冷たい暗黒物質モデルの危機？
暗黒物質ハローの密度プロファイル

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2001年１2月21日
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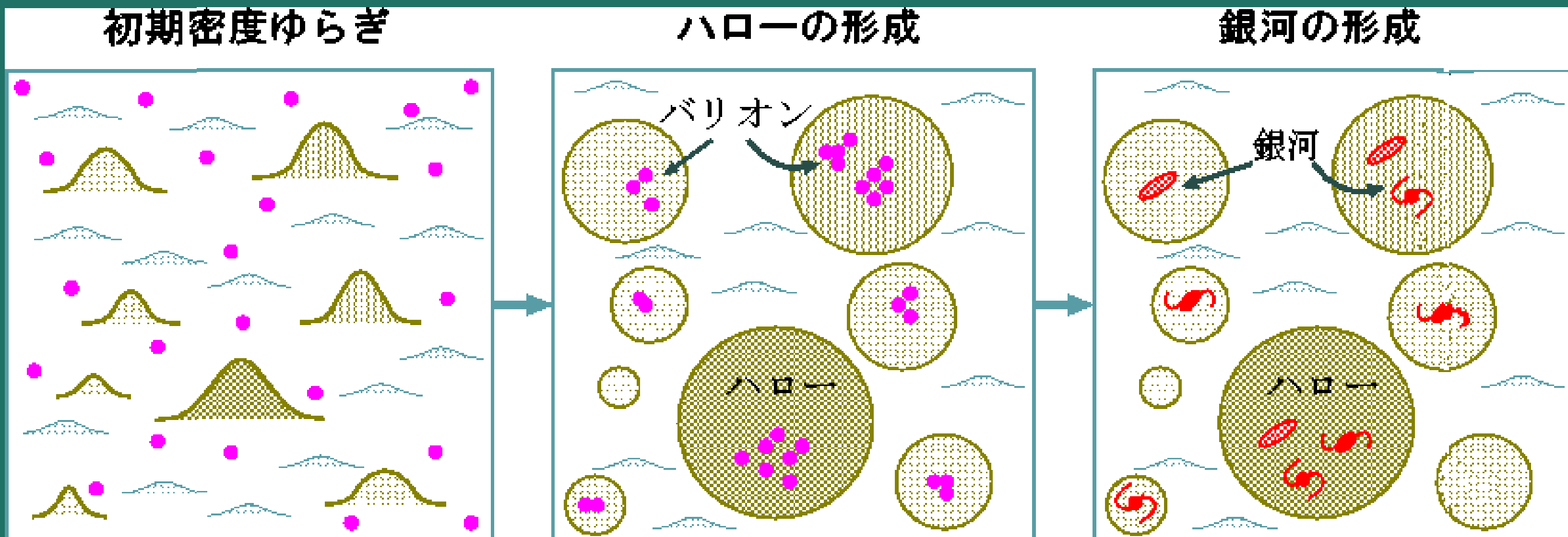
重力不安定による構造形成の描像



重力進化

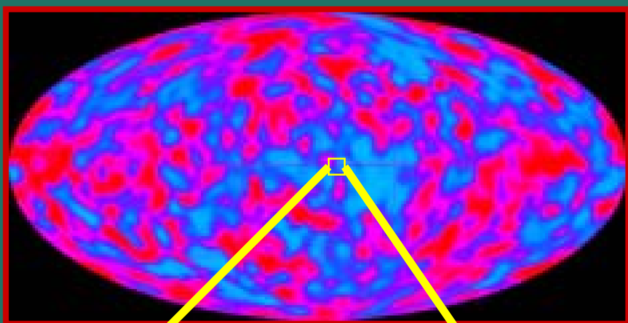
ガスの冷却
輻射過程
星形成進化
…

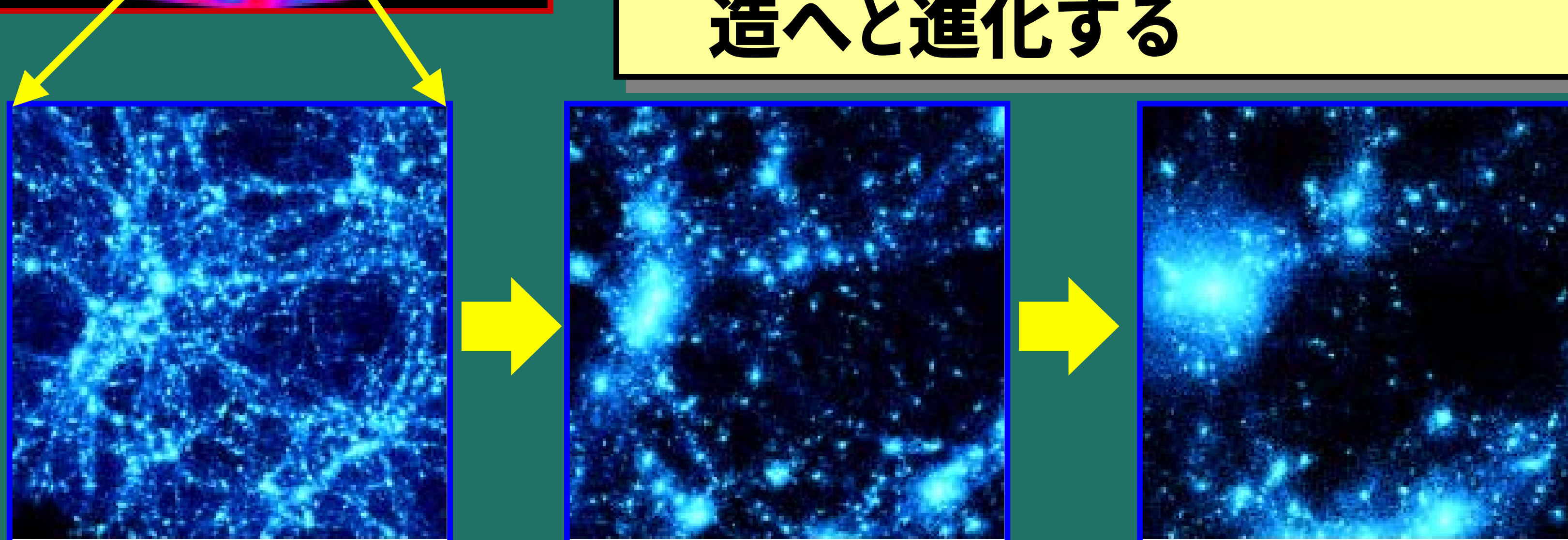
ダークハロー（ダークマター の自己重力系）の形成が天体形成において最も基本的な素過程

樽家 (2001) 日本物理学会誌

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





暗黒物質ハロー密度プロファイル研究の意義

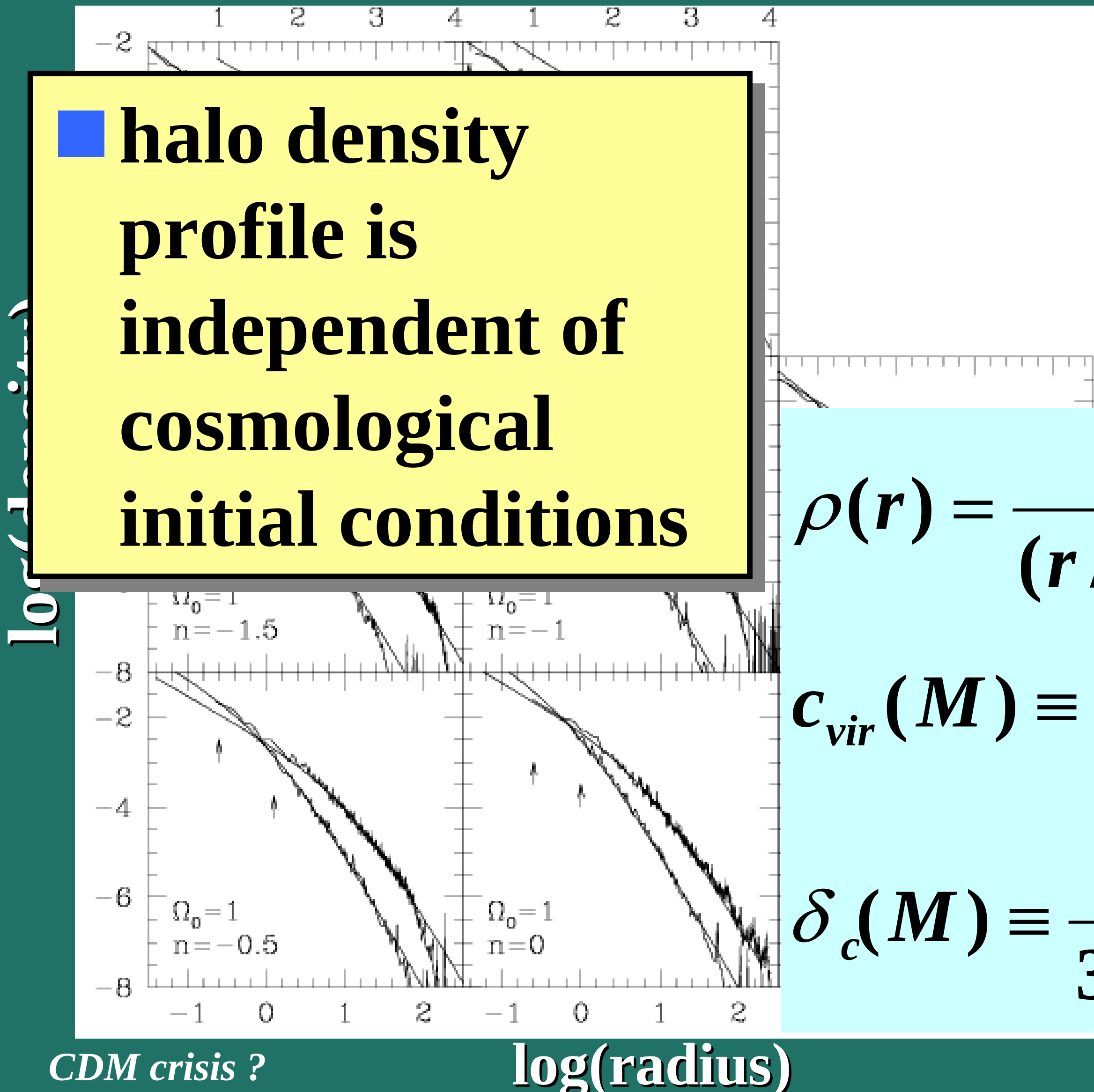
- **Theoretical interest:** ***what is the final state of the cosmological self-gravitating system ?***
  - forget cosmological initial conditions?
  - keep initial memory somehow?
- **Practical importance:** ***testable predictions for galaxies and clusters***

  can distinguish the underlying cosmological model through comparison with observations (i.e., galactic rotation curve, gravitational lensing, X-ray/SZ observation)

NFW(1996)以前の研究のまとめ

- **1970:** **Peebles**; **N-body simulation (N=300).**
- **1977:** **Gott**; **secondary infall model** $\rho \propto r^{-9/4}$.
- **1985:** **Hoffman & Shaham**; **predict that density profile around density peaks is** $\rho \propto r^{-3(n+3)/(n+4)}$.
- **1986:** **Quinn, Salmon & Zurek**; **N-body simulations (N〜10000), 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** $\rho \propto r^{-1}(r+r_s)^{-3}$.

NFW 普遍密度プロファイル



- **halo density profile is independent of cosmological initial conditions**

Navarro, Frenk & White (1997)

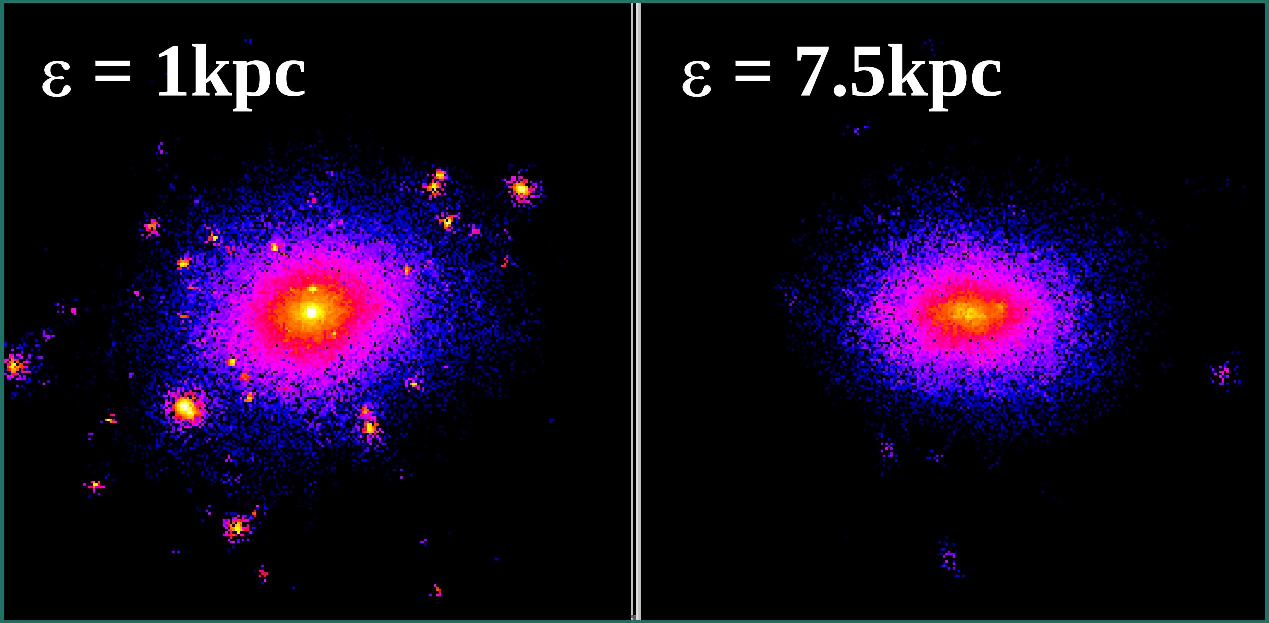
$$\rho(r) = \frac{\delta_c \rho_{crit}}{(r/r_s)(1+r/r_s)^2}$$

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

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

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)

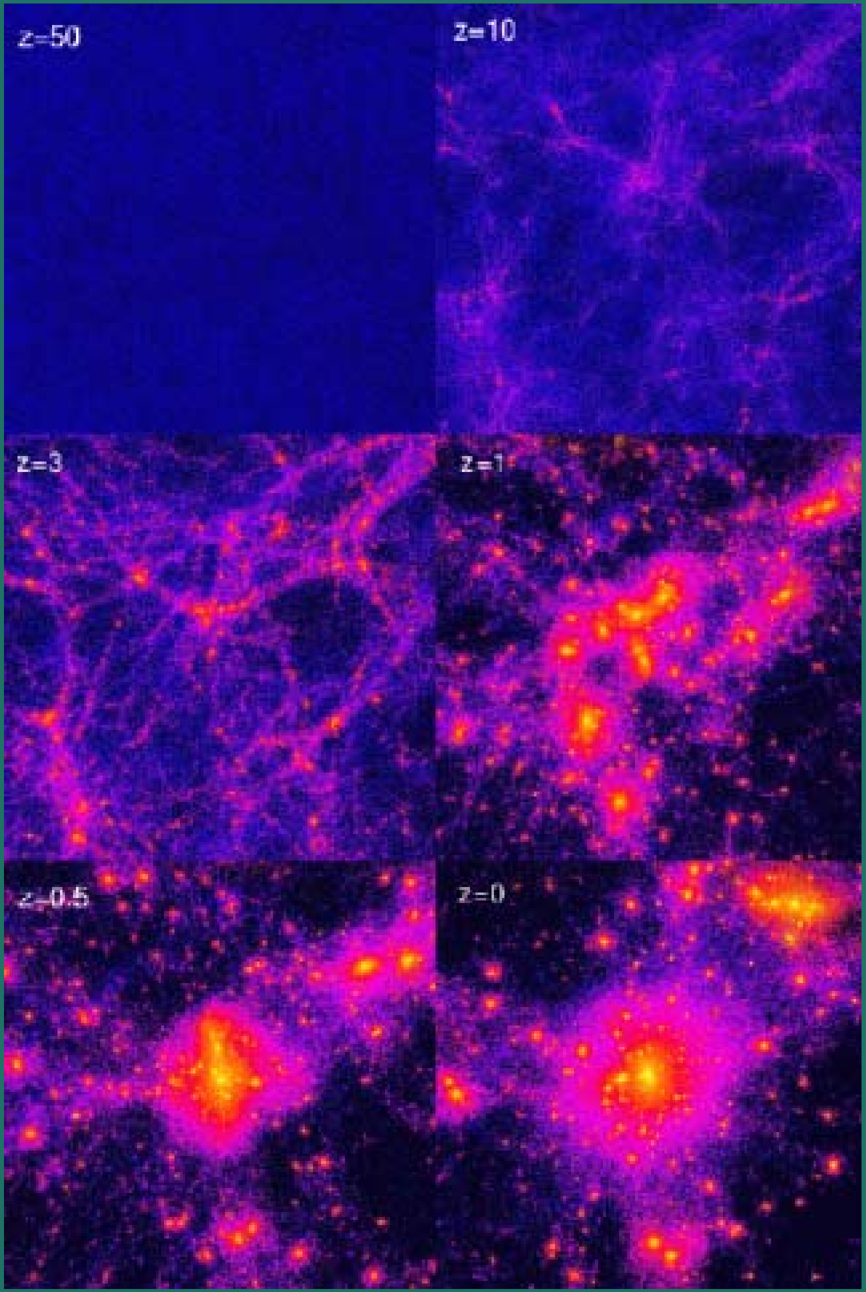


central 500kpc region of a simulated halo in SCDM

Moore (2001)

高分解能シミュレーションの例

Yoshida et al. (2000)



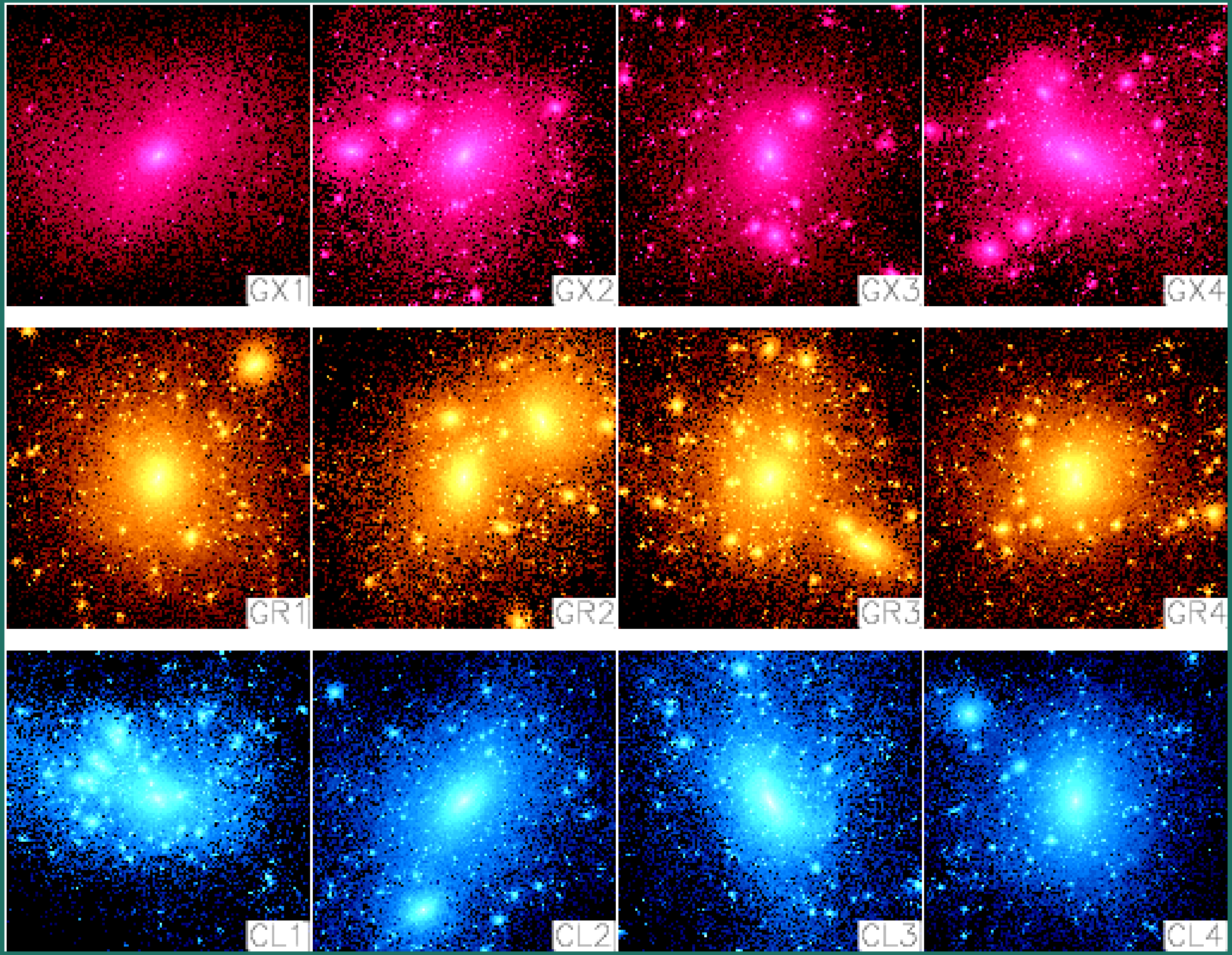
Moore (2001)

シミュレーションハローギャラリー

銀河スケール
~ $5 \times 10^{12} M_{sun}$

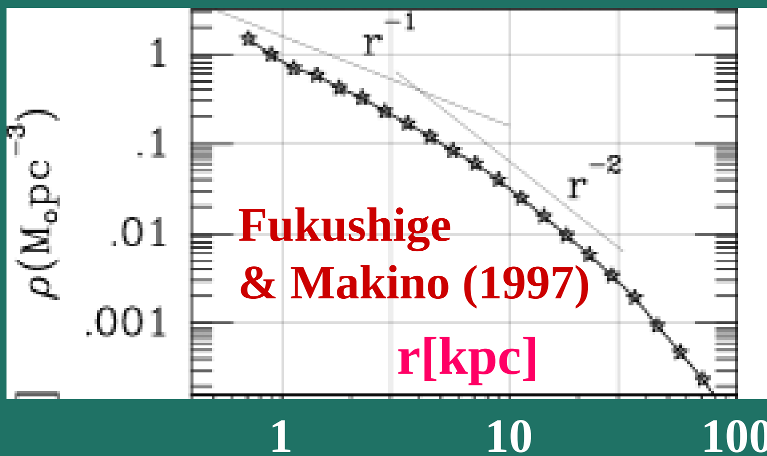
銀河群スケール
~ $5 \times 10^{13} M_{sun}$

銀河団スケール
~ $3 \times 10^{14} M_{sun}$

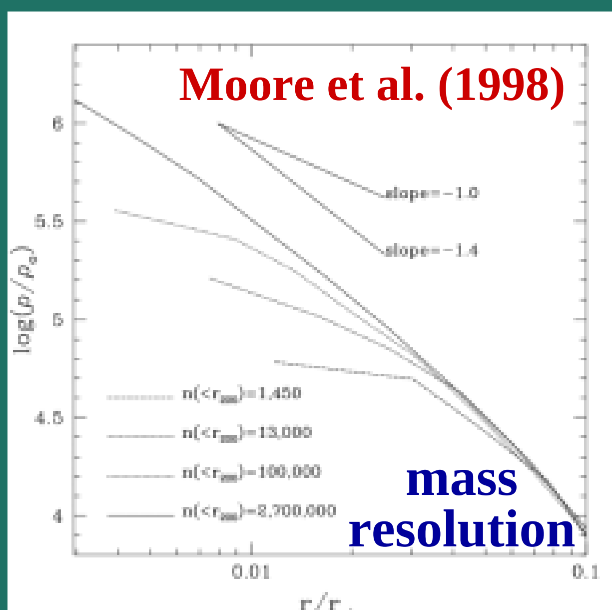


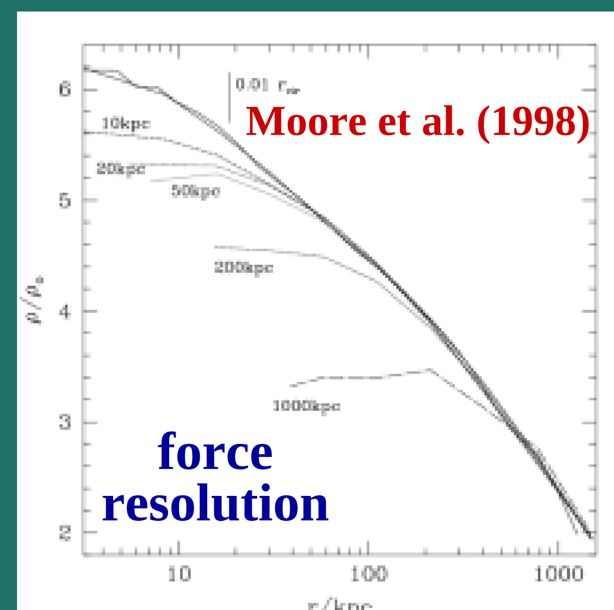
Jing & Suto (2000)

高分解能シミュレーションでのプロファイル

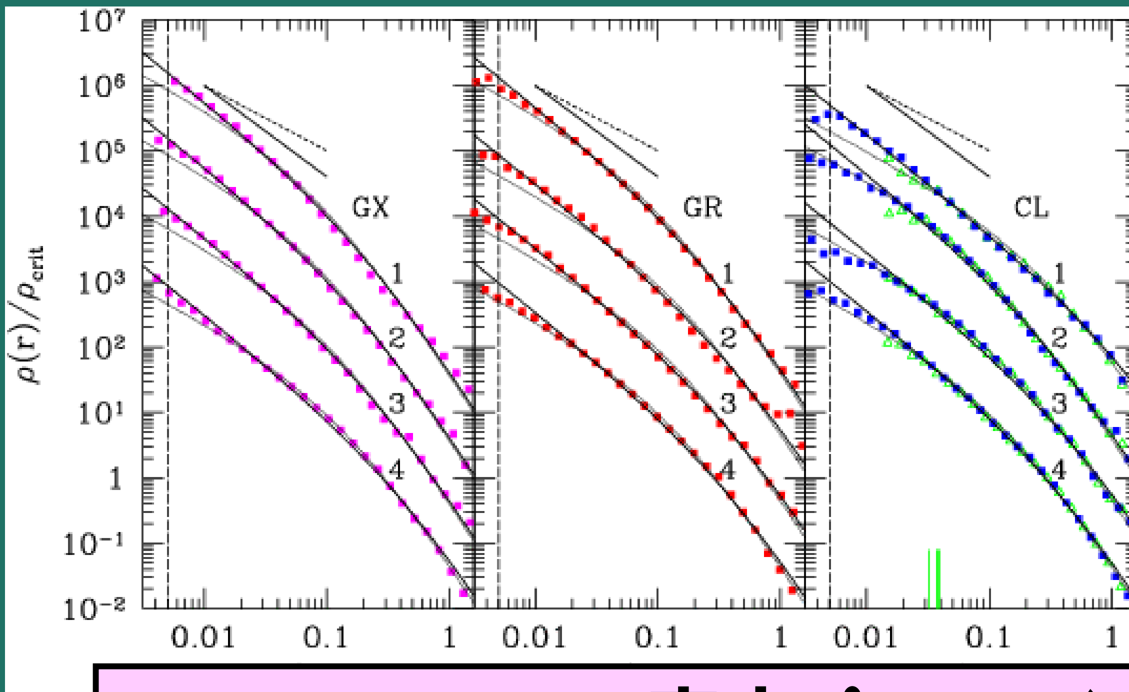


- inner slope in higher-resolution simulations is steeper (~ –1.5) than the NFW value (–1.0)

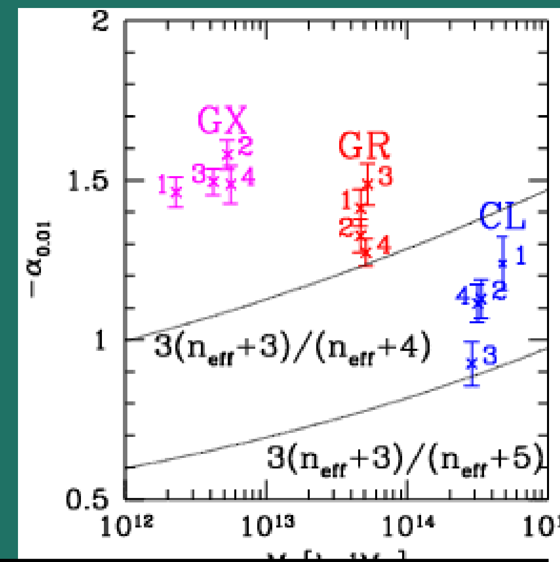




数値シミュレーションのまとめ



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!**

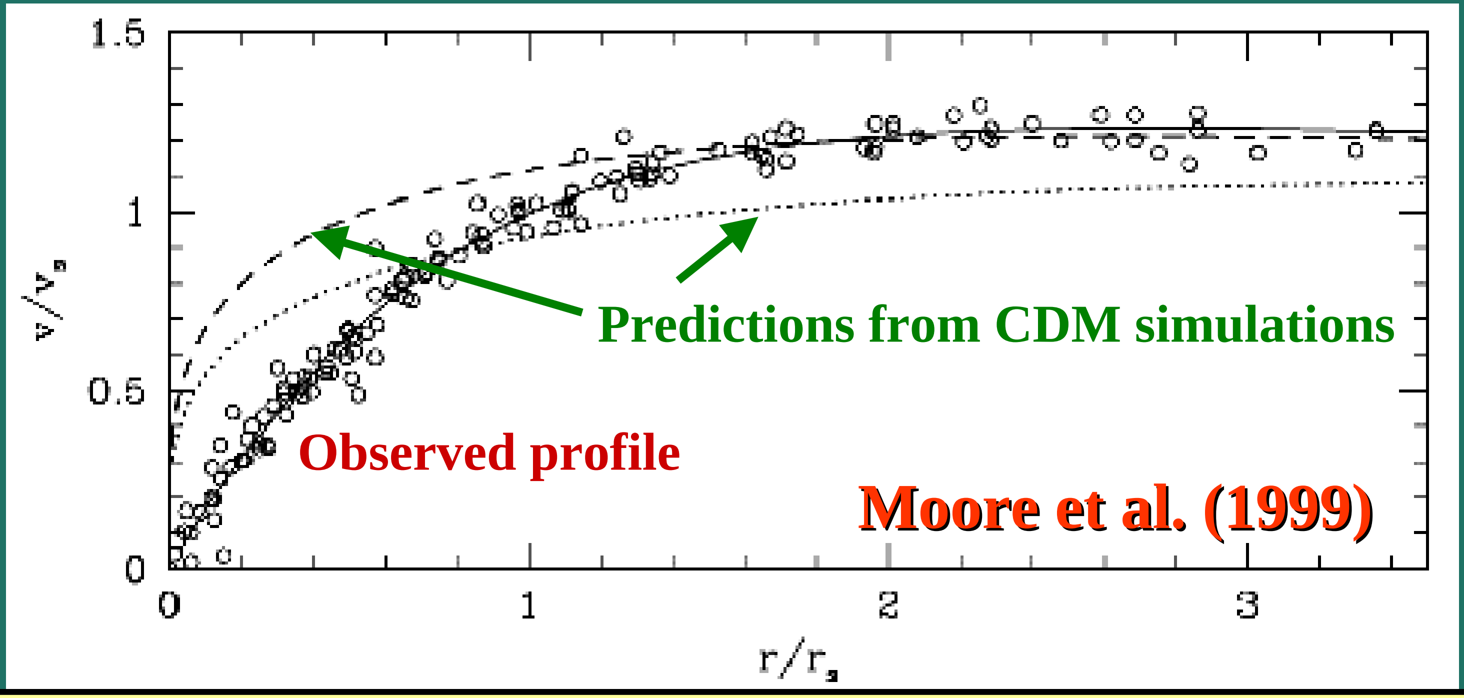
$$\rho(r) = \frac{\delta_c \rho_{crit}}{(r/r_s)^{\alpha}(1+r/r_s)^{3-\alpha}} \quad \alpha \approx 1.5$$

理論モデルのまとめ

- ***Simulations***
  - Profiles of dark matter halos seem to be fairly universal (at least approximately)
  - Shape of halo profiles is independent of the cosmological initial conditions
  - Cusp rather than core in the central region
- ***Theoretical models***
  - The presence of cusp is consistent.
  - Inner slope is expected to depend on the primordial spectrum of fluctuations in general.

⇒ 観測データとの比較が重要

銀河の回転曲線は中心コアを示唆



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

⇒ CDM **シミュレーションと矛盾？**

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

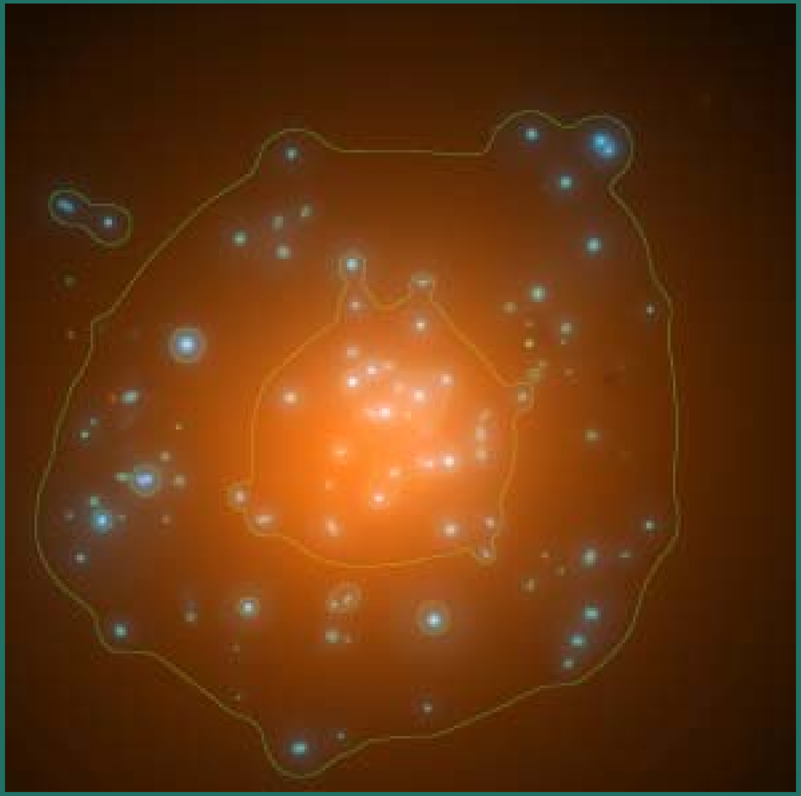
銀河団による重力レンズアークの形成

銀河団CL0024+1654の重力レンズ

HST image

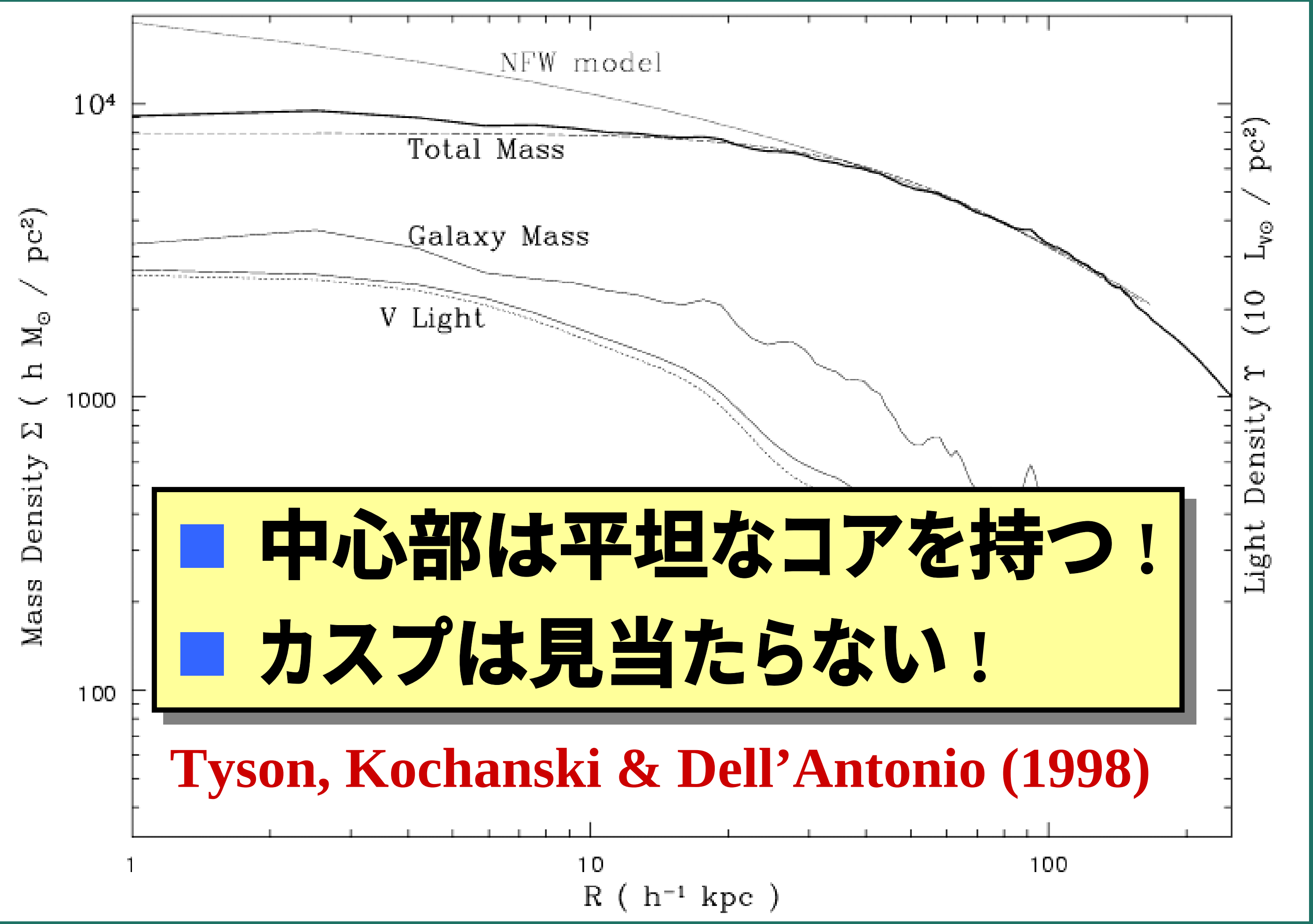
Z=0.39, $L_X = 5 \times 10^{43}\ h^{-2}$ erg/s

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
平坦なコアが存在？

理論
初期条件に依存？

シミュレーション
中心で－１．５の冪？

- **観測、シミュレーション、理論の不整合**

⇒　***さらなる検証が必要！***

冷たい暗黒物質モデルの危機？

- ***Observations favor the presence of core rather than cusp.***
  - Rotation curves of low-surface brightness galaxies
  - Cluster mass profile from gravitational lensing
  - still controversial, but ...
- ***Cold dark matter is really collisionless ?***

  Self-interacting dark matter

  (Spergel & Steinhardt 2000)
- ***Baryon physics***
  - Bar-driven core formation ? (Weinberg & Katz 2001)
  - Radiative cooling, star formation

Self-interacting dark matter

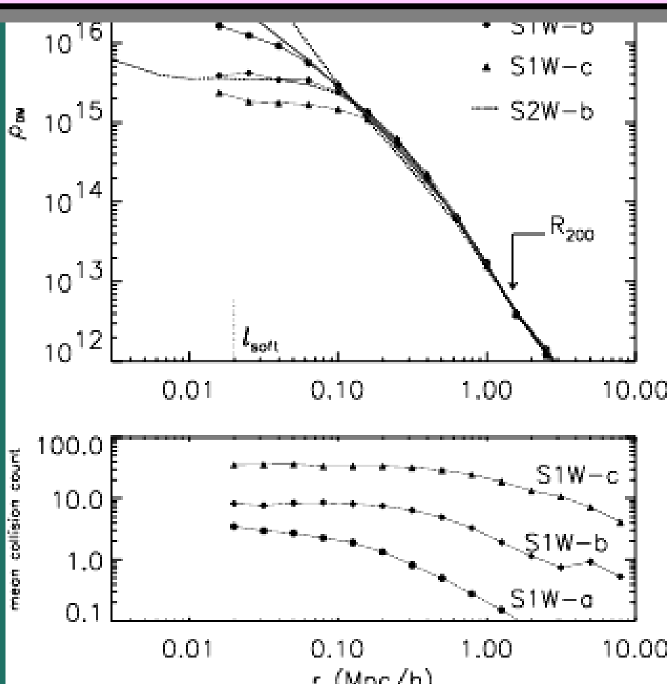
- ***Collisionless dark matter***
  - reproduces nicely the observed large-scale structure of the universe ($r \gg 1\mathrm{Mpc}$)
  - **problems on smaller scales (r<1Mpc)**

    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

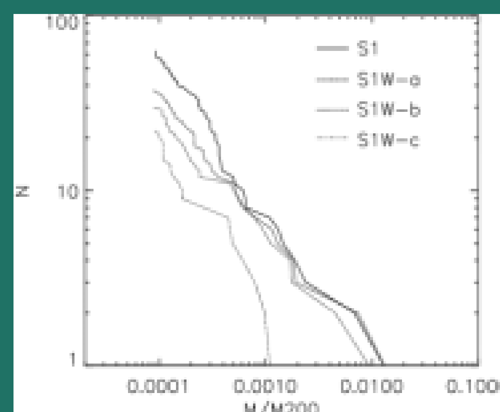
$$(mn)\frac{\sigma}{m}\ell = 1 \quad \Rightarrow \quad \frac{\sigma}{m} = 2\mathrm{cm}^2/\mathrm{g}\left(\frac{10^4\rho_{\mathrm{crit}}}{\rho_{\mathrm{center,cl}}}\right)\left(\frac{1\mathrm{Mpc}}{\ell}\right)$$

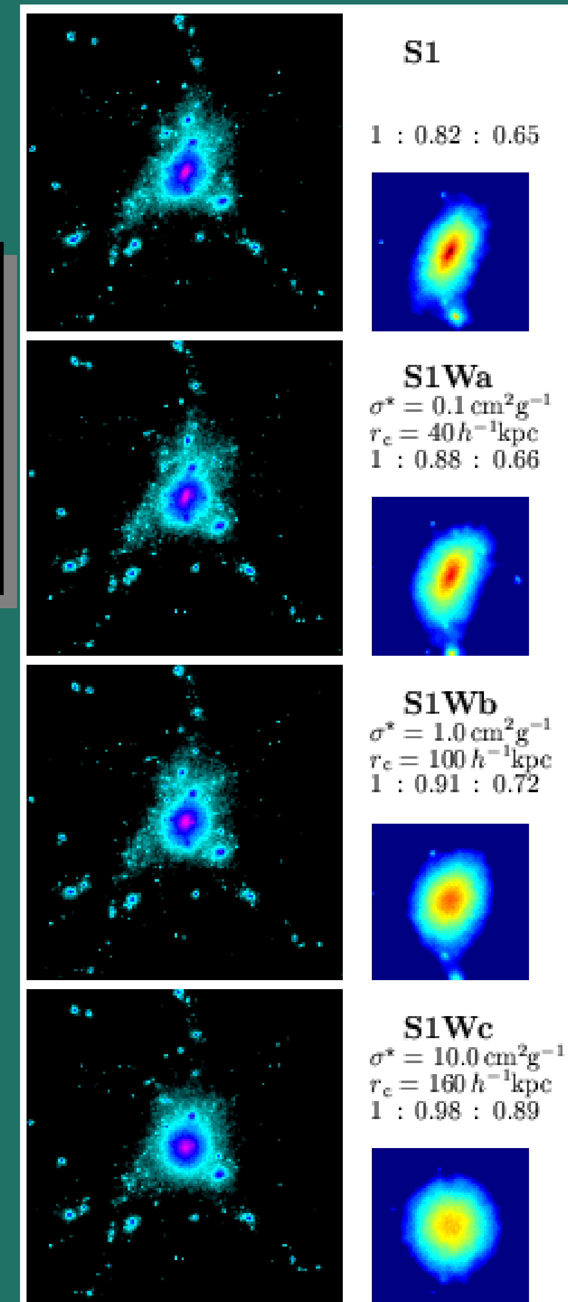
Collisional Dark Matter

- σ→∞では、中心のカスプはより強くなる
- σ/*m*〜1 cm²/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)





■ 光線は重力場によって曲げられる

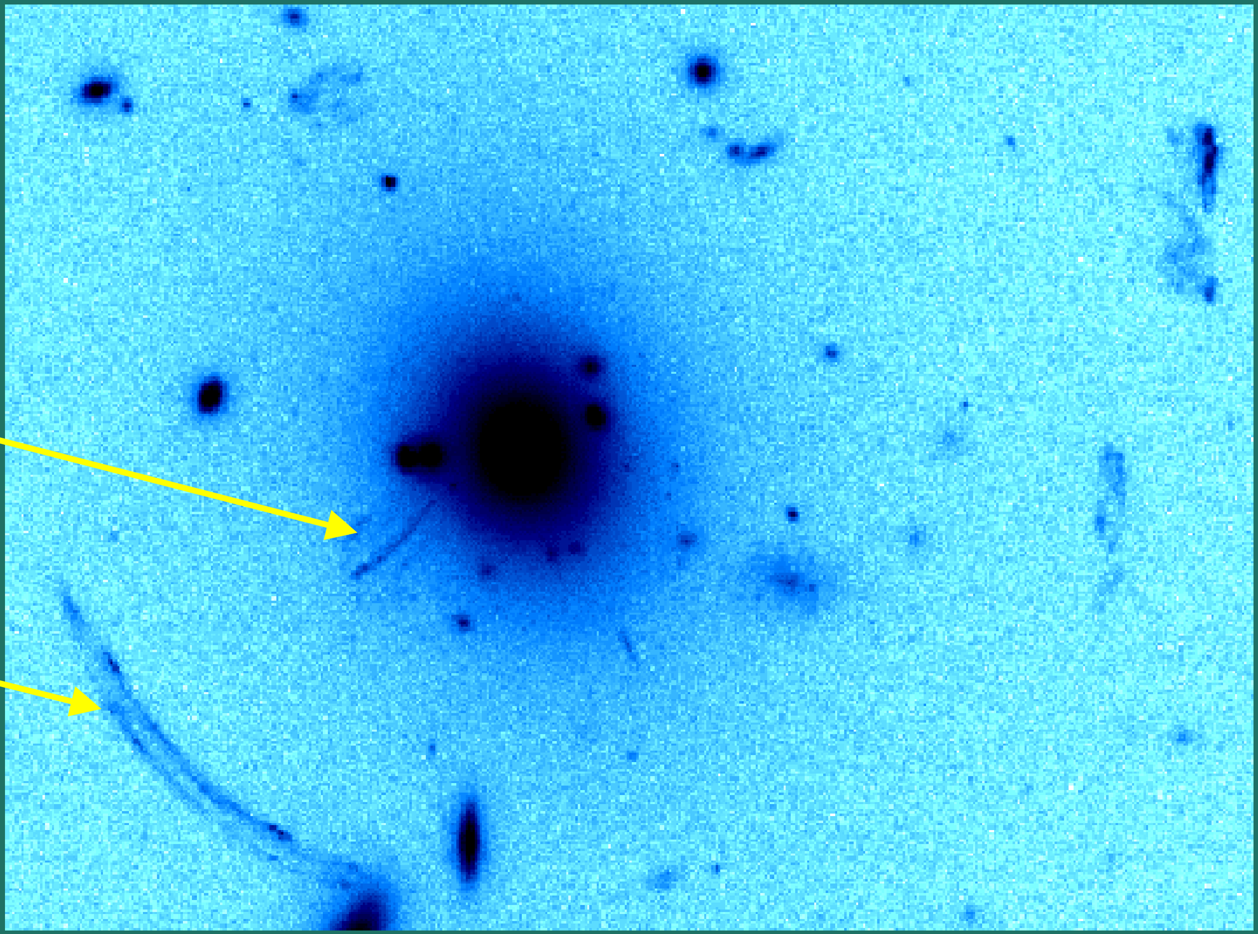
- 天体が多重像をつくる (強い重力レンズ)
- 天体の形状が変形を受ける (弱い重力レンズ)
- 天体の見かけの明るさが増光する (マイクロレンズ)

Tangential and radial arcs

MS2137-2353
(z=0.313)

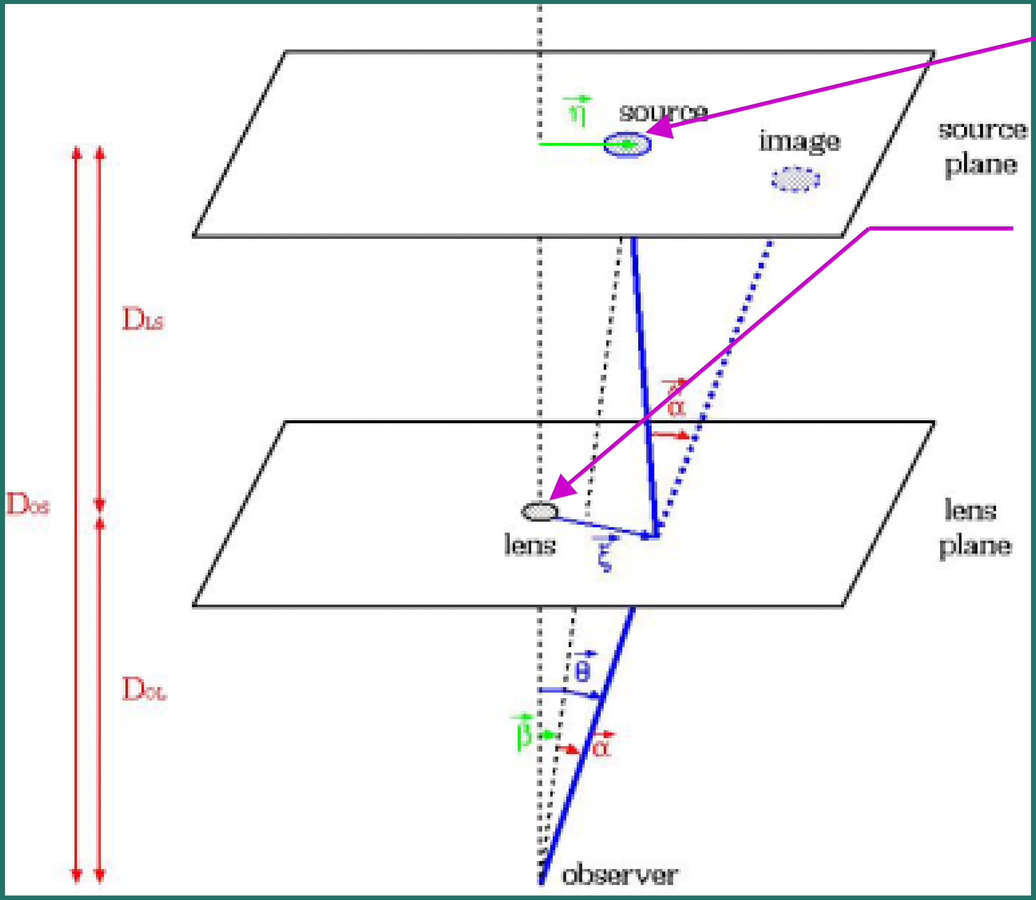
Radial arc

Tangential arc



Hammer et al. (1997)

重力レンズモデル



source: **銀河**

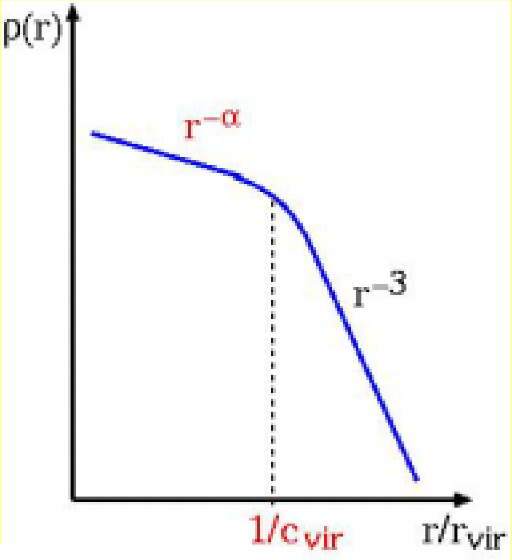
lens:
ダークハロー(銀河団)

- **予想されるアークの数を計算**
- tangential arc
  radial arc
  } **両方を考える**

Model for halo density profile

- ***Halo density profile***

$$\rho(r) = \frac{\rho_{\rm crit}\delta_{\rm c}}{(r/r_{\rm s})^{\alpha}(1 + r/r_{\rm s})^{3-\alpha}}$$



- ***Concentration parameter***

$$c_{\rm vir}(M, z) = \frac{r_{\rm vir}(M, z)}{r_{\rm s}(M, z)}$$

$$c_{\rm vir}(M, z) = c_{\rm norm}\frac{2-\alpha}{1+z}\left(\frac{M_{\rm vir}}{10^{14}h^{-1}M_{\odot}}\right)^{-0.13}$$

- ***Log-normal distribution for scatter in c_{norm}***

$\Delta(\log c_{vir})=0.18$ (Bullock et al. 2001; Jing 2000)

- ***Free parameters: c_{norm} and α***

Expected number of arcs

Number of arcs per unit solid angle

$$N_{\rm tot} = \int_{z_{\rm L,min}}^{z_{\rm L,max}} dz_{\rm L} \int_{M_{\rm min}(z_{\rm L})}^{\infty} dM\, N(M, z_{\rm L})\, n_{\rm PS}(M, z_{\rm L})(1+z_{\rm L})^3 4\pi D_{\rm OL}^2 \frac{c\,dt}{dz_{\rm L}}$$

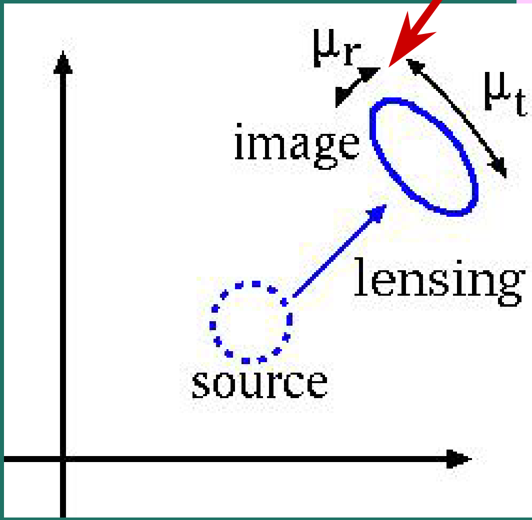
halo mass function (lens objects)

Number of arcs per given halo

$$N(M, z_{\rm L}) = \int_{z_{\rm L}}^{z_{\rm S,max}} dz_{\rm S}\, \sigma(M, z_{\rm L}, z_{\rm S}) \frac{c\,dt}{dz_{\rm S}} (1+z_{\rm S})^3 \int_{L_{\rm min}}^{\infty} dL\, n_{\rm g}(L, z_{\rm S})$$

Cross section of arc formation in a given halo

Galaxy luminosity function (sources)

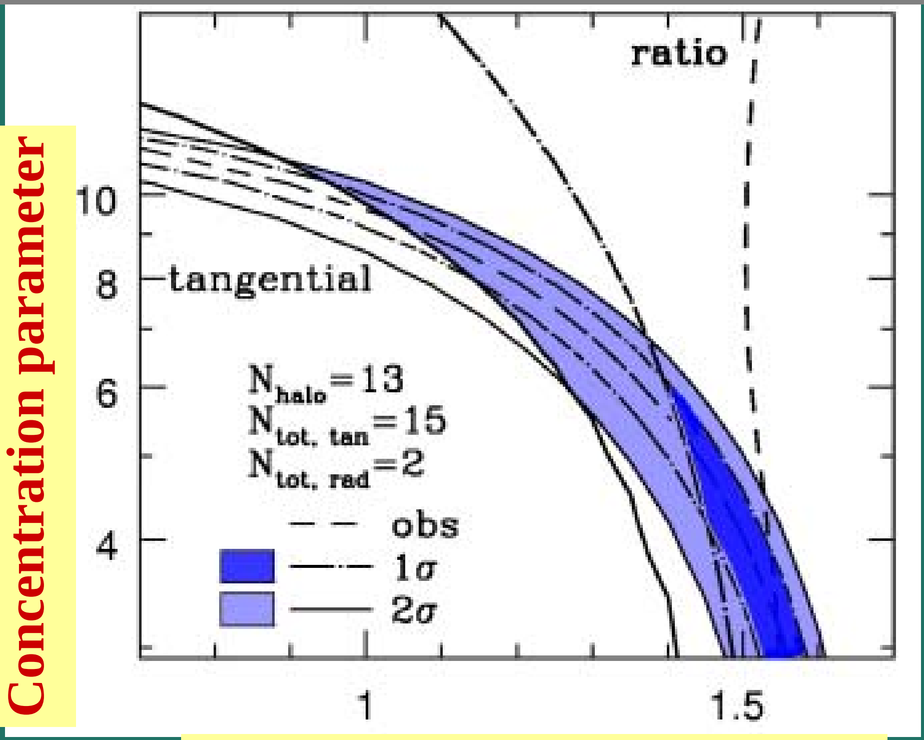


Oguri, Taruya & Suto (2001)

Constraints from the existing arc samples

- **tentative application to 13 galaxy clusters with $S_X > 10^{-12}$ erg/s/cm^2 and $0.1 < z_L < 0.4$**
  $\Rightarrow$ **$N_{tot,\ tan}=15$, $N_{tot,\ rad}=2$** **(Luppino et al. 1999)**

Observed high-frequency of radial arcs favors the steep central cusp in massive halos as indeed suggested by CDM simulations
(Molikawa & Hattori 2001)

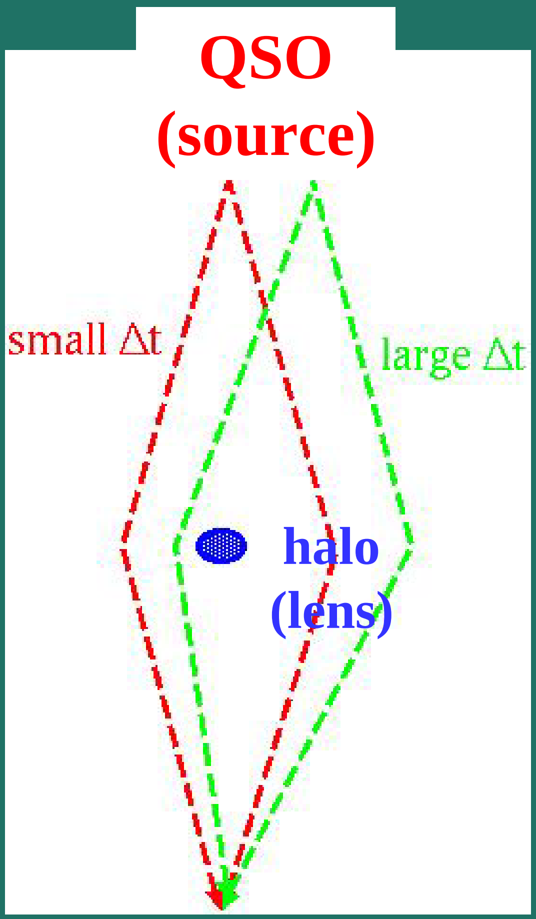


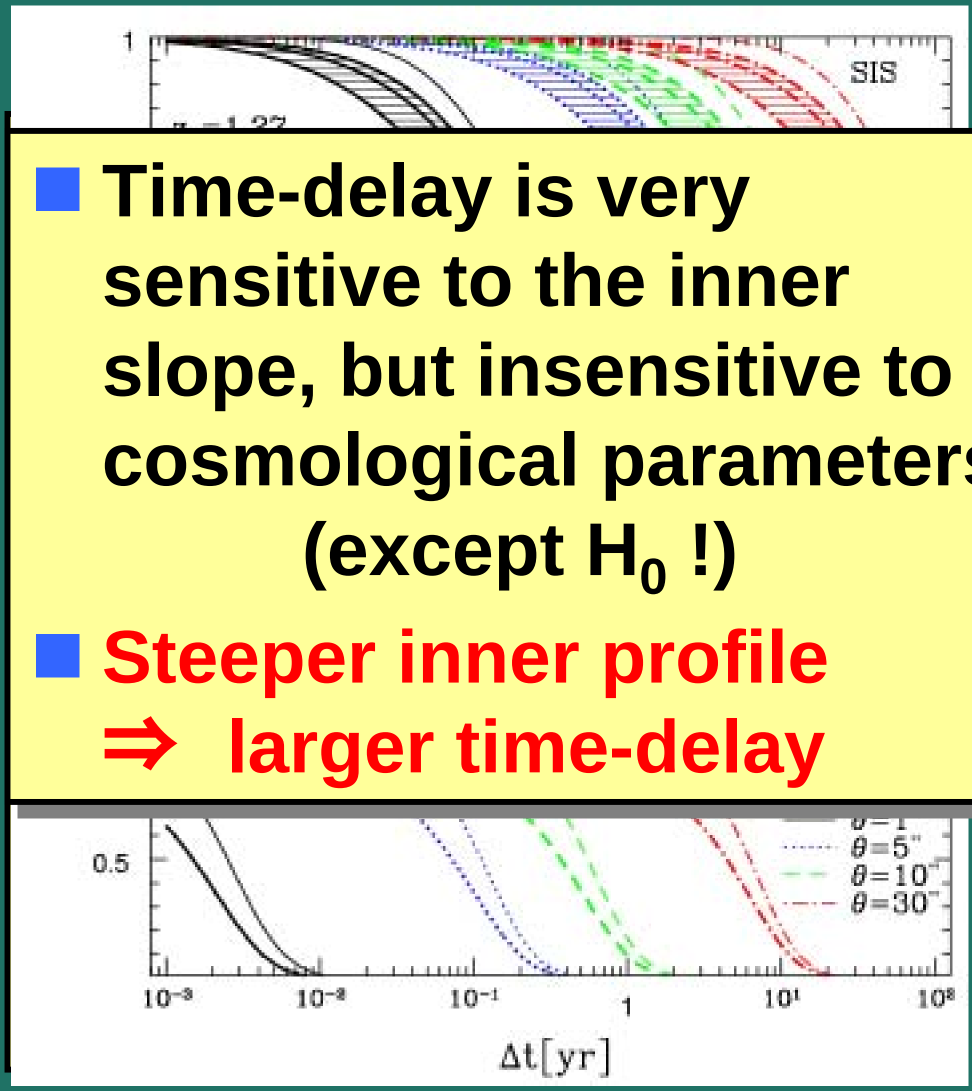
Concentration parameter

Inner slope of density profile

Oguri, Taruya & Suto (2001)

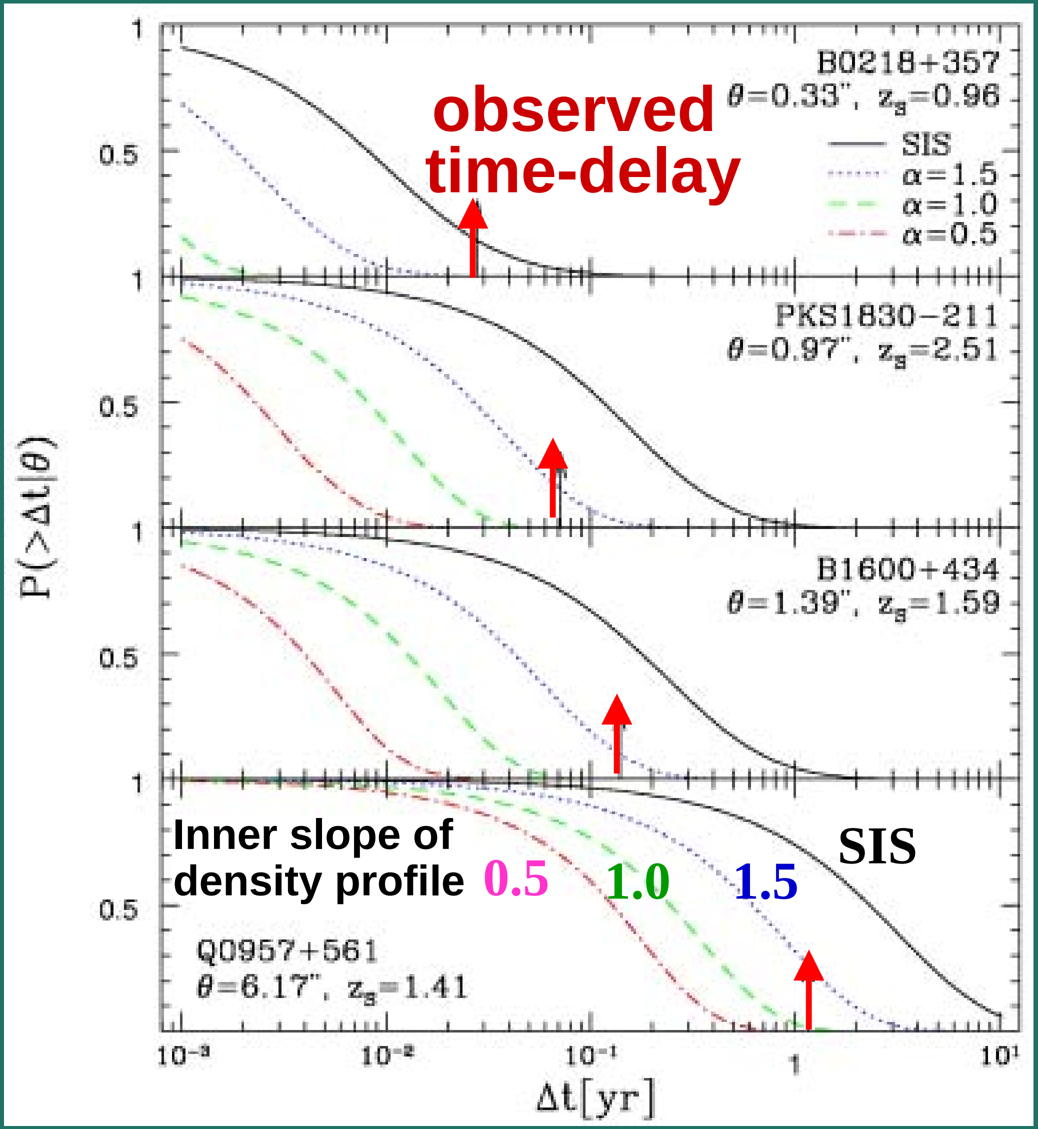
Time-delay in QSO multiple images to probe the halo density profile





- Time-delay 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



- Observed time-delay is consistent with predicted time-delay probability when the density profile has a steep cusp $\propto r^{-1.5}$

Oguri, Taruya, Suto & Turner (2002)

現状の要約

- ***The situation is confusing at best.***
  - Numerical simulations for collisionless dark matter consistently suggest the formation of a central cusp ($\propto r^{-1.5}$) rather than a core.
  - No convincing theoretical model yet which accounts for the universality of the shape of the profile.
  - Collisional dark matter with an appropriate cross section can erase the central cusp but result in too spherical halos.
  - Galactic rotation curves indicate a relatively flat core rather than a cusp, but gravitational lensing indicates the contrary.
- ***More work remains to be done.***