Strong Lensing and the Density Profiles of Halos and Galaxies

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Is Cold Dark Matter in trouble?

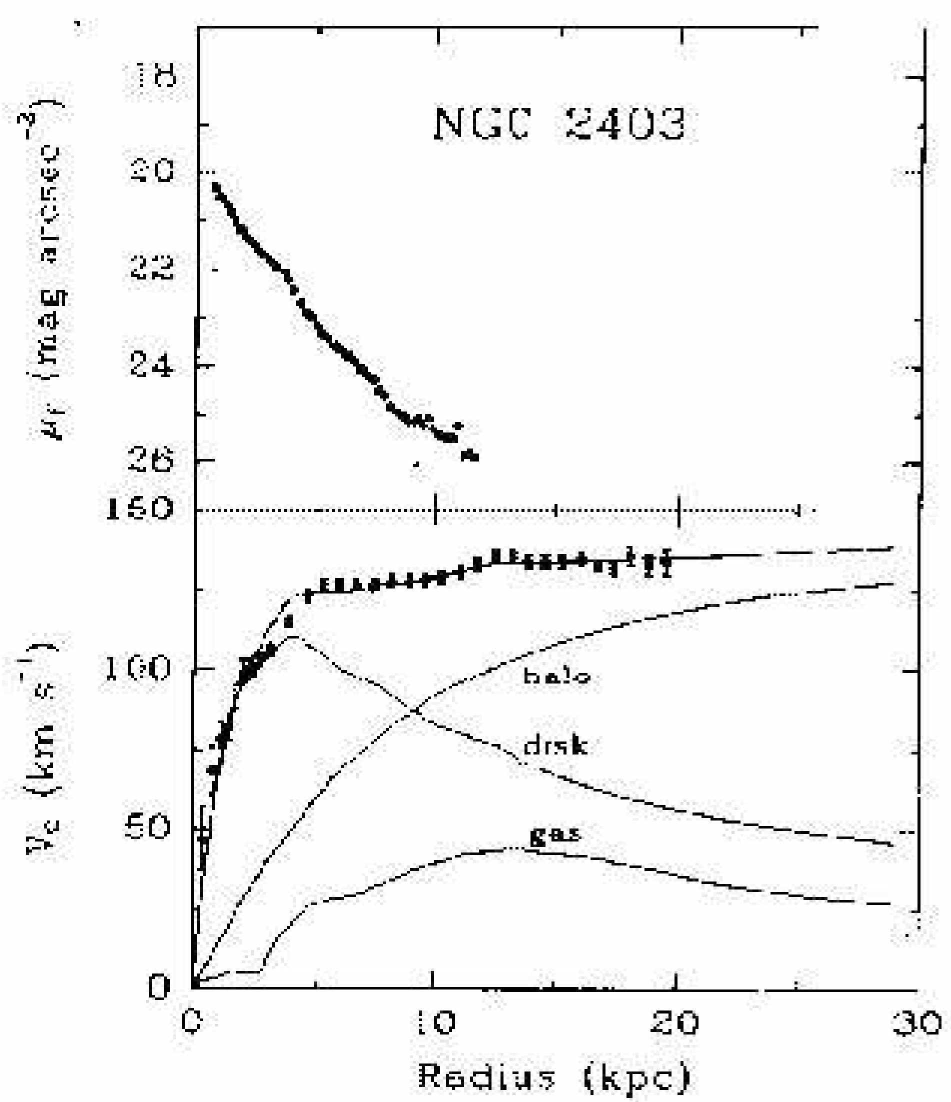
"There does not seem to be a coherent pattern to the present list of challenges to the CDM model"
(Peebles & Ratra, astro-ph/0207347).

Density profiles of galaxies are shallower than predicted;
few dwarf satellite galaxies observed than predicted
$\Rightarrow$ **decrease** the small-scale power

But

Quasars (powered by black holes?) observed out to $z \approx 6$
$\Rightarrow$ **increase** the small-scale power

Galaxy Rotation curves, circa 1975



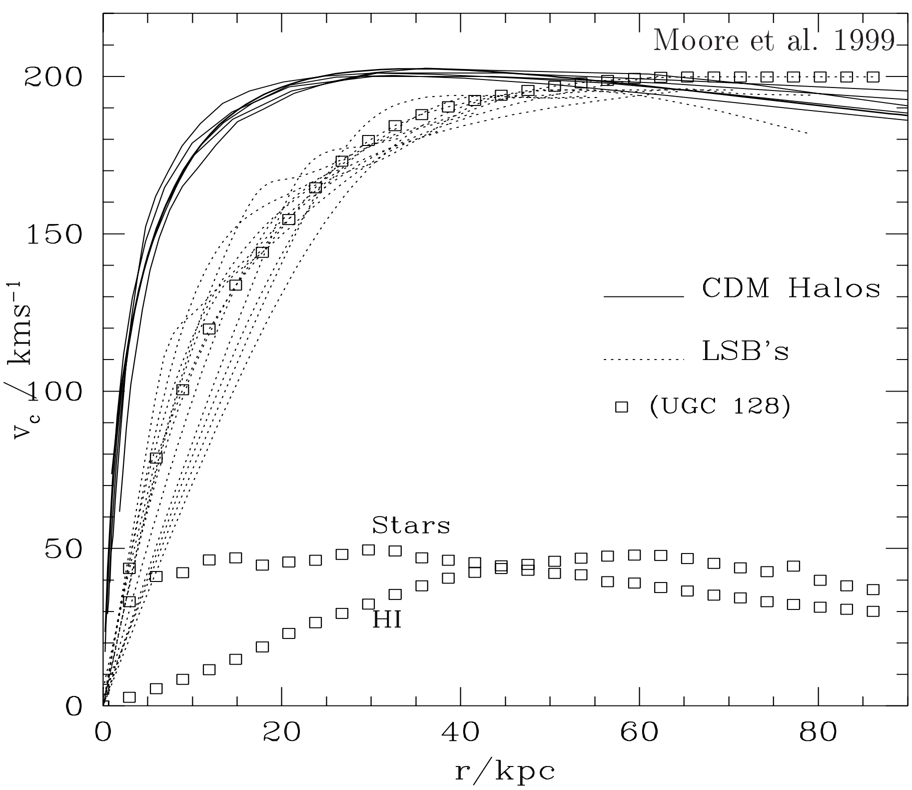
$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

Luminous M only, expect $\qquad v \propto r^{-0.5}$

Including the dark halo, expect $\qquad v^2 \propto r^2 \rho(r)$

Galaxy Rotation curves, circa 2000

UGC 128, de Blok & McGaugh



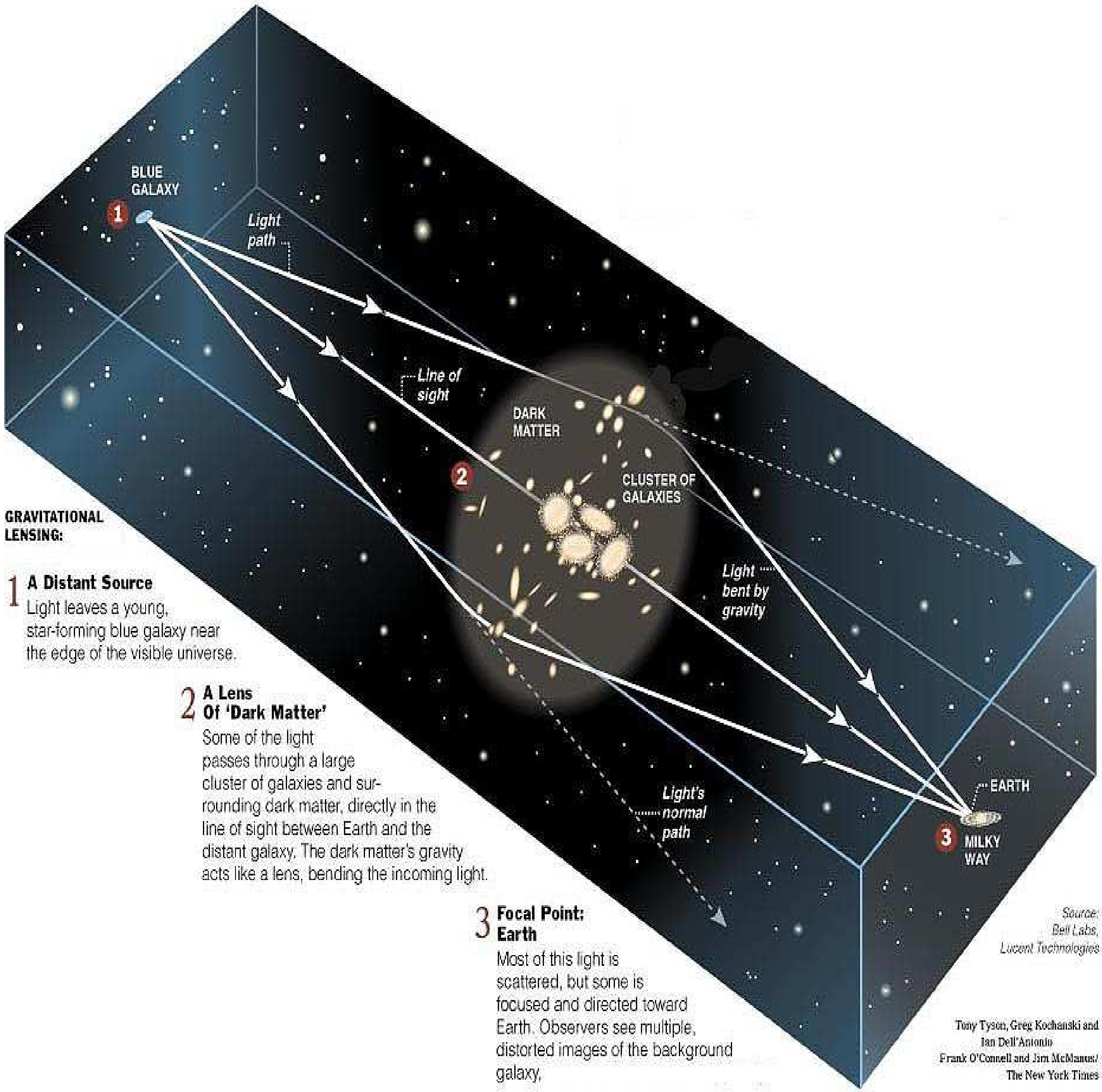
Suggested modifications to CDM

- Feedback by supernovae, star formation, or winds
- Self-Interacting Dark Matter
  but: unnatural particle physics; makes halos that are too round; may lead to core collapse
- Primordial spectrum with less power at small scales
  but: small scale power will be regenerated in nonlinear collapse
- Warm Dark Matter
  but: may leave the Ly-α forest with too little power

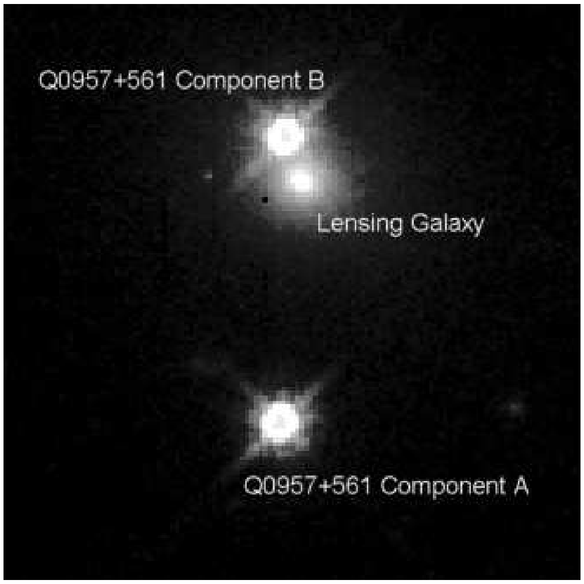
Which modification of CDM works?

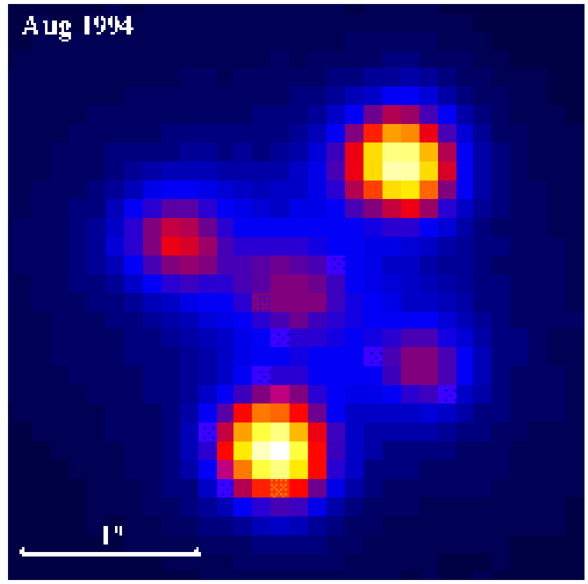
Is a modification of CDM needed?

Strong Gravitational Lensing !

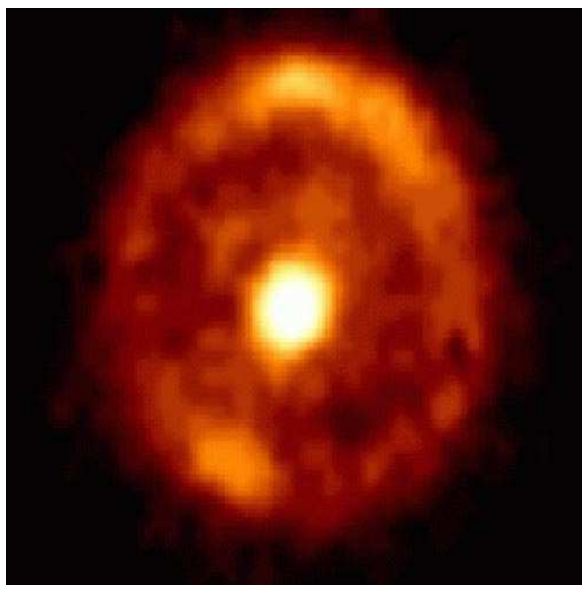


Q 2237+0305 (G. Lewis and M. Irwin, WHT)





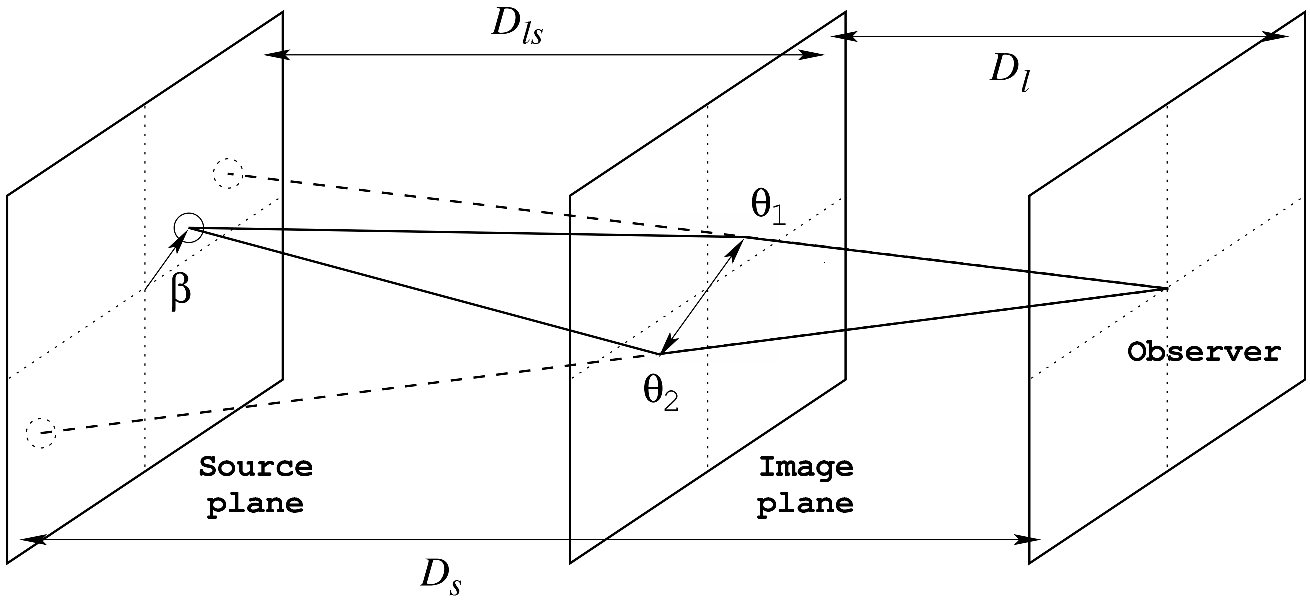
B1938+666 (L.J. King, NICMOS, HST)



Gravitational lensing theory

From general relativity,

$$n(\mathbf{r}) = 1 - \frac{2\phi(\mathbf{r})}{c^2}$$



The lens potential:

$$\psi(\boldsymbol{\theta}) \equiv \frac{2}{c^2}\frac{D_{ls}}{D_l D_s}\int_{-\infty}^{+\infty}\phi(\boldsymbol{\theta}, l)dl$$

Apply Fermat's principle:

$$t = \frac{1+z_l}{c}\int_S^O n(\mathbf{r})d\mathbf{r} = \frac{1+z_l}{c}\int_S^O d\mathbf{r} - \frac{1+z_l}{c^3}\int_S^O 2\phi(\mathbf{r})d\mathbf{r}$$

$$t(\boldsymbol{\theta}) = t_0 + \left(\frac{1+z_l}{c}\right)\left(\frac{D_l D_s}{D_{ls}}\right)\left[\frac{1}{2}|\boldsymbol{\theta} - \boldsymbol{\beta}|^2 - \psi(\boldsymbol{\theta})\right]$$

The lens equation:

$$\boldsymbol{\theta} = \boldsymbol{\beta} - \nabla\psi(\boldsymbol{\theta})$$

Optical depth for lensing

$d\tau =$ (density of galaxies) $\times$ (lensing cross-section) $\times c\, dt$

$$\tau = \int_0^{z_s} dz_l \frac{dD_l}{dz_l} (1+z_l)^3 \times \int_0^{\infty} dL \frac{d\phi}{dL}(L)\, \sigma_{\rm SIS}(L, z_l, z_s) B(L, z_l, z_s)$$

Required input:

- Cosmology (Ω_M, Ω_Λ)
- Luminosity (or mass) function:

$$\begin{aligned} \frac{d\phi}{dL}(L)\, dL &= \phi_* \left(\frac{L}{L_*}\right)^{\alpha} \exp(-L/L_*) \frac{dL}{L_*}, \quad \textbf{or} \\ \frac{d\phi}{d\ln M} &= 0.315 \frac{\rho_M}{M} \frac{d\ln\sigma^{-1}}{d\ln M} \exp(-|\ln\sigma^{-1} + 0.61|^{3.8}) \end{aligned}$$

- Cross-section for lensing, e.g. SIS: $\rho(r) = \sigma^2/(2\pi G r^2)$

$$\sigma_{\rm SIS} = \pi(\theta_E D_l)^2 = 16\pi^3 \left(\frac{\sigma}{c}\right)^4 \left(\frac{D_l D_{ls}}{D_s}\right)^2$$

- relate L to σ: Faber-Jackson relation

$$\frac{L}{L_*} = \left(\frac{\sigma}{\sigma_*}\right)^{\gamma} \qquad \gamma \sim 4$$

Strong Lensing as a Probe of Cosmology

- Many papers since the late 1980s; the idea is

$$N_{\rm lens} \propto {\rm Volume} = \frac{r^2(z)}{H(z)}$$

- Kochanek (1996) $\Omega_\Lambda < 0.66$ at 95% CL.

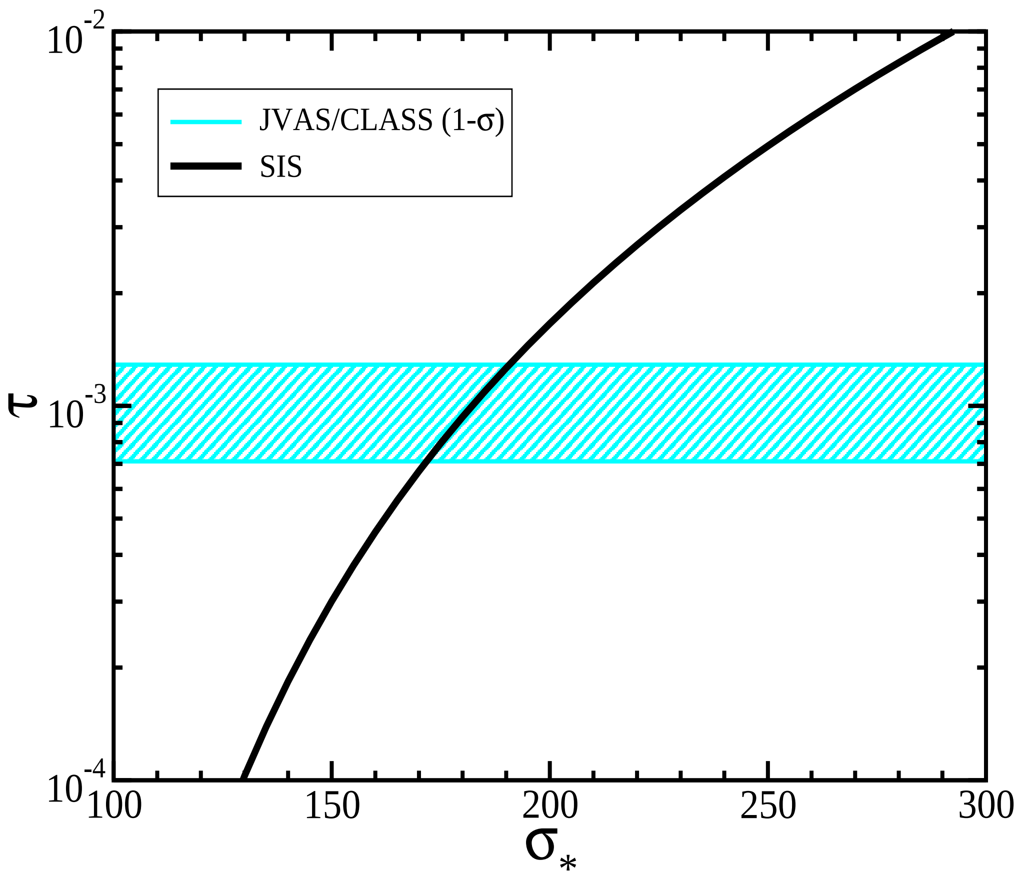
- But other parameter choices may favor high Ω_Λ (Cheng & Krauss 1999, Chiba & Yoshii 1999)

- also Kochanek 1994, 1995, Im et al. (1997), Waga & Miceli 1999, Cooray, Quashnock & Miller 1999, Sarbu, Rusin & Ma 2001, Chae et al. 2002 but much better...

Strong Lensing as a Probe of Lens Properties !

(Krauss, 1990s)

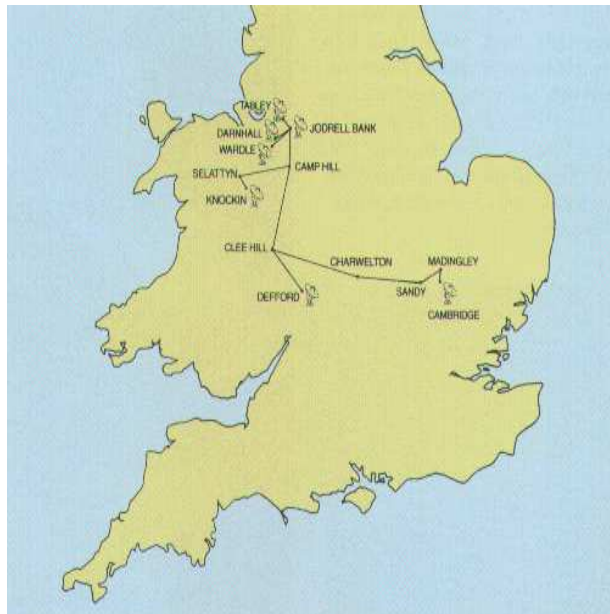
$$
\begin{aligned}
d\ln\tau \;=\;& 2.07\, d\ln z_s + 1.00\, d\ln\phi_* + 0.69\, d\ln\alpha + \\
& \mathbf{4.16}\, d\ln\sigma_* + 0.69\, d\ln\gamma - 0.61\, d\ln\Omega_M + 0.61\, d\ln w.
\end{aligned}
$$



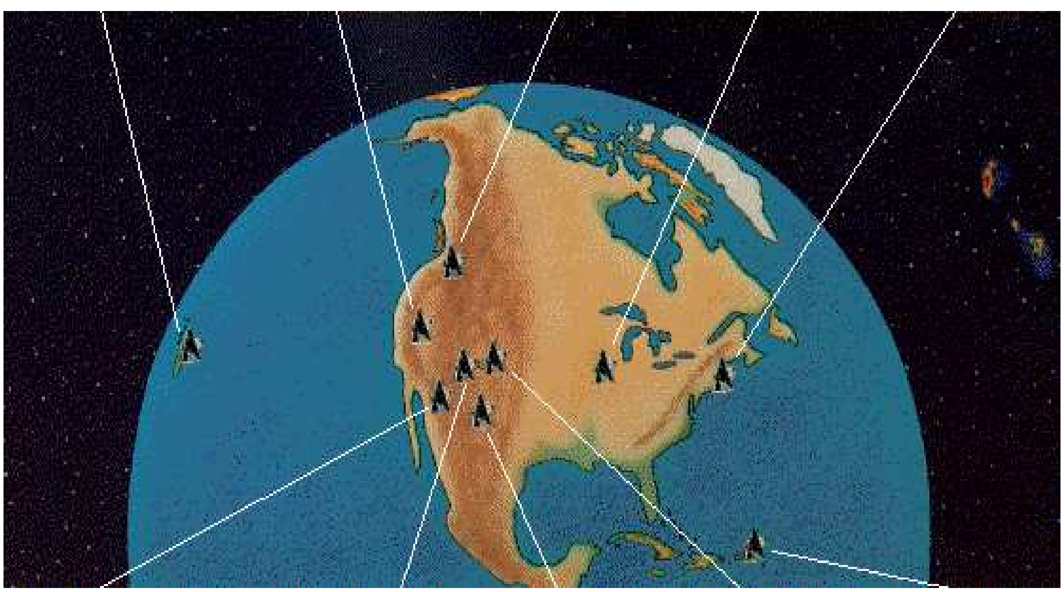
Jodrell-Very Large Array Astrometric Survey / Cosmic Lens All-Sky Survey (JVAS/CLASS)

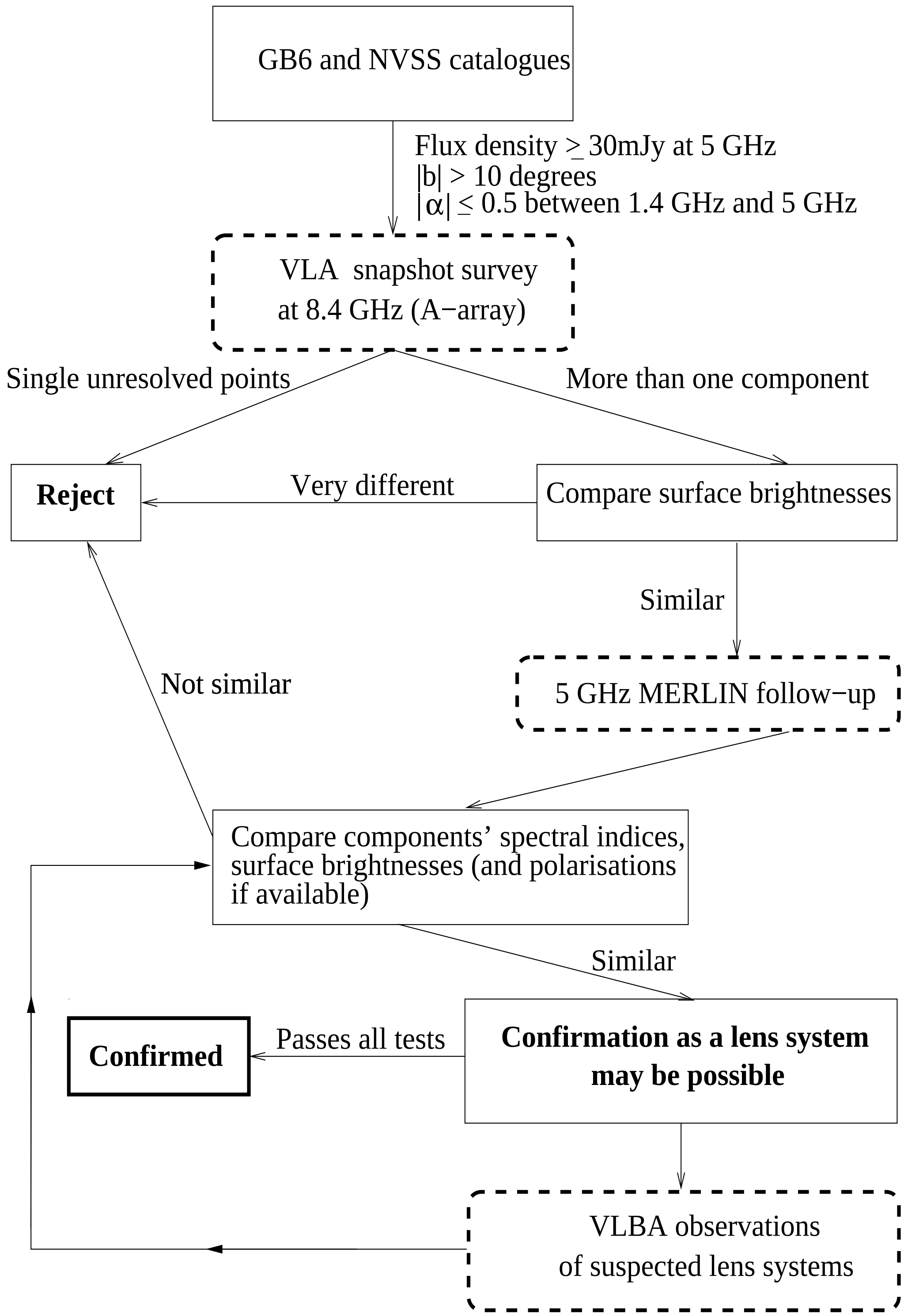
Very Large Array (VLA)

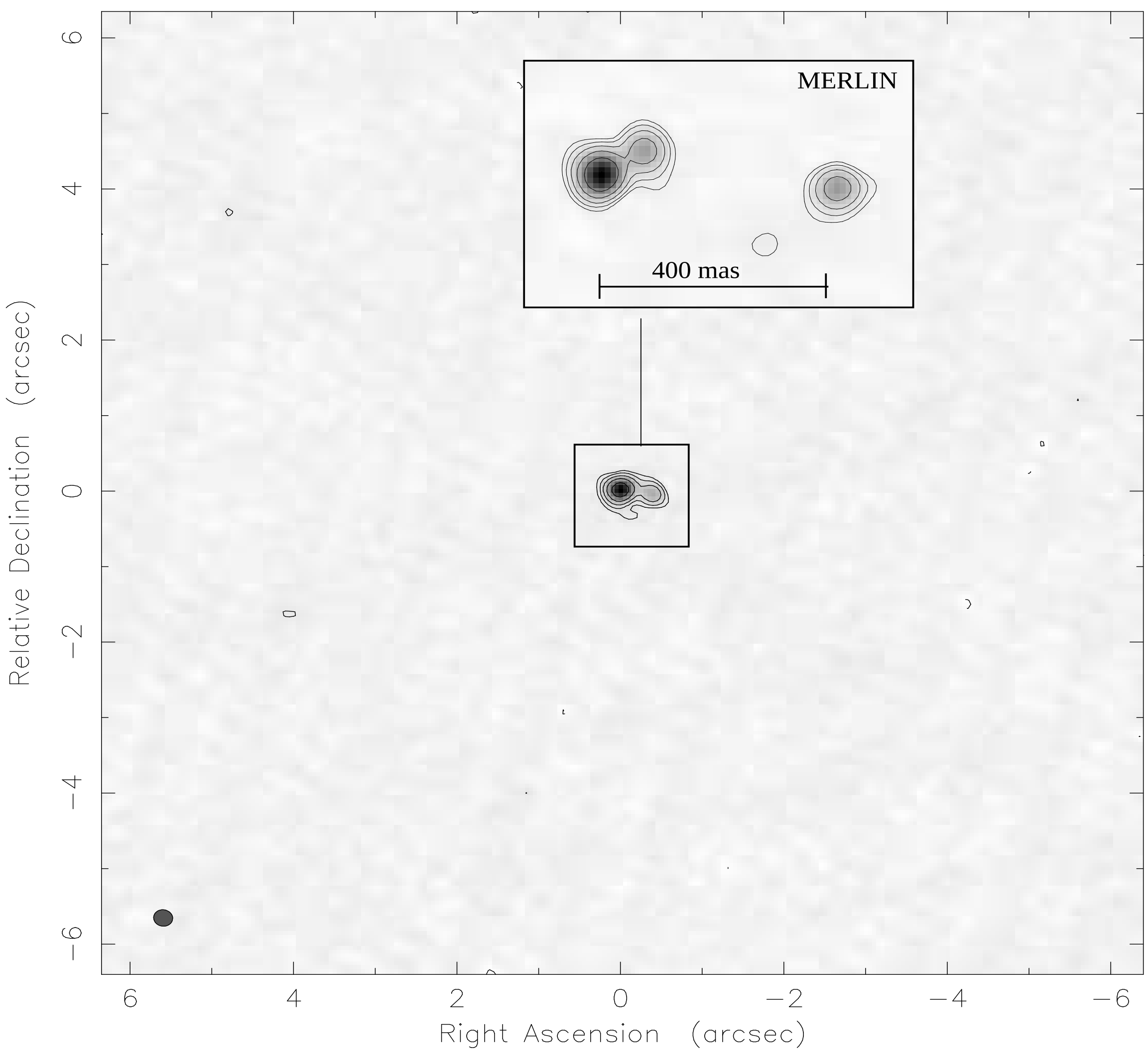
Multi-Element Radio-Linked Interferometer Network (MERLIN)



Very Long Baseline Array (VLBA)



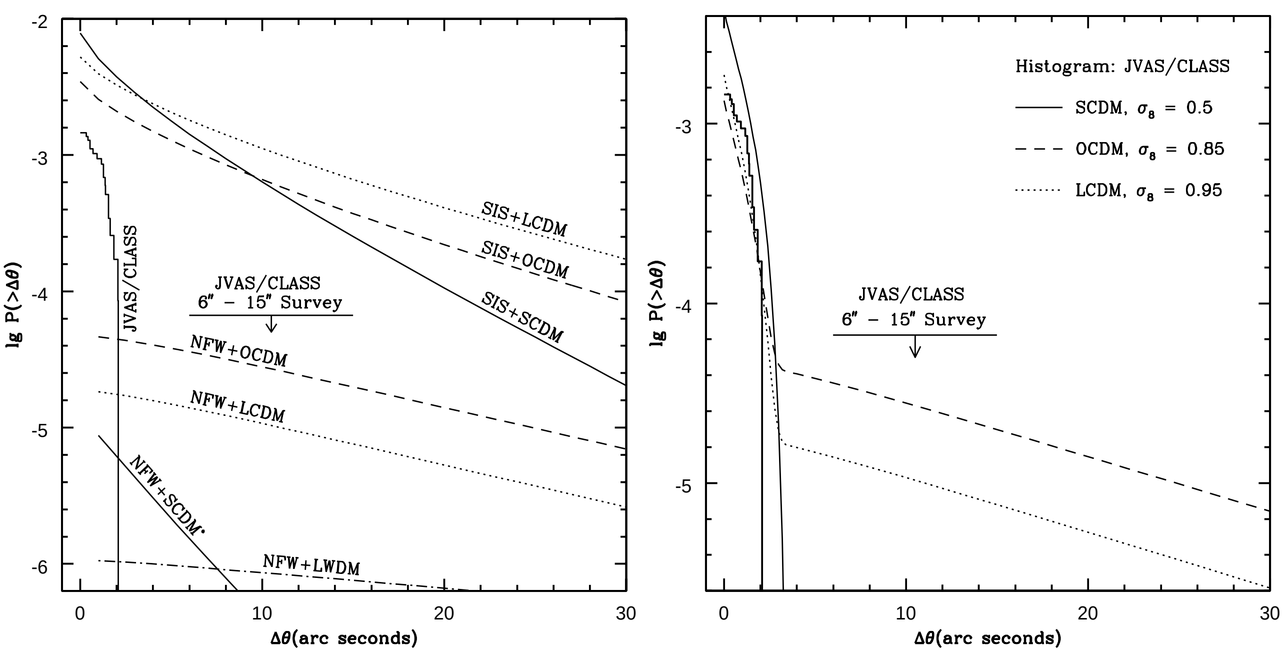

GB6 and NVSS catalogues
Flux density ≥ 30mJy at 5 GHz
|b| > 10 degrees
|α| ≤ 0.5 between 1.4 GHz and 5 GHz
VLA snapshot survey
at 8.4 GHz (A−array)
Single unresolved points
More than one component
Reject
Very different
Compare surface brightnesses
Similar
5 GHz MERLIN follow−up
Not similar
Compare components' spectral indices,
surface brightnesses (and polarisations
if available)
Similar
Confirmed
Passes all tests
Confirmation as a lens system
may be possible
VLBA observations
of suspected lens systems



MERLIN
400 mas
Relative Declination (arcsec)
Right Ascension (arcsec)
6
4
2
0
−2
−4
−6

JVAS/CLASS: some peculiar results

- All images are doubles or quads (odd image number theorem?)
- Surprisingly many spiral galaxy lenses
- No dark lenses
- No image separations larger than 3 arcsec $\Rightarrow$
  Li & Ostriker 2001: there are two populations of objects
  $M \lesssim 10^{13} M_{\odot}$ ("galaxies") with $\rho(r) \propto r^{-2}$
  $M \gtrsim 10^{13} M_{\odot}$ ("clusters") with $\rho(r) \propto r^{-1}$

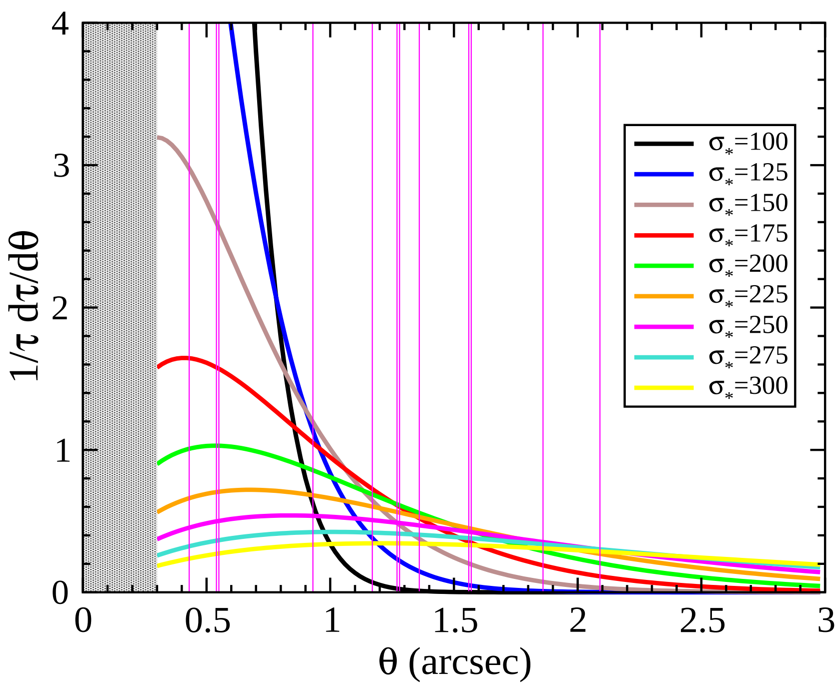


Elliptical galaxies in JVAS/CLASS

Survey	Lens	z_l	z_s	θ	Reference
JVAS/MG	J0414+054	0.96	2.64	2.09	Hewitt et al. 1992
CLASS	B0128+437	—	—	0.54	Phillips et al. 2000
CLASS	B0712+472	0.41	1.34	1.27	Jackson et al. 1998
CLASS	B0739+366	—	—	0.54	Marlow et al. 2001
JVAS	B1030+074	0.60	1.54	1.56	Xanthopoulos et al. 1998
CLASS	B1152+199	0.44	1.02	1.56	Myers et al. 1999
JVAS	B1422+231	0.34	3.62	1.28	Patnaik et al. 1992b
CLASS	B1555+375	—	—	0.43	Marlow et al. 1999
CLASS	B1933+503	0.76	—	1.17	Sykes et al. 1998
JVAS	B1938+666	0.88	—	0.93	King et al. 1997
CLASS	B2045+265	0.87	1.28	1.86	Fassnacht et al. 1999
CLASS	B2319+051	0.62	—	1.36	Rusin et al. 2001a

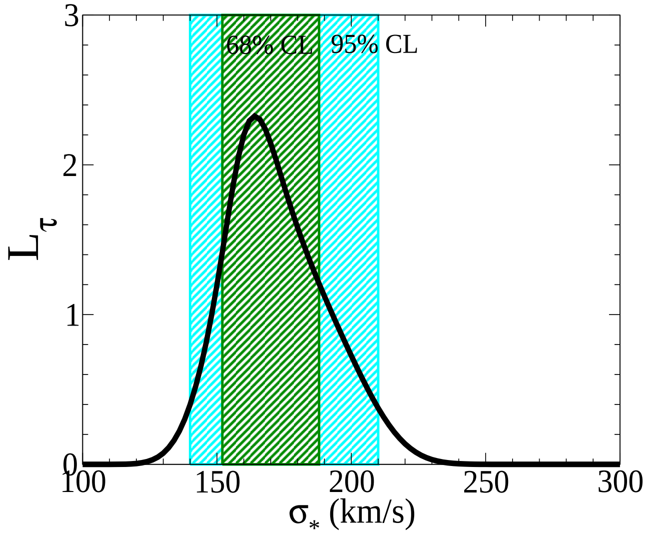
$$\tau = \int_0^{z_s} dz_l \frac{dD_l}{dz_l} (1+z_l)^3 \times \int_{L_{\rm min}}^{\infty} dL \frac{d\phi}{dL}(L)\, \sigma_{\rm SIS}(L, z_l, z_s) B(L, z_l, z_s)$$

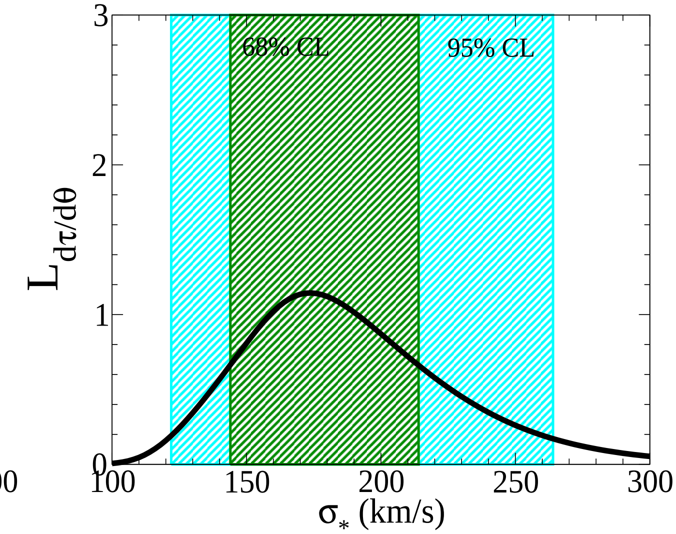
$$\rho(r) = \frac{\sigma^2}{2\pi G r^2}$$

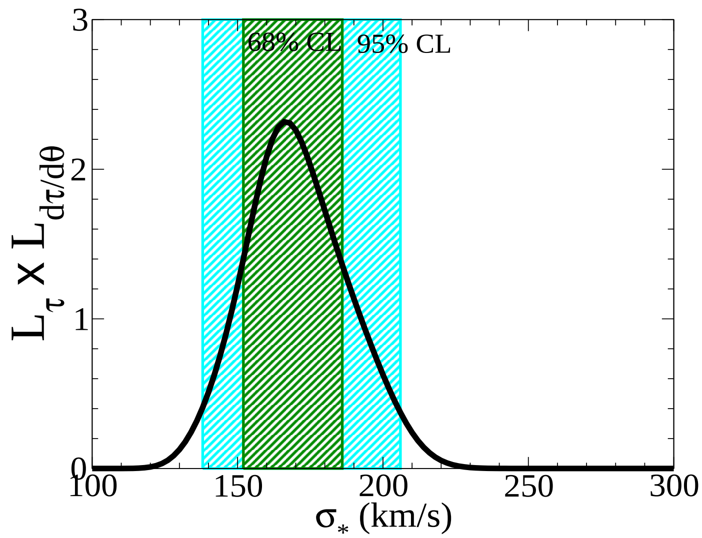


Parameters:
σ_*, γ, ϕ_*, α

Results – SIS Profile







$$138\,\mathrm{km/s} \leq \sigma_* \leq 206\,\mathrm{km/s}\ (95\%\ \mathrm{CL})$$

less than the widely used 225 km/s!

Constraining the Profile of Elliptical Galaxies

Generalized Navarro-Frenk-White profile:

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\beta}\left[1 + \left(\frac{r}{r_s}\right)\right]^{3-\beta}}$$

N-body simulations: $\beta = 1$ (NFW 1997), $\beta = 1.5$ (Moore et al. 1999)

Halo mass:

$$M \equiv M_{200} = 200\left(\frac{4\pi}{3} r_{200}^3(z)\rho_c(z)\right)$$

Halo concentration:

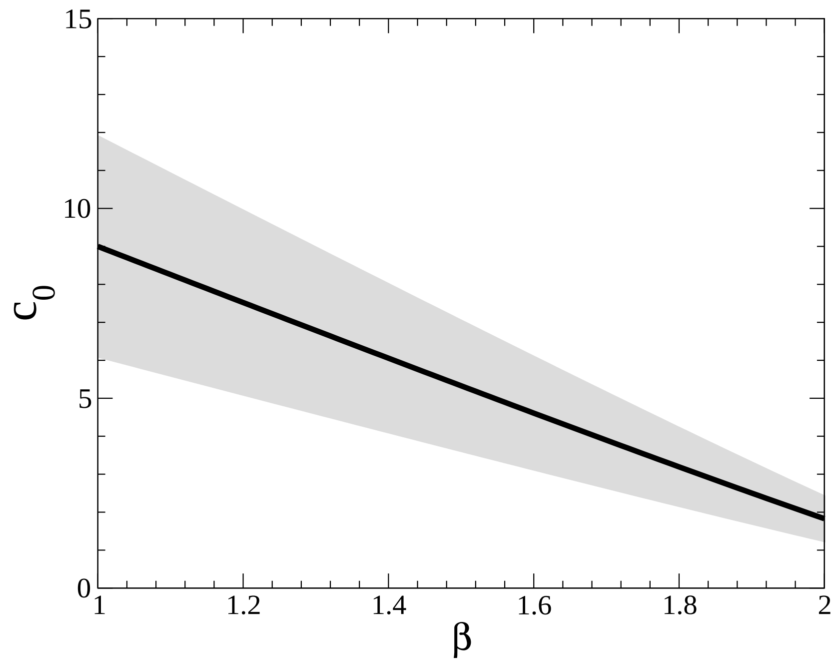
$$c(z) \equiv \frac{r_{200}(z)}{r_s(z)}$$

Given β, $c(z)$ and for a given mass M:

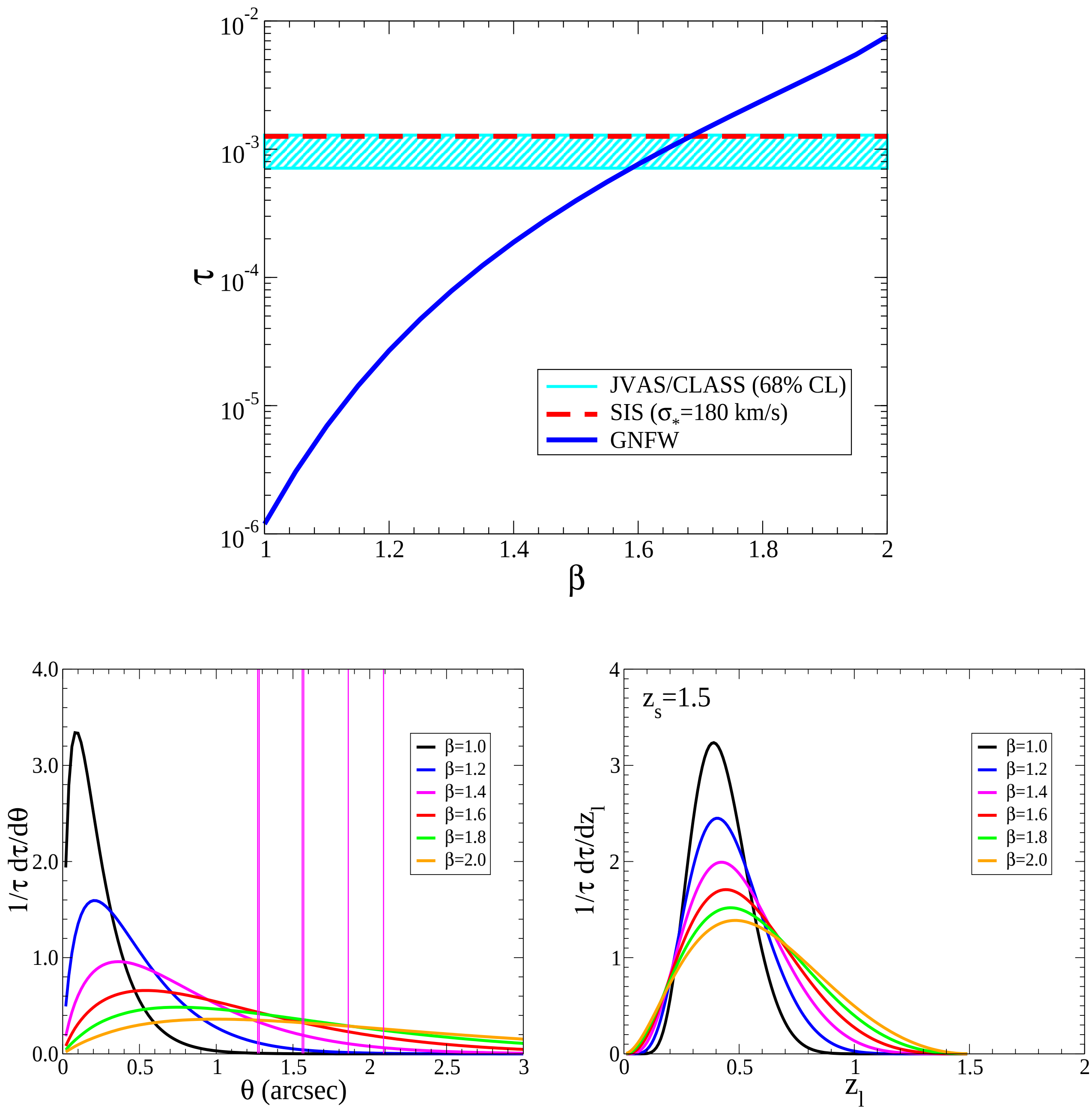
1. Compute $r_s(z)$, $\rho_s(z)$
2. Numerically solve the lens equation to get splittings, lensing cross-section
3. Numerically solve to get magnification bias

Concentrating on the concentration...

$$c(z) = \frac{c_0}{(1+z)}\left(\frac{M}{M_*}\right)^{-0.13} \qquad \text{(Bullock et al. 2001)}$$



Dependences on β



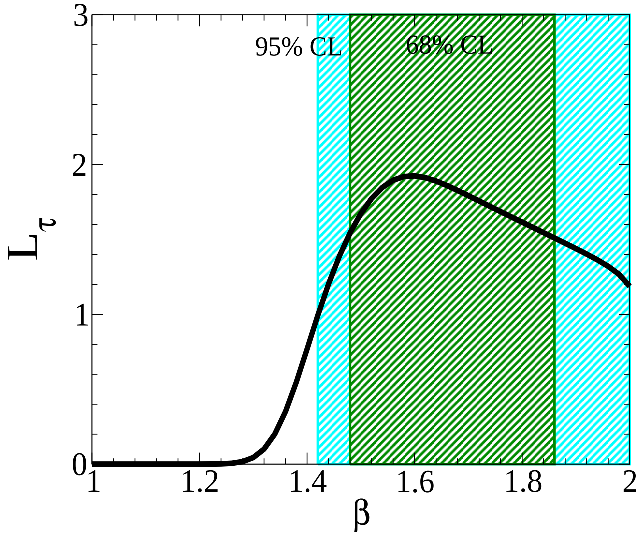
Parameter set

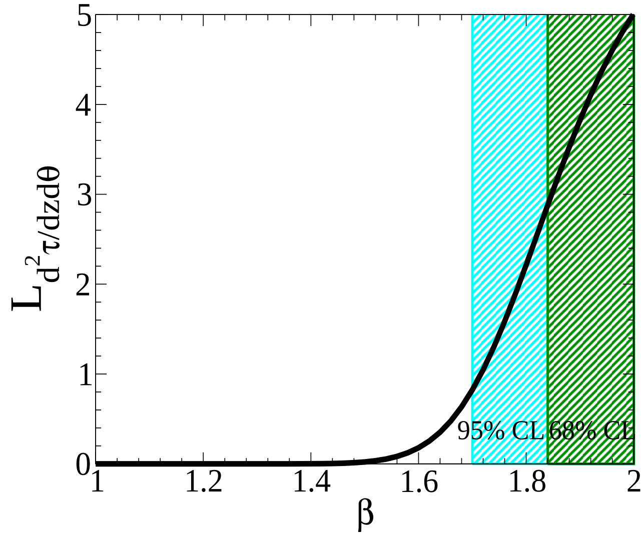
Parameter we want: β

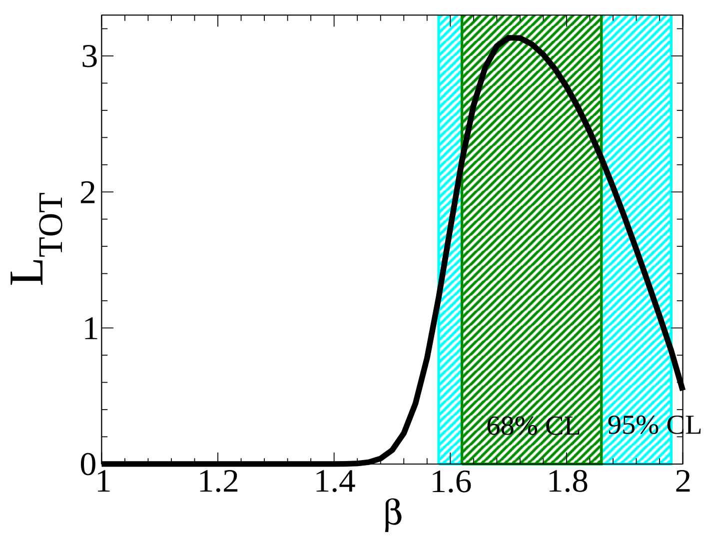
Parameters to marginalize over:

$$\begin{aligned}
\sigma_* &\in [120, 270] \text{ km/s} \\
\phi_* &\in [0.5, 1.5] \times 0.6 \times 10^{-2}\, h^3\, \text{Mpc}^{-3} \\
\gamma &\in [3.5, 4.0] \\
\alpha &\in [-1.3, -0.7]
\end{aligned}$$

Results – GNFW Profile





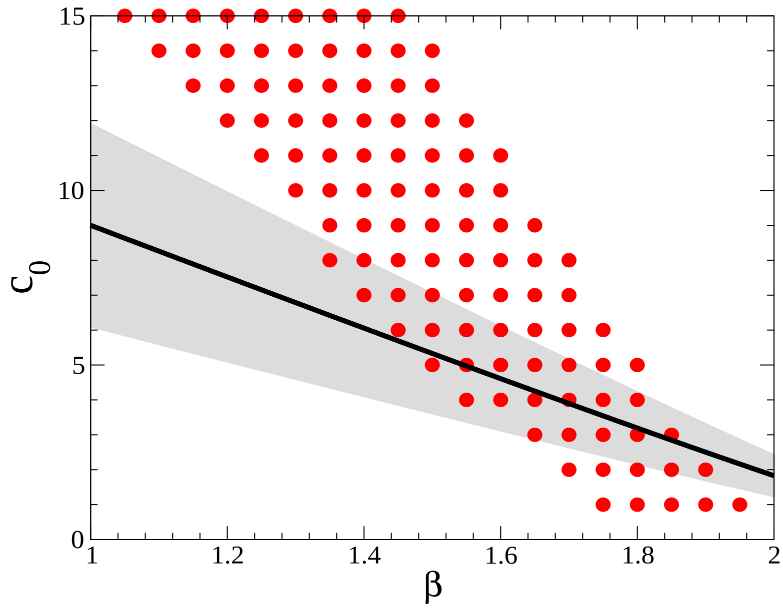


$$1.58 \leq \beta \leq 1.98 \text{ (95\% CL)}$$

$\rightarrow$ NFW profile ($\beta = 1$) strongly ruled out

GNFW Results

Let c_0 be a completely free parameter, then



Shallow NFW profiles are expected to become steeper galaxy profiles because:

1. Baryonic infall will make the profile steeper, roughly SIS
2. Massive black holes in centers of galaxies would steepen the profile
3. No detected odd images $\Rightarrow \beta \simeq 2$ (Rusin & Ma 2001)

or maybe not:

1. Direct lens modelling gives β anywhere between 1 and 2
2. Merging BHs would have the opposite effect (Meritt & Milosavljević)

Redshift evolution

The main caveat: redshift evolution of the

1. Number density of galaxies, and/or
2. Lens profile

So, we have measured the "redshift-averaged σ_*" (and β)

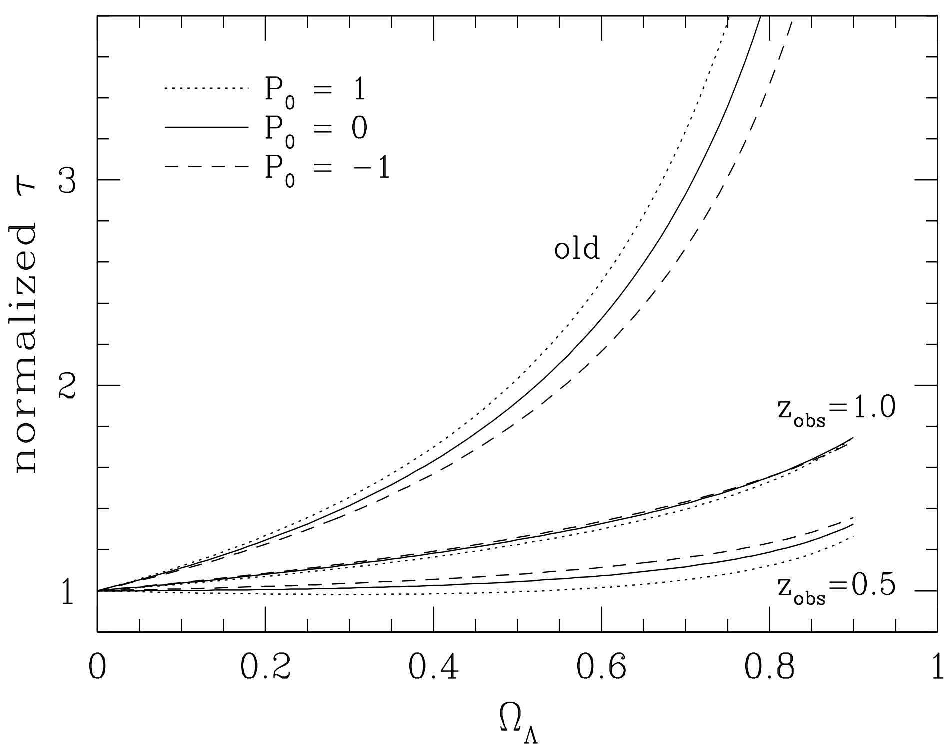
Redshift evolution

Assume e.g.

$$\phi_*(z) = \phi_*(0)10^{0.4Pz}$$

Keeton (2001): why not **normalize** lensing statistics to the number counts of galaxies at some z?

- Old way: fixed, "known" $\phi_*(z)$
- New way: variable $\phi_*(z)$ so as to reproduce $N_{\rm gal}(z) = \phi_*(z) \times {\rm Volume}\,(\Omega_M, \Omega_\Lambda)$



But: σ_* will also be z-dependent, may cancel the effect of $\phi_*(z)$.

Conclusions

- CDM may have some problems on small scales / central galaxy profiles
- Strong (and weak) lensing are ideal tools to test/constrain CDM
- Strong lensing best used to probe lens (galaxy, halo) parameters, and not cosmology
- In fact, cosmological constraints due to strong lensing cannot be trusted
- No lenses at $\theta > 3''$ $\Longrightarrow$ two populations of galaxies:
  SIS "galaxies" and NFW "clusters"
- Our analysis: $\sigma_* \approx 180\,\mathrm{km/s}$, $\beta \approx 1.6\text{-}2.0$ for ellipticals
- More lenses needed!