GAS β PROBLEM IN GALAXY CLUSTERS

(see e.g. Schneider)

GAS ↓ hydrostatic eq.

ICM

$$\frac{d\phi}{dr} = -\frac{1}{\rho}\frac{dP}{dr}$$

M → TOTAL MASS within RADIUS r

$$\frac{d\phi}{dr} = \frac{GM(r)}{r^2} = -\frac{1}{\rho_{gas}}\frac{d\rho_{gas}}{dr} = -\frac{1}{\rho_{gas}}\frac{d}{dr}\left(\rho_{gas}\frac{KT}{\mu m_p}\right)$$

$m_p \equiv$ proton mass $\quad \mu =$ mean molecular weight ~ 0.6 (0.58?)

$$\frac{GM(r)}{r^2} = -\frac{1}{\rho_{gas}}\frac{K}{\mu m_p}\left(\rho_{gas}\frac{dT}{dr} + \frac{T\, d\rho_{gas}}{dr}\right)$$

$$M(r) = -\frac{KT}{\mu m_p}\cdot r\left[\frac{d\ln\rho}{d\ln r} + \frac{d\ln T}{d\ln r}\right]$$

TO FIT THE GAS DISTRIBUTION, THE β model is used (CAVALIERE & FUSCO-FEMIANO 1976)

$$\rho_{gas}(r) = \rho_{0\,gas}\left(1 + \left(\frac{r}{r_{0\,gas}}\right)^2\right)^{-3/2\,\beta_{fit,gas}}$$

in 2-D

$$\Sigma_{gas}(R) = \Sigma_{0\,gas}\left(1 + \left(\frac{R}{r_{0\,gas}}\right)^2\right)^{-\frac{3}{2}\beta_{fit\,gas}+\frac{1}{2}}$$

typically $\beta_{fit,gas} = \frac{2}{3}$

emissivity X $\propto \rho^2$ ⇒ surface brightness

then projected

$$S_X = S_{0X}\left(1 + \left(\frac{R}{r_{0X}}\right)^2\right)^{-3\beta_{fit\,gas}+\frac{1}{2}}$$

$$\rho_{gas} \xrightarrow[r\to\infty]{} r^{-2} \qquad \Sigma_{gas} \xrightarrow[R\to\infty]{} R^{-1}$$

GALAXIES

TO FIT GALAXY DISTRIBUTION

$$\rho(r) = \rho_0 \left(1+\left(\frac{r}{r_0}\right)^2\right)^{-3/2\,\beta_{fit,gal}}$$

2D

$$\Sigma(R) = \Sigma_0 \left(1+\left(\frac{R}{R_0}\right)^2\right)^{-\frac{3}{2}\beta_{fit,gal}+\frac{1}{2}}$$

observation historically

$\beta_{fit,gal} = 1$

$\rho(r) \xrightarrow[r\to\infty]{} r^{-3}$

$\Sigma(R) \xrightarrow[R\to\infty]{} R^{-2}$

King model

(also called law of modified Hubble)

Jeans equation (Binney and Tremaine)

$$M(r) = -\frac{\sigma_r^2\, r}{G}\left[\frac{d\ln\rho_{gal}}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

σ_r = radial component of velocity dispersion

σ_θ = tangential component

$$\beta(r) \equiv 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$$

velocity anisotropy parameter

$$\underbrace{\sigma_r = \sigma_\theta \Rightarrow \beta = \emptyset}_{\text{isotropic orbits}}$$

Now $M(r) = M(r)$ as determined using ICM or galaxies

ASSUMPTION OF ISOTHERMALITY

T indep. of r, σ_r indep. of r

$$-\frac{KT}{\mu m_p}\frac{d\ln\rho_{gas}}{dr} = -\sigma_r^2\frac{d\ln\rho_{gal}}{dr} - \frac{2\beta\sigma_r^2}{r}$$

(1) from images

$$\frac{\dfrac{d\ln\rho_{gas}}{dr}}{\dfrac{d\ln\rho_{gal}}{dr} + 2\dfrac{\beta}{r}} = \frac{\sigma_r^2}{\dfrac{KT}{\mu m_p}}$$

(2) from spectra

spectral β

$$\beta_{spec} \equiv \frac{\sigma_{LOS}^2}{\dfrac{KT}{\mu m_p}}$$

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line of sight

$$\beta_{spec} = \frac{\sigma^2_{LOS}}{\frac{KT}{\mu m_p}}$$

over global measure (whole cluster!)

$$\sigma^2_{LOS} = (\sqrt{3})^2 \sigma^2_{TOT} = \sigma_z^2$$

* the ratio of energy x unit mass between galaxies and gas

(in fact, for gas particle $\frac{1}{2} m v^2 = \frac{3}{2} KT$ Theorem of equipartition

$$V^2_{1D} = \cancel{3}\frac{KT}{m} = \cancel{3}\frac{KT}{\mu m_p}$$)

For the part 1, assume to compute it at large radii (whole cluster!)

e.g.

$$\rho = \left(1 + \left(\frac{r}{r_0}\right)^2\right)^{-3/2 \beta_{fit}} \longrightarrow$$

$$\frac{d \ln \rho}{dr} = \frac{\left(-\frac{3}{2}\beta_{fit}\right)\left(1+\left(\frac{r}{r_0}\right)^2\right)^{-\frac{3}{2}\beta_{fit}-1} \cdot 2r}{\left(1+\left(\frac{r}{r_0}\right)^2\right)^{-3/2 \beta_{fit}}} =$$

$$= \frac{\left(-\frac{3}{2}\beta_{fit}\right)\cancel{\left(\quad\right)^{-3/2 \beta_{fit}}} \cdot \left(\quad\right)^{-1} \cdot 2r}{\cancel{\left(\quad\right)^{-3/2 \beta_{fit}}}} =$$

$$= -3\beta_{fit}\left(1+\left(\frac{r}{r_0}\right)^2\right)^{-1} \xrightarrow[r\to\infty]{} \frac{-3\beta_{fit}}{r^2}$$

$$\beta_{spec} = \frac{-3\beta_{fit, gas} \cdot \frac{1}{2}}{-3\beta_{fit, gal} \cdot \frac{1}{2} + \frac{2\beta}{2}}$$

ASSUMPTION β anisotropy $= \emptyset$

$$\beta_{spec} = \frac{+\beta_{fit\,gas}}{\beta_{fit\,gal}}$$

Historically from observations:

$\beta_{fit,gas} = \frac{2}{3}$ $\beta_{fit\,gal} = 1$

$\beta_{spec} > 1$

$\Longrightarrow$ $> 1 = < 1$

β problem!

with better data in '80 years

$\beta_{fit\,gal} \sim 0.8$ $\beta_{spec} \lesssim 1$ — ~ 1 for clusters; < 1 for groups

$$\boxed{\lesssim 1 = 0.8}$$

OK!

before, external cluster regions too poorly sampled

before too small data sample
No good member selection in clusters

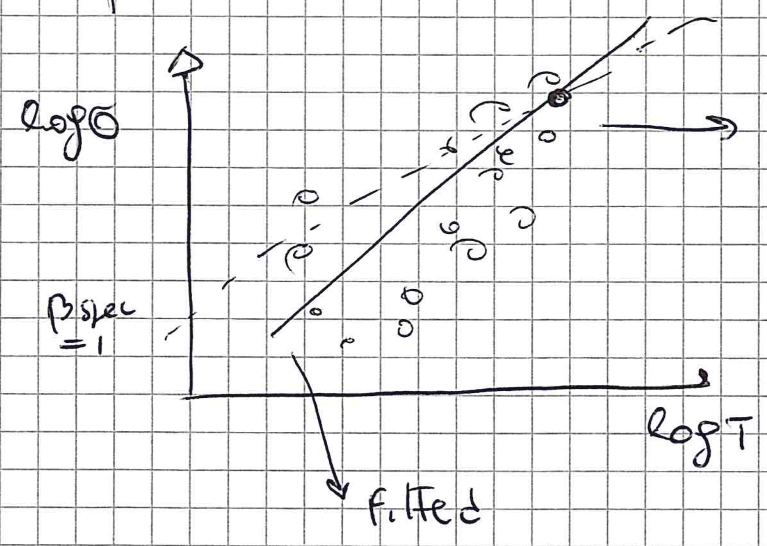
β problem 2 (still present)

from theory of violent relaxation
(gas + gals both form cluster
Together at the ~~same~~ Time)
COMMON INFALL
Lynden-Bell 1967 $\rightarrow$ $\beta_{spec} = 1$

that is energy x unit mass equipartition

Instead if gas ~~[illegible]~~ infalls when
potential is already formed
$\frac{3}{2}\frac{kT}{\mu m_p} \sim -\phi \qquad \phi \sim -9\,\sigma_{LOS}^2$
(SARAZIN 1986)
$\rightarrow \beta_{spec} << 1$

$\beta_{spec} = 1$ is expected but ...



$\rightarrow$ OK for clusters

NO for groups
$\sigma_v^2 < \frac{kT}{\mu m_p}$

WHY ?

1) dynamical friction is more important in groups $\Rightarrow$ galaxies are slowed down in groups

2) ICM is heated by AGN
$T_{AGN} << T_{cluster}$ ICM but
$T_{AGN} \sim T_{GROUP}$ ICM

3) problems of member selection in group? poor numbers? difficulty in estimate of σ_v ?

to date, β problem 2 is not solved!

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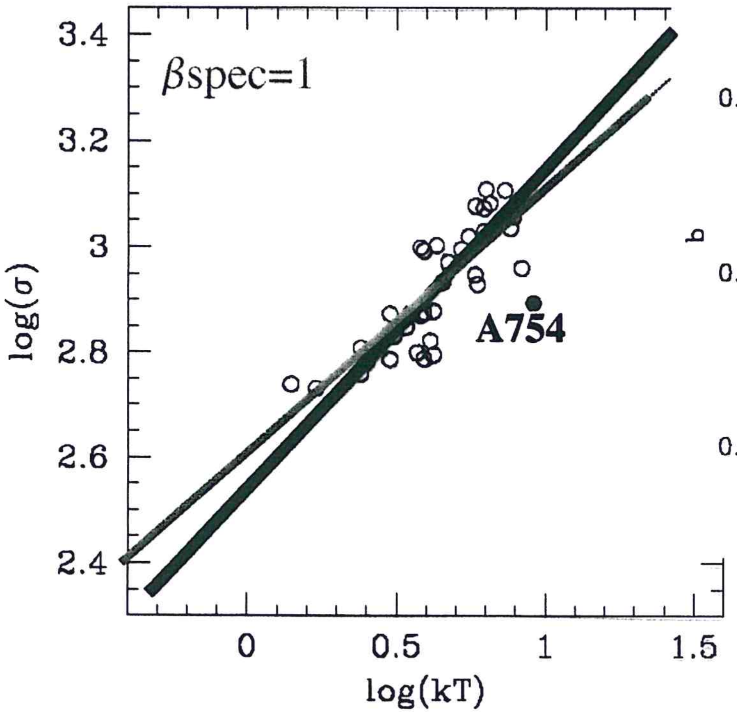
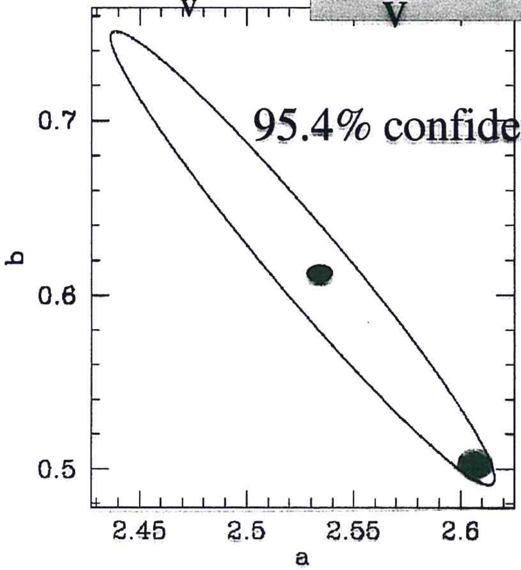
Velocity Dispersion and X–ray Temperature

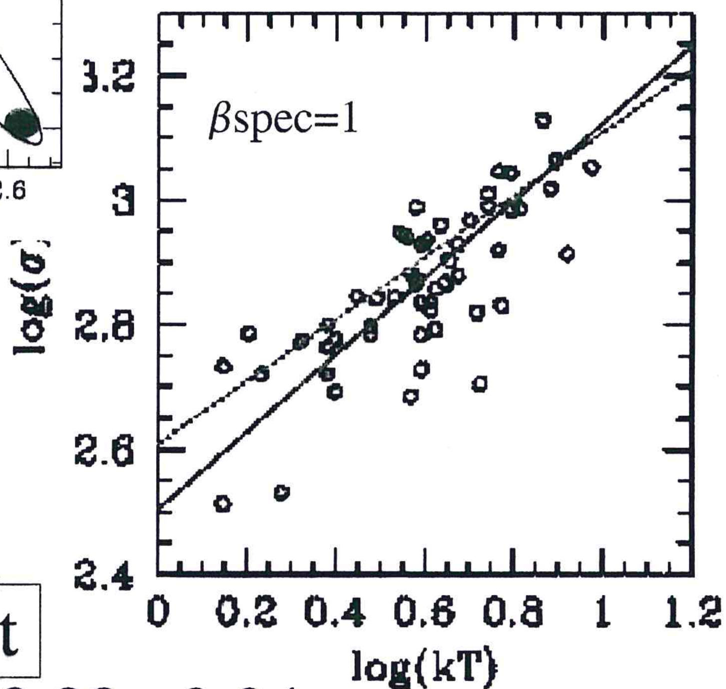
(with Fadda, Giuricin, Mardirossian, Mezzetti, Biviano 1996, ApJ 457, 61).
T_X from David et al. (1993).
37 nearby clusters with reliable σ_v:

$$\sigma_v = 10^{2.53\pm0.04} \times T_X^{\,0.61\pm0.05}$$





$\sigma_v = 10^{2.51\pm0.03} \times kT^{0.62\pm0.04}$



(coll. with Giuricin, Mardirossian, Mezzetti, and Boschin 2000, ApJ 505, 74; 55 clusters)

No longer consistent model of perfect gals/ICM energy equipartition! $\beta_{spec} = 0.88\pm0.04$