Gravitational Redshifts in Clusters of Galaxies

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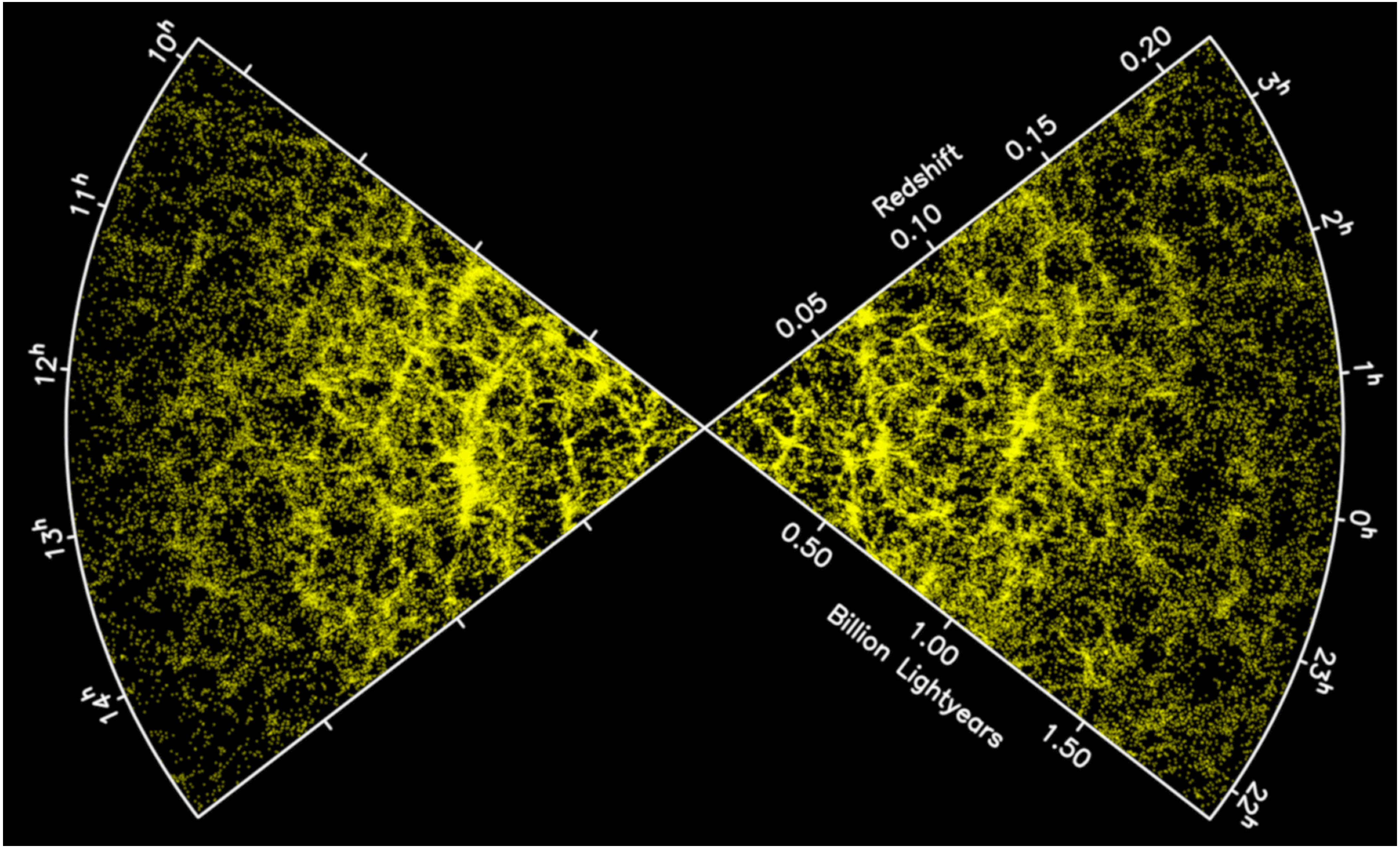
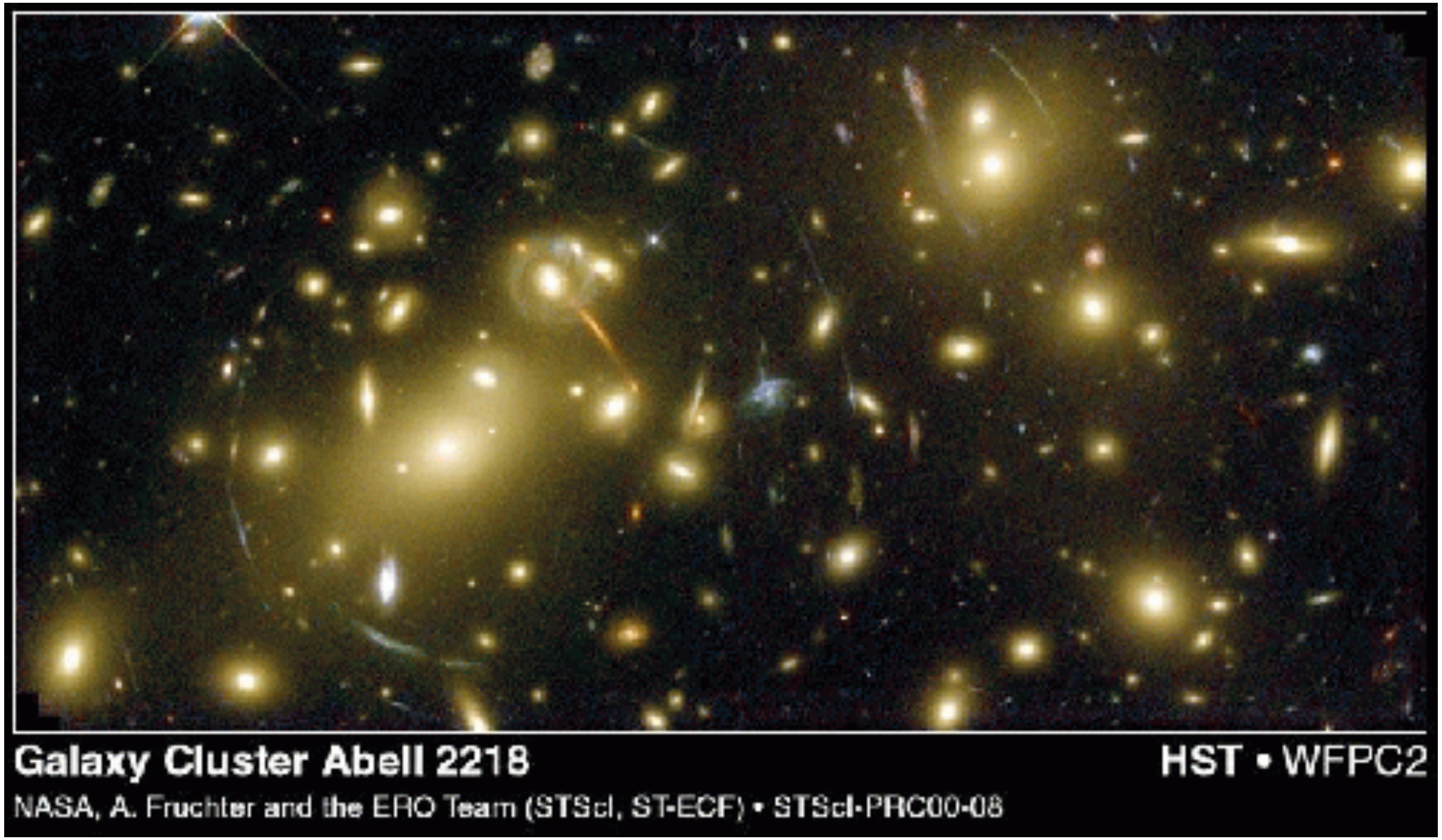
The cosmic web in the 2df galaxy redshift survey

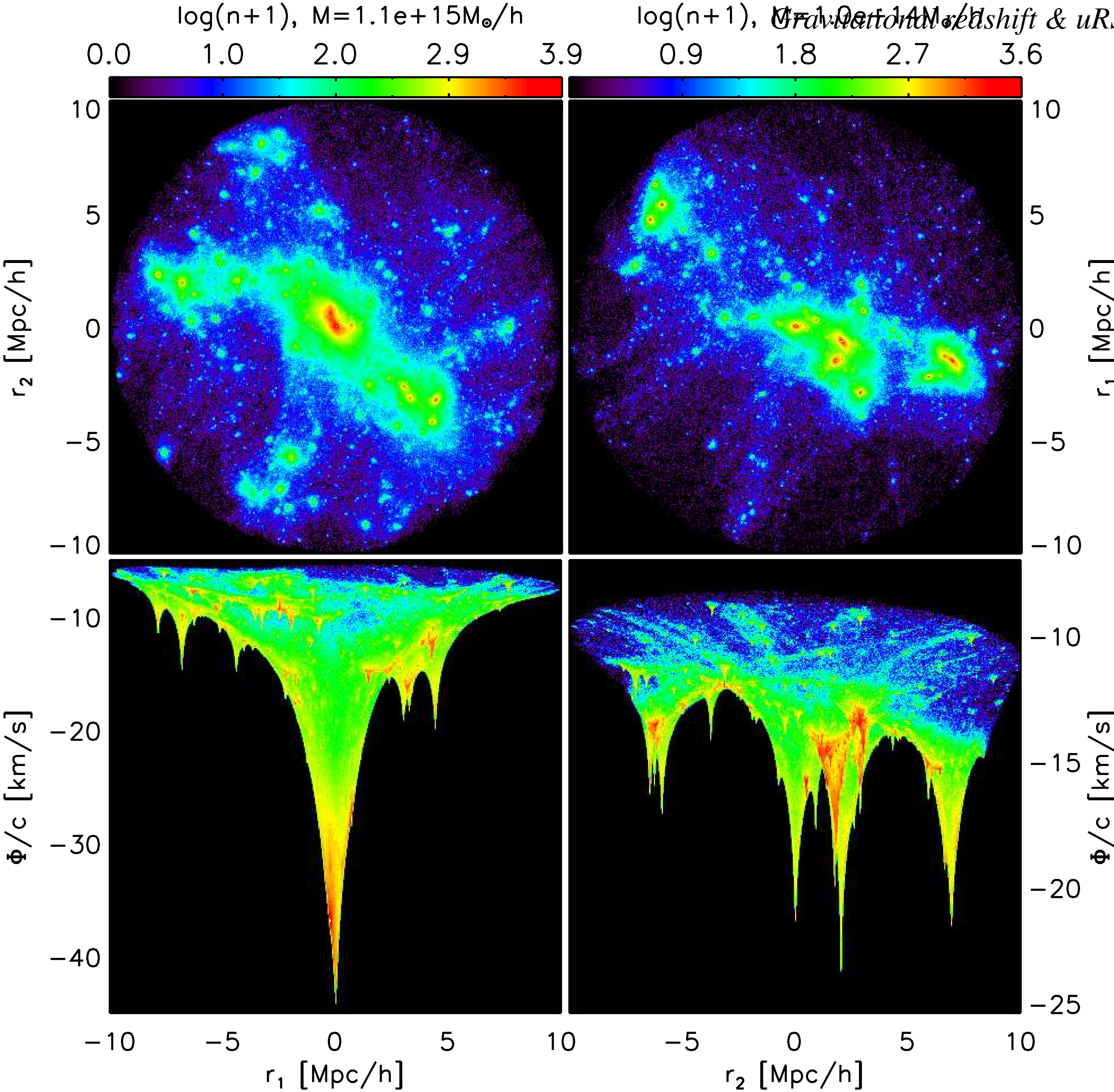


Clusters of galaxies



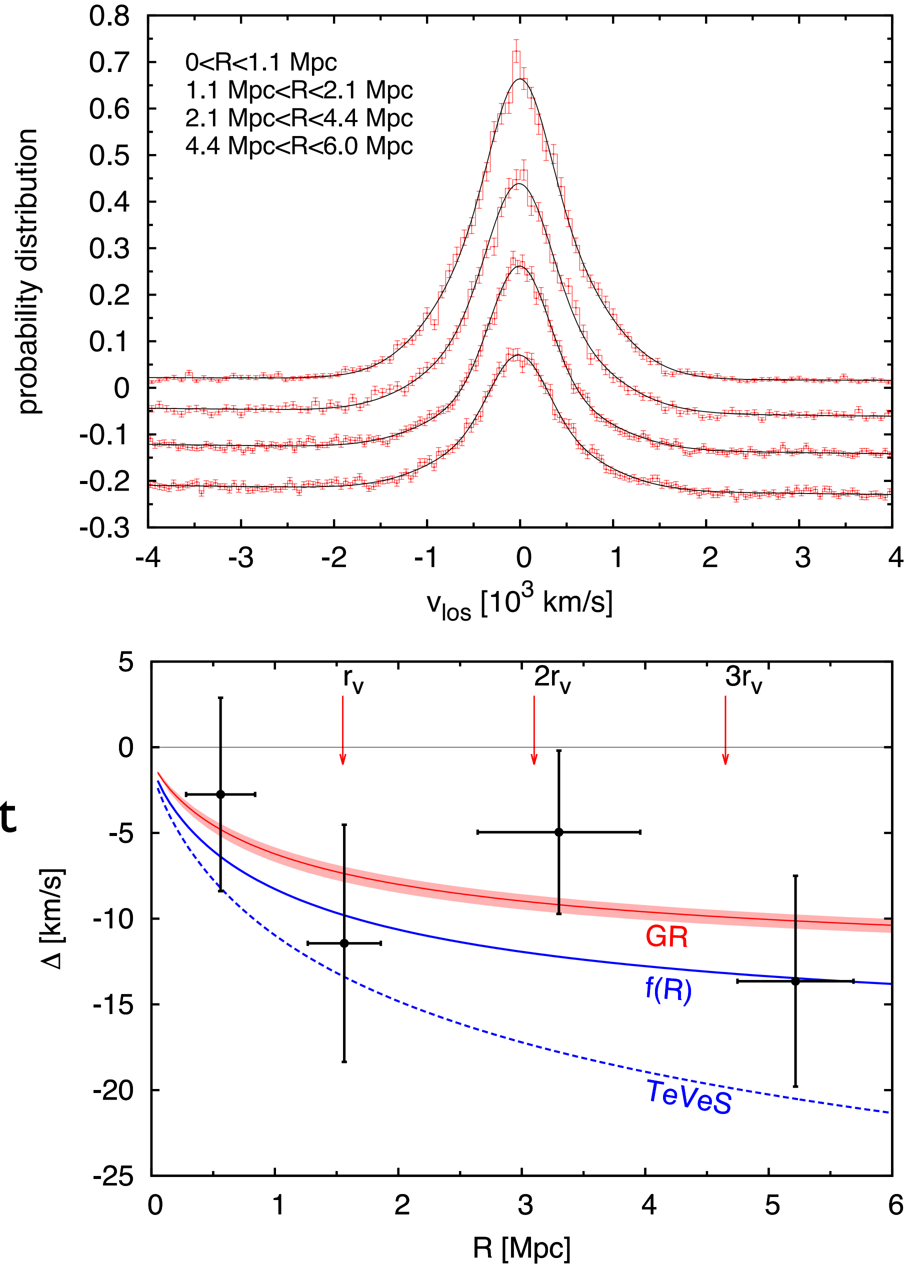
- Largest bound virialised systems $\sim 10^{14}$-$10^{15} M_{sun}$
- Velocity dispersion $\sigma_v \sim 1000$ km/s ($\sim 0.003c$)
  - so grav. potential is $\varphi \sim \sigma_v^2 \sim 10^{-5}\, c^2$
- Centres - often occupied by the brightest galaxy (BCG)
  - Usually very close to peak of light, X-rays, DM

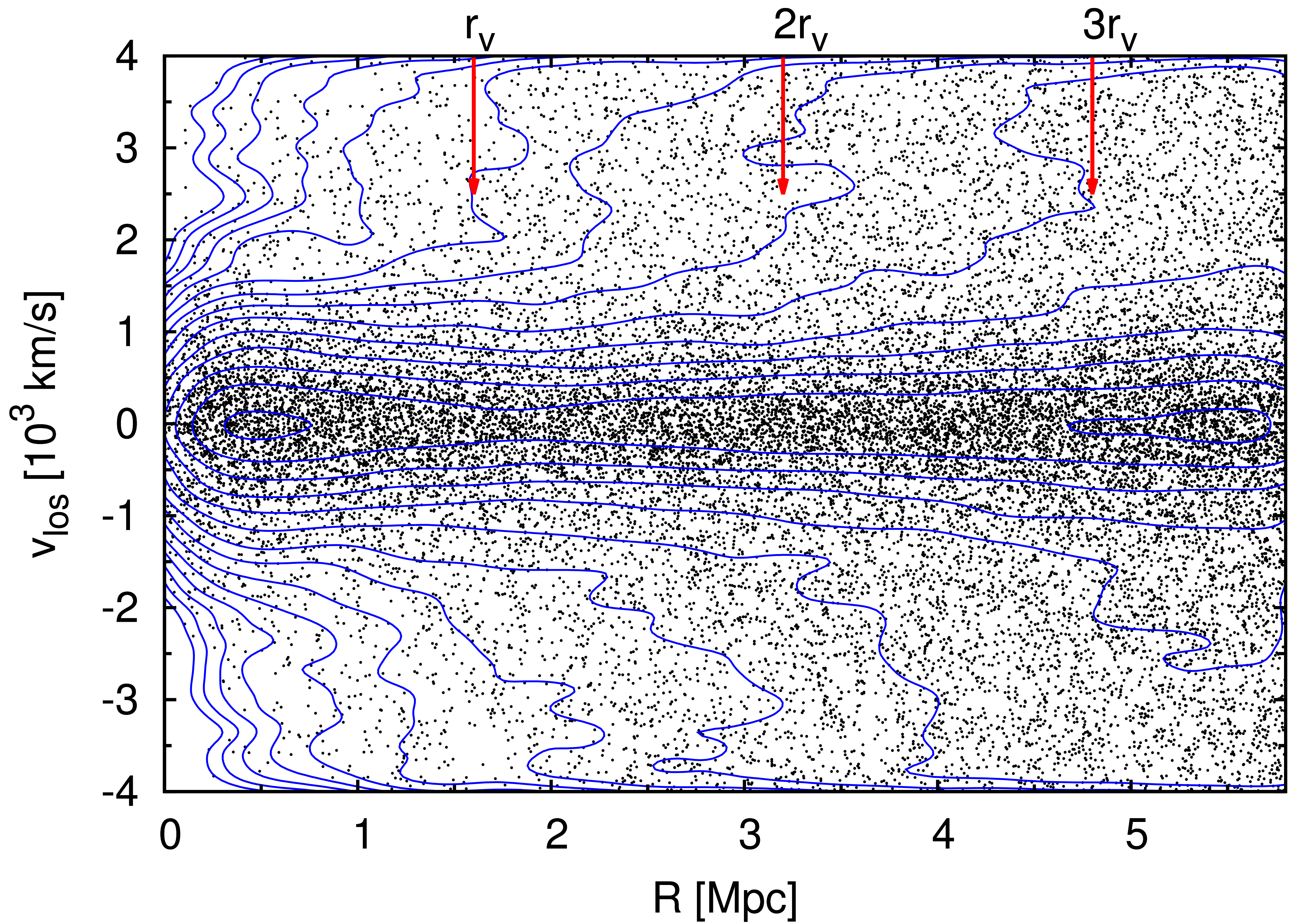
Clusters in the Millenium Simulation (Y. Cai)



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 suggested before (Cappi 1995; Broadhurst+Scannapiaco, ...)

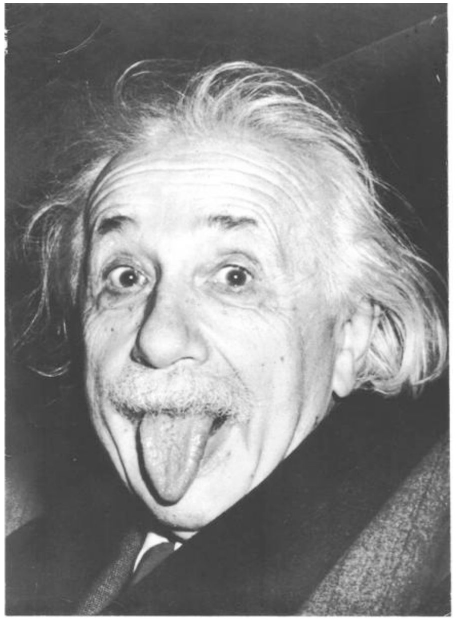


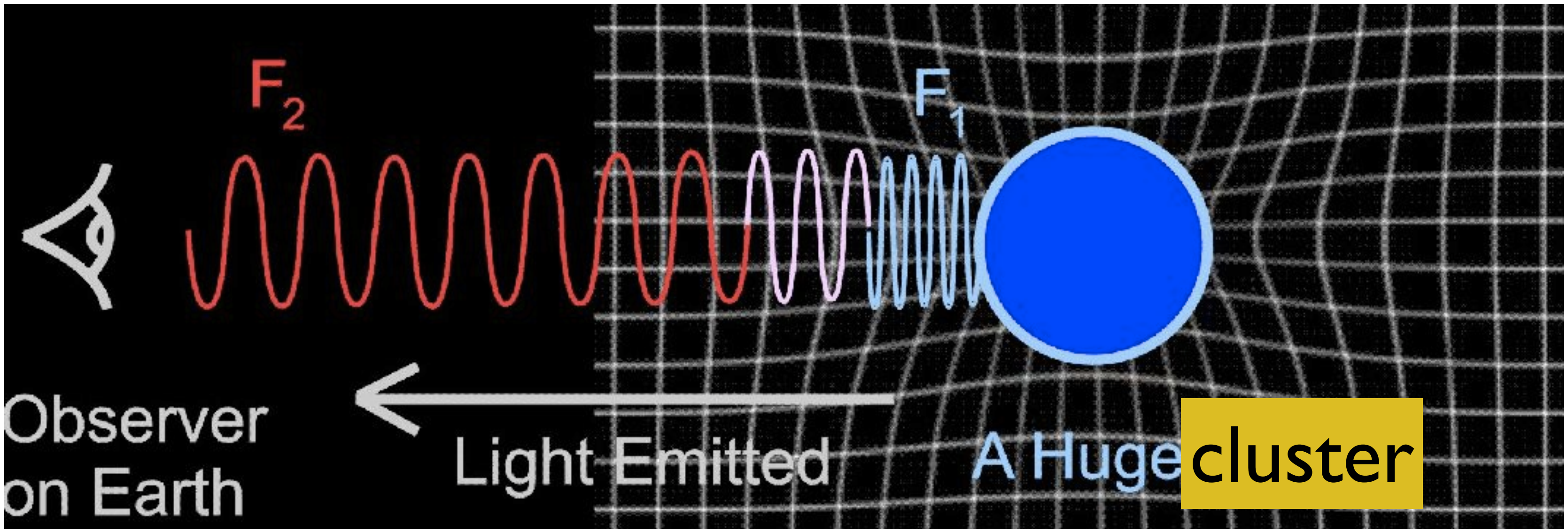


r_v
$2r_v$
$3r_v$
v_{los} [10^3 km/s]
R [Mpc]
4
3
2
1
0
-1
-2
-3
-4
0
1
2
3
4
5

The physics of cluster gravitational redshifts

- Einstein gravity
  - gravitational "time dilation"
- Weak field limit
  - $\delta\nu/\nu = -\Phi/c^2$
- Measured by Pound & Rebka (Harvard '59)

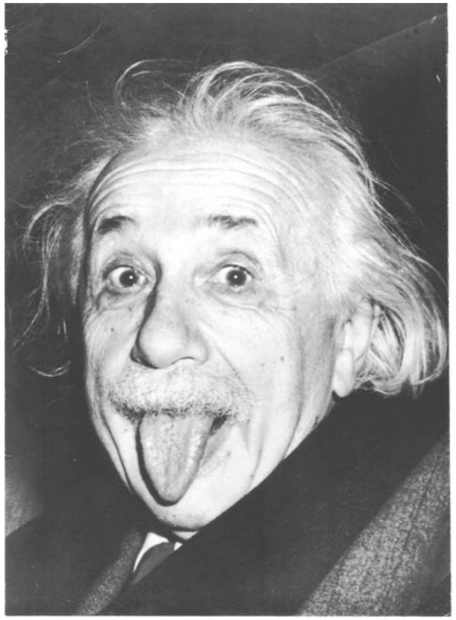




Is that it?

Equivalence principle & the Pound + Rebka experiment

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



- Einstein's Equivalence Principle: Observers on earth should see light red-shifted.
- Pound and Rebka (1959, 1960): He was right.

GRAVITATIONAL RED-SHIFT IN NUCLEAR RESONANCE

R. V. Pound and G. A. Rebka, Jr.
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received October 15, 1959)

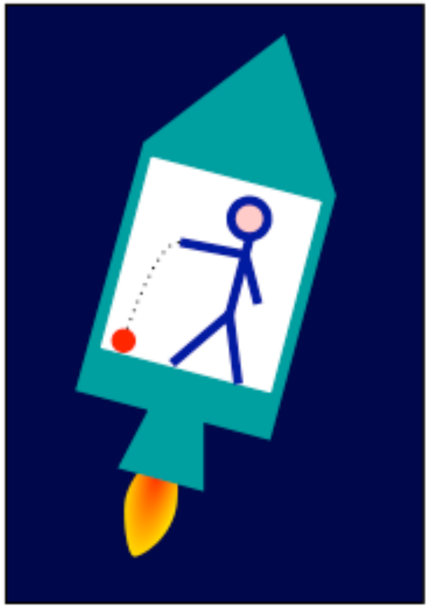
It is widely considered desirable to check experimentally the view that the frequencies of electromagnetic spectral lines are sensitive to the gravitational potential at the position of the emitting system. The several theories of relativity predict the frequency to be proportional to the gravitational potential. Experiments are proposed to observe the timekeeping of a "clock" based on an atomic or molecular transition, when held aloft in a rocket-launched satellite, relative to a similar one kept on the ground. The frequency ν_h and thus the timekeeping at height h is related to that at the earth's surface ν_0 according to

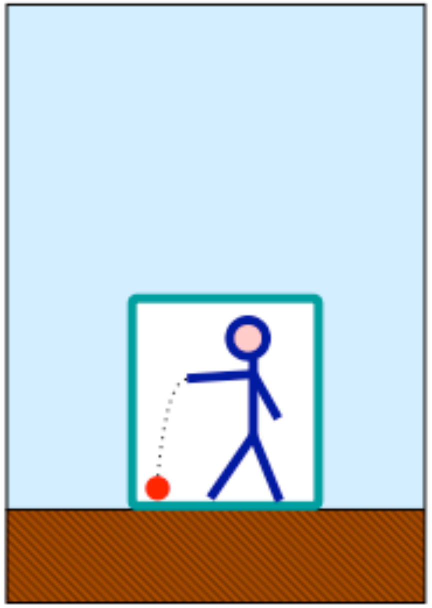
$$\Delta\nu_h = \nu_h - \nu_0 = \nu_0 gh/c^2(1+h/R)$$
$$\approx \nu_0 h \times (1.09\times 10^{-18}),$$

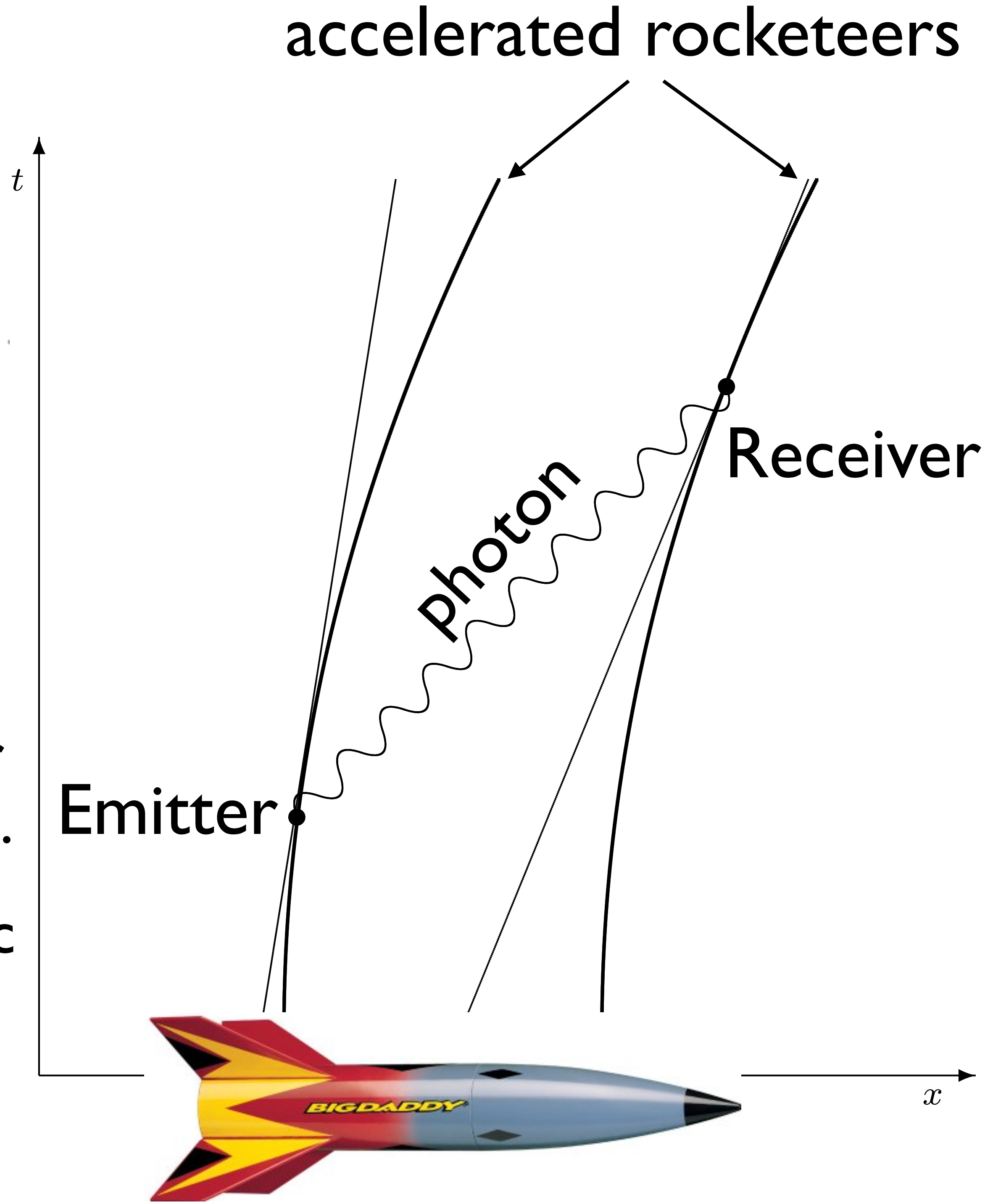
where R is the radius of the earth and h is the altitude measured in cm. Very high accuracy is required of the clocks even with the altitudes available with artificial satellites. Although several ways of obtaining the necessary frequency stability look promising, it would be simpler if a way could be found to do the experiment between fixed terrestrial points. In particular, if an accuracy could be obtained allowing the measurement of the shift between points differing as little as one to ten kilometers in altitude, the experiment could be performed between a mountain and a valley, in a mineshaft, or in a borehole.

Recently Mössbauer has discovered[1] a new aspect of the emission and scattering of γ rays by nuclei in solids. A certain fraction f of γ rays of the nuclei of a solid are emitted without

Einstein's calculation of the redshift in a rocket







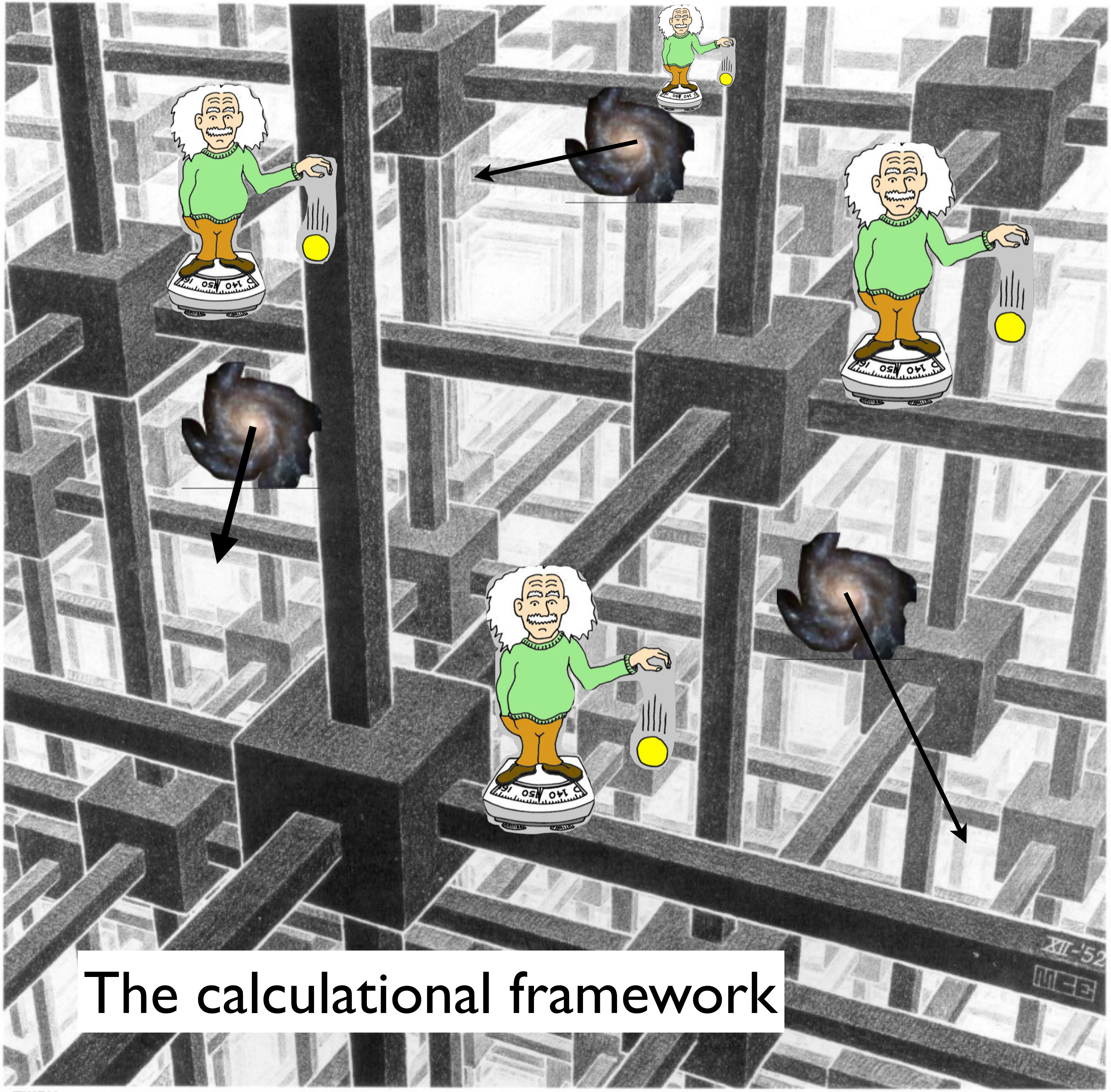
- during time $\delta t = x / c$ it takes the photon to make trip the velocity of receiver changes: $\delta v = g\,\delta t = g\,x / c$.
- Doppler shift: $\delta\lambda/\lambda = \delta v / c = g\,x / c^2$
- But is this gravity?

How to understand the gravitational redshift in clusters?

- Pound and Rebka confirmed that accelerated observers on earth see same $\delta\lambda/\lambda$ as rocketeers - in absence of gravity!
  - gravity is "transformed away" for freely-falling observers
  - like galaxies in a cluster ….

- Textbooks: cosmological redshift caused by expansion of space
  - Synge, Bunn & Hogg.. all redshifts are “kinematic”
  - But clusters are not expanding ….

- So naïve application of Einstein (Newton+Doppler) formula is questionable at best.



The calculational framework

Zhao, Peacock & Li, 2012

- δz is <u>not</u> just a gravitational redshift
- Sources are <u>moving</u>, so we also see a
  - *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 special relativistic time dilation - <u>moving clocks run slow</u>
- Generally of same order of magnitude as gravitational redshift from virial theorem, Jeans eq…

- Is that the full story?

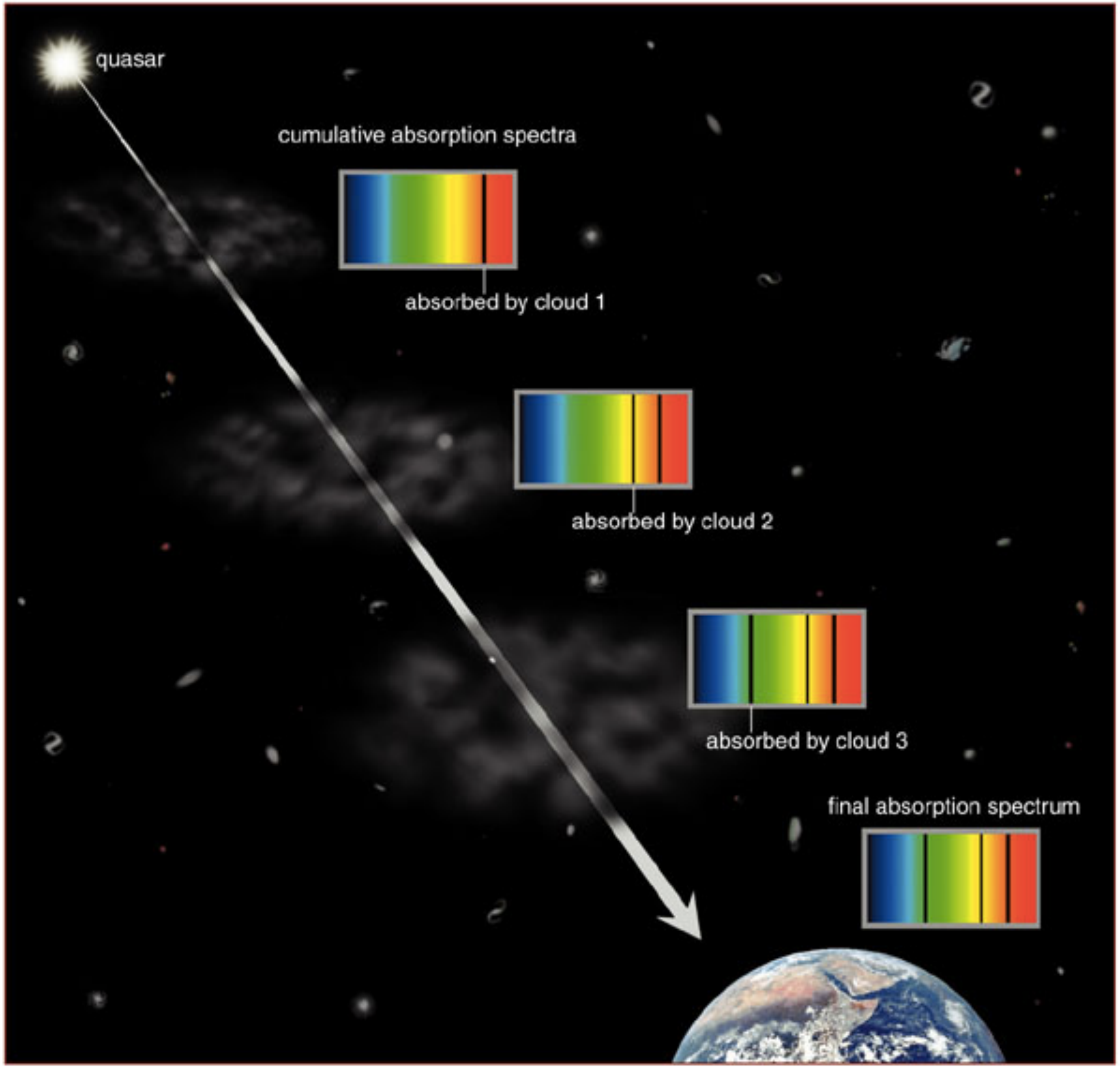
No - there is another effect of same order

- <u>Light cone effect</u>
  - if we observe swarm of objects - using light as a messenger - *we will tend to see more objects moving away from us than towards us*
  - this gives an extra red-shift
  - also of the same order of magnitude as the gravitational redshift

Light-cone effect

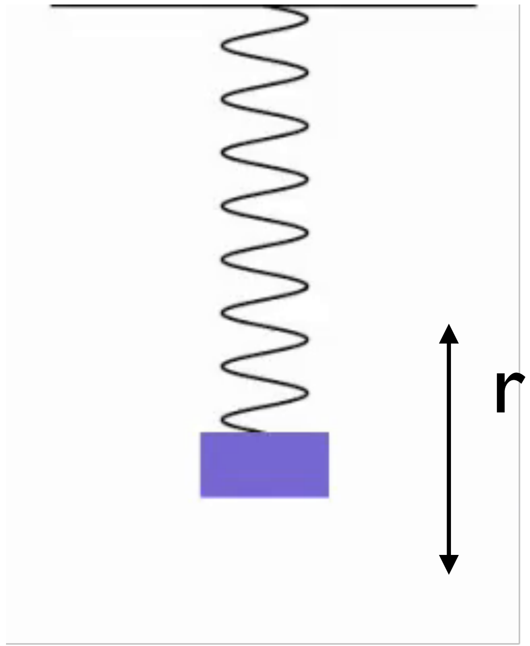
- Light cone effect
  - we will see more particles moving away from us in a photograph of a swarm of particles
    - past light cone of event of our observation overtakes more galaxies moving away than coming towards us
    - just as a runner on a trail sees more hikers going the other way...
    - So *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)

Quasar absorption lines

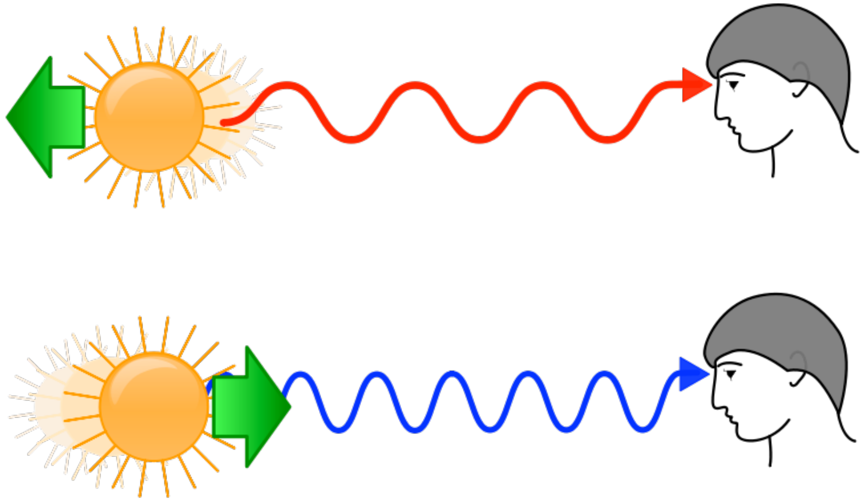


Another way to understand the light-cone effect

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



Yet another view of the light-cone effect



- Consider a particle oscillating in a square well potential and emitting pulses at a steady rate (2N per period)
- Observer sees intervals between pulses red- or blue-shifted
  - N short intervals followed by N long intervals
- In observation taken at a random time there is a greater chance to catch the particle when it is moving away
- In an observation of an ensemble of particles more particles will be seen going away from the observer

Why is the transverse Doppler effect a redshift?

- Transverse Doppler redshift effect:
  - first order Doppler shift ~v/c is large but averages to zero
  - residual is a quadratic $\sim(v/c)^2$ effect which caused randomly moving objects appear redshifted on average
  - can also be understood as a time dilation effect
- But moving objects have more energy per unit mass (in the observer frame)
- So if they convert their rest mass to photons we should see a blue-shift on average

a thought experiment

- bake cake, light candles, spin the cake up on a turntable and measure the energy of the photons (in the lab frame)
- <1st order Doppler shift> = 0
- 2nd order transverse Doppler effect gives a redshift
- but the candles are moving....
- so they have more energy (in our frame) per unit rest mass...
- so shouldn't we see a transverse Doppler blueshift?

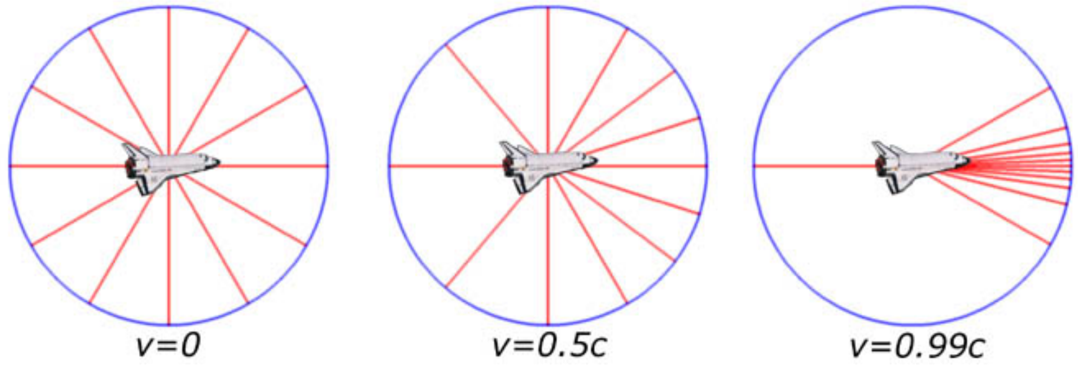
How do we resolve this?

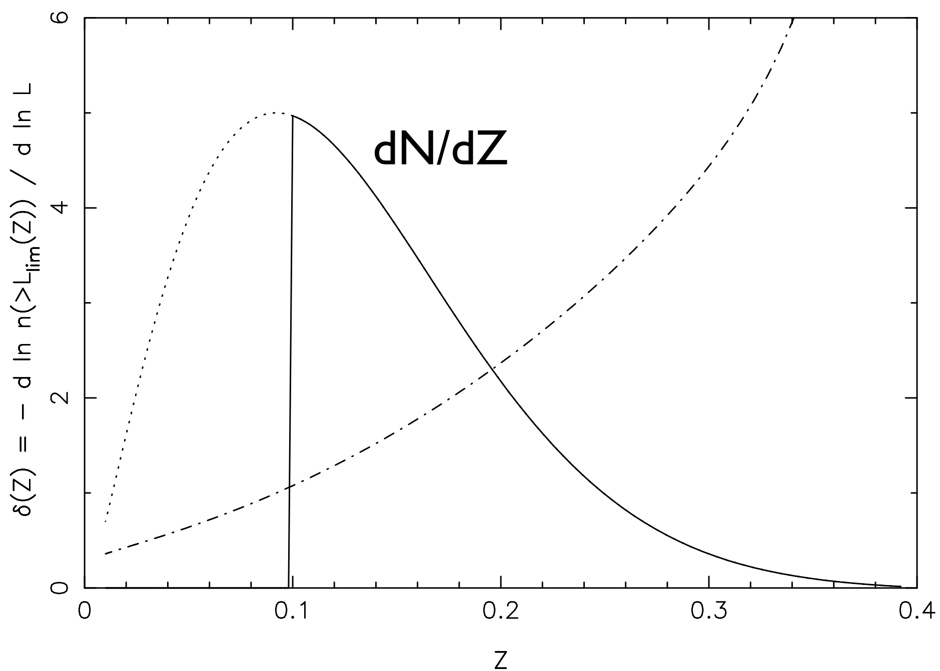
Transverse Doppler Effect: Redshift or Blueshift?

- Averaging over <u>objects</u> vs averaging over <u>photons</u>
  - averaging over *objects* we will see a redshift
    - but objects emitting isotropically in their rest frame do not emit isotropically in the lab frame - more photons come out in the forward direction - and these have a blue shift on average in the lab frame
    - this flips the sign of the effect
  - e.g. unresolved objects show blue shift (e.g. stars in the BCG or low resolution 21cm radio for integrated cluster z)
  - here we have a hybrid situation:
    - redshifts are measured for *objects*
    - but objects are *selected* according to flux density

Surface brightness modulation

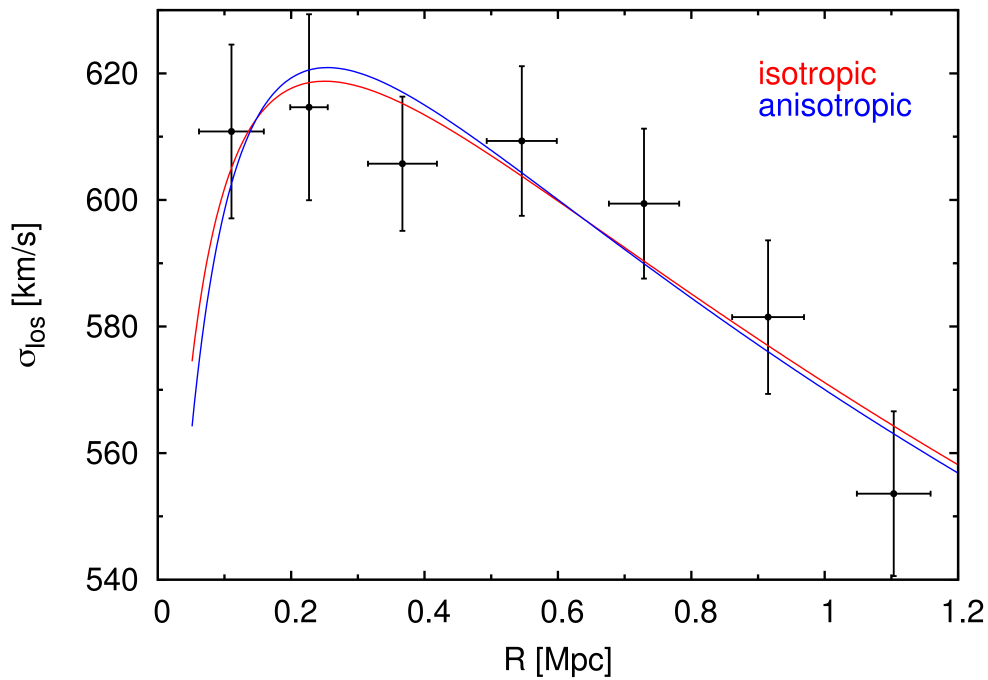
- Line of sight velocity changes surface brightness
  - relativistic beaming (aberration) plus change of frequency
- but doesn't change the surface area
- so velocities modulate luminosity
  - depends on SED: $\delta L/L = (3 + \alpha)v/c$
  - $\alpha \sim= 2$, so big amplification
  - spectroscopic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

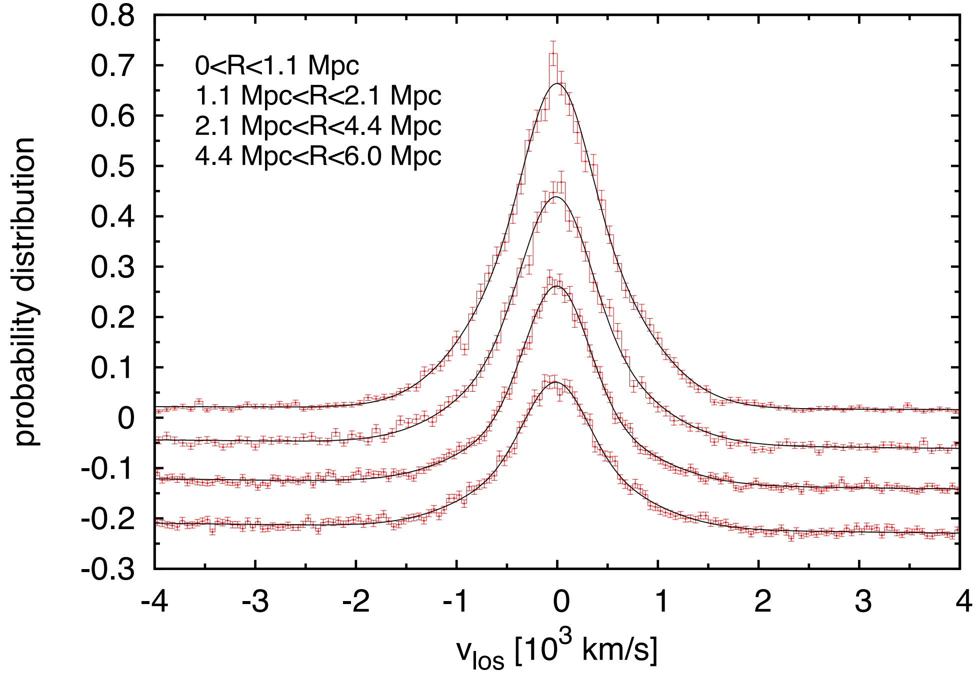




Corrected grav-z measurement

- 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





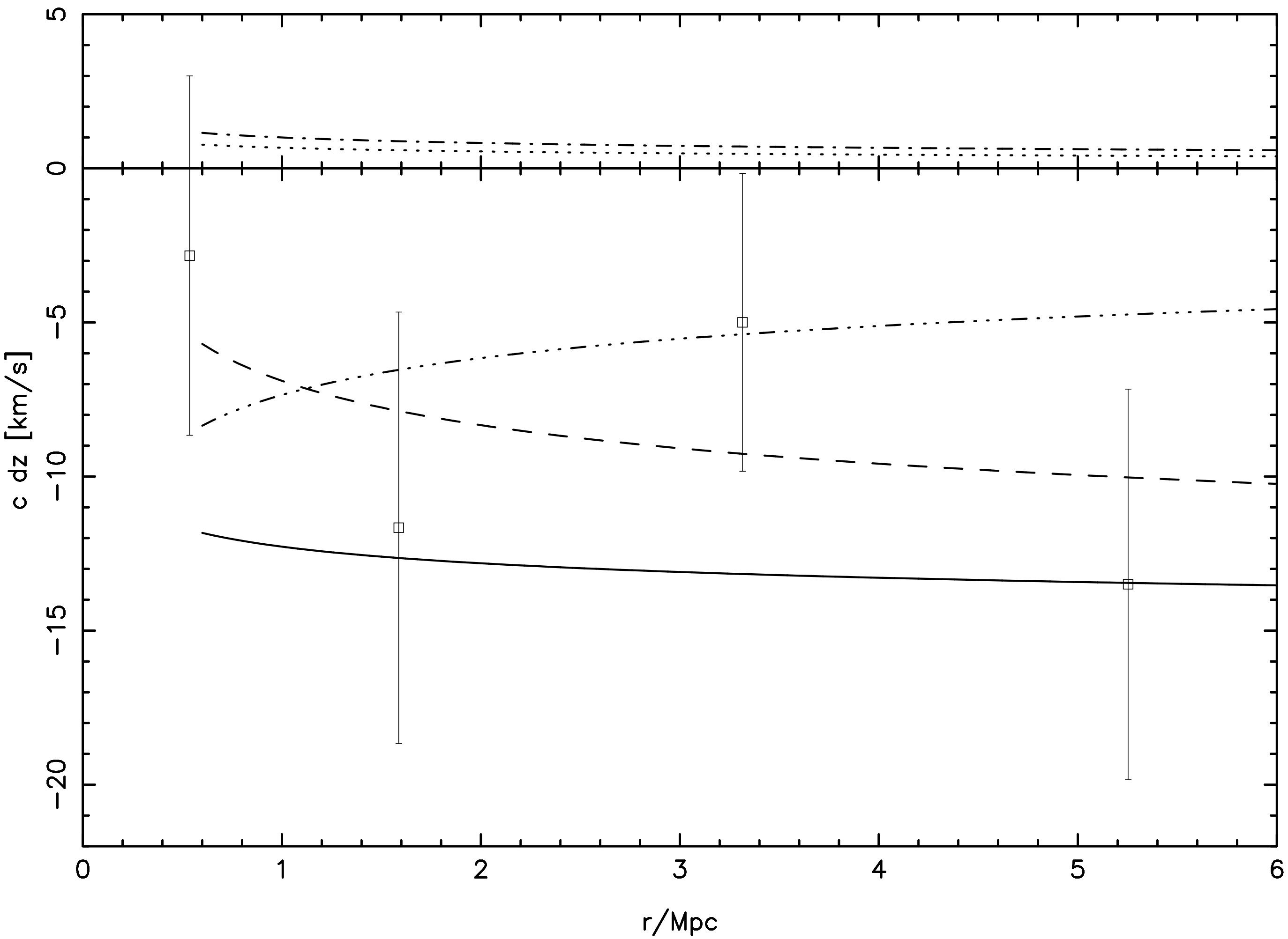


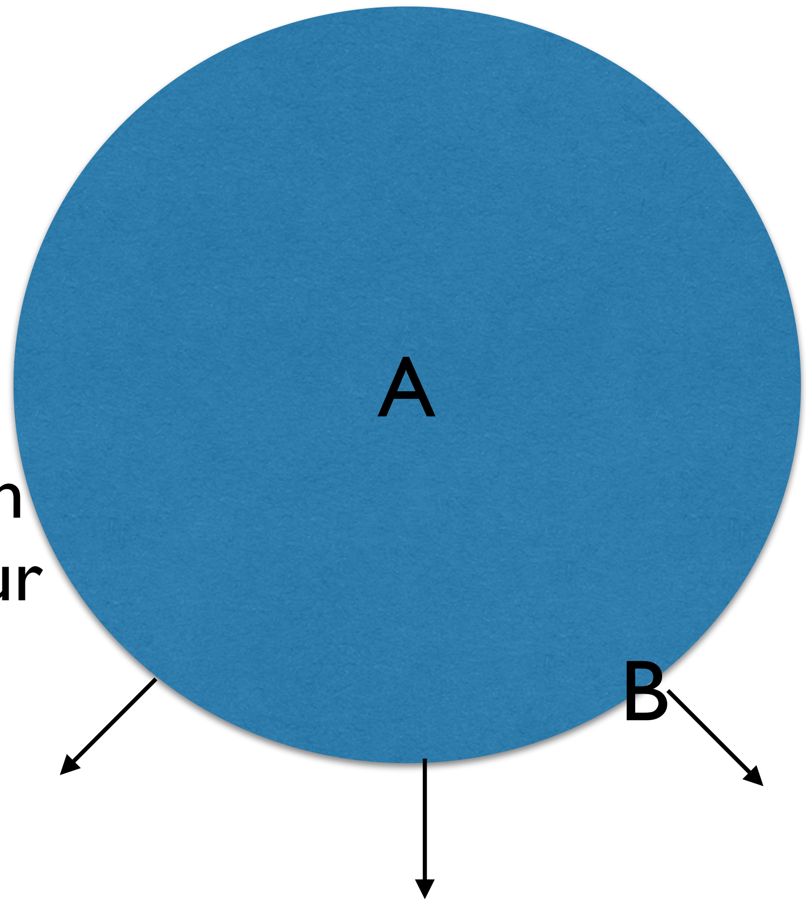
Figure 3. Data points from figure 2 of WHH and prediction based on mass-traces-light cluster halo profile and measured velocity dispersions as described in the main text. The dashed line is the gravitational redshift prediction, which is similar to the WHH model prediction. The dot-dash line is the transverse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

- Cosmology textbooks: expansion of space <u>causes</u> redshift
- Bunn & Hogg 2009: *"A gravitational redshift is just a Doppler shift viewed from an unnatural coordinate system*"
- But this confuses <u>gravity</u> and <u>acceleration</u>
- In GR the gravitational field is the Riemann (curvature) tensor
  - just the <u>tidal field</u> in the Newtonian limit
    - measured from relative motion of test particles
  - Quite distinct from <u>acceleration</u>
- So is there a truly <u>gravitational</u> component to the redshift?
  - and why does e.g. cosmological z appear kinematical?

Why is the gravitational-z hidden in cosmology?

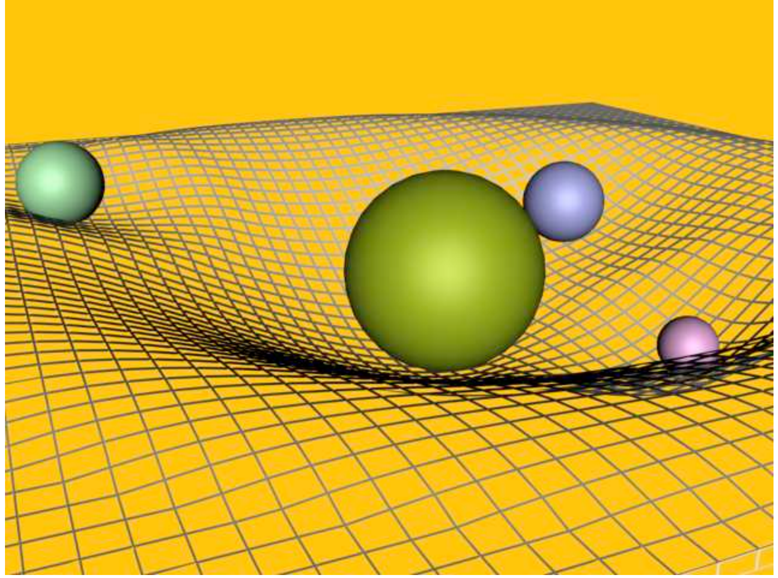
- Consider expanding sphere of dust and source A sending photon to receiver B
- Photon suffers gravitational <u>red-shift</u> climbing up the potential and then a Doppler red-shift on reception
- For source B sending to A the photon has a Doppler red-shift (as seen in our frame) then enjoys a gravitational <u>blue-shift</u>
- But the net effect is the same.
- The opposite gravitational shifts are <u>cancelled</u> by the Doppler shift change
- But this is a <u>special</u> situation



The non-kinematic part of the redshift

- Consider pair of freely-falling observers 1,2 in arbitrary gravitational field who exchange a photon.
- Use rigid, non-rotating lattice picture to calculate changes in wavelength and proper separation (work in CoM frame)
    - work to 2nd order in v/c and 1st order in φ/c^2
- $\Delta\lambda/\lambda = \mathbf{n} \,.\, (\mathbf{v}_1 - \mathbf{v}_2)_{t1} / c + \int d\mathbf{r} \,.\, (\mathbf{g}_2 - \mathbf{g}(\mathbf{r})) / c^2$ (1)
- $\Delta D/D = \mathbf{n} \,.\, (\mathbf{v}_1 - \mathbf{v}_2)_{t1} / c + \Delta\mathbf{r} \,.\, (\mathbf{g}_2 - \mathbf{g}_1) / 2c^2$ (2)
- Both are 1st order Doppler (with <u>initial</u> Δv) plus 'tidal' term
- <u>Spatially constant tidal field stretches λ just like D</u>
    - includes Minkowski spacetime and FRW
        - but that's because of special *symmetry* of FRW
    - does not apply for a galaxy cluster
- extra intrinsically gravitational term (gradient of tide)

What does it mean?



- Probe of curvature of space in GR?
  - *matter tells space how to curve*
  - *space tells matter how to move....*
- Like how lensing tests gravity?
- Not quite:
  - motion of galaxies & grav-z are determined only by g_{tt}
- It is really a test of the <u>equivalence principle</u>
  - A test of theories with extra long-range non-gravitational "fifth" forces
  - Common feature of string-inspired cosmology; models where DM and DE interact; f(R) gravity …..
  - though such theories are already constrained by X-ray temp. vs galaxy motions in clusters....

Conclusions

- Gravitational redshifts in clusters of galaxies have been measured!
- Technically challenging but apparently real and prospects for better measurements and extension to larger scales is promising.
- Potentially useful test of alternatives to GR & 5th forces
- But also interesting as a "sand-box" that illustrates some subtleties of simple special relativity + Newtonian gravity
- Effect raises some questions of principle about how to think about redshifts in cosmology and astronomy in general.
- Redshifts are not purely kinematic - there is an truly gravitational component - but it is hidden in cosmology