Exploring the Cosmological Impact of Powerful Classical Double Radio Galaxies

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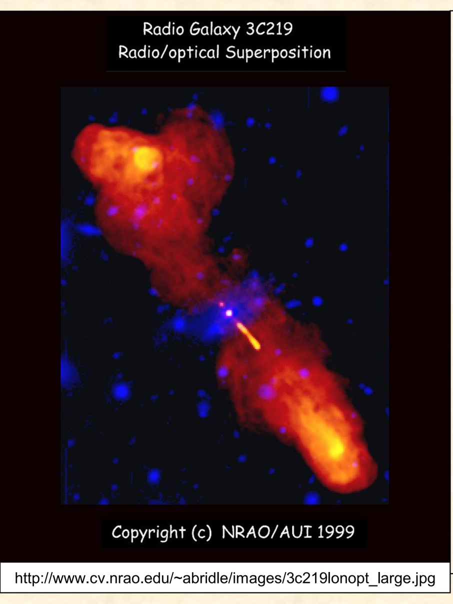

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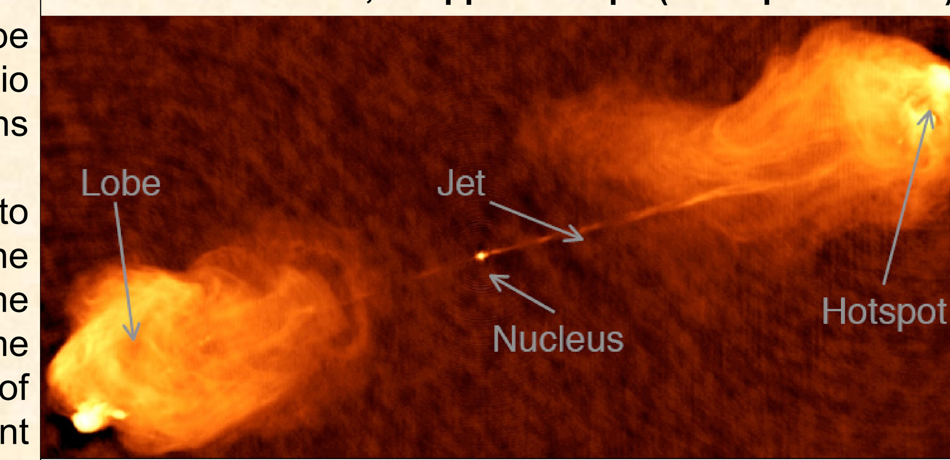
Abstract

Radio Galaxies (RGs) are claimed to have substantially influenced the growth and evolution of large scale structures in the universe. In order to probe these impacts in more detail, I investigated evolutionary models of FR II RGs. I compared three semi-analytical models for the dynamical and radio lobe power evolution of FR II galaxies, by performing multi-dimensional Monte Carlo simulations and virtual radio surveys. The model predictions were compared with observational samples using extensive statistical tests. I also produced modifications to the original models.

I found that better fits to most of the data distributions can be found with sensible choices of model parameters, but no model gives a good match to all of the survey data simultaneously. Also, no pre existing or modified model can provide adequate fits for the spectral index distributions. The observational datasets are too small to completely discriminate among the models. I calculated the volume fraction of the "relevant universe" (volume of the baryonic WHIM filaments) cumulatively occupied by multiple generations of expanding radio galaxy lobes over the quasar era. This volume filling factor is smaller than previously estimated. Nonetheless, the allowed ranges of various model parameters produce a rather wide range of astrophysically interesting relevant volume fraction values. I conclude that the expanding RGs born during the quasar era may still play significant roles in the cosmological history of the universe.

•Barai & Wiita 2006, MNRAS, 372, 381 (astro-ph/0510724)
•Barai & Wiita 2007, to appear in ApJ (astro-ph/0611689)



Cygnus A - Chris Carilli (Perley R. A., Dreher J. W. & Cowan J. J., 1984, ApJ, 285, 35L)

Introduction

- Fanaroff Riley Class II RG
  - Edge-brightened and more powerful
- Electrons in radio lobe magnetic field produce synchrotron radiation

Motivation

- Comoving space density of FR II RGs were higher during the **Quasar Era (1.5 < z < 3)**
- Expanding RGs had significant impact on
  - Galaxy formation & evolution, large-scale structures
  - Triggering star formation
  - Spreading metals and magnetic field into the IGM

Goal

- Probe the impact of RGs on the cosmological history of Universe, and test the robustness of the exciting claims
- How much volume fraction of the Relevant Universe (baryonic filaments only) do radio lobes occupy cumulatively over Quasar era?
- Model the individual & cosmological evolution of RGs

Procedures

- Semi-analytical models for RG dynamics & power evolution
- Compare model predictions with observations
  - Virtual Radio Surveys -- Monte Carlo Simulations
- Extensive statistical tests quantifying the success of a model
- Choose best model, estimate physical implications

Observations

- Low frequency: 151 & 178 MHz
- Redshift-complete subsamples from flux-limited, complete radio surveys in Cambridge catalogs: 3CRR, 6CE, 7CRS

Observables [z, P, D, α]

- z – Redshift
- P_{151} – Specific Power at 151 MHz
- D_{proj} – Projected Linear size
- α_{151} – Spectral index at 151 MHz [$P_\nu \sim \nu^{-\alpha}$]

Complete Samples

Survey	Flux Limit (Jy)	No. of Sources[a]	Sky Area (sr)
3CRR	S_{178}[b] > 10.9 $S_{151} > 12.4$	145	4.23
6CE	$2 \leqslant S_{151} \leqslant 3.93$	56	0.102
7CRS	$S_{151} > 0.5$	126	0.022
7CI	$S_{151} \geqslant 0.51$	37	0.0061
7CII	$S_{151} \geqslant 0.48$	40	0.0069
7CIII	$S_{151} > 0.5$	49	0.009

Modifications to the Models

BRW-modified, MK-modified:
- Hot spot size grows as source ages
- r_{hs} vs. L data
  - Jeyakumar & Saikia, 2000
- Quadratic fit gave least reduced χ^2

K2000:
- Kaiser proposed modification to KDA
  - Different ρ_{head}/ρ_{lobe}

KDA-modified:
- Increasing axial ratio

$$R_T' = \frac{L}{2r_{hs}} \qquad R_T' = F_0\left(\frac{L}{L_0}\right)^{\gamma}$$

Alternative RLF:
- Grimes, Rawlings & Willott (2004)
- z_0 = 1.684, Δz_0 = 0.447

Dynamical Evolution

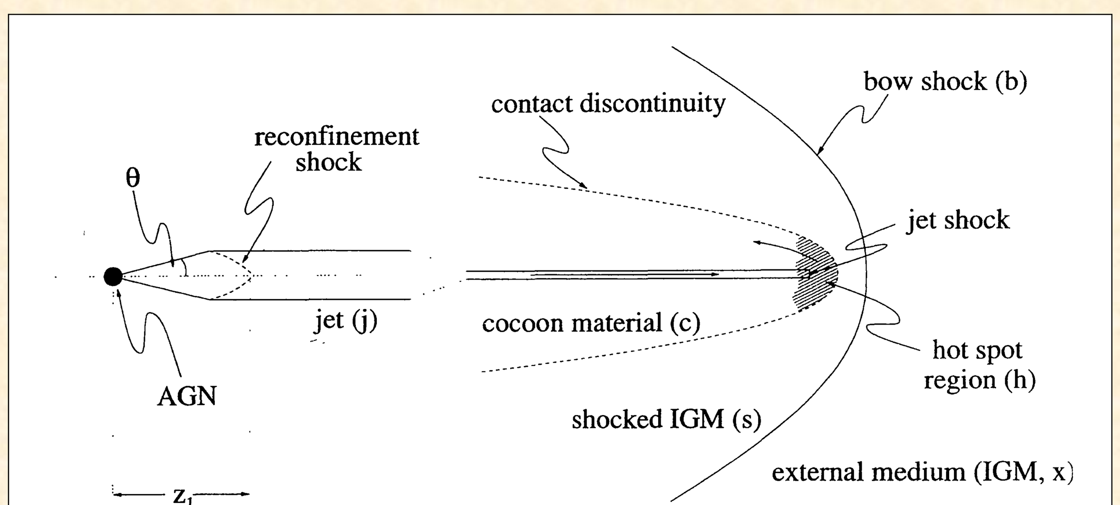
Kaiser & Alexander (1997)

- Ambient medium power-law density

$$\rho(r) = \rho_0\left(\frac{r}{a_0}\right)^{-\beta}$$

- Total Linear Size

$$D(t) = 3.6 a_0\left(\frac{t^3 Q_0}{a_0^5 \rho_0}\right)^{1/(5-\beta)}$$



Simplified Model of a Radio Source (Kaiser & Alexander, 1997)

Models of Radio Lobe Power Evolution

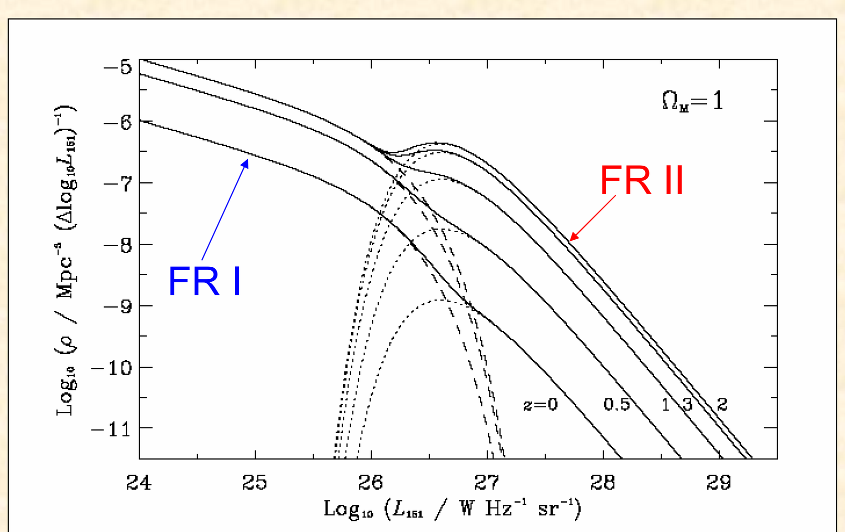
- **KDA** : Kaiser, Dennett-Thorpe & Alexander, 1997
- **BRW** : Blundell, Rawlings & Willott, 1999
- **MK** : Manolakou & Kirk, 2002
- **K2000** : Kaiser, 2000
- **BRW-modified**: Vary hotspot size
- **MK-modified** : Vary hotspot size
- **KDA-modified** : Vary axial ratio

$$P_\nu = \frac{\sigma_T c}{6\pi}\frac{B^2}{2\mu_0}\frac{\gamma^3}{\nu} n(\gamma) V$$

Power Losses

$$\frac{d\gamma}{dt} = -\frac{a_1 \gamma}{3t} - \frac{4\sigma_T}{3 m_e c}\left(\frac{B^2}{2\mu_0} + \frac{B_{CMB}^2}{2\mu_0}\right)\gamma^2$$

Adiabatic Synchrotron Inverse Compton



Radio Luminosity Function (Willott et al., 2001)

Multi-Dimensional Monte-Carlo Simulation (BRW)

- RG population generated from early epoch
  - Jet power distribution
    - if, 5×10^{37} W < Q_0 < 5×10^{42} W
    - **x = 2.6**

$$p(Q_0) \sim Q_0^{-x}$$

  - Redshift distribution
    - $z_0 = 2.2$, $\Delta z_0 = 0.6$

$$\rho(z) \propto \exp\left[-\frac{1}{2}\left(\frac{z - z_0}{\Delta z_0}\right)^2\right]$$

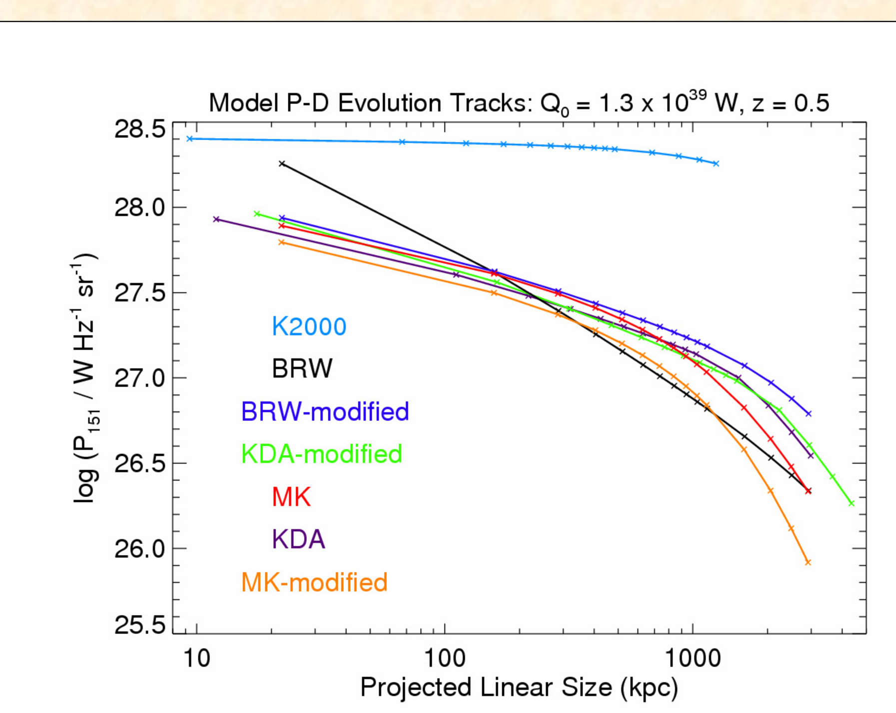
- T_{MaxAge} = 500 Myr
- Each source's P, D evolved according to model
- At t_{age}, if flux reaching earth > survey limit → RG is detected
- A single simulation: Initial ensemble size 10^6–10^7 → **50–200** detected in final virtual surveys

Statistical Tests

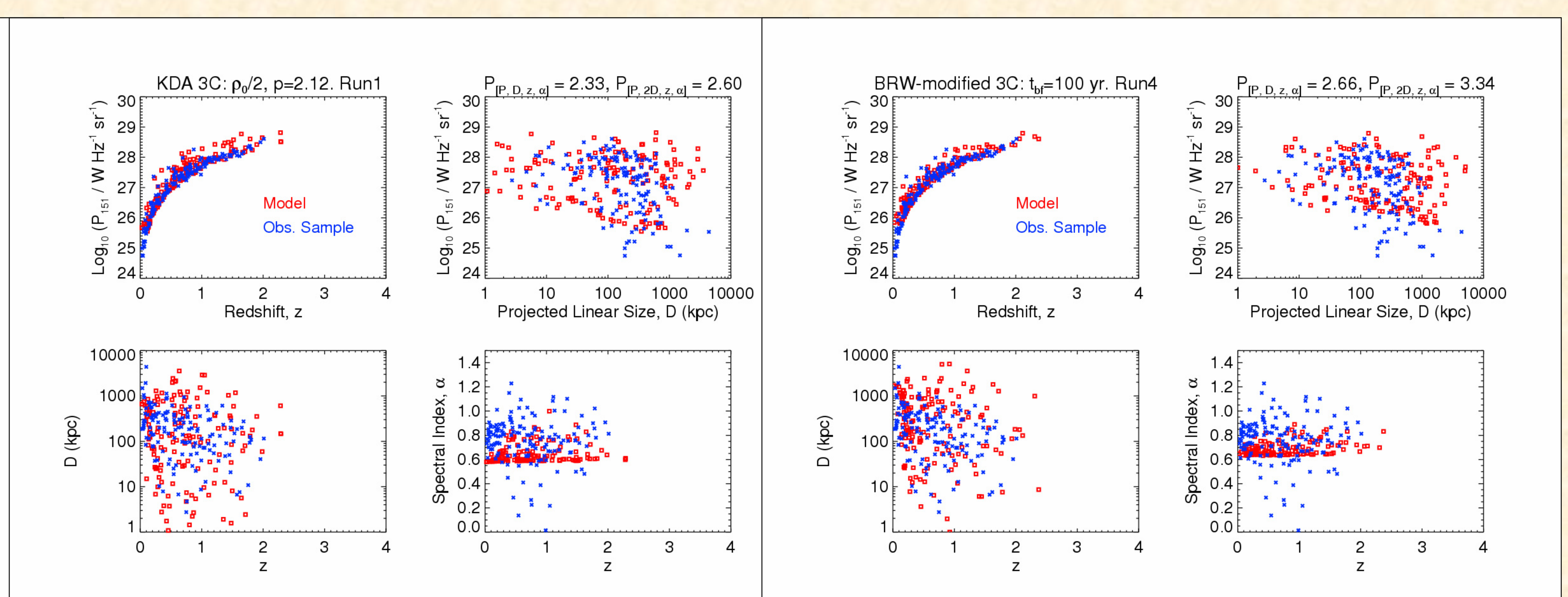
- Kolmogorov – Smirnov Probability, P(K-S)
  - 1-D K-S:
    Add P's for P, D, z, α for the 3 surveys in ratio of the square root of the number detected in a survey: $P_{[P, D, z, \alpha]}$, $P_{[P, 2D, z, \alpha]}$
  - 2-D K-S Test
- Spearman's Partial Rank Correlation Coefficient

"Best 1-D K-S" Results of Models

Model	Age (Myr)	x	Parameter	$P_{[P, D, z, \alpha]}$	$P_{[P, 2D, z, \alpha]}$
KDA	500	2.6	Default	0.881	0.942
	150	3.0	$\rho_0/2$, p=2.12	2.33	2.60
BRW	500	2.6	Default	0.0172	0.0336
	250	3.0	a_0 = 7.5 kpc	1.63	1.73
MK	500	2.6	Default	0.270	0.324
	150	3.0	$\gamma_{max} = 3\times10^8$	2.47	3.58
KDA-modified	500	2.6	Default	1.20	1.41
	200	3.0	Default	2.48	3.14
BRW-modified	500	2.6	Default	0.404	0.407
	300	3.0	t_{bf} = 100 yr	2.66	3.34
MK-modified	500	2.6	Default	0.727	0.767
	150	2.6	β = 1.6	2.73	4.04



[P-D] tracks of different models



[P-D-z-α] planes of two models compared to 3C observations

Statistical Results

- Models give acceptable fits for [P-D-z] distributions of Cambridge catalog subsamples
  - **No good α fit by any model or variations**
- K-S statistic values: MK & KDA > BRW
- Correlation coefficient: KDA > BRW > MK
- Overall best – KDA
- No single model gives excellent fit to all data simultaneously
- BRW-modified: Growing hotspot in BRW model → Less-steep [P-D] tracks, Substantial improvement in K-S stats
- K2000: Too flat [P-D] tracks, Worse statistics
- KDA-modified & MK-modified → Comparable to / slightly better than original KDA & MK
- Grimes et al. RLF → Worse stat. than Willott et al. RLF

Relevant Universe (WHIM)

- Filaments containing overdense baryonic material
  - Warm/hot gas: 10^5 < T < 10^7 °K
- Relevant volume as a fraction of total cosmic volume
  - 0.03 @ z = 2 (Quasar era)
  - 0.1 @ z = 0

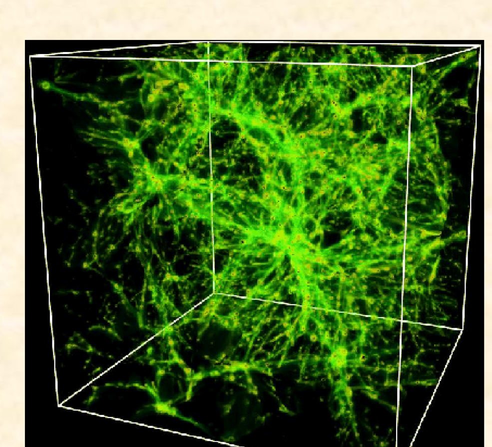
$$\Delta V_{proper} = \frac{\Delta V_{comoving}}{(1+z)^3} \times \frac{3C_{SkyArea}}{4\pi} \times \text{Ratio}_{3C} \times \text{WHIM Frac.}$$

RG Volume

- Cylindrical RGs with R_T = 5
- All live for T_{MaxAge}

$$V_{RG}(t) = \frac{\pi D^3(t)}{4R_T^2}$$

$$\Delta\iota(z) = \frac{\Delta V_{RG(total)}}{\Delta V_{WHIM}}$$


Spatial distribution of WHIM at present epoch (Cen & Ostriker, 1999)

Cumulative Fraction, ζ

- Volume fraction filled by RGs cumulatively over the quasar era
- Gopal-Krishna & Wiita, 2001 (GKW01):

$$\text{No. of generations} = \frac{\text{Quasar Era}}{T_{MaxAge}} = \frac{2\text{ Gyr}}{500\text{ Myr}} = 4$$

- Here:

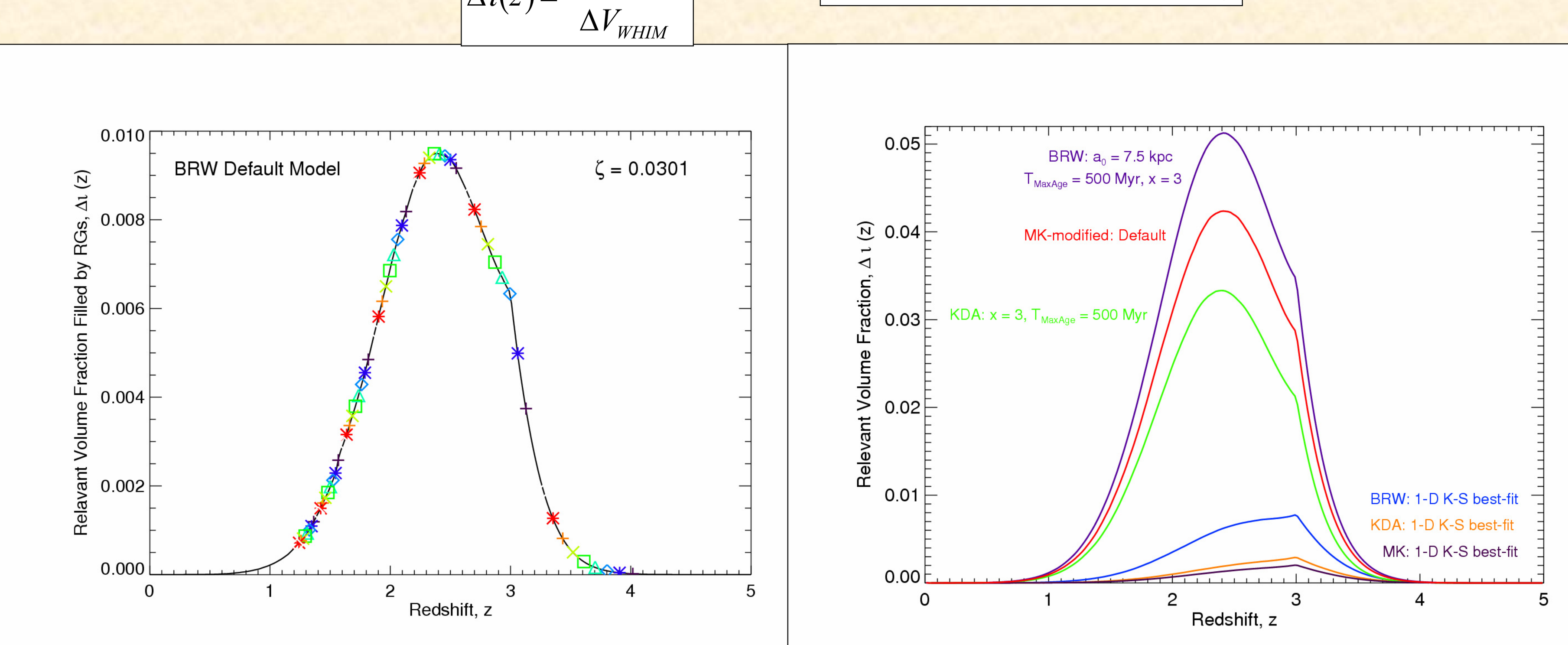
$$\zeta = \sum_{\substack{\text{Over quasar era} \\ \text{In intervals of } T_{MaxAge}}} \Delta\iota(z)$$

Cosmological Implications

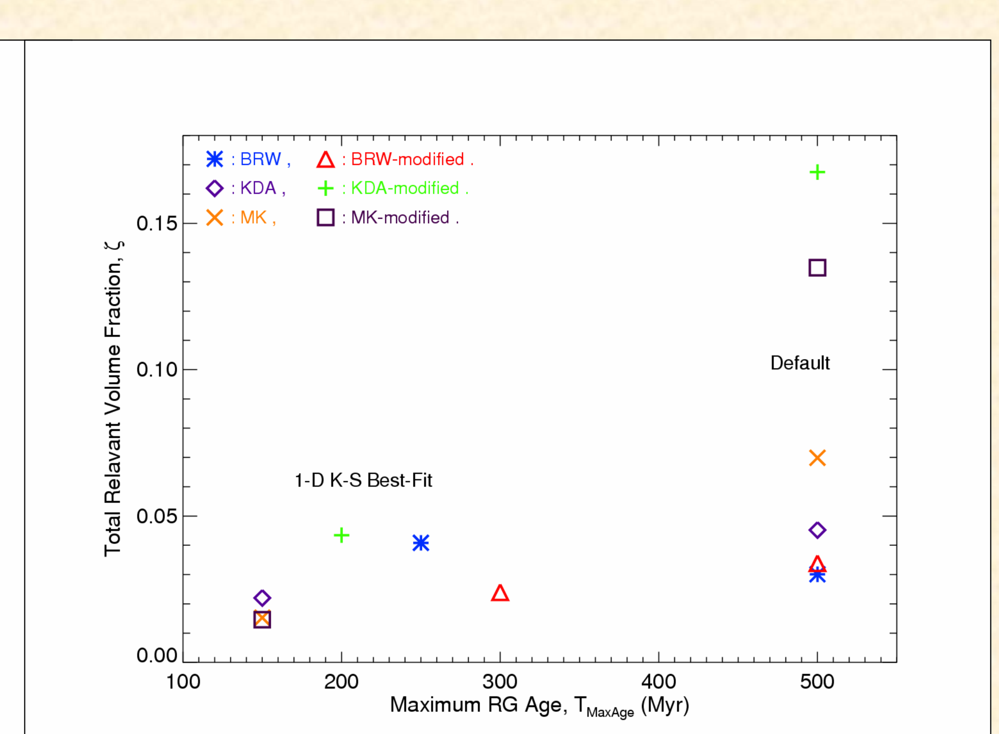
- Wide range of possible filling factors
- Default & "1-D K-S best-fit" parameter variations: $\zeta \simeq$ 2–7 %
- Gopal-Krishna & Wiita, 2001 (using BRW model): $\zeta \simeq$ 50 %
- Deduced some sources of discrepancy
- Could not confidently verify overwhelming RG impact as in GKW01
- Expanding RGs born during quasar era play modest to significant role in cosmology

Summary

- Made comprehensive quantitative comparisons between models of RG evolution (KDA, BRW, MK and their modifications)
  - Using multi-dimensional Monte-Carlo simulations
  - And our extensive statistical analyses
- Some published models give acceptable fits to P, D, z of radio surveys 3C, 6C, 7C
  - α -- Elusive !
- Modified models can give improved fits
- RGs of quasar era may still have substantial impact in cosmology



Relevant Volume filling fraction of different models



Total volume fraction for different AGN lifetimes

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- Willott et al., 2001, MNRAS, 322, 536