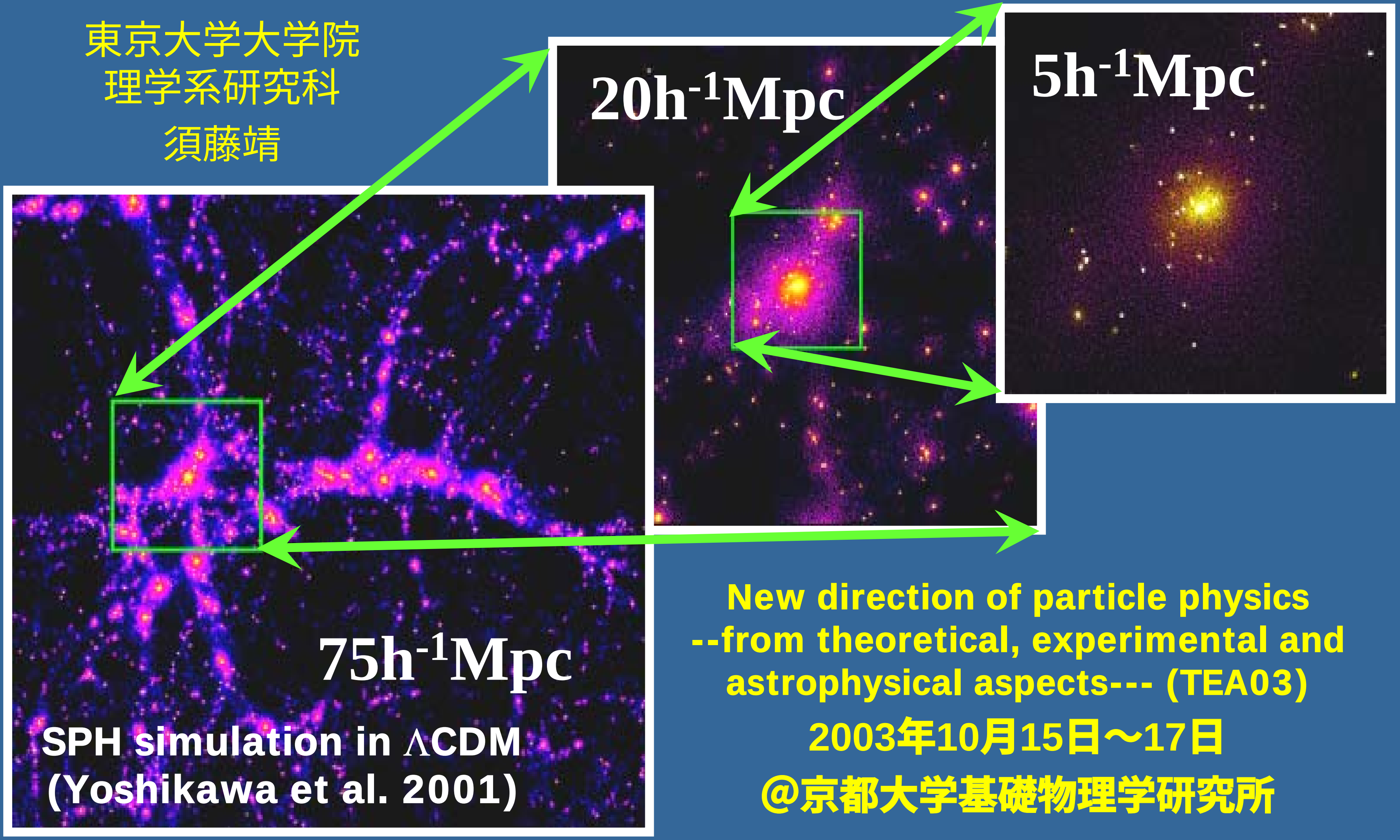
宇宙の階層

大きな構造から小さな構造へ

東京大学大学院
理学系研究科
須藤靖



SPH simulation in ΛCDM
(Yoshikawa et al. 2001)

New direction of particle physics
--from theoretical, experimental and astrophysical aspects--- (TEA03)
2003年10月15日～17日
@京都大学基礎物理学研究所

Expanding the *expanding* universe （膨張宇宙研究の展開）

0th order	一様等方宇宙モデル	宇宙論パラメータ
1st order	密度揺らぎの線形摂動論	宇宙の大構造 マイクロ波背景輻射
2nd order	非線型重力進化	ダークマターの構造形成
3rd order	バリオンガスの進化	第一世代天体と元素の起源
4th order	銀河、星、惑星の形成進化	光り輝く銀河宇宙の誕生
・・・		
L-th order	生命の起源・進化	宇宙論的生物発生学
M-th order	知的生命体への進化	宇宙論的生物進化学
N-th order	文化・文明・宗教	宇宙論的社会学
・・・		

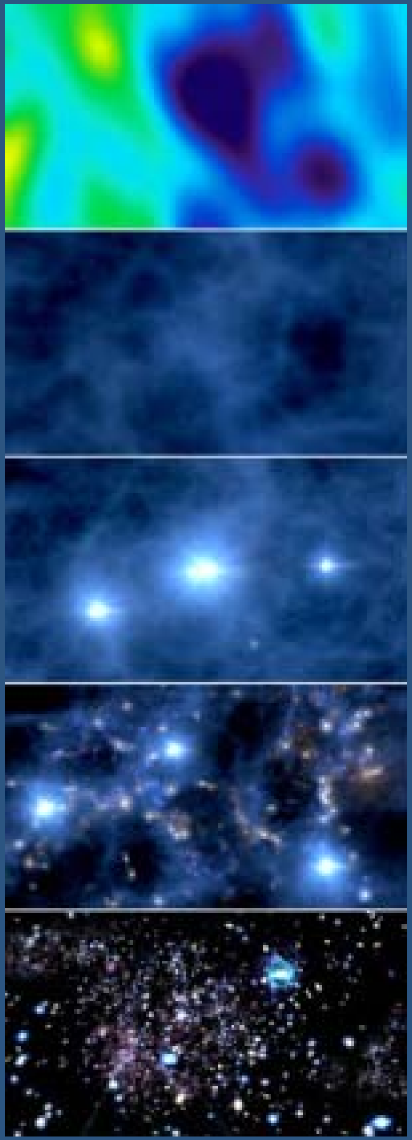
天文学的宇宙論

WMAP

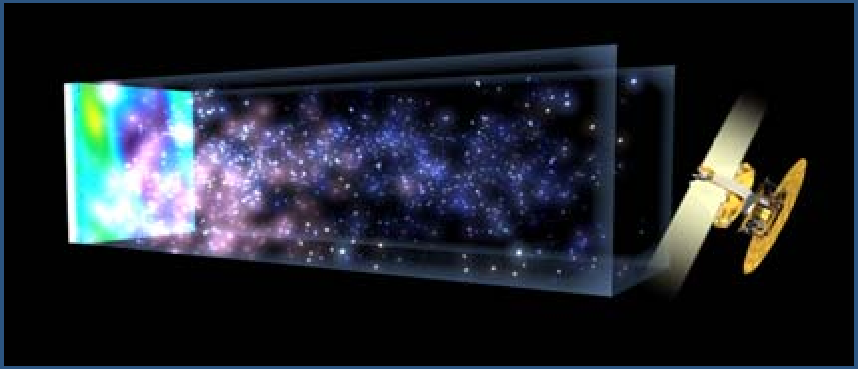
究極の宇宙論

21世紀の宇宙論： 値から理解へ

WMAP 1st year 成果の要約



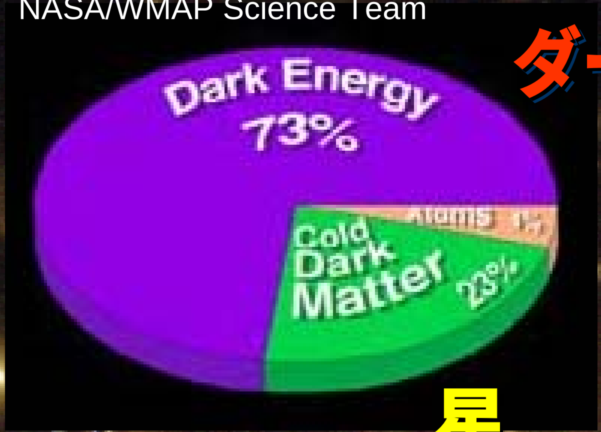
- 容器としての宇宙モデルを確定
- 宇宙の再電離時期
- ほとんどすべてのデータが、驚くべき精度で　「インフレーション＋宇宙定数入りの冷たい暗黒物質モデル」の理論予言とぴたりと一致
- The most revolutionary result out of WMAP is that there is no revolutionary results. (J. Bahcall)



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

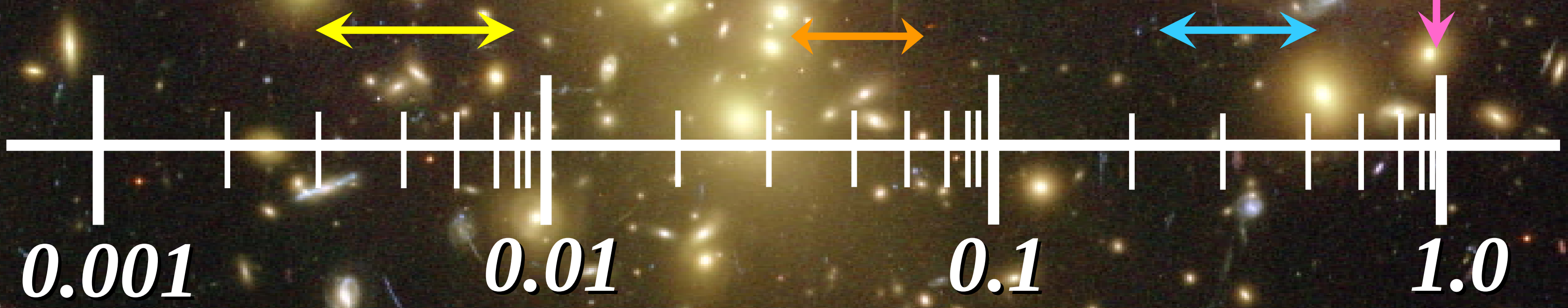
全物質 0.27±0.04

インフレーション

星
0.005±0.002

バリオン
0.044±0.004

CDM
0.23±0.04



宇宙の全質量に占める割合

冷たいダークマターモデル予言と宇宙の構造

- **L>10Mpc: 驚くべき一致**
  - 37万年時点での「初期条件」から出発したCDMモデルによって138億年後の現在の宇宙の銀河分布が「理論」だけで正確に予言できる
  - これは決して自明ではなく、驚異的。大スケールの宇宙はかなり決定論的、必然的な進化を遂げてきたことを示す。
  - 例えば、生物の発現、知的生命体への進化などは、必ずしも必然だけで説明できるわけではなく、何らかの偶然的要素が本質的であったと考える人が多い
- **1Mpc<L<10Mpc: ある程度経験的には理解されている**
  - 銀河団の誕生・質量関数
  - 線形バイアスを仮定した銀河分布
- **L<1Mpc: まだ満足すべき理解には程遠い**
  - 星形成・銀河形成・光度関数・ハッブル系列（形態）の起源
  - 宇宙で最初に誕生した天体はどのようなものか
  - 矮小銀河の存在 （CDMに対する警鐘としてPeeblesが病的に指摘）
  - 銀河・銀河団の密度プロファイル：中心部はカスプ$\rho\propto r^{-1.5}$を持つか、あるいはコア$\rho\propto$一定 になっているか？

大きな構造から小さな構造へ

～ CDM モデルで残された天文学的問題 ～

- 天体の形成とそれによるフィードバック
  - 重力的天体形成から星形成へ
  - 宇宙の第一世代天体と宇宙の再電離
  - 星形成･星進化･超新星爆発によるエネルギーフィードバックによる次世代天体形成の促進･抑制
  - 銀河団のX線光度温度関係(1keV/particle)と非重力加熱
- 銀河分布とダークマター分布の関係
  - 銀河分布の「バイアス」から銀河形成モデルを推測する
- ダークマターハローの密度プロファイル
  - 天体の中心部分の密度は発散しているか（カスプ）、それとも一定か（コア）？
- ダークバリオンは何処に
  - 軟X線領域の精密分光専用衛星DIOS (Diffuse Intergalactic Oxygen Surveyor)による酸素輝線を用いたダークバリオン探査

Part 1:

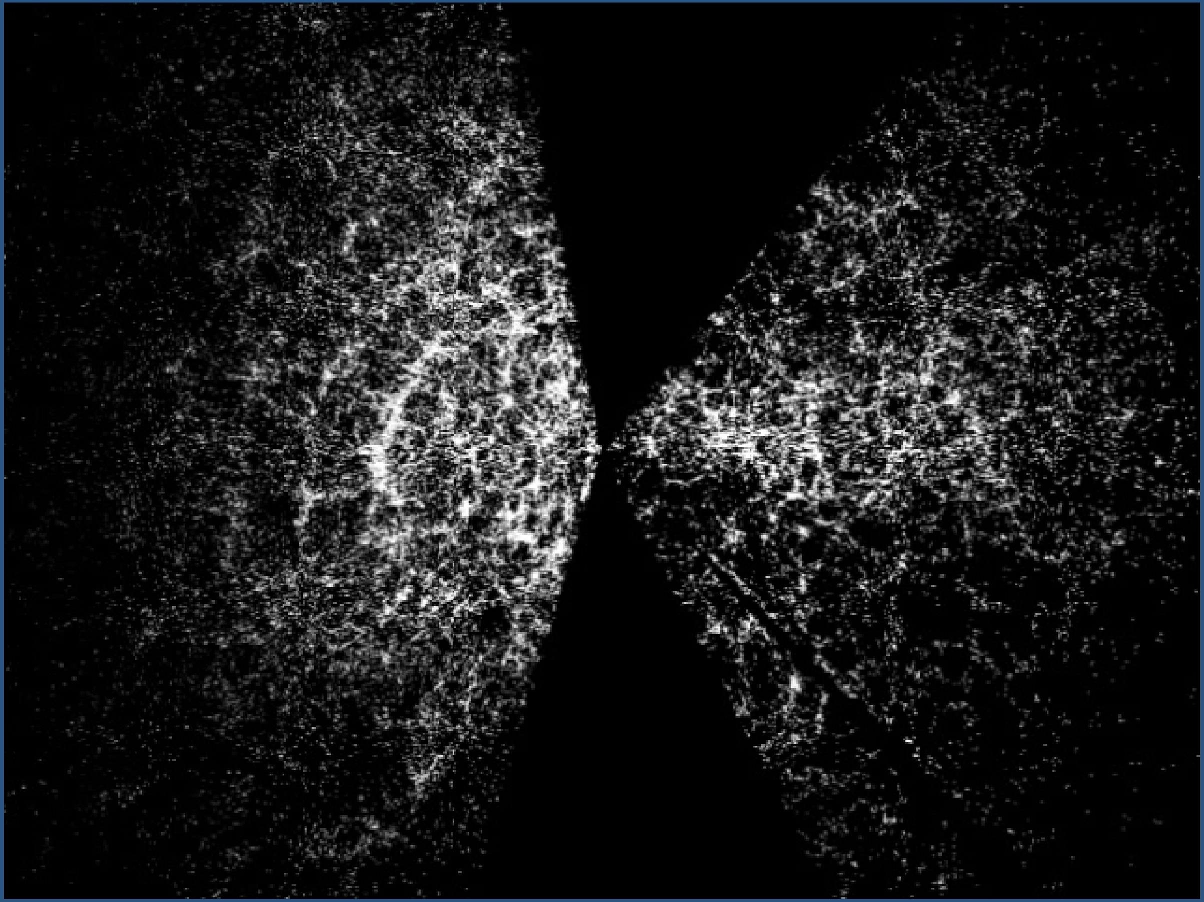
スローンデジタルスカイサーベイによる宇宙銀河地図の作成と銀河のバイアスの定量化

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

史上最大の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

8千万個の銀河を観測、そのなかの80万個の銀河の3次元地図作り

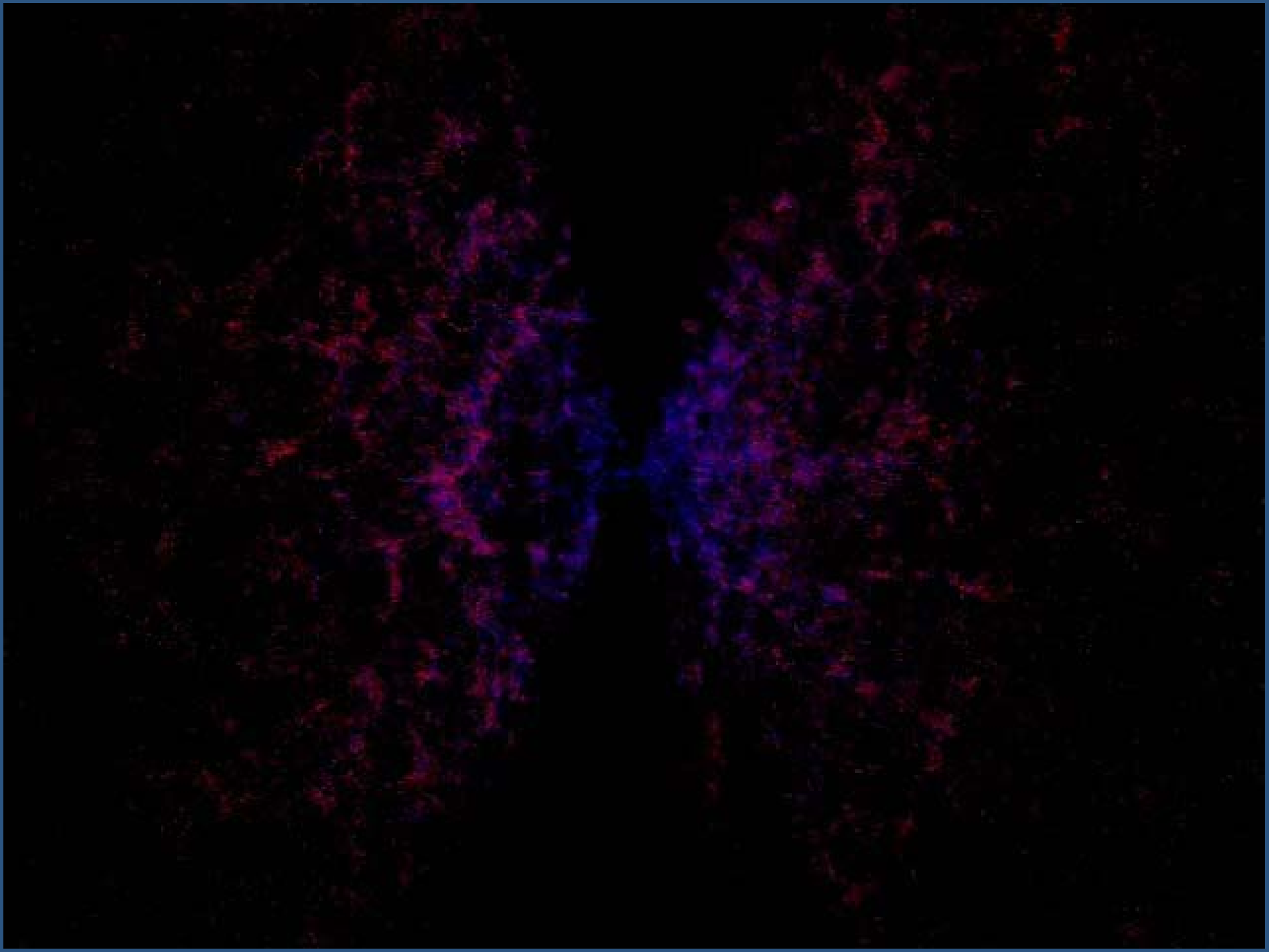


http://www.sdss.org/dr1/

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

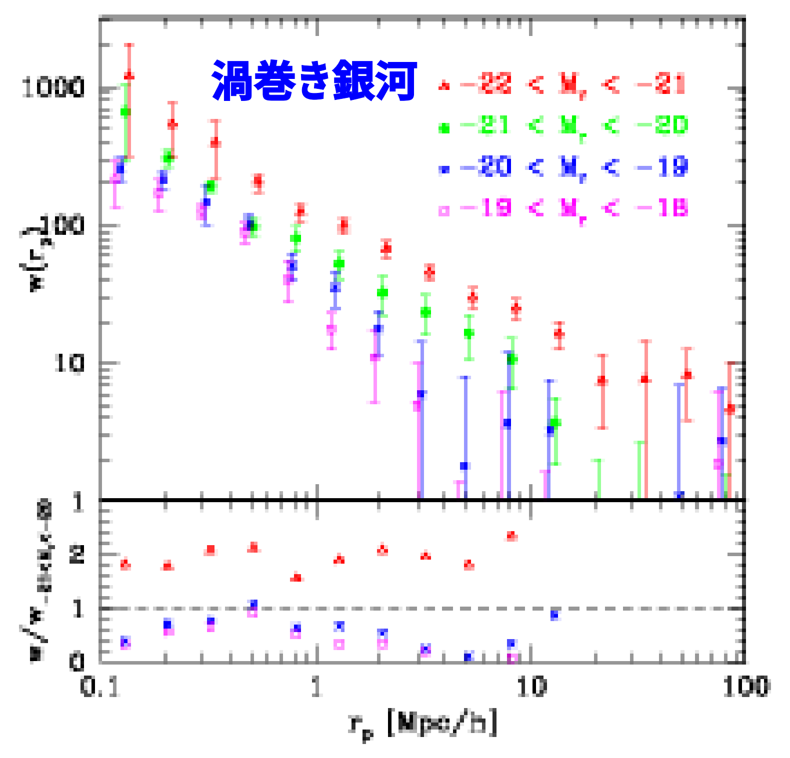
NHK教育　サイエンスZERO　2003年6月11日　0：00　放映

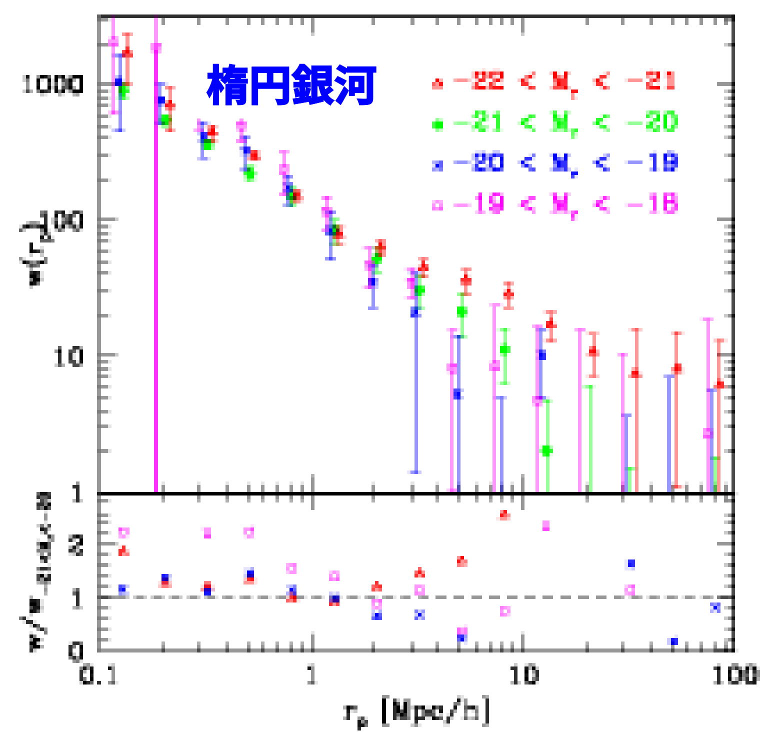
SDSS DR1 galaxies: morphology dependent clustering



NHK教育　サイエンスZERO　2003年6月11日　0：00　放映

SDSS銀河2点相関関数の形態・光度依存性





Kayo et al. (2003)

- early-types are more strongly biased than late-types
- for late-types, luminous galaxies show stronger clustering
- for early-types, the clustering amplitudes are fairly independent of the absolute luminosities of galaxies

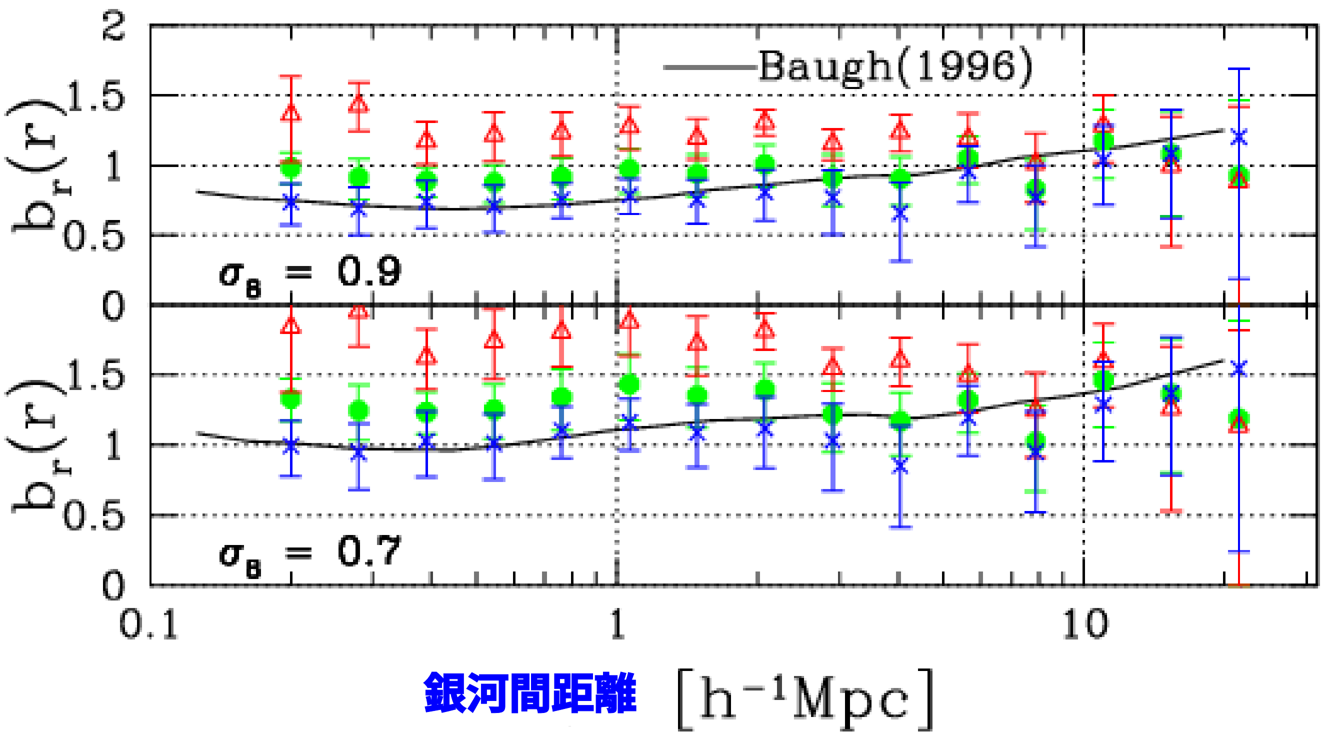
SDSS銀河バイアスの形態依存性

early-type

total

late-type

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



- Galaxy bias is fairly scale-independent
- **Clear morphology dependence:** b=1.2〜1.5 for "early"-types and b=0.7〜0.9 for "late"-types with respect to ΛCDM with σ_8=0.9 (computed semi-analytically using the light-cone average described before)

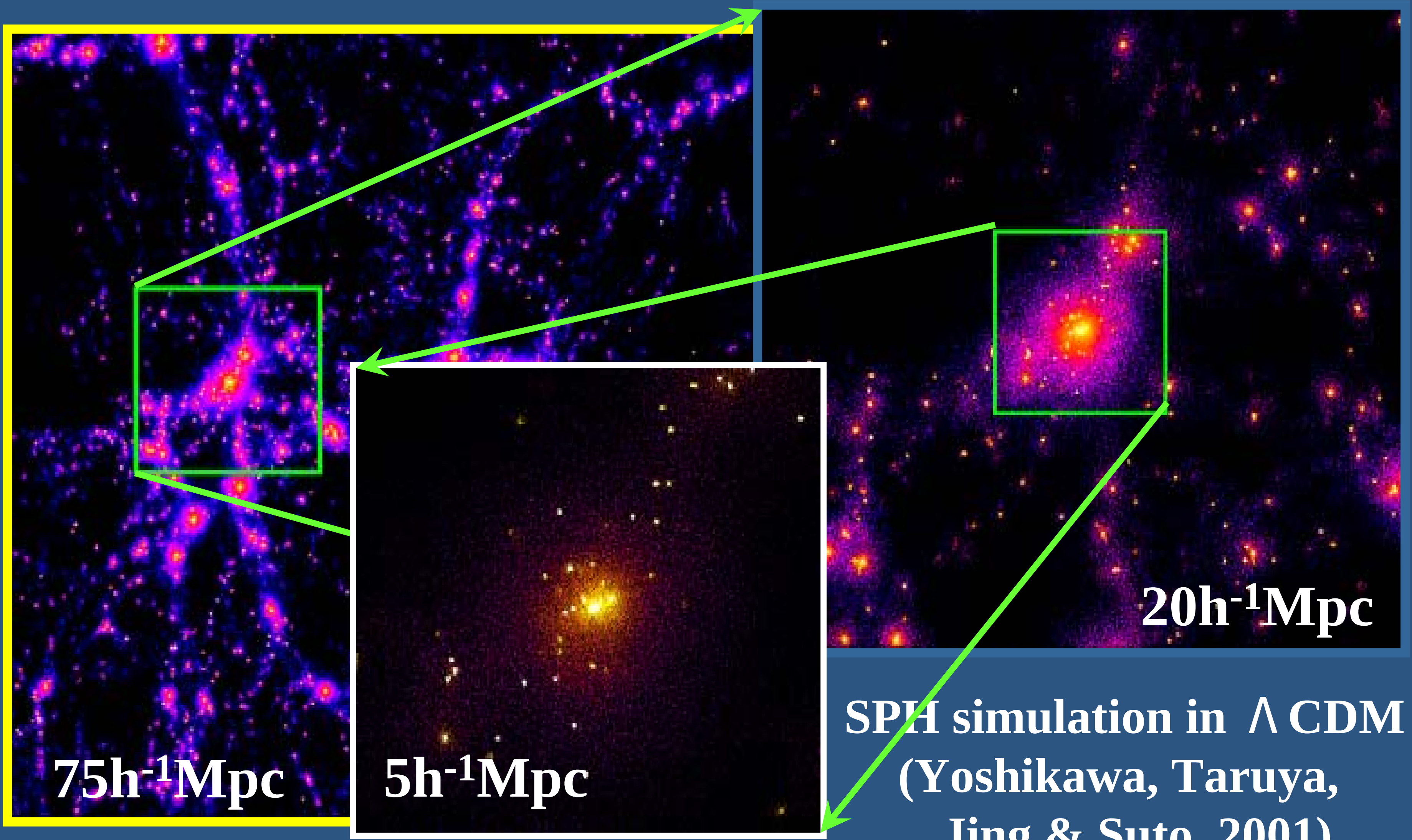
Kayo, Suto, Fukugita, Nakamura, et al. (2003)

宇宙構造進化シミュレーションの例

吉川 耕司、
樽家 篤史、
景 益鵬、
須藤 靖
(2001)

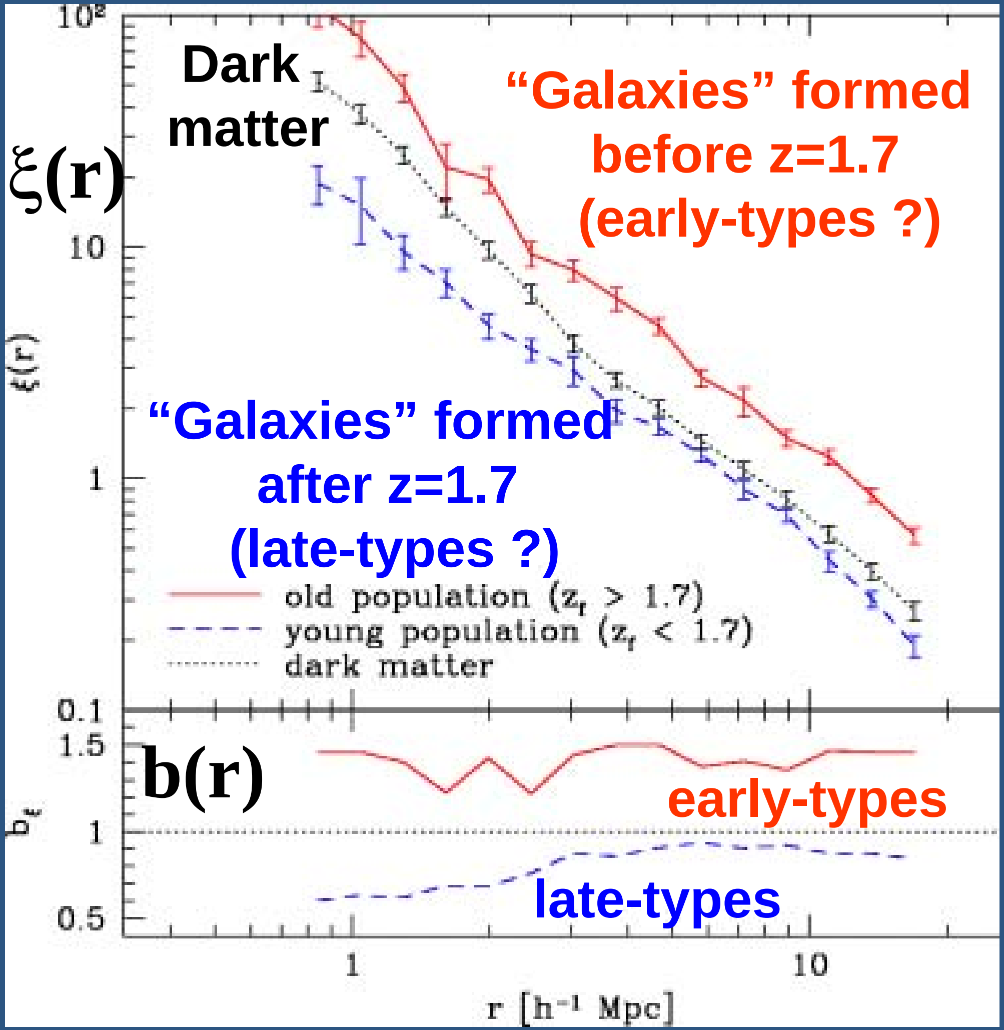
ダークマター分布の進化
⇒ X線で見る現在の高温ガス分布
⇒ 可視光で見える現在の宇宙の銀河分布

SPH simulation: zoom-up



SPH simulation in ΛCDM
(Yoshikawa, Taruya,
Jing & Suto 2001)

Galaxy morphology and formation epoch: indication from SPH simulations



- Simulated "galaxies" formed earlier are more strongly biased
- Recently formed galaxies preferentially avoid high-density regions
- Quite consistent with the SDSS DR1, but still very primitive
- need to elaborate the model further !

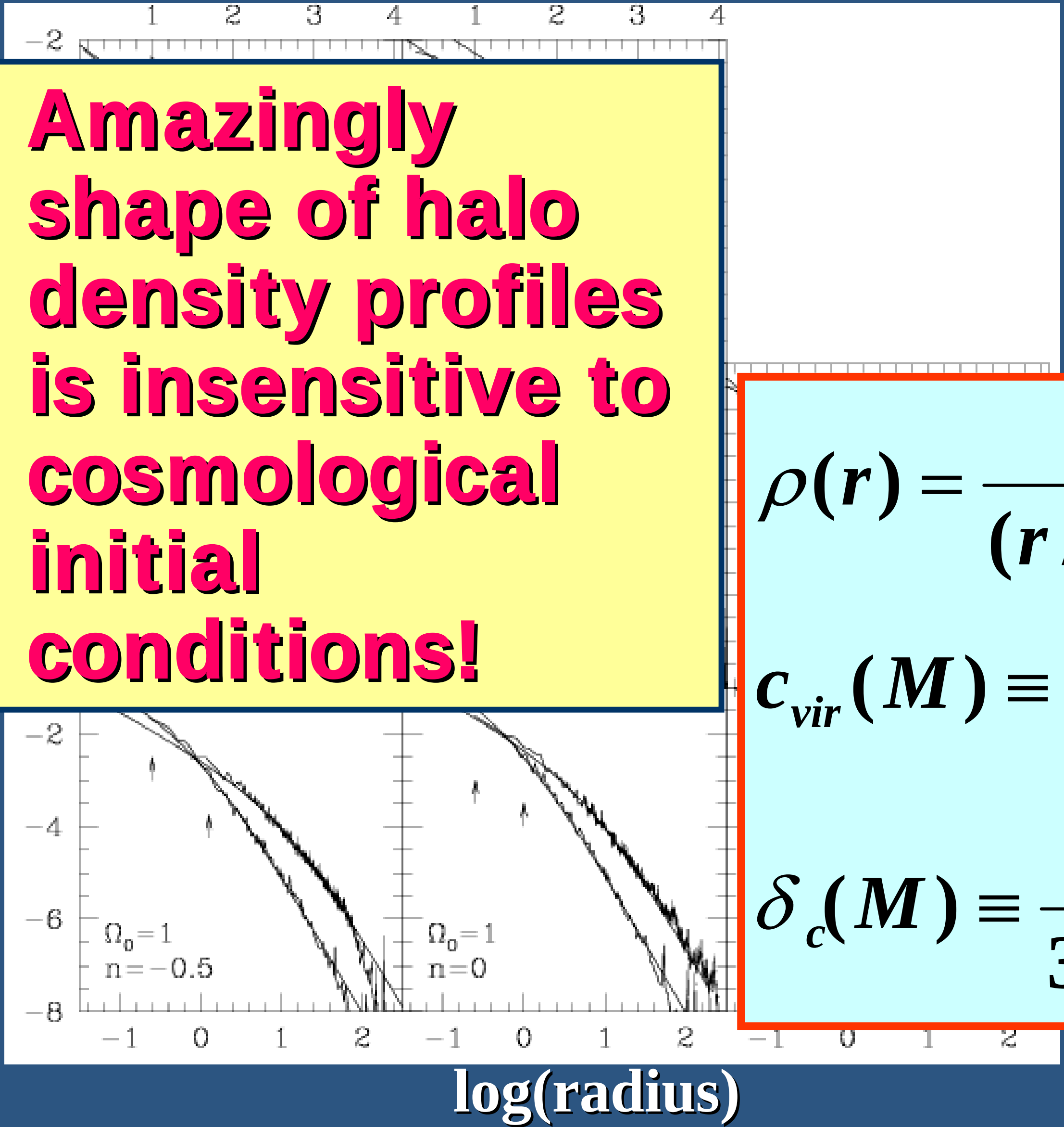
Yoshikawa, Taruya, Jing & Suto (2001)

Part 2:
銀河·銀河団の中心密度プロファイルとダークマターの性質

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

NFW universal density profile



- **Amazingly 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

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

Summary of simulation and theory

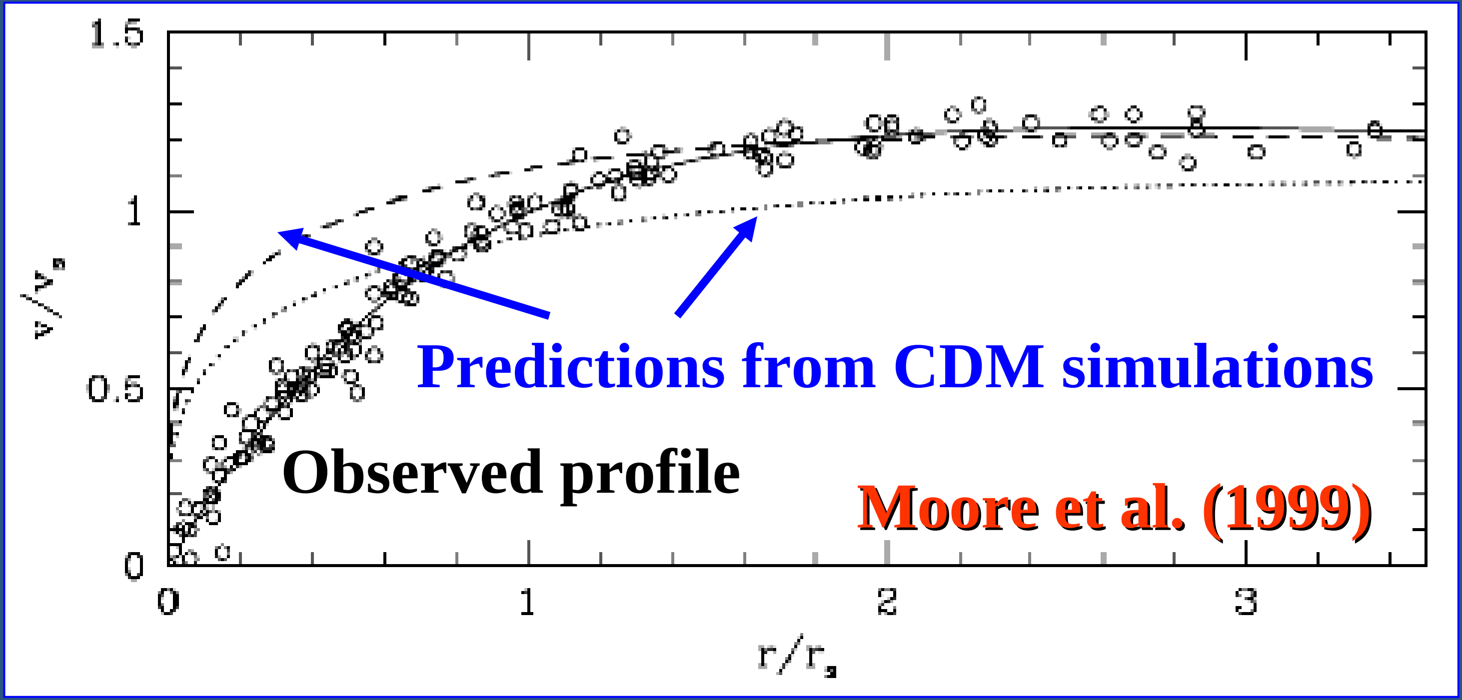
- ***Simulations***
  - Density profiles of dark halos are fairly universal (at least approximately), and are insensitive to the cosmological initial conditions except $r_s(M,z)$
  - Cusp rather than core in the central region

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

- ***"Theoretical" models***
  - Either core or cusp is acceptable.
  - Inner slope is generally expected to depend on the primordial spectrum of fluctuations.

⇒ needs observational confrontation

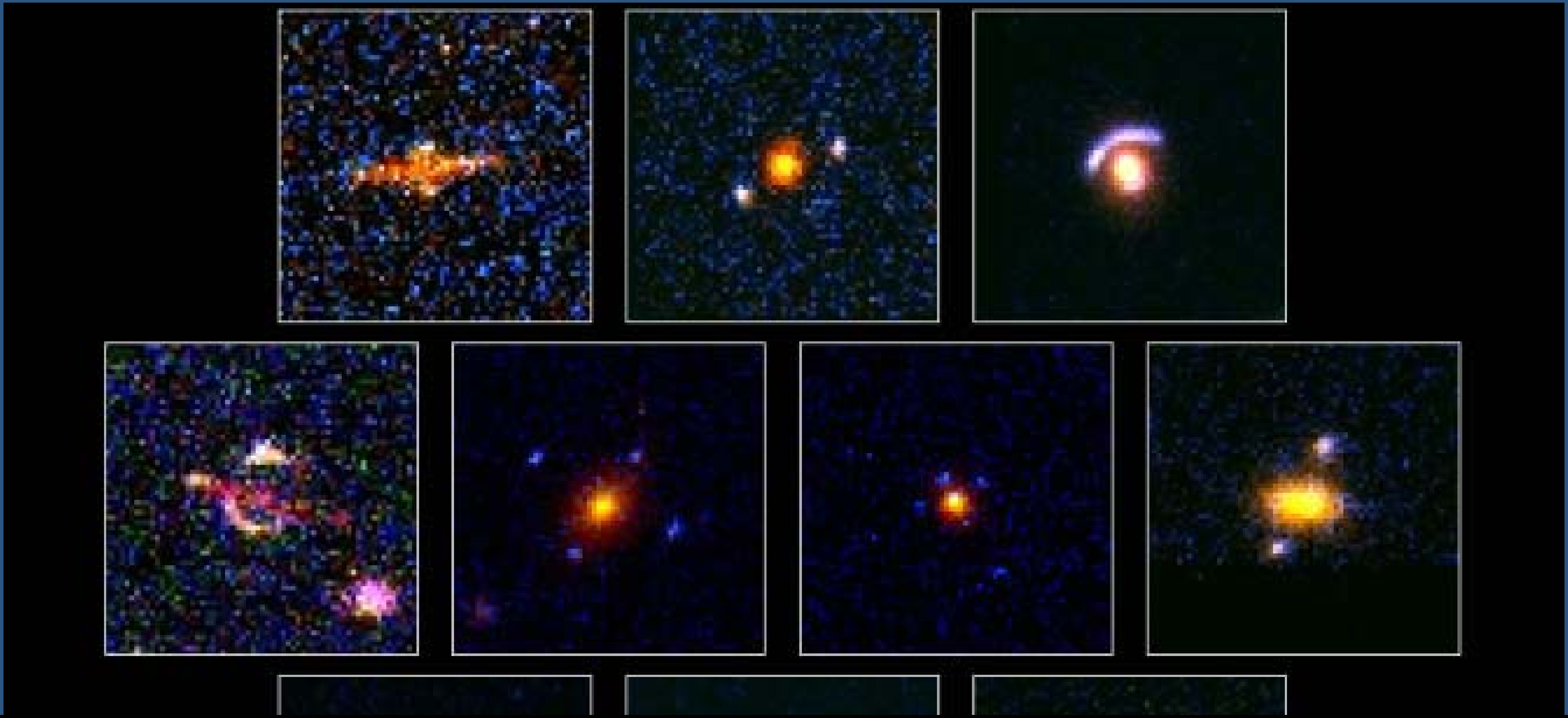
銀河の回転曲線は中心コアを示唆



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

⇒ inconsistent with CDM simulations (?)

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



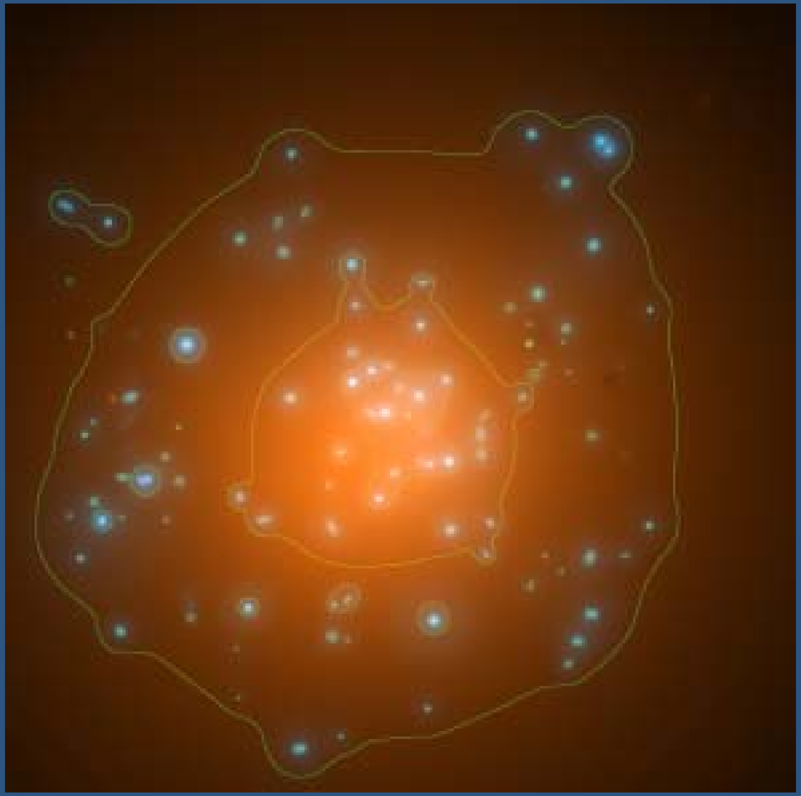
- 光線は重力場によって曲げられる
  - 天体が多重像をつくる (強い重力レンズ)
  - 天体の形状が変形を受ける (弱い重力レンズ)
  - 天体の見かけの明るさが増光する (マイクロレンズ)

銀河団CL0024+1654の重力レンズ

HST image

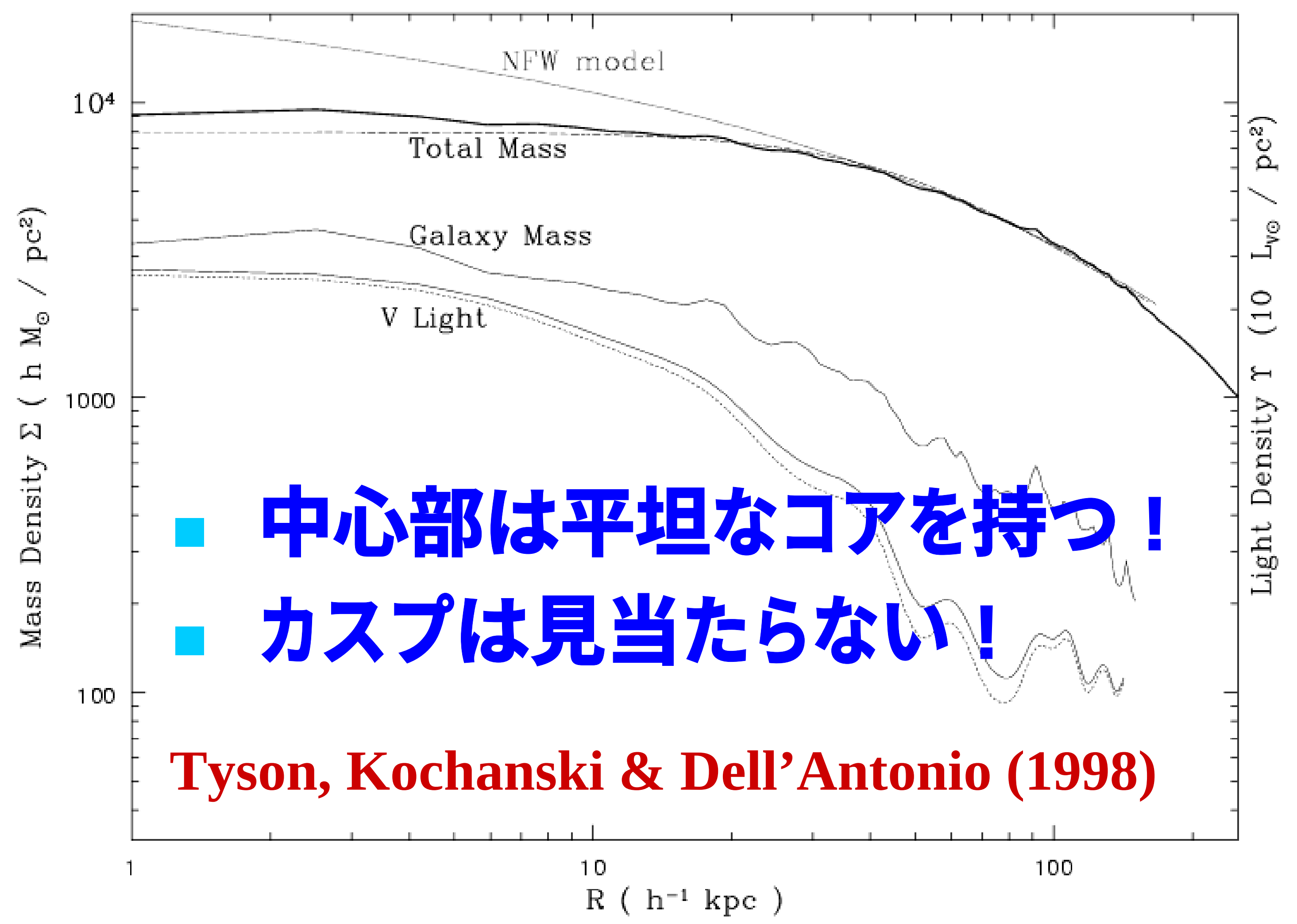
Z=0.39, L_X=5×10^{43} h^{-2} erg/s

reconstructed mass distribution (with 512 parameters)



Tyson, Kochanski & Dell'Antonio (1998)

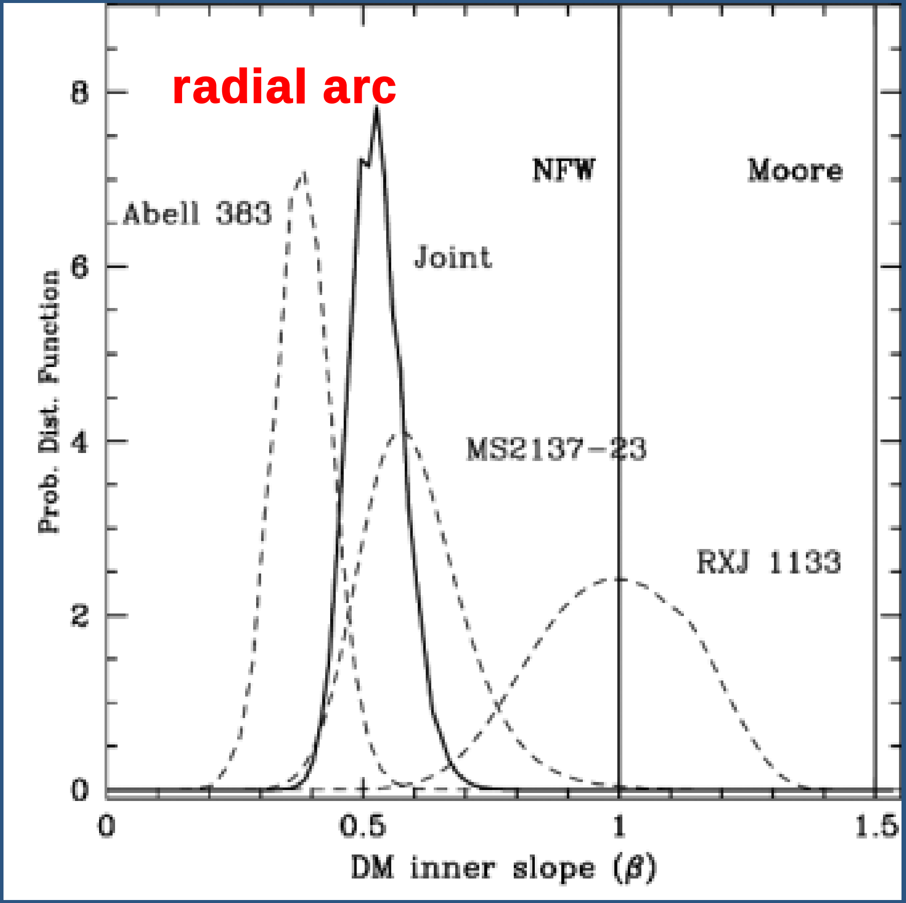
重力レンズデータから再構築されたCL0024+1654の密度分布

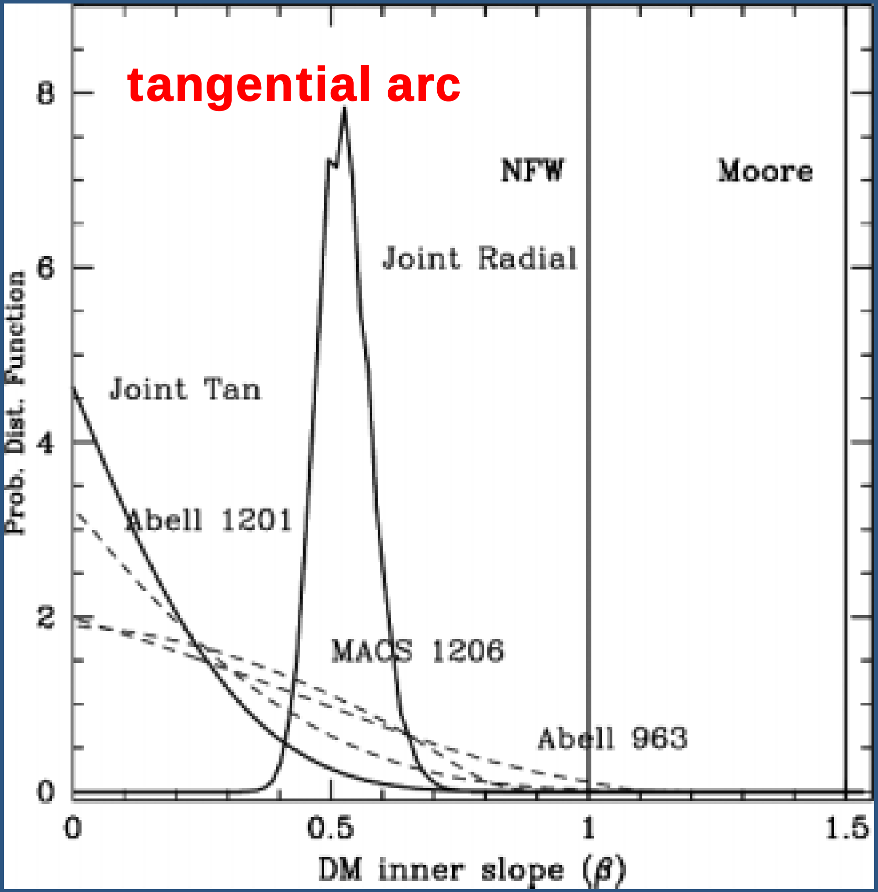


- **中心部は平坦なコアを持つ！**
- **カスプは見当たらない！**

Tyson, Kochanski & Dell’Antonio (1998)

Inner profiles of clusters from lensing analysis





Sand, Treu, Smith & Ellis (2003)

Self-interacting dark matter ?

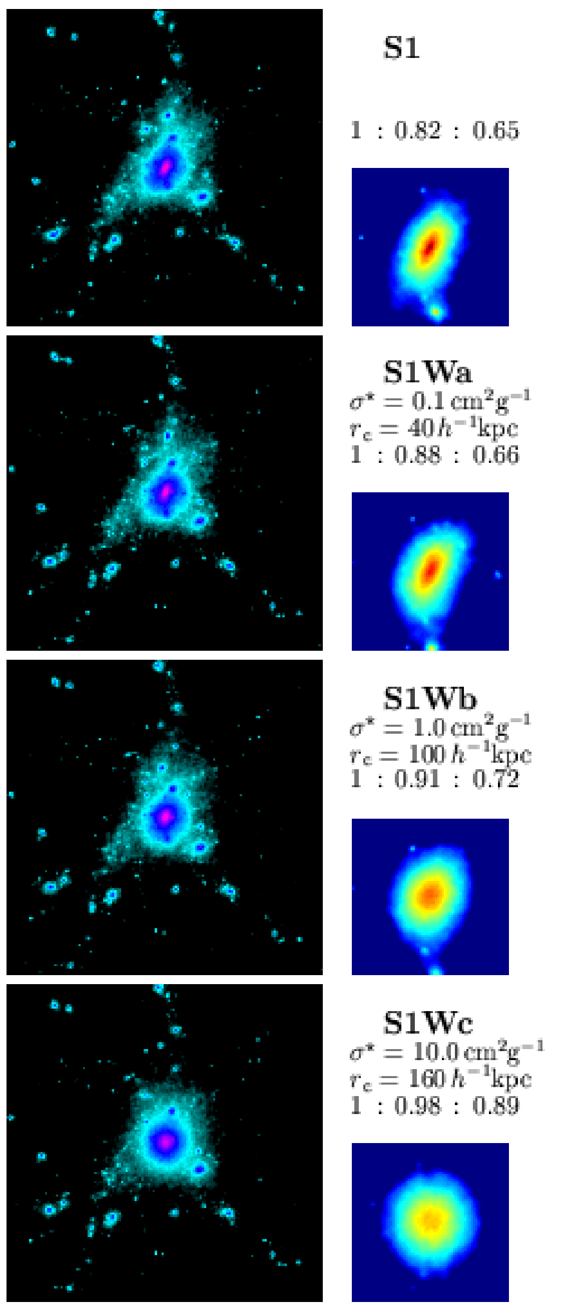
- ***Collisionless dark matter***
  - reproduces nicely the observed large-scale structure of the universe ($r \gg 1$Mpc)
  - **problems on smaller scales ($r<1$Mpc)**

    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

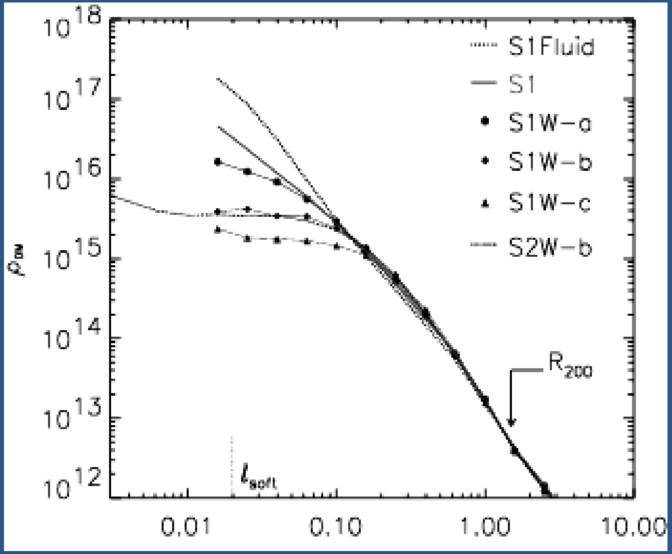
$$(mn)\frac{\sigma}{m}\ell = 1 \quad \Rightarrow \quad \frac{\sigma}{m} = 2\,\mathrm{cm}^2/\mathrm{g}\left(\frac{10^4\rho_{\mathrm{crit}}}{\rho_{\mathrm{center,cl}}}\right)\left(\frac{1\,\mathrm{Mpc}}{\ell}\right)$$

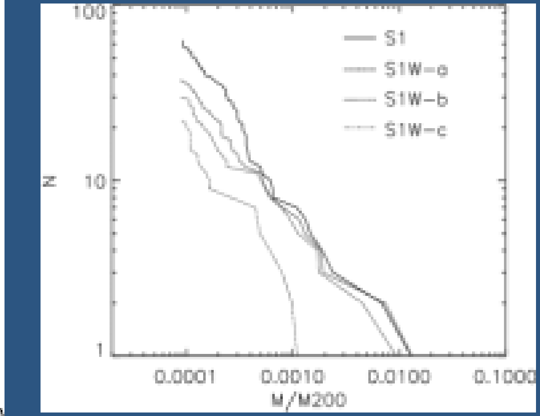
Collisional Dark Matter

- $\sigma \to \infty$では、中心のカスプはより強くなる
- $\sigma / m \sim 1\ \mathrm{cm}^2 / \mathrm{g}$ 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)





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**

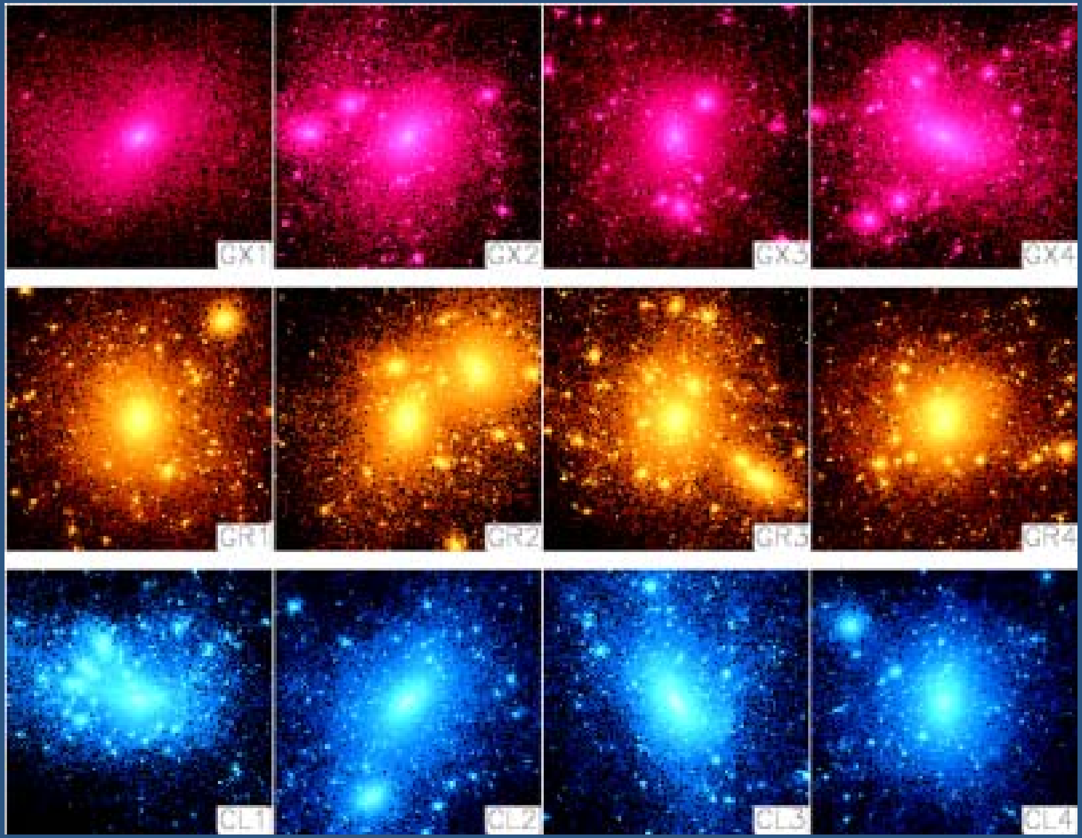
  (Oguri, Taruya, YS + Turner 2002)

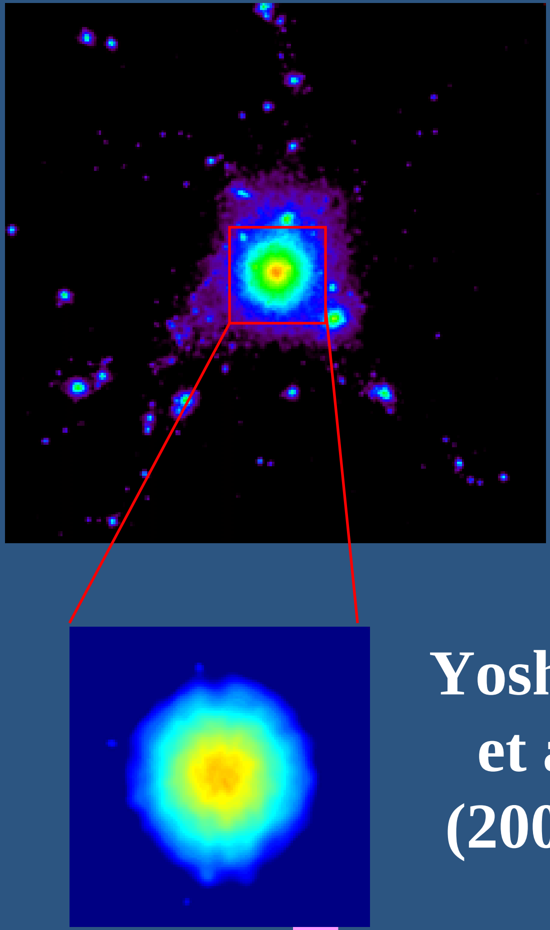
⇒ generally favor a steep cusp ($\alpha \sim -1.5$)

Are Dark Halos Spherical?

Collisionless CDM: NO

Jing & Suto (2000)





Yoshida et al. (2000)

Collisional CDM: YES

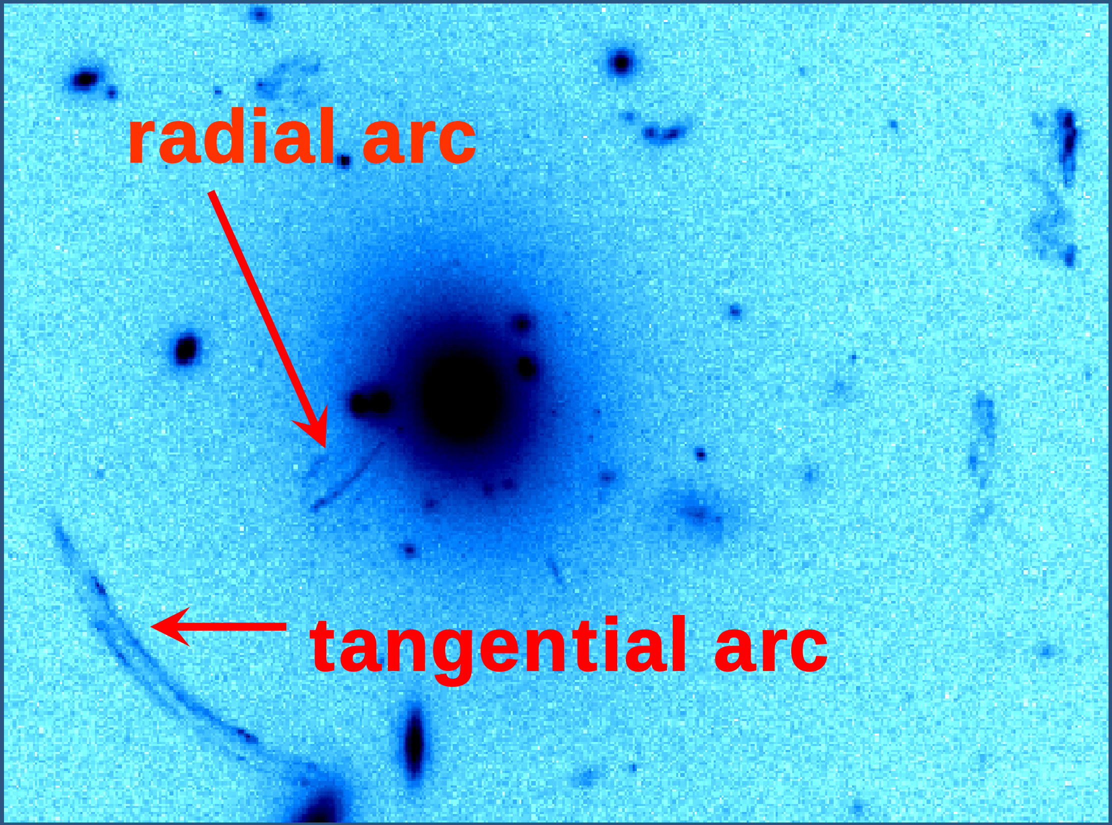
Lensed Arcs in Galaxy Clusters

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

↓

(lensed) arcs

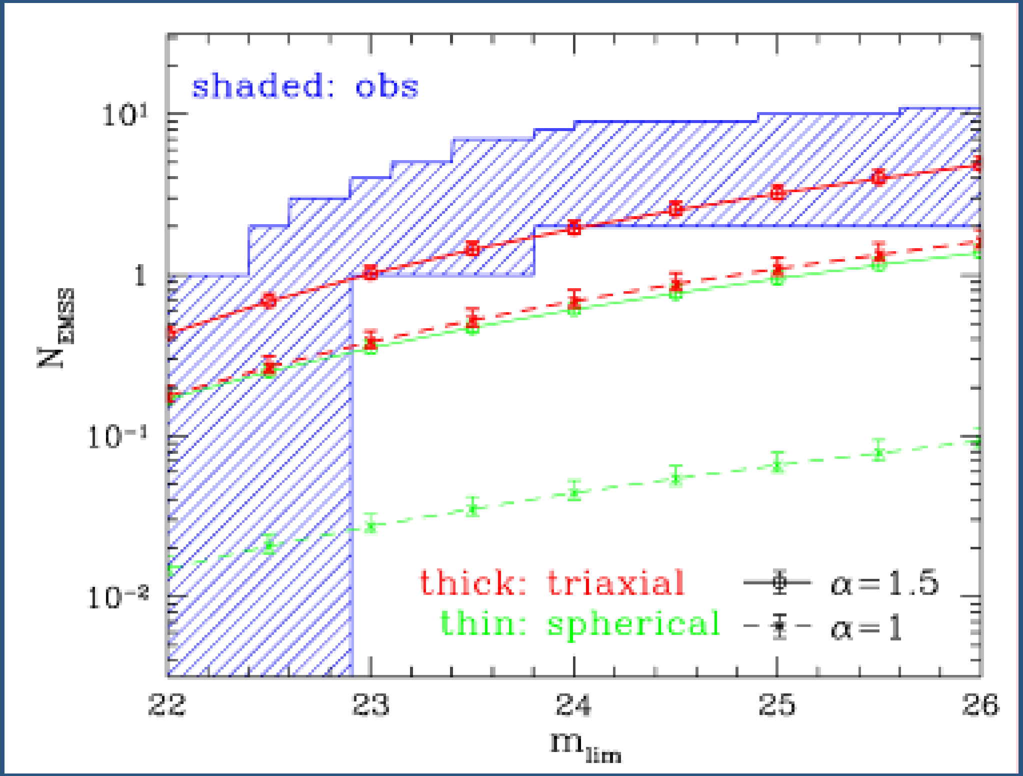
~30 giant arcs are observed so far



Hammer et al. (1997)

Comparison with observed statistics

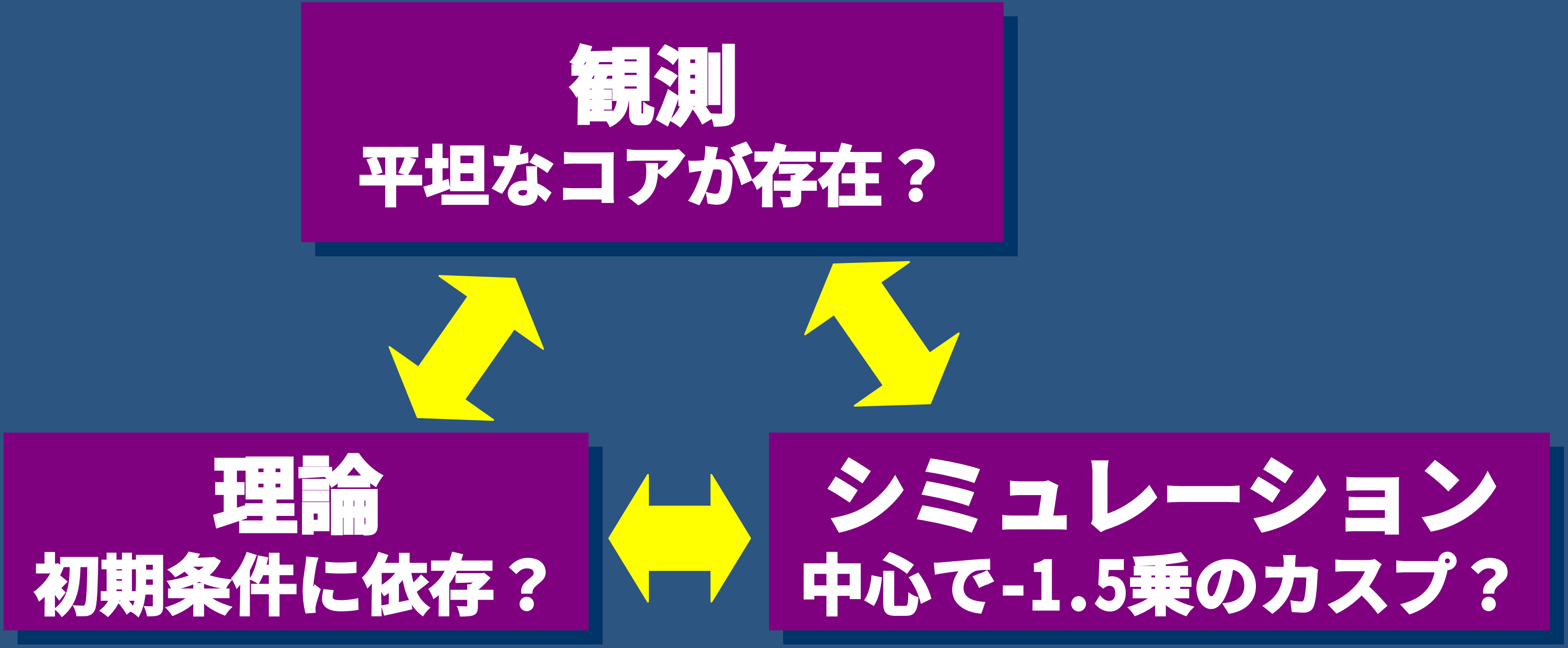
Previous model predictions are known to be significantly smaller than the observed number of lensed arcs (Luppino et al. 1999)



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)

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乗のカスプ？

- 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！*

冷たい暗黒物質モデルの危機？

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

  Self-interacting dark matter

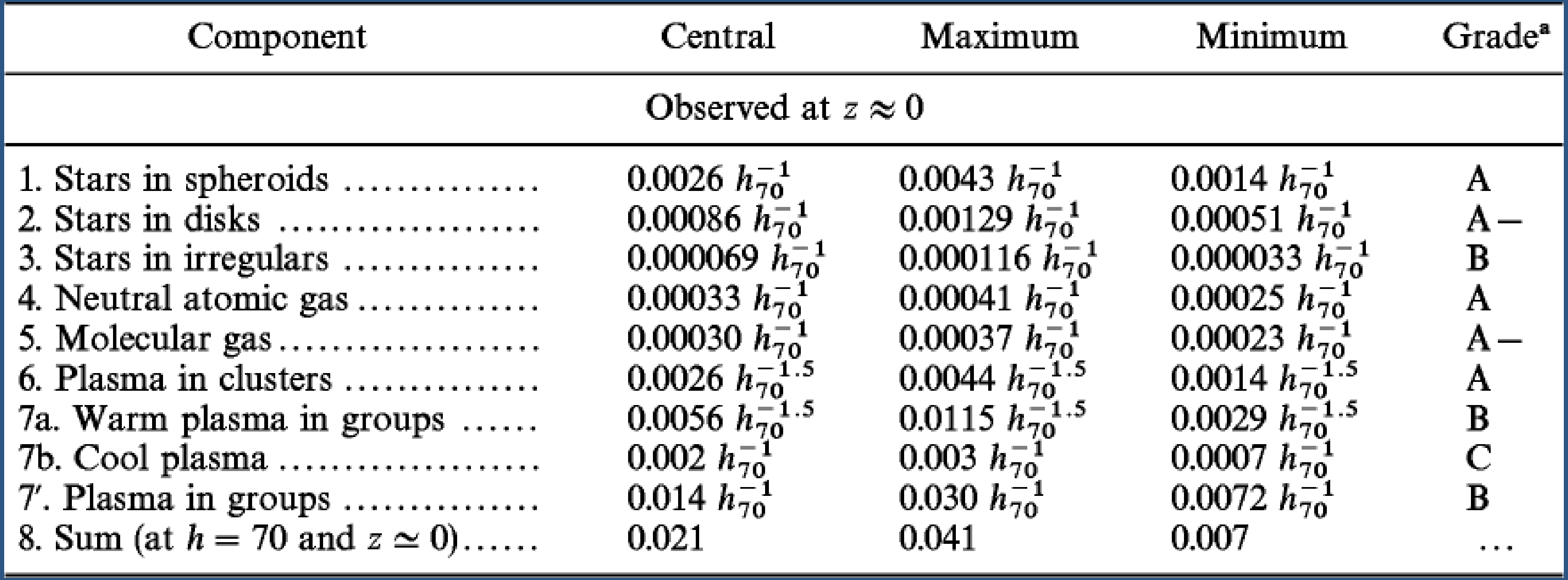
  (Spergel & Steinhardt 1999)
- **Other hydrodynamic/radiative processes ?**
  - Supernova feedback
  - Bar-driven core formation (Weinberg & Katz 2001)
  - …

Part ３：
DIOS衛星によるダークバリオン探査
(Diffuse Intergalactic Oxygen Surveyor)

Where are the baryons ?
cosmic baryon budget

Fukugita, Hogan & Peebles： ApJ 503 (1998) 518

$$\Omega_{star}+\Omega_{HI}+\Omega_{H_2}+\Omega_{hot\,X-ray}=\mathbf{0.0068}^{+0.0041}_{-0.0030}\quad vs\quad \Omega_{BBN}=\mathbf{0.04}\quad (h=0.7)$$



Component	Central	Maximum	Minimum	Grade[a]
Observed at $z \approx 0$				
1. Stars in spheroids	$0.0026\ h_{70}^{-1}$	$0.0043\ h_{70}^{-1}$	$0.0014\ h_{70}^{-1}$	A
2. Stars in disks	$0.00086\ h_{70}^{-1}$	$0.00129\ h_{70}^{-1}$	$0.00051\ h_{70}^{-1}$	A–
3. Stars in irregulars	$0.000069\ h_{70}^{-1}$	$0.000116\ h_{70}^{-1}$	$0.000033\ h_{70}^{-1}$	B
4. Neutral atomic gas	$0.00033\ h_{70}^{-1}$	$0.00041\ h_{70}^{-1}$	$0.00025\ h_{70}^{-1}$	A
5. Molecular gas	$0.00030\ h_{70}^{-1}$	$0.00037\ h_{70}^{-1}$	$0.00023\ h_{70}^{-1}$	A–
6. Plasma in clusters	$0.0026\ h_{70}^{-1.5}$	$0.0044\ h_{70}^{-1.5}$	$0.0014\ h_{70}^{-1.5}$	A
7a. Warm plasma in groups	$0.0056\ h_{70}^{-1.5}$	$0.0115\ h_{70}^{-1.5}$	$0.0029\ h_{70}^{-1.5}$	B
7b. Cool plasma	$0.002\ h_{70}^{-1}$	$0.003\ h_{70}^{-1}$	$0.0007\ h_{70}^{-1}$	C
7′. Plasma in groups	$0.014\ h_{70}^{-1}$	$0.030\ h_{70}^{-1}$	$0.0072\ h_{70}^{-1}$	B
8. Sum (at $h = 70$ and $z \simeq 0$)......	0.021	0.041	0.007	...

- The observed baryons in the present universe amount merely to （10～30） % of the big-bang nucleosynthesis prediction and WMAP value

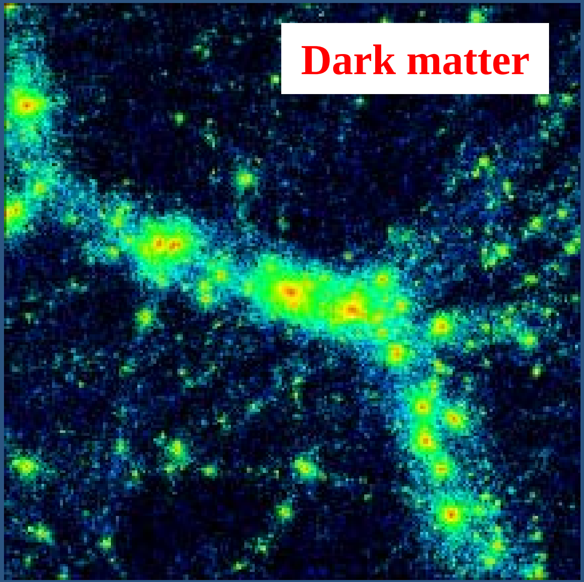
A cluster region in SPH simulation

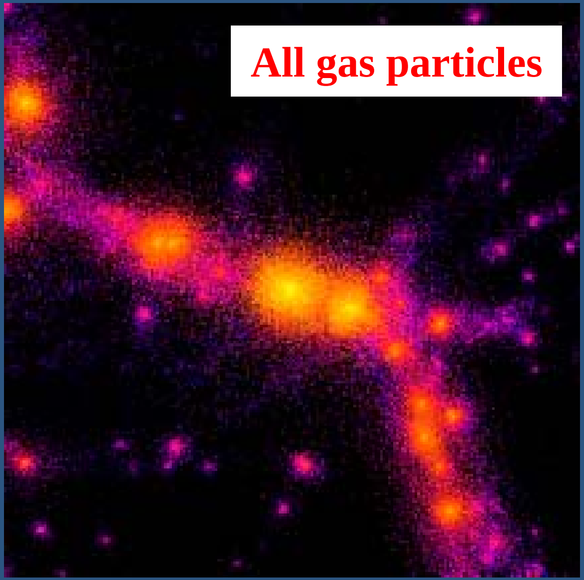
A $(30h^{-1}\mathrm{Mpc})^3$ box around a massive cluster at $z=0$

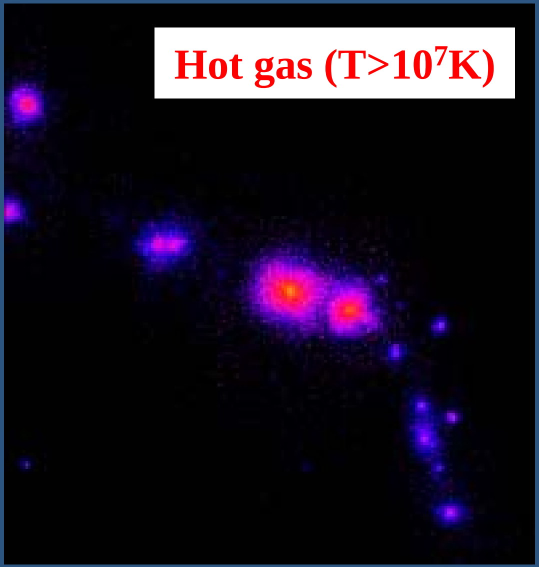
ΛCDM SPH simulation

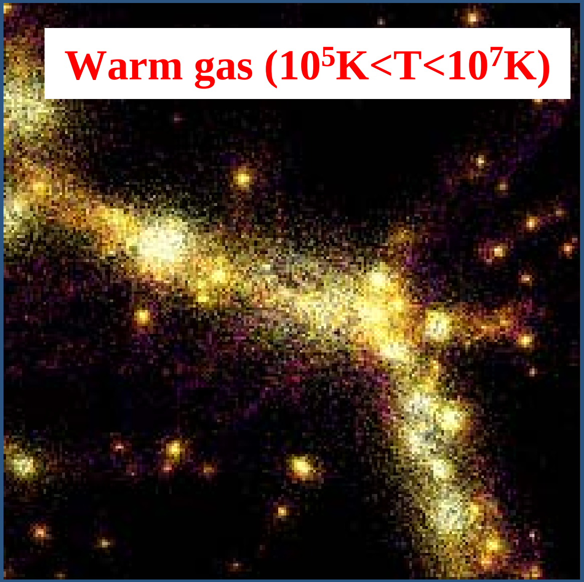
(Yoshikawa et al. 2001)


Galaxy (cold clump)


Dark matter


All gas particles


Hot gas ($T>10^7$K)


Warm gas ($10^5\mathrm{K}<T<10^7\mathrm{K}$)

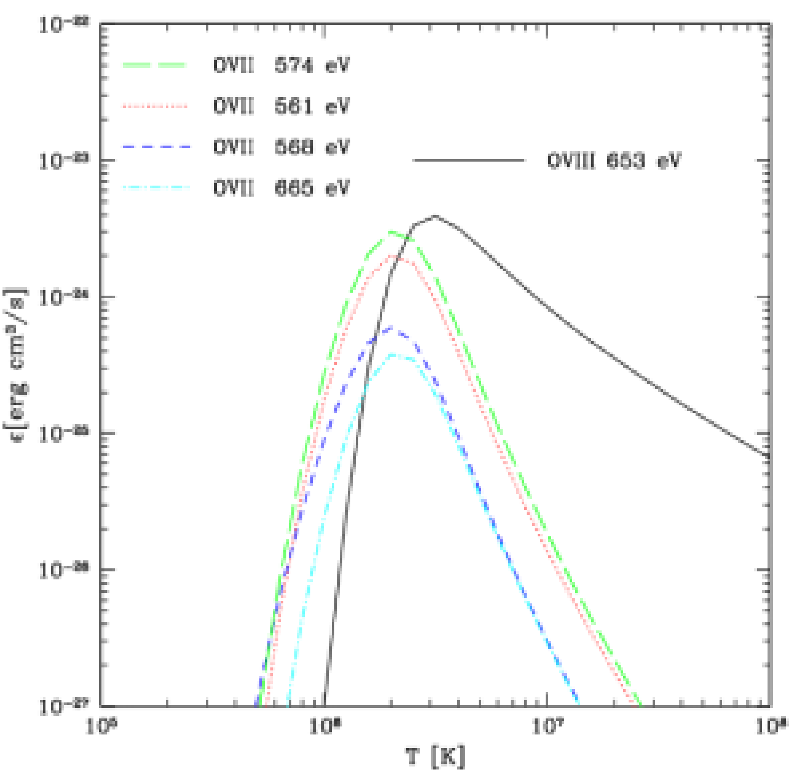
WHIM as missing cosmic baryons

- ~40% of the total cosmic baryons may exist as **Warm-Hot Intergalactic Medium (WHIM)** with $10^5\mathrm{K}<T<10^7\mathrm{K}$
- **WHIM is supposed to distribute diffusely along filamentary structures** connecting nearby clusters/ groups of galaxies
- **Direct detection of WHIM is difficult**
  - OVI absorption line systems in UV (1032Å, 1038Å doublets)
  - OVII (574.0 eV) and OVIII (653.6 eV) absorption line systems in X-ray spectra of background QSOs
  - Bumpy features in Soft X-ray background spectrum

Emission lines of Oxygen in WHIM

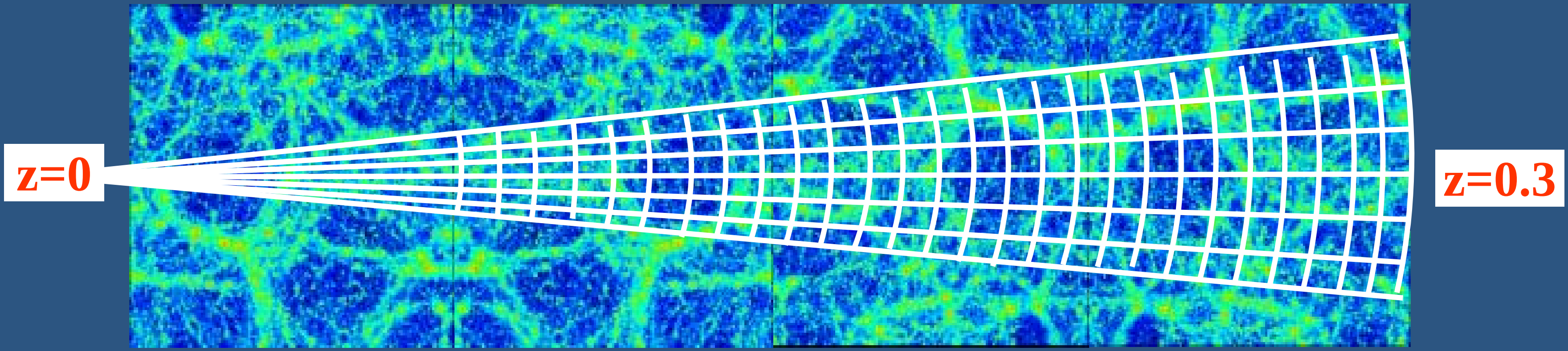
OVII (561eV, 568eV, 574eV, 665eV) , OVIII (653eV)

- **Why oxygen emission lines ?**
    - Most abundant other than H and He
    - Good tracers of gas around $T=10^6 \sim 10^7$ K
    - No other prominent lines in E=500-660eV
    - Not restricted to regions towards background QSOs



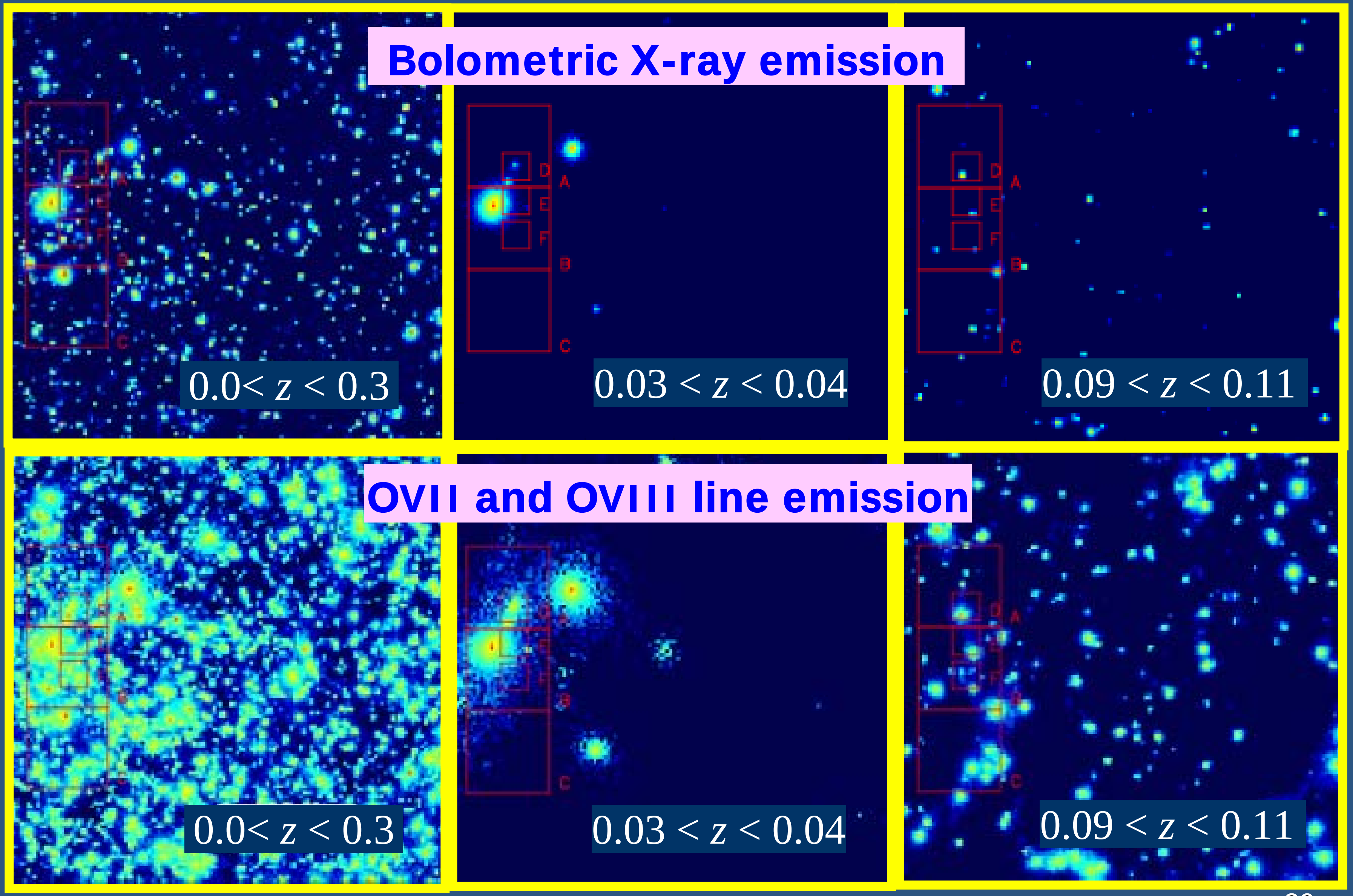
⇒ ***systematic WHIM survey***

Light-cone output from simulation



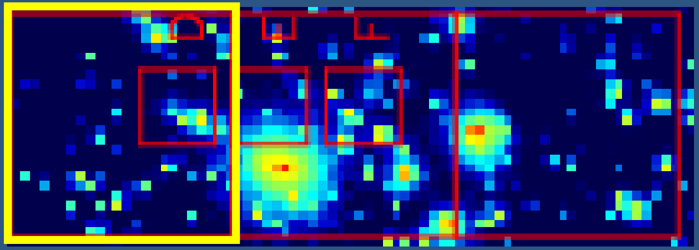
- **Cosmological SPH simulation** in $\Omega_m=0.3$, $\Omega_\Lambda=0.7$, $\sigma_8=1.0$, and $h=0.7$ CDM with $N=128^3$ each for DM and gas (Yoshikawa, Taruya, Jing, & Suto 2001)
- **Light-cone output from z=0.3 to z=0** by stacking 11 simulation cubes of $(75h^{-1}\mathrm{Mpc})^3$ at different z
- **5°×5° FOV mock data** in 64x64 grids on the sky
- 128 bins along the redshift direction ($\Delta z=0.3/128$)

Surface brightness on the sky


Bolometric X-ray emission

OVII and OVIII line emission

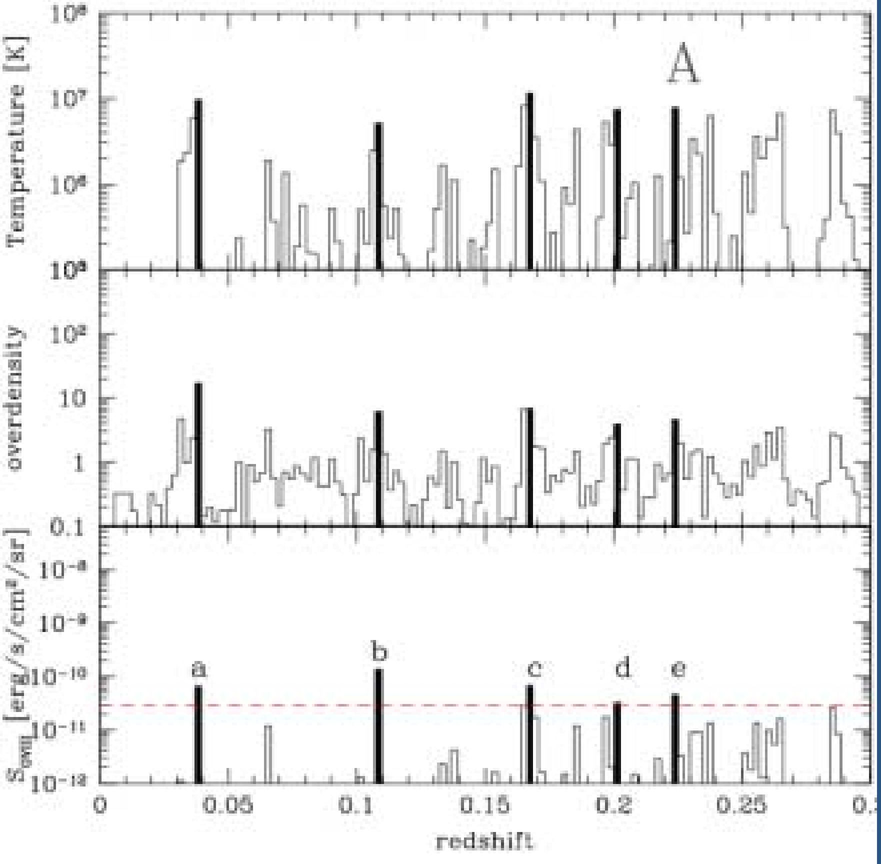
Simulated spectra: region A

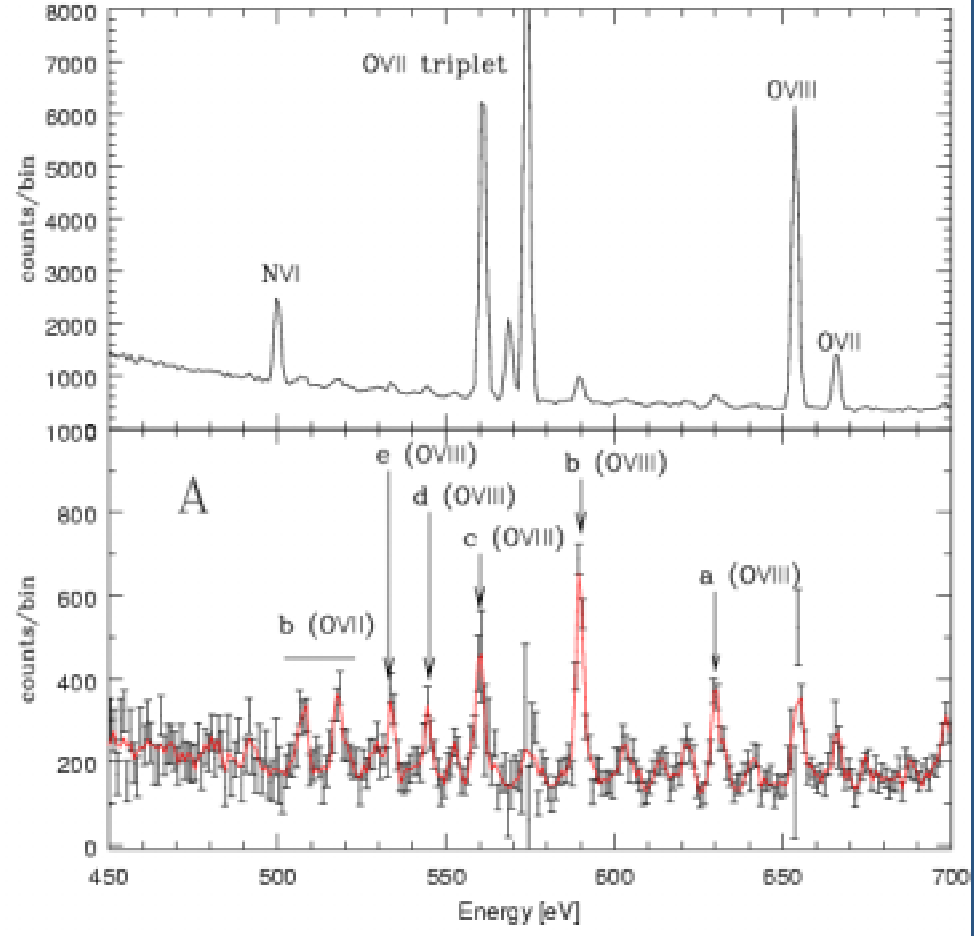


A

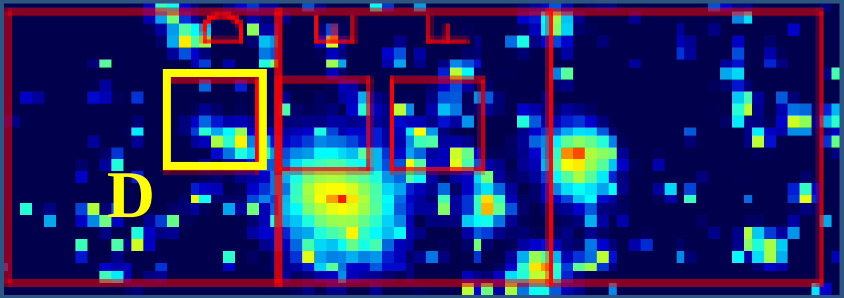
0.94 ° ×0.94 ° = 0.88 deg^2

$T_{exposure}$= 3x10^{5}sec



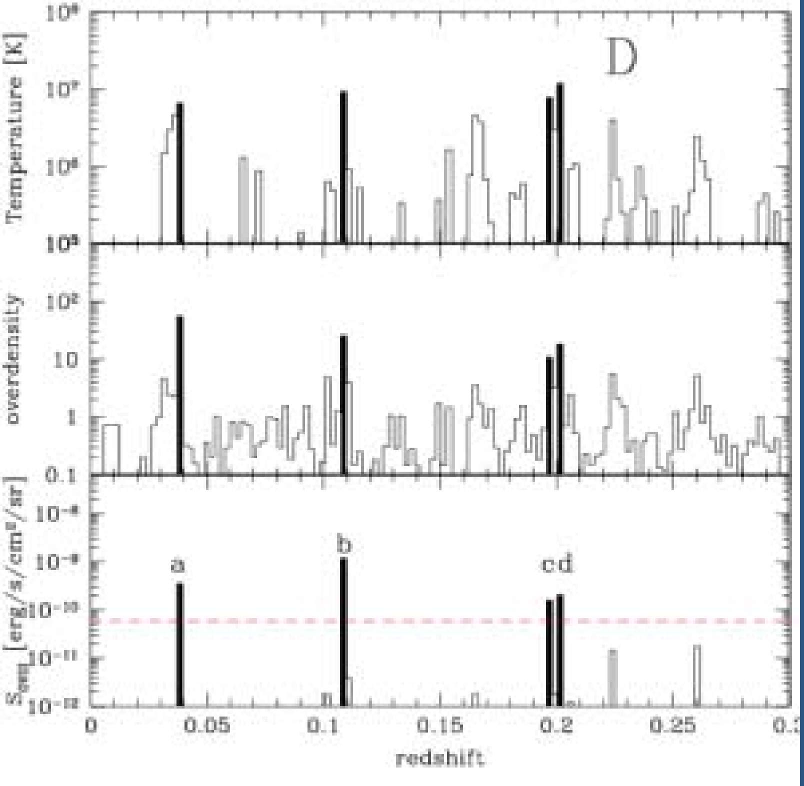


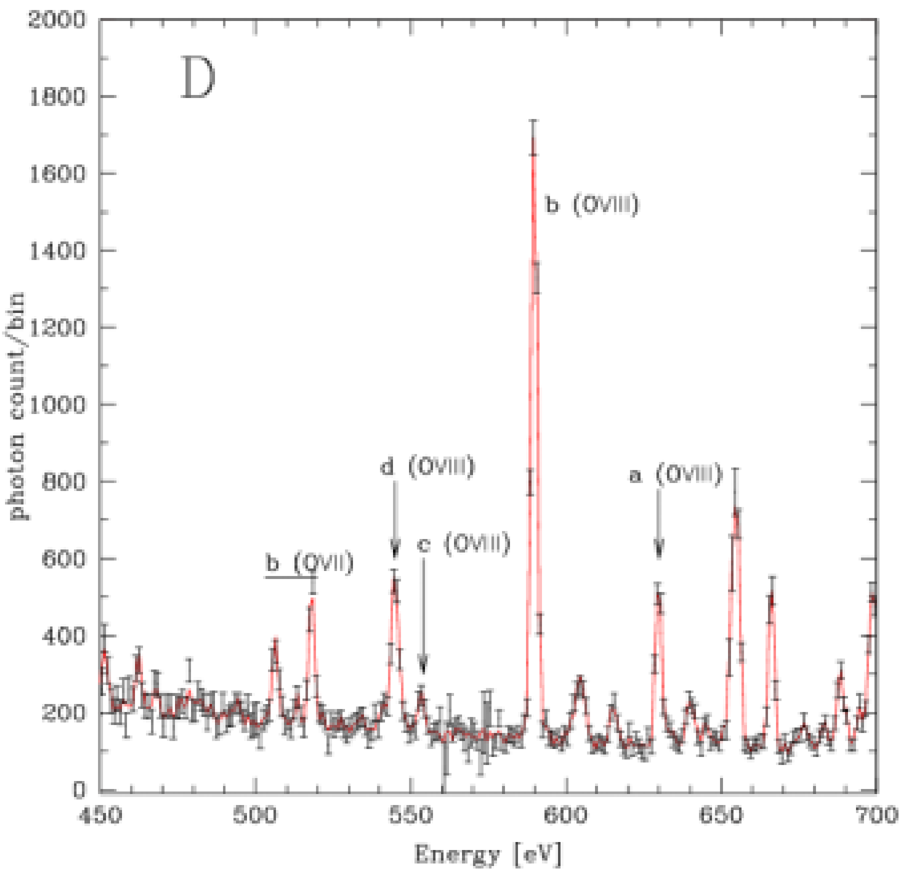
Simulated spectra: region D



19'x19' = 0.098 deg^2

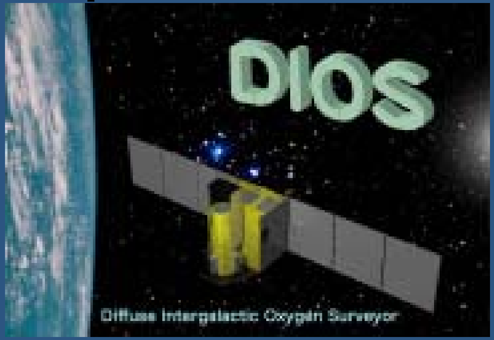
$T_{exposure}$=10^{6}sec





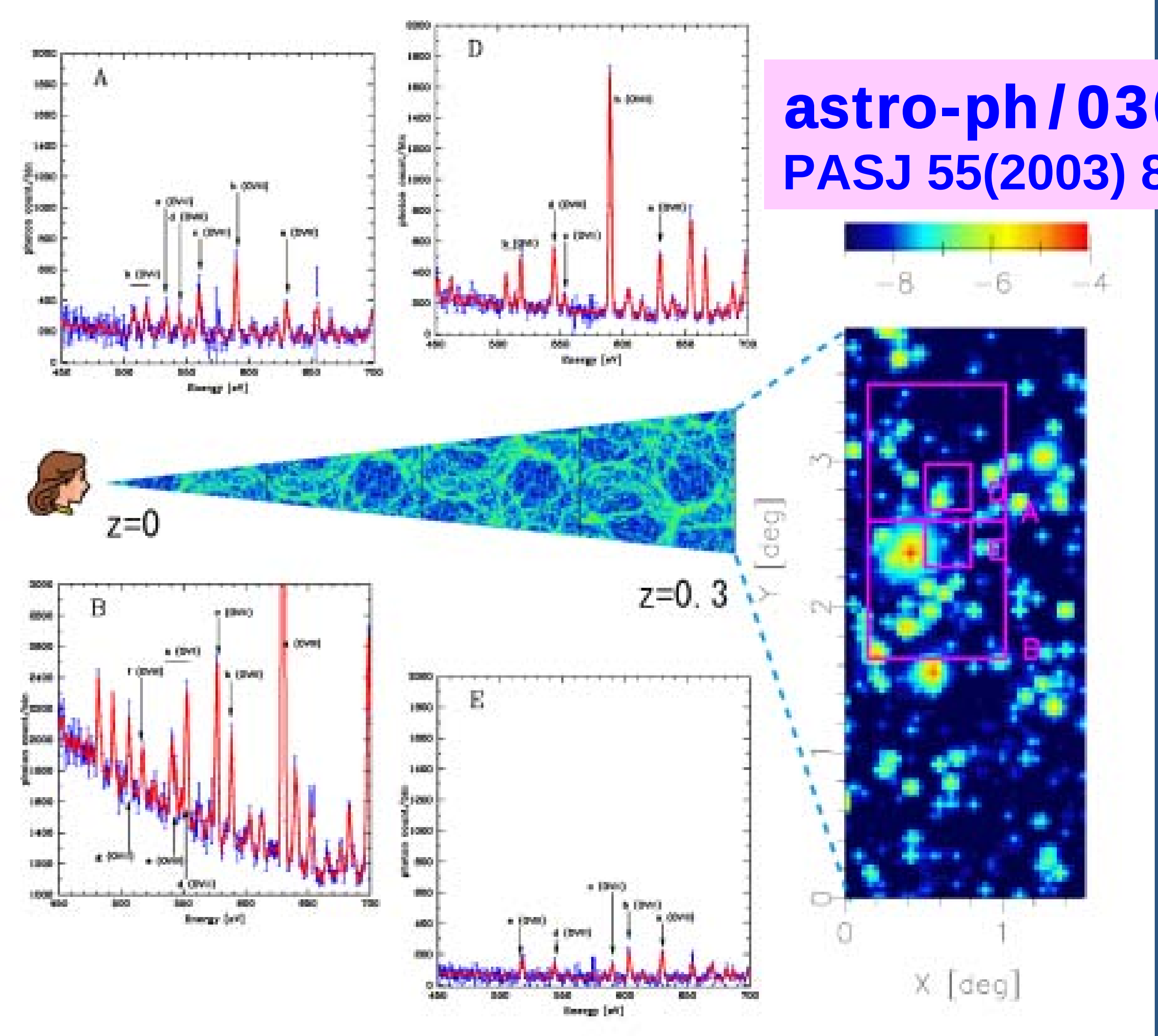
Detectability of Warm-Hot Intergalactic Medium via Oxygen emission lines

- Mock spectra from cosmological SPH simulation
- **With our proposed mission (20-30) percent of the total cosmic baryons will be detected via Oxygen emission lines** in principle.
  - $\Delta E = 2\mathrm{eV}$, $S_{\mathrm{eff}}\,\Omega = 100$ [cm^2 deg^2]
  - flux limit = 6×10^{-11} [erg/s/cm^2/str]



- Things remain to be checked
  - Validity of the collisional ionization equilibrium ?
  - How to properly identify the oxygen lines from the background/noises in reality ?

DIOS : Japanese proposal of a dedicated X-ray mission to search for missing baryons



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(**D**iffuse **I**ntergalactic **O**xygen **S**urveyor)

DIOS: Diffuse Intergalactic Oxygen Surveyor

A Japanese proposal of a dedicated X-ray mission to search for missing baryons

- A dedicated satellite with cost < 40M USD to fill the gap between Astro-E2 (2005) and NeXT (2010?). Launch at Japan in 2009 (?).
- Unprecedented energy spectral resolution $\Delta E=2$eV in soft X-ray band (0.1-1keV)
- Aim at detection of (20-30) percent of the total cosmic baryons via Oxygen emission lines
  - $\Delta E=2$eV, $S_{\mathrm{eff}}\,\Omega=100$ [cm^2 deg^2]
  - flux limit = 6×10^{-11} [erg/s/cm^2/str]
- PI: Takaya Ohashi (Tokyo Metropolitan Univ.)

MBE: a competing proposal

- PI: Wilt Sanders (UW-Madison SSEC)
- X-Ray Calorimeter Telescope Development
  - UW-Madison, NASA/GSFC, Lockheed-Martin
- Spacecraft: Spectrum Astro SA-200S Bus
- Time schedule: the concept study start is in November 2003, and launch is scheduled for August 2007.
- Cost: $118.96M in FY2003 USD

UW-Madison Space Science and Engineering Center

Missing Baryon Explorer

Surveys of the Low Energy X-Ray Diffuse Background to Complete Our Picture of the Universe

http://www.ssec.wisc.edu/baryons/index.html

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 ⇒ $\Omega_m=0.27\pm0.04$, $\Omega_\Lambda=0.73\pm0.04$, $h=0.71\pm0.04$ 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