Galaxy, Group, and Cluster Mass Profiles from Small Scales out to the Virial Radius

David Buote (UC Irvine)

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Outline

Tilt of the Fundamental Plane

- Mass Slope -- Size Relation for Ellipticals

Missing Baryons & Feedback

- Isolated Elliptical Galaxy: NGC 720

Biases from Spherically Averaging Galaxy Clusters

Guidelines for Applying Hydrostatic Equilibrium

(Buote & Humphrey, arXiv:1104.0012)

1. **Regular Morphology:** Select systems which tend to have a regular, approximately circular or elliptical X-ray image morphology. If the image has asymmetric features, they should be preferably confined to spatial regions that are small compared to the region of interest; e.g., the inner region showing evidence of possible AGN feedback.

2. **Gas Emission Dominates:** Unresolved discrete sources should not dominate the X-ray emission. As a rough guide, at least half the X-ray luminosity within the optical half-light radius should originate from hot gas.

3. **Acceptable HE Fit?** Determine whether a hydrostatic model is able to provide an acceptable fit to the density and temperature profiles of the hot ISM over the region of interest.

4. **Compare to Different Techniques:** When possible, compare the mass profile obtained via the hydrostatic approximation with that obtained by an independent method; e.g., stellar dynamics, gravitational lensing. The hydrostatic equilibrium approximation is judged to be useful if it provides mass measurements of comparable (or better) quality than other techniques -- or provides any information when no other technique is available.

Fundamental Plane of Elliptical Galaxies

$$\log_{10} R_e = (1.2 - 1.5) \log_{10} \sigma_0 - 0.8 \log_{10} \langle I \rangle_e + const$$ Obs

(rms scatter in Re 15-20%)

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(rms scatter in Re 15-20%)

$$\log_{10} R_e = 2\log_{10}\sigma_0 - \log_{10}\langle I\rangle_e + \log_{10}\frac{M}{L} + const$$ VT

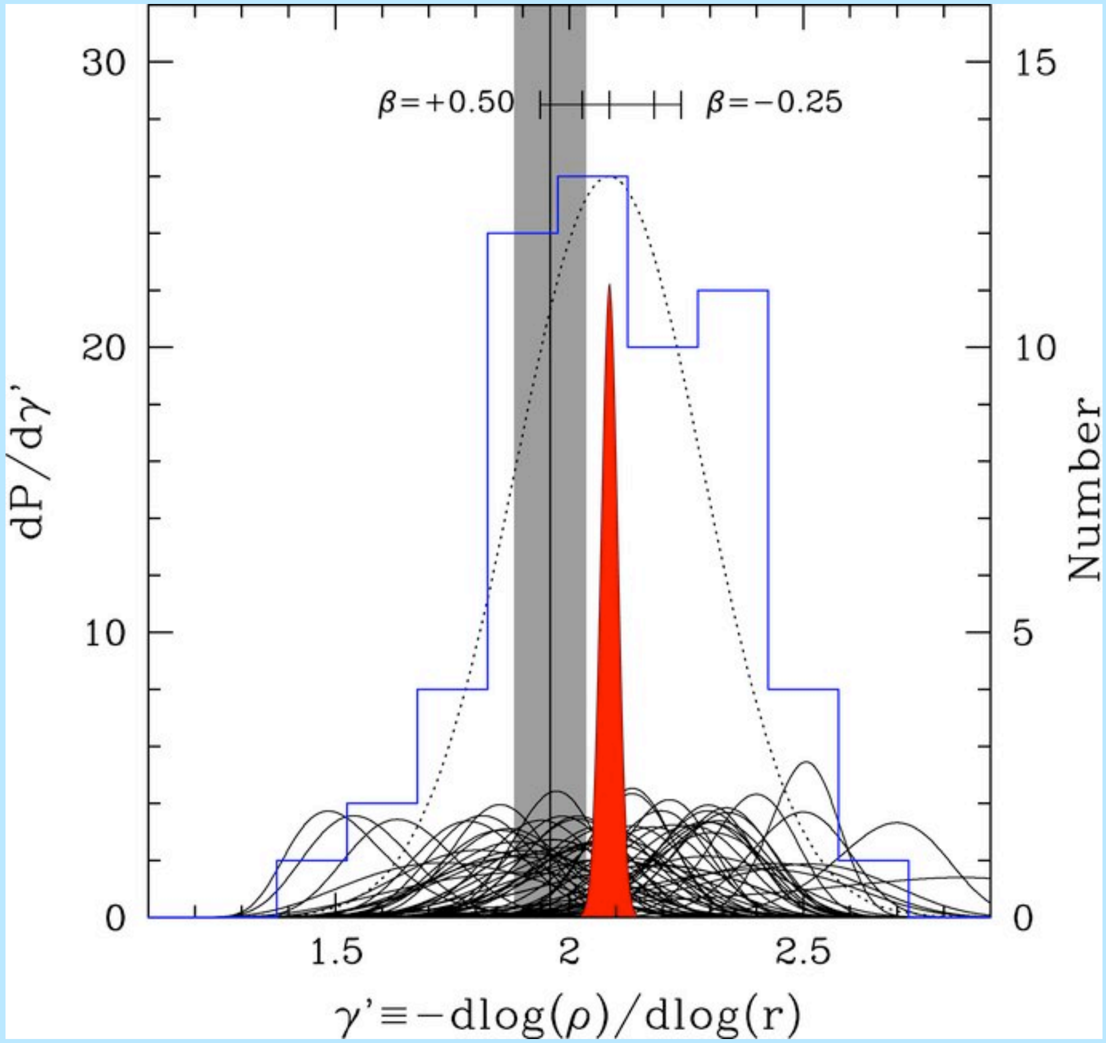
“Tilt” of FP

M/L or Homology Variations or Both?

Mass Profile Slopes

SLACS (58 ETGs)
Lensing + Stellar Dynamics

$$\rho_m \sim r^{-\alpha},\ \alpha \approx 2$$



(Koopmans et al. 2009, ApJ, 703, L51)

Mass Profile Slopes

SLACS (58 ETGs)
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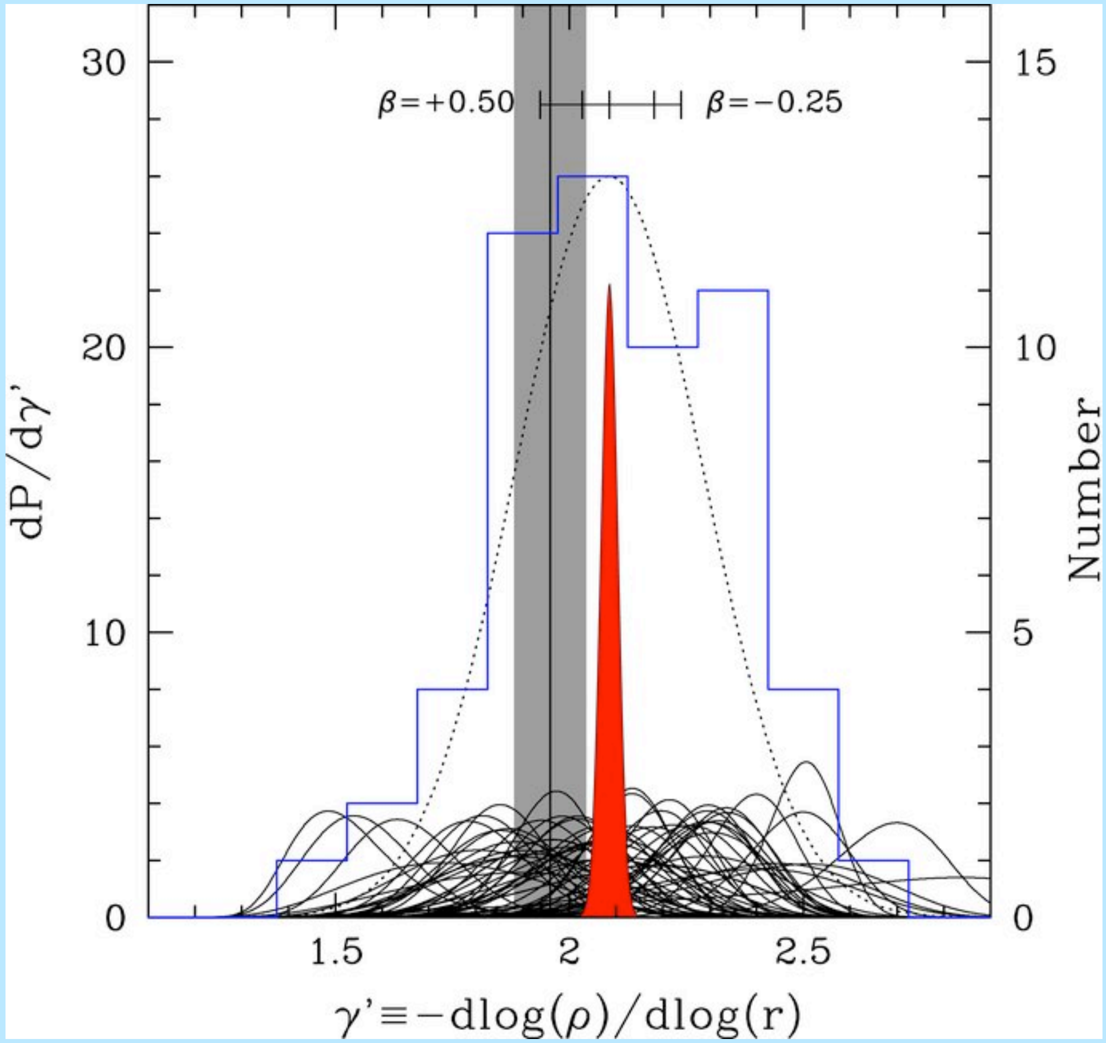
$$\rho_m \sim r^{-\alpha},\ \alpha \approx 2$$

Seen Before with X-Rays:
Einstein (e.g., Trinchieri et al. 1986)
ROSAT (e.g., Kim & Fabbiano 1995; Buote & Canizares 1994, 1998)
Chandra+XMM (e.g., Fukazawa et al. 2006; Humphrey et al. 2006; Churazov et al. 2008, 2010)



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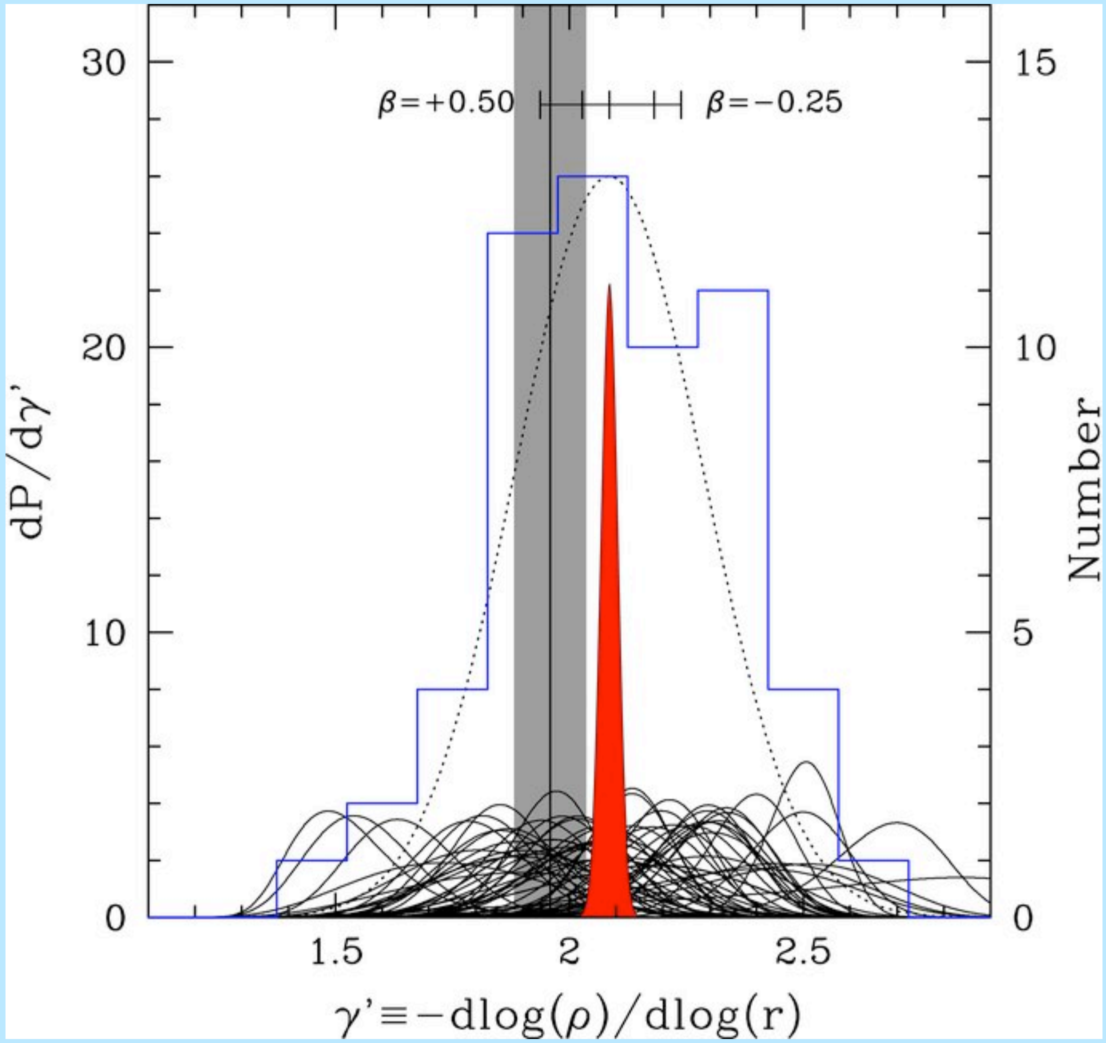

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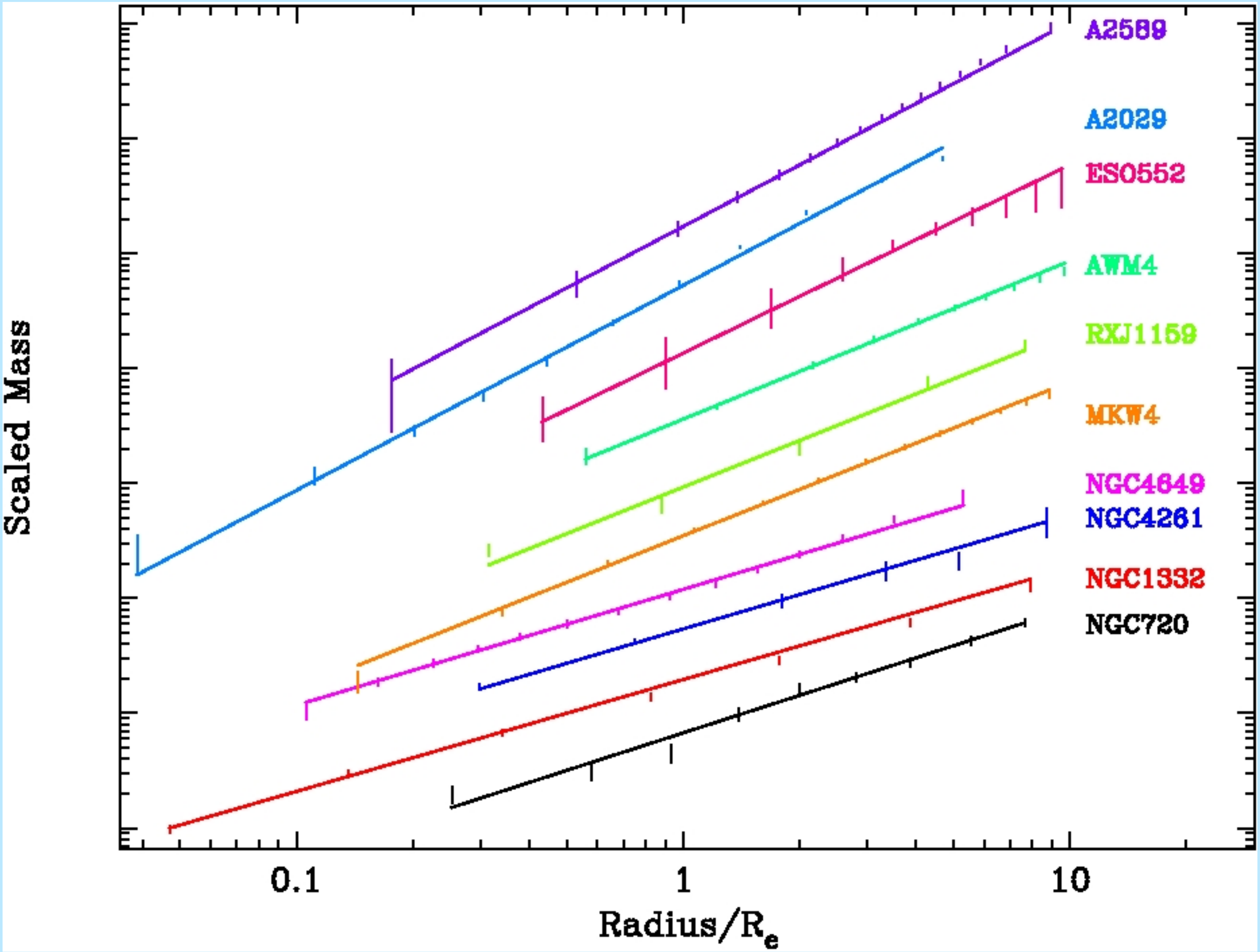
Clusters: Shallower Slopes: (X-ray: e.g., Voigt & Fabian 2006; Optical: Kelson et al. 2002; Sand et al. 2004)

Power-Law Mass Profiles



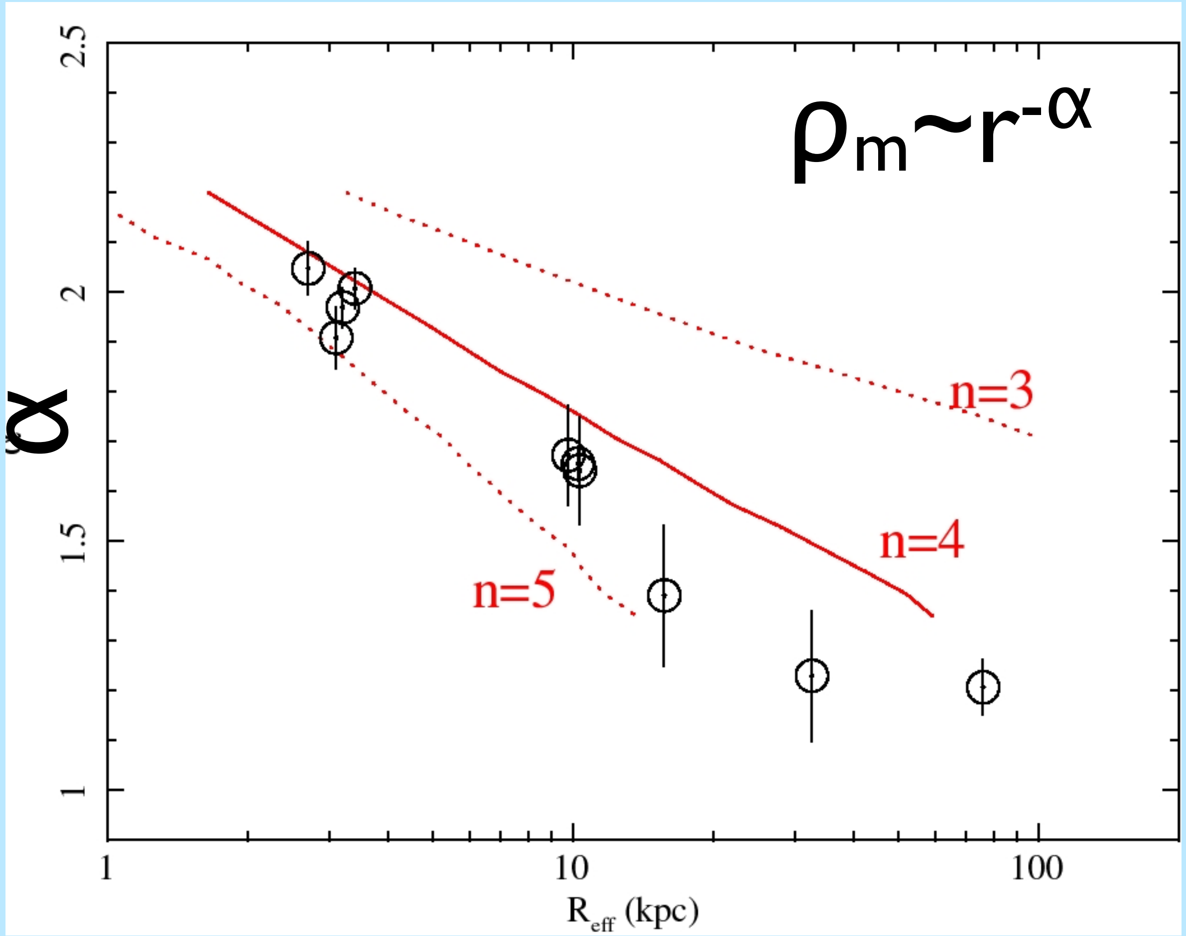
Clusters

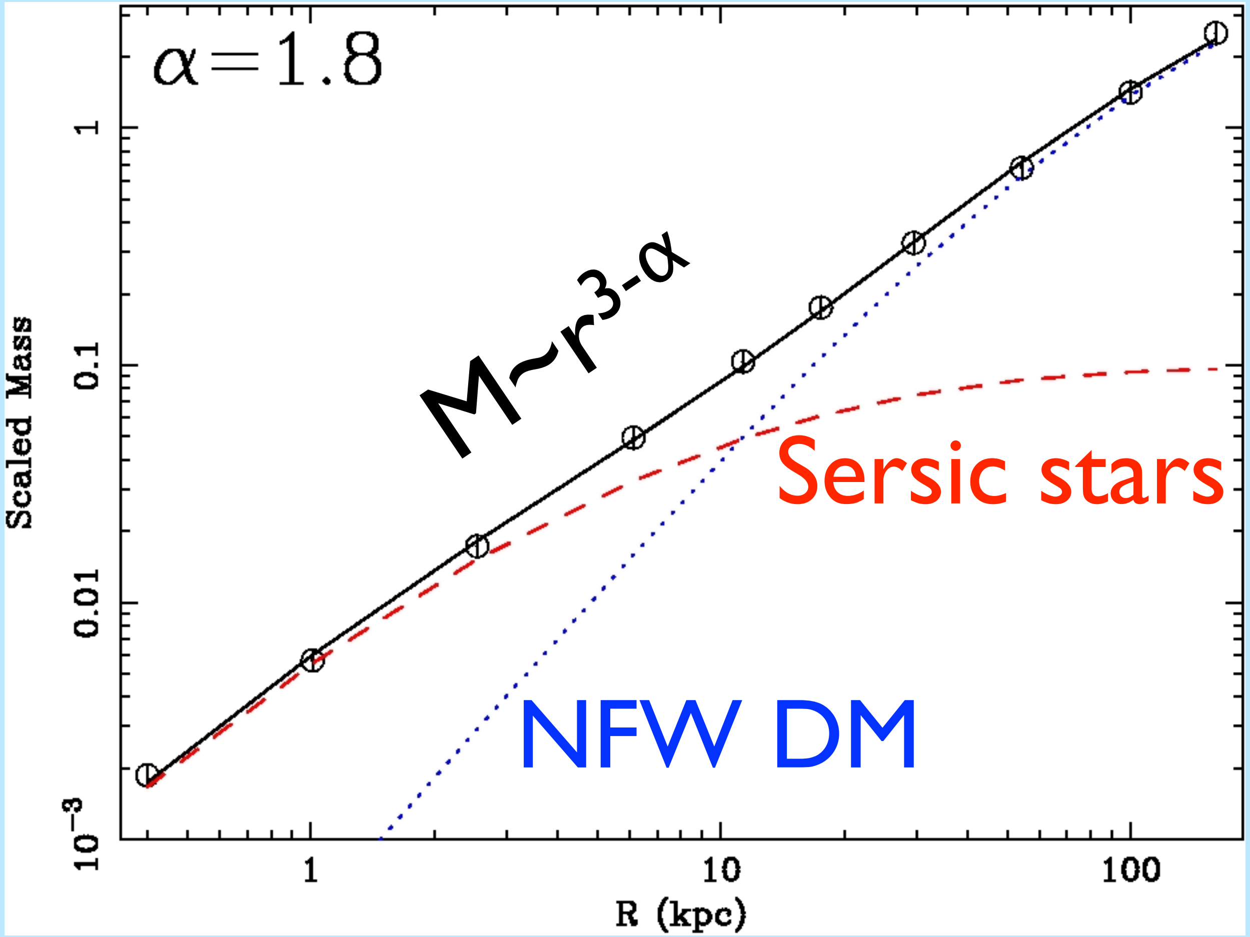
Groups

Galaxies

(Humphrey & Buote 2010, MNRAS, 403, 2143)

Slope-R_e Relation

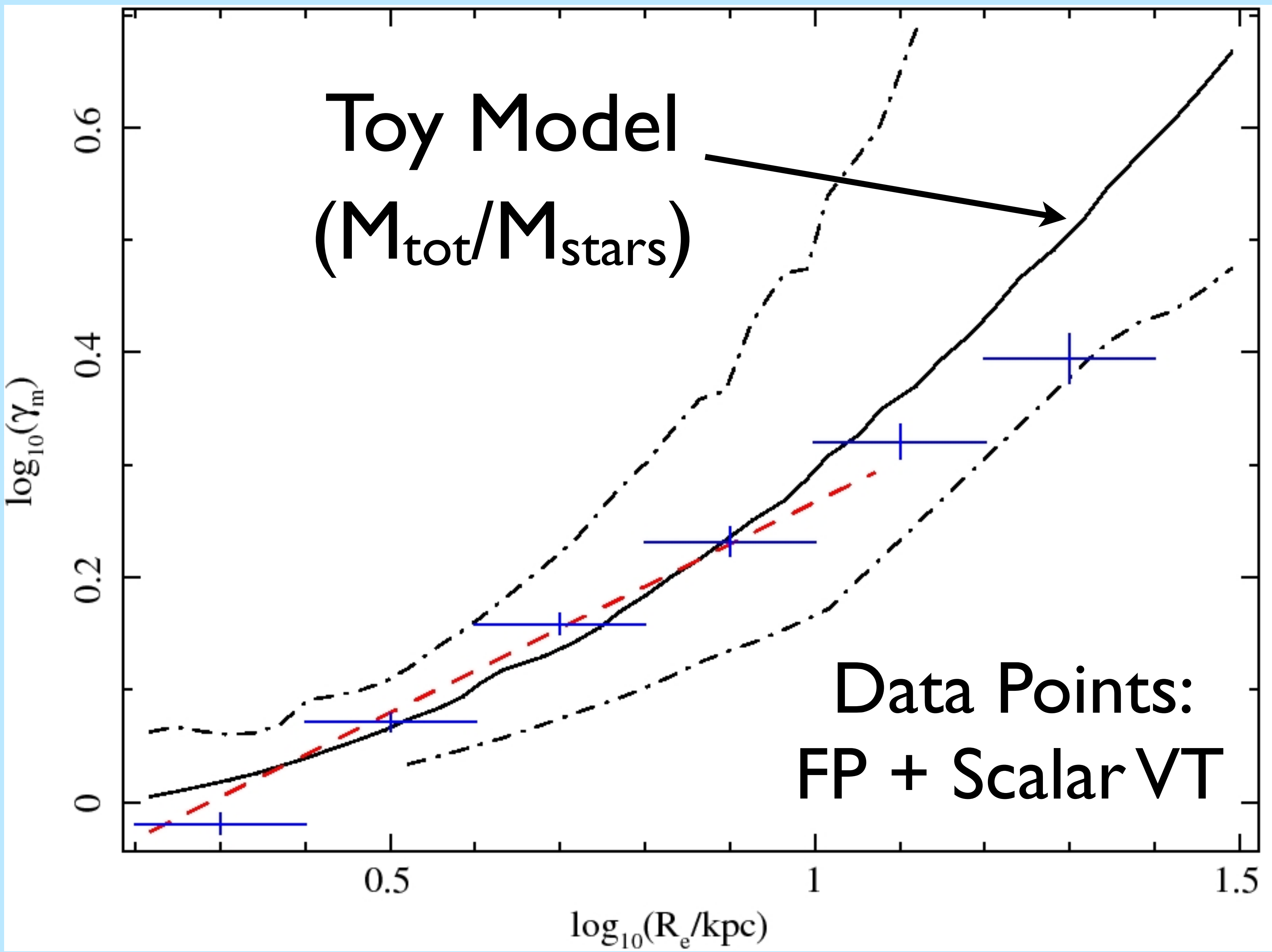




(Humphrey & Buote 2010, MNRAS, 403, 2143)

$$\alpha = 2.31 - 0.54 R_e \; (\text{for } \; n \approx 4)$$

Tilt of Fundamental Plane

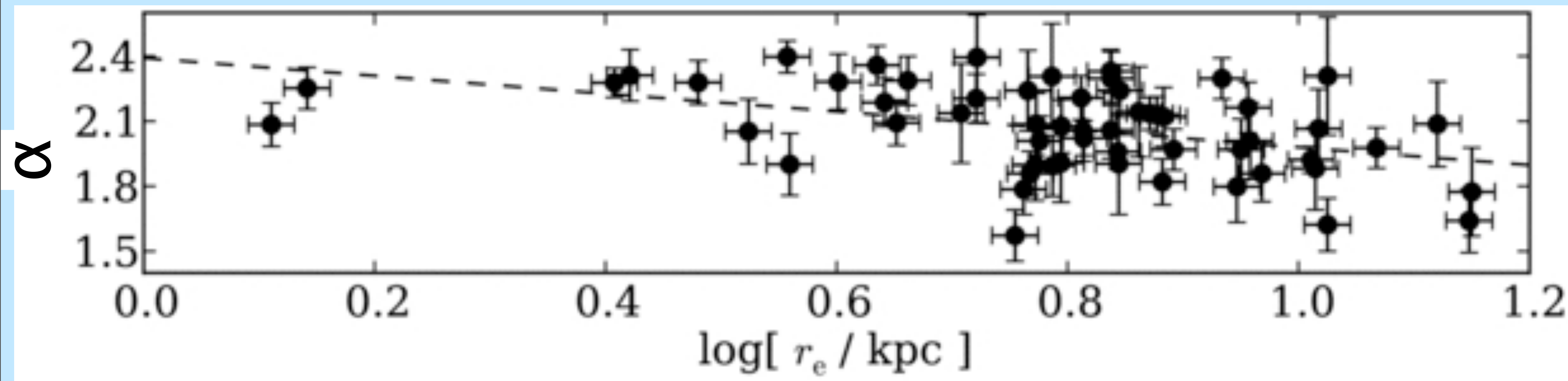


(M_{tot}/L)

Are Nearly Power-Law Mass Profiles a Fundamental Feature of Galaxy Formation?

SLACS -- Dynamics + Lensing

(Auger et al. 2010, ApJ, 724, 511)

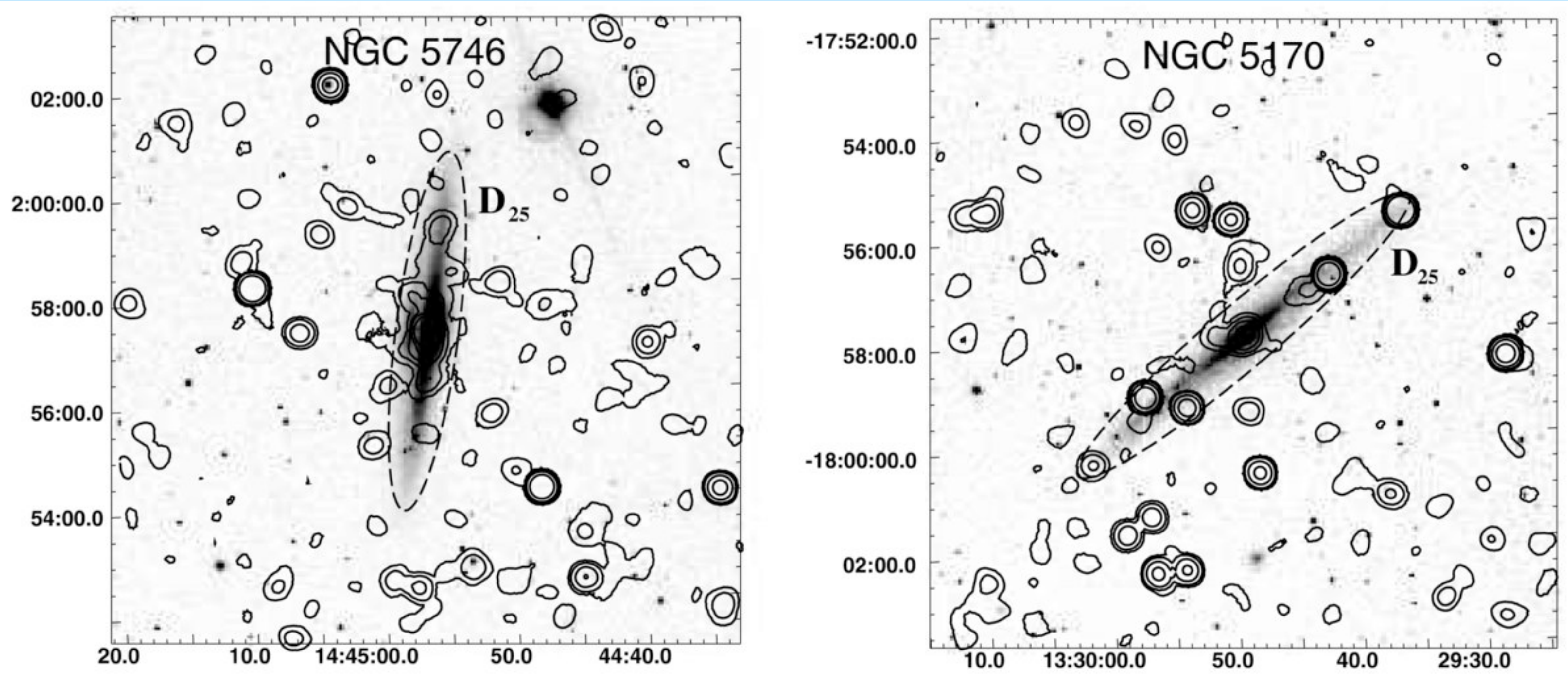


$$\alpha = 2.39(\pm 0.10) - 0.41(\pm 0.12) R_e$$

Very consistent with X-ray determination, supporting evidence for both approaches

Missing Baryons: Hot Gas Around Spirals

(Benson, Bower, Frenk, & White 2000, MNRAS, 314, 557)

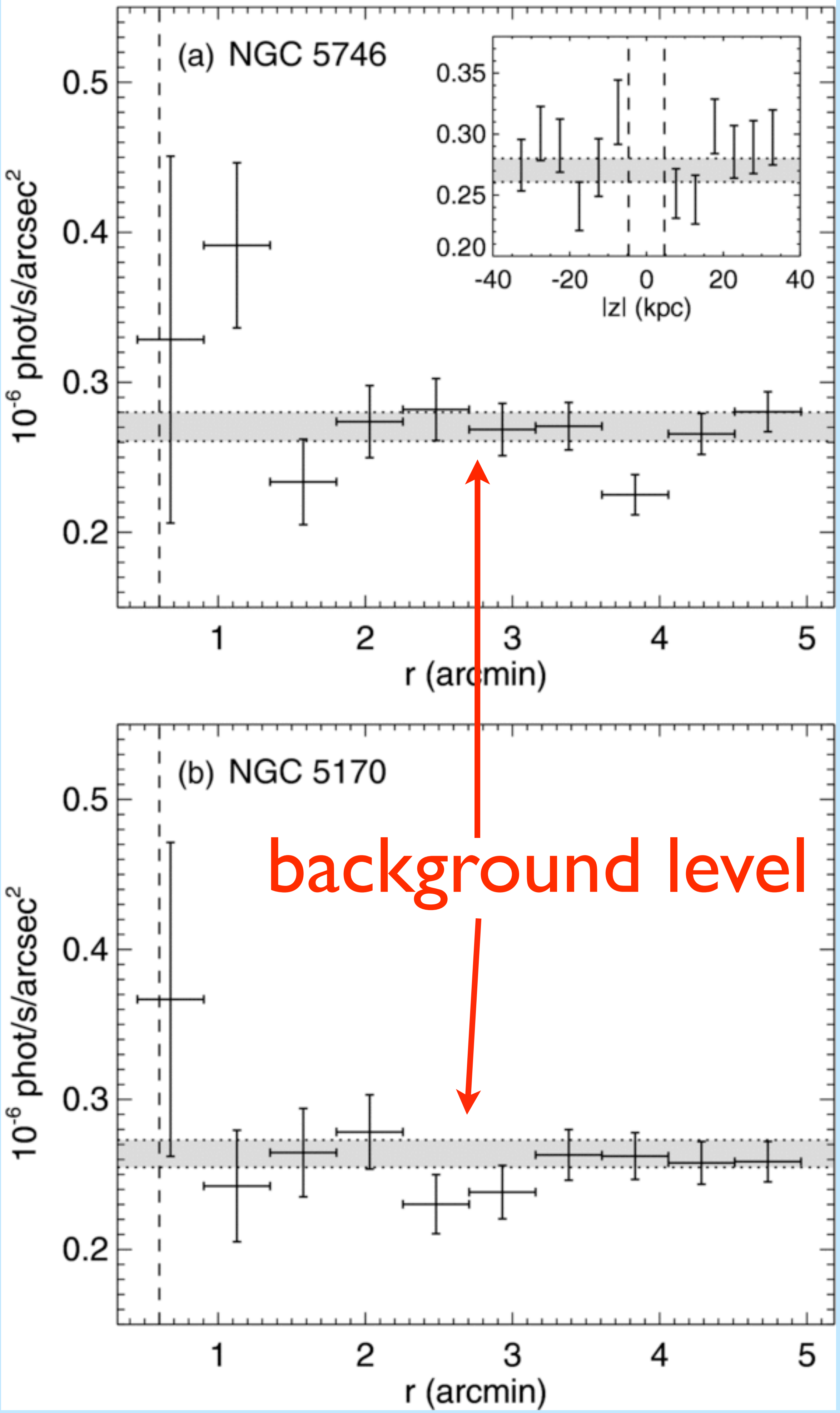


(Rasmussen et al. 2009)

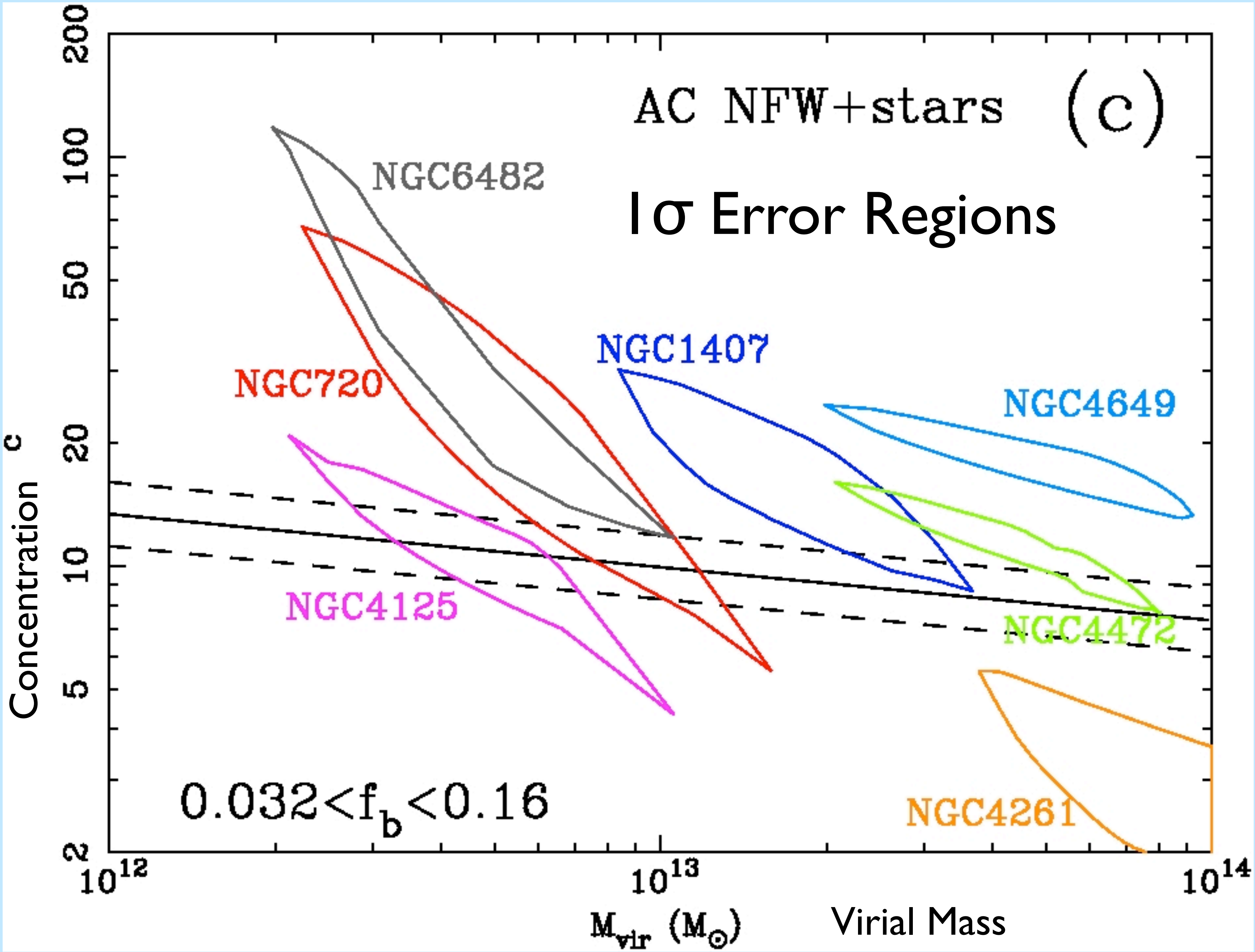
- No evidence for large amount of extended hot gas

- "Missing Baryons" not yet found in disk galaxies

(Rasmussen et al. 2009)



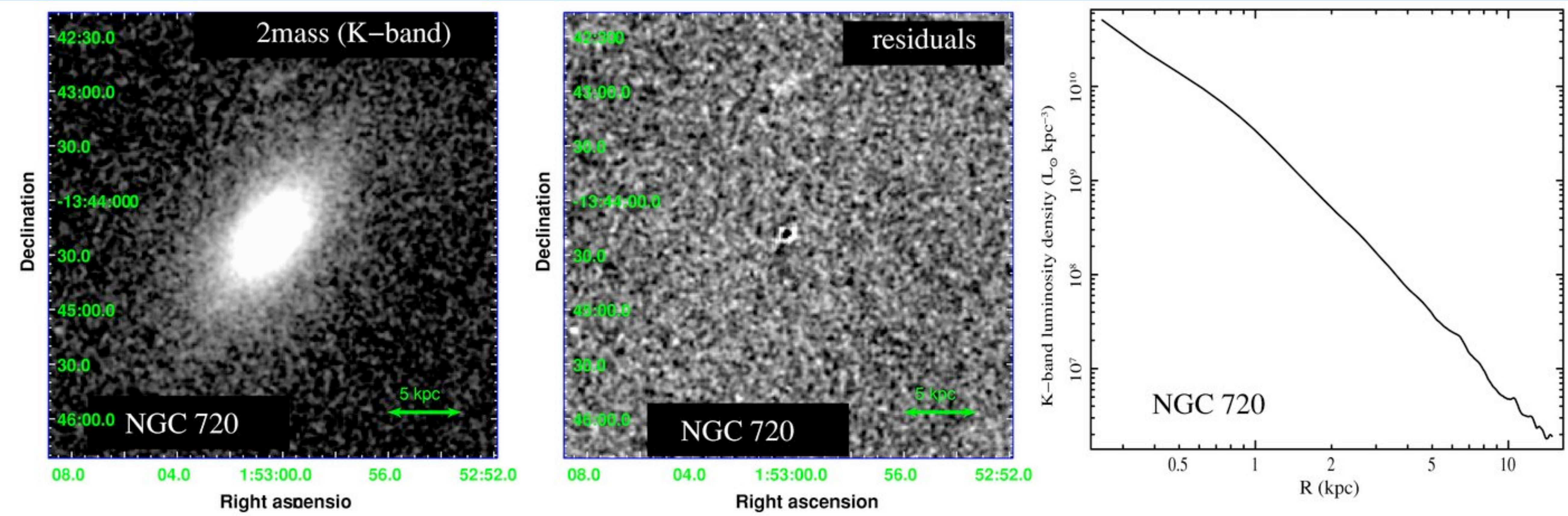
X-Ray Constraints on Masses of Ellipticals



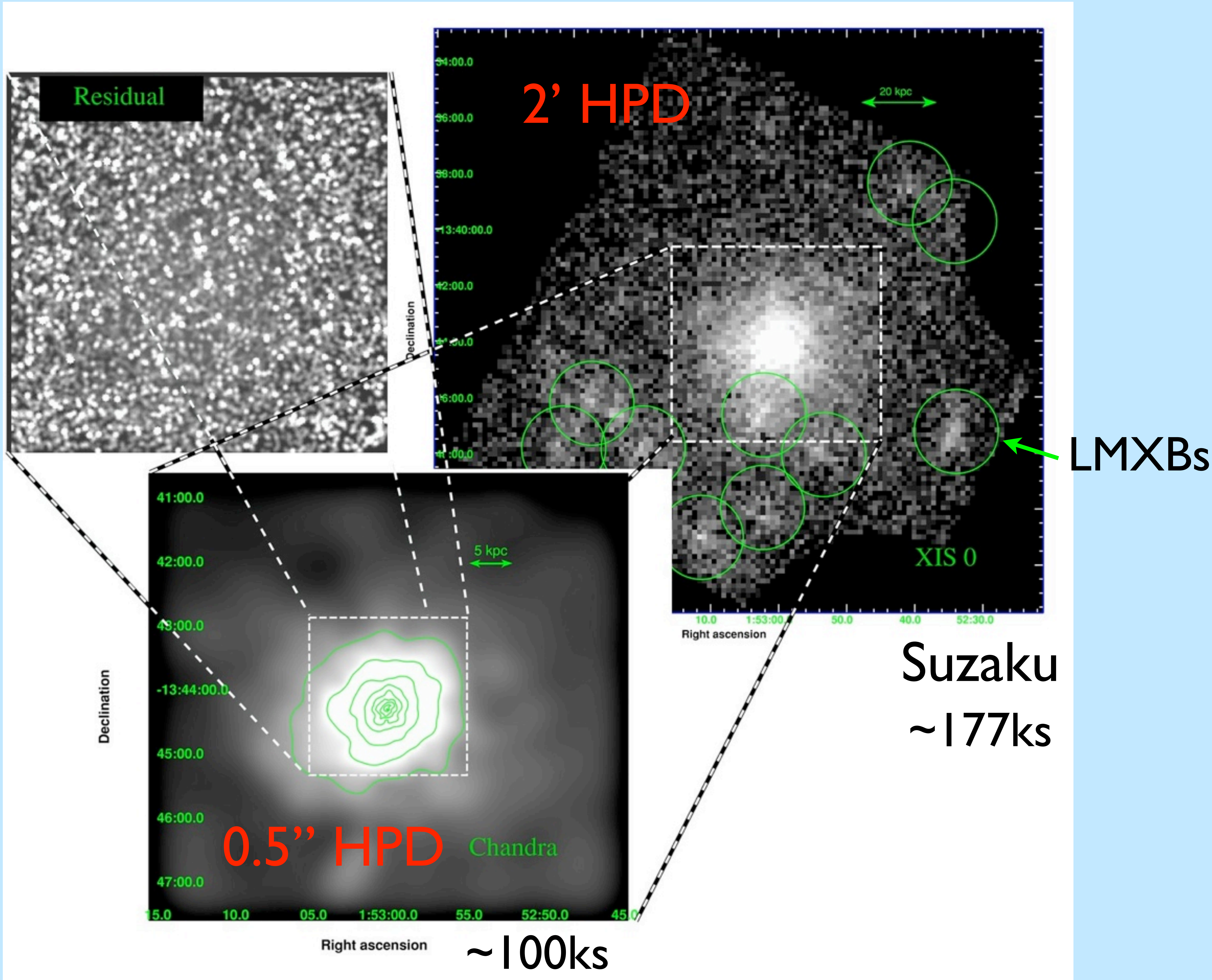
(Humphrey, Buote, Gastaldello, Zappacosta, Bullock, Brighenti, & Mathews 2006, ApJ, 646, 899)

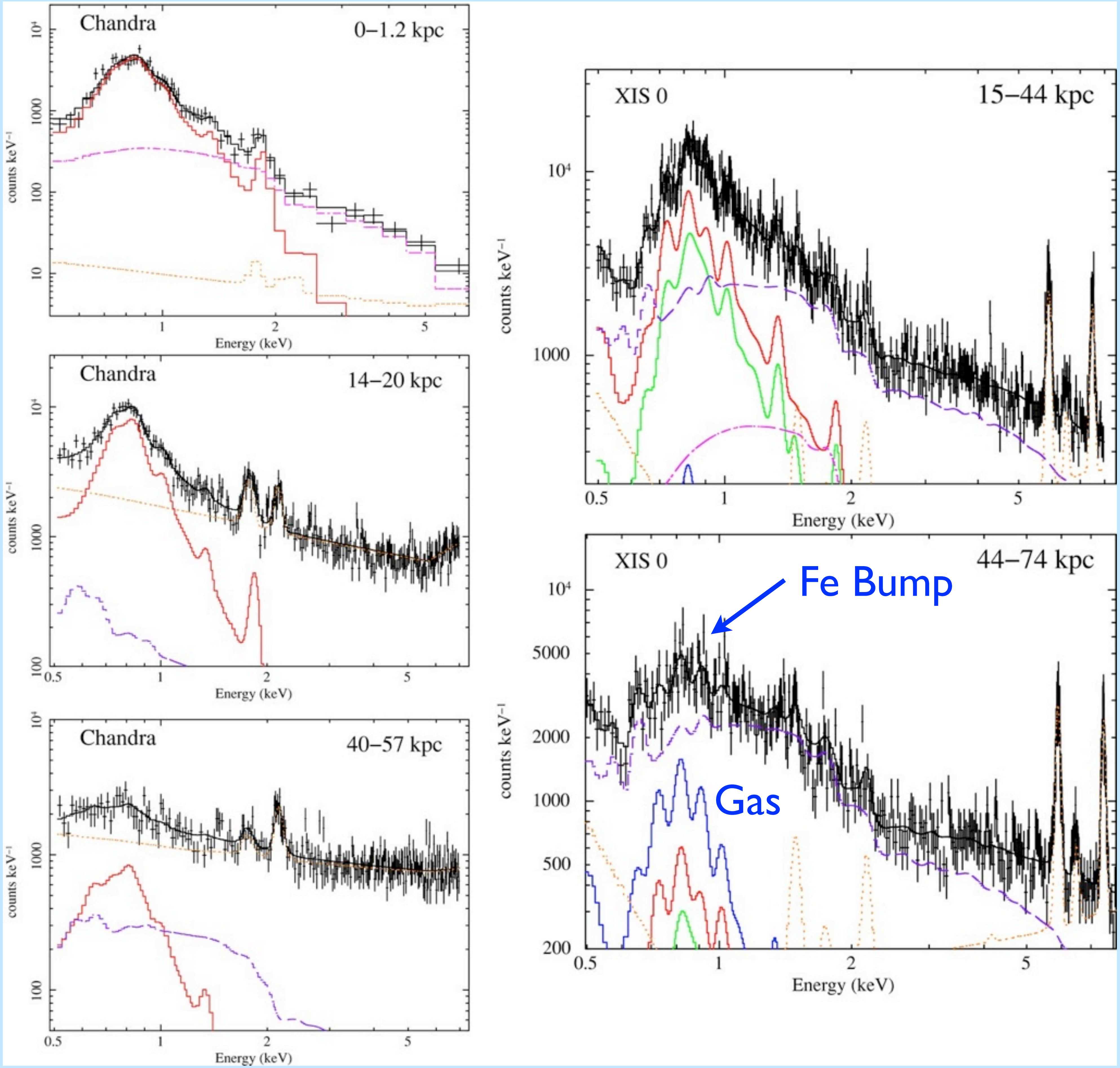
NGC 720

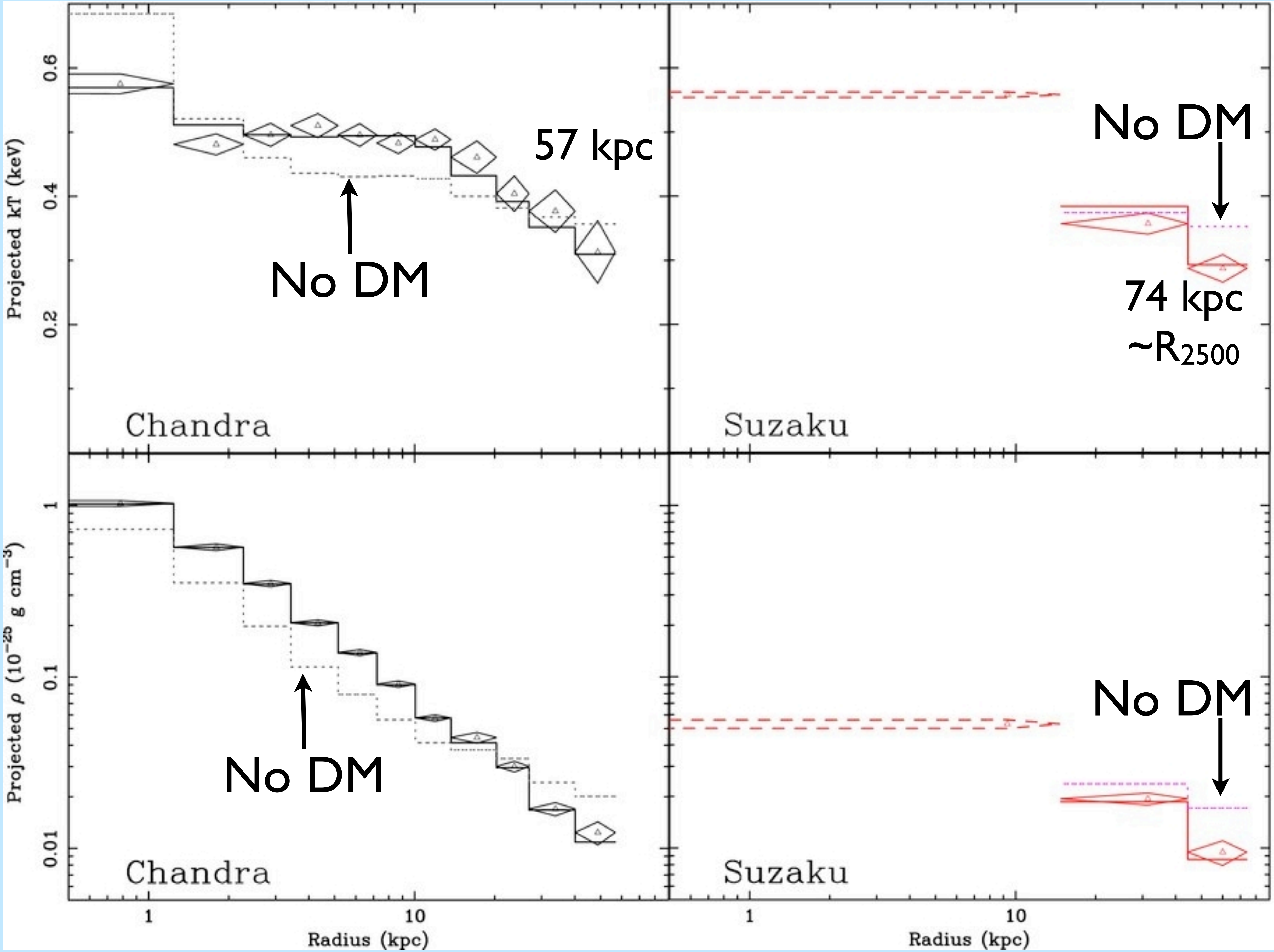
- D=26 Mpc
- E4
- Very Isolated, No AGN disturbance



(Humphrey, Buote, Canizares, Fabian, & Miller 2011, ApJ, 729, 53)


Residual
2' HPD
20 kpc
XIS 0
Declination
Right ascension
10.0
1:53:00
50.0
40.0
52:30.0
LMXBs
Suzaku
~177ks
41:00.0
42:00.0
43:00.0
-13:44:00.0
45:00.0
46:00.0
47:00.0
5 kpc
0.5" HPD
Chandra
Declination
15.0
10.0
05.0
1:53:00.0
55.0
52:50.0
45.0
Right ascension
~100ks


Chandra
0–1.2 kpc
Chandra
14–20 kpc
Chandra
40–57 kpc
XIS 0
15–44 kpc
XIS 0
44–74 kpc
Fe Bump
Gas
counts keV−1
Energy (keV)


Projected kT (keV)
0.6
0.4
0.2
57 kpc
No DM
Chandra
No DM
74 kpc
~R2500
Suzaku
Projected ρ (10^-25 g cm^-3)
1
0.1
0.01
No DM
Chandra
No DM
Suzaku
1
10
Radius (kpc)
1
10
Radius (kpc)

Mass Determination Method

"Entropy-Based"

Input S(r) & M(r)

Solve ⇓ H.E.

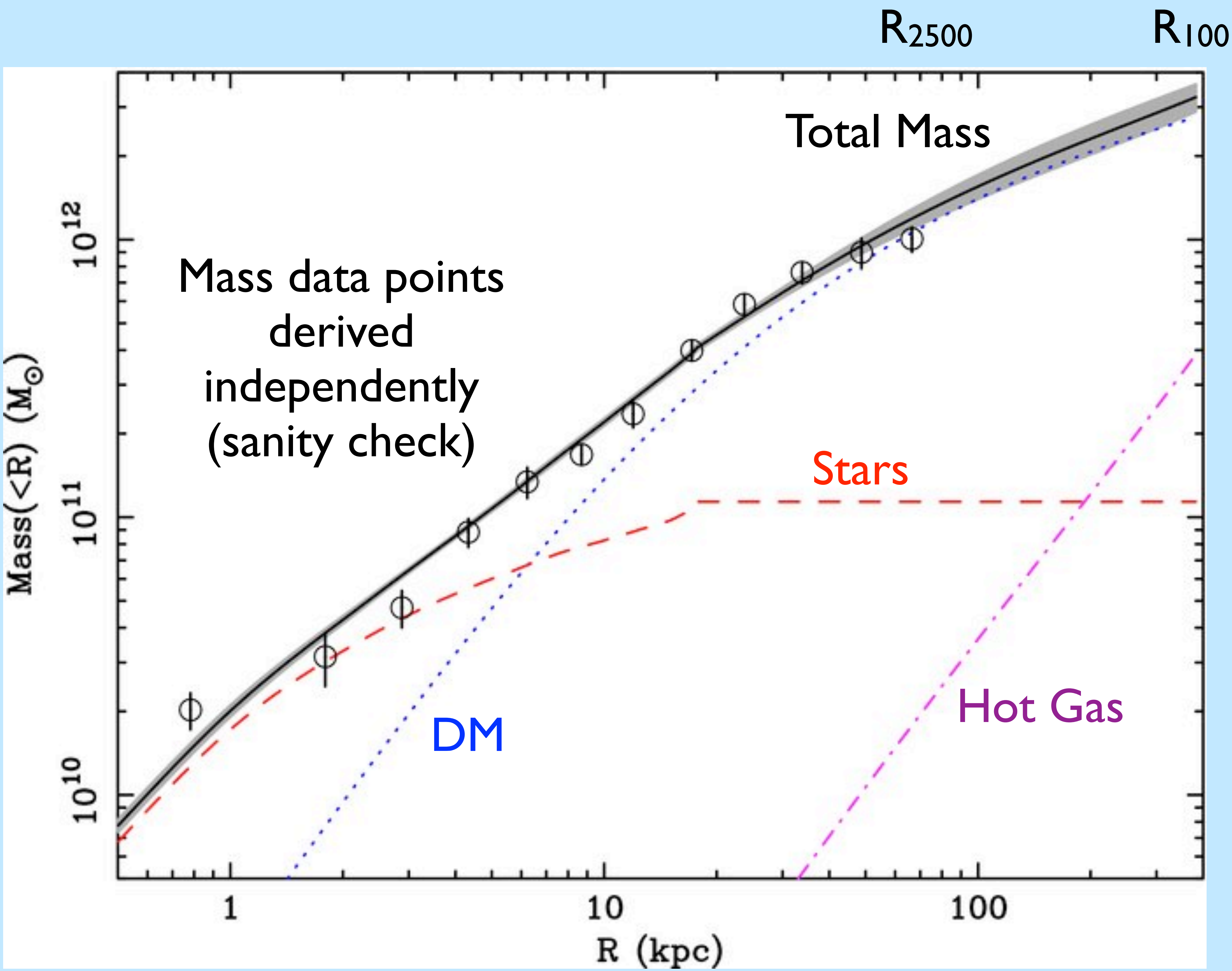
Output ρ_{gas}(r) and T(r)

We use assumed parameterized models of S & M and then fit the ρ_{gas} & T data

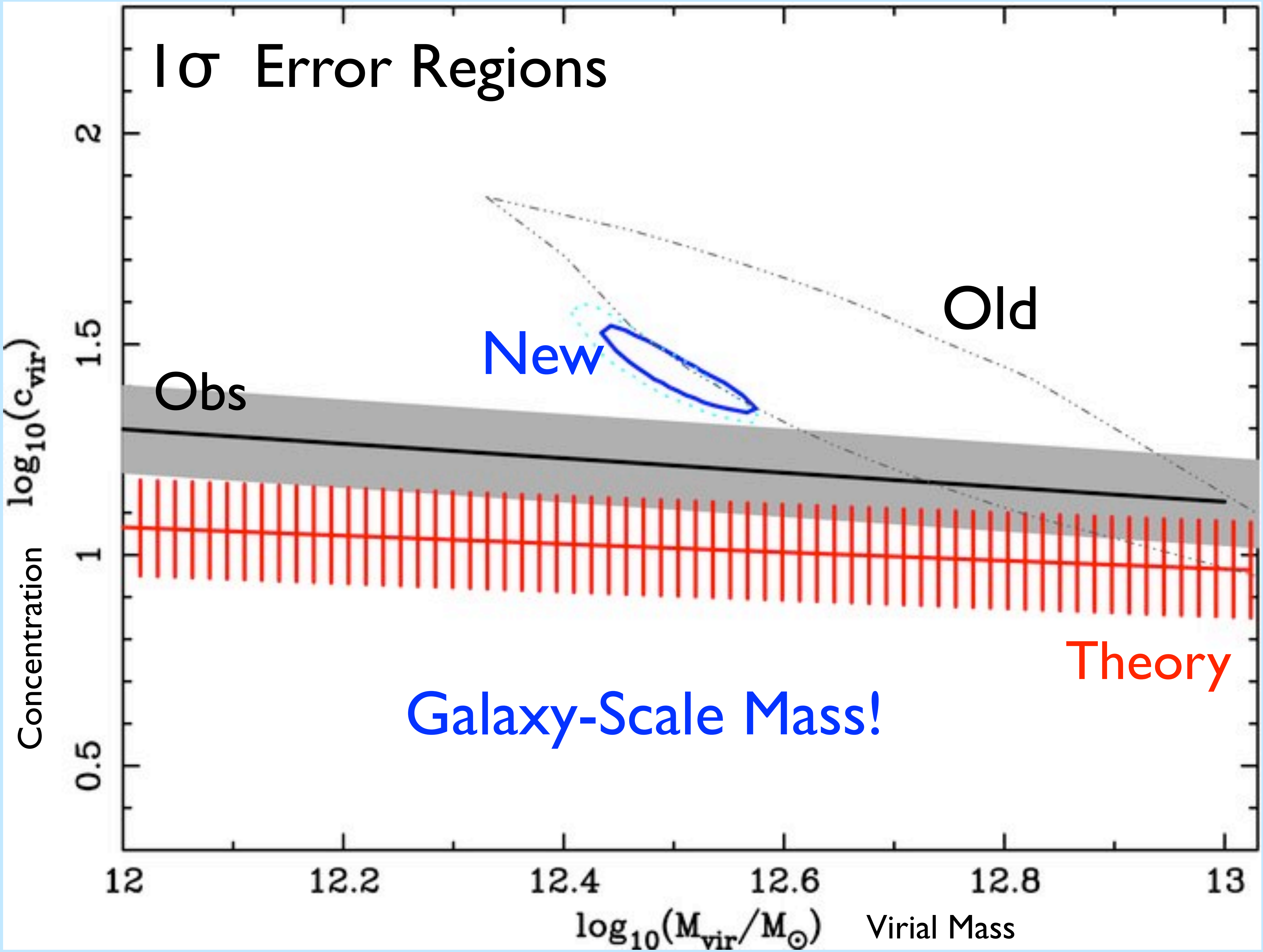
Free Parameters

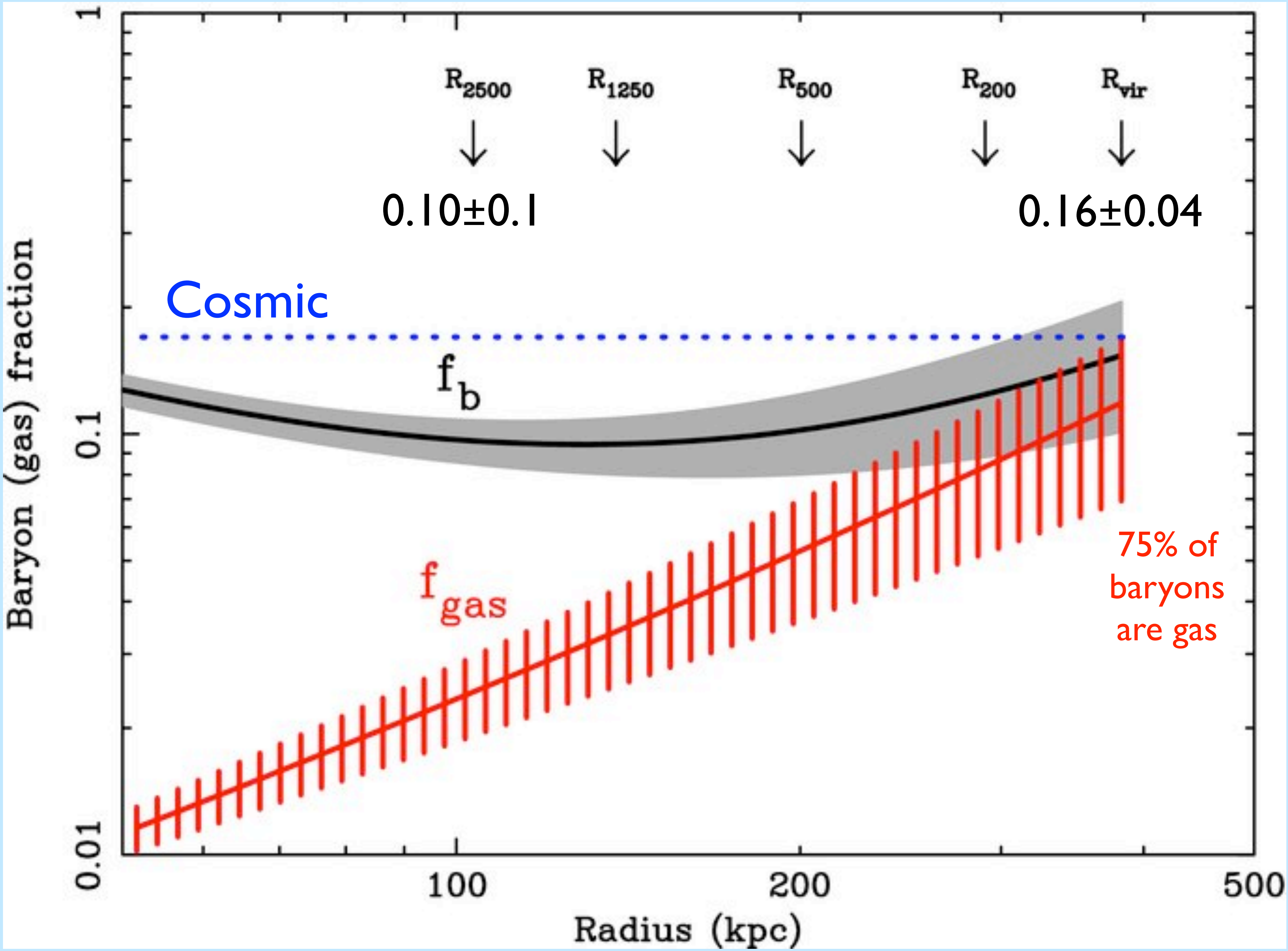
- Temperature/Pressure -- normalization (1)
- $S \propto \rho^{-2/3}T$ -- broken power-law + const (5)
- M (3)
  - Black Hole -- M_{BH} (fixed)
  - DM Halo -- NFW C_{Δ}, M_{Δ} (2)
  - Stars -- $M_{\star}/L_J$ (1)

9 Free Parameters Constrained by 26 Data Points



(spherically averaged)


1σ Error Regions
New
Old
Obs
Theory
Galaxy-Scale Mass!
Concentration
$\log_{10}(c_{vir})$
2
1.5
1
0.5
12
12.2
12.4
12.6
12.8
13
$\log_{10}(M_{vir}/M_{\odot})$
Virial Mass



Baryon (gas) fraction
Radius (kpc)
1
0.1
0.01
100
200
500
R2500
R1250
R500
R200
Rvir
0.10±0.1
0.16±0.04
Cosmic
fb
fgas
75% of
baryons
are gas

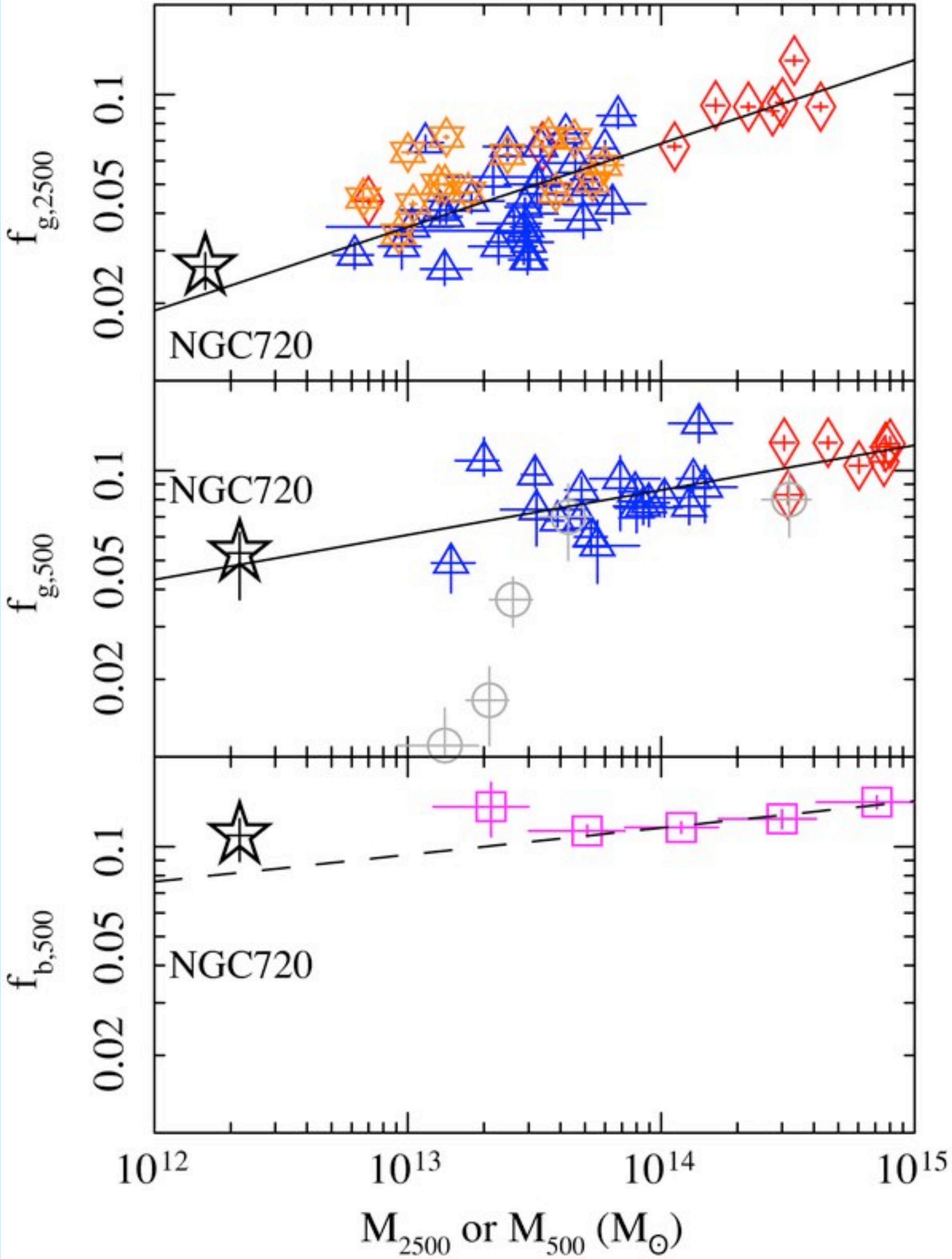
Error Budget

TABLE 4
Baryon fraction results and error budget

Test	$f_{g,2500}$	$f_{g,500}$	$f_{g,vir}$	$f_{b,2500}$	$f_{b,500}$	$f_{b,vir}$
Marginalized	$0.027^{+0.003}_{-0.004}$	$0.06^{+0.009}_{-0.02}$	$0.12^{+0.05}_{-0.03}$	0.10 ± 0.01	$0.11^{+0.02}_{-0.02}$	0.16 ± 0.04
Best-fit	(0.024)	(0.053)	(0.119)	(0.096)	(0.102)	(0.154)
Systematic error estimates						
ΔDM profile	-0.004 (±0.003)	-0.024 (±0.01)	$-0.085 \left({}^{+0.01}_{-0.01}\right)$	-0.013 (±0.01)	-0.044 (±0.01)	-0.114 (±0.01)
ΔAC	-0.001 (±0.004)	$-0.010 \left({}^{+0.01}_{-0.01}\right)$	$-0.019 \left({}^{+0.05}_{-0.03}\right)$	-0.026 (±0.01)	-0.023 (±0.02)	-0.035 (±0.04)
ΔBackground	-0.003 (±0.003)	-0.001 (±0.01)	$+0.03$ (±0.04)	$-0.005 \left({}^{+0.01}_{-0.01}\right)$	±0 (±0.02)	$+0.02 \left({}^{+0.04}_{-0.03}\right)$
ΔSWCX	±0 (±0.002)	$+0.001 \left({}^{+0.01}_{-0.01}\right)$	$+0.03 \left({}^{+0.03}_{-0.04}\right)$	$+0.003$ (±0.01)	$+0.005$ (±0.01)	$+0.03 \left({}^{+0.03}_{-0.04}\right)$
ΔEntropy	±0 (±0.004)	-0.018 (±0.01)	${}^{+0.02}_{-0.04}$ (±0.05)	±0 (±0.01)	${}^{+0.01}_{-0.01}$ (±0.02)	${}^{+0.01}_{-0.05}$ (±0.05)
Δ3d	$+0.005 \left({}^{+0.004}_{-0.005}\right)$	$+0.010$ (±0.02)	$+0.04 \left({}^{+0.05}_{-0.08}\right)$	$+0.01$ (±0.01)	$+0.01$ (±0.03)	$+0.03 \left({}^{+0.06}_{-0.08}\right)$
ΔSpectral	${}^{+0.001}_{-0.008}$ (±0.003)	-0.026 (±0.01)	${}^{+0.02}_{-0.07}$ (±0.05)	${}^{+0.00}_{-0.03} \left({}^{+0.01}_{-0.01}\right)$	${}^{+0.01}_{-0.04}$ (±0.02)	${}^{+0.03}_{-0.09}$ (±0.05)
ΔWeighting	-0.001 (±0.002)	±0 (±0.01)	$+0.01$ (±0.05)	-0.006 (±0.01)	-0.003 (±0.01)	$+0.008$ (±0.05)
ΔFit priors	${}^{+0.007}_{-0.004}$ (±0.004)	${}^{+0.01}_{-0.02}$ (±0.02)	${}^{+0.02}_{-0.04} \left({}^{+0.06}_{-0.05}\right)$	${}^{+0.01}_{-0.01}$ (±0.01)	±0.02 (±0.02)	${}^{+0.01}_{-0.06}$ (±0.06)
ΔInstrument	-0.008 (±0.005)	-0.025 (±0.02)	-0.067 (±0.06)	-0.021 (±0.01)	-0.032 (±0.02)	-0.081 (±0.05)
ΔStars	±0 (±0.004)	$-0.006 \left({}^{+0.02}_{-0.01}\right)$	$+0.008$ (±0.05)	${}^{+0.02}_{-0.01} \left({}^{+0.03}_{-0.05}\right)$	$-0.008 \left({}^{+0.03}_{-0.02}\right)$	${}^{+0.01}_{-0.01} \left({}^{+0.05}_{-0.06}\right)$
ΔDistance	$-0.002 \left({}^{+0.004}_{-0.003}\right)$	$-0.007 \left({}^{+0.02}_{-0.01}\right)$	$+0.001 \left({}^{+0.05}_{-0.04}\right)$	${}^{+0.00}_{-0.00}$ (±0.01)	$-0.006 \left({}^{+0.02}_{-0.02}\right)$	-0.006 (±0.05)
ΔFit radius	$-0.007 \left({}^{+0.007}_{-0.005}\right)$	-0.019 (±0.02)	$-0.064 \left({}^{+0.07}_{-0.04}\right)$	-0.017 (±0.02)	$-0.032 \left({}^{+0.03}_{-0.02}\right)$	$-0.076 \left({}^{+0.08}_{-0.04}\right)$
ΔCovariance	$-0.002 \left({}^{+0.004}_{-0.003}\right)$	-0.005 (±0.01)	$+0.02 \left({}^{+0.04}_{-0.06}\right)$	$+0.002$ (±0.01)	±0.00 (±0.02)	$+0.003$ (±0.05)

Note. — Marginalized values and 1-σ confidence regions for the gas fraction ($f_{g,\Delta}$) and baryon fraction ($f_{b,\Delta}$) measured at various overdensities (Δ). We also provide the best-fitting parameters in parentheses, and a breakdown of possible sources of systematic uncertainty, following Table 3. We find that f_b is reasonably robust to most sources of systematic uncertainty, especially within R_{2500}.

(see Humphrey's talk on RXJ 1159+1101)



Group and Cluster Data from:

Gastaldello et al. 2007;
Sun et al. 2009;
Vikhlinin et al. 2006;
Dai et al. 2009

Baryon fractions from Giodini et al. 2009

Future Work

- Deep, Offset Suzaku Data for N720 to go out to R_{500}
- Follow-up of X-ray snapshot sample of 35 isolated ellipticals -- w/ T. Ponman, E. O'Sullivan (Birmingham) & C. Topchyan (UC Irvine)

Spherically Averaging Galaxy Clusters

- Clusters are not spherical
- Precision measurements / Scaling Relations
- Observer (2D) vs. Theorist (3D)

History in X-Rays

- Piffaretti, Jetzer, Schindler (2003, A&A, 398, 41) -- Isothermal Triaxial Beta Model Fitted to 10 ROSAT clusters
- Gavazzi (2005, A&A, 443, 793): Isothermal NFW Spheroids, Face-On projections

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Typically <~ 5% Differences (total mass)

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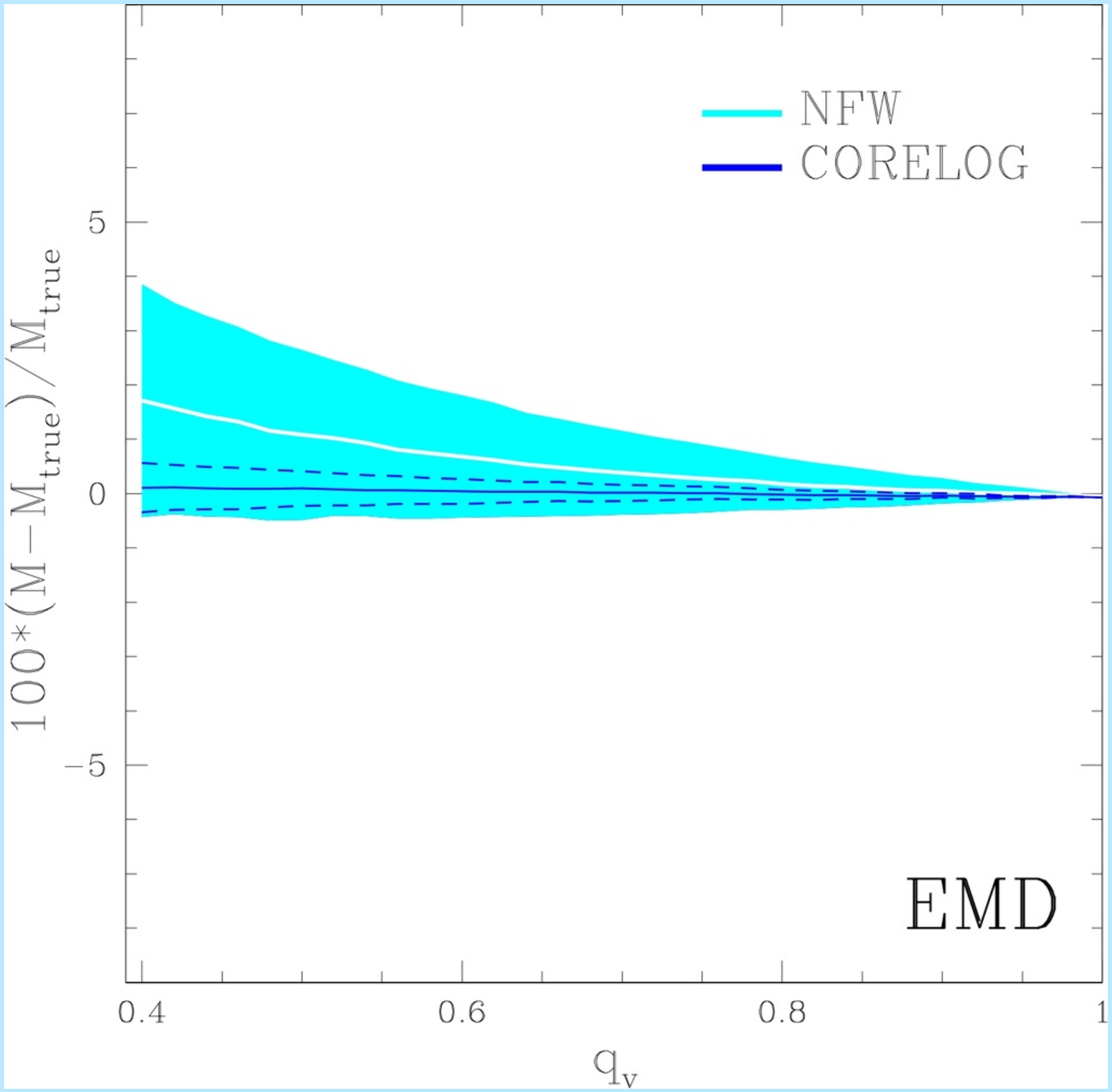
No Angle Averaging

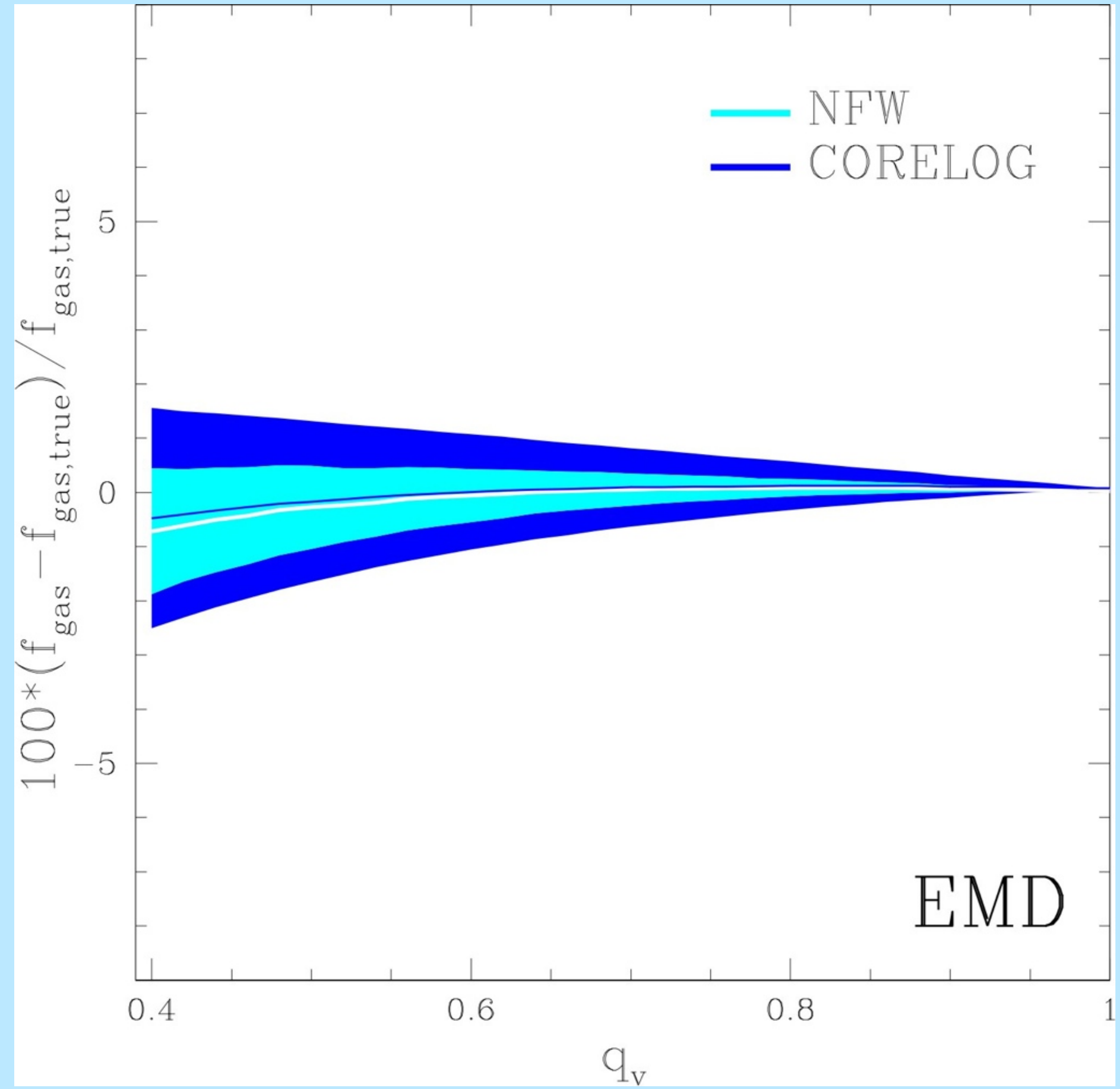
Angle-Averaged Bias & Scatter

(Buote & Humphrey, 2011a,b, in prep)

- Hydrostatic Equilibrium
- **Triaxial** (T=0.5) and Spheroids (T=0,1)
- Mass: NFW or CORELOG ($\rho \sim r^{-2}$)
- ICM: Isothermal or Polytropic ($\gamma = 1.2$)
- Global Quantities (R_{500})

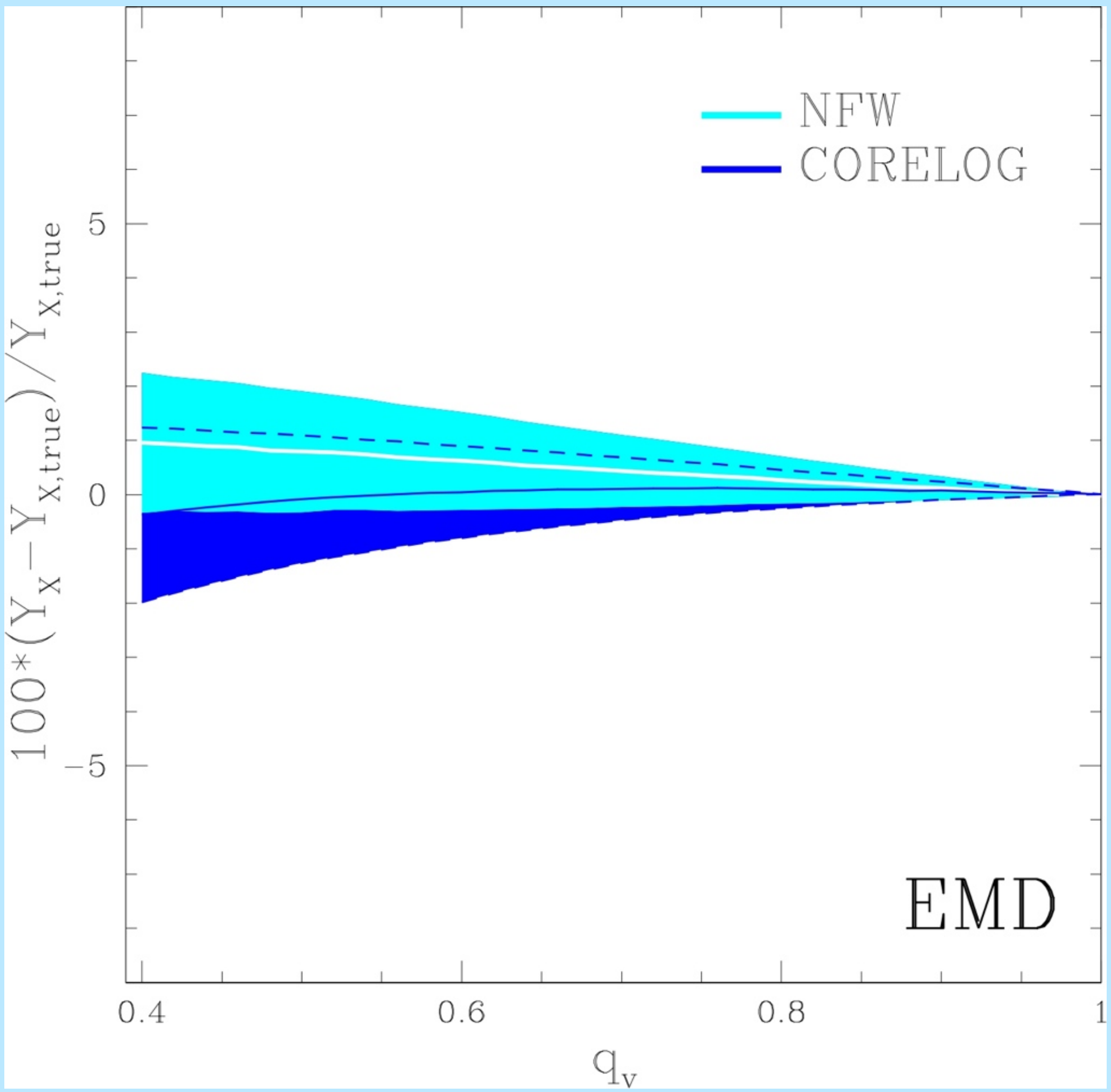
Mass & Gas Fraction

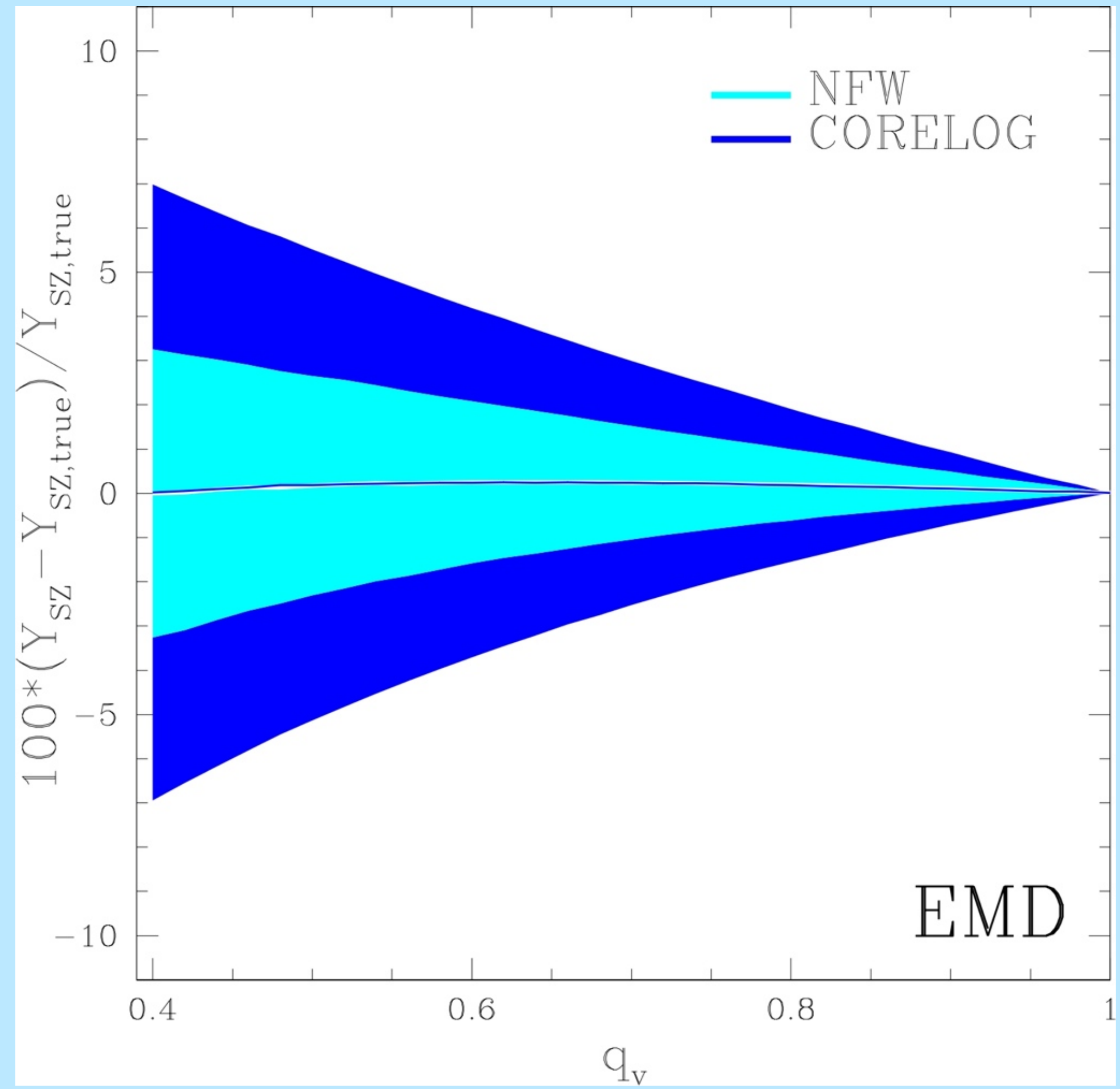




- Bias <~ 1% (solid white & blue lines)
- Scatter: <~ 2%

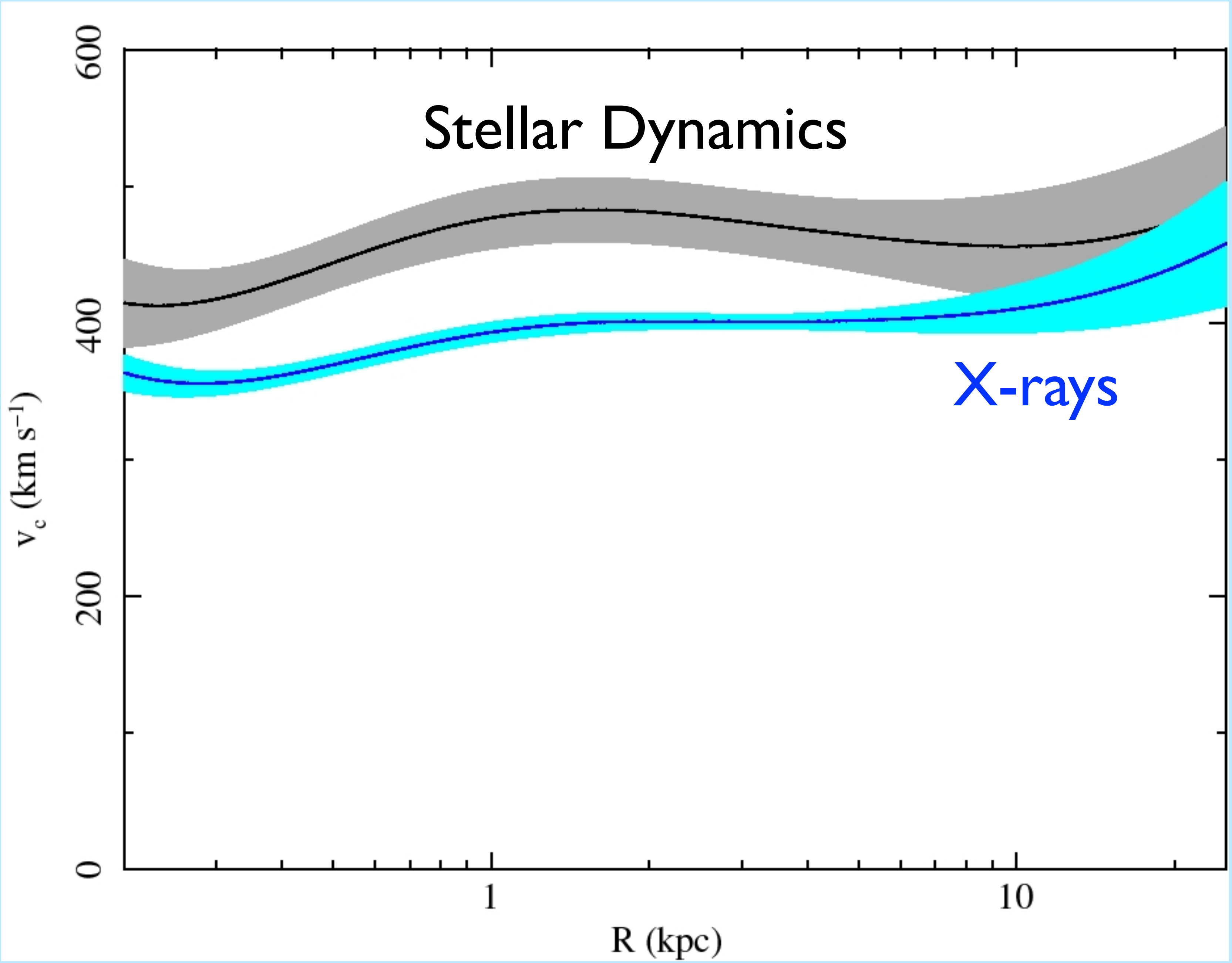
Y_X and Y_{SZ}





- Y_{sz} bias ~0%
- Y_x scatter < Y_{sz} scatter

Non-Thermal Gas Support in NGC 4649



(Humphrey, Buote, Gebhardt, Brighenti, & Mathews, in prep)

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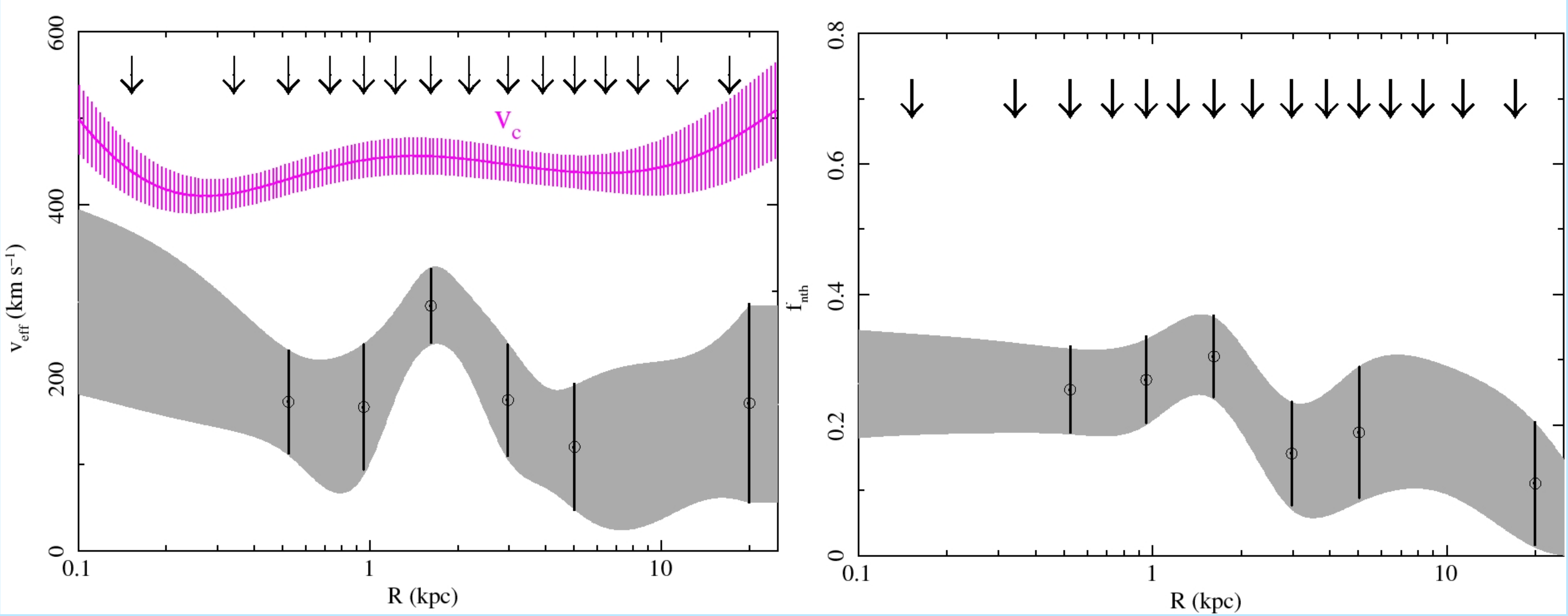

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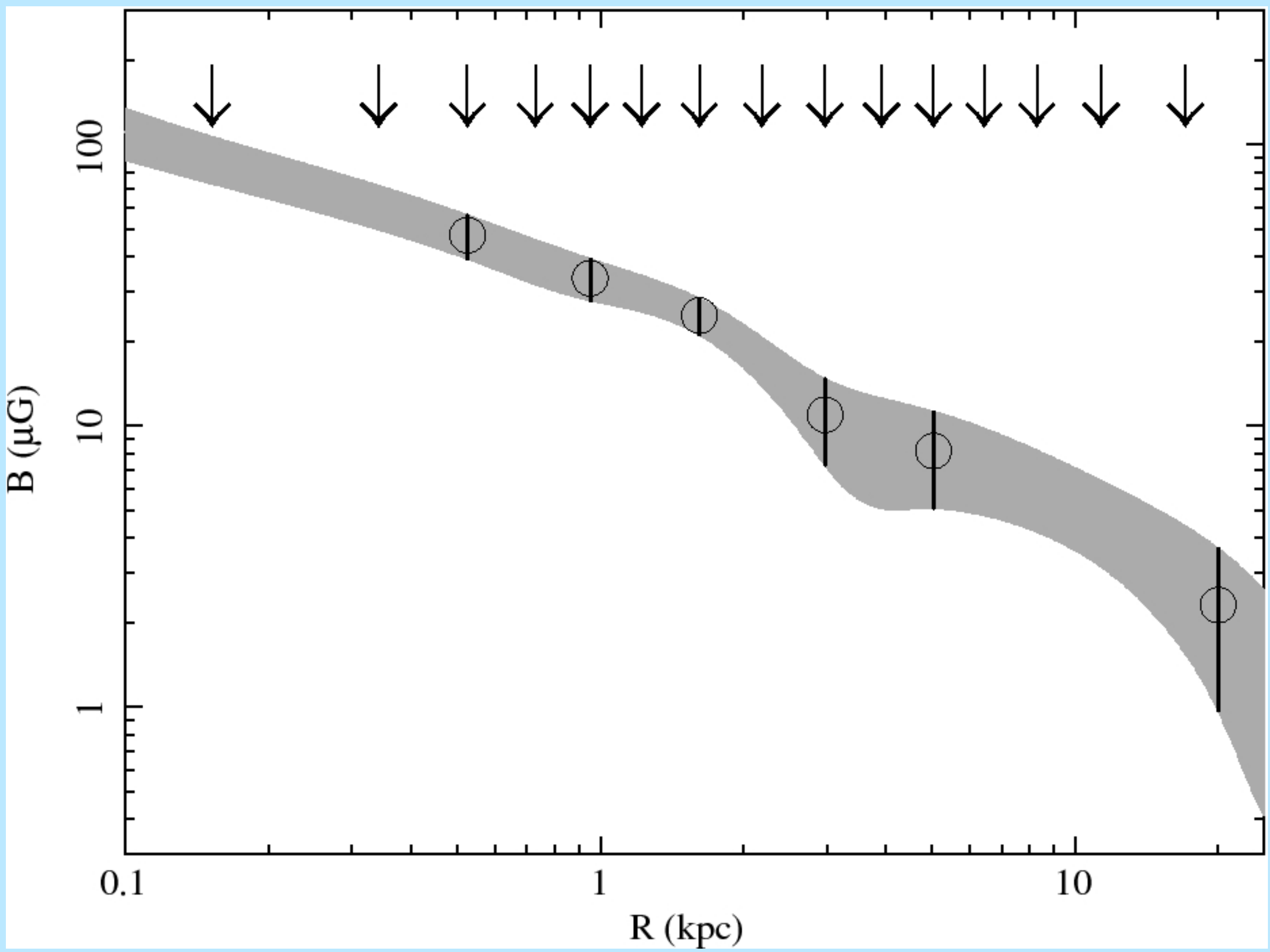

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