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

rXiv:1303.3663

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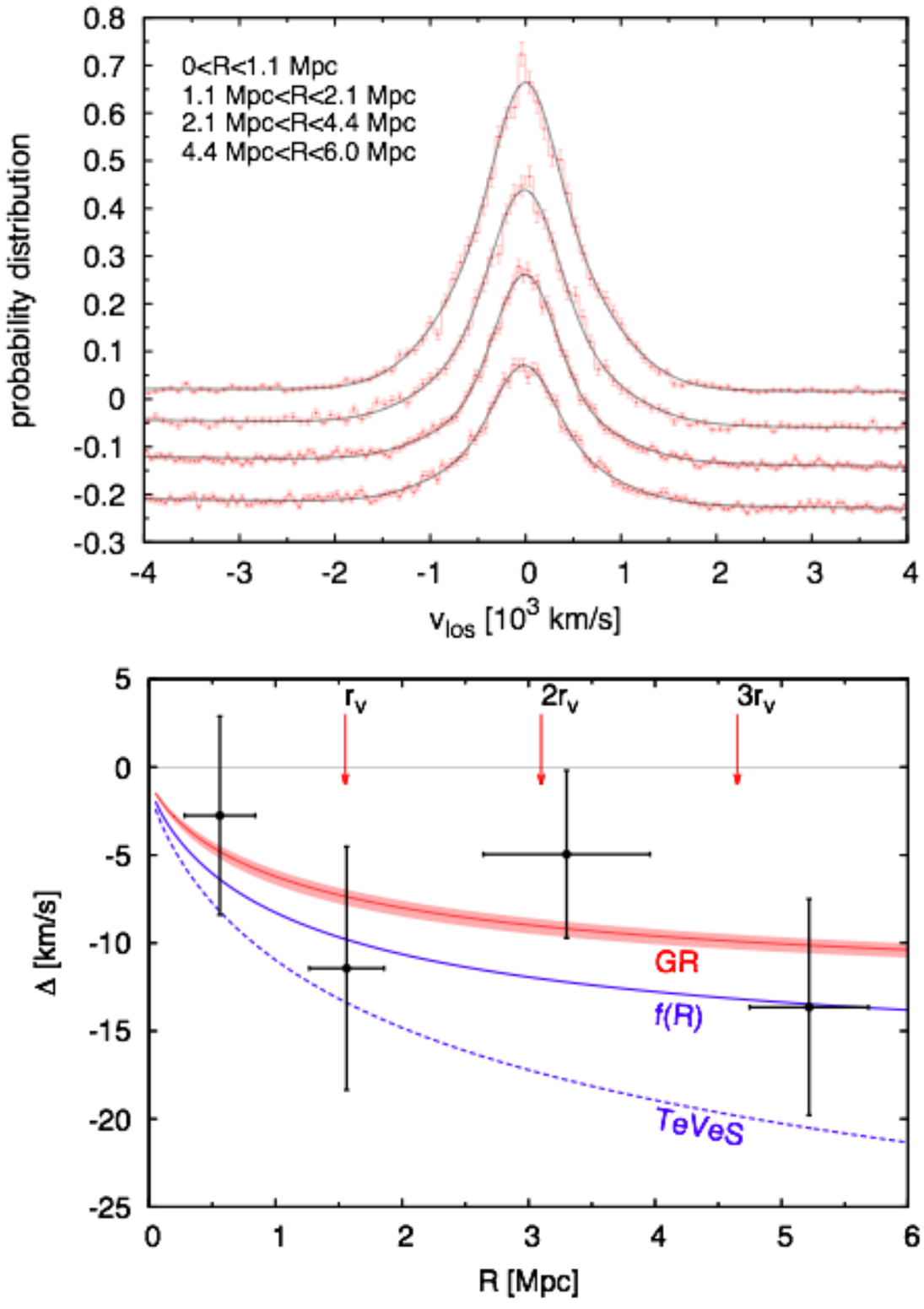
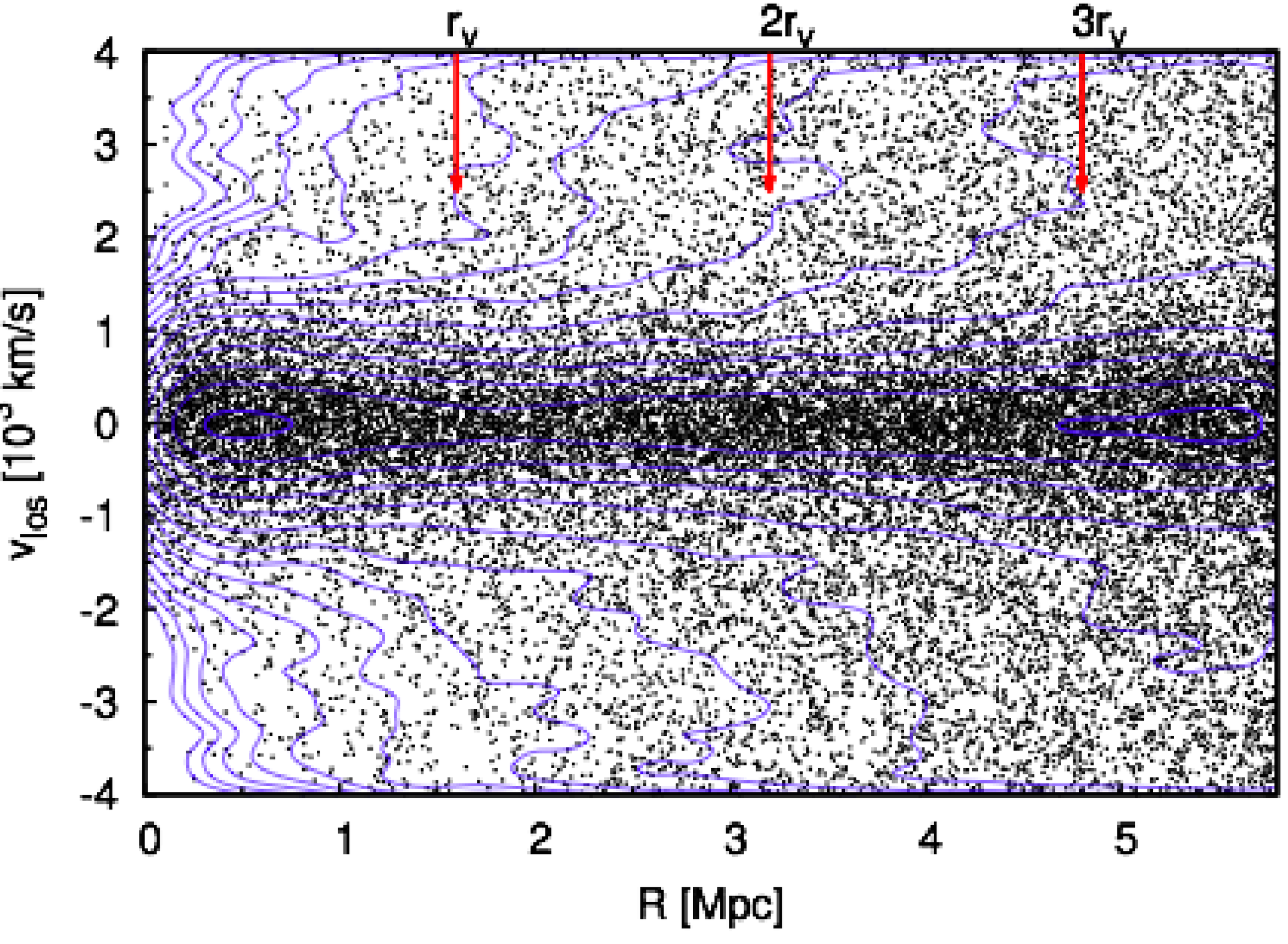
Wojtak, Hansen & Hjorth, Nature 2011

- Wojtek, Hansen & Hjorth stacked 7,800 galaxy clusters from SDSS DR7 in redshift space
  - centres defined by the brightest cluster galaxies (BCGs)
  - 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 1995; 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]

- δz is not just gravitational redshift
  - Zhao, Peacock & Li, 2012
- Sources are moving, so we also see
  - *transverse Doppler effect:*
    - 1st order Doppler effect averages to zero, but....
    - to 2nd order $\langle \delta z \rangle = \langle v^2/c^2 \rangle /2$
    - can be understood as time dilation
- Generally of same order of magnitude as gravitational redshift from virial theorem, Jeans eq...
- And this doesn't really test GR
  - see also Bekenstein & Sanders, 2012
  - more later.....
- Is that the full story?

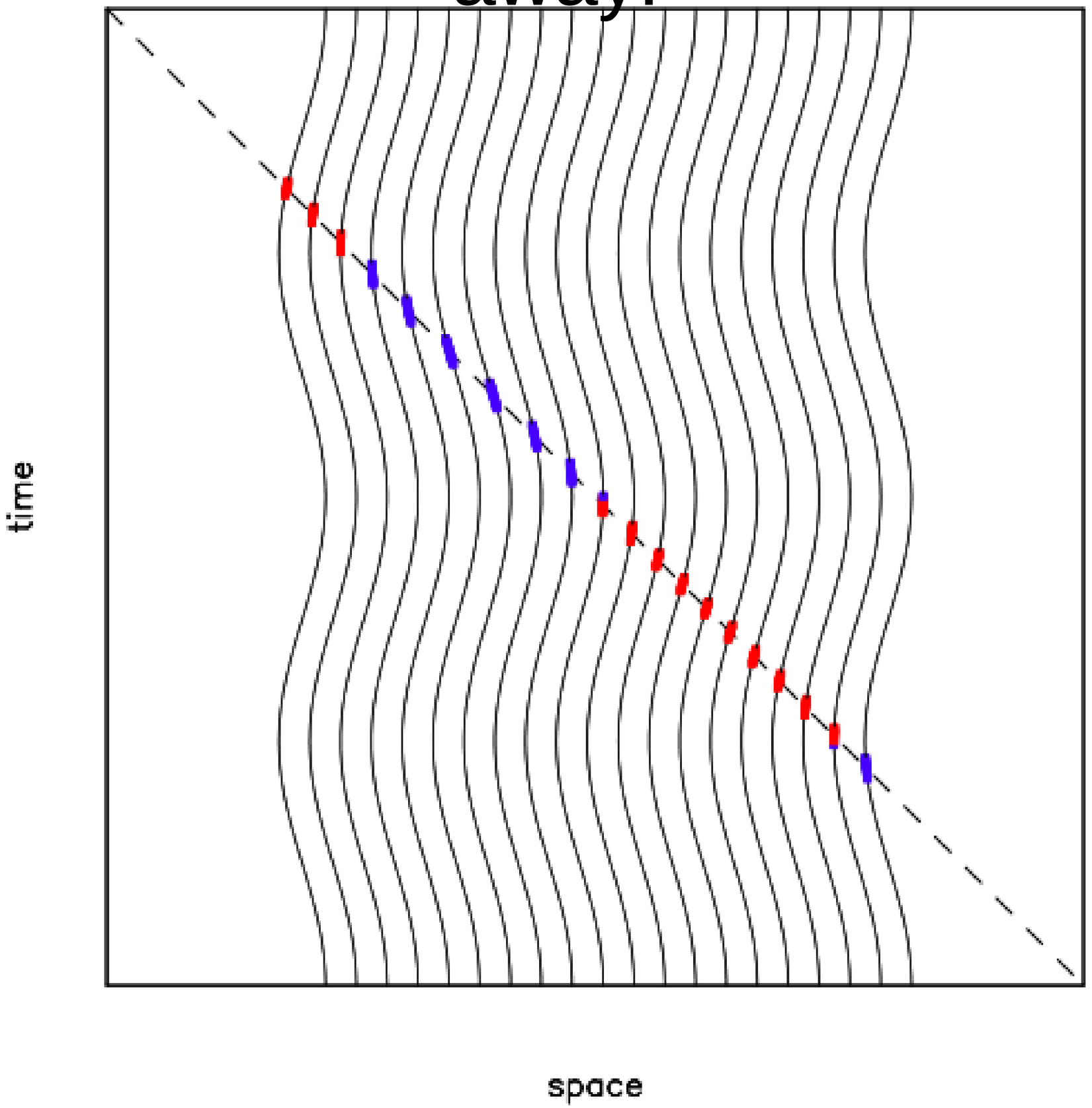
No - there is another effect of same order

- 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 in a photograph of a swarm of particles
    - past light cone of event of our observation overtakes more galaxies moving away than coming towards us
      - just as a runner on a trail sees more hikers going the other way...
    - So *not* Lorentz-Fitzgerald contraction effect
- phase space density contains a factor (1-v/c)
- $\langle \delta z \rangle = \langle (v_{los}/c)^2 \rangle$
- same sign as TD effect
  - 2/3 magnitude (for isotropic orbits)

Light-cone effect - more particles moving away!



Another way to look at LC effect

- Particle oscillating in a pig-trough
  - $r(t) = a \cos(\omega t + \varphi)$
  - $v(t)/c = -(a\omega/c) \sin(\omega t + \varphi)$
  - v(t) averages to zero
    - average could be over phase or time

QuickTime™ and a
GIF decompressor
are needed to see this picture.

- but $v_{obs} = v + (r/c)\, dv/dt + ...$
  - where r/c is the look-back time
  - and the extra term does *not* average to zero
- ~ same as Einstein prediction for Pound & Rebka
  - $\delta z \approx \langle r\, dv/dt \rangle / c^2$.

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

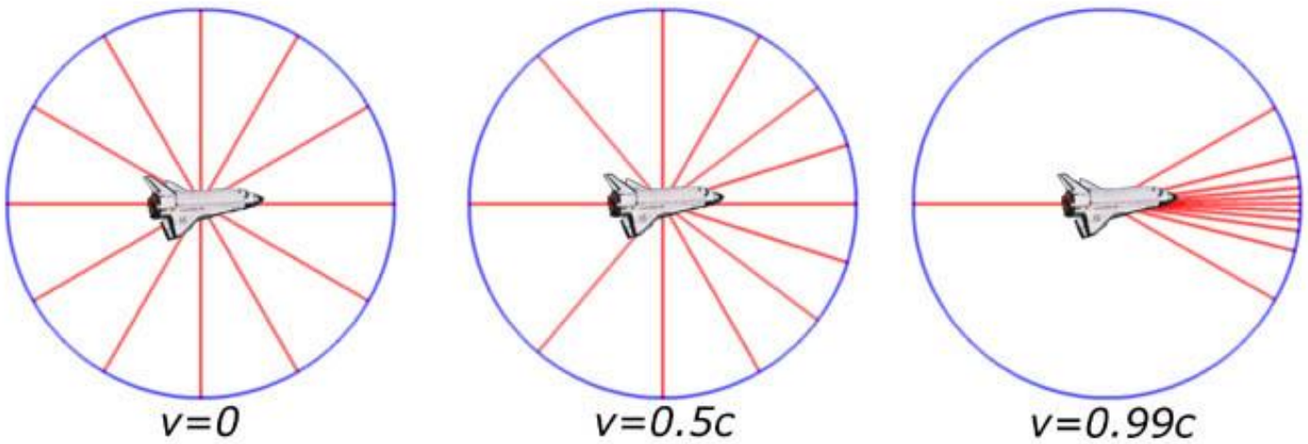
- Why is the transverse Doppler effect a *red*-shift?
  - Take a birthday cake; light the candles and put it on a turntable and spin it.
  - Detect all the photons and measure their frequency
  - Compare with non-rotating experiment.
- Shouldn't we see *blue*-shift $\lambda_{obs} = \lambda_{em}/\gamma$? As moving candles have more energy than candles at rest
- 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

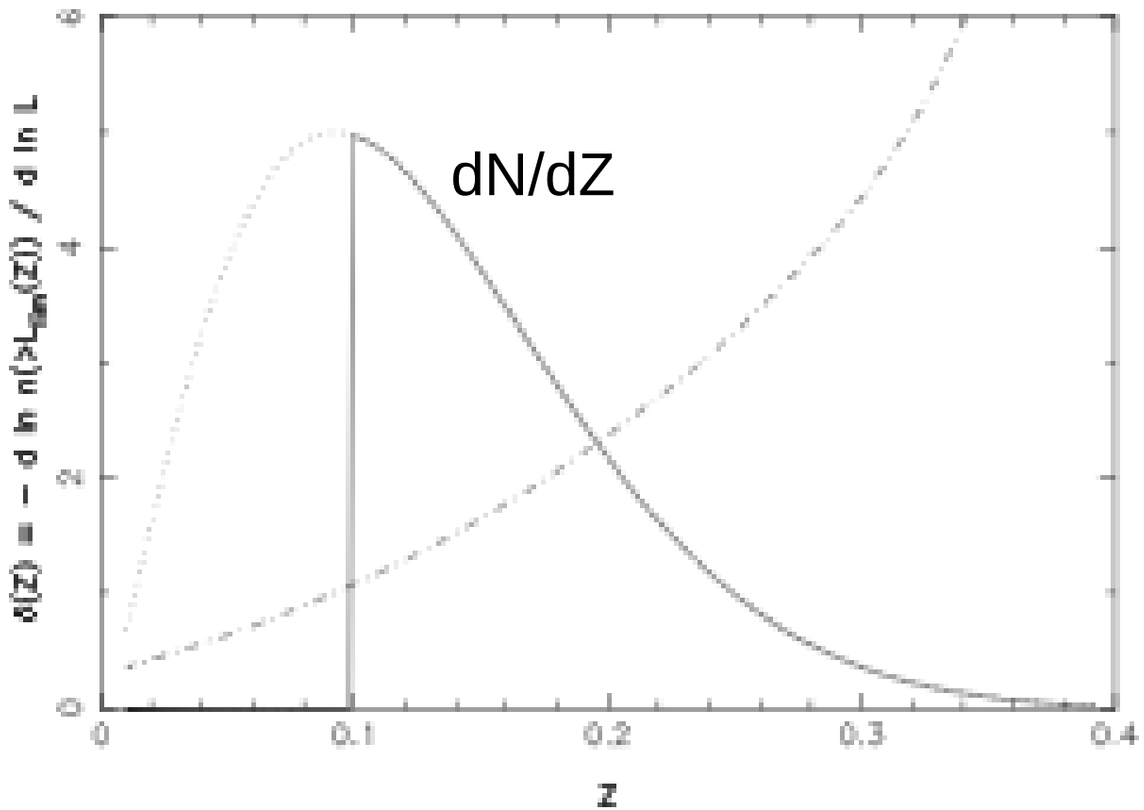
Unresolved sources composed of moving sources have a net transverse Doppler *blue*-shift

- 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 <u>photons</u> from an object composed of moving sources must, on average, be <u>blue</u>-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 radiating isotropically in the observer (or lab) frame
- It is a mild <u>relativistic beaming</u> effect:
  - 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

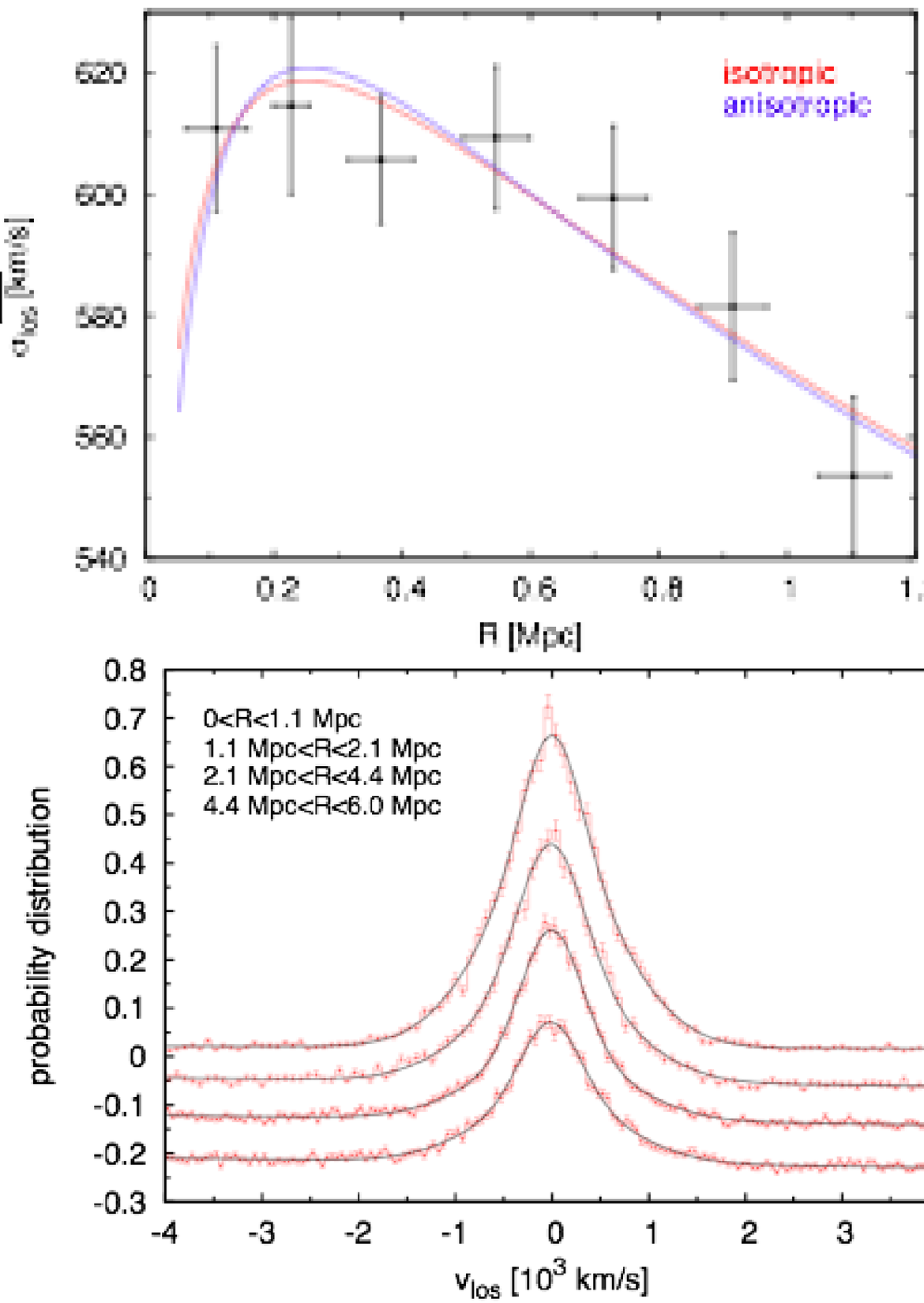
- Line of sight velocity changes surface brightness
  - relativistic beaming (aberration) plus change of frequency
- but doesn't change the surface area
- so velocities modulate luminosity
  - depends on SED: $\delta L/L = (3 + \alpha)v/c$
    - $\alpha \sim= 2$, so big amplification
    - spectroscopic 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 larger because the sample here is limited to bright end of the luminosity function





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



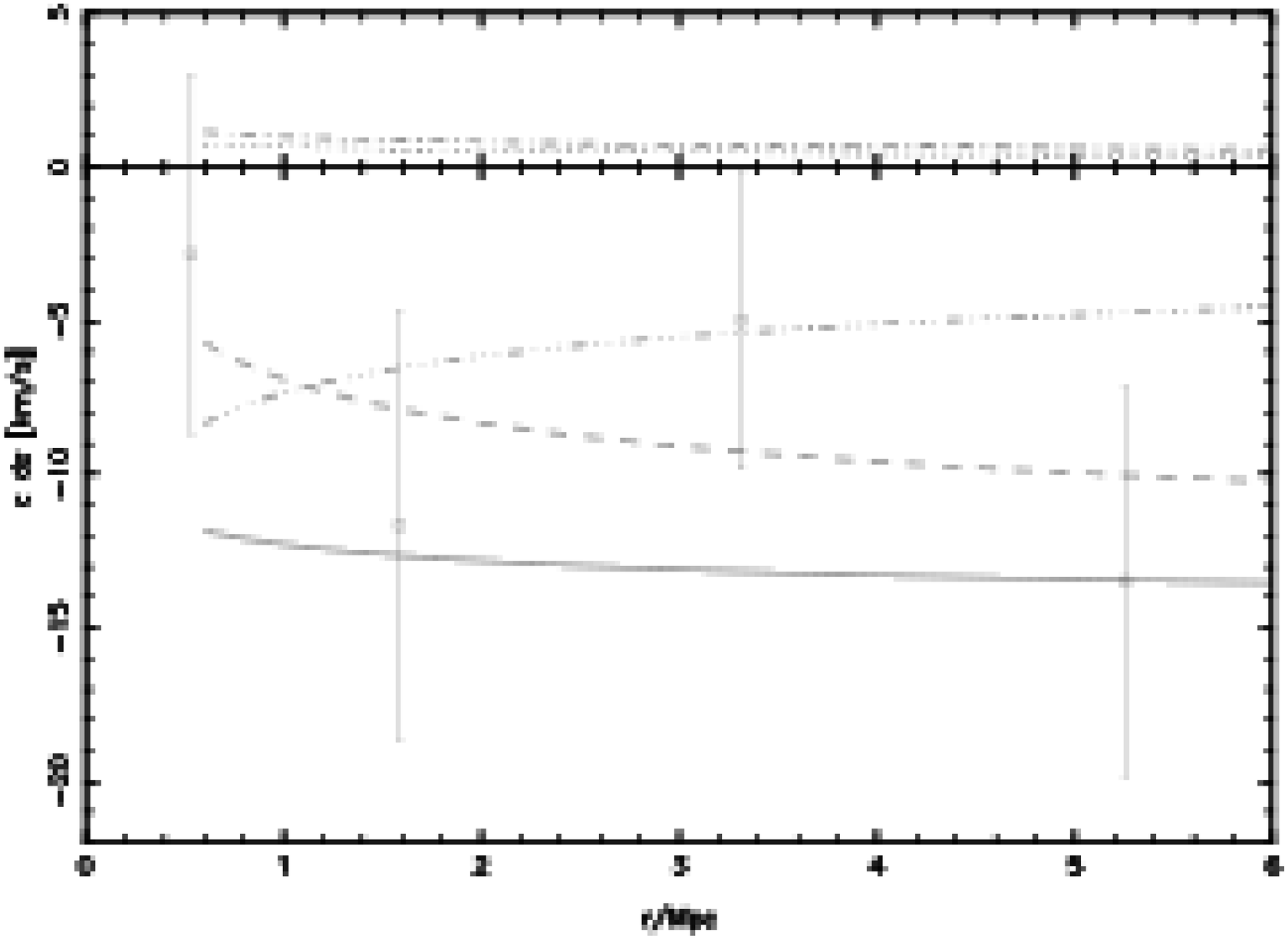
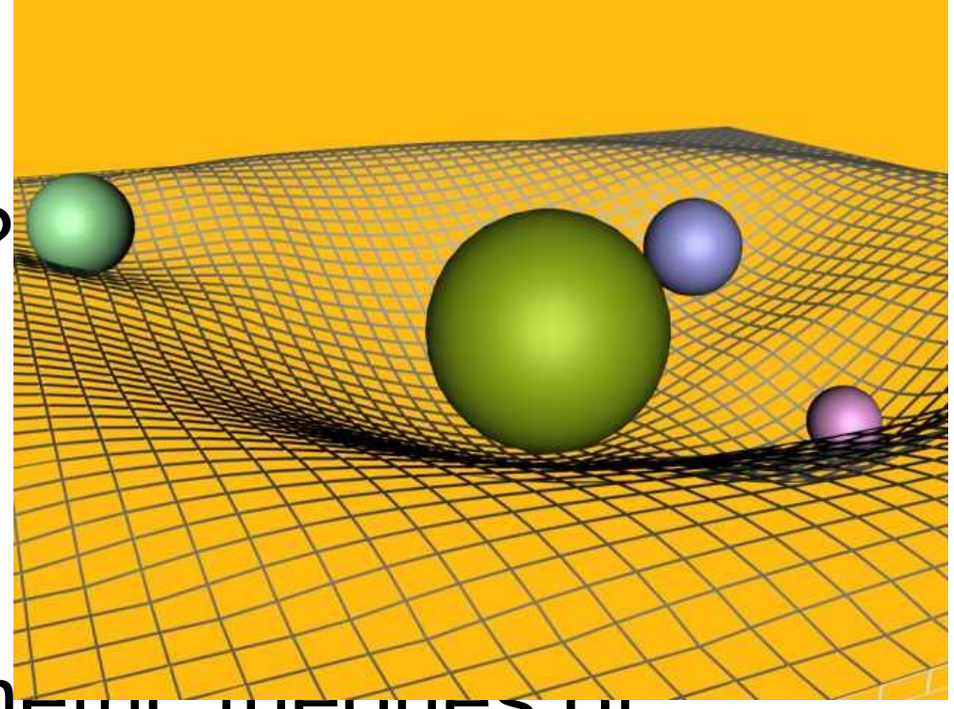


Figure 3. Data points from figure 2 of WHH and prediction based on mass-traces-light cluster halo profile and measured velocity dispersions as described in the main text. The dashed line is the gravitational redshift prediction, which is similar to the WHH model prediction. The dot-dash line is the transverse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

What else does it mean?



- Probe of curvature of space in GR?
  - matter tells space how to curve
  - space tells matter how to move...
- Sadly no....
- Effect does not rule out any most metric theories of gravity
  - motion non-relativistic matter & gravitational redshifts are determined only by 'g_{tt}'; the spatial metric is irrelevant
- It is really a test of the equivalence principle
- Provides 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 and (maybe) f(R) gravity (Hui, Nicolis & Stubbs 2009).
  - though 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?
  - Croft arXiv:1304.4124
  - Bonvin, Hui & Gaztanaga 1309.1321
- Tie in with peculiar velocities, grav lensing
- Lots of rich material in the front-back asymmetry of the galaxy correlation function.

Conclusions:

- Gravitational redshifts in clusters have been measured!
- but the interpretation is considerably more complicated than originally thought
- The static gravitational redshift is augmented by 3 other kinematic effects that are generally of the similar magnitude
  - time dilation + light-cone effect + relativistic beaming
- These measurements essentially provide a test of the equivalence principle
  - i.e. whether light and galaxies “fall” the same way in clusters
  - constrains “5th force” theories
  - and we can expect more precise measurements in the near future


140
150
140
150
140
150
140
150

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) / γ
- Enshrined in text books (e.g. Tolman) and there it rested
- until ‘60s, when Ott (1963) and Arzelies (1965) turned it all around T = γ 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
- But now seems anachronistic....

Relativistic Transformation Laws for Thermodynamic Variables (*).

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(ricevuto il 18 Ottobre 1965)

1. - Introduction.

ARZELIÈS (1) and GAMBA (2) have recently suggested that the hitherto generally accepted transformation laws of relativistic thermodynamics (3) are incorrect, and in need of revision. Superficially their results resemble those of OTT (4), inasmuch as all three authors advocate the same transformation laws for temperature and heat transfer, namely

$$T = T_0(1-\beta^2)^{-\frac{1}{2}}, \qquad dQ = dQ_0(1-\beta^2)^{-\frac{1}{2}}, \tag{1}$$

However, they do not agree about the transformation laws for certain other thermodynamic variables, notably the internal energy of the system. It is the purpose of this note to point out that, although the formulae (1) are unexceptionable, the arguments presented by ARZELIÈS and GAMBA are wrong, particularly in respect of the transformation laws of energy and work. Our results are in complete agreement with those of OTT. We shall also show that for very similar reasons the treatment of the problem of the stressed lever given by ARZELIÈS (5) is erroneous, and that the conventional solution to this problem (6) is in fact perfectly correct.

We begin, in Sect. 2, with some general remarks on the relativistic transformation laws of thermodynamic variables. Then in Sect. 3 we discuss the specific case of the total energy, illustrating our remarks with the example of cavity radiation discussed by GAMBA. In Sect. 4 we consider the work done in changing the volume or pressure of the system. Finally, Sect. 5 is devoted to a demonstration of the necessity for, and physical reality of, the kind of energy flux which plays a crucial

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(1) H. ARZELIÈS: *Nuovo Cimento*, **35**, 792 (1965).

(2) A. GAMBA: *Nuovo Cimento*, **37**, 1792 (1965).

(3) See for example, W. PAULI: *Theory of Relativity* (London, 1958), p. 154.

(4) H. OTT: *Zeits. f. Phys.*, **175**, 70 (1963).

(5) H. ARZELIÈS: *Nuovo Cimento*, **35**, 792 (1965).

(6) See for example R. C. TOLMAN: *Relativity, Thermodynamics and Cosmology* (Oxford, 1950), p. 19.

Biro & Van 2010

ABOUT THE TEMPERATURE OF MOVING BODIES

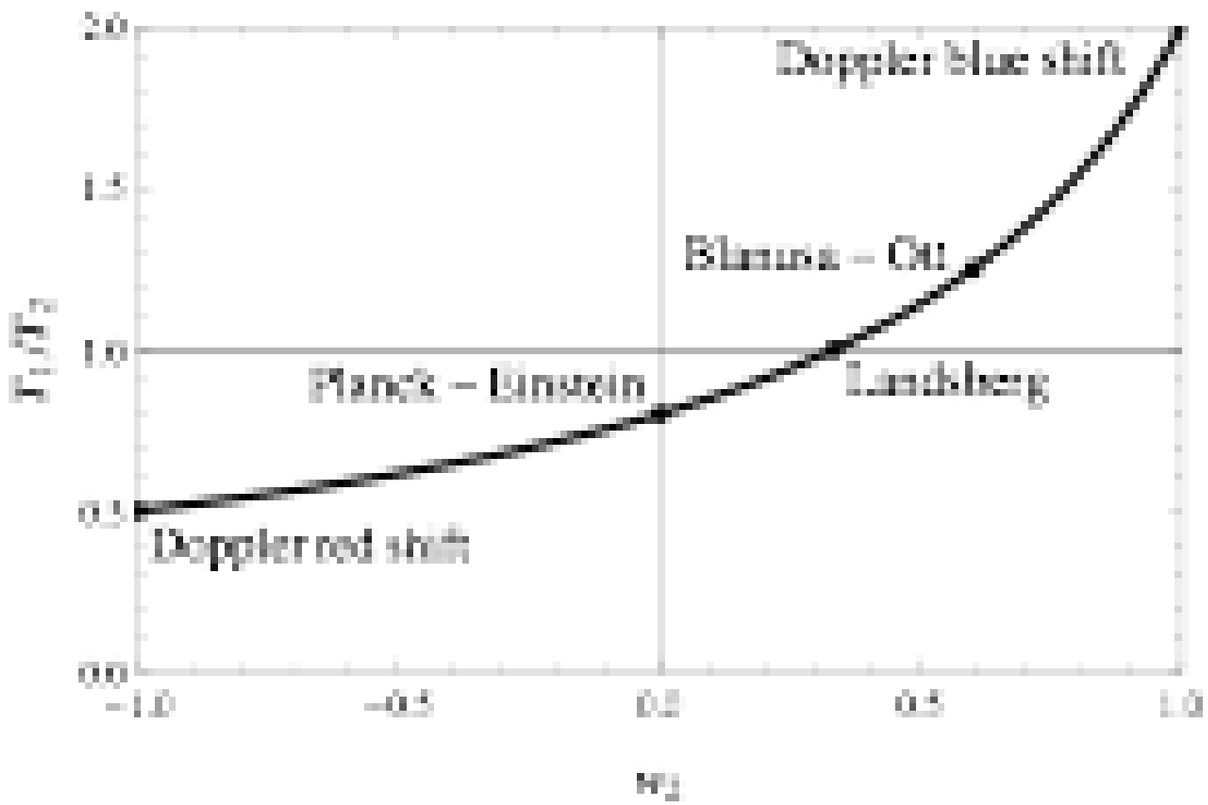

FIGURE 1. Ratio of the temperatures of the observed body in its rest frame, T_2 to that shown by an ideal thermometer, T_1 as a function of the the speed of the heat current in the body, w_2 while approaching with the relative velocity $v = -0.6$.