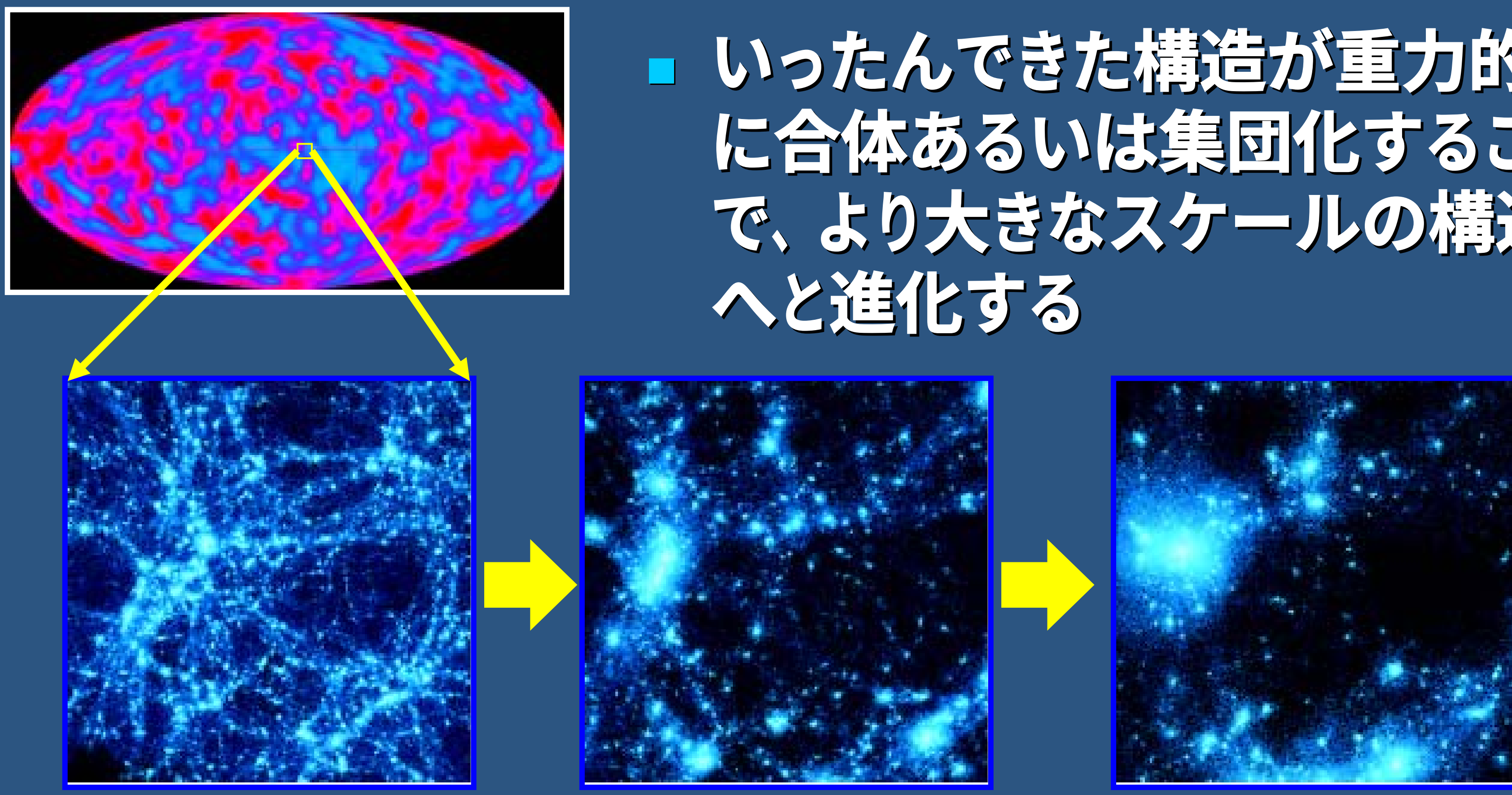
宇宙構造形成パラダイムと冷たいダークマター

東京大学　大学院理学系研究科
須藤　靖

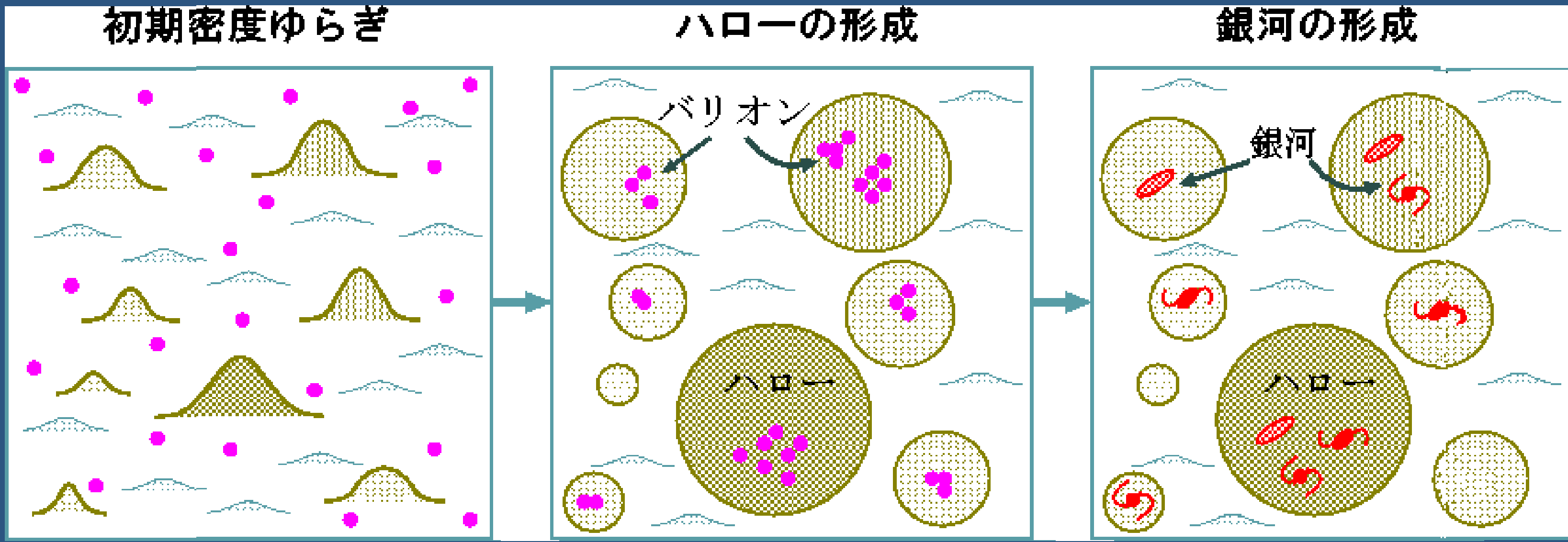
2003年7月8日
東京大学　宇宙線研究所

宇宙の構造形成シナリオ

- 小さなスケールの構造ほど初期に形成される
- いったんできた構造が重力的に合体あるいは集団化することで、より大きなスケールの構造へと進化する



重力不安定による構造形成パラダイム



重力進化

ガスの冷却
輻射過程
星形成進化
…

樽家篤史 (2001) 日本物理学会誌

ダークハロー (ダークマターの自己重力系) の形成が天体形成において最も基本的な素過程

SPH simulation: movie

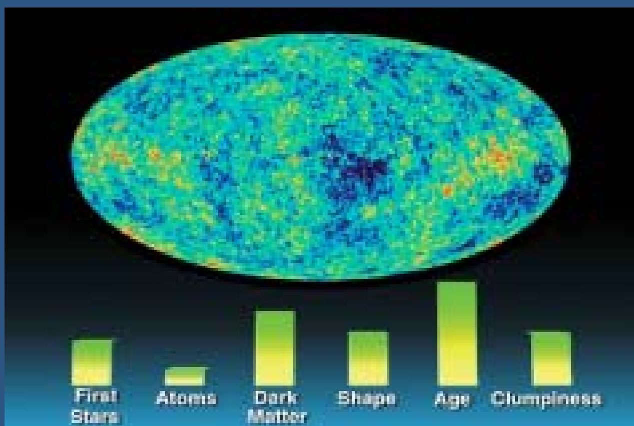
SPH simulation in ΛCDM : dark matter ⇒ hot gas ⇒ galaxy (Yoshikawa, Taruya, Jing & Suto 2001)

Confronting elements of the CDM paradigm

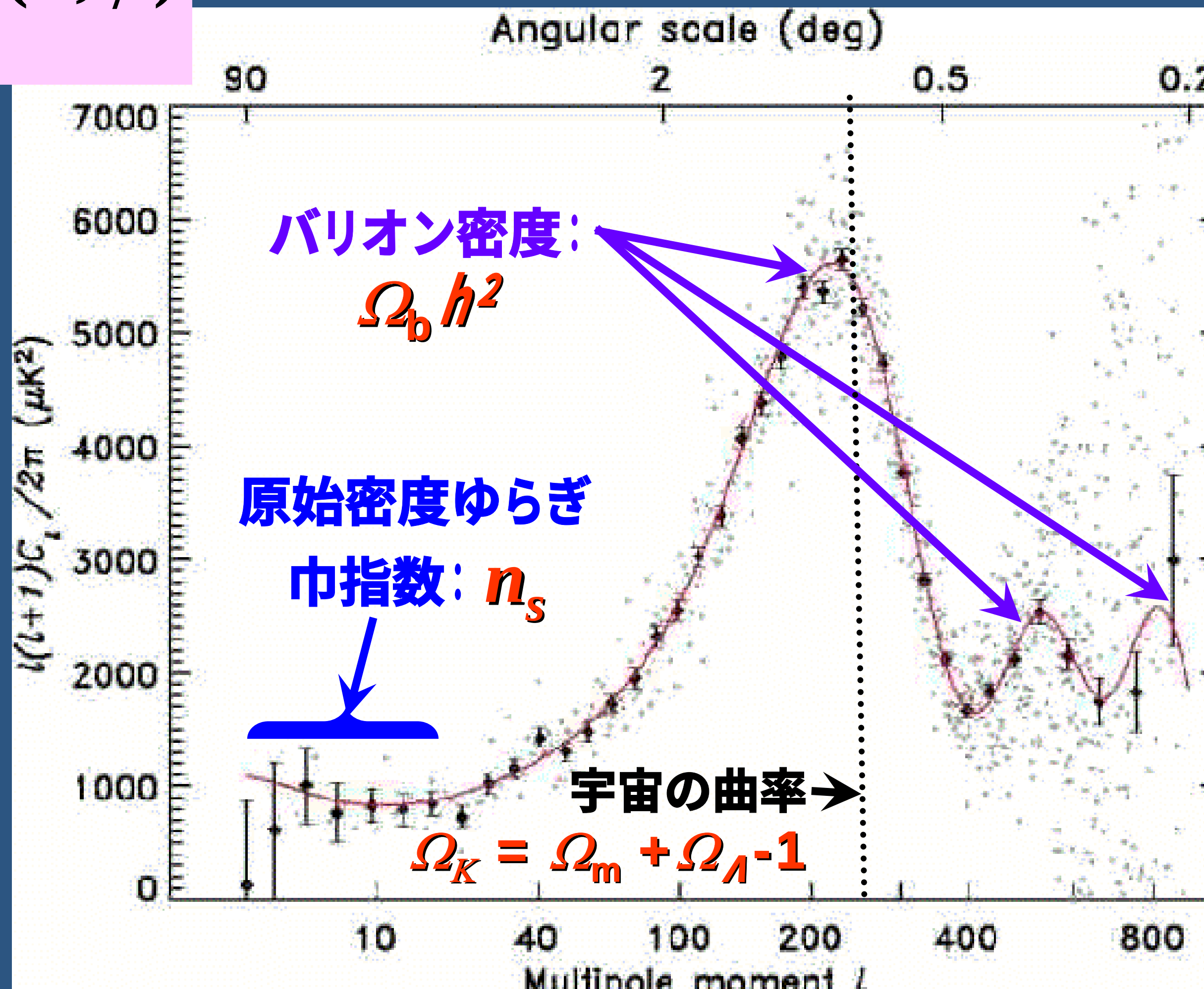
- **Global cosmological parameters**
  - **Fairly well established – confirmed by WMAP**
- Large-scale structure
  - Galaxy biasing with respect to CDM distribution
- Galaxy cluster abundance
  - Amplitude of CDM density fluctuations
- Density profile of dark halos
  - Cusp or core in the central region
- Substructures
  - Formation efficiency of visible objects out of CDM halos

WMAPが観測した温度ゆらぎパワースペクトル

$$\frac{\delta T}{T}(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

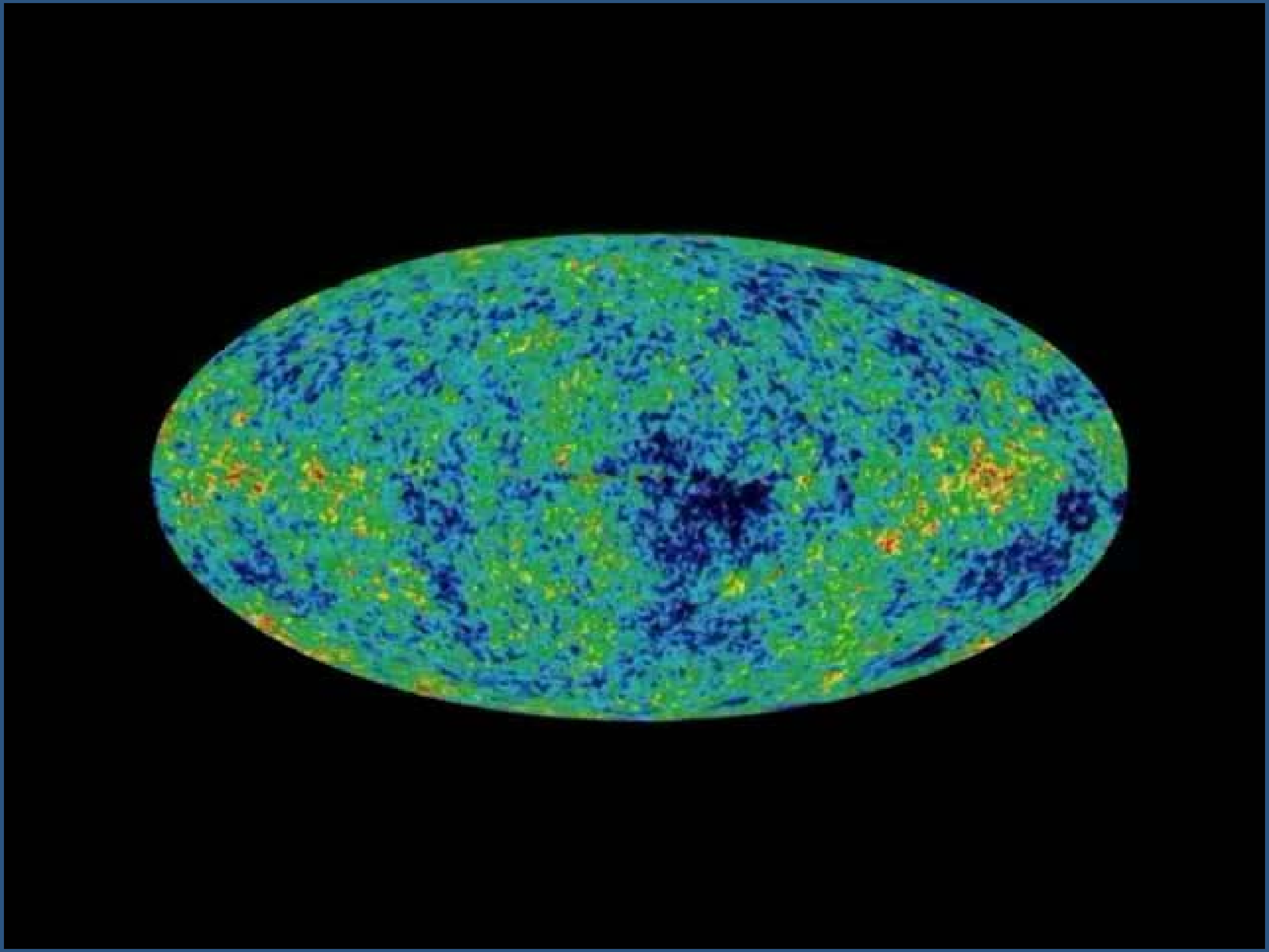


$$C_l = \left\langle a_{lm} a_{lm}^* \right\rangle$$



Spergel et al.
astro-ph/0302209

CMBから現在の宇宙へ

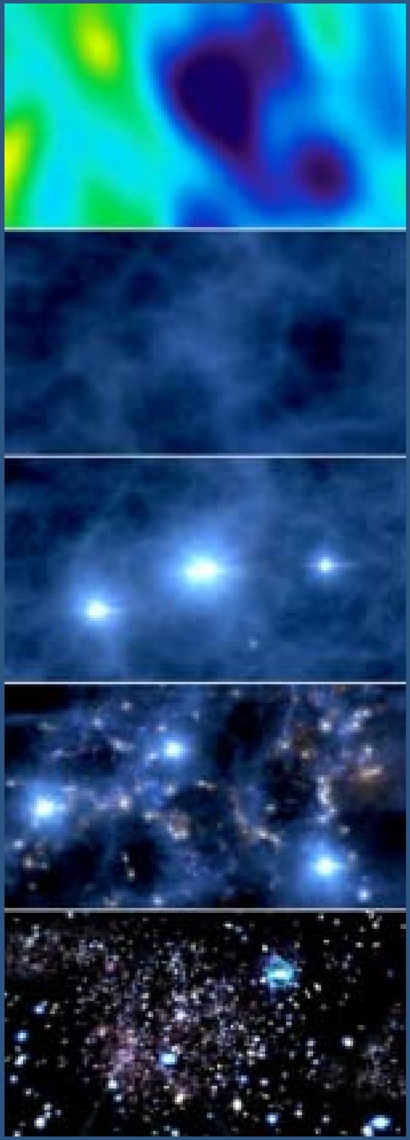


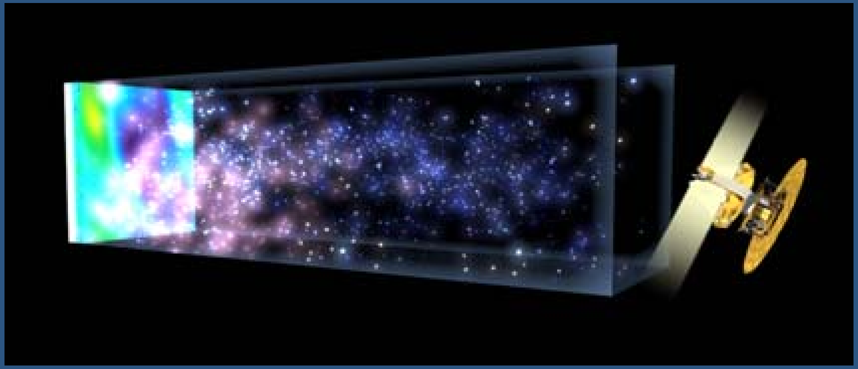
NASA/WMAP Science Team

http://lambda.gsfc.nasa.gov

WMAP 1st year 成果の要約

- 容器としての宇宙モデルを確定
- 宇宙の再電離時期
- ほとんどすべてのデータが、驚くべき精度で 「インフレーション＋宇宙定数入りの冷たい暗黒物質モデル」の理論予言とぴたりと一致
- The most revolutionary result out of WMAP is that there is no revolutionary results. (J. Bahcall)





WMAPが決定した
宇宙論パラメータ

Old Universe - *New* Numbers

$\Omega_{tot} = 1.02 \pm 0.02$

$w < -0.78$ (95% CL)

$\Omega_\Lambda = 0.73 \pm 0.04$

$\Omega_b h^2 = 0.0224 \pm 0.0009$

$\Omega_b = 0.044 \pm 0.004$

$n_b = (2.5 \pm 0.1) \times 10^{-7}\,\mathrm{cm}^{-3}$

$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$

$\Omega_m = 0.27 \pm 0.04$

$\Omega_\nu h^2 < 0.0076$ (95% CL)

$m_\nu < 0.23$ eV (95% CL)

$T_{cmb} = 2.725 \pm 0.002$ K

$z_r = 20^{+10}_{-9}$ (95% CL)

$t_r = 180^{+220}_{-80}$ Myr (95% CL)

$r(k_0 = 0.002\,\mathrm{Mpc}^{-1}) < 0.71$ (95% CL)

$A(k_0 = 0.05\,\mathrm{Mpc}^{-1}) = 0.833^{+0.086}_{-0.083}$

$n_\gamma = 410.4 \pm 0.9\,\mathrm{cm}^{-3}$

$n_s = 0.99 \pm 0.04$ (WMAP only)

$n_s(k_0 = 0.05\,\mathrm{Mpc}^{-1}) = 0.93 \pm 0.03$ with $dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$

$\eta = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$

$\Omega_b \Omega_m^{-1} = 0.17 \pm 0.01$

$\sigma_8 = 0.84 \pm 0.04$

$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$

$z_{dec} = 1089 \pm 1$

$\Delta z_{dec} = 195 \pm 2$

$h = 0.71^{+0.04}_{-0.03}$

$r_s = 147 \pm 2$ Mpc

$d_C = 14.0^{+0.2}_{-0.3}$ Gpc

$\theta_A = 0.^\circ 598 \pm 0.^\circ 002$

$l_A = 301 \pm 1$

$t_0 = 13.7 \pm 0.2$ Gyr

$t_{dec} = 379^{+8}_{-7}$ kyr

$\Delta t_{dec} = 118^{+3}_{-2}$ kyr

$z_{eq} = 3233^{+194}_{-210}$

$\tau = 0.17 \pm 0.04$

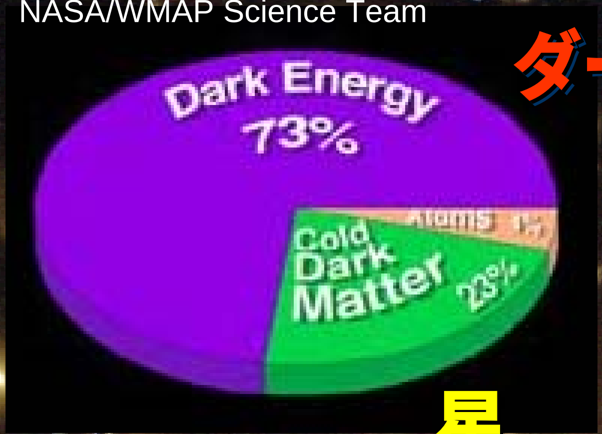
These "best" cosmological parameter values are from a combination of a wide variety of cosmological measurements, including the WMAP, COBE, CBI, and ACBAR CMB measurements and 2dFGRS, HST, SNIa, and Lyman-alpha forest measurements.

http://lambda.gsfc.nasa.gov

現在の宇宙の組成

http://lambda.gsfc.nasa.gov

NASA/WMAP Science Team



総量= 1.02±0.02

ダークエネルギー（宇宙定数） 0.73±0.04

全物質 0.27±0.04

星 0.005±0.002

バリオン 0.044±0.004

CDM 0.23±0.04

理論予言

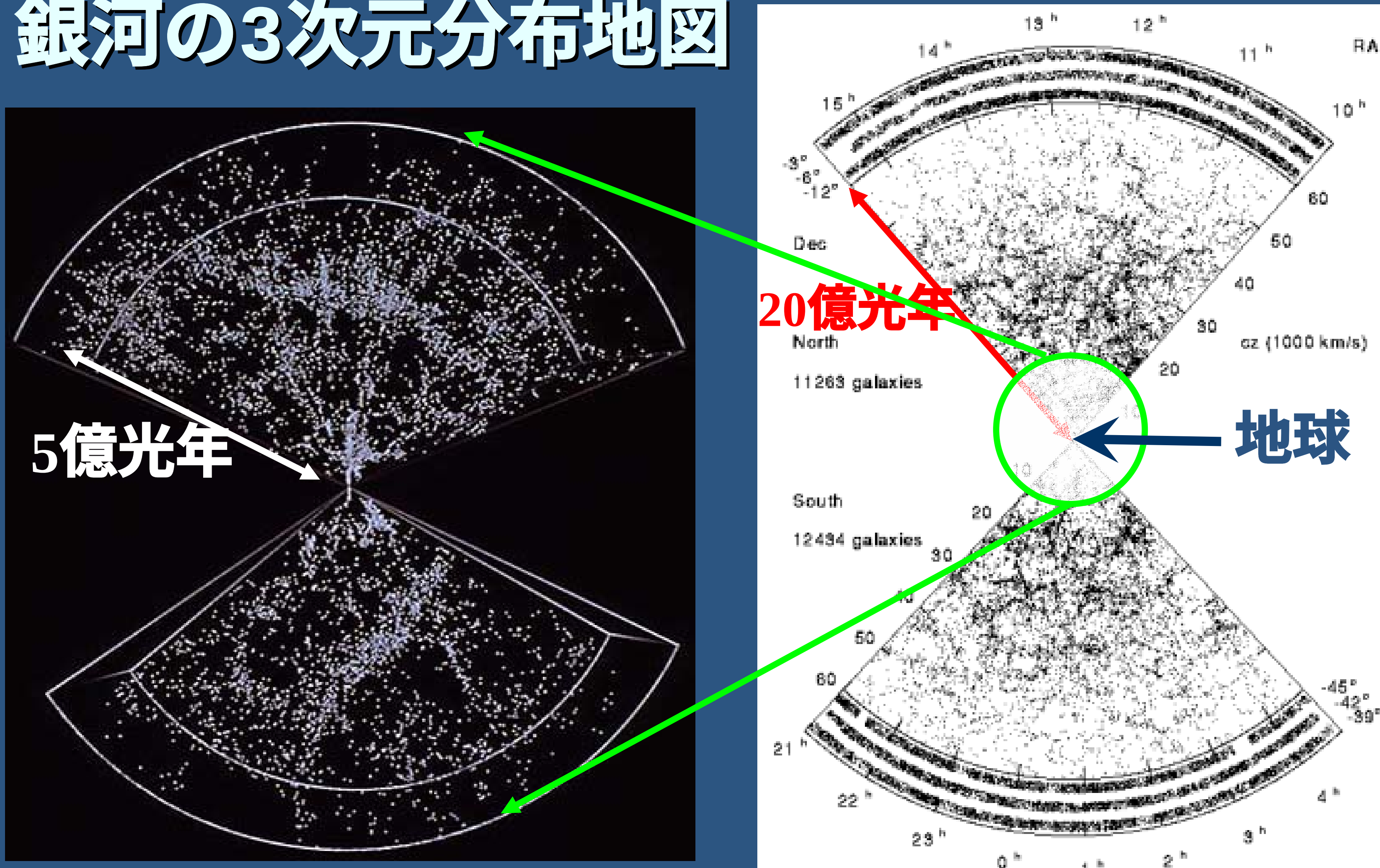
0.001　0.01　0.1　1.0

宇宙の全質量に占める割合

Confronting elements of the CDM paradigm

- Global cosmological parameters
  - Fairly well established – confirmed by WMAP
- **Large-scale structure**
  - **Galaxy biasing with respect to CDM distribution**
- Galaxy cluster abundance
  - Amplitude of CDM density fluctuations
- Density profile of dark halos
  - Cusp or core in the central region
- Substructures
  - Formation efficiency of visible objects out of CDM halos

銀河の3次元分布地図

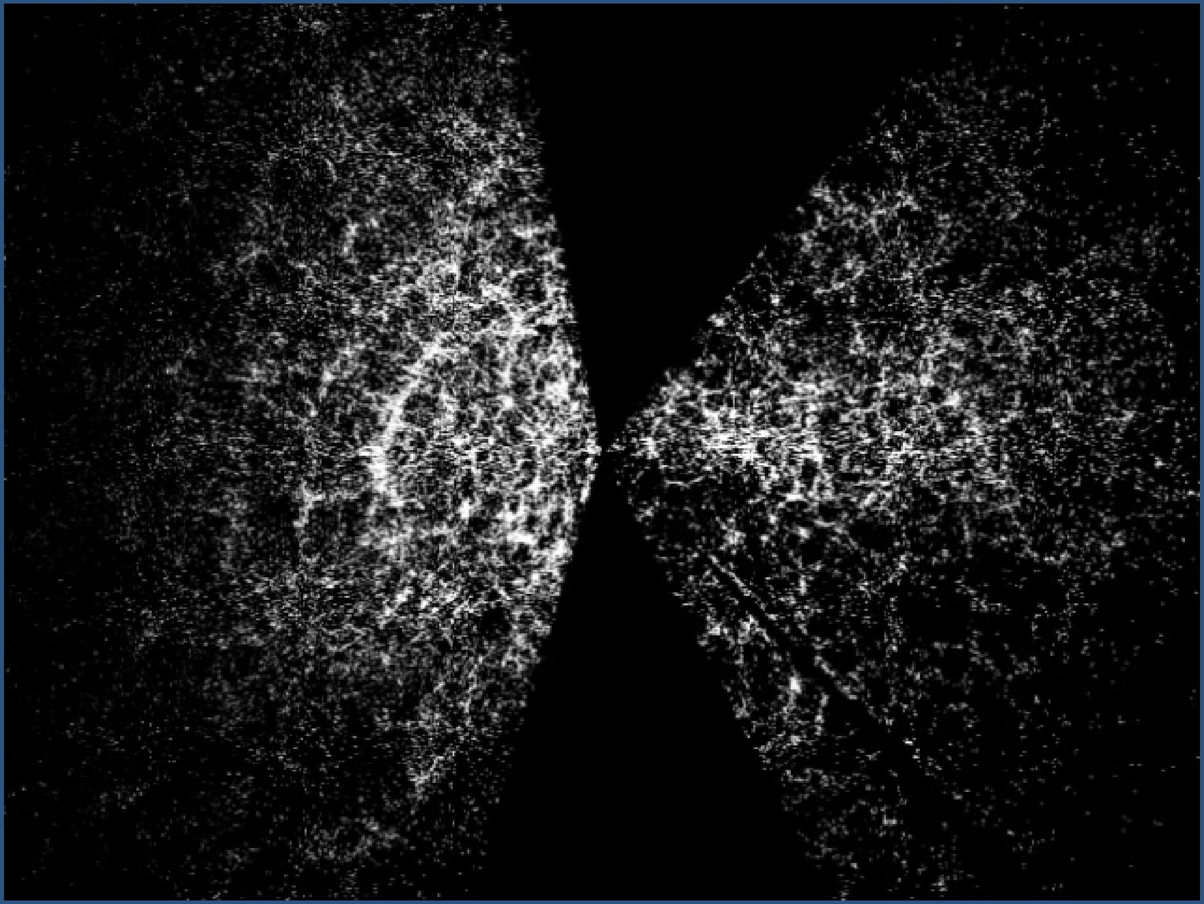


CfA galaxy redshift survey:
Geller, da Costa & Huchra (1992)

Las Campanas redshift survey:
Schectman et al. (1996)

より広い銀河地図作りをめざして：
日米独共同スローンデジタルスカイサーベイ

1億個の銀河を観測、100万個の銀河の地図作り



http://www.sdss.org/dr1/

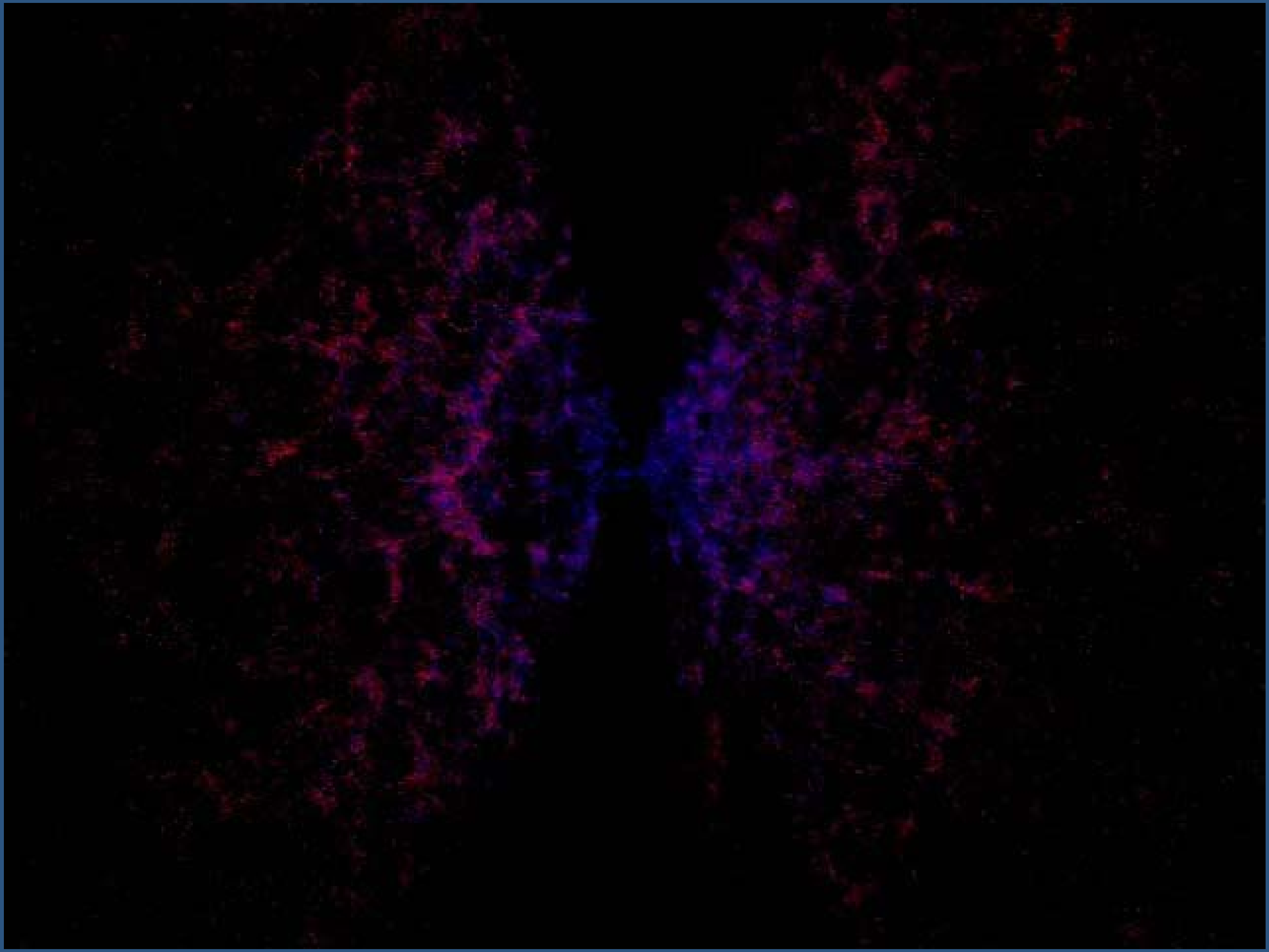
文部科学省
Ministry of Education,Culture,
Sports, Science and Technology

NHK教育　サイエンスZERO　2003年6月11日　0：00　放映

Tour in SDSS DR1 galaxies

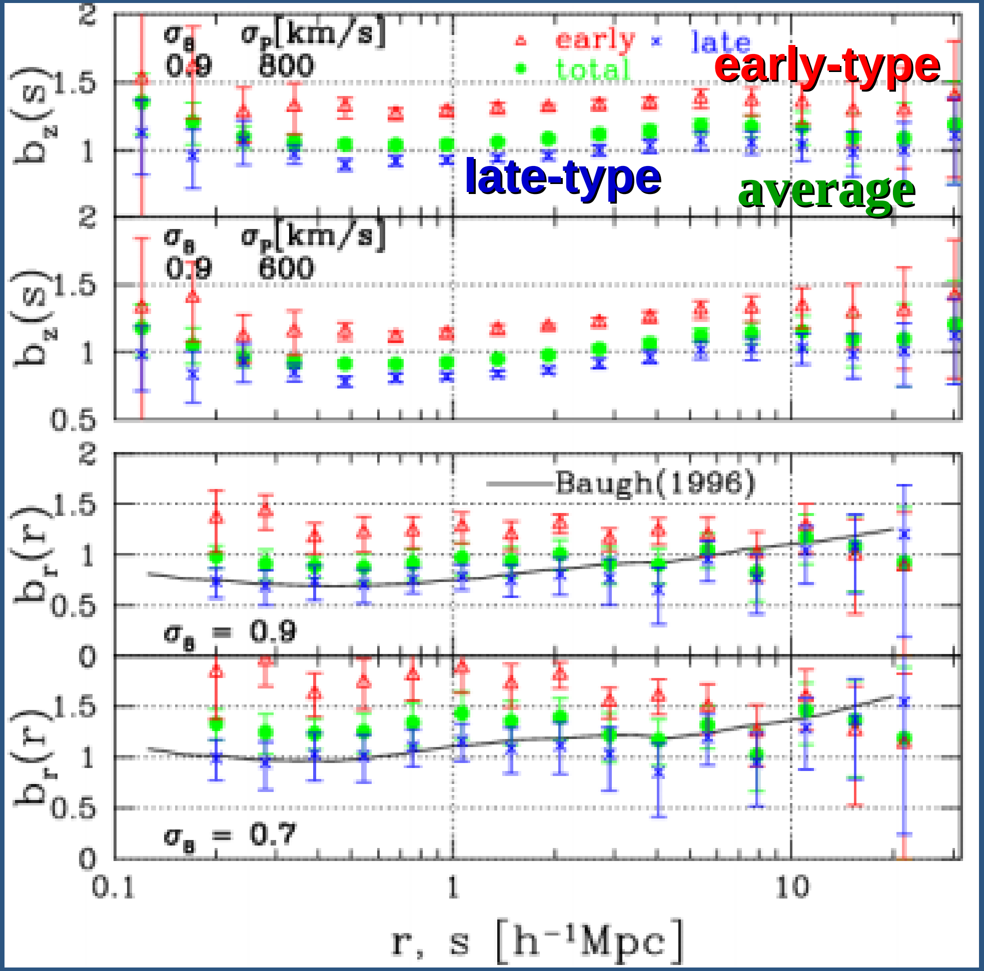
NHK教育　サイエンスZERO　2003年6月11日　0：00　放映

SDSS DR1 galaxies: morphology dependent clustering



NHK教育　サイエンスZERO　2003年6月11日　0：00　放映

Morphology-dependent SDSS galaxy bias



σ_8 : assumed fluctuation amplitude

σ_p : pair-wise velocity dispersion [km/s]

$$b \equiv \sqrt{\xi(galaxies)/\xi(\Lambda\mathrm{CDM})}$$

- galaxy bias is fairly scale-independent, if ΛCDM (+ σ_8, σ_p) assumed.
- clear morphology dependence; "early"-types are positively biased relative to mass, while "late"-types are anti-biased.

Kayo, Suto, Fukugita, Nakamura, et al. , in preparation

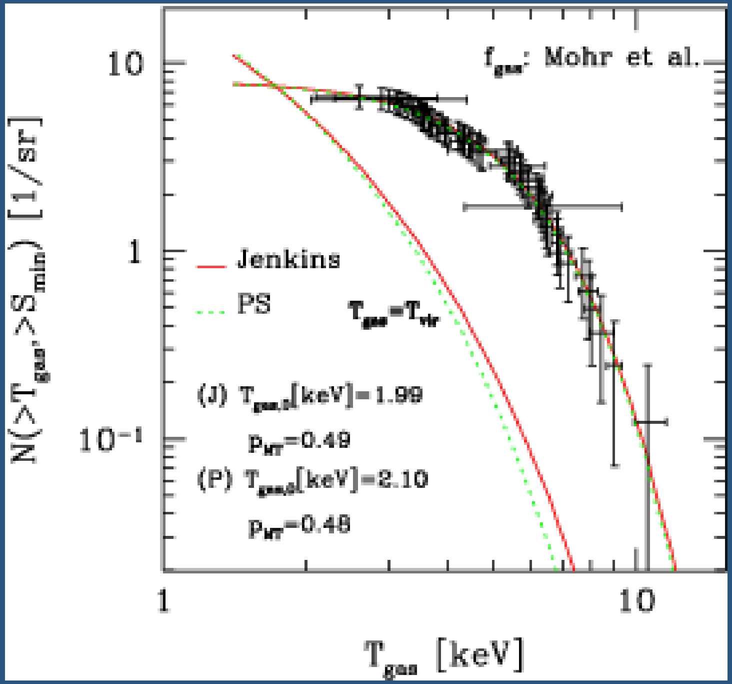
Large-scale structure and mass density of the universe

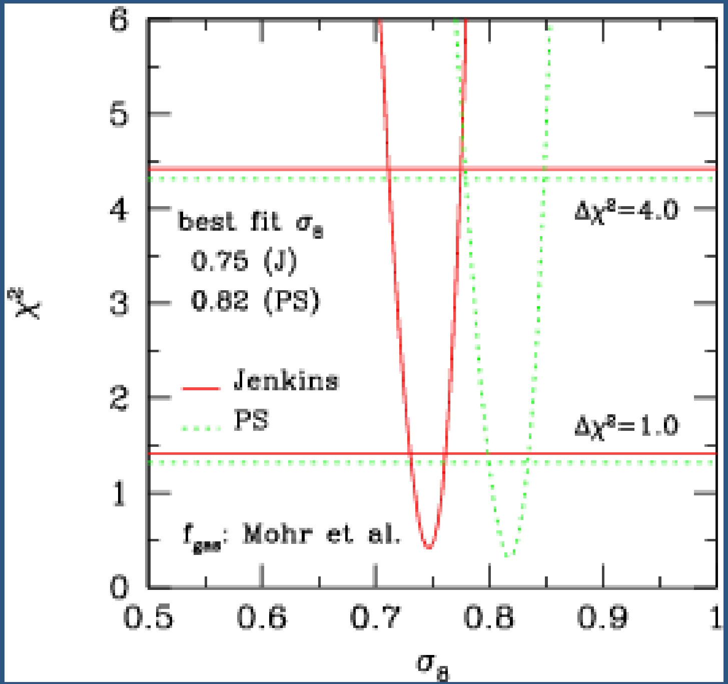
NHK教育　サイエンスZERO　2003年6月11日　0：00　放映

Confronting elements of the CDM paradigm

- Global cosmological parameters
  - Fairly well established – confirmed by WMAP
- Large-scale structure
  - Galaxy biasing with respect to CDM distribution
- **<u>Galaxy cluster abundance</u>**
  - **<u>Amplitude of CDM density fluctuations</u>**
- Density profile of dark halos
  - Cusp or core in the central region
- Substructures
  - Formation efficiency of visible objects out of CDM halos

σ_8 from the Xray-cluster abundance





best-fit mass-temperature relation + X-ray cluster abundance in Ω_0=0.3, λ_0=0.7, h=0.7 CDM

$\Rightarrow$ σ_8=0.82 (Press-Schechter mass function)

σ_8=0.75 (Jenkins et al. mass function)

(Shimizu, Kitayama, Sasaki + YS 2003)

Confronting elements of the CDM paradigm

- Global cosmological parameters
  - Fairly well established – confirmed by WMAP
- Large-scale structure
  - Galaxy biasing with respect to CDM distribution
- Galaxy cluster abundance
  - Amplitude of CDM density fluctuations
- **Density profile of dark halos**
  - **Cusp or core in the central region**
- Substructures
  - Formation efficiency of visible objects out of CDM halos

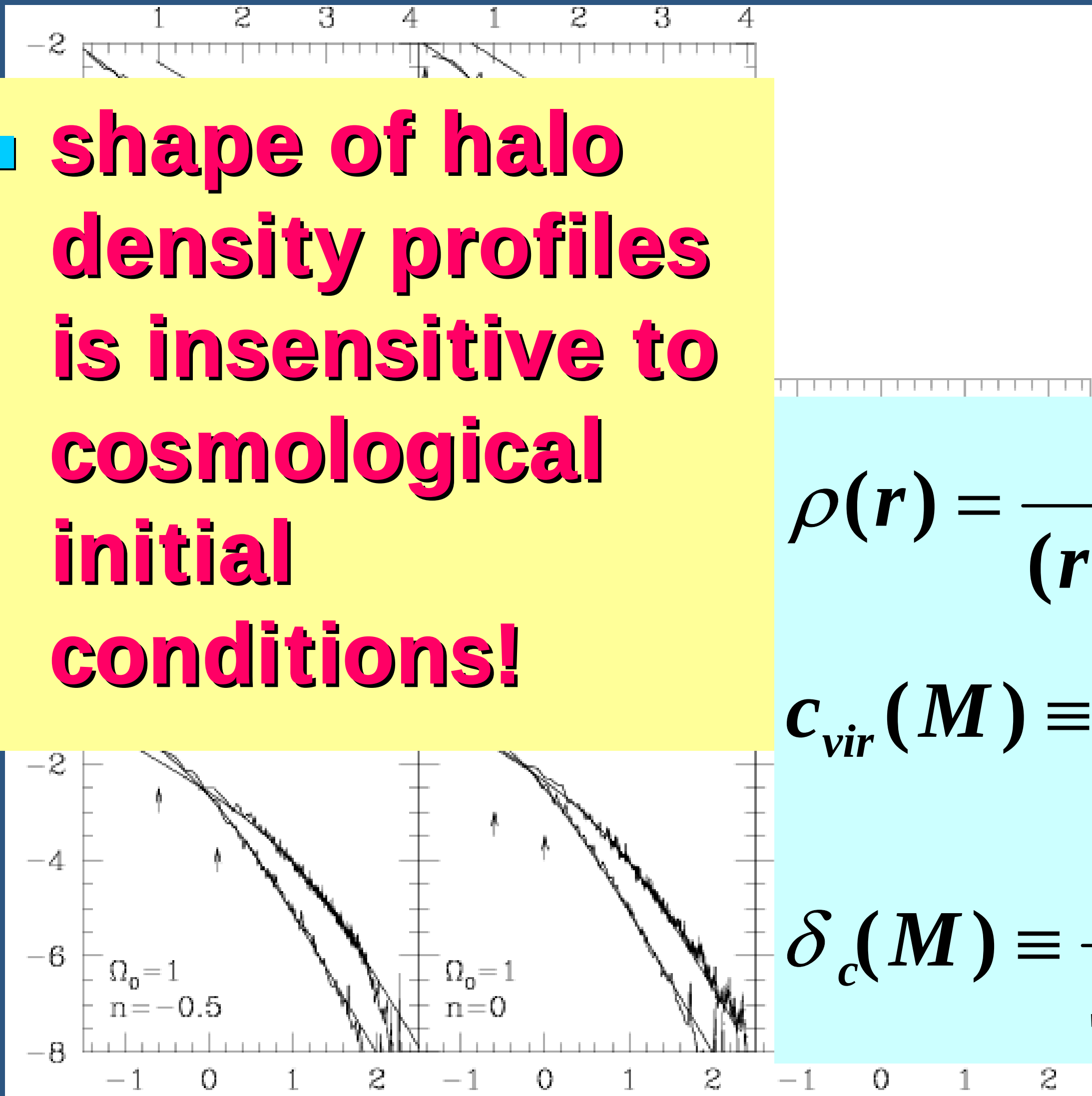
Why density profiles of dark halos ?

- **Theoretical interest:** ***what is the final state of the cosmological self-gravitating system ?***
  - forget cosmological initial conditions?
  - keep initial memory somehow?
- **Practical importance:** ***testing cosmology and/or nature of dark matter***
  - galactic rotation curve, gravitational lensing
  - X-ray/SZ observations of clusters
  - modeling the dark matter clustering

Brief history (before NFW)

- 1970: Peebles; N-body simulation (N=300).
- 1977: Gott; secondary infall model $\rho \propto r^{-9/4}$.
- 1985: Hoffman & Shaham; predicted that density profile around density peaks is $\rho \propto r^{-3(n+3)/(n+4)}$.
- 1986: Quinn, Salmon & Zurek; N-body simulations ($N \sim 10^4$) confirmed $\rho \propto r^{-3(n+3)/(n+4)}$.
- 1988: Frenk, White, Davis & Efstathiou; N-body simulations ($N=32^3$), showed that CDM model can reproduce the flat rotation curve out to 100kpc.
- 1990: Hernquist; proposed an analytic model with a central cusp for elliptical galaxies $\rho \propto r^{-1}(r+r_s)^{-3}$.
- 1996: Navarro, Frenk & White; universal density profile for dark matter halos.

NFW universal density profile



log(radius)

- **shape of halo density profiles is insensitive to cosmological initial conditions!**

Navarro, Frenk & White (1997)

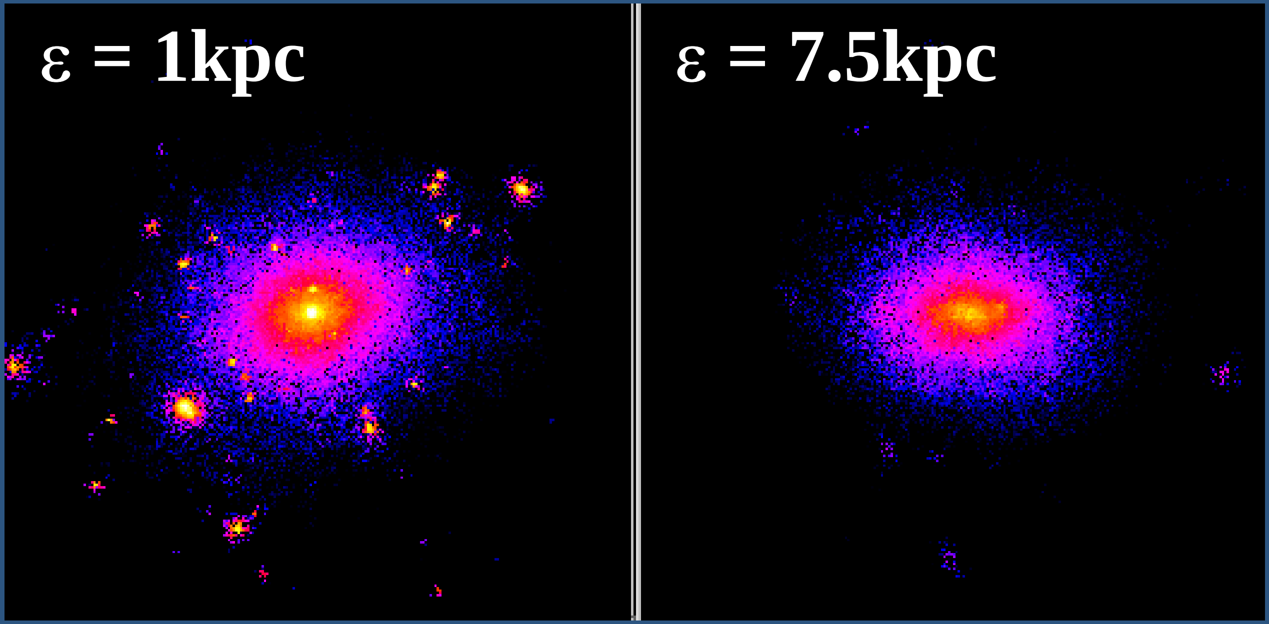
$$\rho(r) = \frac{\delta_c \rho_{crit}}{(r/r_s)(1+r/r_s)^2}$$

$$c_{vir}(M) \equiv \frac{r_{vir}(M)}{r_s(M)}$$ **concentration parameter**

$$\delta_c(M) \equiv \frac{\Delta_{vir}\Omega_0 c^3}{3[\ln(1+c) - c/(1+c)]}$$

高分解能数値シミュレーションの必要性

- low mass/force resolutions
  ⇒ shallower potential than real
  ⇒ artificial disruption/overmerging
  (especially serious for small systems)



central 500kpc region of a simulated halo in SCDM

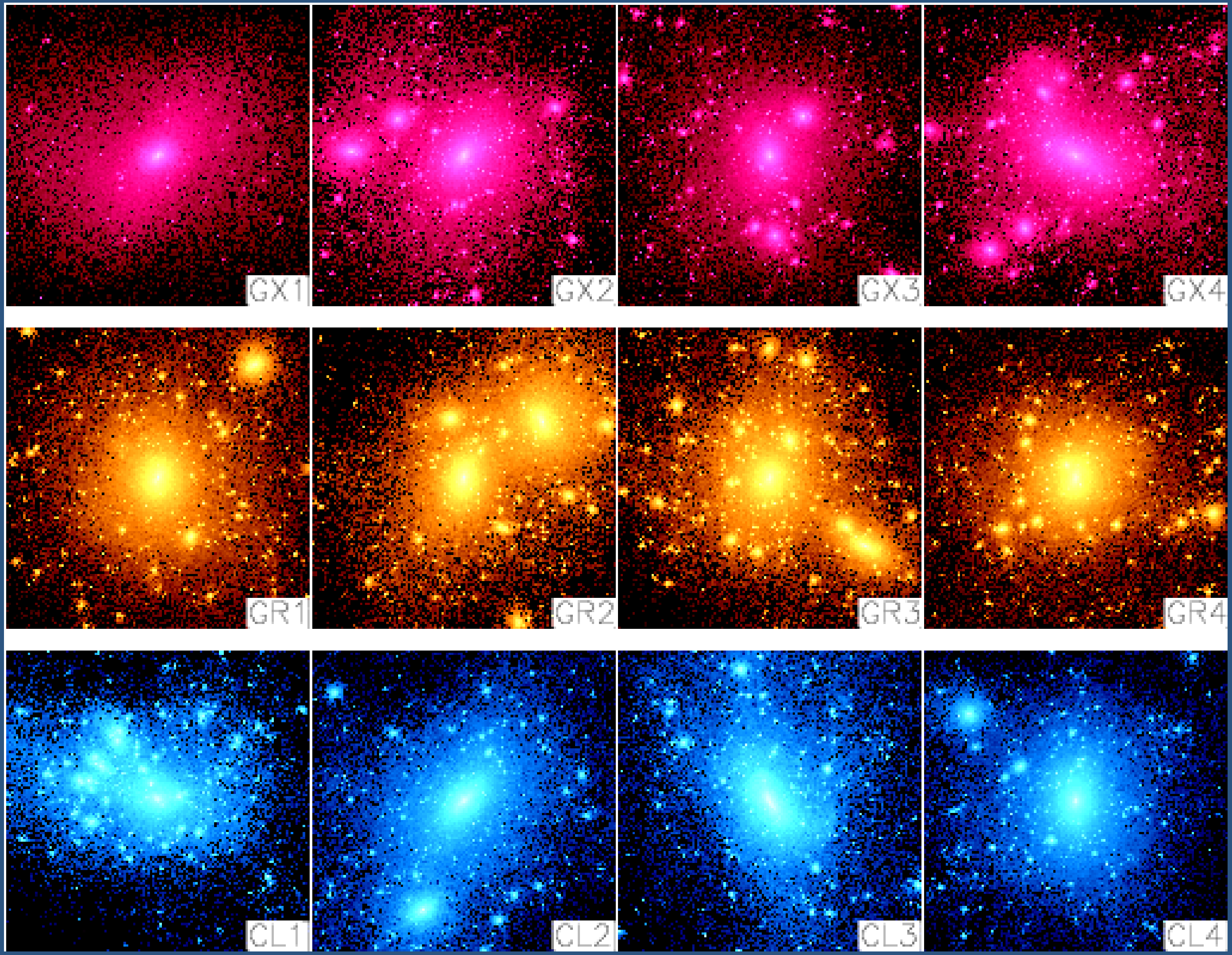
Moore (2001)

シミュレーションハローギャラリー

銀河スケール
~ $5 \times 10^{12} M_{sun}$

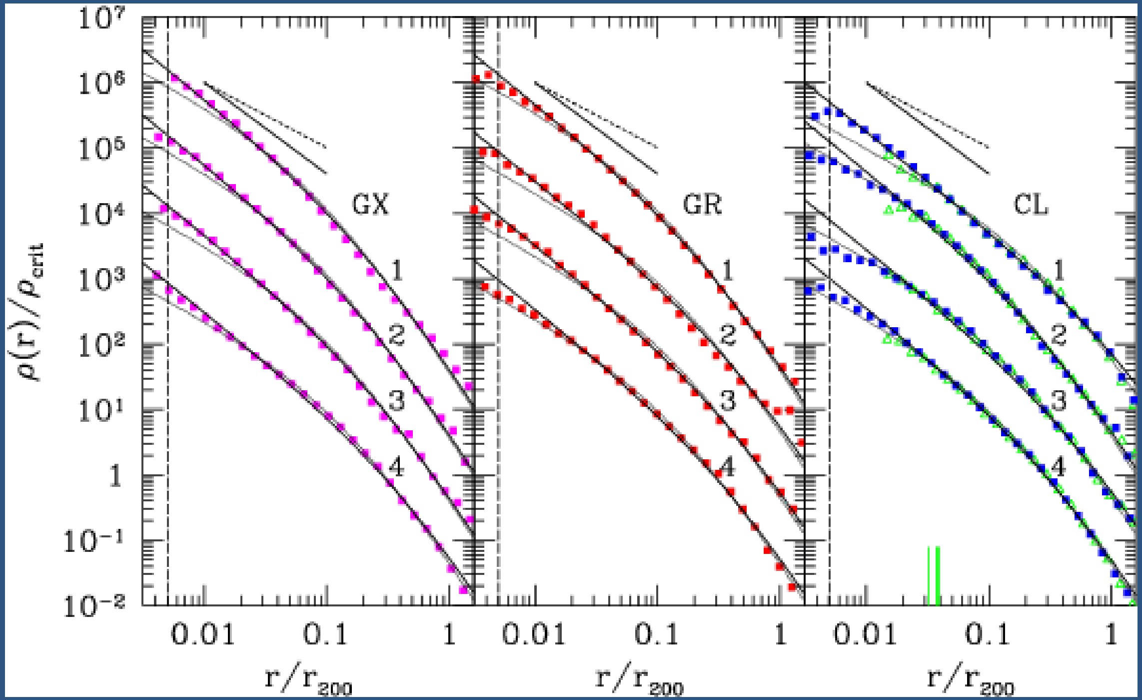
銀河群スケール
~ $5 \times 10^{13} M_{sun}$

銀河団スケール
~ $3 \times 10^{14} M_{sun}$

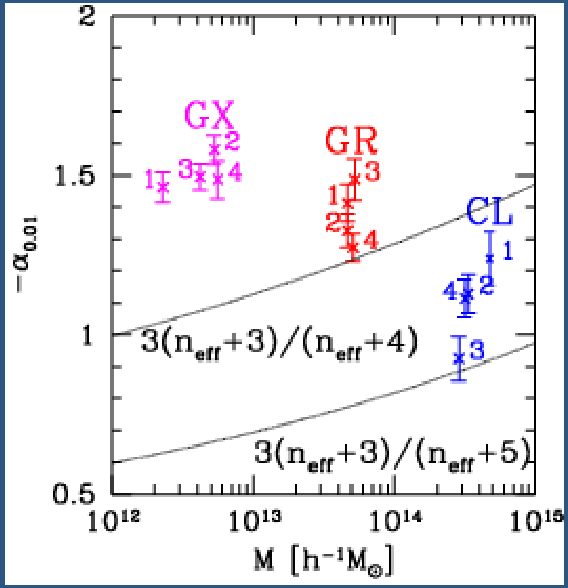


Jing & Suto (2000)

数値シミュレーションのまとめ



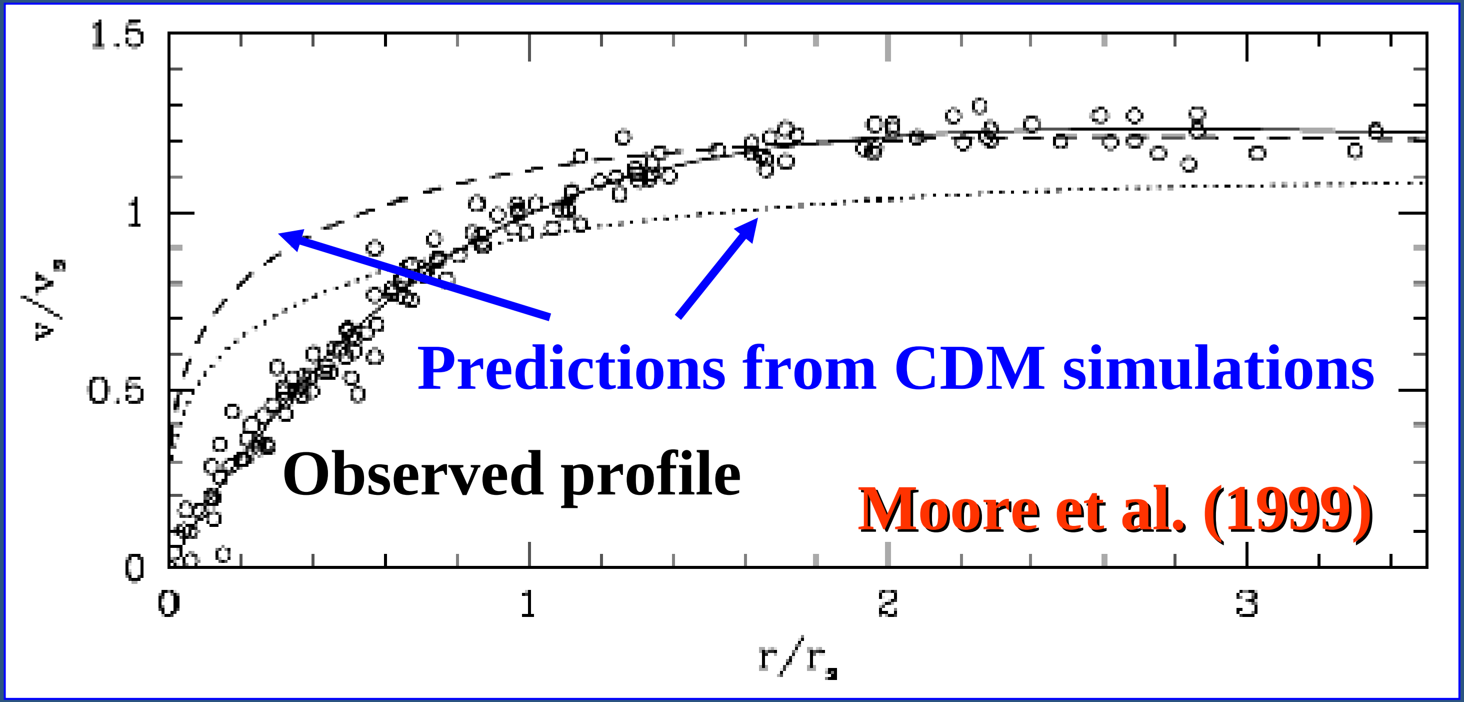
Jing & Suto (2000)



- CDMハローの密度プロファイルはほぼ普遍的で、内側は∝$r^{-1.5}$程度のカスプを持つ!

$$\rho(r) = \frac{\delta_c \rho_{crit}}{(r/r_s)^{\alpha}(1+r/r_s)^{3-\alpha}} \quad \alpha \approx 1.5$$

Rotation curves of DM dominated galaxies



- dwarf spirals to giant low surface brightness galaxies indicate the central cores rather than cusps !

  ⇒ inconsistent with CDM simulations (?)

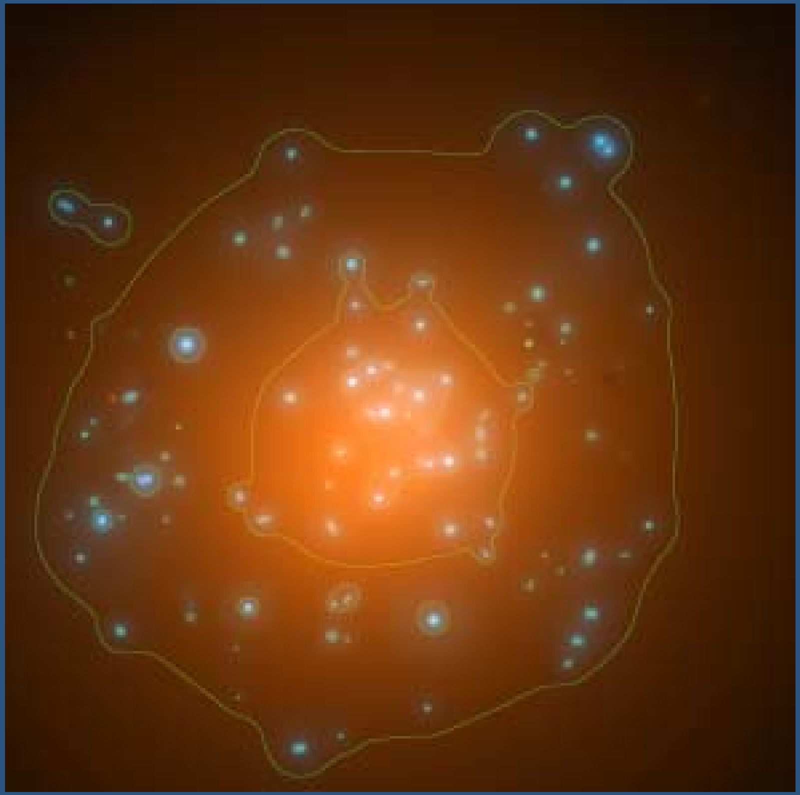
  (Moore et al. 1999; de Blok et al. 2000; Salucci & Burkert 2000)

銀河団CL0024+1654の重力レンズ

HST image

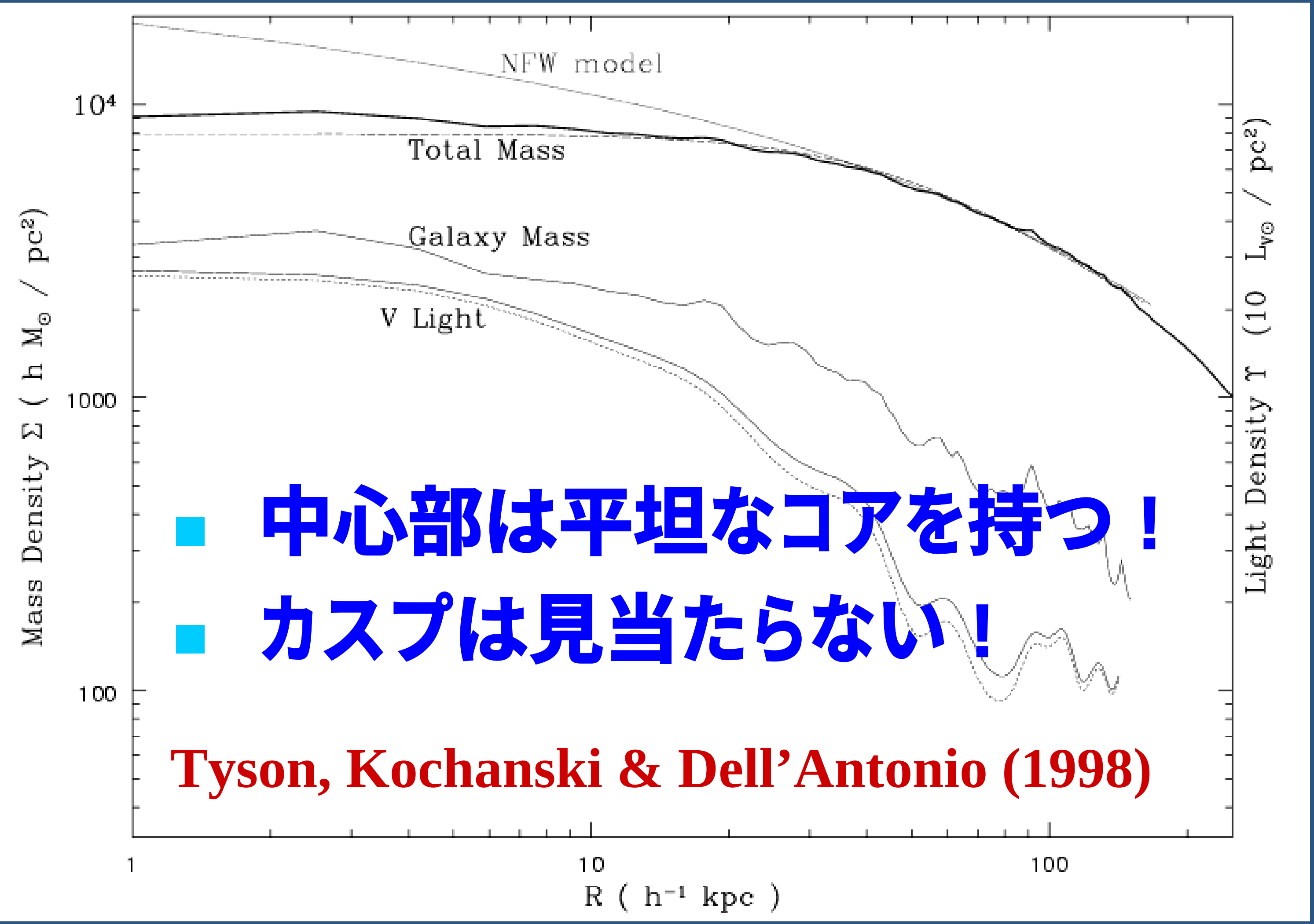
Z=0.39, $L_X = 5 \times 10^{43}\ h^{-2}$ erg/s

reconstructed mass distribution (with 512 parameters)



Tyson, Kochanski & Dell'Antonio (1998)

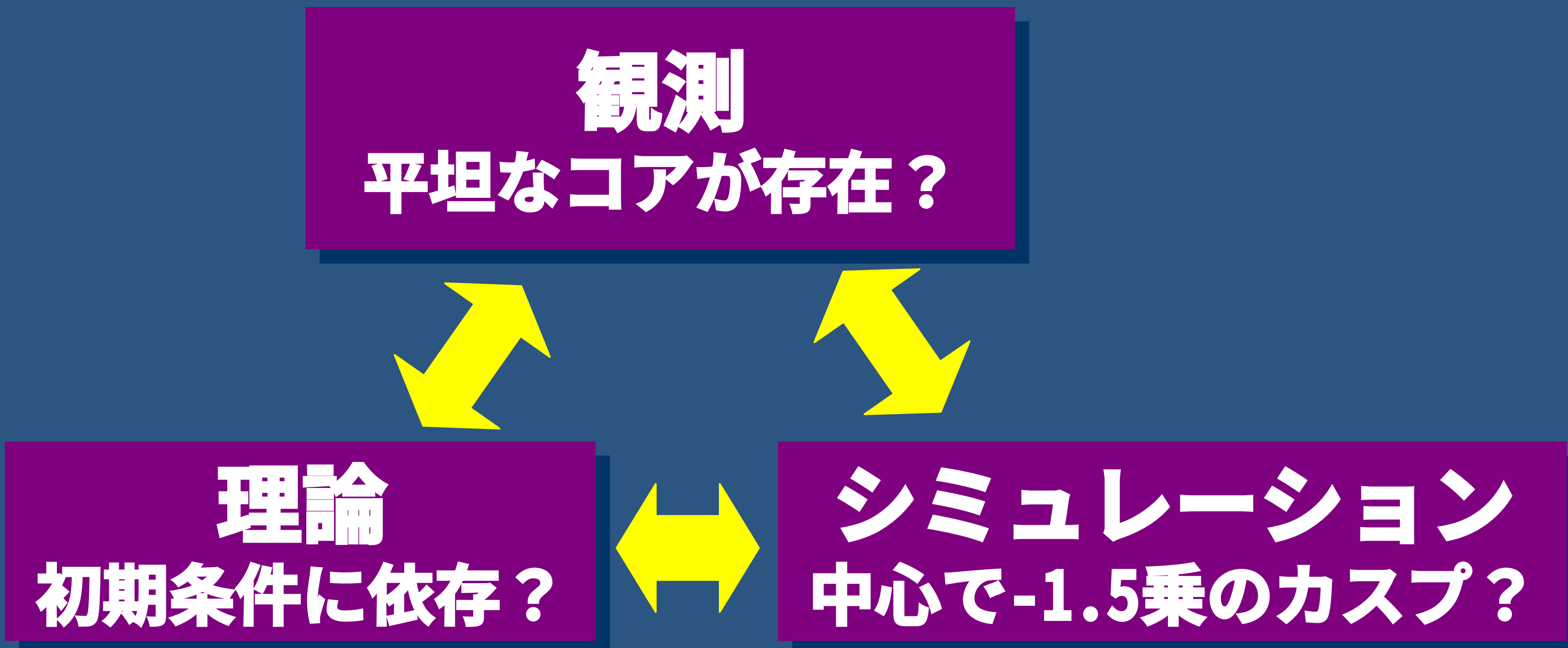
重力レンズデータから再構築されたCL0024+1654の密度分布



- 中心部は平坦なコアを持つ！
- カスプは見当たらない！

Tyson, Kochanski & Dell'Antonio (1998)

密度プロファイル研究の現状



- 観測、シミュレーション、理論がすべて不整合

⇒ ***さらなる検証が必要！***

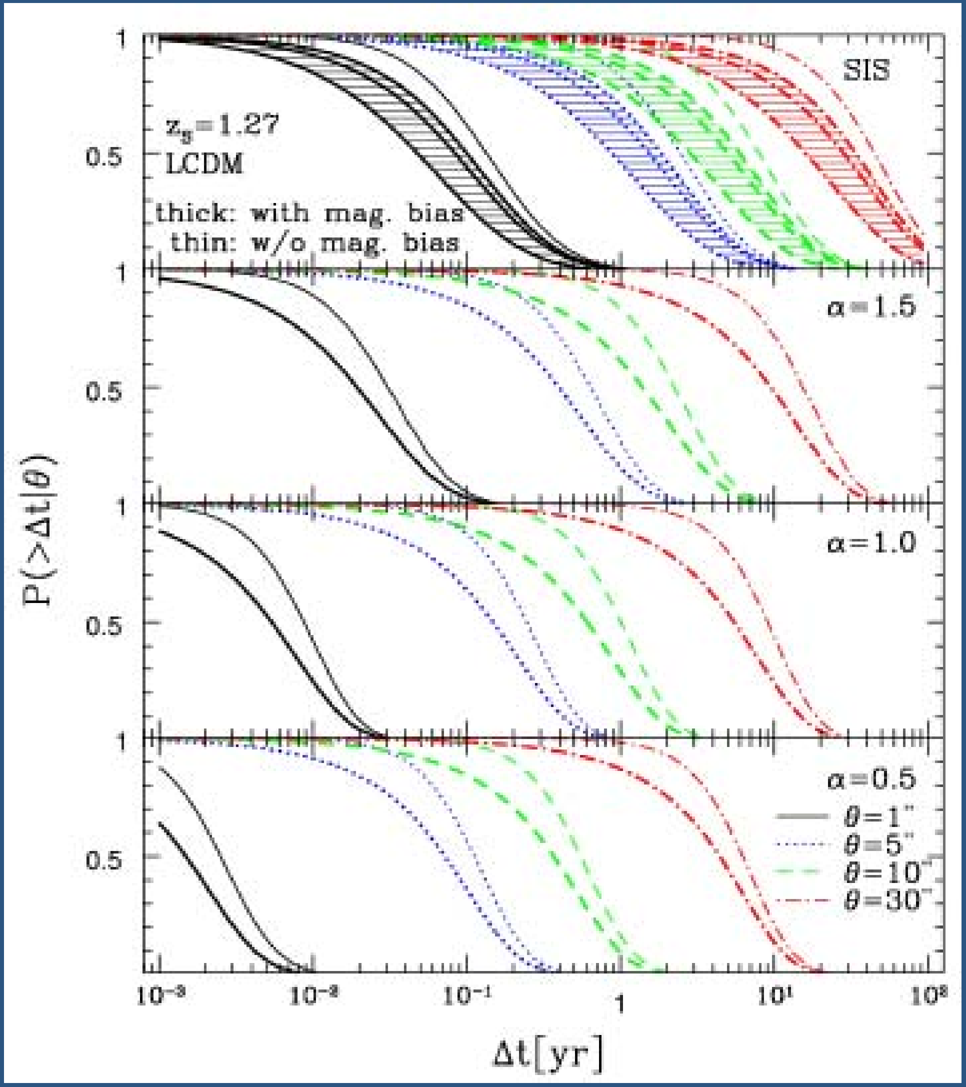
Constraining halo central density profiles with gravitational lensing

- **Statistics of QSO multiple images**
  (Wyithe, Turner & Spergel 2001; Keeton & Madau 2001; Li & Ostriker 2001; Takahashi & Chiba 2001)
- **Arc statistics of clusters of galaxies**
  (Bartelmann et al. 1998; Molikawa & Hattori 2001; Oguri, Taruya + YS 2001, Oguri, Lee + YS 2003)
- **Time-delay statistics of QSO multiple images**
  (Oguri, Taruya, YS + Turner 2002)

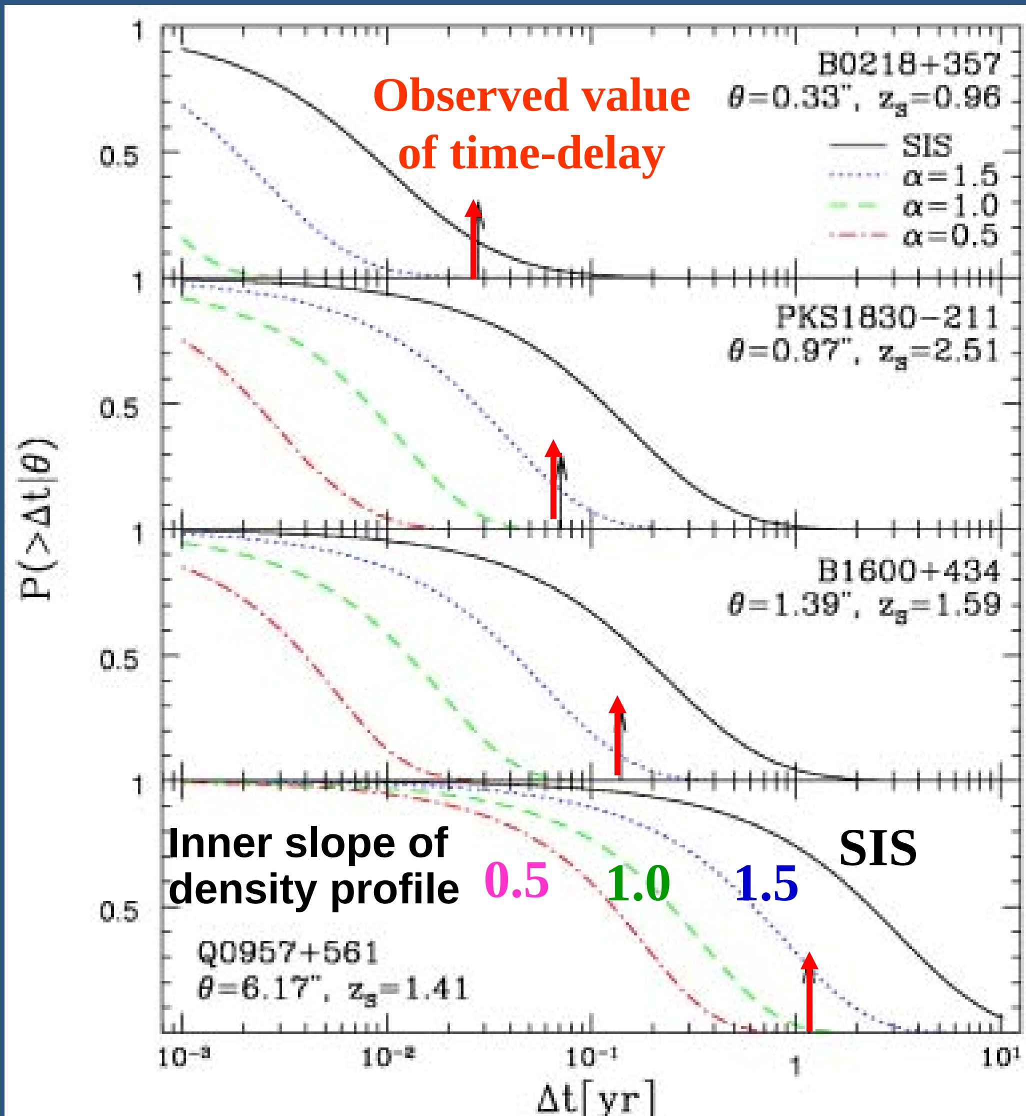
⇒ generally favor a steep cusp ($\alpha \sim -1.5$)

Time-delay in QSO multiple images to probe the halo density profile

- **Time-delay among QSO multiple images is very sensitive to the inner slope, but insensitive to cosmological parameters (except H_0 !)**
- **Steeper inner profile ⇒ larger time-delay**



Tentative applications to 4 lens systems



- Time-delays of existing lens systems are consistent with predicted time-delay probability when the density profile has a steep cusp $\propto r^{-1.5}$

Oguri, Taruya, YS + Turner (2001)

Self-interacting dark matter ?

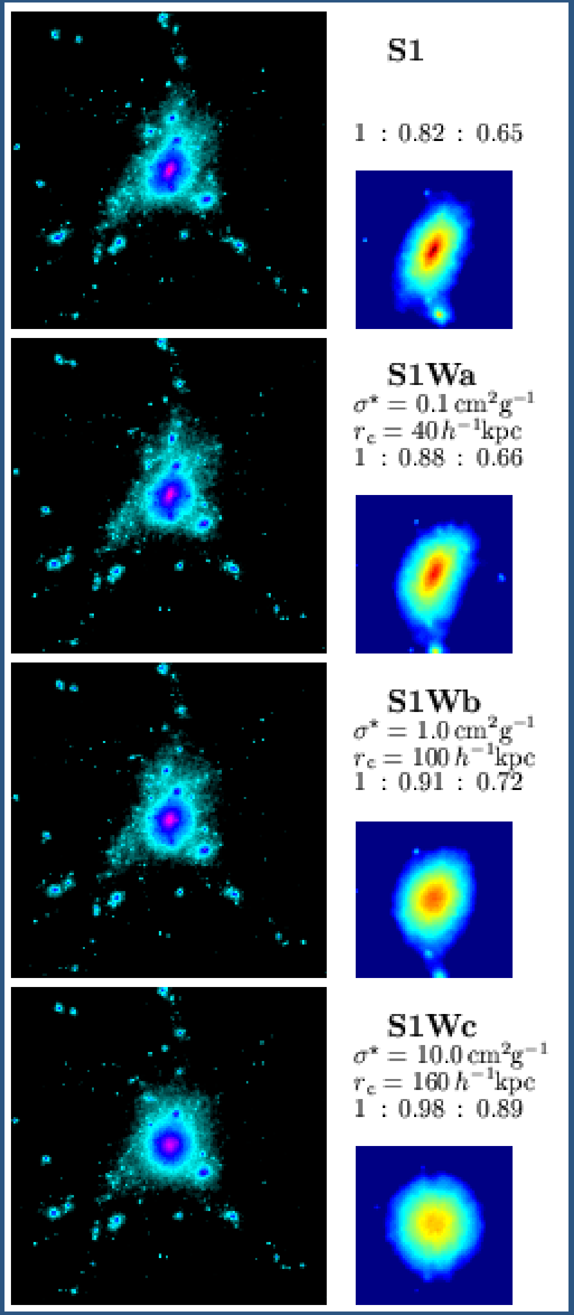
- ***Collisionless dark matter***
  - reproduces nicely the observed large-scale structure of the universe (r≫1Mpc)
  - **problems on smaller scales (r<1Mpc)**

    LSB rotation curves, soft core in CL0024+1624, prediction of a factor of ten more subhalos than observed in the Local Group
- Required scattering cross section for self-interacting dark matter

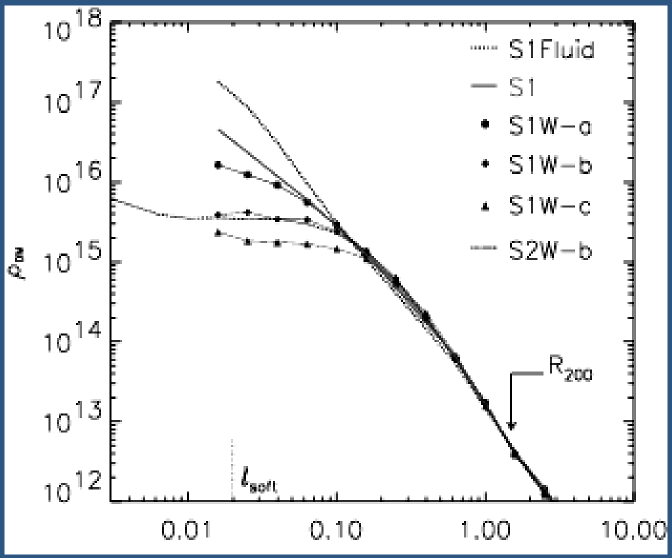
$$(mn)\frac{\sigma}{m}\ell = 1 \quad \Rightarrow \quad \frac{\sigma}{m} = 2\mathrm{cm}^2/\mathrm{g}\left(\frac{10^4 \rho_{\mathrm{crit}}}{\rho_{\mathrm{center,cl}}}\right)\left(\frac{1\mathrm{Mpc}}{\ell}\right)$$

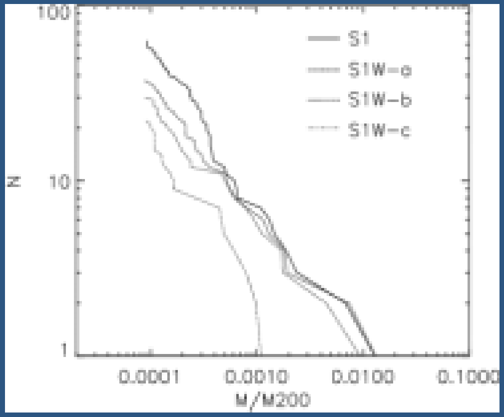
Collisional Dark Matter

- σ→∞では、中心のカスプはより強くなる
- σ / *m*～1 cm^2 / g 程度の相互作用があれば、中心部のカスプがなくなりコアが形成される一方、ハローはほぼ球対称となる



Yoshida et al. (2000)

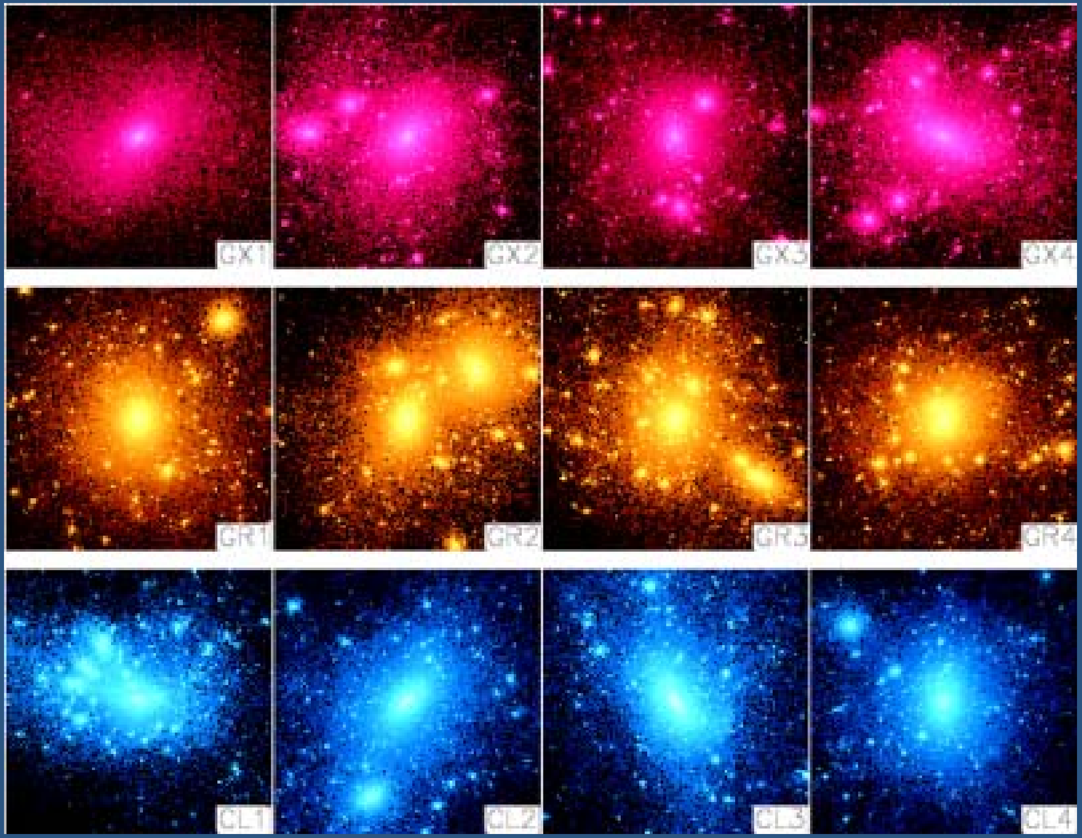


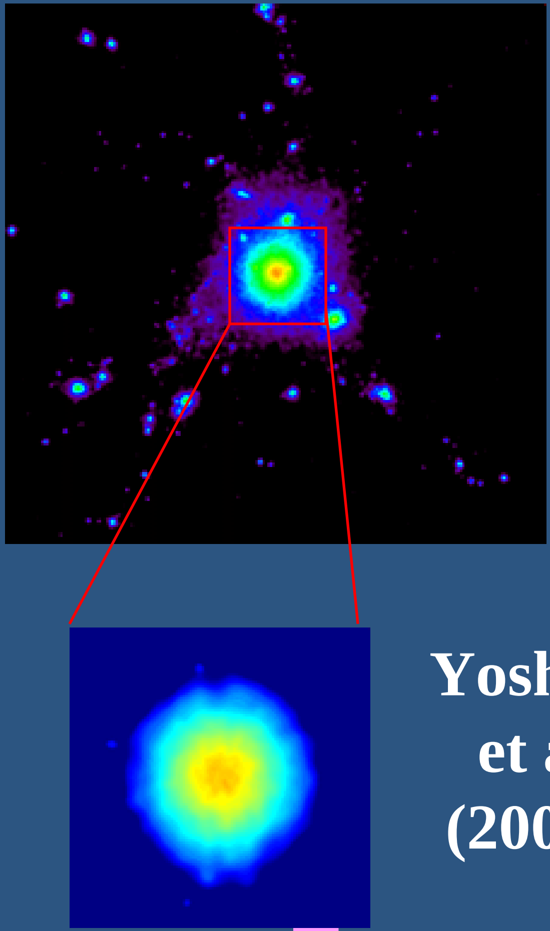


Are Dark Halos Spherical?

Collisionless CDM: NO

Jing & Suto (2000)



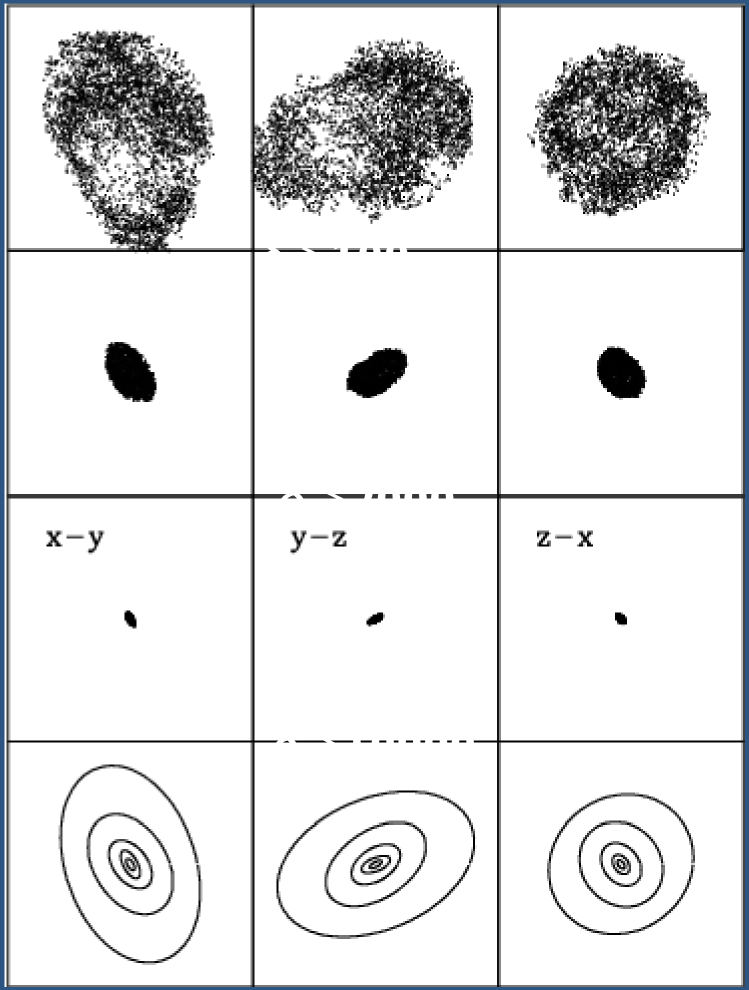


Yoshida et al. (2000)

Collisional CDM: YES

An improved model for dark matter halo: triaxial universal density profile

Isodensity of a cluster-scale halo



$$\rho(R) = \frac{\delta_c \rho_{crit}}{(R/R_s)^{\alpha}(1+R/R_s)^{3-\alpha}}$$

$$R^2(\rho) \equiv \frac{X^2}{a^2(\rho)} + \frac{Y^2}{b^2(\rho)} + \frac{Z^2}{c^2(\rho)}$$

Jing & Suto, ApJ, 574 (2002) 538

- Non-spherical effects have several important implications for SZ, X-ray, and lensing observations.

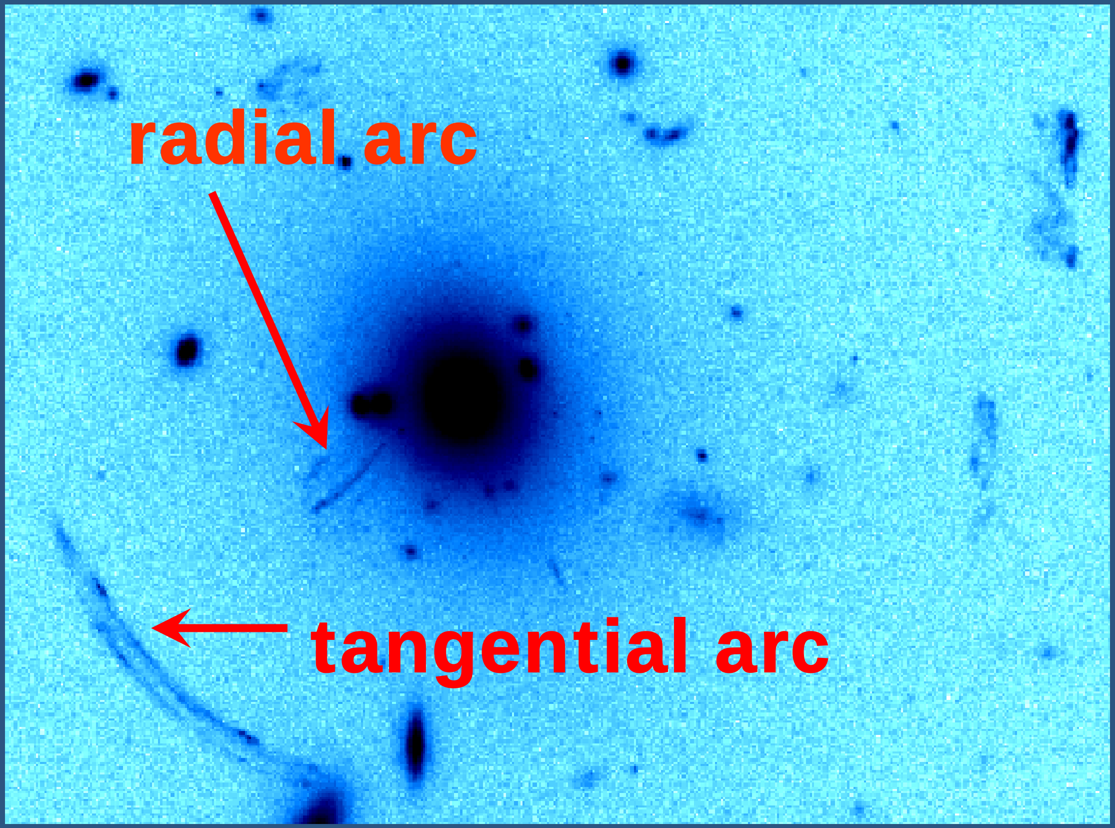
Lensed Arcs in Galaxy Clusters

Cluster of galaxies distort the images of background galaxies by gravitational lensing

↓

(lensed) arcs

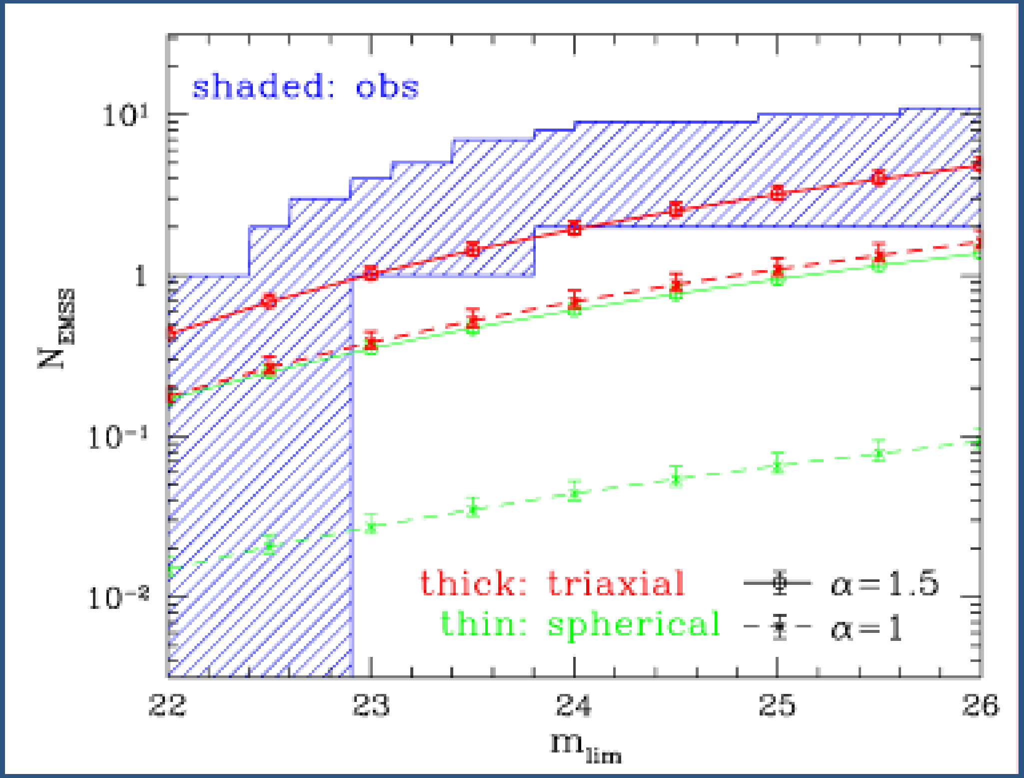
~30 giant arcs are observed so far



Hammer et al. (1997)

Comparison with observed statistics

Previous model predictions are known to be significantly smaller than the observed number of lensed arcs (Luppino et al. 1999)



More realistic modeling of dark halos from simulations (inner slope of α=1.5 and non-sphericity) reproduces the observed frequency of arcs.

(Oguri, Lee + YS 2003)

まとめと今後の展望

- 冷たいダークマターを仮定した構造形成モデルは0次近似としては驚くべき成功を収めている。
  - Ω_m〜0.3, Ω_Λ〜0.7, h〜0.7 ⇒ Ω_m=0.27±0.04, Ω_Λ=0.73±0.04, h=0.71±0.04 の時代へ
- 天文学の今後の問題:
  - 第一世代の天体形成と宇宙再加熱モデル
  - ダークマターと "ルミナス天体" との関係
  - 小スケールでのCDMの難点(?)
- 物理学に残された本質的課題:
  - ダークマターの直接検出
  - ダークエネルギー(宇宙定数)は本当にあるか

SDSS観測@アパッチポイント天文台

NHK教育　サイエンスZERO　2003年6月11日　0:00　放映

WMAP衛星宇宙の旅

NASA / WMAP
Science Team

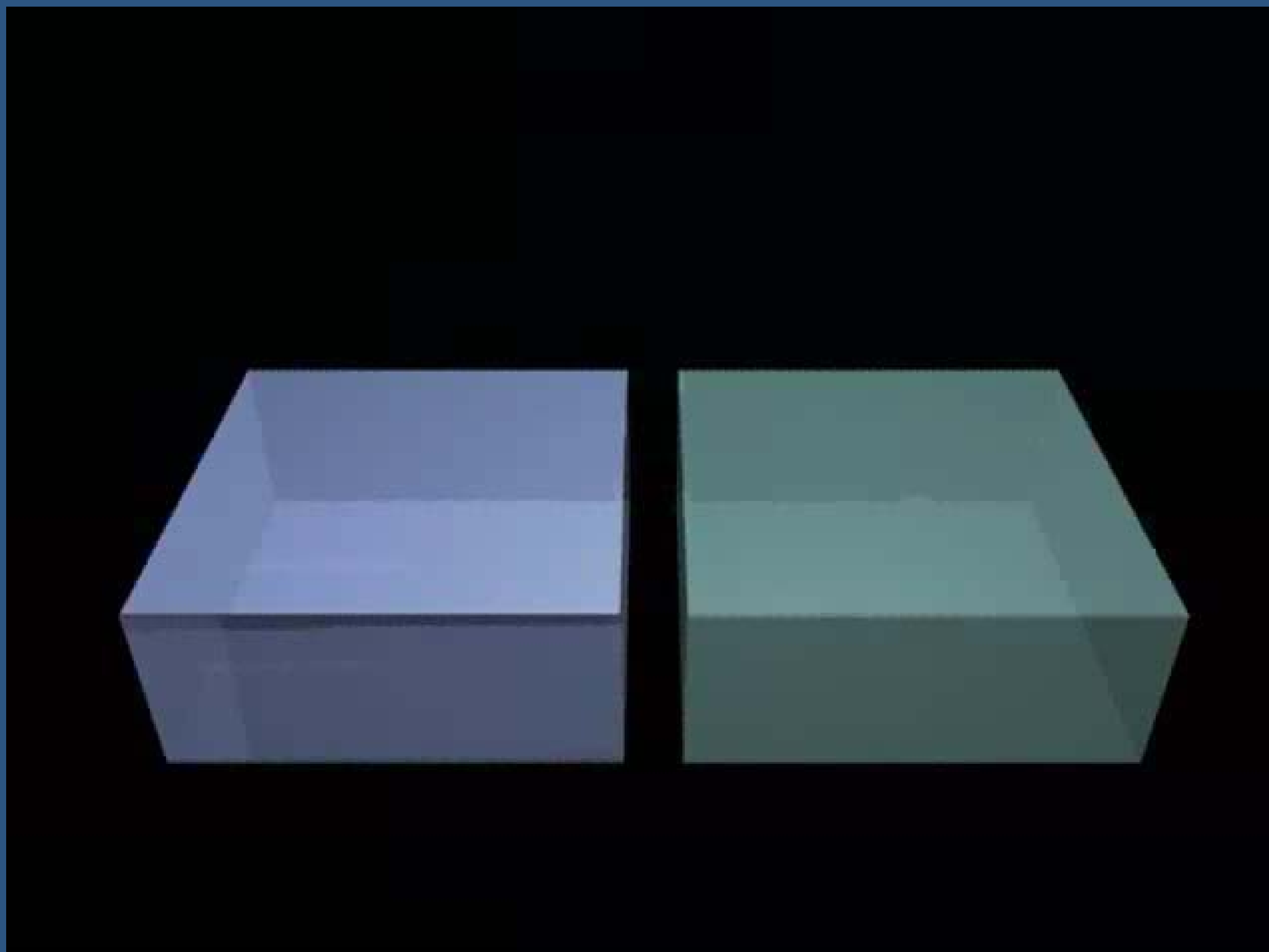
http: / / lambda.gsfc.nasa.gov

CMBと宇宙の曲率

NASA / WMAP Science Team

http: / / lambda.gsfc.nasa.gov

重力ゆらぎによるCMB温度ゆらぎパターン



NASA / WMAP
Science Team

http: / / lambda.gsfc.nasa.gov