Measuring Gravitational Redshifts in Galaxy Clusters (arxiv:1303:3663)

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Ripples in the Cosmos
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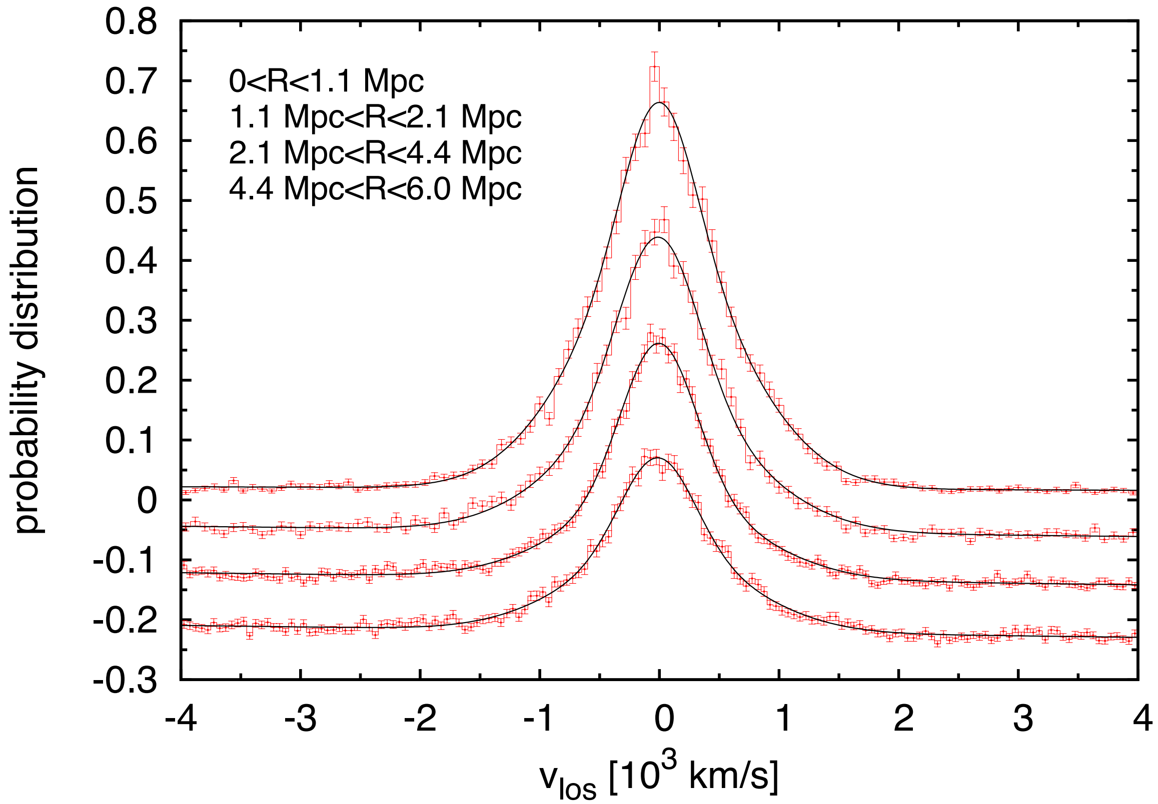
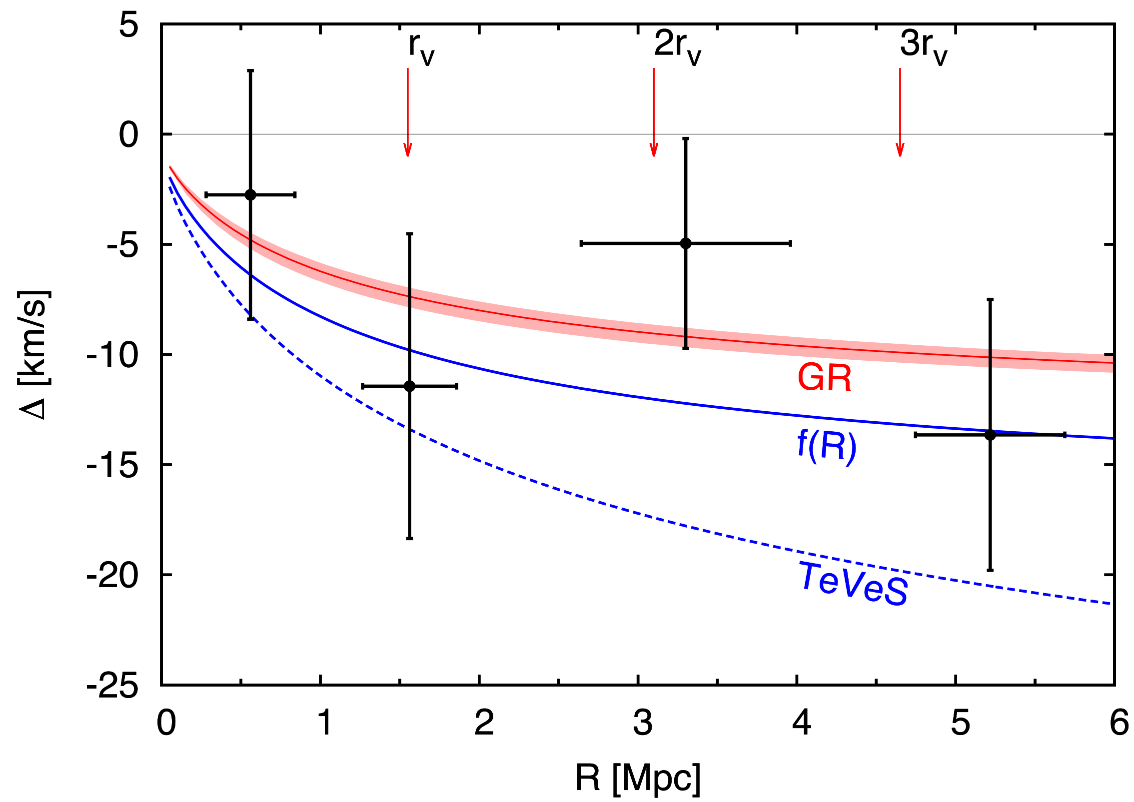
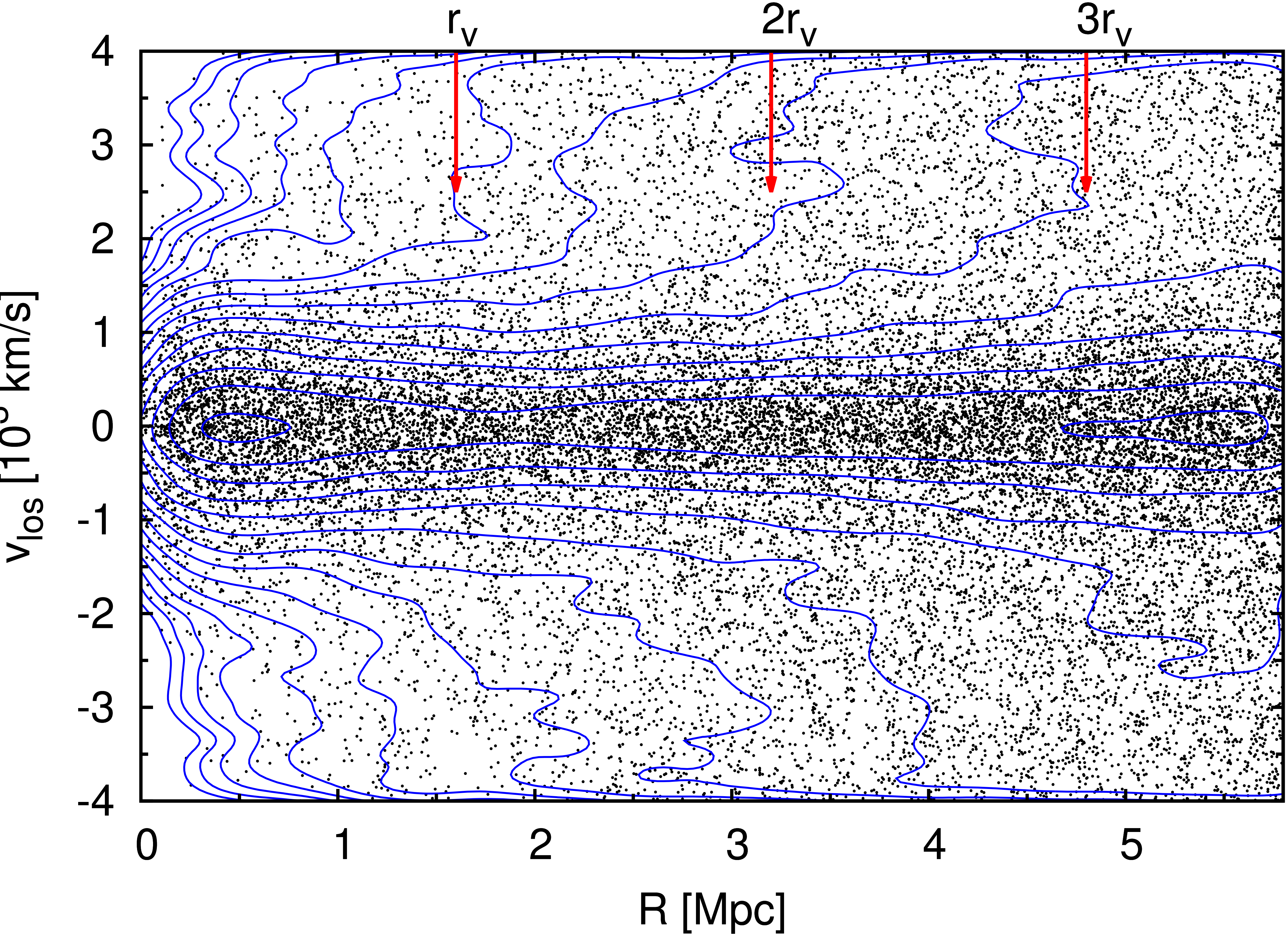
Wojtak, Hansen & Hjorth, Nature 2011

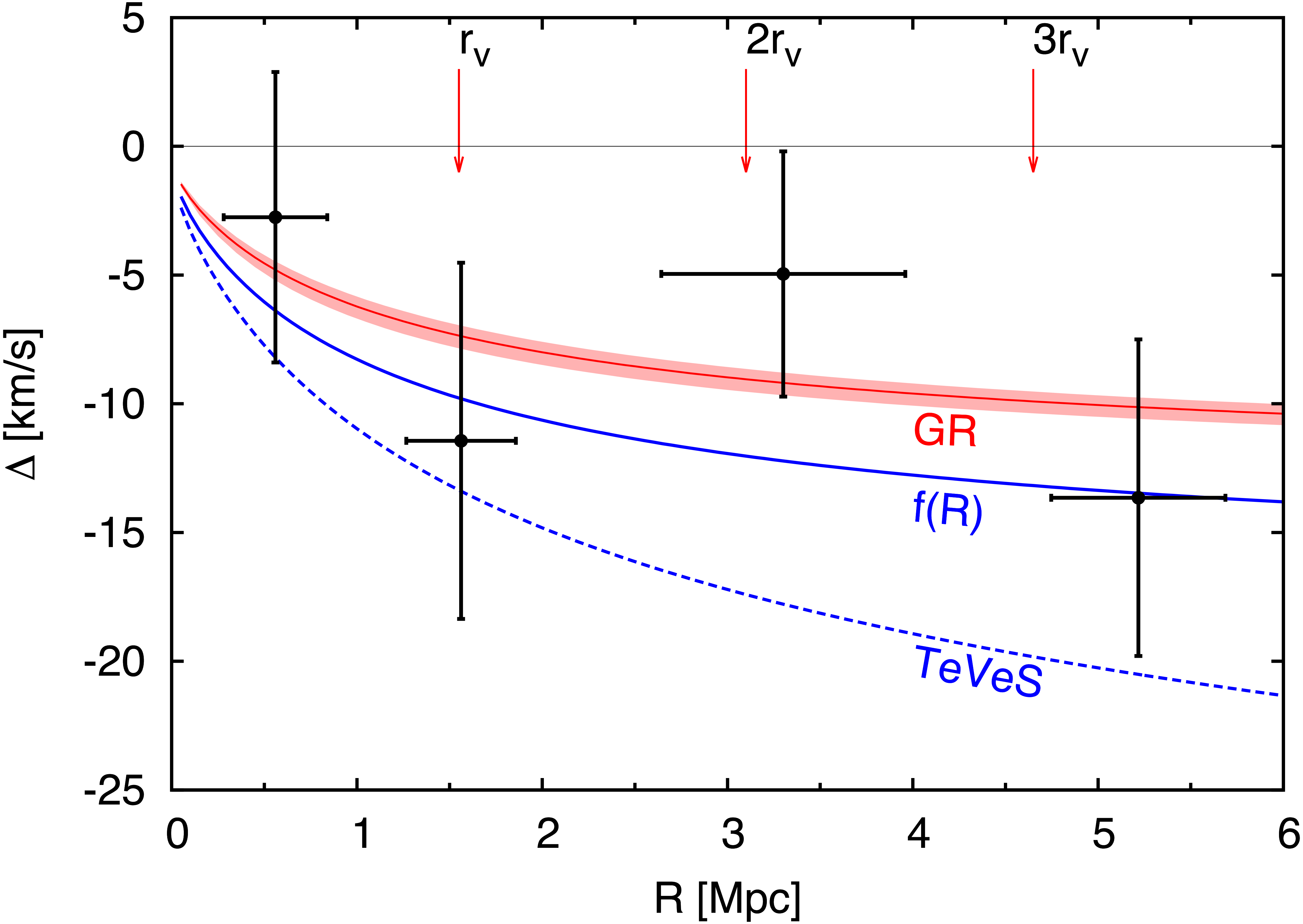
- Wojtek, Hansen & Hjorth stacked 7,800 galaxy clusters from SDSS DR7 in redshift space
  - centre defined by the brightest cluster galaxy
  - approx 10 redshifts per cluster
- They found a net offset (blue-shift) corresponding to v = -10 km/s
  - c.f. ~600km/s l.o.s velocity dispersion
- Interpreted as gravitational redshift effect
  - right order of magnitude, sign
- “Confirms GR, rules out TeVeS”
- Had been discussed before (Cappi, Broadhurst+Scannapiaco, ...)
- related to conventional “RSD”...







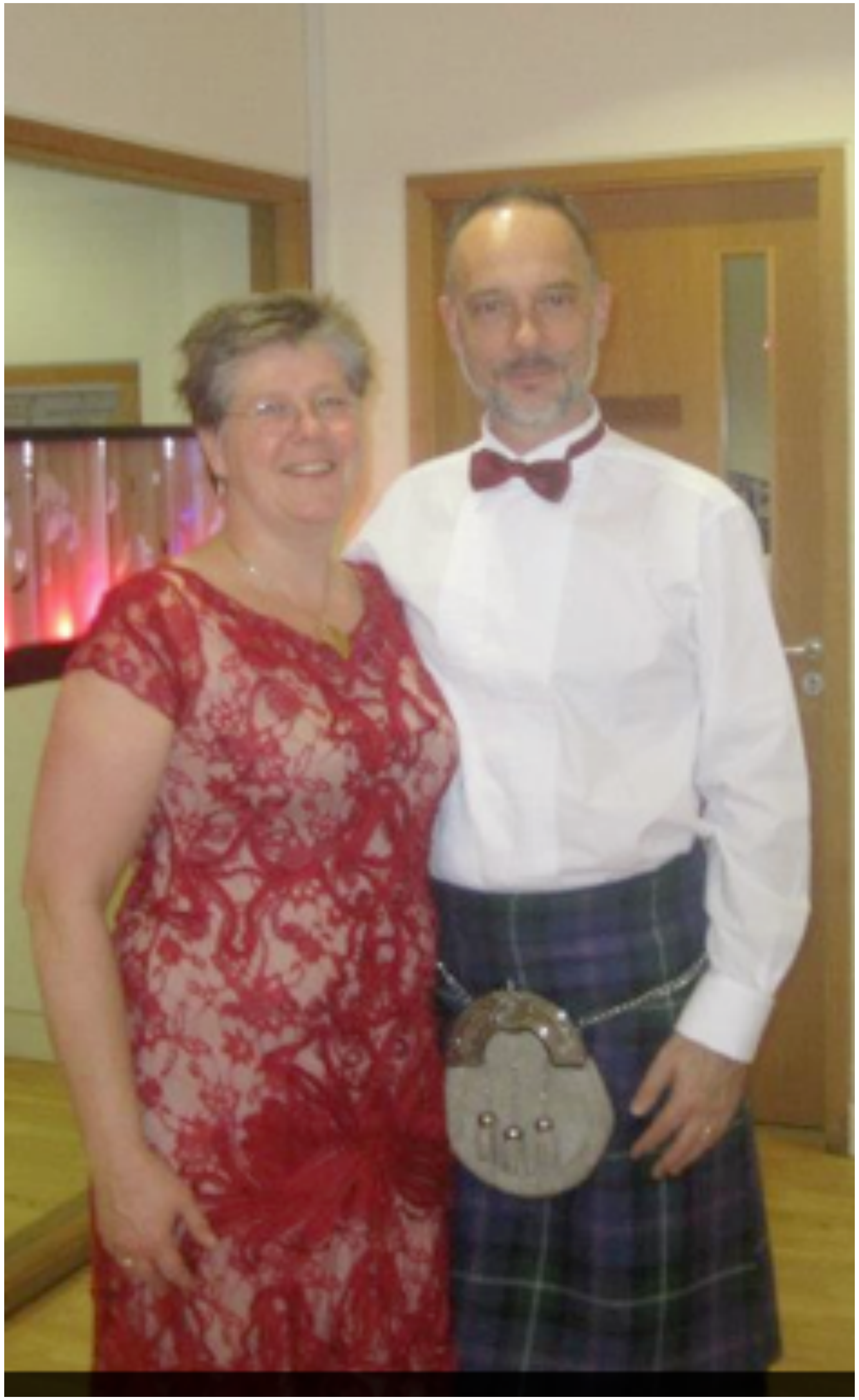
r_v
2r_v
3r_v
4
3
2
1
0
-1
-2
-3
-4
v_los [10^3 km/s]
0
1
2
3
4
5
R [Mpc]



5
0
-5
-10
-15
-20
-25
0
1
2
3
4
5
6
r_v
$2r_v$
$3r_v$
Δ [km/s]
R [Mpc]
GR
f(R)
TeVeS

Zhao, Peacock & Li, 2012

- delta-z is not just gravitational redshift
- Sources are <u>moving</u>, so we also see
  - *transverse Doppler effect:*
    - 1st order Doppler effect averages to zero, but....
    - to 2nd order <delta-z> ~= <v^2/c^2>/2
    - can be understood as time dilation
- Generally of same order of magnitude as gravitational redshift
  - from virial theorem, Jeans eq...
- And it doesn't really test GR
  - see also Bekenstein & Sanders, 2012
  - more later.....

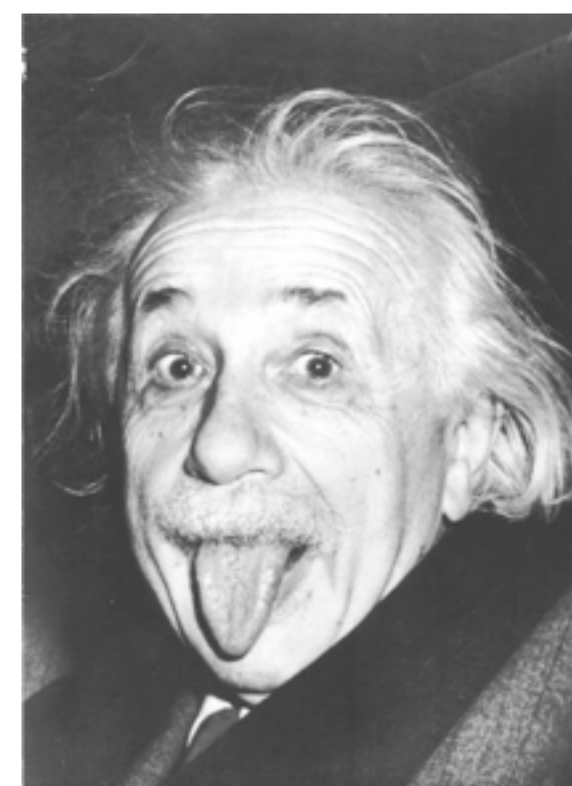


Why should see a gravitational redshift anyway?

- Einstein's invented GR by elevating Galileo's *observation* that all things fall in the same way under gravity to a *principle*
- Principle of Equivalence: space-time is *locally flat.*
  - *gravity vanishes for freely falling observers*
  - *gravitational redshifts* are only seen by non-inertial observers
    - (like Pound and Rebka (1960))
  - e.g. cosmological redshift: purely Doppler, no grav-z
    - more correctly a sequence of small Doppler shifts
- But galaxies seen by SDSS (and Earth!) are also in free fall - so should there be a gravitational redshift? (answer: yes)
  - Best to calculate with fictitious non-inertial observers on some kind of rigid lattice.
  - Use local Doppler shifts to go from galaxy to grid and from grid to observer and so on...

Equivalence principle & gravitational redshift

$$\left(\frac{\Delta E}{E}\right)_{down} - \left(\frac{\Delta E}{E}\right)_{up} = (5.1 \pm 0.5)x10^{-15}$$



- Einstein: Equivalence means that observers being accelerated by the stress in the ground under them imparting momentum to them will see light being Doppler shifted exactly as would a pair of astronauts in empty space being accelerated by a rocket.
- Pound and Rebka (1960): He was right.

But that way of thinking leads one to....

- Light cone effect
  - we will naturally tend to see more objects moving away from us than towards us in any observation made using light as a messenger
  - this gives an extra red-shift effect
  - again of the same order of magnitude as the gravitational redshift

Light-cone effect

- Light cone effect
  - we will see more galaxies moving away from us
    - past light cone of event of our observation overtakes more galaxies moving away than coming towards us
  - phase space density contains a factor $(1-v/c)$
  - $\langle \text{delta-}z \rangle = \langle (v_{los}/c)^2 \rangle$
  - same sign as TD effect
    - 2/3 magnitude (isotropic orbits)

Another way to look at LC effect

- Particle oscillating in a pig-trough
  - r(t) = a cos(wt + phi)
  - v(t)/c = -(aw/c) sin(wt + phi)
  - v(t) averages to zero
    - average could be over phase or time
- but v_{obs} = v + (x/c) dv/dt + ...
  - where x/c is the look-back time
  - and the extra term does *not* average to zero
- ~ same as Einstein prediction for Pound & Rebka
  - i.e. Doppler effect with delta-z = g x / c.

But wait! There's something fishy here...

- Why is the transverse Doppler effect a *red*-shift?
  - Take a birthday cake; light the candles and put it on a turntable and spin it.
  - Detect all the photons and measure their frequency
  - Compare with non-rotating experiment.
- Shouldn't we see *blue*-shift f_obs = gamma * f_em?
- Or what if we have a swarm of moving astrophysical sources destroying rest mass and turning it into light and we catch all the photons and measure their energy.
  - Do we see a red-shift? If so, how is can that be compatible with energy conservation?
    - This is SR, so unlike in cosmology, energy *is* supposed to be conserved

Unresolved sources composed of moving sources have a transverse Doppler *blue*-shift

- A single object will appear red-shifted (on average)
- A swarm of objects will have an additional red-shift from their motions (light-cone effect)
- But photons from a body composed of moving sources must, on average, be blue-shifted
  - if not, energy conservation would be violated
- The apparent contradiction is resolved once you appreciate that a source that radiates isotropically in its rest frame is not isotropic in the observer (or lab) frame
- Relativistic beaming:
  - slightly more photons emerge in the forward direction
  - and these pick up a 1st order Doppler blue-shift
  - which leads to a 4th effect:

Surface brightness modulation

- Line of sight velocity changes surface brightness
  - relativistic beaming (aberration)
  - plus change of frequency
- velocities modulate luminosity
  - effect depends on SED: delta-L/L = (3 + alpha)v/c ~= $5v_{los}/c$
- spectroscopic sample is flux limited at r=17.8
  - delta-n/n = - d ln n(>L_{lim}(Z))/d ln L * delta-L/L
- opposite sign to LC, TD effects, but much larger
  - because sample is limited to bright end of the LF

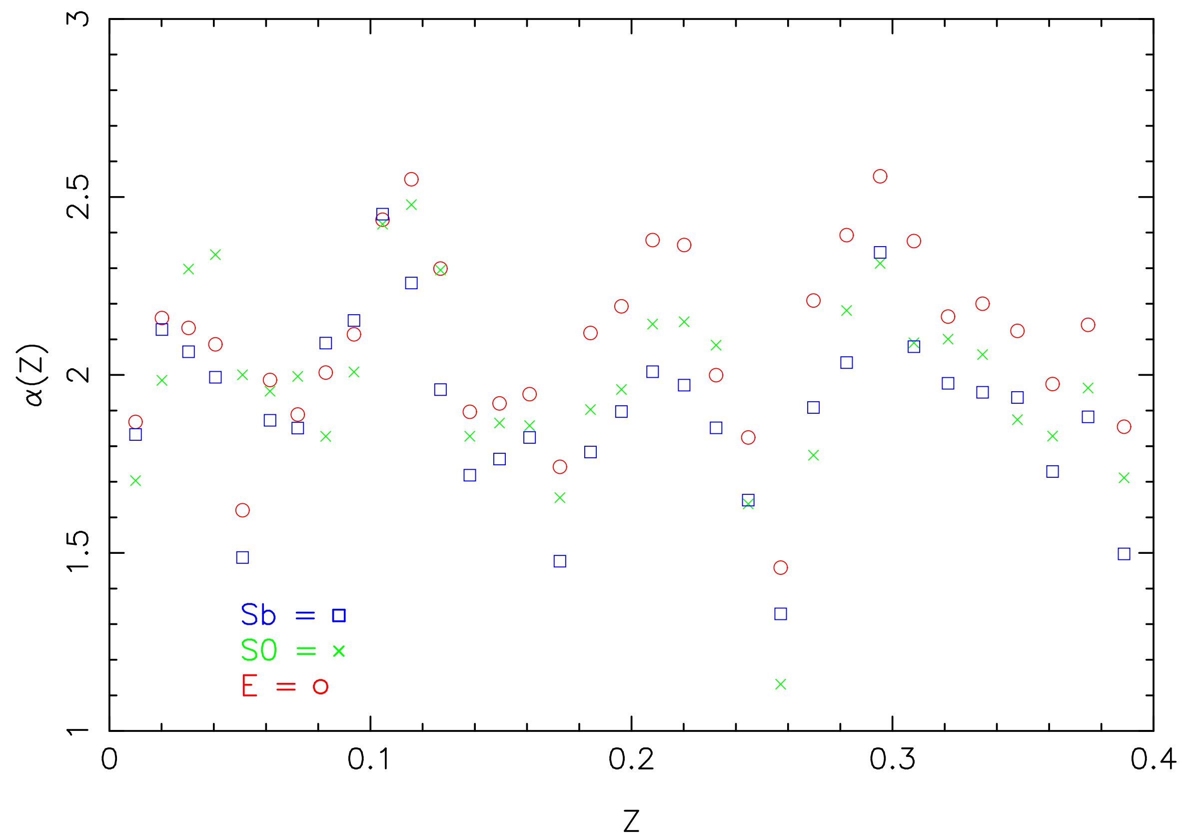
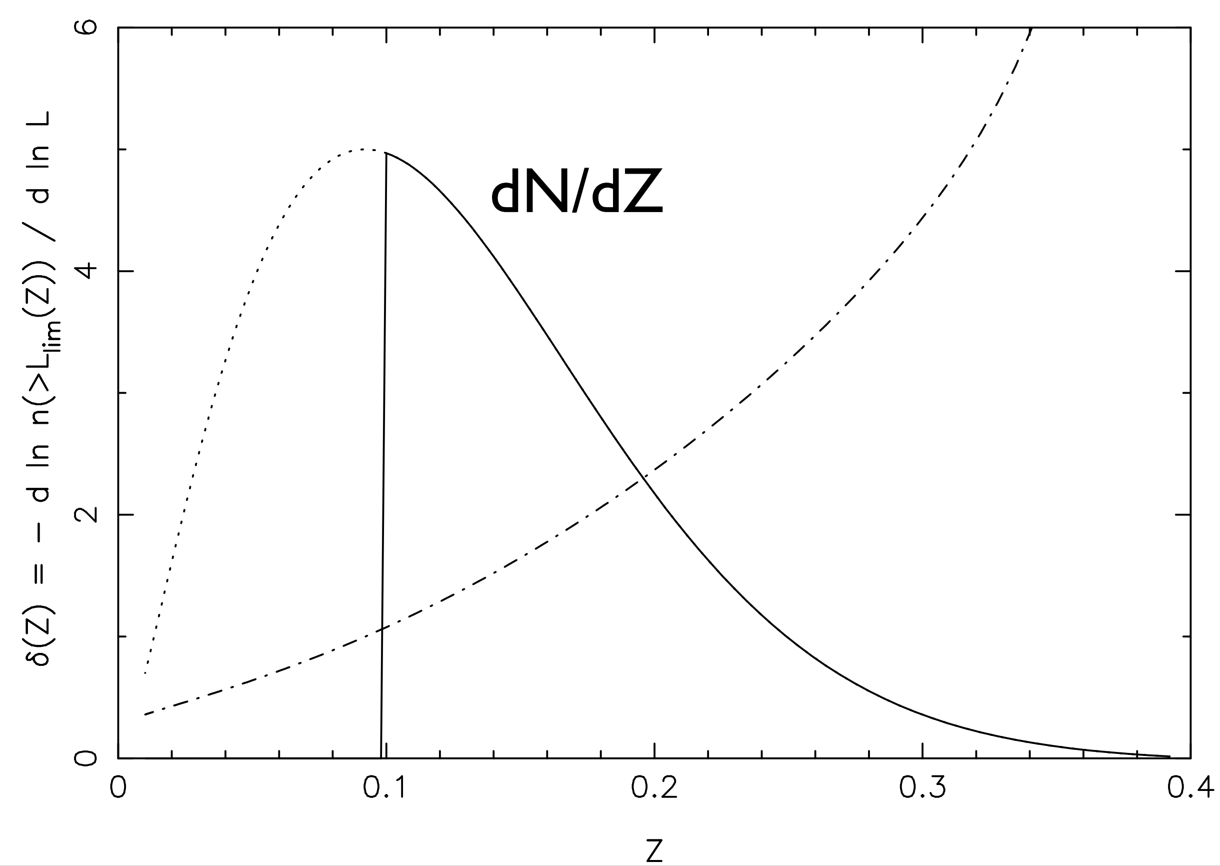
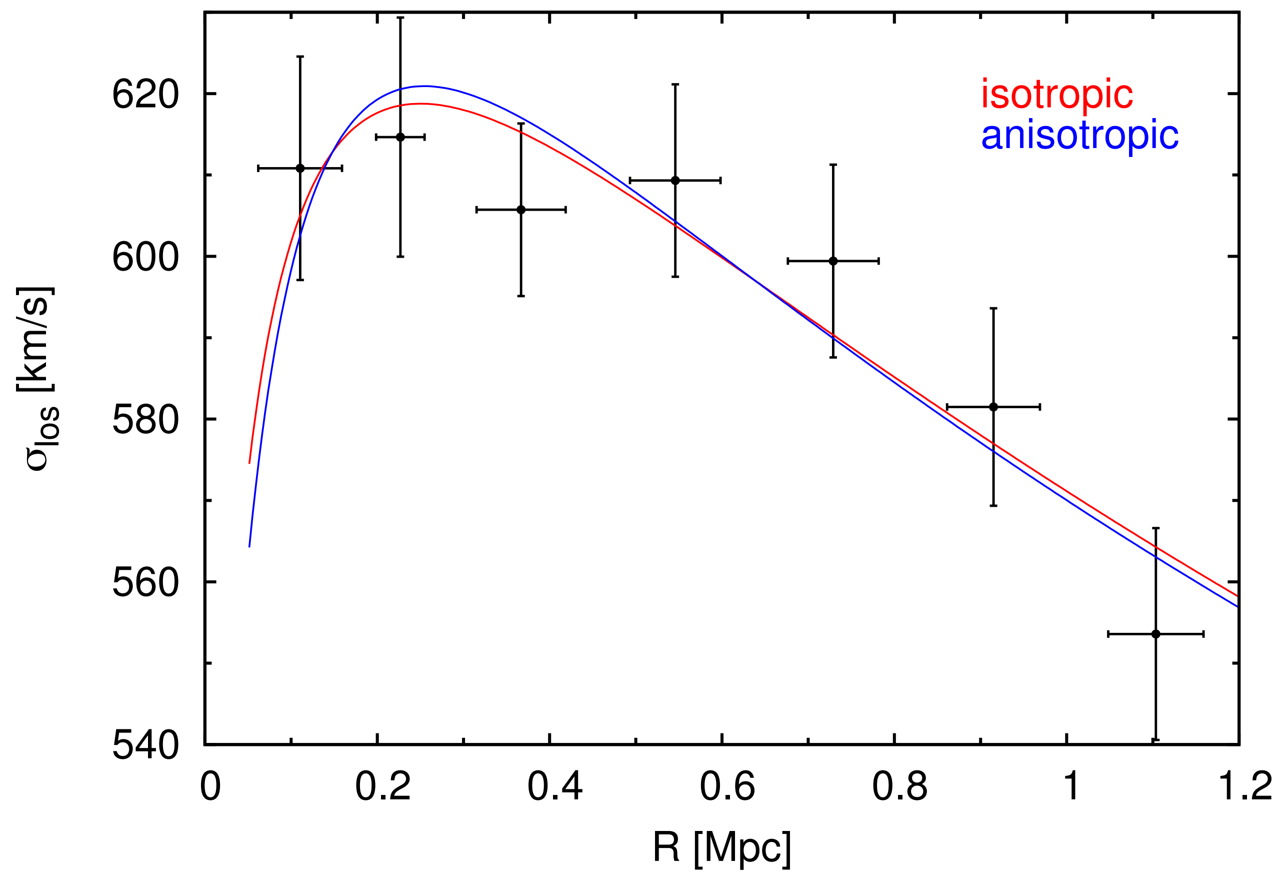


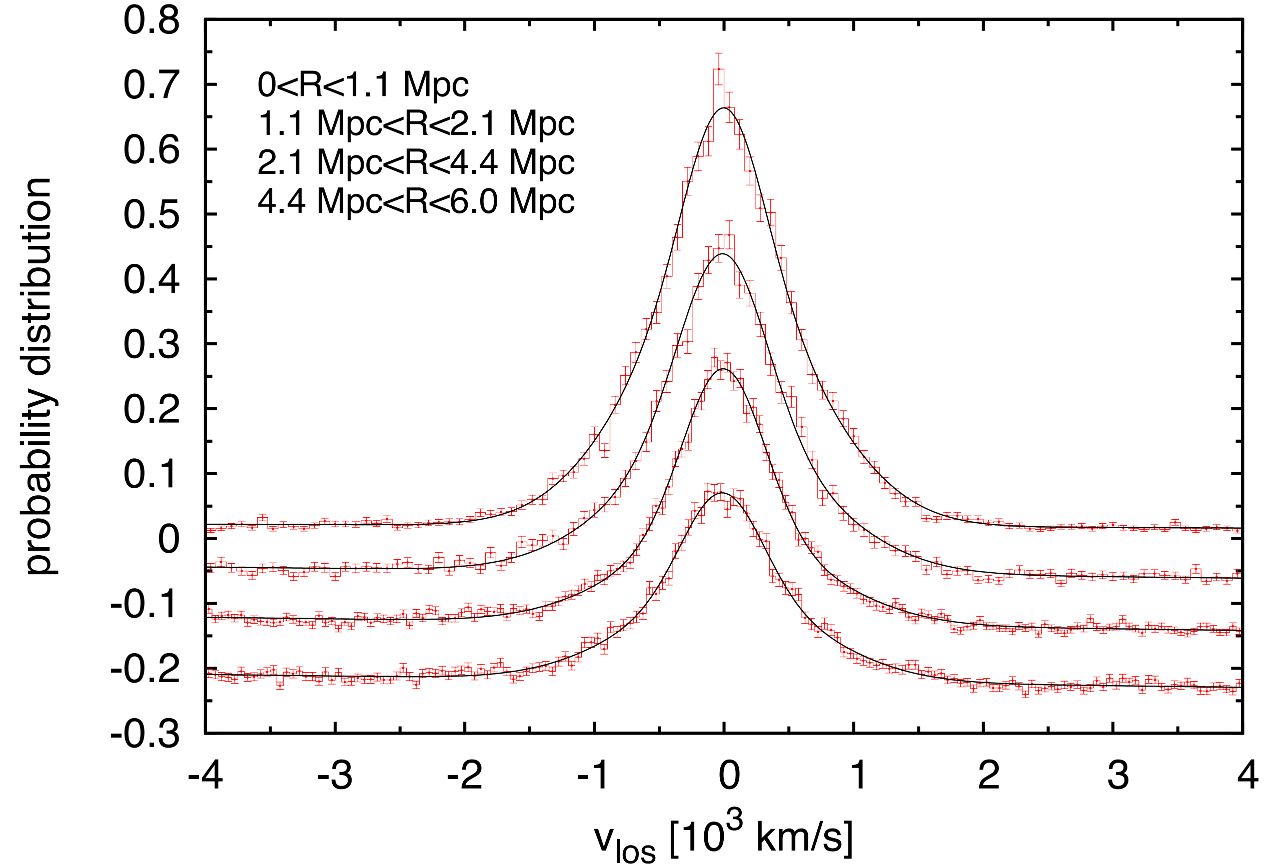
Figure 1. Spectral index vs. redshift for representative galaxy types observed in Sloan r-band



Corrected grav-z measurement

- Fairly easy to correct for TD +LC+SB effects
  - TD depends on vel. disp. anisotropy
  - LC+SB directly measured
  - net effect is a blue-shift
    - ~-9km/s in centre, falling to ~-6km/s at larger r
  - minor effects from infall/ outflow velocity
  - Substantial change in measured grav-z term
    - but still consistent with dynamical mass estimate





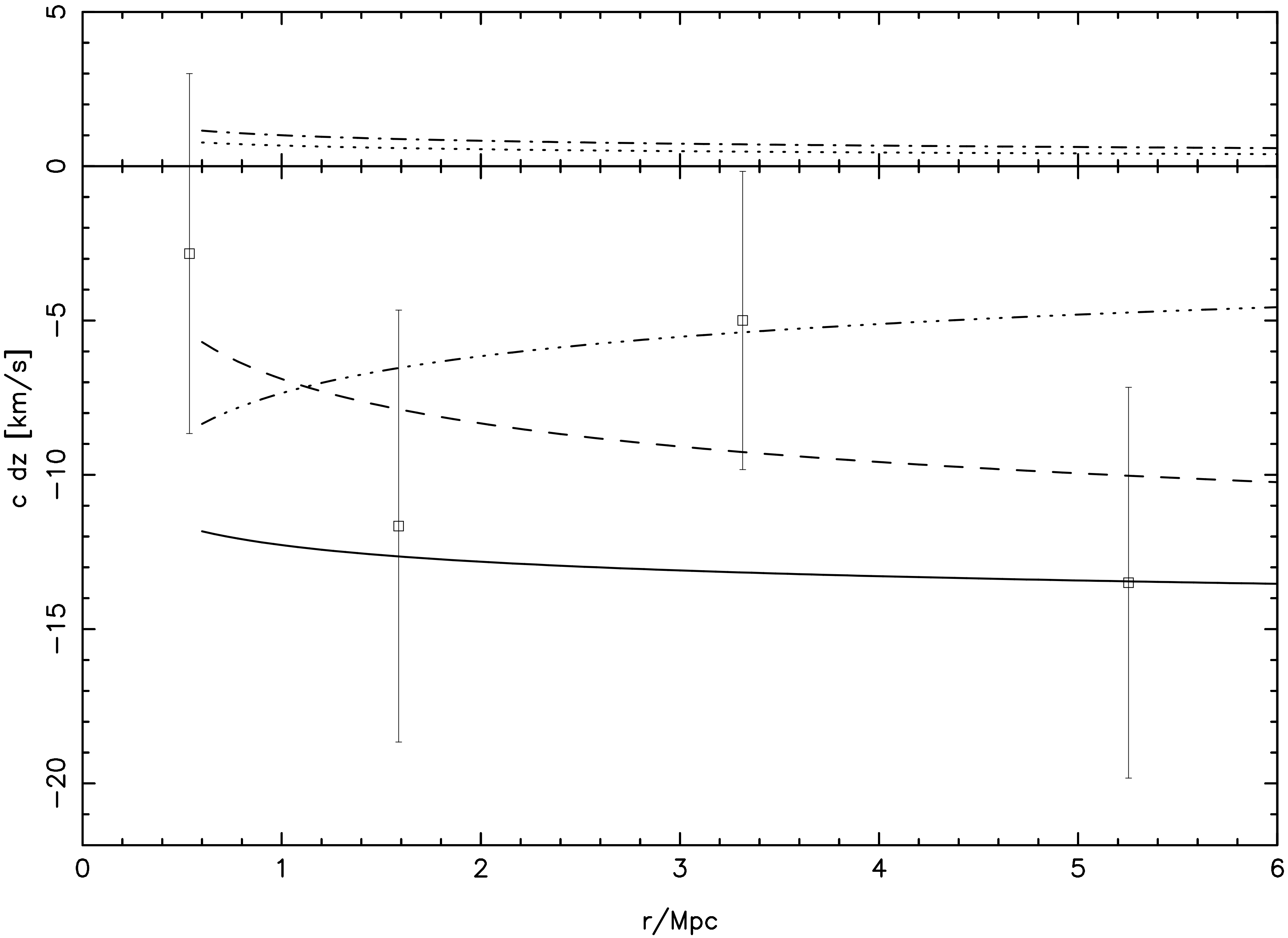


Figure 3. Data points from figure 2 of WHH and prediction based on mass-traces-light cluster halo profile and measured velocity dispersions as described in the main text. The dashed line is the gravitational redshift prediction, which is similar to the WHH model prediction. The dot-dash line is the transverse Doppler effect. The dotted line is the LC effect. The triple dot-dash line is the surface brightness effect. The solid curve is the combined effect.

Dynamical Analysis of a Composite Cluster

- General approach is to use velocity dispersion of stacked cluster to predict gravity
  - then integrate g to get potential
  - and potential gives redshift
- But this is a composite - not a single relaxed cluster
  - so it does not obey Vlasov (aka CBE equation)
- But there is still continuity
  - momentum cannot be accumulating at any radius
  - so Euler equation is obeyed
  - but gravity recovered is $\langle g \rangle_{galaxies}$
  - this gives asphericity bias
  - exploring via simulations (Cai *et al.* in progress)

Extension to Larger Scales

- Gravitational redshift (+ kinematic effects) dominant on small scales
  - infall/outflow effects are relatively small
- But at larger scales they become important
  - dominant at low-z - at high-z all several similar terms

$$\rho'(\mathbf{r}_\perp, \beta_x) = \rho(\mathbf{r}_\perp, \beta_x) + \int dx \, \{$$

$$(\beta_x^2/2 + \langle \beta_\perp^2 \rangle /2 - \Phi/c^2) \frac{\partial \rho(\mathbf{r}, \beta_x)}{\partial \beta_x}$$

$$+ ((3 + \alpha(Z))\delta(Z)\beta_x - 2Hx(\delta(Z) - 1)/cZ)\rho(\mathbf{r}, \beta_x)$$

$$+ \frac{x}{c}\dot{\rho}(\mathbf{r}, \beta_x) \ \} \, .$$

What does it mean?

- Effect is very small - and hard to measure
  - measuring 10km/s offset with 600km/s vel disp is impressive
  - requires careful modeling of background & cluster in f(v)
  - and predicting potential from kinematics is not trivial
    - though rather sensitive to vel disp for BCGs
  - but it probably is a real measurement of grav-z
- Effect does not rule out any sensible metric theory of gravity
  - non-relativistic matter & grav-z determined only by h_tt
- It is really only a test of the equivalence principle
- But therefore does provide a test of theories that invoke long-range non-gravitational forces in the "dark sector"
  - e.g. Gradwohl & Frieman 1992; Farrar & Peebles 2004; Farrar & Rosen 2007; Keselman, Nusser & Peebles 2010; and many, many more....
  - but such theories are already constrained by X-ray temp. vs galaxy motions in clusters

Future prospects...

- Can expect immediate improvements in measurement
    - 3x increase in number of redshifts available (BOSS)
    - and more to come: big-BOSS, ASKAP-Wallaby+WNSHS
- Extension to larger scales? (e.g. Croft arXiv:1304.4124)
- Tie in with peculiar velocities, grav lensing
- Lots of rich material in the front-back asymmetry of the galaxy correlation function.

A strange incident in the history of physics (C. Moller, 1967)

- 1905 - Einstein establishes SR
- By 1909, Planck, Einstein, Pauli all concluded that temperature of a moving body is T(rest frame) / gamma.
- Enshrined in text books (e.g. Tolman) and there it rested
- until '60s, when Ott (1963) and Arzelies (1965) turned it all around T = gamma * T(rest frame)
- much confusion ensued
    - P.T. Landsberg (2 Nature articles, '66, 67) "Does a moving body appear cool" (ans: no!)
    - largely clarified by Kibble, '66: Ott, Arzelies were right!
- issue reverberates to this day:
    - Dunkel, Haenggi, & Hilbert 2009 - light-cone effect

Biro & Van 2010

ABOUT THE TEMPERATURE OF MOVING BODIES

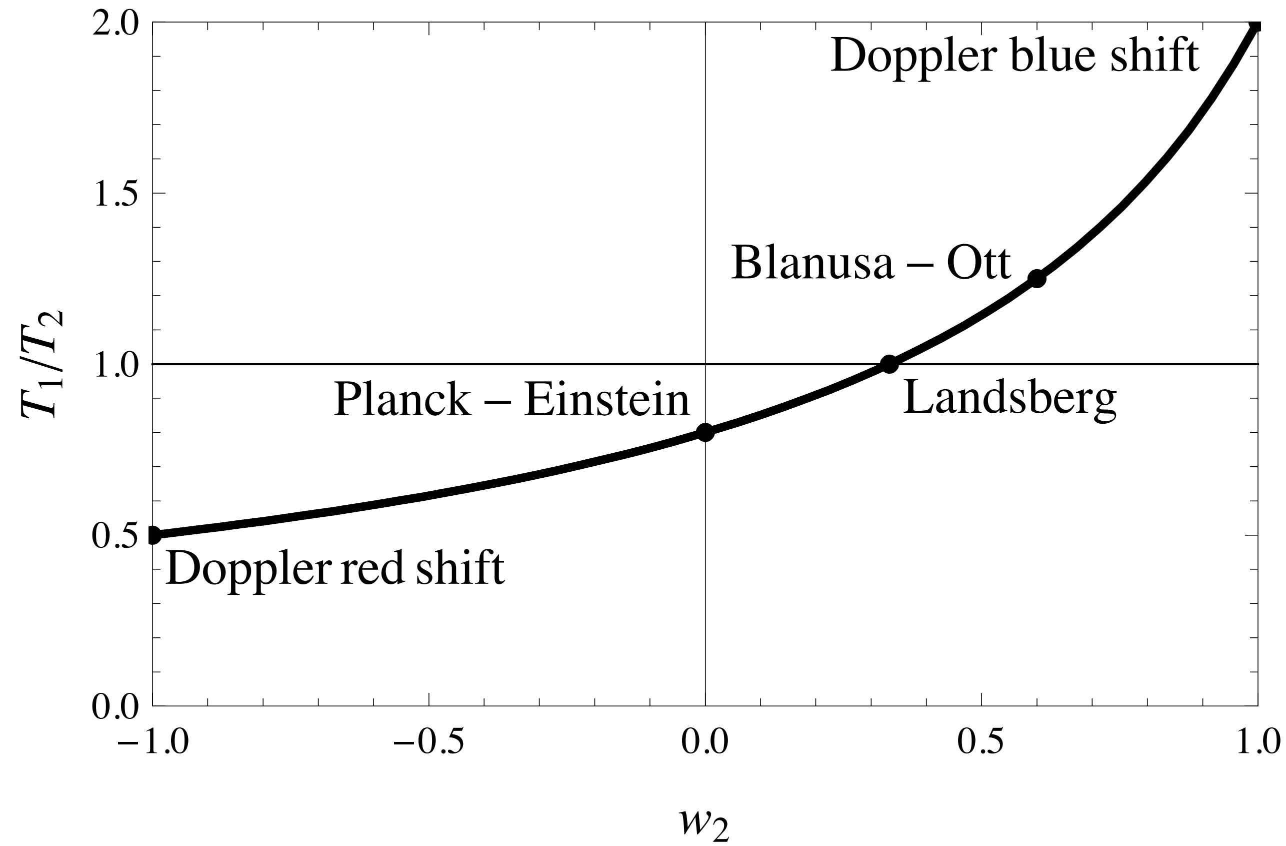
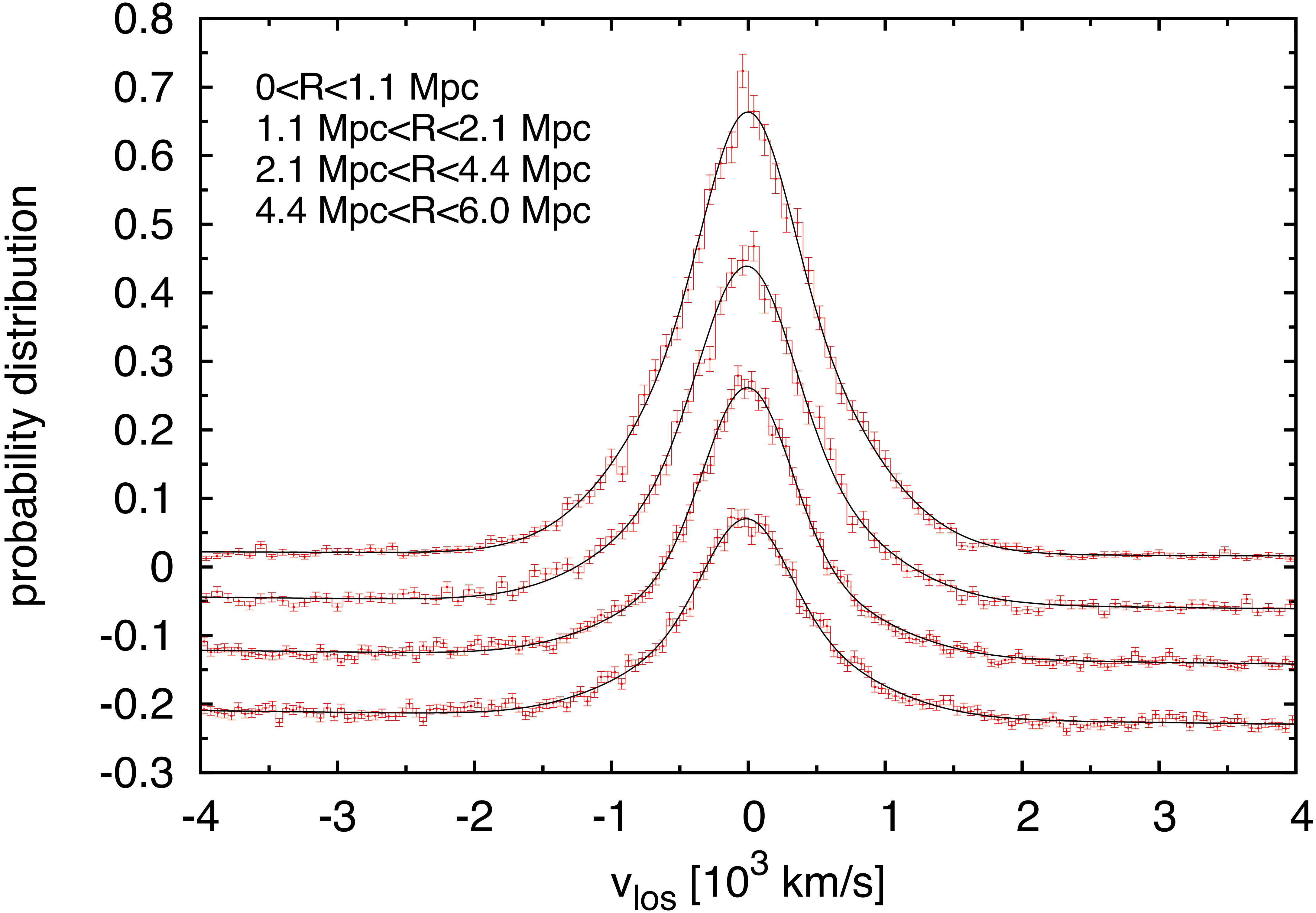
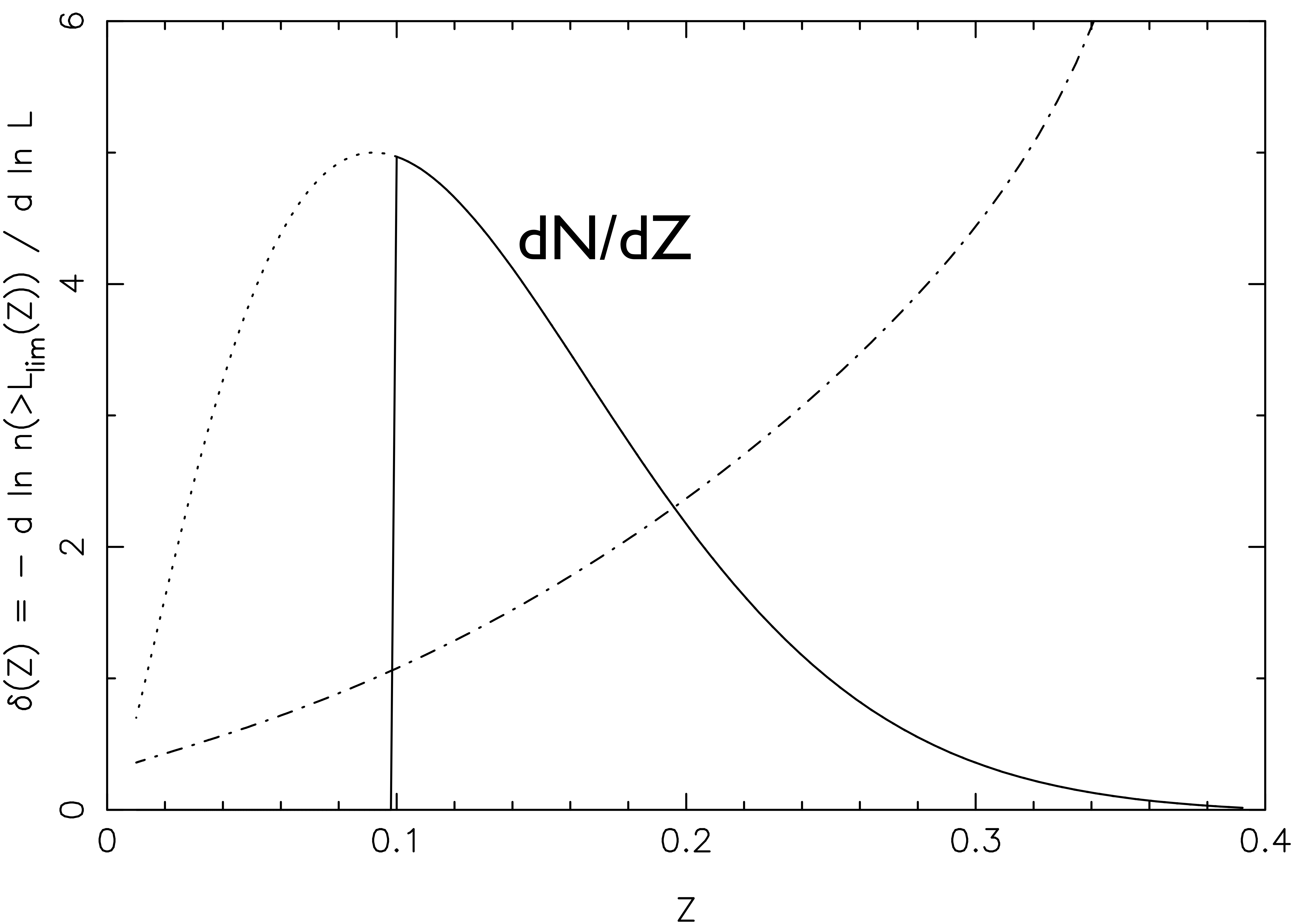
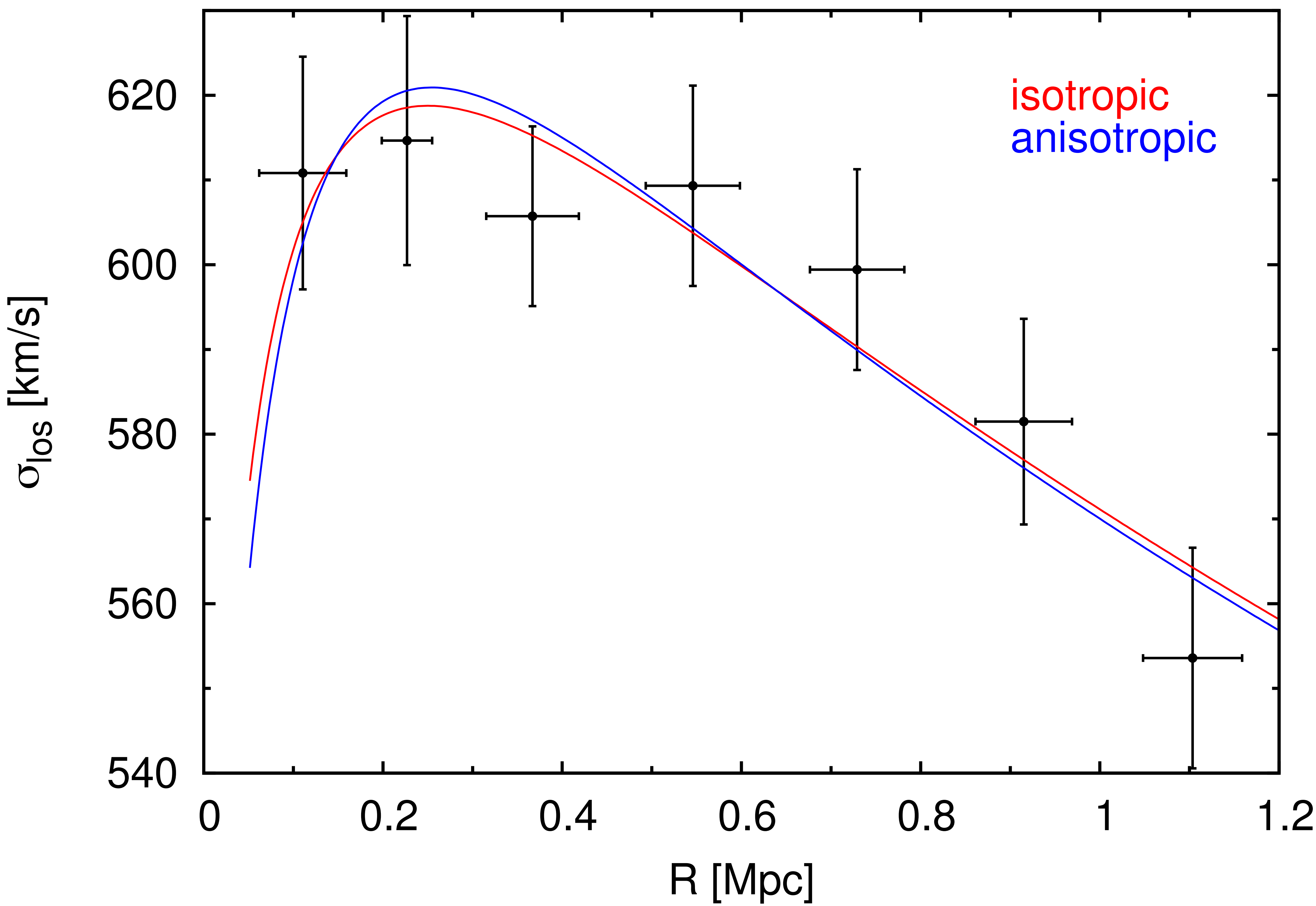


FIGURE 1. Ratio of the temperatures of the observed body in its rest frame, T_2 to that shown by an ideal thermometer, T_1 as a function of the the speed of the heat current in the body, w_2 while approaching with the relative velocity $v = -0.6$.


0<R<1.1 Mpc
1.1 Mpc<R<2.1 Mpc
2.1 Mpc<R<4.4 Mpc
4.4 Mpc<R<6.0 Mpc
probability distribution
v_{los} [10^3 km/s]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-4
-3
-2
-1
0
1
2
3
4



dN/dZ
$\delta(Z) = -\,d \ln n(>L_{lim}(Z))\ /\ d \ln L$
0
2
4
6
0
0.1
0.2
0.3
0.4
Z



isotropic
anisotropic
620
600
580
560
540
σ_{los} [km/s]
0
0.2
0.4
0.6
0.8
1
1.2
R [Mpc]