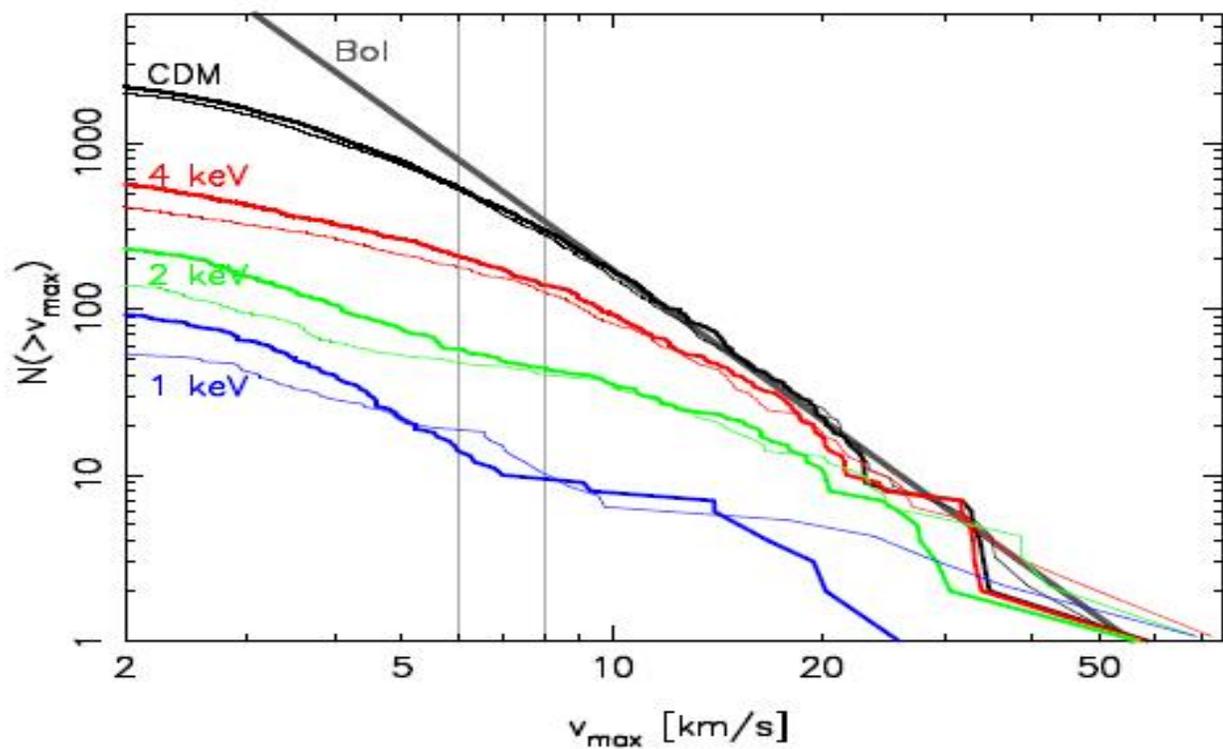
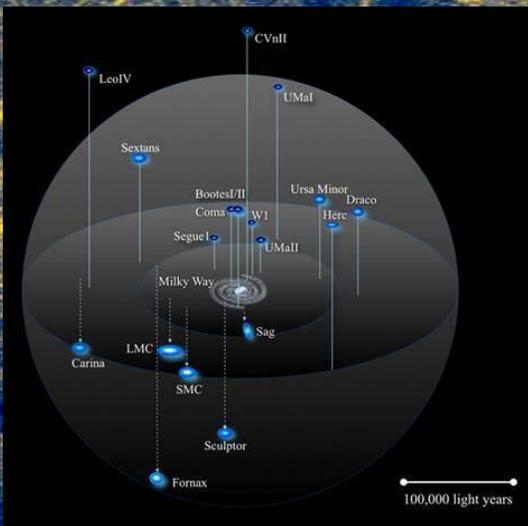
暗物质粒子属性与子结构数目



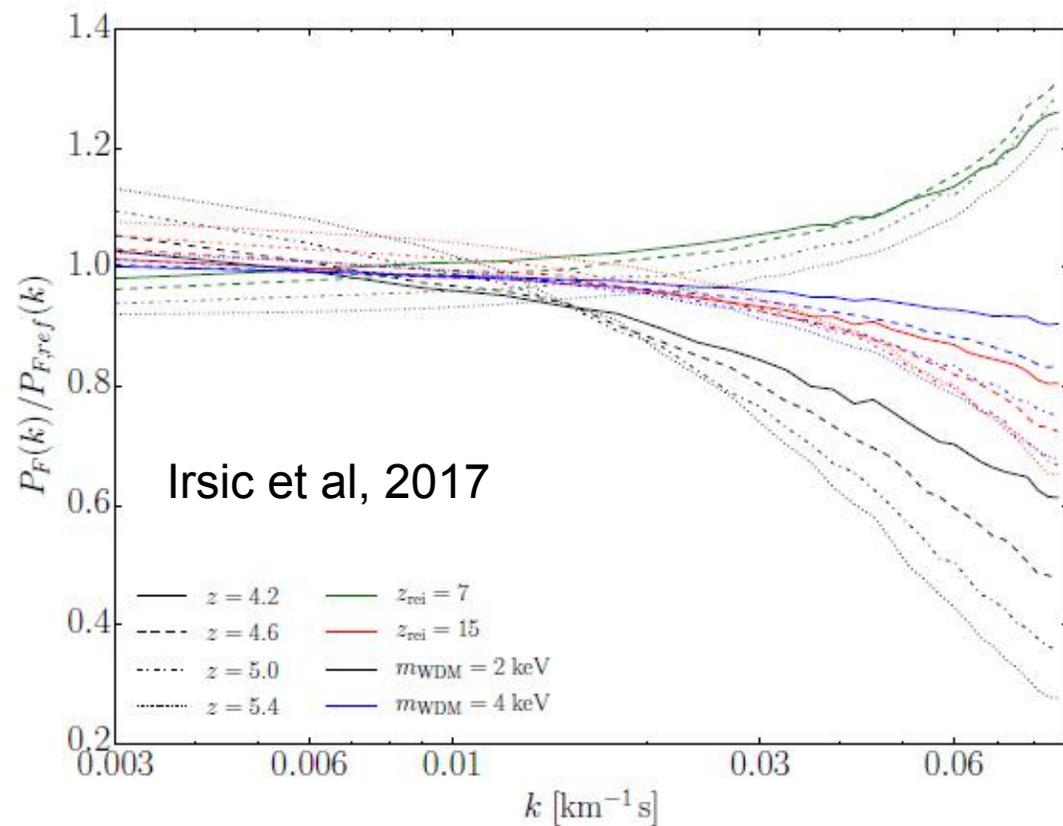
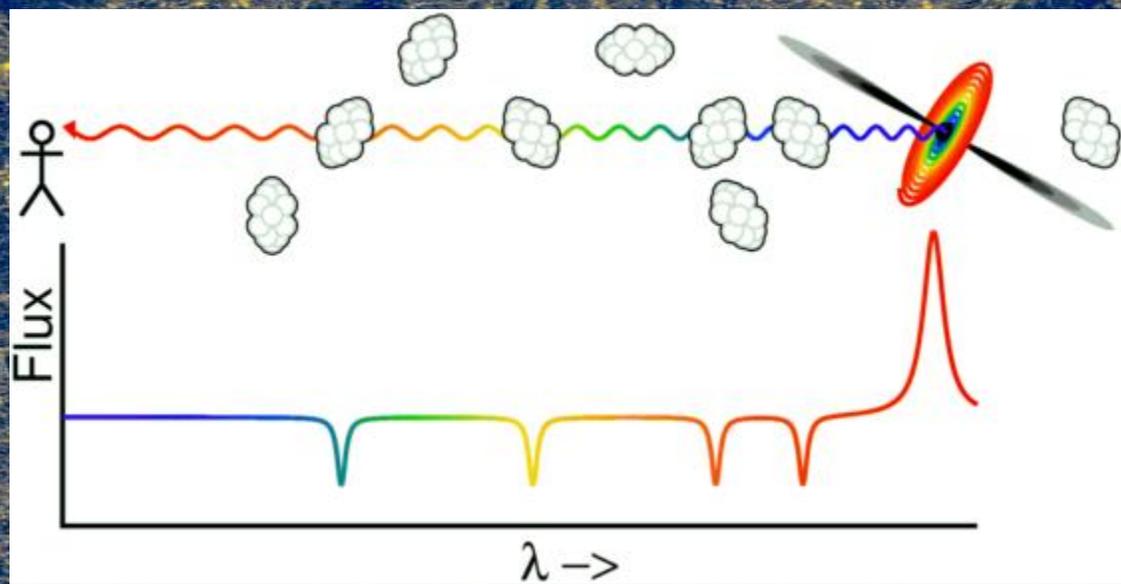
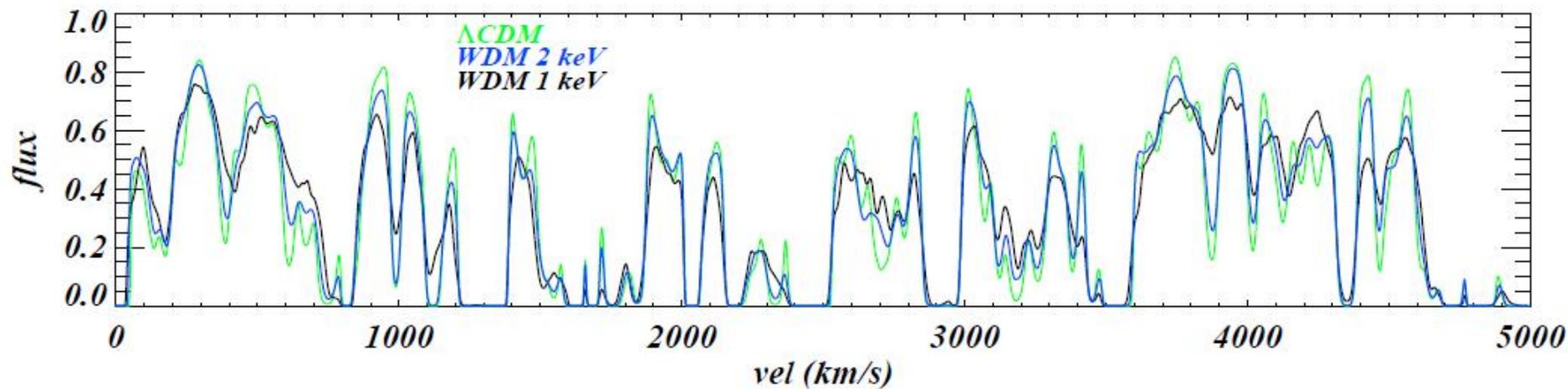
目前只能限定到 $10^9 M_{\odot}$ ，但是不能有效区分冷/温暗物质



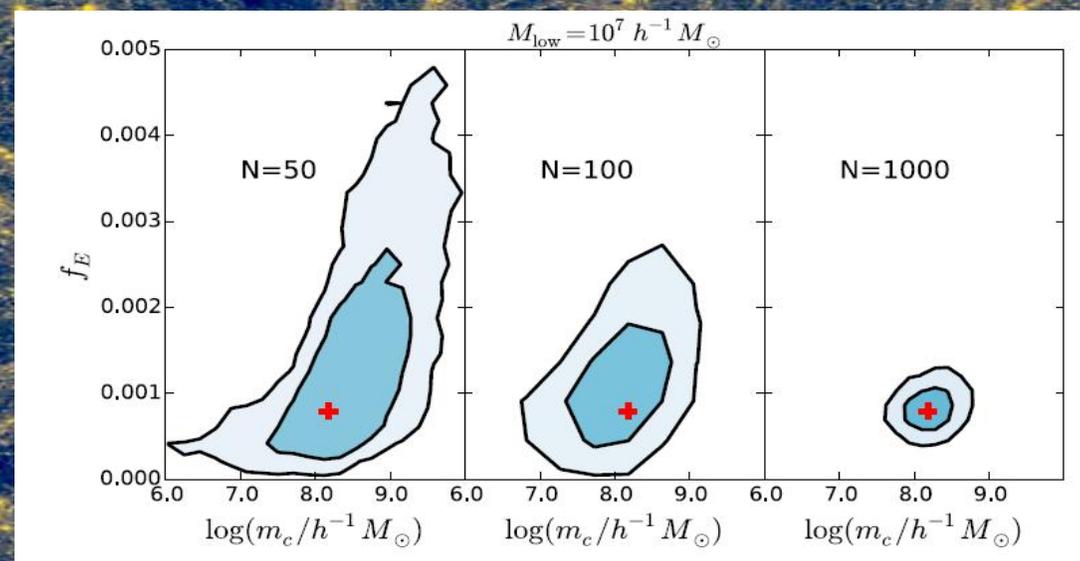
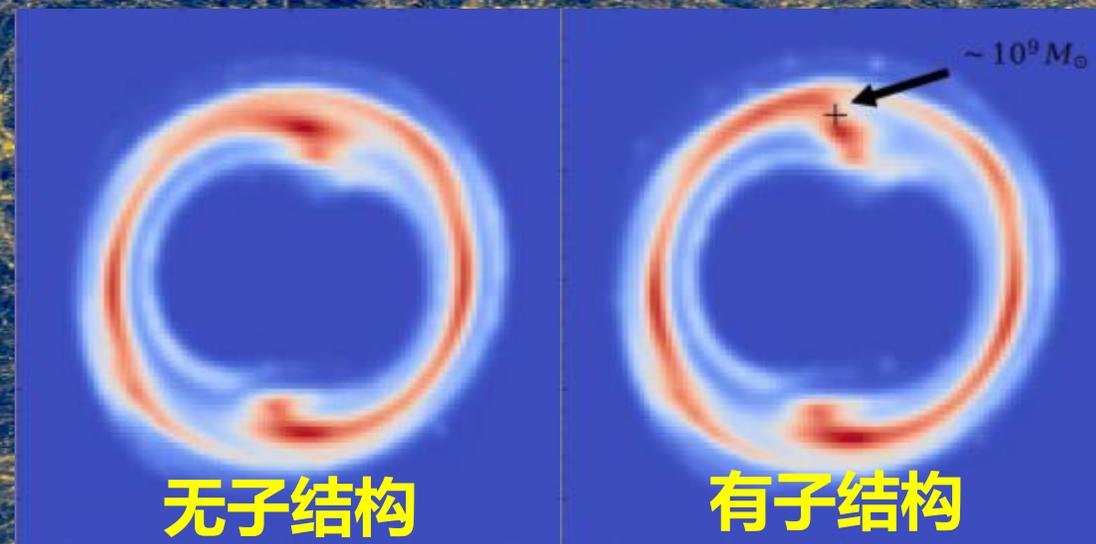
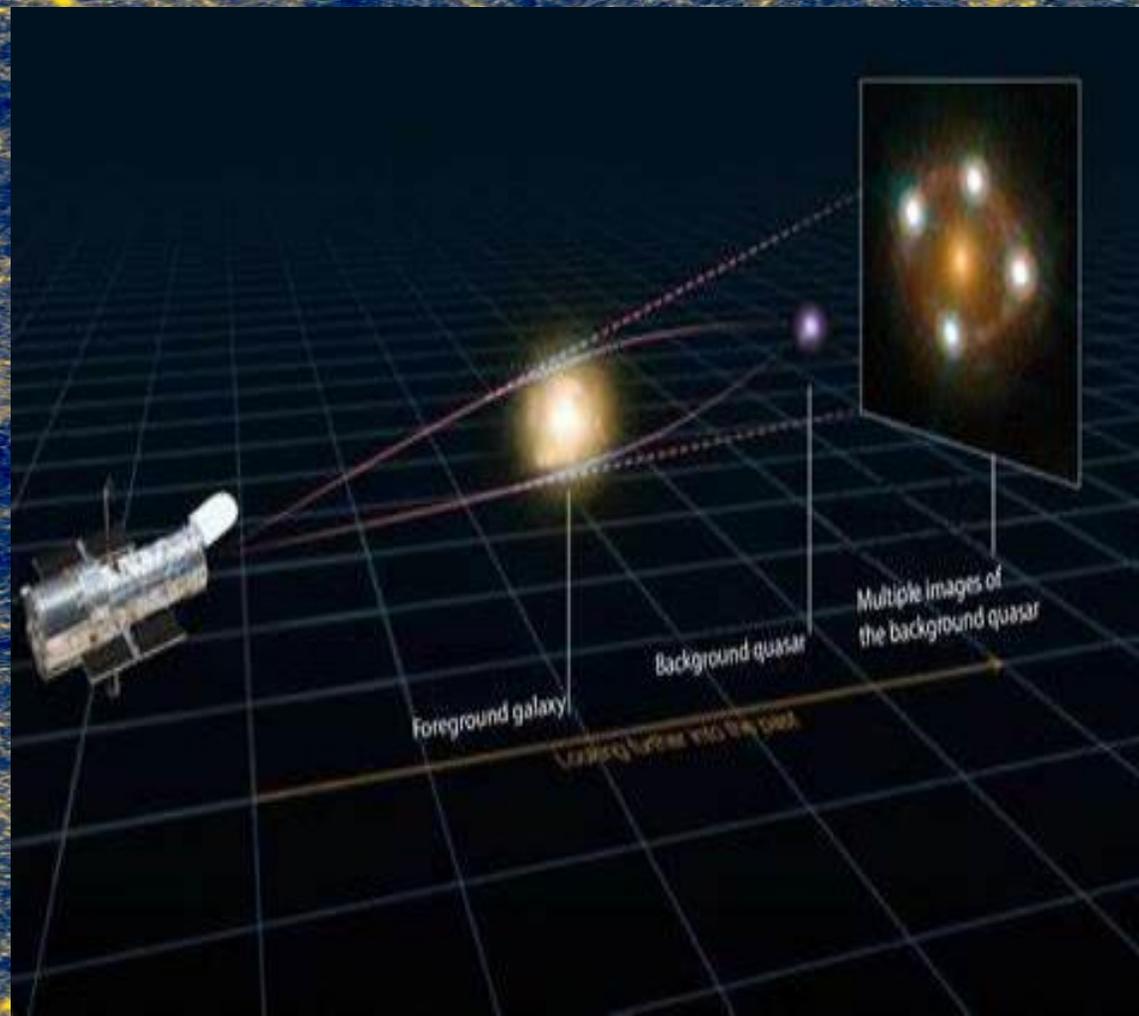
暗物质粒子属性与 银河系卫星星系数目

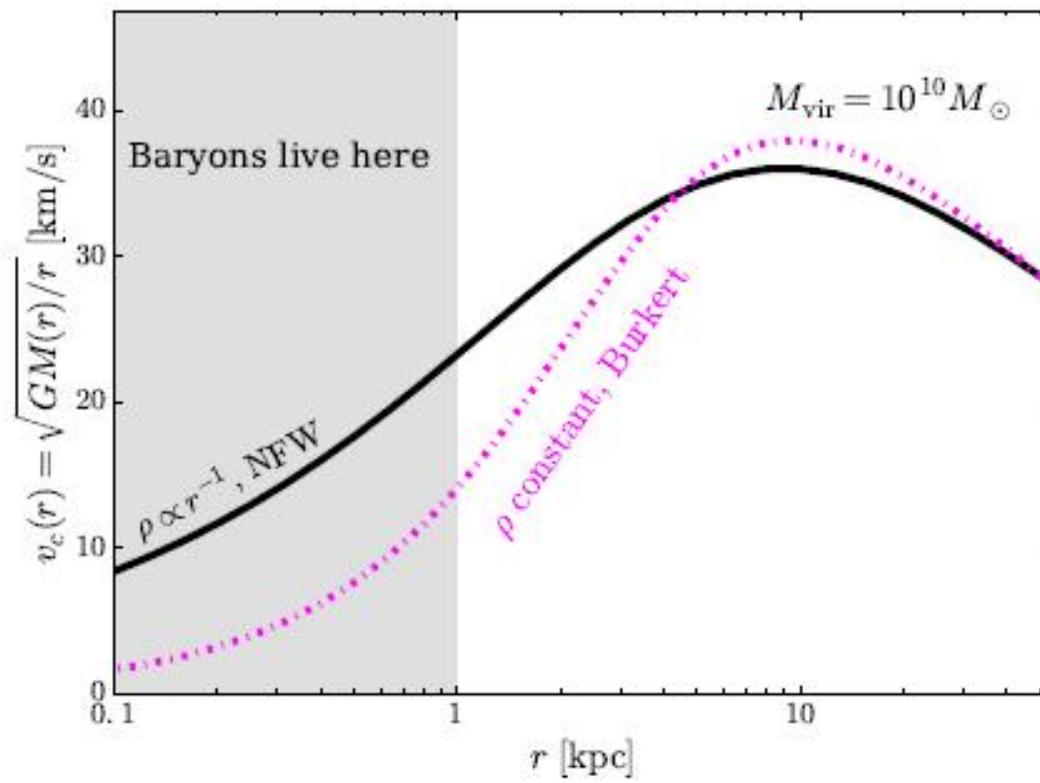
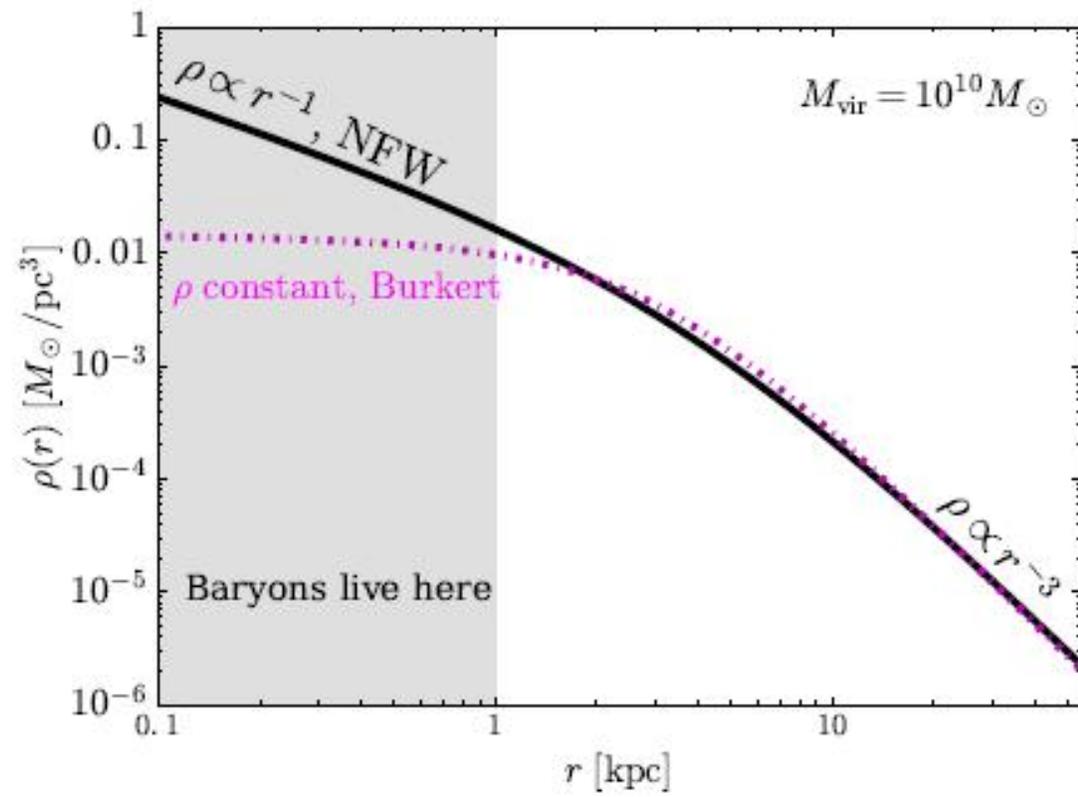


暗物质粒子属性 与Ly-a Forest



暗物质粒子属性与 强引力透镜





Buckley & Peter, 2018

Reference	Probe	$\frac{m_{th}}{\text{keV}}$ 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

$m_p > 3\text{keV}$

Enzi, et al, 2020

天文对于暗物质粒子碰撞截面的限制

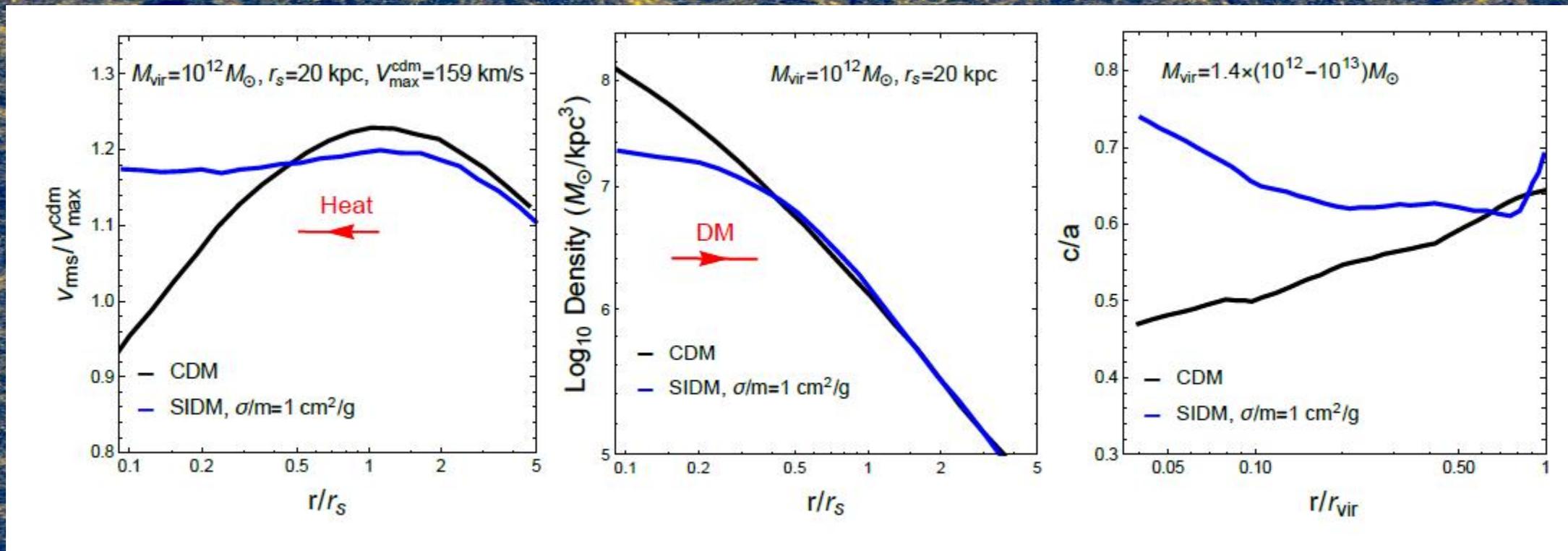
• 暗物质粒子如果有相互作用，湮灭

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

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

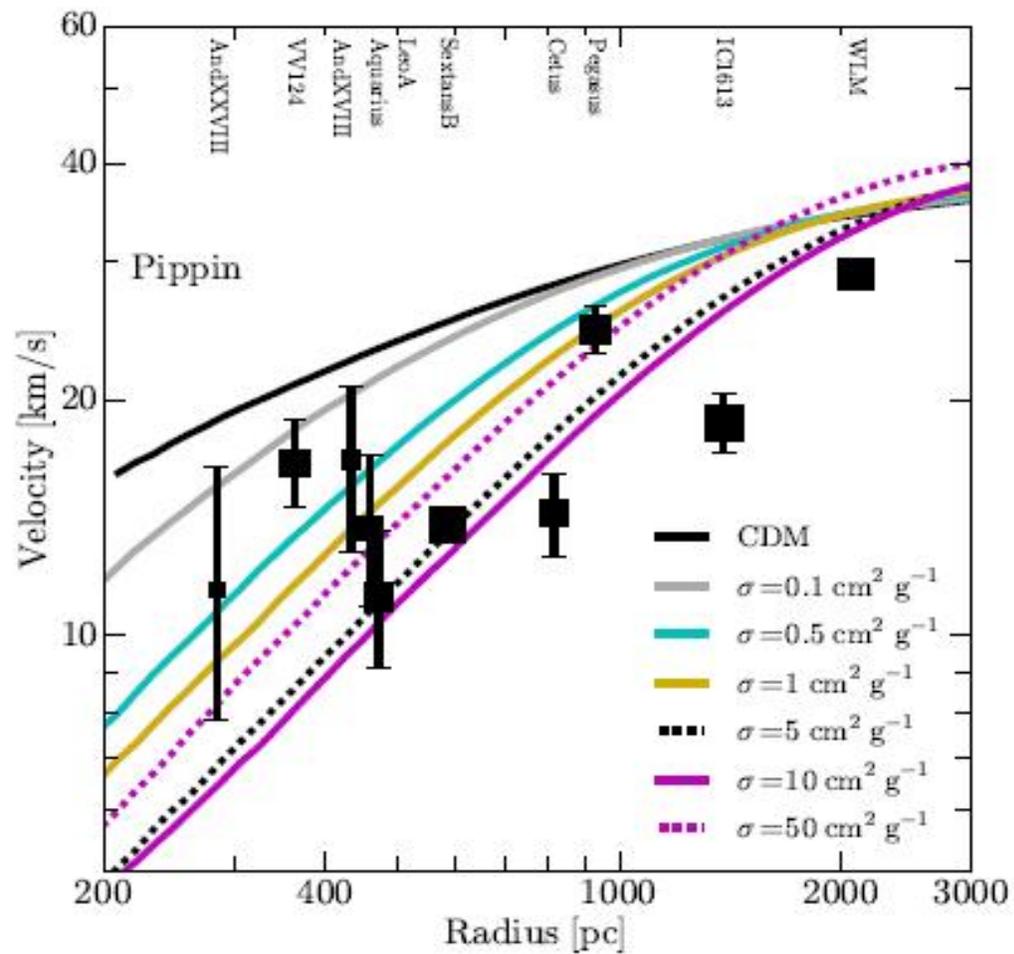
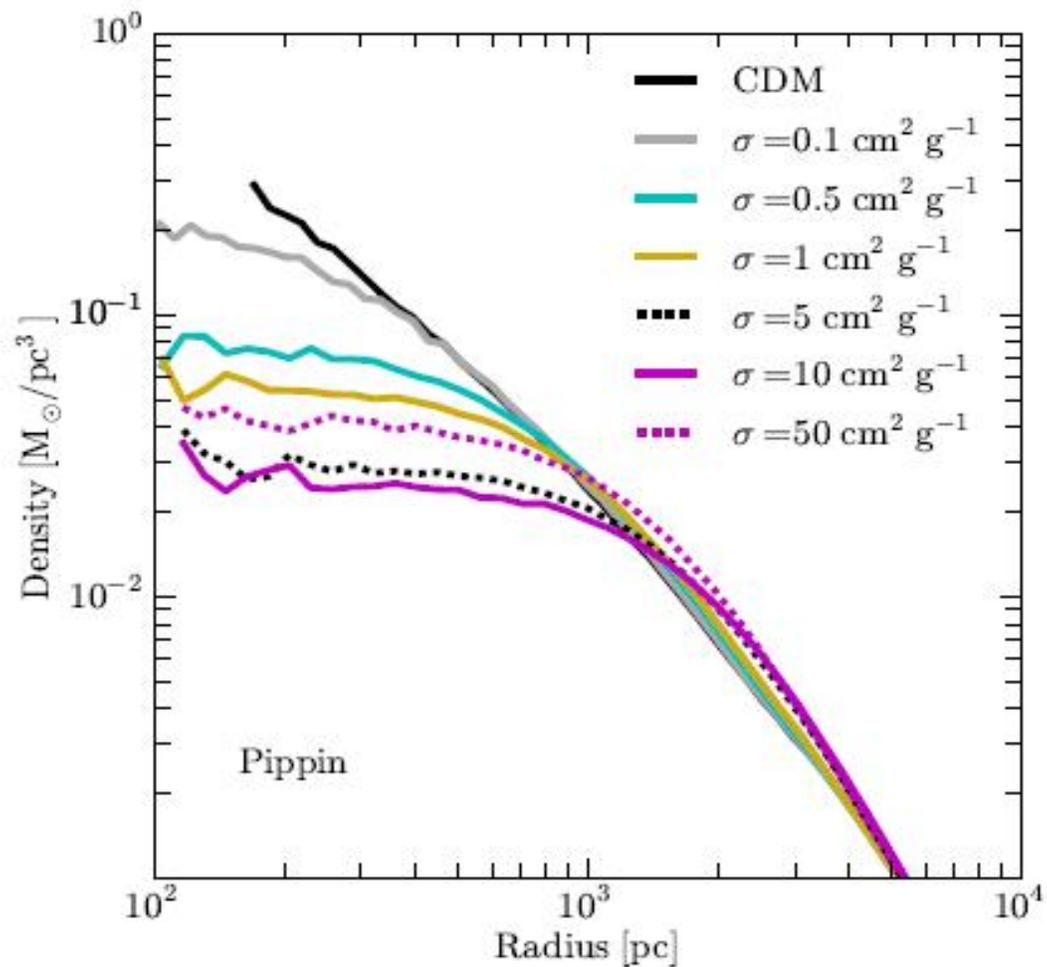
$$1 \text{ cm}^2 / \text{g} \approx 2 \times 10^{-24} \text{ cm}^2 / \text{GeV}$$

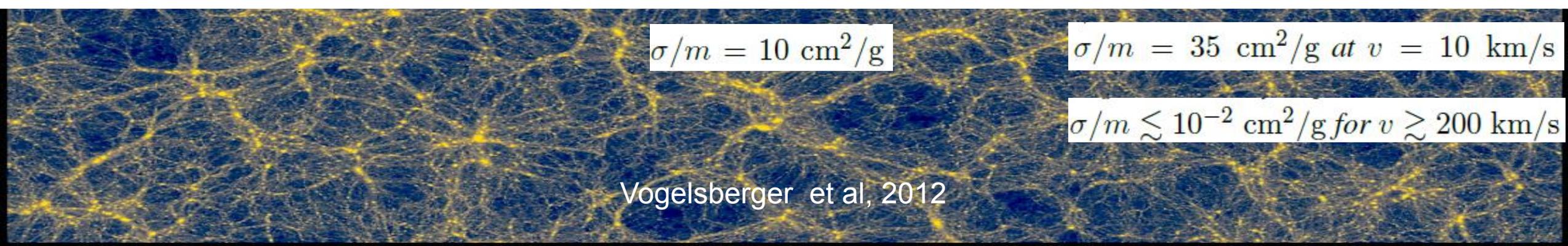
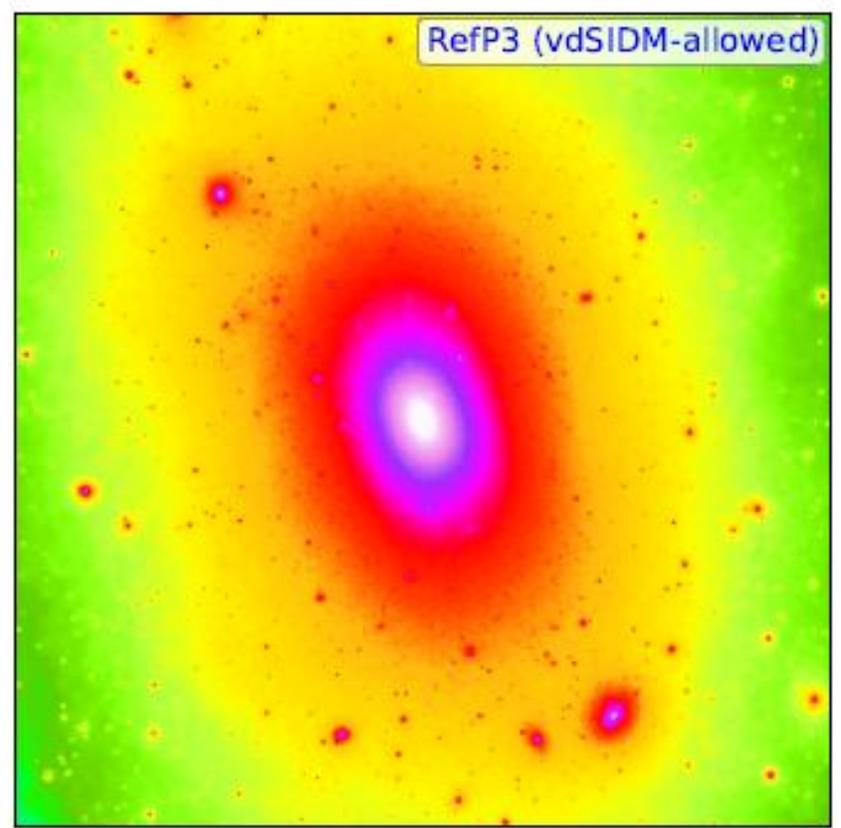
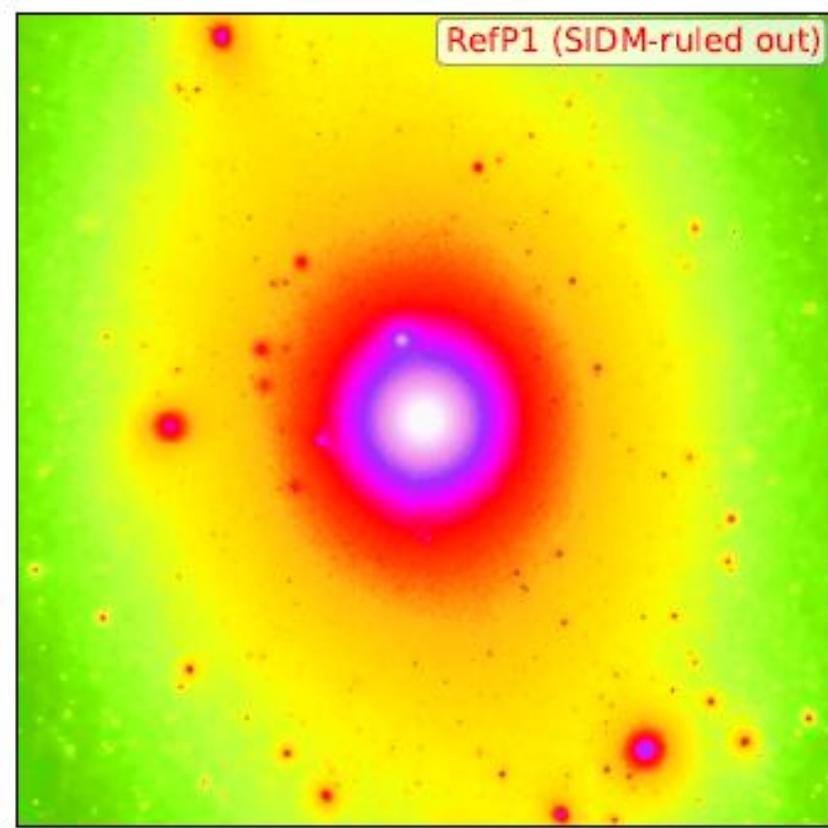
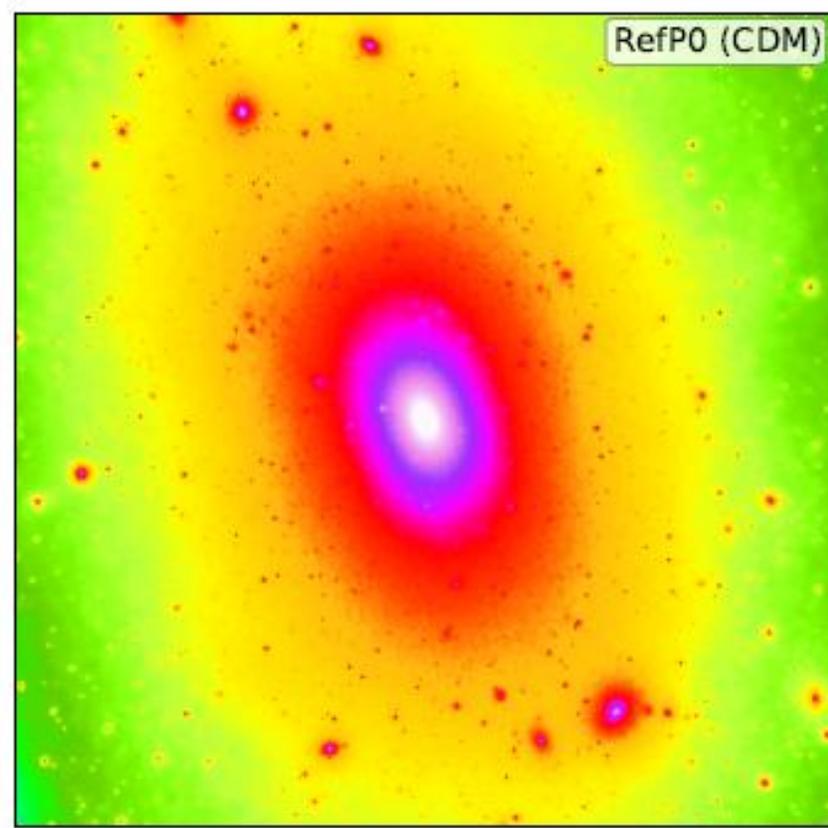
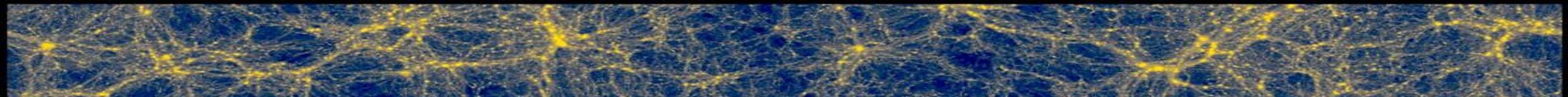
暗物质粒子作用截面与暗物质晕内部结构



Tulin & Yu, 2018

暗物质粒子作用截面与暗物质晕内部结构





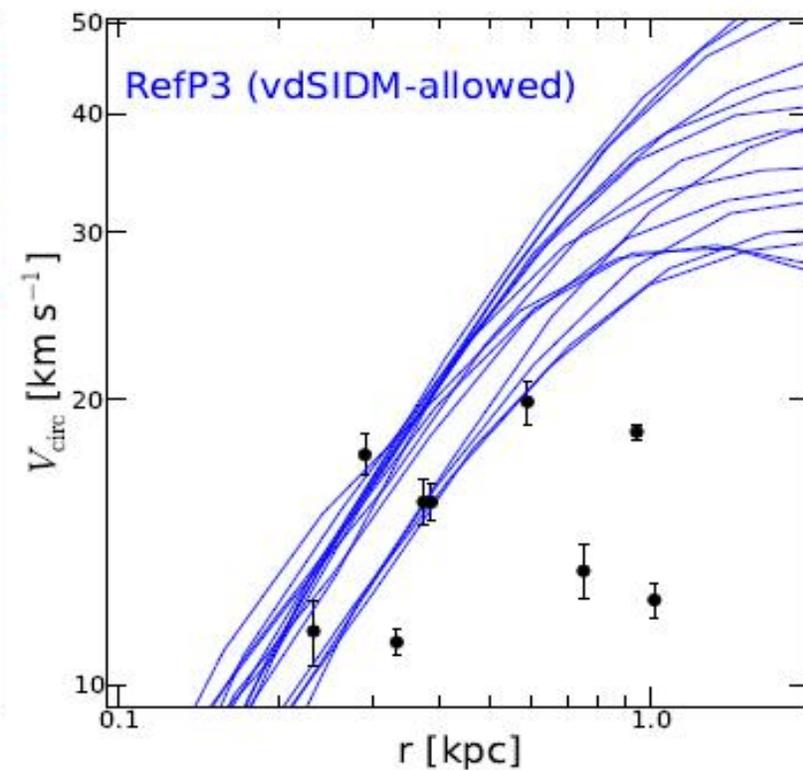
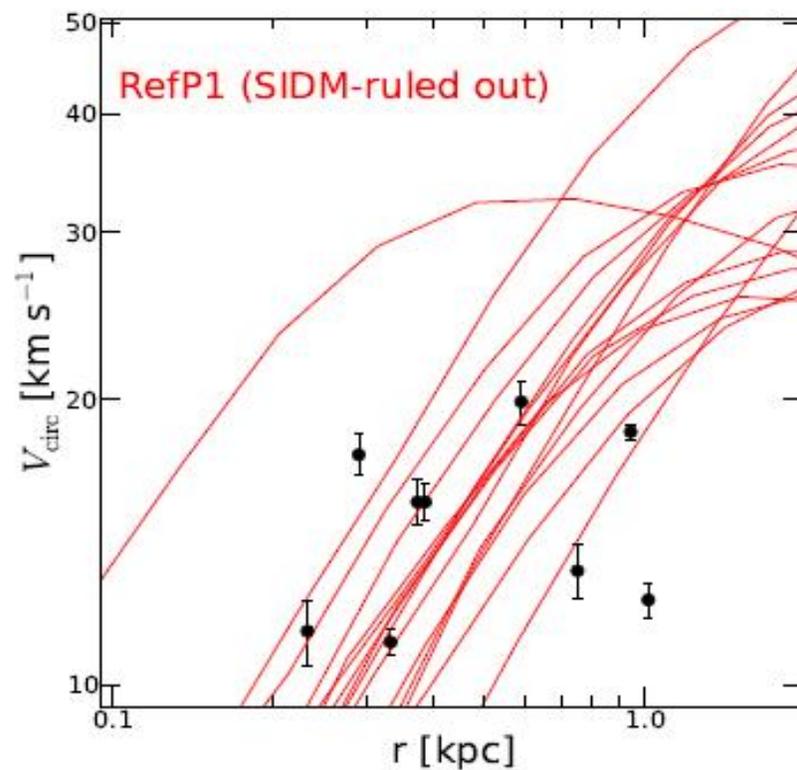
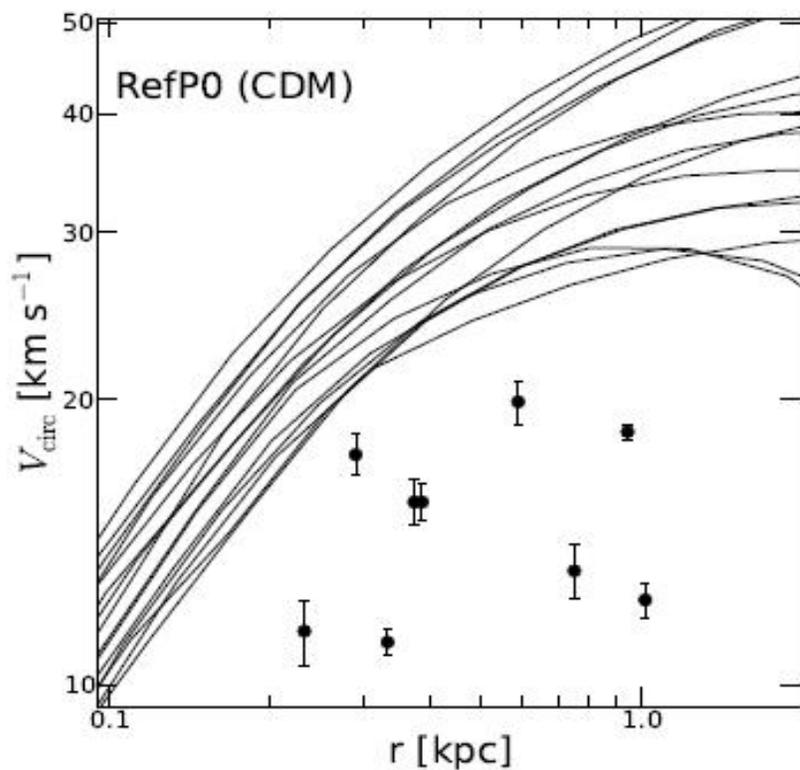
$$\sigma/m = 10 \text{ cm}^2/\text{g}$$

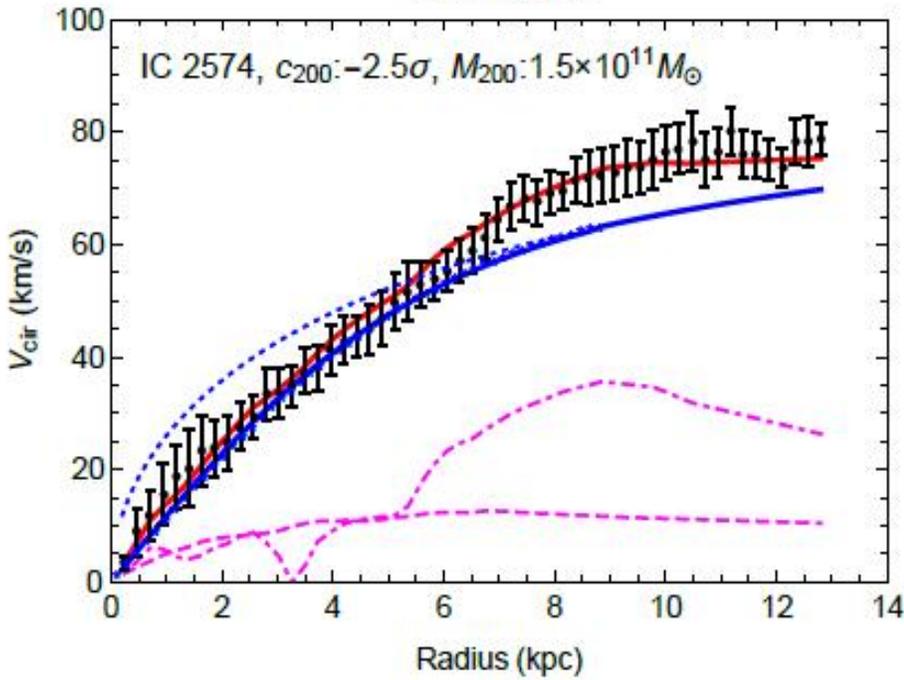
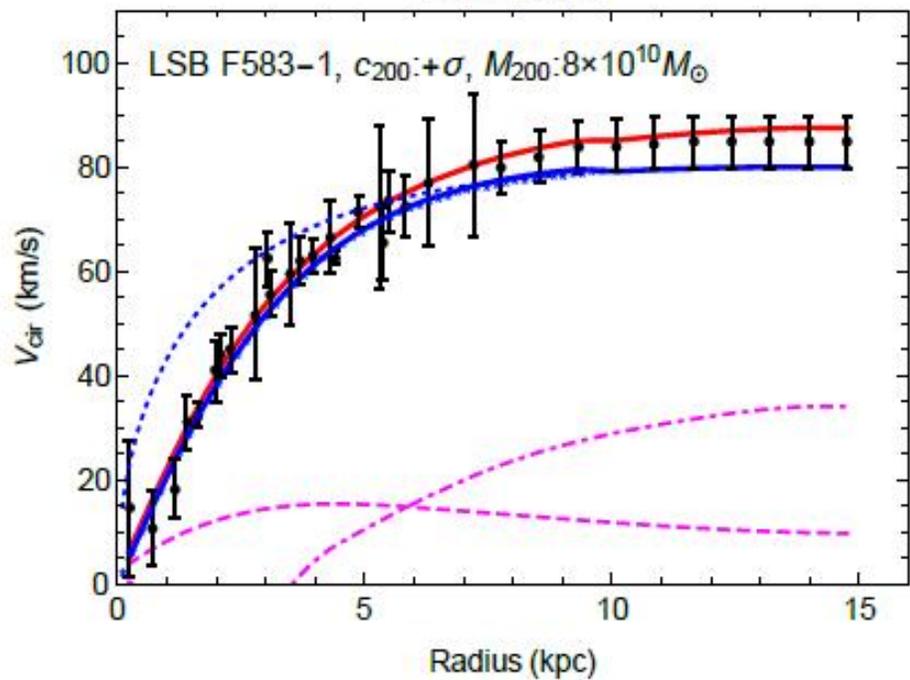
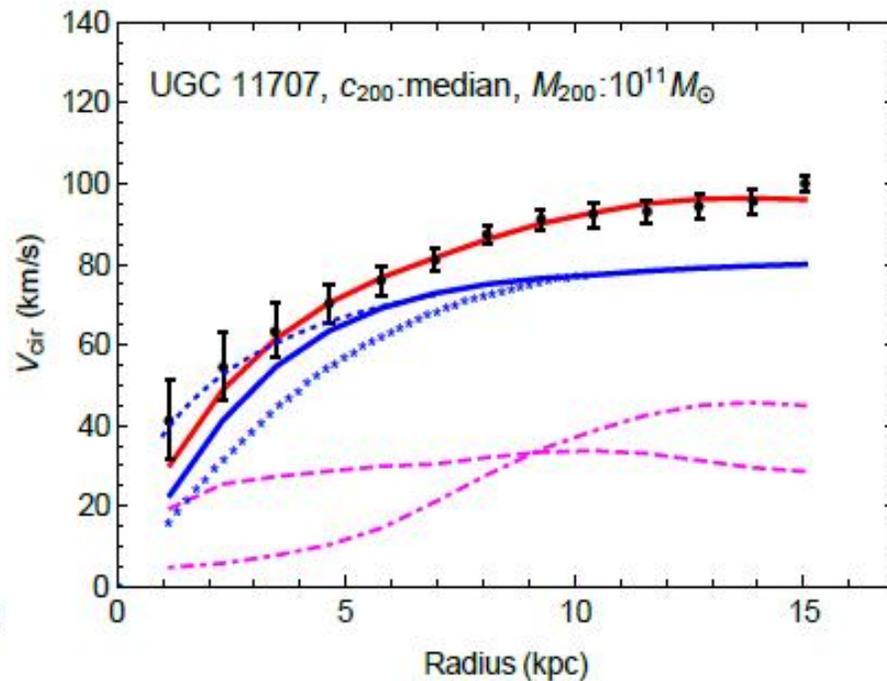
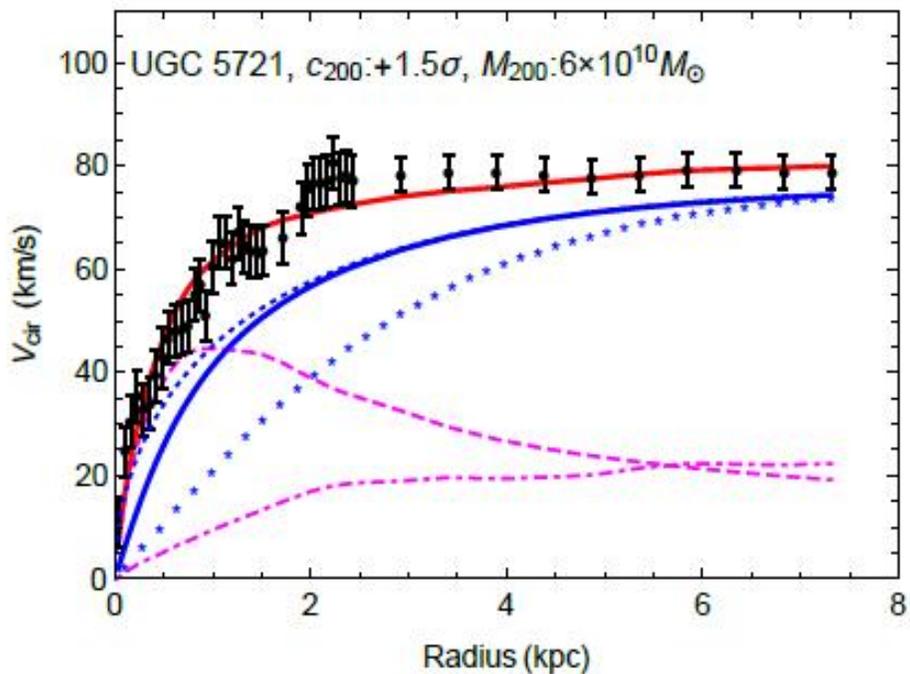
$$\sigma/m = 35 \text{ cm}^2/\text{g at } v = 10 \text{ km/s}$$

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

Vogelsberger et al, 2012

暗物质粒子作用截面与矮星系旋转曲线

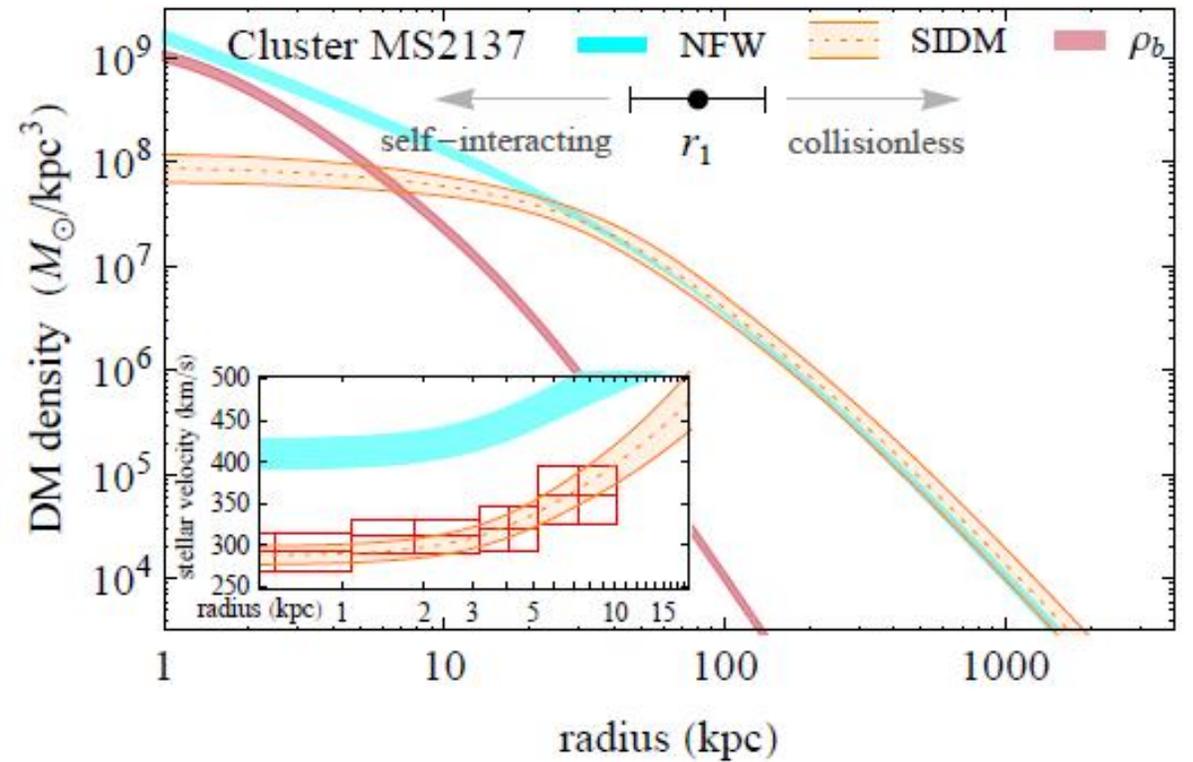
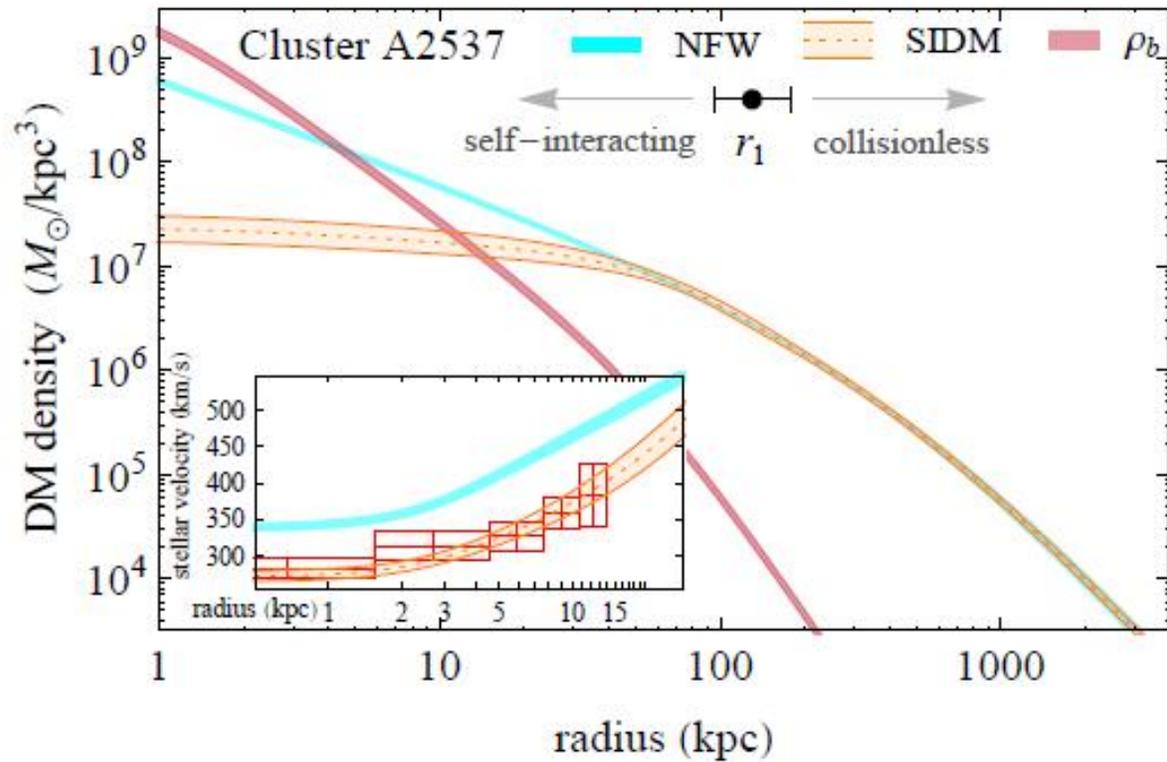




$$\sigma/m = 3 \text{ cm}^2/\text{g}$$

Kamada et al 2016

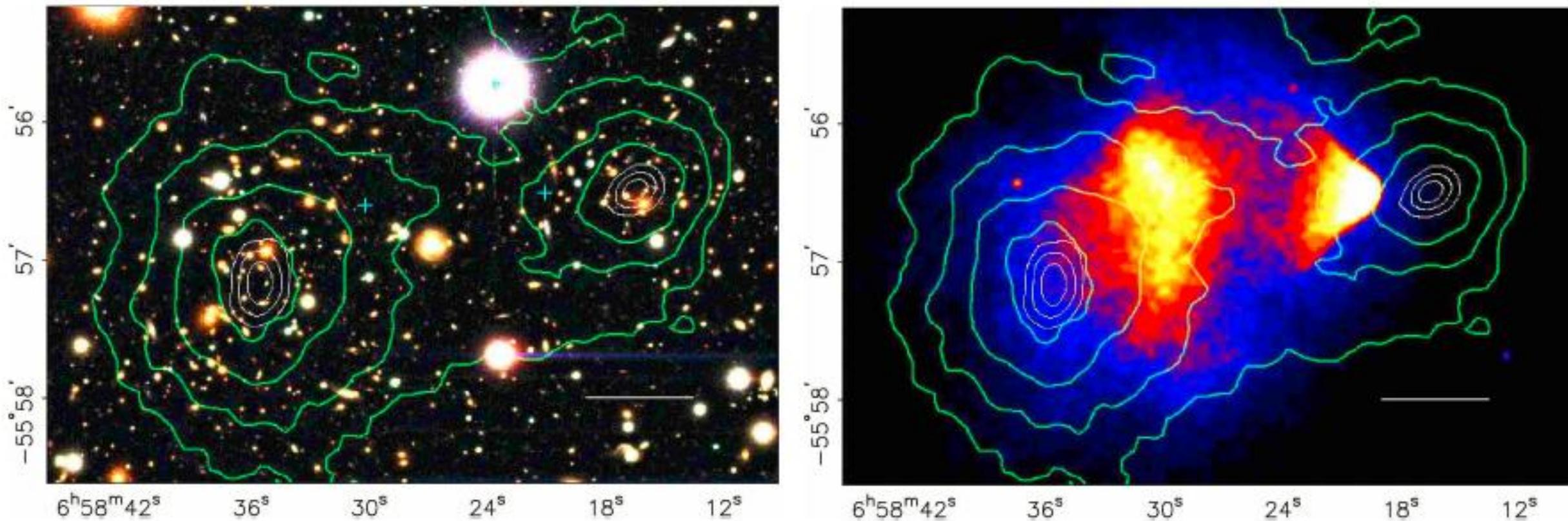
暗物质粒子作用截面与矮星系旋转曲线



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

Kaplinghat et al, 2016

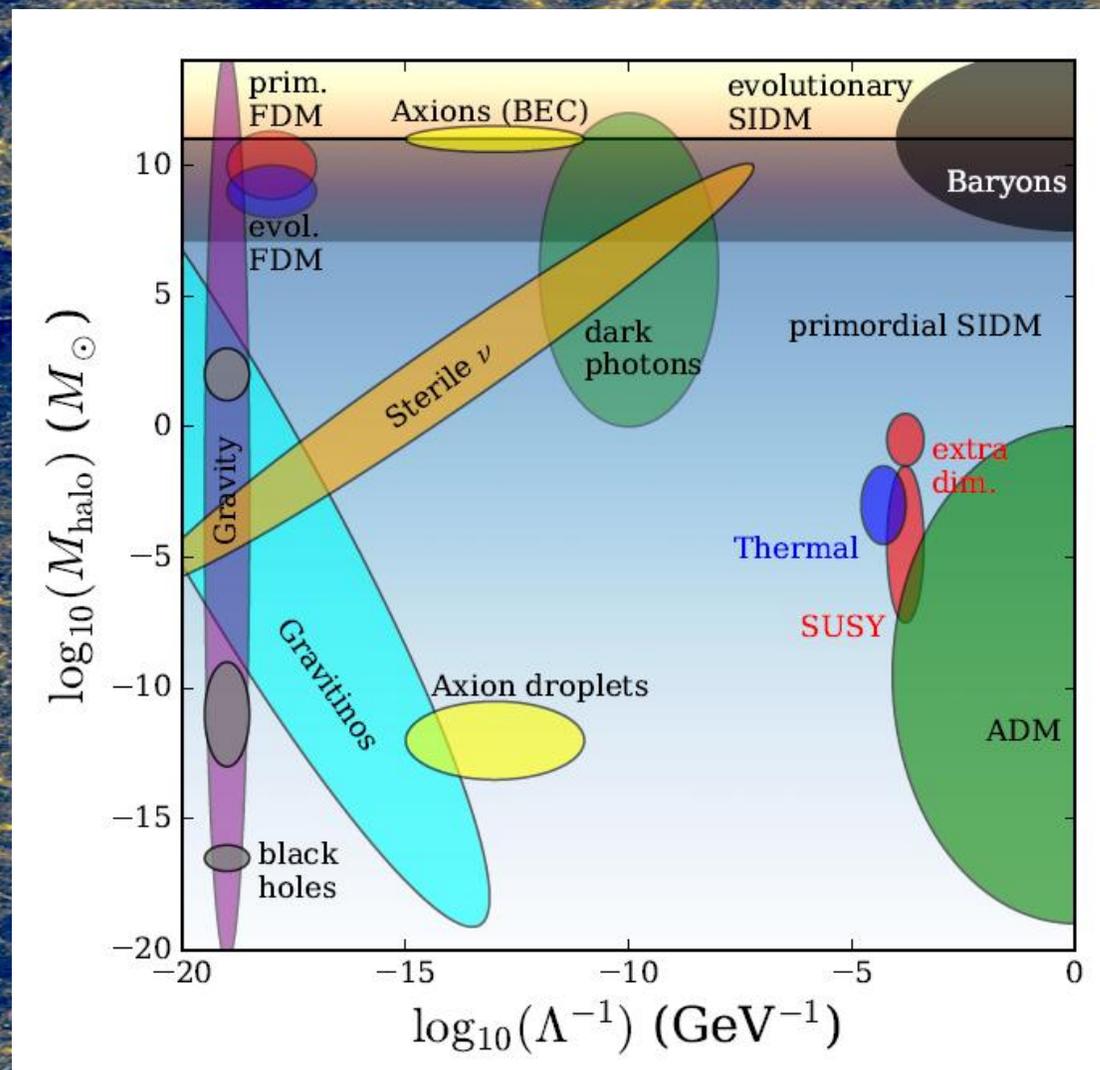
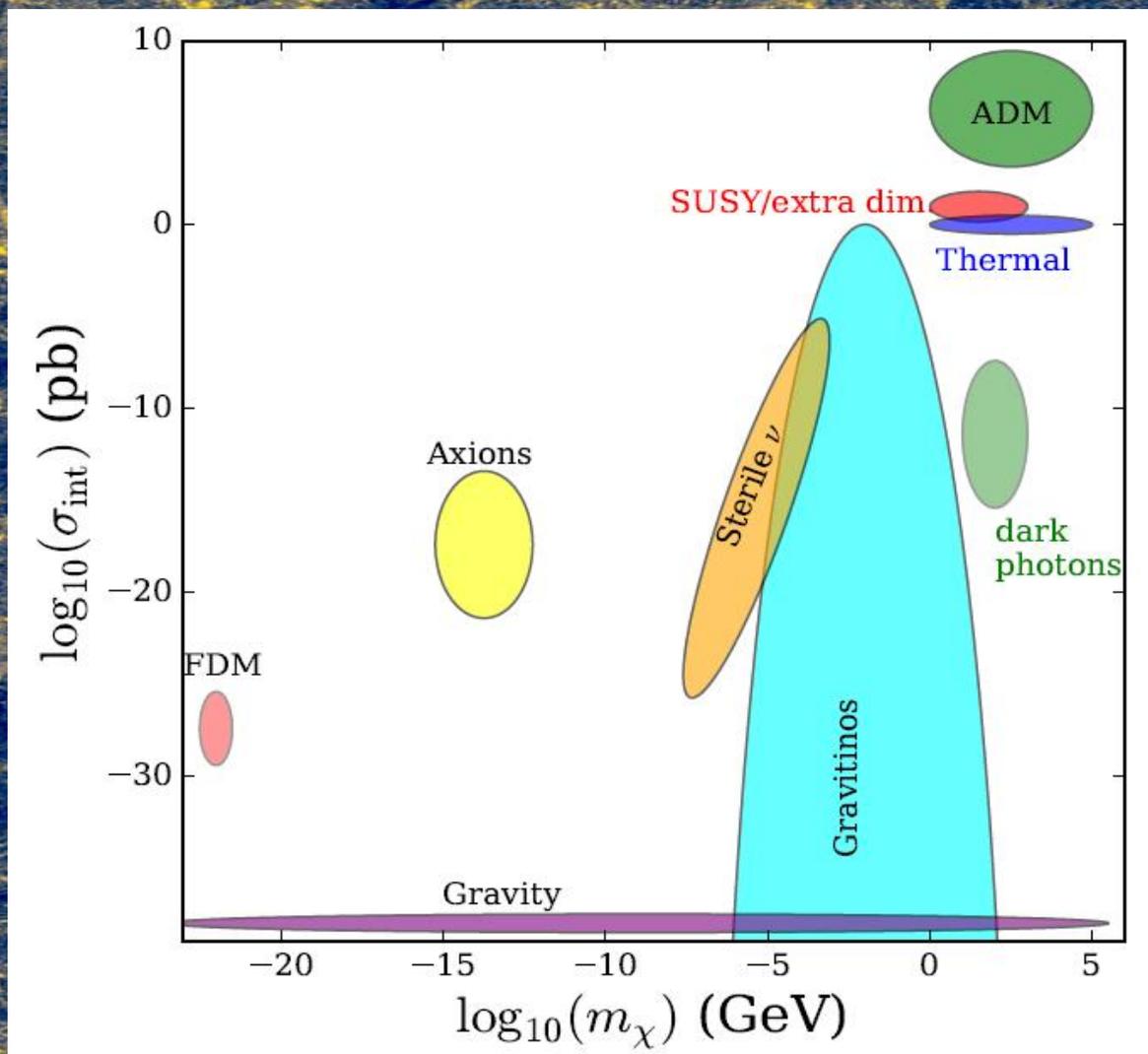
暗物质粒子作用截面与暗晕的并合



Clowe et al. 2006

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

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



Buckley & Peter, 2018

精确测量太阳邻域内暗物质密度

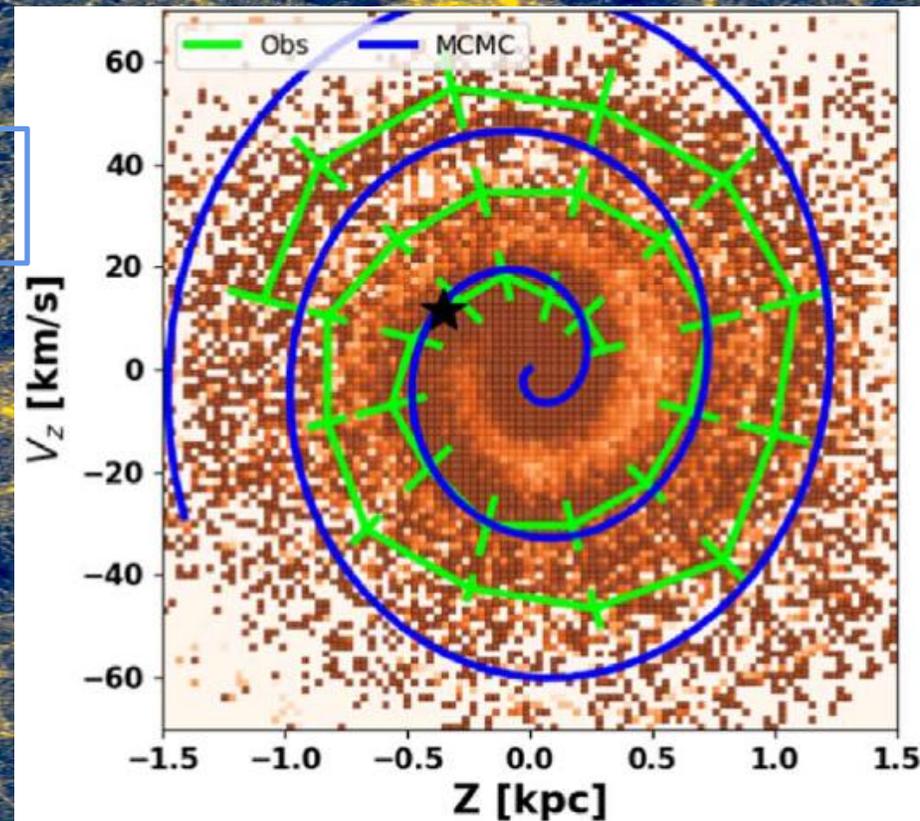
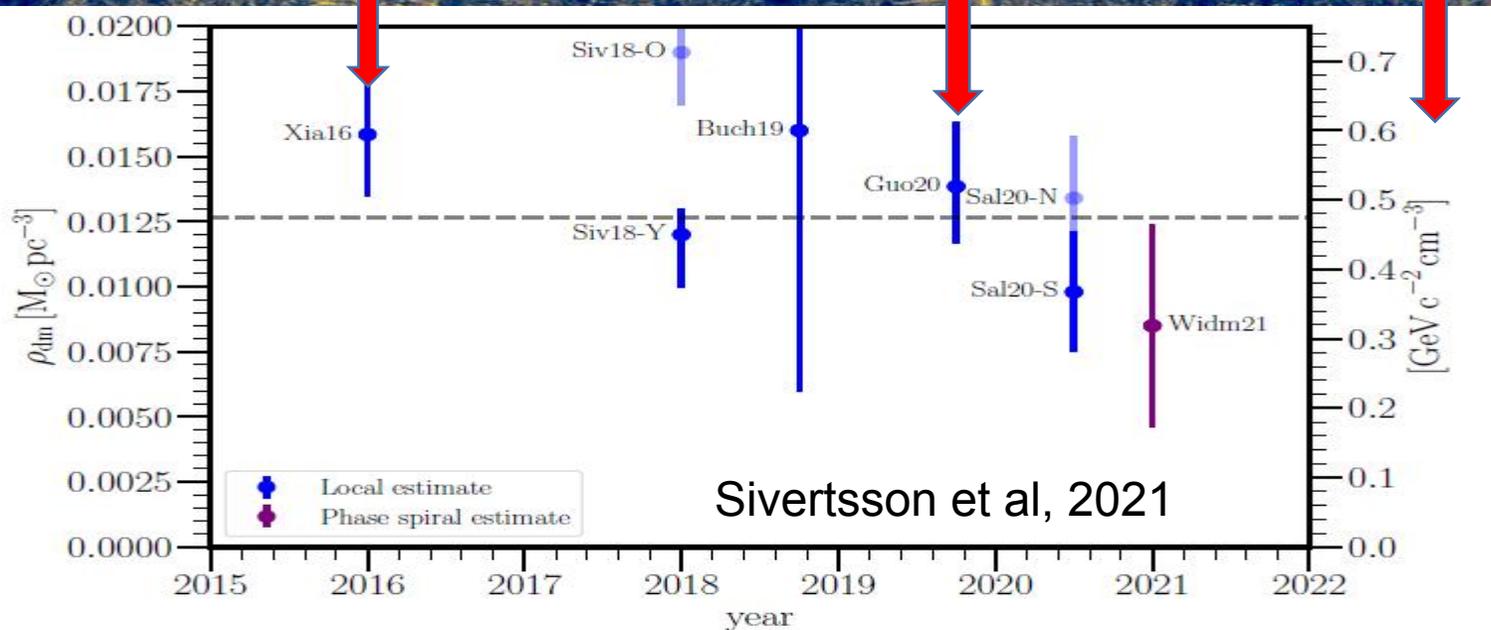
- 对银河系内暗物质分布进行整体（统计）测量，内插太阳邻域处暗物质密度
- 对太阳系附近几百pc左右体积内恒星进行动力学建模，直接测量本地密度

精确测量太阳邻域内暗物质密度

DR-2
约一千万样本

DR-5
约一百万样本

DR-9
五十万样本

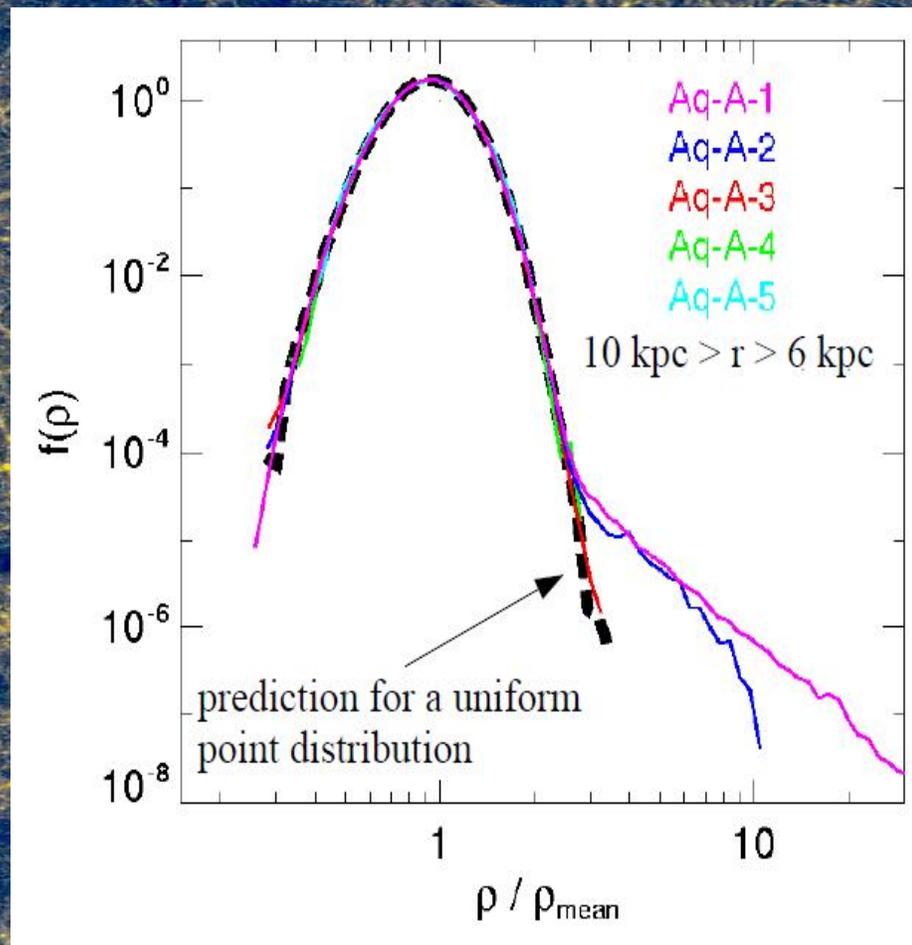


太阳附近暗物质密度测量精度将决定地面暗物质直接探测实验的成败！

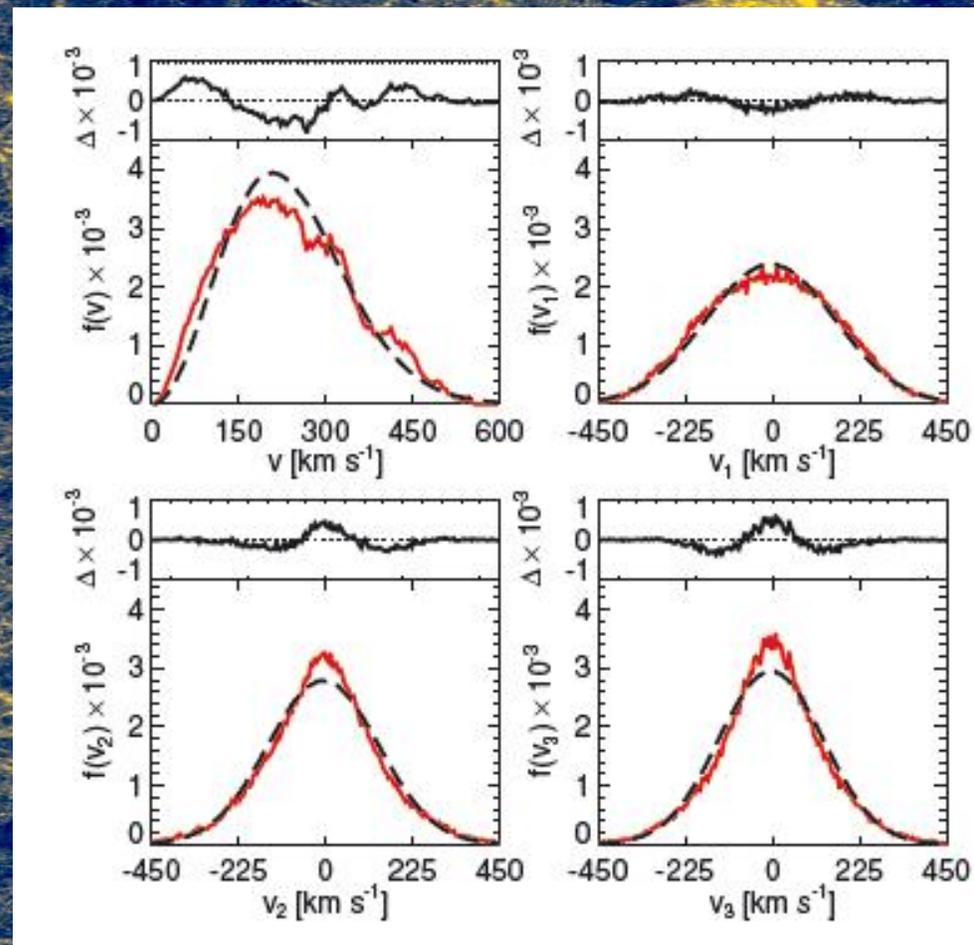
系统噪音：

- 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

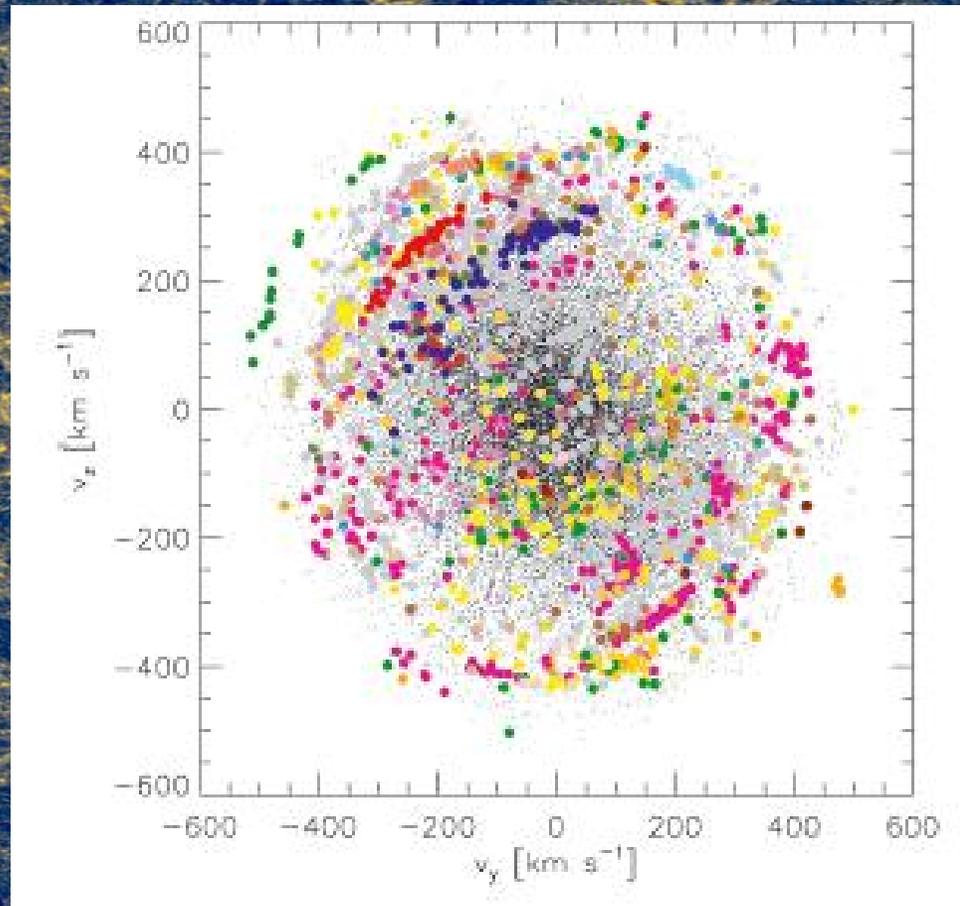


平滑, 子结构 $< 10^{-4}$

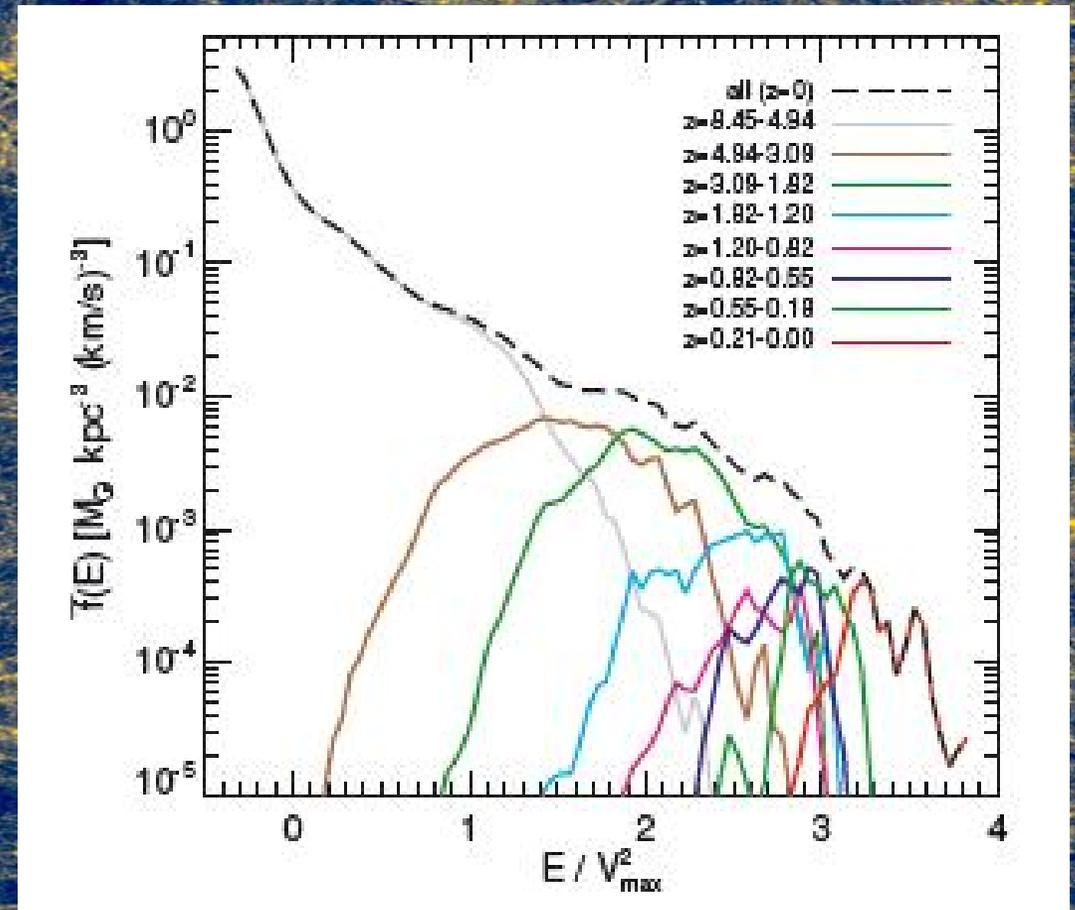


各向异性, 平滑, 无子结构, 但幅度分布有子结构

太阳领域暗物质密度和速度分布



速度空间的结构

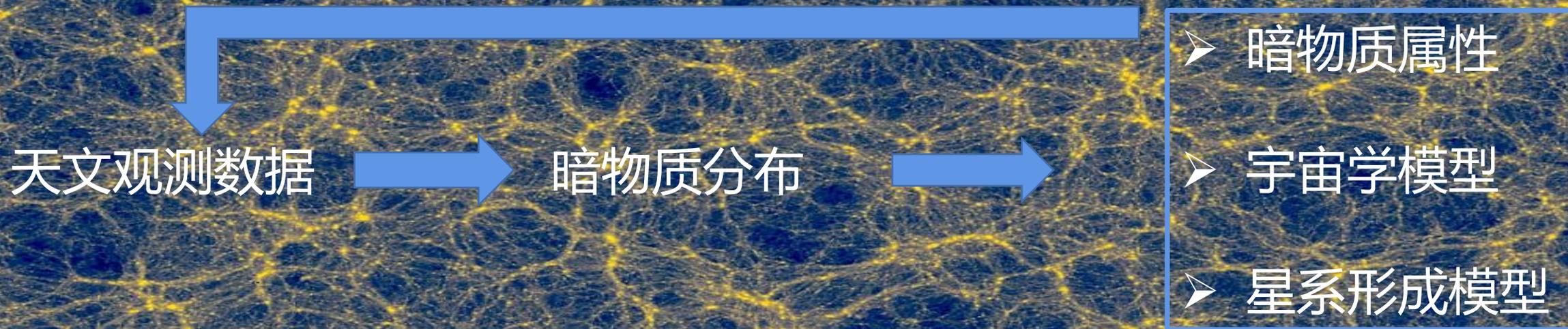


能量空间结构

都比较明显 → 暗物质天文学

小结

- 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



粒子物理

天体物理

理论

精确的宏观效应预测



实验

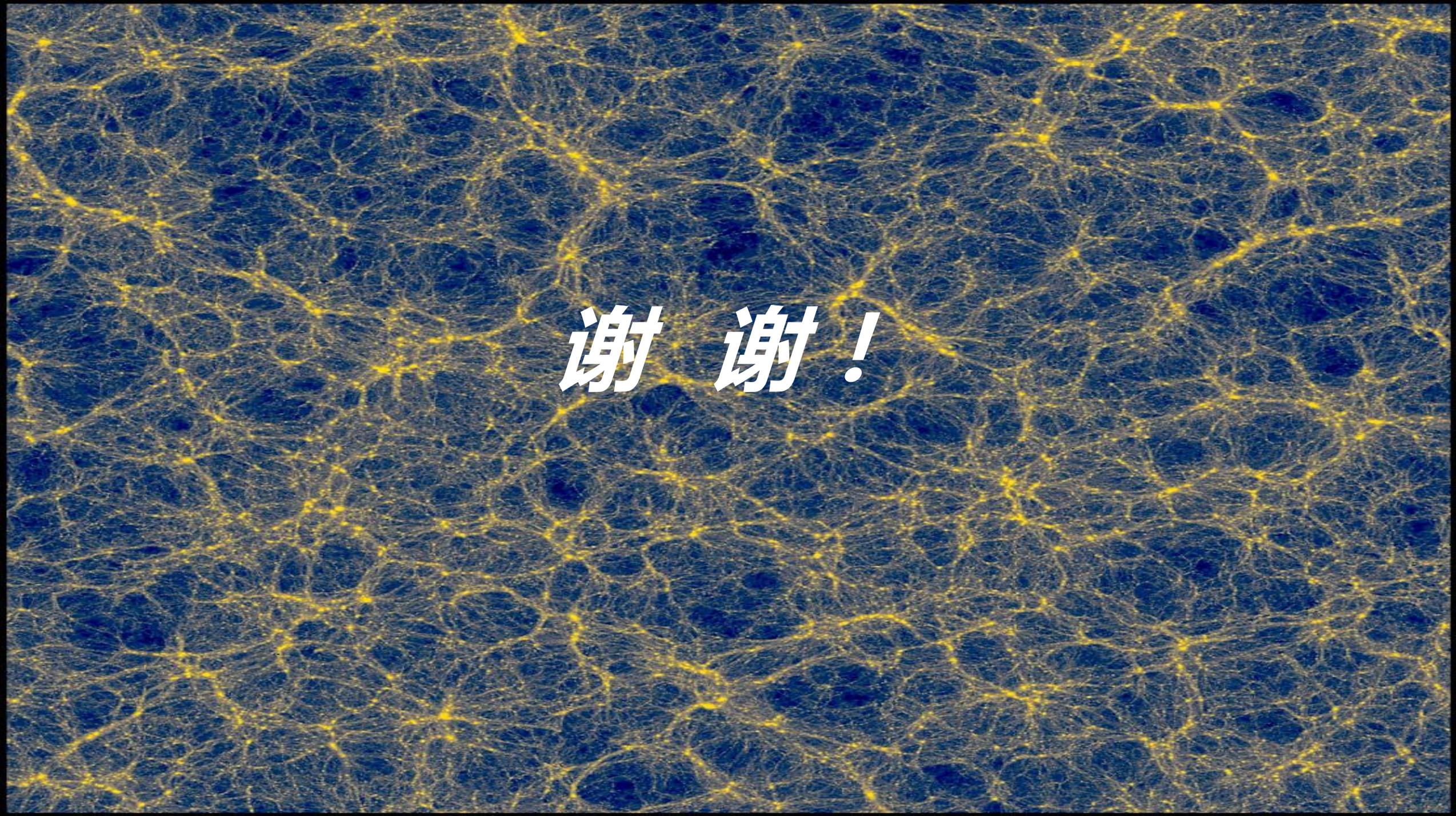
精确的参数限制？



眼里只有你：暗物质



宇宙那么大，我们尽力了



谢谢!