Gravitational Redshifts in Clusters of Galaxies

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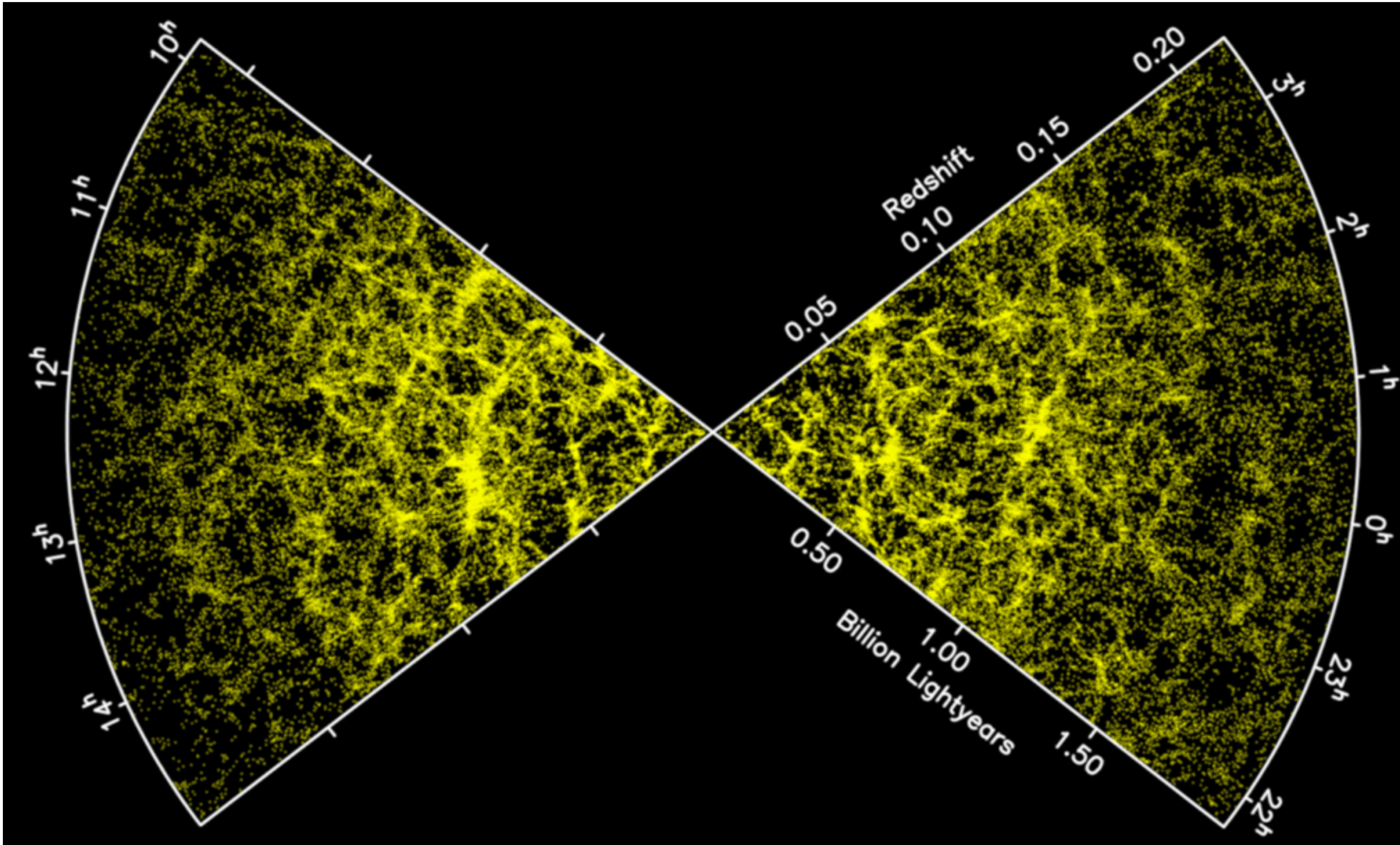
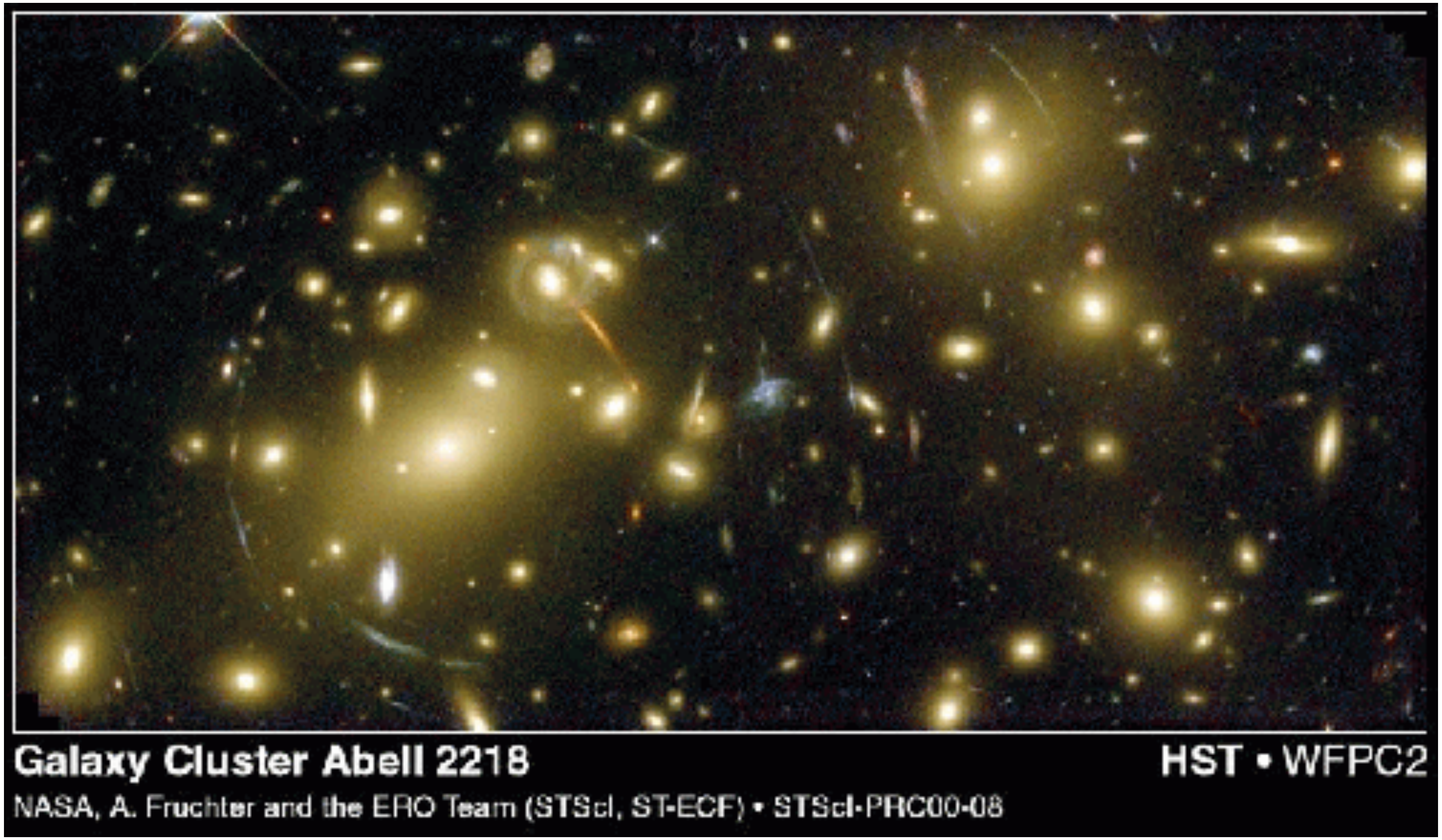
The cosmic web in the 2df galaxy redshift survey

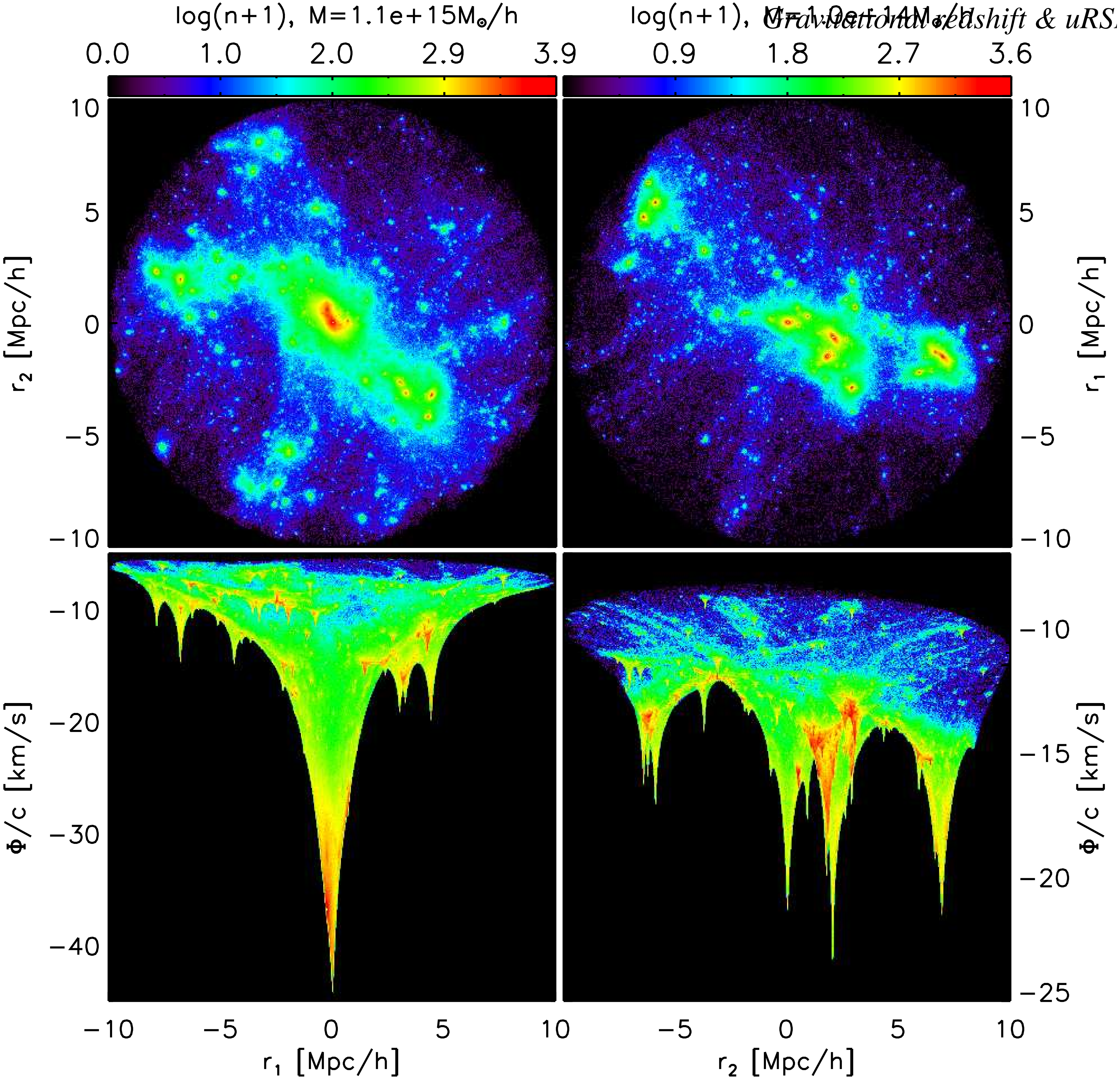


Clusters of galaxies



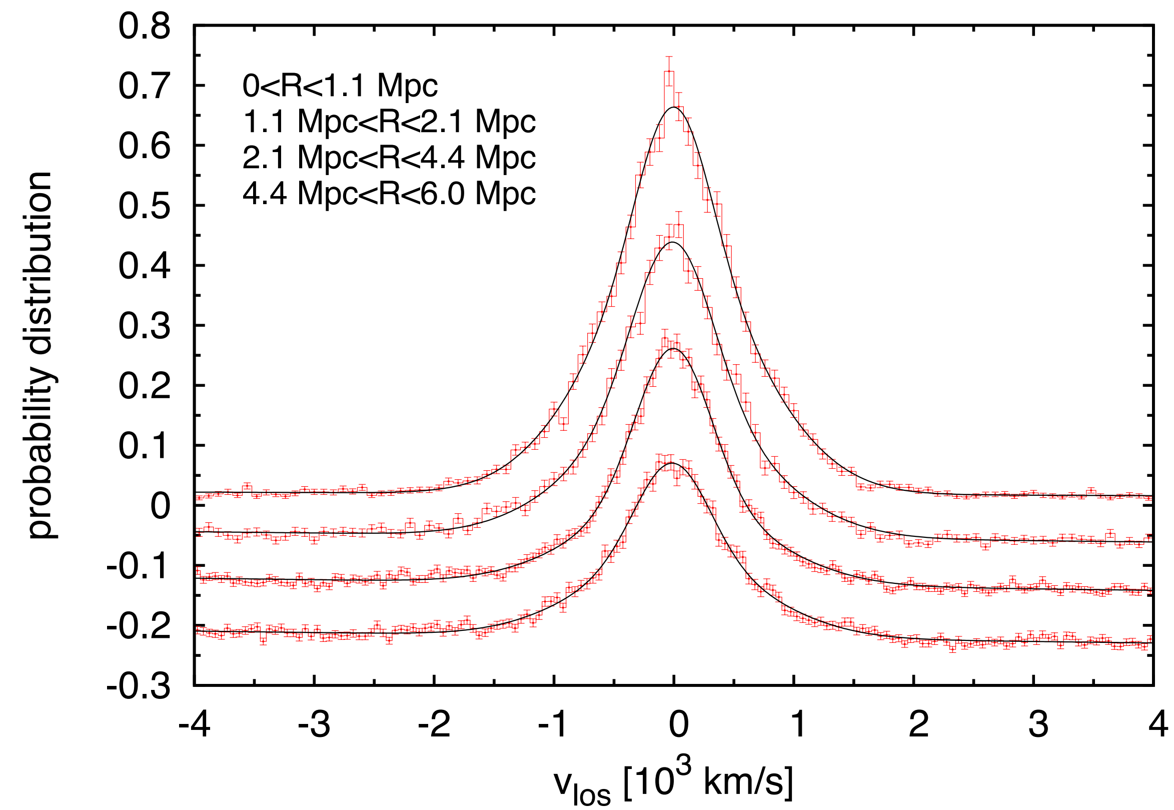
- Largest bound virialised systems ~10^{14}-$10^{15} M_{sun}$
- Velocity dispersion σ_v~1000 km/s (~0.003c)
  - so grav. potential is $\varphi \sim \sigma_v^2 \sim 10^{-5}\ c^2$
- Centres - often occupied by the brightest galaxy (BCG)
  - Usually very close to peak of light, X-rays, DM

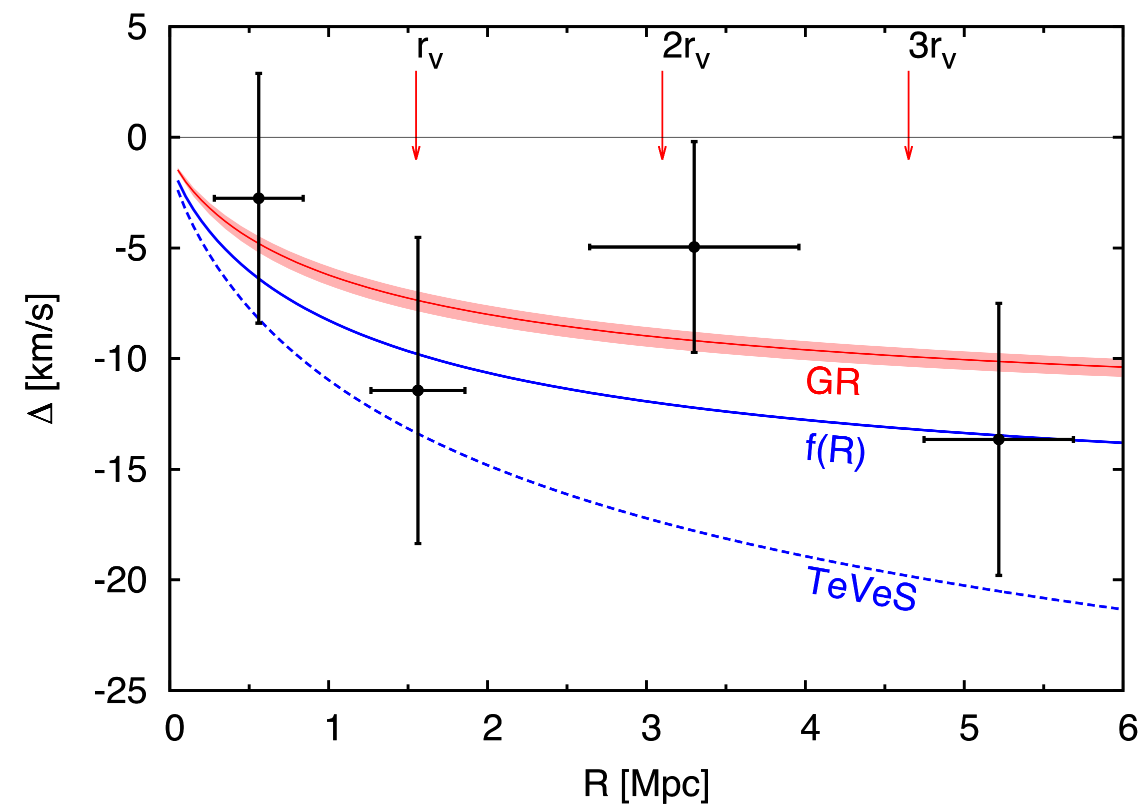
Clusters in the Millenium Simulation (Y. Cai)

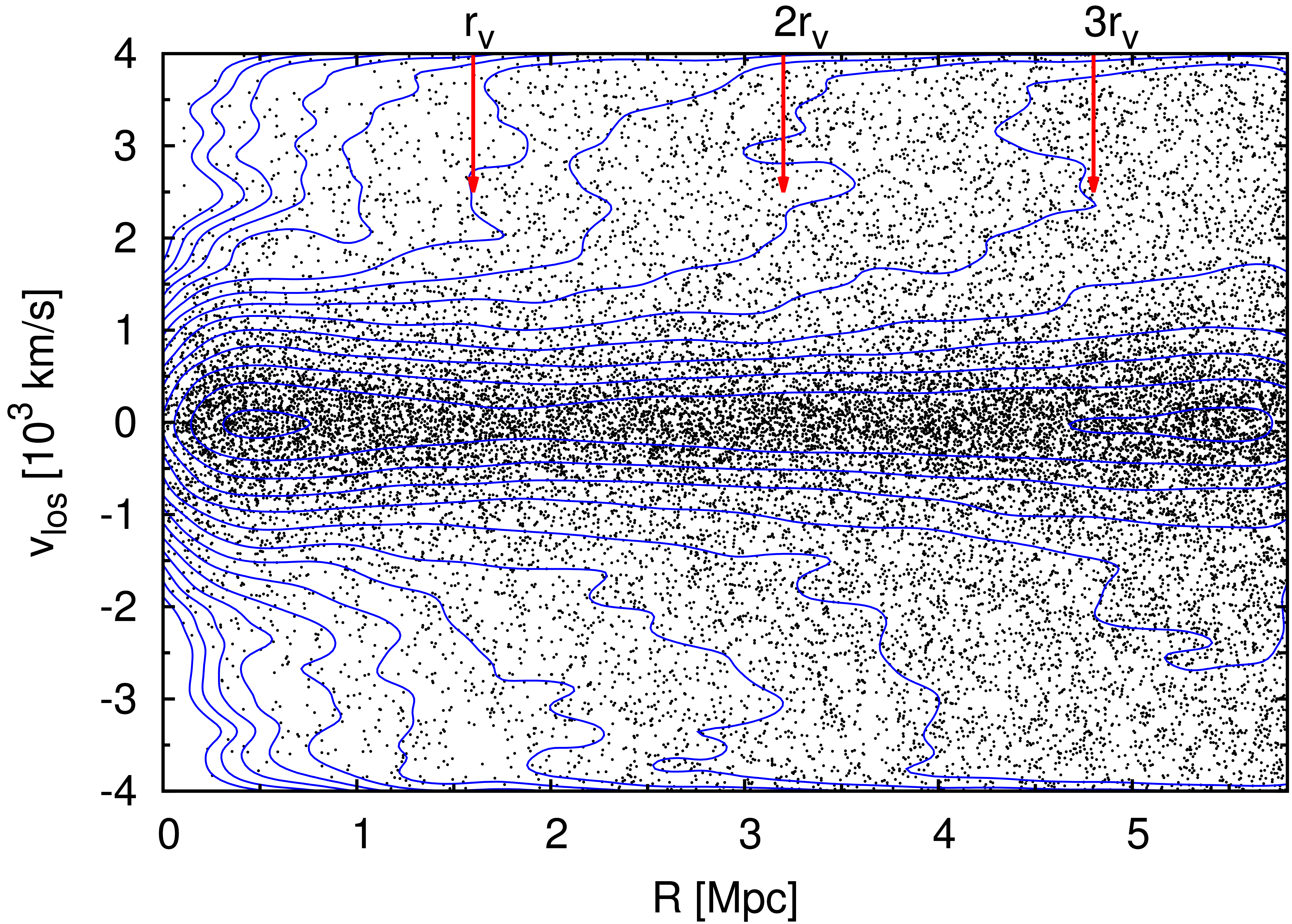


Wojtak, Hansen & Hjorth (Nature 2011)

- 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, ...)



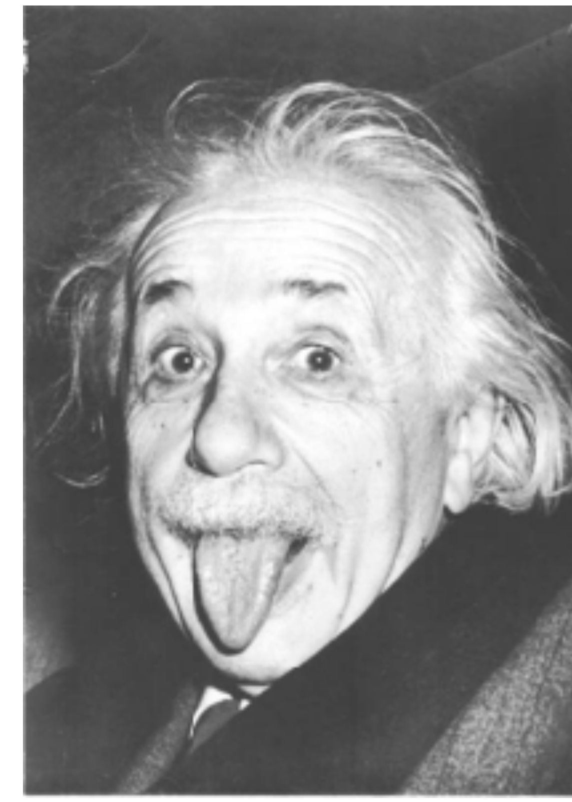


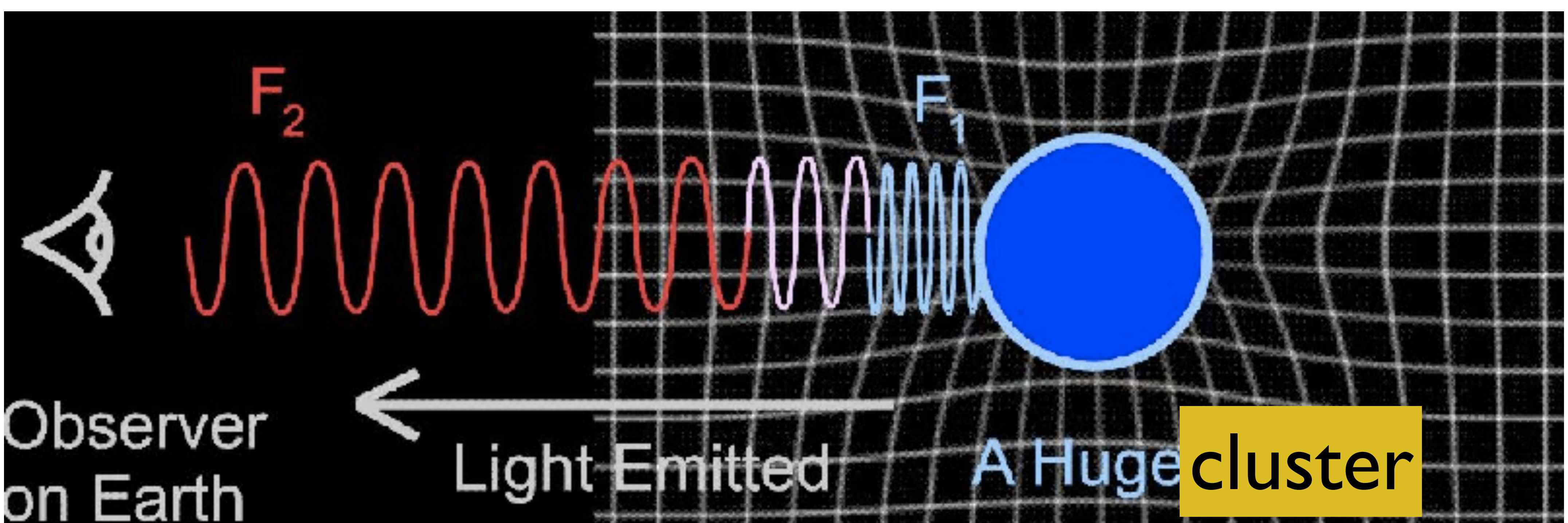


r_v
2r_v
3r_v
4
3
2
1
0
-1
-2
-3
-4
v_los [10^3 km/s]
0
1
2
3
4
5
R [Mpc]

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)

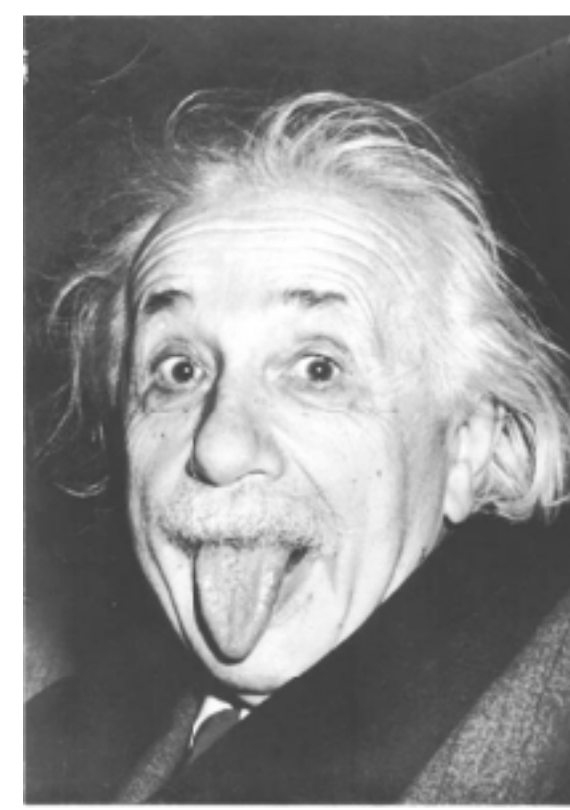




Is that it?

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 bore-hole.

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 (1910) thought experiment

The gravitational redshift experiment. Let us first imagine performing an idealized experiment, first suggested by Einstein. (i) Let a tower of height h be constructed on the surface of Earth, as in Fig. 5.1. Begin with a

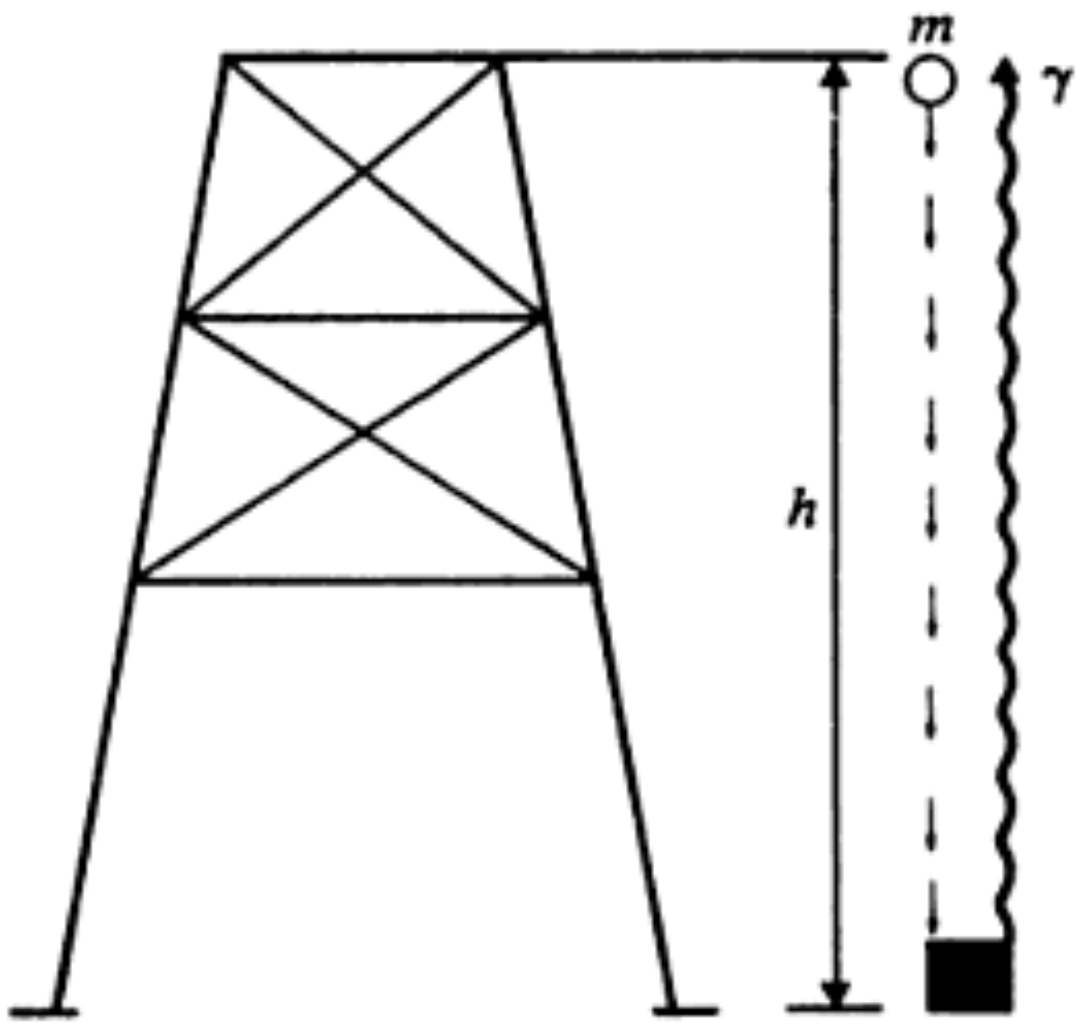
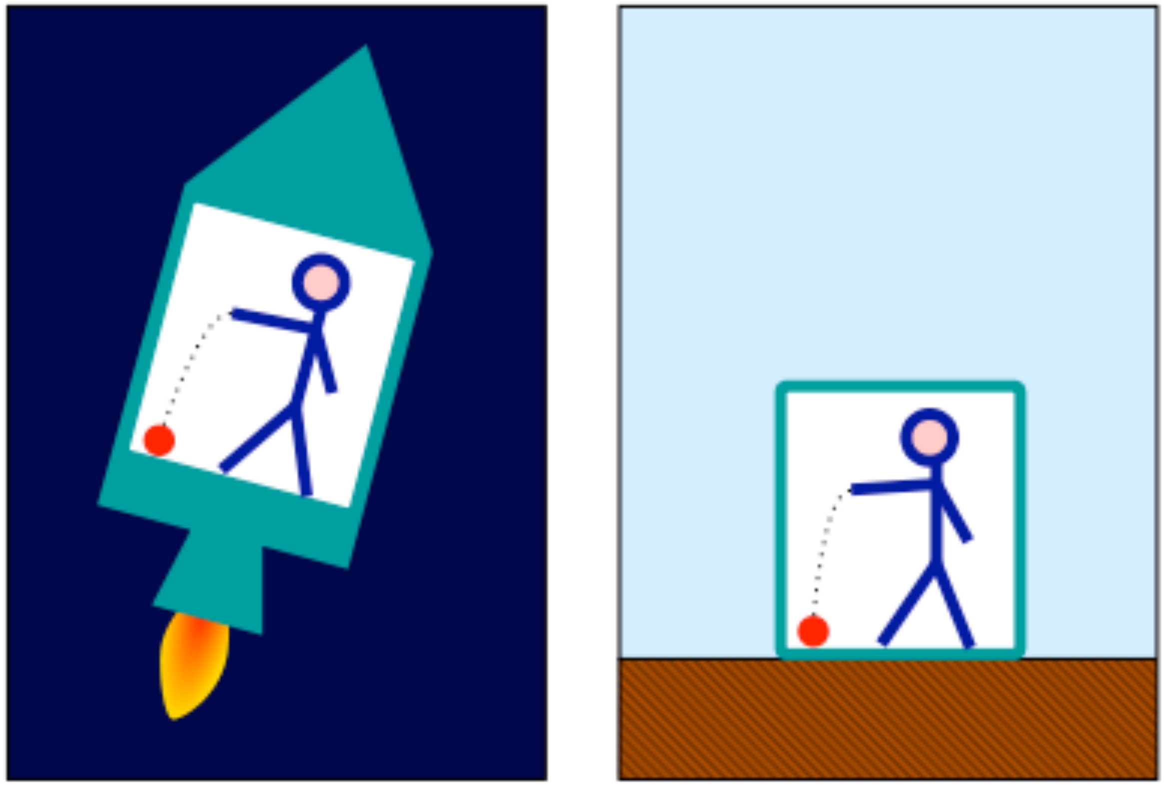
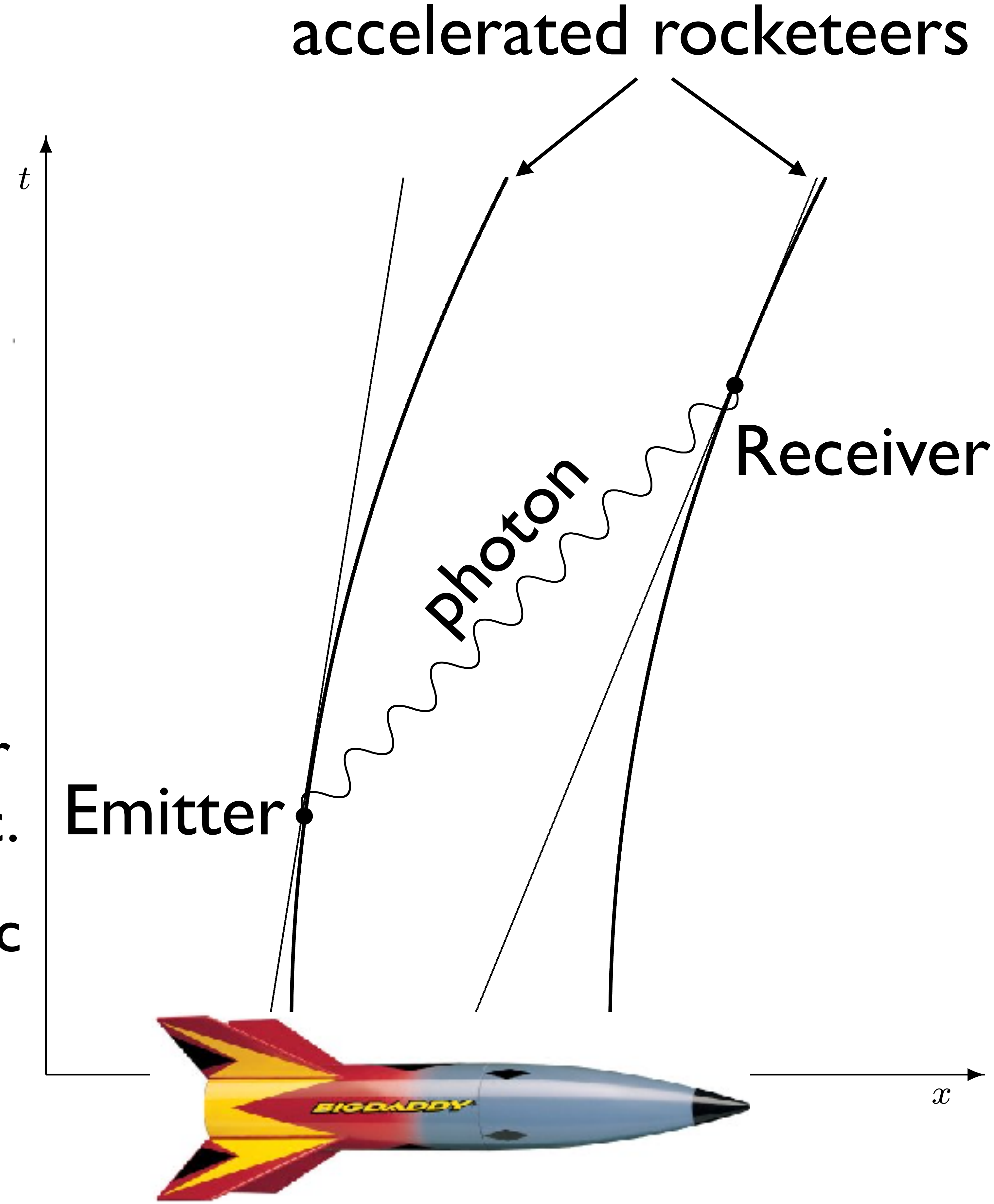


Fig. 5.1 A mass m is dropped from a tower of height h. The total mass at the bottom is converted into energy and returned to the top as a photon. Perpetual motion will be performed unless the photon loses as much energy in climbing as the mass gained in falling. Light is therefore redshifted as it climbs in a gravitational field.

Einstein's calculation of the redshift in a rocket





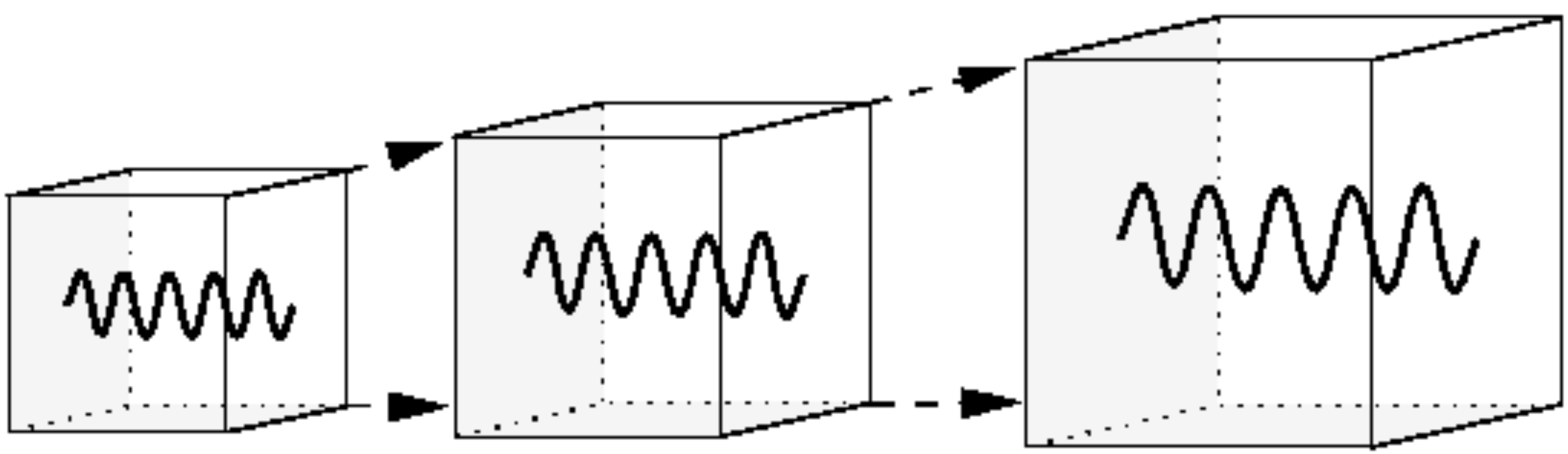
- during time $\delta t = x / c$ it takes the photon to make trip the velocity of receiver changes: $\delta v = g\ \delta t = g\ x / c$.
- Doppler shift: $\delta\lambda/\lambda = \delta v / c = g\ x / c^2$
- But is this <u>gravity</u>?

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!
  - but gravity is "transformed away" for freely-falling observers
  - like galaxies in a cluster ….
- Textbooks: cosmological redshift caused by expansion of space
  - But clusters are not expanding ….
- So naïve application of Einstein (Newton+Doppler) formula is questionable at best.

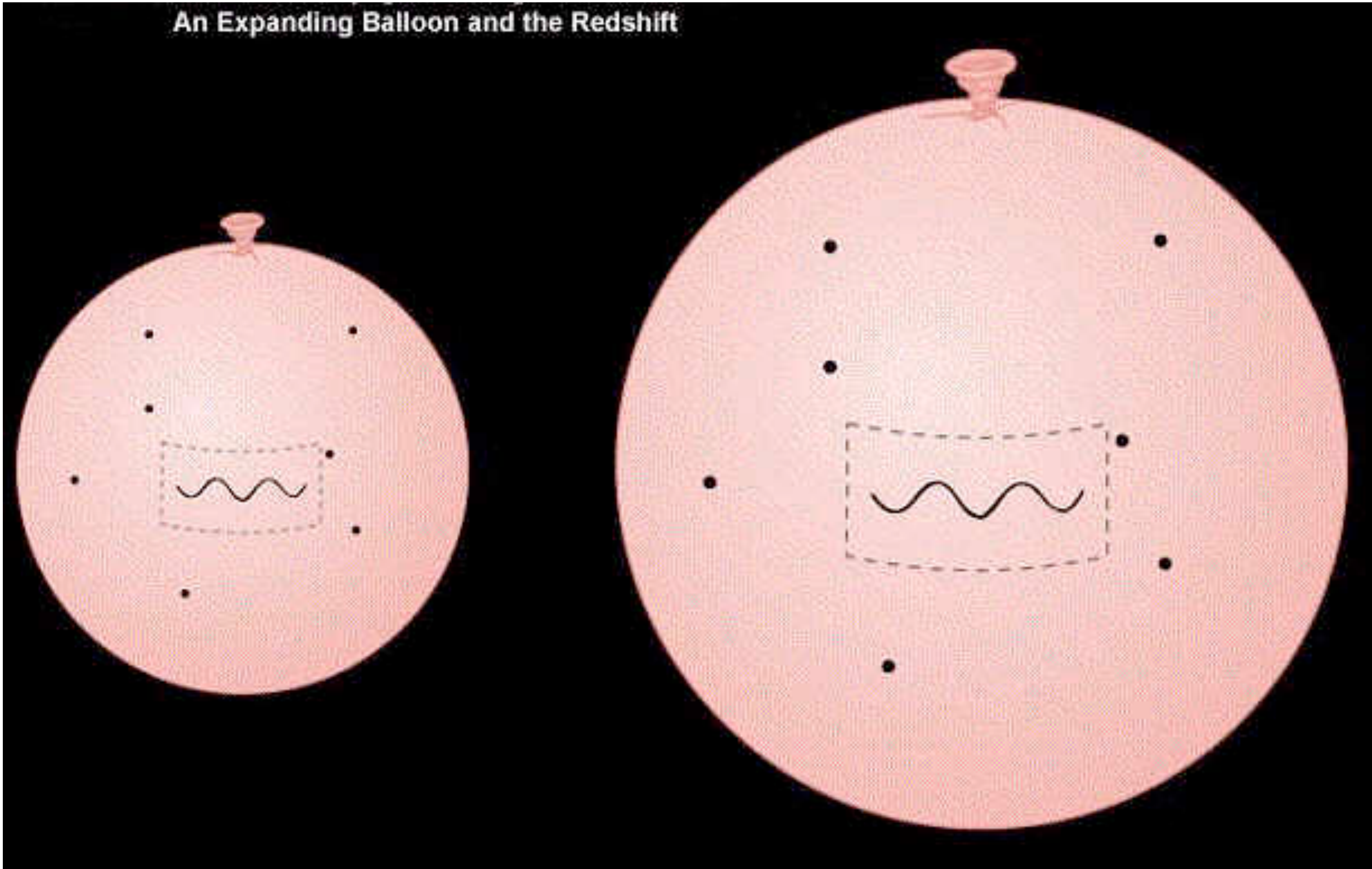
Redshift in homogeneous FLRW cosmology...

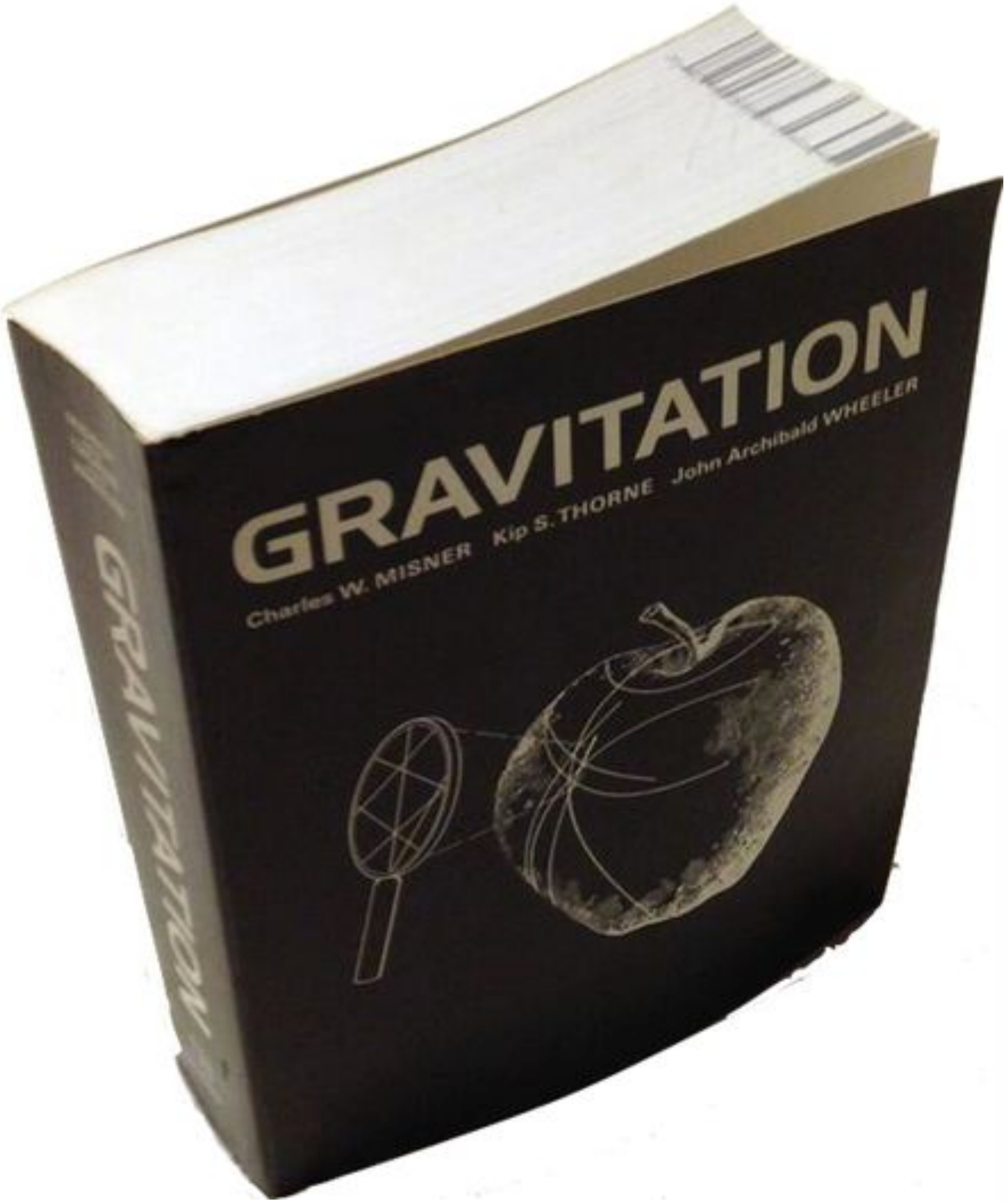
- Wavelength scales as a(t) - but why?
  - Analogy with expanding reflecting cavity
    - a) lots of little redshifts as photons bounce off walls
    - b) symmetry - standing waves - fixed # of nodes
  - either way: accumulated effect: $\lambda \sim a(t)$

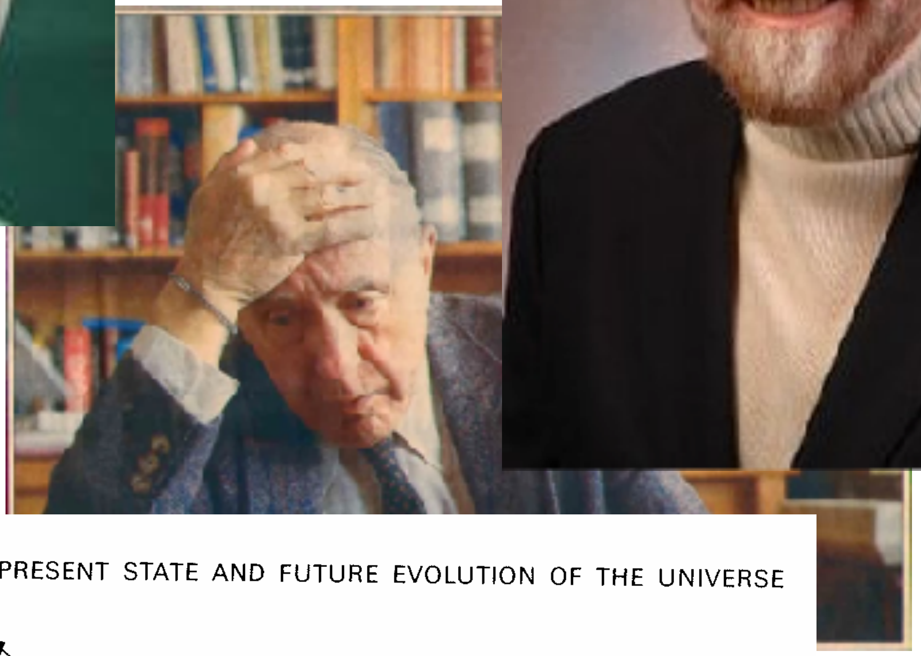


from Peacock

The rubber balloon analogy







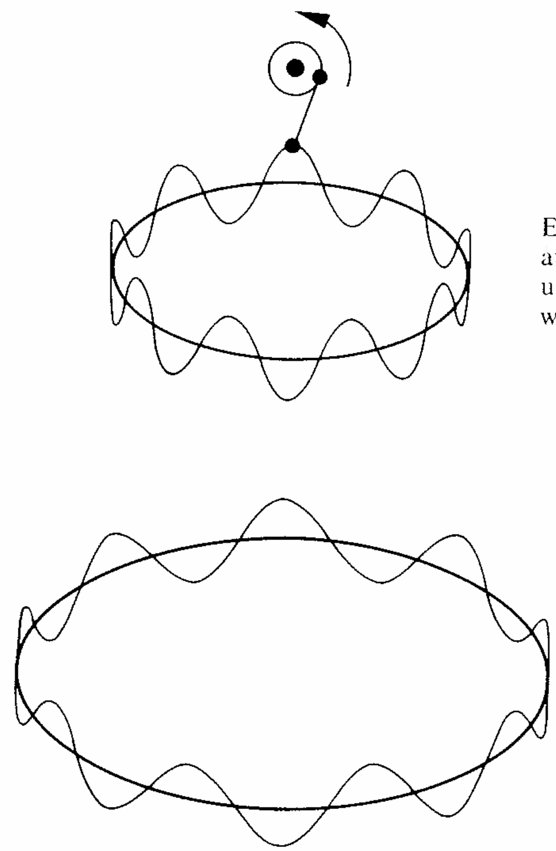
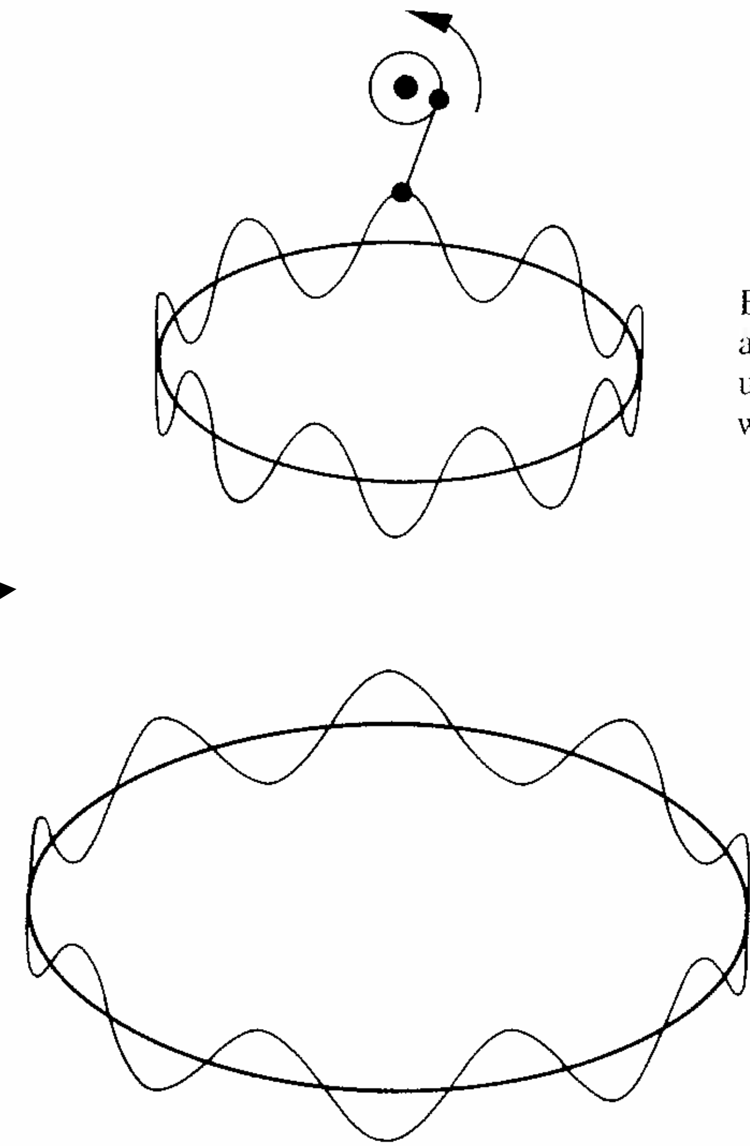


Figure 29.1.
Redshift as an effect of standing waves. The ratio of wavelengths, $\lambda_{rec}/\lambda_{em}$, is identical with the ratio of dimensions, a_{rec}/a_{em} in any closed spherically symmetrical (Friedmann) model universe. The atom excites an n-node standing wave in the universe. The number n stays constant during the expansion

Misner, Thorne and Wheeler

redshift as an effect on standing waves....

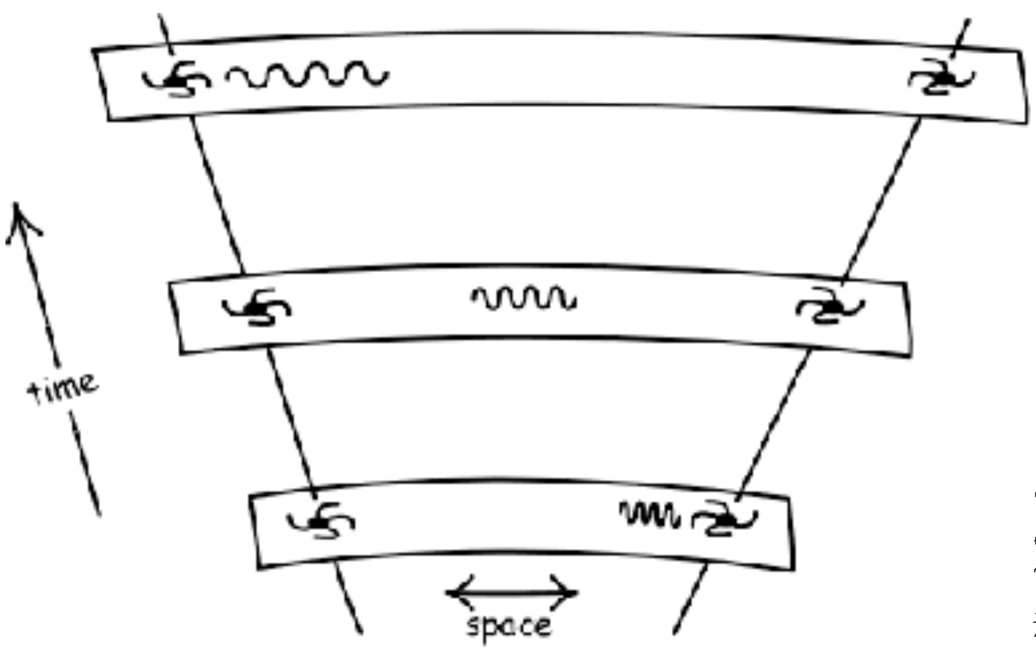


Emission:
atom excites n-node standing wave;
universe small, $a(t_e) = a_{\text{em}}$;
wavelengths small, $\lambda(t_e) = \lambda_{\text{em}}$.

Reception:
universe larger, $a(t_r) = a_{\text{rec}}$;
wavelengths larger, $\lambda(t_r) = \lambda_{\text{rec}}$;
number of nodes in standing wave unchanged:

$$n = \text{constant} = \frac{2\pi a_{\text{rec}}}{2\pi \lambda_{\text{rec}}} = \frac{a_{\text{em}}}{\lambda_{\text{em}}}.$$

Figure 29.1.
Redshift as an effect of standing waves. The ratio of wavelengths, $\lambda_{\text{rec}}/\lambda_{\text{em}}$, is identical with the ratio of dimensions, $a_{\text{rec}}/a_{\text{em}}$ in any closed spherically symmetrical (Friedmann) model universe. The atom excites an n-node standing wave in the universe. The number n stays constant during the expansion. Therefore wavelengths increase in the same proportion as the dimensions of the universe. One sees immediately in this way that the redshift is independent of all such details as (1) why the expansion came about (spherical symmetry, but arbitrary equation of state); (2) the rate—uniform or nonuniform—at which it came about; and (3) the distance between source and receptor at emission, at reception, or at any time in-between. The reasoning in the diagram appears to depend on the closure of the universe (standing waves; $k = +1$ rather than 0 or -1). That closure is not required for this simple result is seen from the further analysis given in the text.



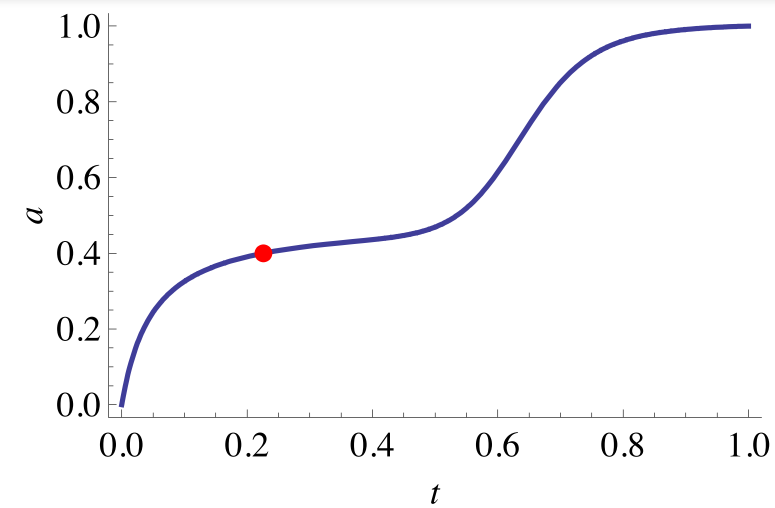
But is <u>this</u> a standing wave?

Expanding space and redshifts in textbooks.....

- E.R. Harrison (2000)

We suppose that all galaxies are comoving and that their light is received by observers who are also comoving. Light leaves a galaxy, which is stationary in its own local region of space, and is received by observers who are also stationary in their own local region of space. Between the galaxy and the observers light travels through vast regions of expanding space. What happens is immediately obvious: All wavelengths of the light are stretched by the expansion of space (see Figure 11.1). It is as simple as that.

Expansion redshifts are produced by the expansion of space between bodies that are stationary in space: They depend on the increase of distance between the emitter and the receiver during the time of propagation; they are the result of recession velocities and not peculiar velocities; and they are not governed by the rules of special relativity.



- Wolfgang Rindler (1970)

Note that the cosmological red shift is really an *expansion* effect rather than a *velocity* effect.

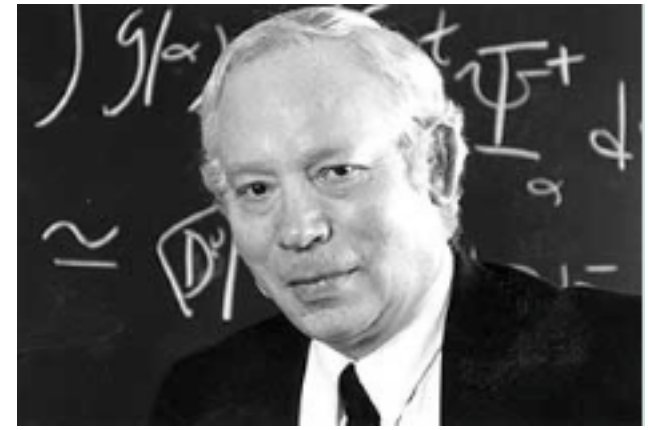
Space is expanding ... and this causes redshifts

is redshift caused by expansion of space?

- Textbooks are correct
  - λ does increase with a(t)
- But is it reasonable to say expansion causes the shift?
- And is it obvious?
  - what is the mechanism by which space stretches light?
  - is space expanding in this room?
  - is space expanding in a cluster of galaxies?

Expanding Space: the Root of all Evil?*

Matthew J. Francis[1,4], *Luke A. Barnes*[1,2], *J. Berian James*[1,3] & *Geraint F. Lewis*[1]



However, the academic argument surrounding the expansion of space is not as clear as standard explanations suggest; an interested student and reader of New Scientist may have seen Martin Rees & Steven Weinberg (1993) state

> ...how is it possible for space, which is utterly empty, to expand? How can nothing expand? The answer is: space does not expand. Cosmologists sometimes talk about expanding space, but they should know better.

But see also Weinberg, 1st 3 Minutes, p31: "One can think of the wave crests being pulled farther and farther apart by the expansion of the universe."

while being told by Harrison (2000) that

> expansion redshifts are produced by the expansion of space between bodies that are stationary in space

What is a lay-person or proto-cosmologist to make of this apparently contradictory situation?

thermodynamic perspective

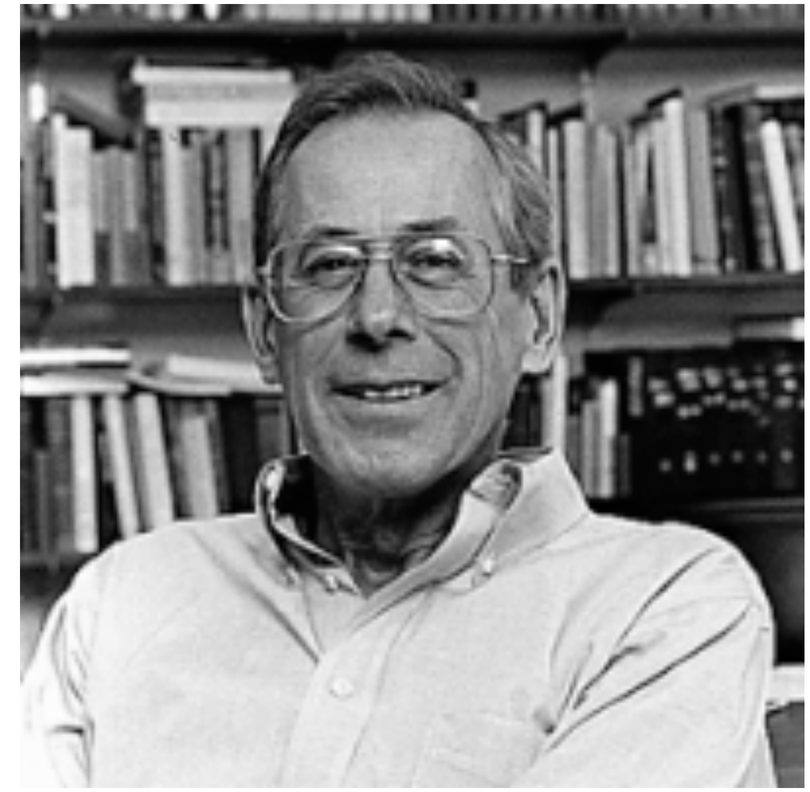
- <u>1) Thermodynamics plus photons as quanta:</u>
  - Ist law of thermodynamics: dE = pdV (or $T^{0\mu}{}_{;\mu} = 0$)
    - with pressure $P = \rho c^2/3$
    - and $E = mc^2$
    - $d\rho/dt = -3H(\rho + P / c^2)$
    - implies $\rho_{rad} \sim a^{-4}$
  - plus conservation of photon number (or entropy)
    - $n_\gamma \sim a^{-3}$
- With $E_\gamma = h\nu$ gives $\lambda \sim a$

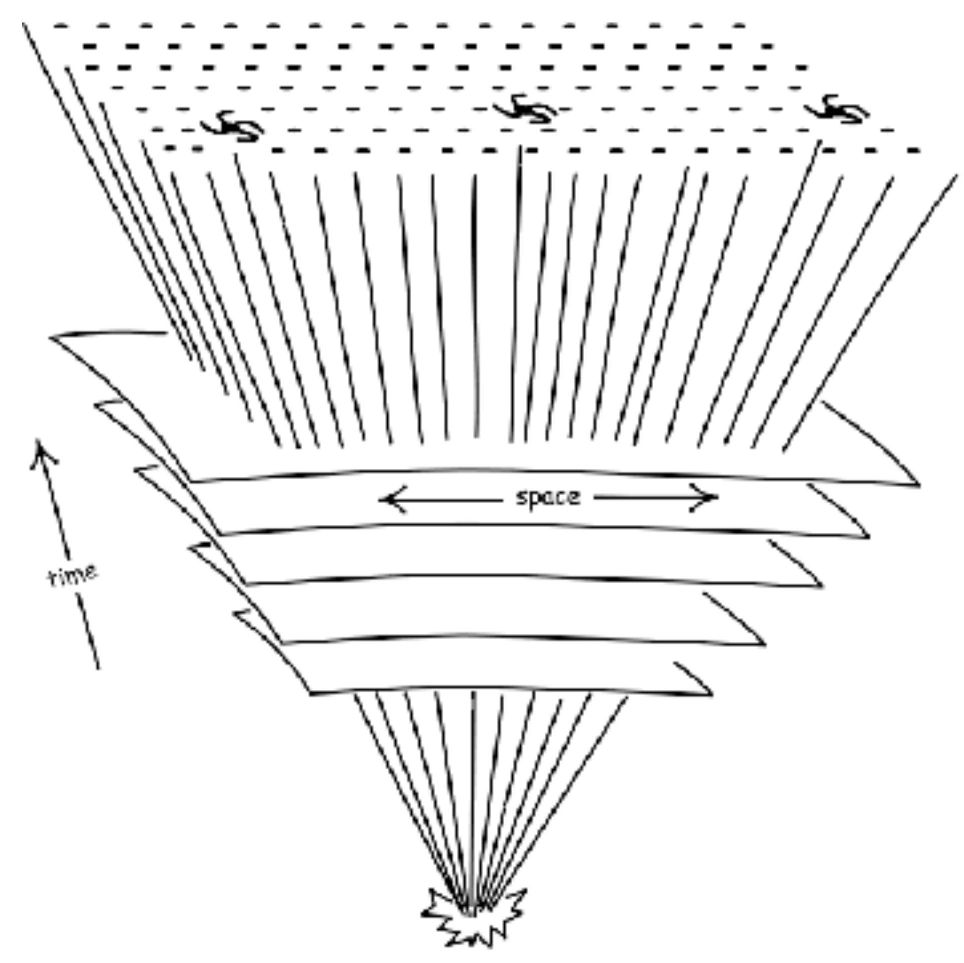
Mathematics of radiation in "expanding space"

- In non-expanding space, extremizing the action
  - $S = \int dt\, d^3x\, L(\partial_t\varphi, \nabla_x\varphi)$
  - with $L = ((\partial_t\varphi)^2 - (\nabla_x\varphi)^2)/2$ (i.e. massless scalar field)
- Gives the wave equation with propagation speed c (unity here)
  - $\partial_t^2\varphi - \nabla_x^2\varphi = 0$
- Write physical coordinate $x = a(t)\, r$ ('comoving' coordinate)
  - $\delta S = \delta \int dt\, d^3r\, L'(\partial_t\varphi, \nabla_r\varphi) = 0$
    - with $L' = a(t)^3 L$ (and $\nabla_r\varphi = a(t)\, \nabla_x\varphi$)
  - Gives $\partial_t^2\varphi + 3\, H\, \partial_t\varphi - a^{-2}\nabla_r^2\varphi = 0$
    - expansion gives extra 'damping', or 'friction', term $3\, H\, \partial_t\varphi$ involving the expansion rate $H = (da/dt)/a$.
    - standing waves (in r): energy density $(\partial_t\varphi)^2 \sim a^{-4}$
  - Oscillator with (slowly) time varying frequency
    - adiabatic invariant $E/\omega \sim a^{-3}$ - like n = #-density of photons
- Again, all consistent with thermodynamics and $\lambda \sim a$

Peebles ('71) explanation of cosmological redshift

- The redshift $\lambda_{rec}/\lambda_{em}$ is the product of a lot of small shifts between a set of FOs along the look-back path
- In the vicinity of a neighouring pair of FOs
  - space-time is locally flat, so
  - incremental redshifts are Doppler shifts
- Yields differential equation
  - $d\lambda/\lambda = da/a$ with solution $\lambda \propto a(t)$
- So fractional change in proper separation is the same as the fractional change in λ
- i.e. $\delta \log(\lambda/D) = 0$

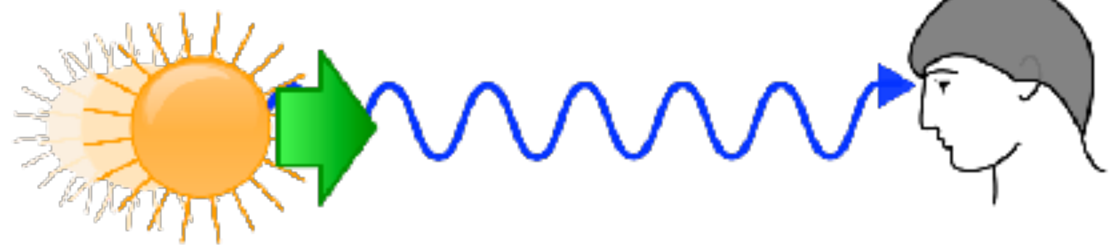




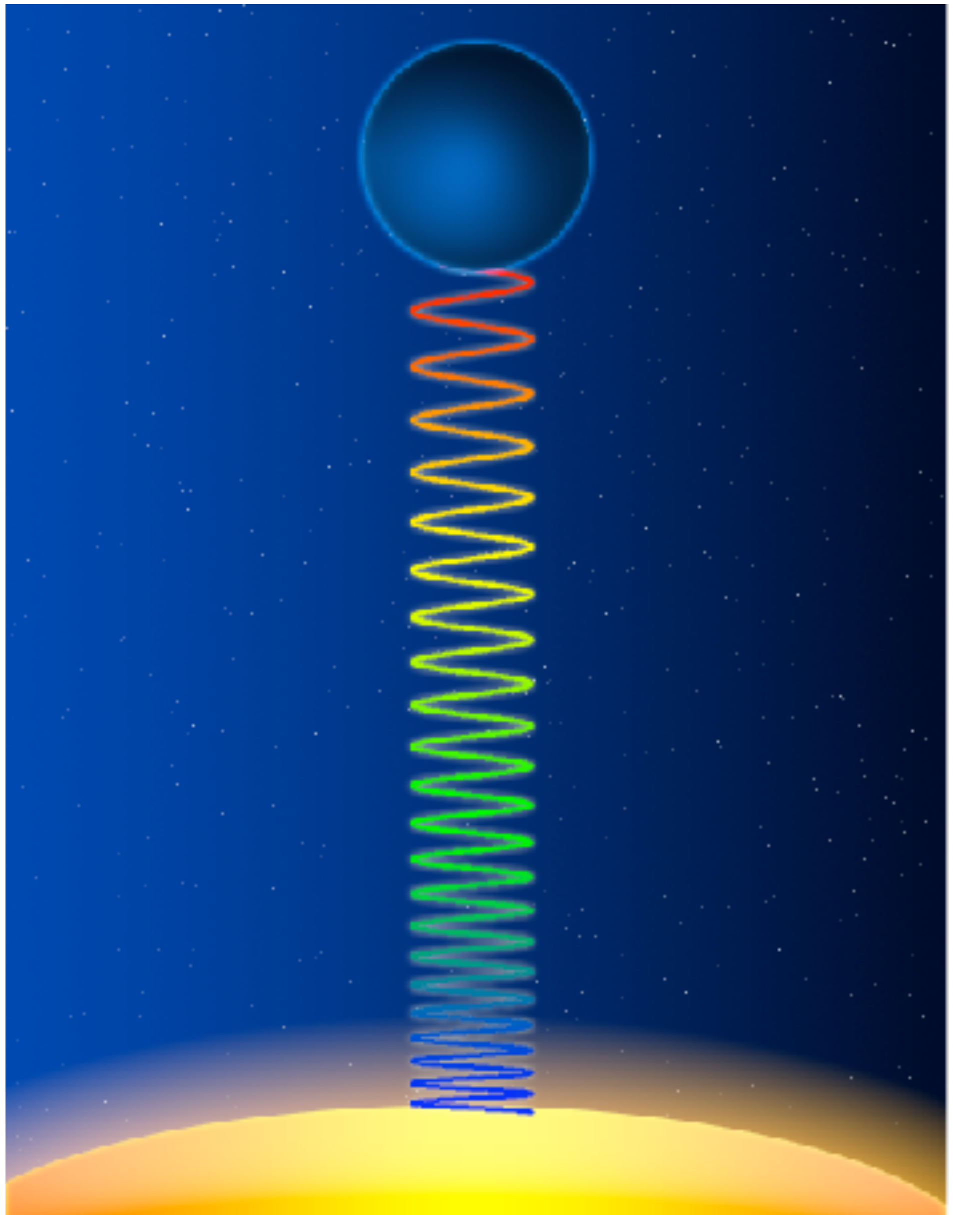
Redshift and expansion in cosmology

- So in cosmology wavelength λ <u>is</u> tied to expansion a(t)
  - many different arguments support this
  - may or may not be <u>caused</u> by it
- If observer/source are moving apart then λ increases
- Exactly as for Doppler shift in empty space
- So any <u>gravitational</u> component to redshift - i.e. that due to the presence of <u>matter</u> - is somehow <u>hidden</u>
- Q: Is this a general principle?

What about redshifts in a *lumpy* universe?



- Bondi (1947): Spherical models:
  - for low-Z, redshift is product of Doppler and gravitational redshift
- But Synge (1960) argued that *all* redshifts are Doppler shifts
  - “In attributing a *cause* to this spectral shift, one would say .... that the spectral shift was caused by the relative velocity of the source and the observer".



Synge, 1960; General Relativity

- Observed (or emitted) energy is dot product of observer 4-velocity and the photon 4-momentum.
- → wavelength shift is given by Doppler's formula with "relative velocity" being the l.o.s. component of the difference of the receiver 4-velocity and a parallel transported version of the emitter 4-velocity
- "Not a gravitational redshift as the Riemann tensor does not appear in formula"

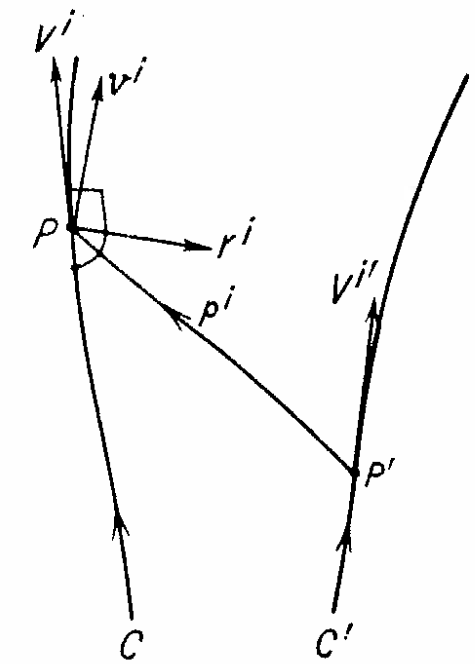


Fig. 10 – Relative velocity and Doppler effect (mechanical)

some luminous object, such as a star or planet. We connect them with null geodesics such as $P'P$. We cannot immediately compare the 4-velocity V^i of C at P with the 4-velocity $V^{i'}$ of C' at P', because they are vectors at different events. The obvious plan is to bring them to a common event by subjecting $V^{i'}$ to parallel transport along $P'P$; this gives us at P the vector

$$v_i = g_{ij'}V^{j'}, \tag{32}$$

where $g_{ij'}$ is the parallel propagator [II–(71)]. Let $\lambda^i_{(\alpha)}$ be a frame of reference on C with $\lambda^i_{(4)} = V^i$. This might be a Fermi frame, but the question does not arise at the moment, because we are c

We now define the 3-velocit components

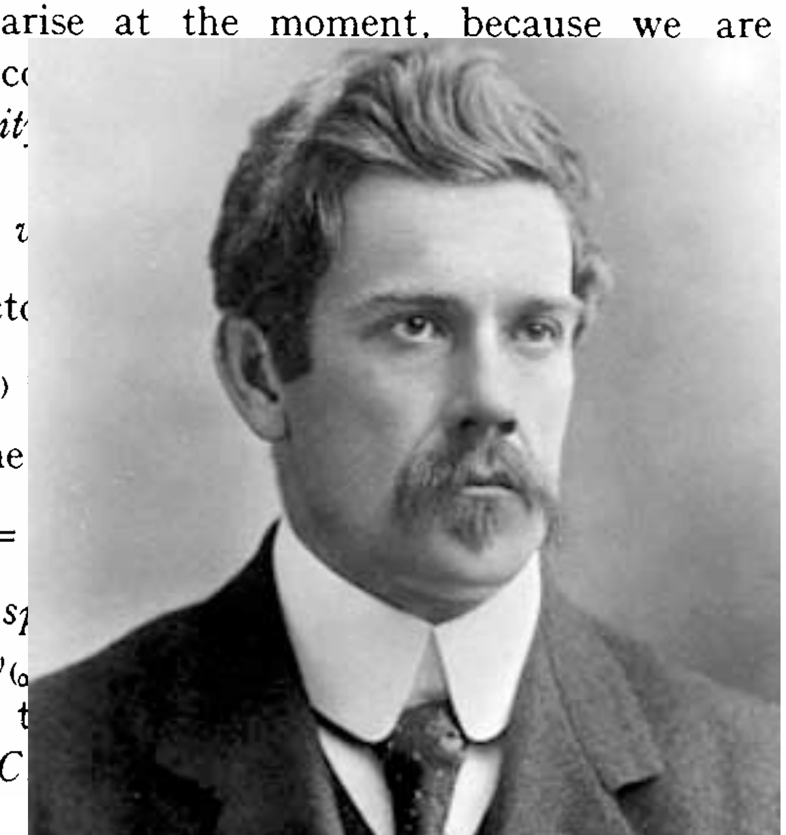
Since v^i and V^i are unit vect

$v_{(4)}$

is expressible in terms of the

$v^{(4)} = - v_{(4)} =$

We may call v the *relative s* all the three components $v_{(\alpha)}$ parallel for transport along t that C' is *at rest* relative to C



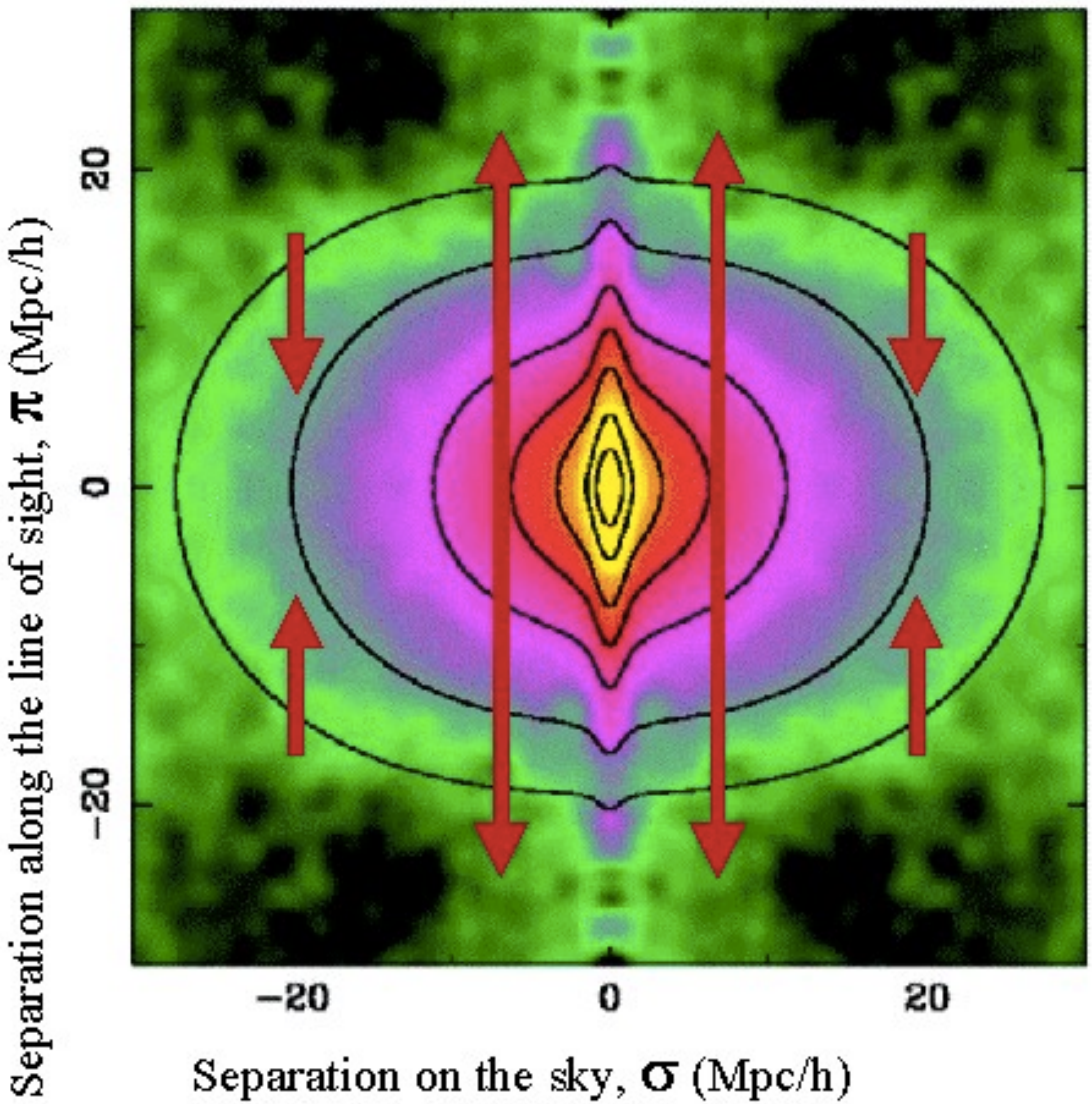
Bunn & Hogg, 2009

- Like Peebles they break photon path into a set of intervals
  - set of intervening observers along line of sight
  - local flatness $\rightarrow$product of Doppler shifts
- But intervening observers need not be freely falling
- Claim: Any incremental shift can be *considered* to be either *Doppler* or *gravitational*
  - "gravitational redshifts are just Doppler shifts viewed from an unnatural coordinate system"
  - "an enlightened cosmologist would never try to draw any distinction"
- All redshifts can (and should!) be considered to be Doppler, or 'kinematic' in nature. (much like Synge)
- See also Rindler for equivalence of accel^{n} and gravity

"Relativistic" redshift space distortions

- NK '87: Low order redshift space distortion (RSD) analysis
  - really velocity space distortion: $cz = Hr + v_{pec}$
- Recent studies have gone further:
  - e.g. Yoo, Fitzpatrick & Zaldarriaga (2009)
    - first order perturbation theory
      - $\Delta_z = \Delta_r + ...$
      - allowed for grav-z, "light-cone" effects
    - => extra terms (sub-dominant at low-z, sub-horizon scale)
- Key feature: front-back asymmetry
  - requires cross-correlation of 2 samples with different bias
    - e.g. bright vs faint (B&F) (or clusters and galaxies!)
- Another feature:
  - No grad(φ) term in $\Delta_z - \Delta_r$ ...... but only at 1st order

Redshift space distortions (symmetric)



e.g. Bonvin, Hui & Gaztanaga (2014)

$$\delta\mathbf{x} = \frac{1}{\mathcal{H}}\Big[\hat{\mathbf{n}}\cdot(\mathbf{V}-\mathbf{V}_0) - (\Psi-\Psi_0)\Big]\hat{\mathbf{n}}\,,$$

$$\begin{aligned}\Delta_{\rm B}(z,\hat{\mathbf{n}}) &= \Delta_{\rm B}^{\rm st}(z,\hat{\mathbf{n}}) + \Delta_{\rm B}^{\rm rel}(z,\hat{\mathbf{n}}) \\ &+ \Delta_{\rm B}^{\rm lens}(z,\hat{\mathbf{n}}) + \Delta_{\rm B}^{\rm AP}(z,\hat{\mathbf{n}})\,, \end{aligned} \qquad (30)$$

where

$$\Delta_{\rm B}^{\rm st}(z,\hat{\mathbf{n}}) = b_{\rm B}\delta(z,\hat{\mathbf{n}}) - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\hat{\mathbf{n}})\,, \qquad (31)$$

$$\begin{aligned}\Delta_{\rm B}^{\rm rel}(z,\hat{\mathbf{n}}) &= \frac{1}{\mathcal{H}}\partial_r\Psi + \frac{1}{\mathcal{H}}\dot{\mathbf{V}}\cdot\hat{\mathbf{n}} \qquad (32)\\ &- \left[\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r\mathcal{H}} - 1 + 5s_{\rm B}\left(1-\frac{1}{r\mathcal{H}}\right)\right]\mathbf{V}\cdot\hat{\mathbf{n}}\,,\end{aligned}$$

$$\Delta_{\rm B}^{\rm lens}(z,\hat{\mathbf{n}}) = (5s_{\rm B}-2)\int_0^r d\tilde{r}\frac{(r-\tilde{r})\tilde{r}}{2r}\nabla_\perp^2(\Phi+\Psi)\,, \qquad (33)$$

$$\begin{aligned}\Delta_{\rm B}^{\rm AP}(z,\hat{\mathbf{n}}) &= (\partial_r - \partial_\eta)\Big(\Delta_{\rm B}^{\rm st} + \Delta_{\rm B}^{\rm rel} + \Delta_{\rm B}^{\rm lens}\Big) \\ &\cdot \frac{\partial r(z,\Omega)}{\partial\Omega}\cdot\delta\Omega\,. \end{aligned} \qquad (34)$$

The quantity $b_{\rm B}$ denotes the bias of the bright galaxies and $s_{\rm B}$ is their effective number count slope. *Expressions* (31) *to* (34) *are valid in any theory in which photons travel on null geodesics; no assumptions have been made about the dynamics of gravity.* In theories in which the galaxies (i.e. non-relativistic tracers) also move on geodesics, we can use the Euler equation

$$\dot{\mathbf{V}}\cdot\hat{\mathbf{n}} + \mathcal{H}\mathbf{V}\cdot\hat{\mathbf{n}} + \partial_r\Psi = 0\,, \qquad (35)$$

to simplify eq. (32) to

$$\Delta_{\rm B}^{\rm rel}(z,\hat{\mathbf{n}}) = -\left[\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r\mathcal{H}} + 5s_{\rm B}\left(1-\frac{1}{r\mathcal{H}}\right)\right]\mathbf{V}\cdot\hat{\mathbf{n}}\,. \qquad (36)$$

The gravitational redshift effect, $\partial_r\Psi/\mathcal{H}$, is therefore canceled by a combination of the light-cone effect and part of the Doppler effect.

No grad-Ψ term!

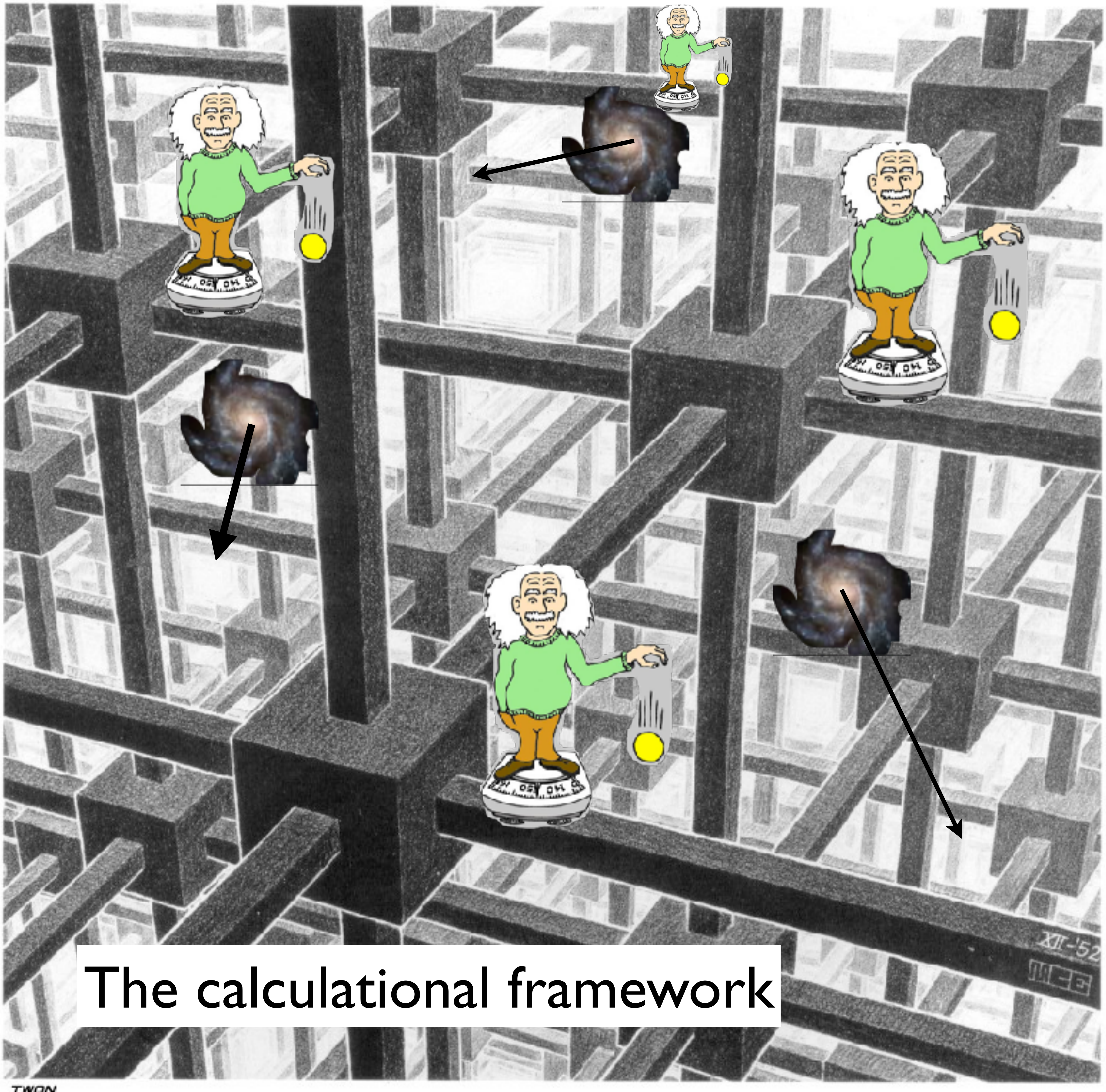
as expected from principle of equivalence

ideas about redshifts in astronomy - summary

- The redshift of light in cosmology
  - redshift is caused by the expansion of space?
  - standing waves in a cavity
  - Maxwell's equations in expanding space:
    - "Hubble damping" + the adiabatic invariant
  - Thermodynamics & photons as particles
  - Peebles' picture - lots of little Doppler shifts
- The redshift of light in general
  - Synge ('60): redshifts "caused by the relative velocity..."
  - Bunn & Hogg ('09): "gravitational redshifts are just Doppler shifts viewed from an unnatural coordinate system"
  - 1st order "relativistic" redshift space distortion (Yoo+09)
    - $\Delta_z = \Delta_r + ...$ is also purely a "Doppler" effect

"what causes redshifts?" and why do we care?

- All the foregoing support the "kinematic picture" for astronomical redshifts.
  - redshifts come entirely from motions
  - in nice accord with Equivalence Principle
- But clusters are not expanding!
  - and observers, sources are freely falling
  - *so why would we see any gravitational redshift?*
- At the very least one might have doubts about the Einstein/ Newton/Pound+Rebka picture
- What additional physics might there be?



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?

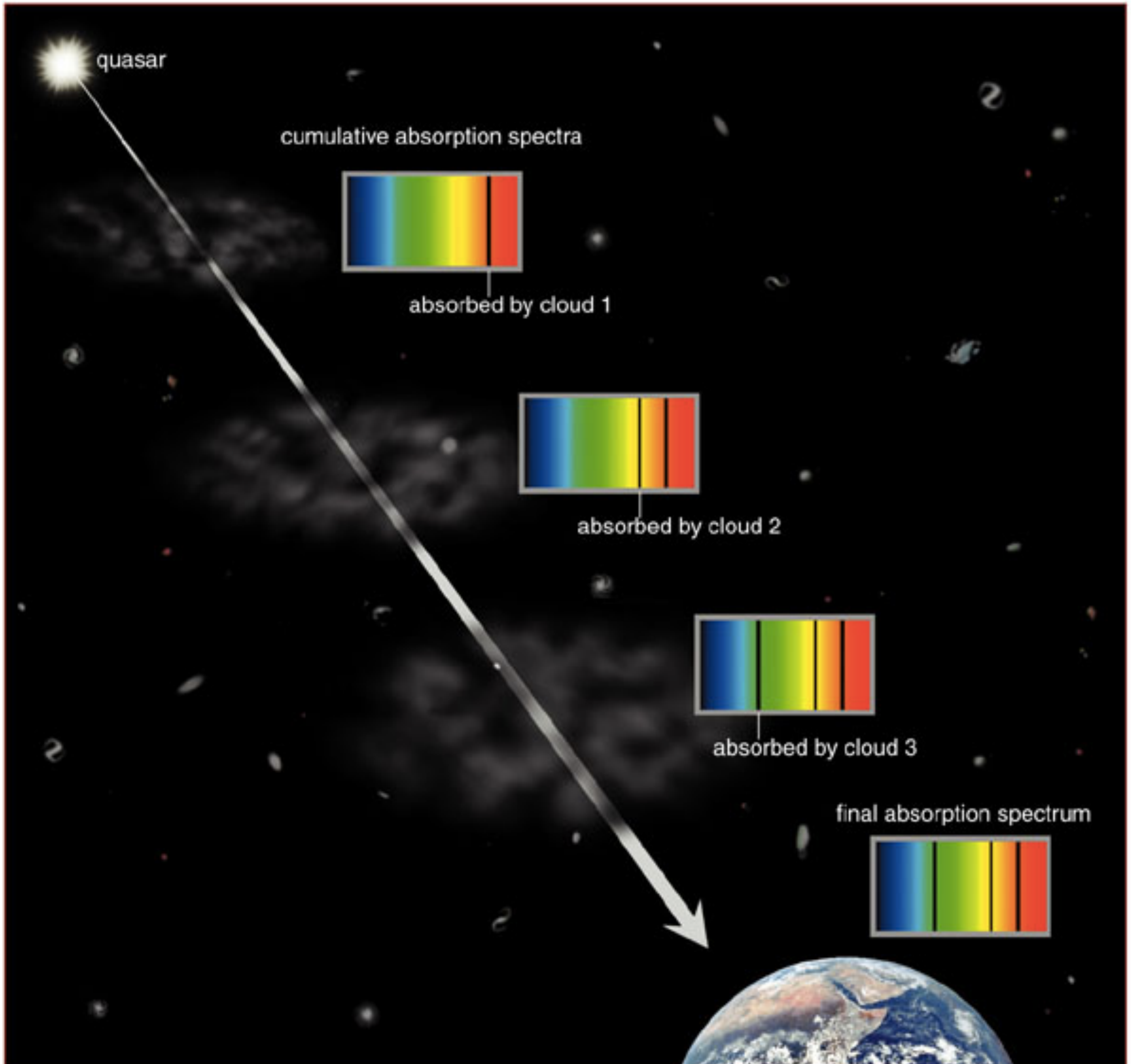
No - there is another effect of same order

- Light cone effect
  - 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

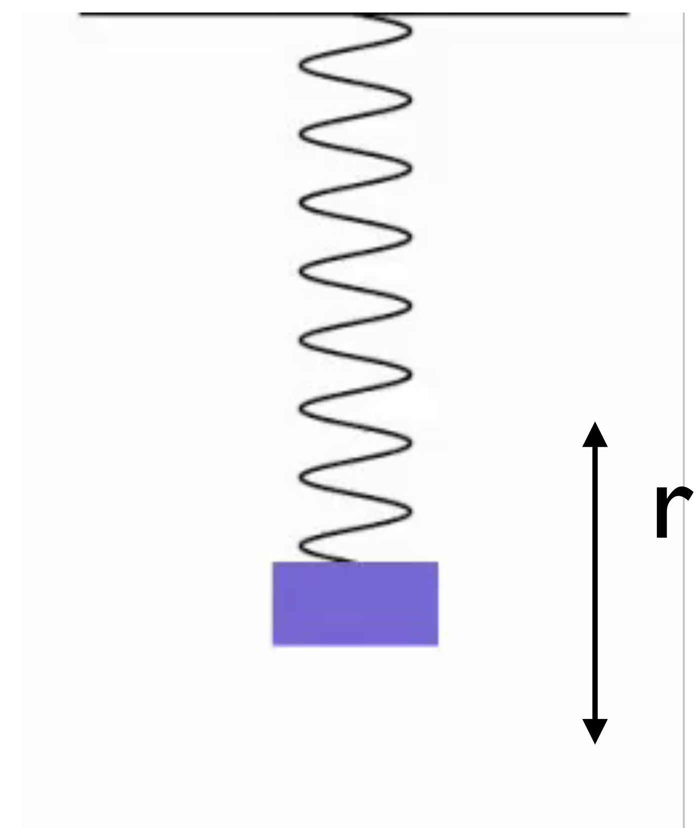
- Light cone effect
  - we will see more particles moving away from us in a photograph of a swarm of particles
    - past light cone of event of our observation overtakes more galaxies moving away than coming towards us
    - just as a runner on a trail sees more hikers going the other way...
    - So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

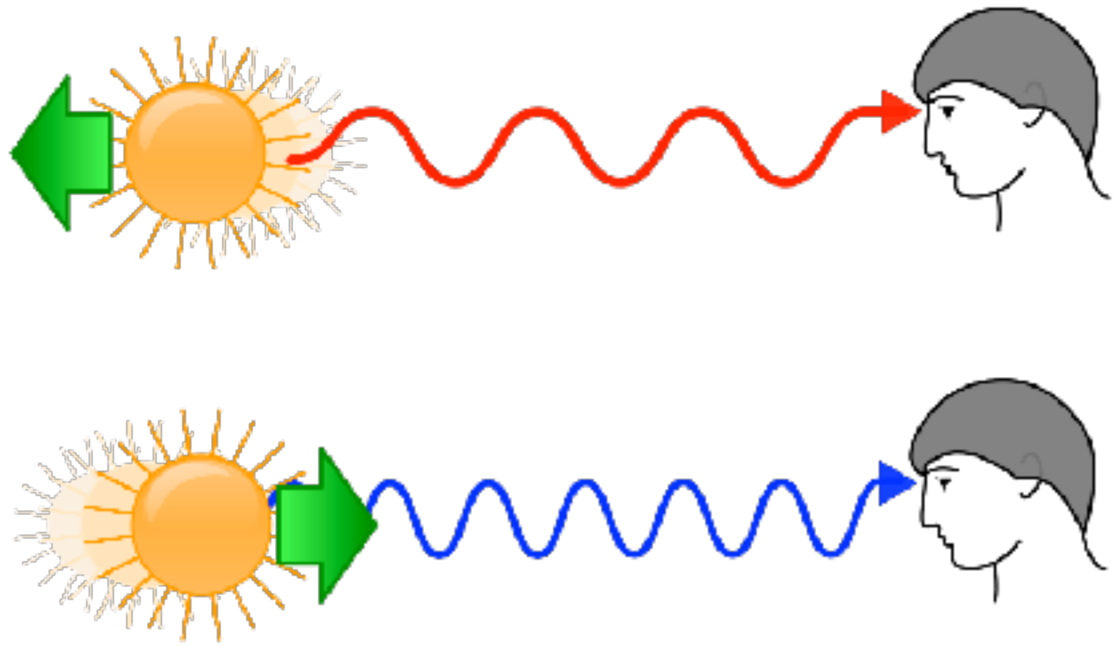


Another way to understand the light-cone effect

- 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?

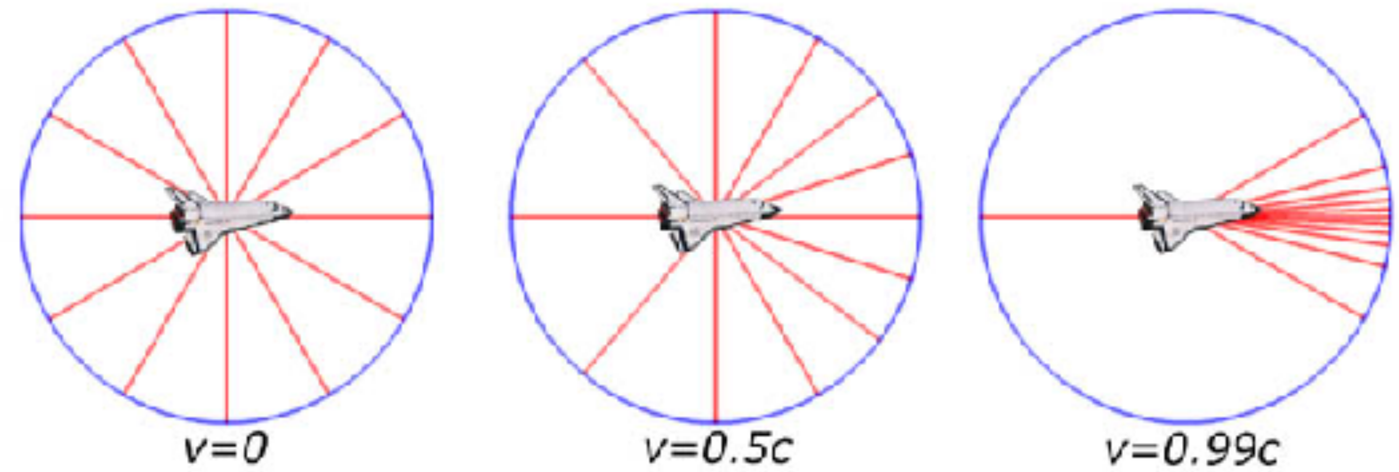
How do we resolve this?

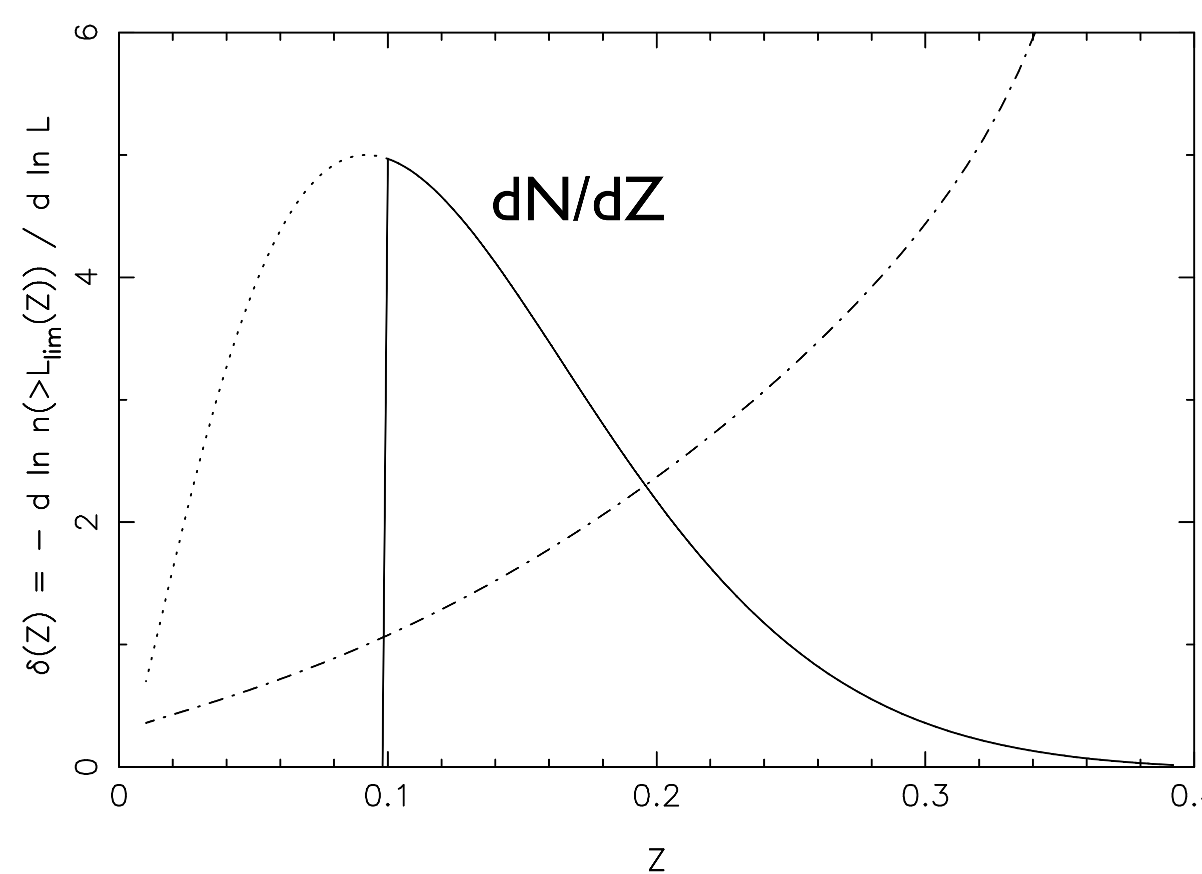
Transverse Doppler Effect: Redshift or Blueshift?

- Averaging over objects vs averaging over photons
  - 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

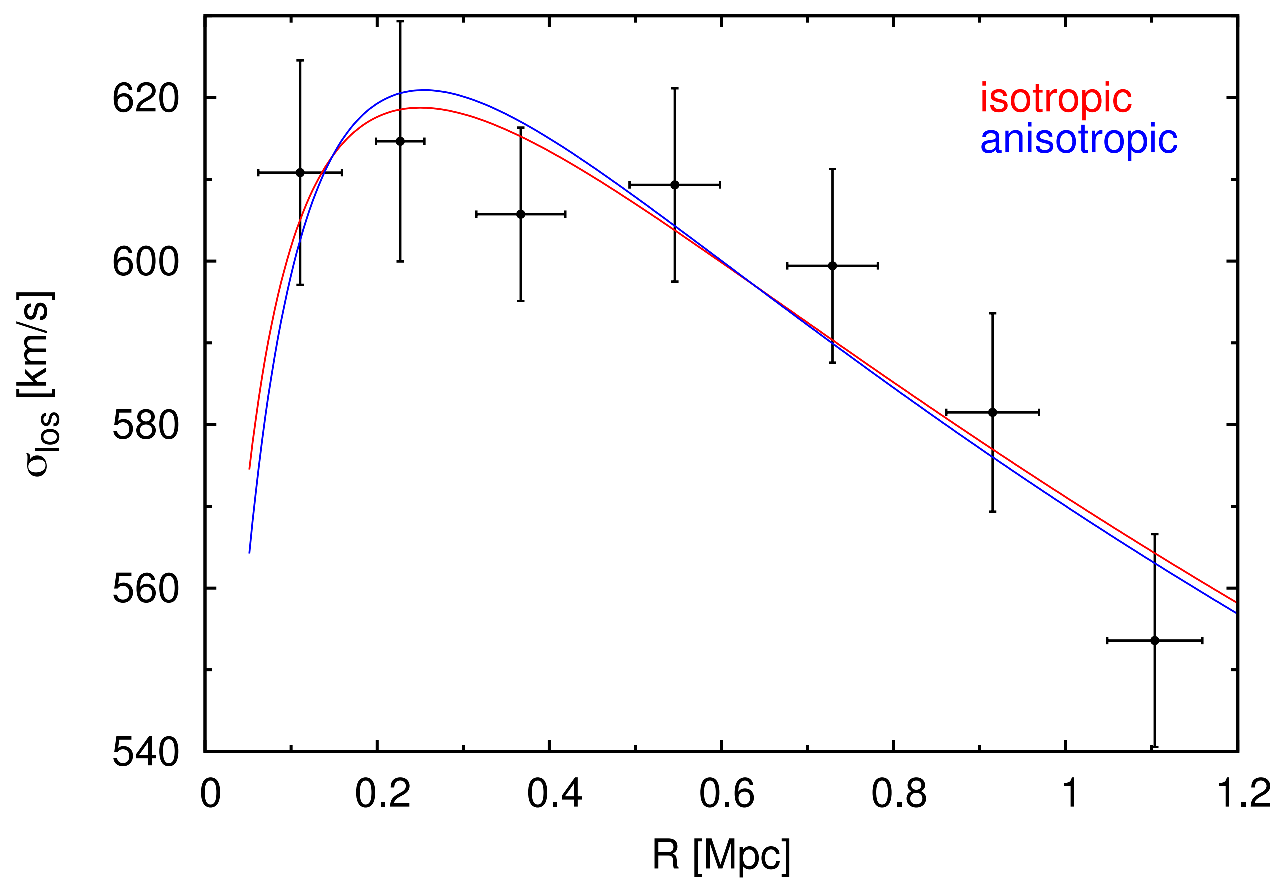
- Line of sight velocity changes surface brightness
  - relativistic beaming (aberration) plus change of frequency
- but doesn't change the surface area
- so velocities modulate luminosity
  - depends on SED: $\delta L/L = (3 + \alpha)v/c$
  - α ~= 2, so big amplification
  - spectroscopic sample is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

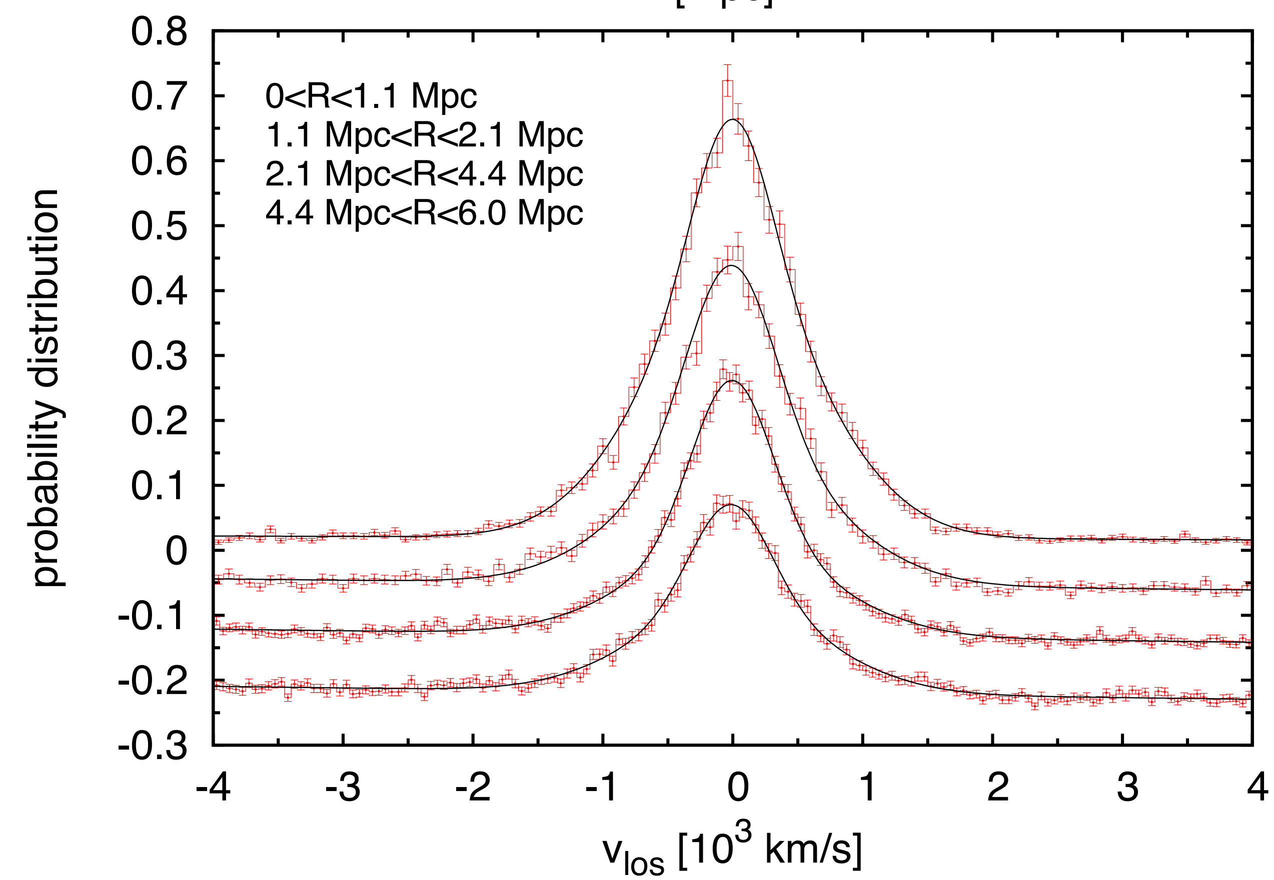




Corrected grav-z measurement

- 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





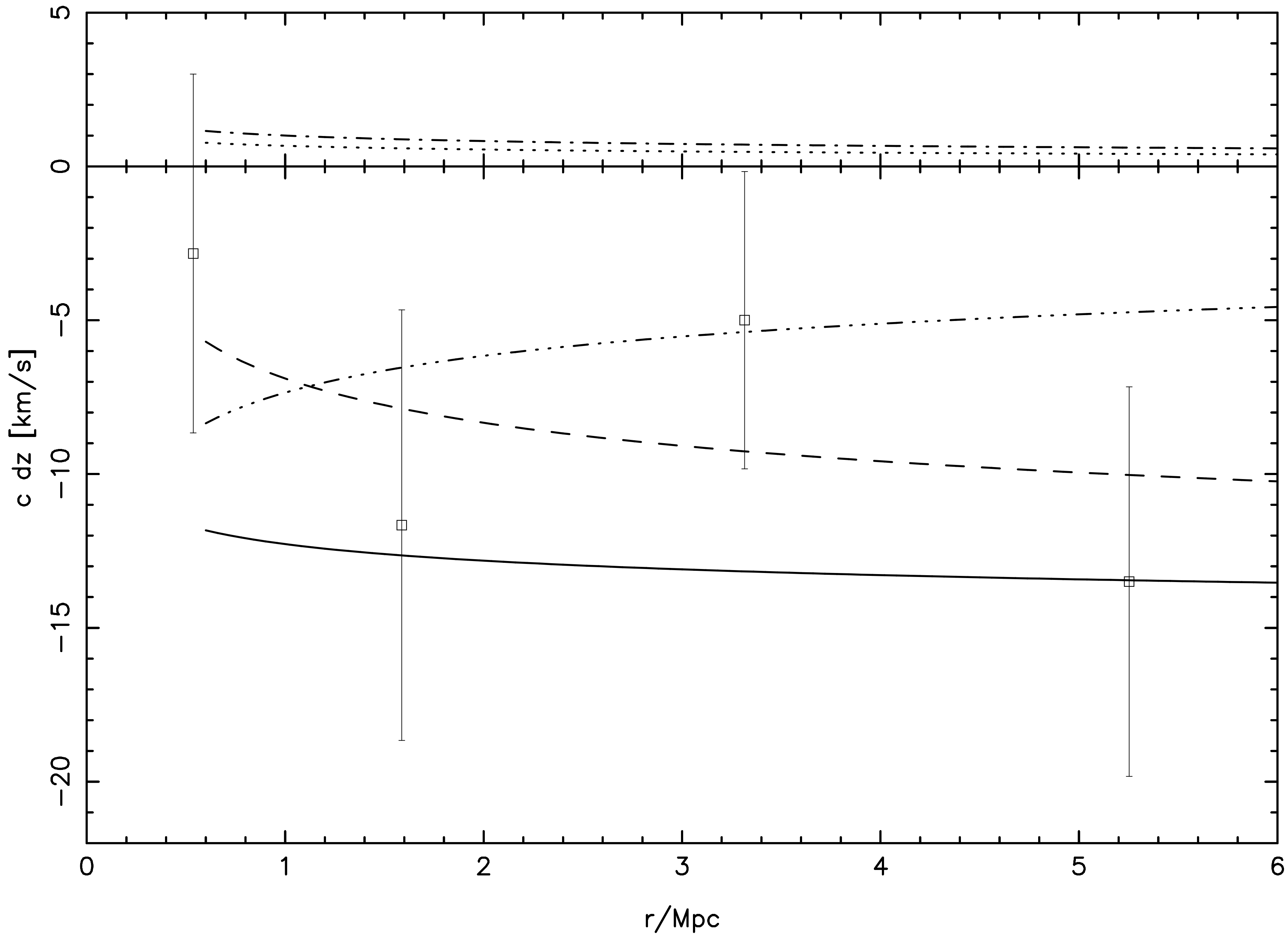


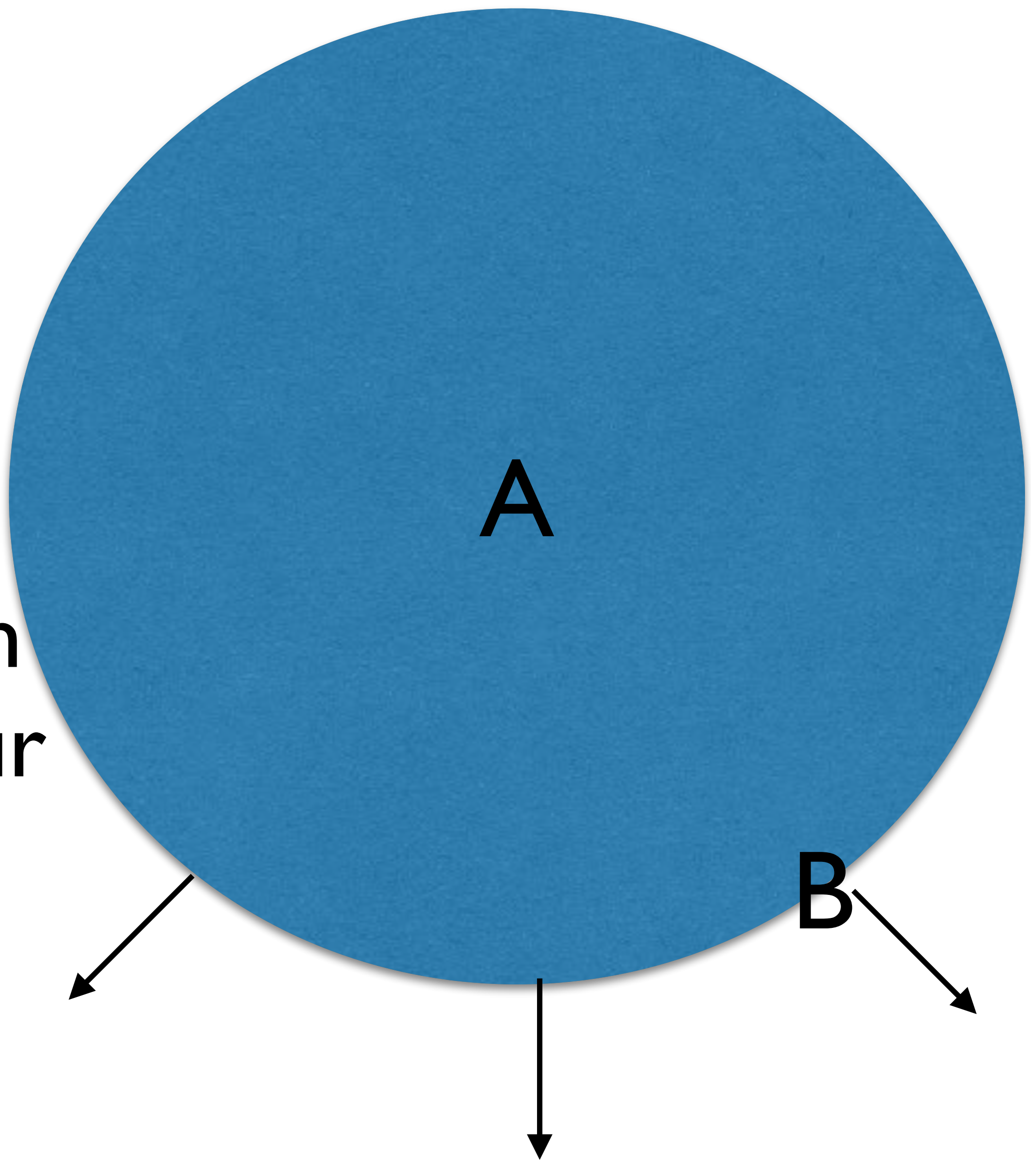
Figure 3. Data points from figure 2 of WHH and prediction based on mass-traces-light cluster halo profile and measured velocity dispersions as described in the main text. The dashed line is the gravitational redshift prediction, which is similar to the WHH model prediction. The dot-dash line is the transverse 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 causes redshift
- Bunn & Hogg 2009: *"A gravitational redshift is just a Doppler shift viewed from an unnatural coordinate system*"
- But are gravity and acceleration the same thing?
- In GR the gravitational field is the Riemann (curvature) tensor
  - just the tidal field in the Newtonian limit
    - measured from relative motion of test particles
  - Quite distinct from acceleration
- So is there a truly gravitational 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 red-shift 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 blue-shift
- But the net effect is the same.
- The opposite gravitational shifts are cancelled by the Doppler shift change
- But this is a special 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)

Why we see a gravitational z in clusters

- The "kinematic picture" is <u>wrong</u>
  - redshifts are <u>not</u> solely determined by change of separation of observer, source
  - there is an additional, <u>intrinsically gravitational, effect</u>
  - but the gravitational-z comes from <u>gradients</u> of the tide
    - that's why it's not seen in FRW cosmology
      - a consequence of symmetry
- Total z is kinematic plus an integral involving grad(tide)
  - sums to give naive (P&R) gravitational redshift
- but we also have the TD, LC and SB effects..

Modelling gravitational-z in simulations (Cai+'06)

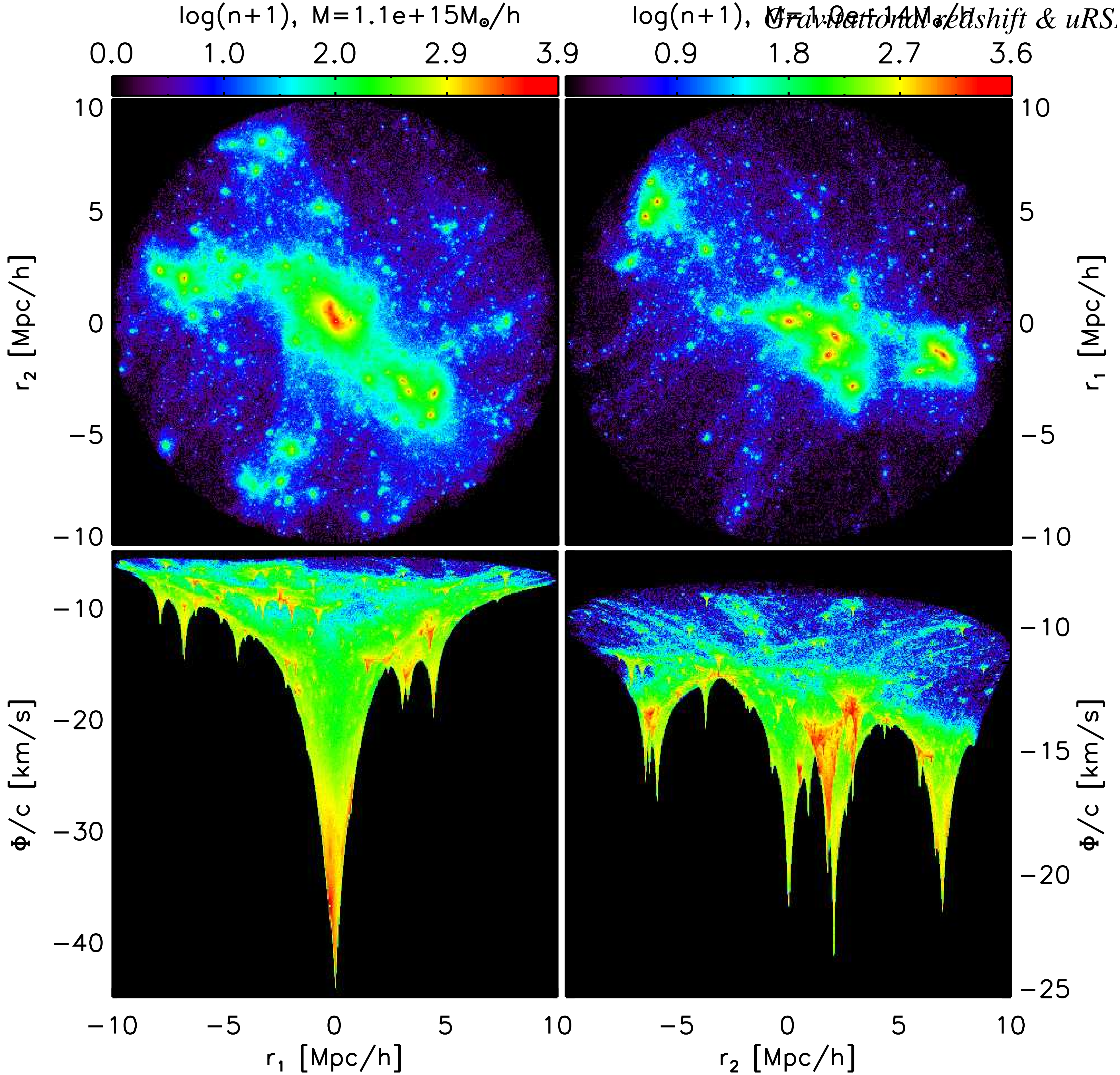
- NK'13 modelling assumed virialised (non-expanding) clusters
  - this breaks down at large r
  - need to allow for infall
  - asymmetry gives other biases
- Cai+2016 have used Millennium simulation to quantify this
  - formalism for extracting observables from "snapshots":

$$
\begin{aligned}
cz = & Hx + v_x + v^2/2c - \Phi/c \\
& - xg_x + Hxv_x/c + \left[H^2 - \ddot{a}/(2a^2)\right] x^2/c,
\end{aligned}
$$

  - includes light-cone effects
  - valid to 2nd order in velocity (Hubble and/or peculiar)

Clusters in the Millenium Simulation (Y. Cai)

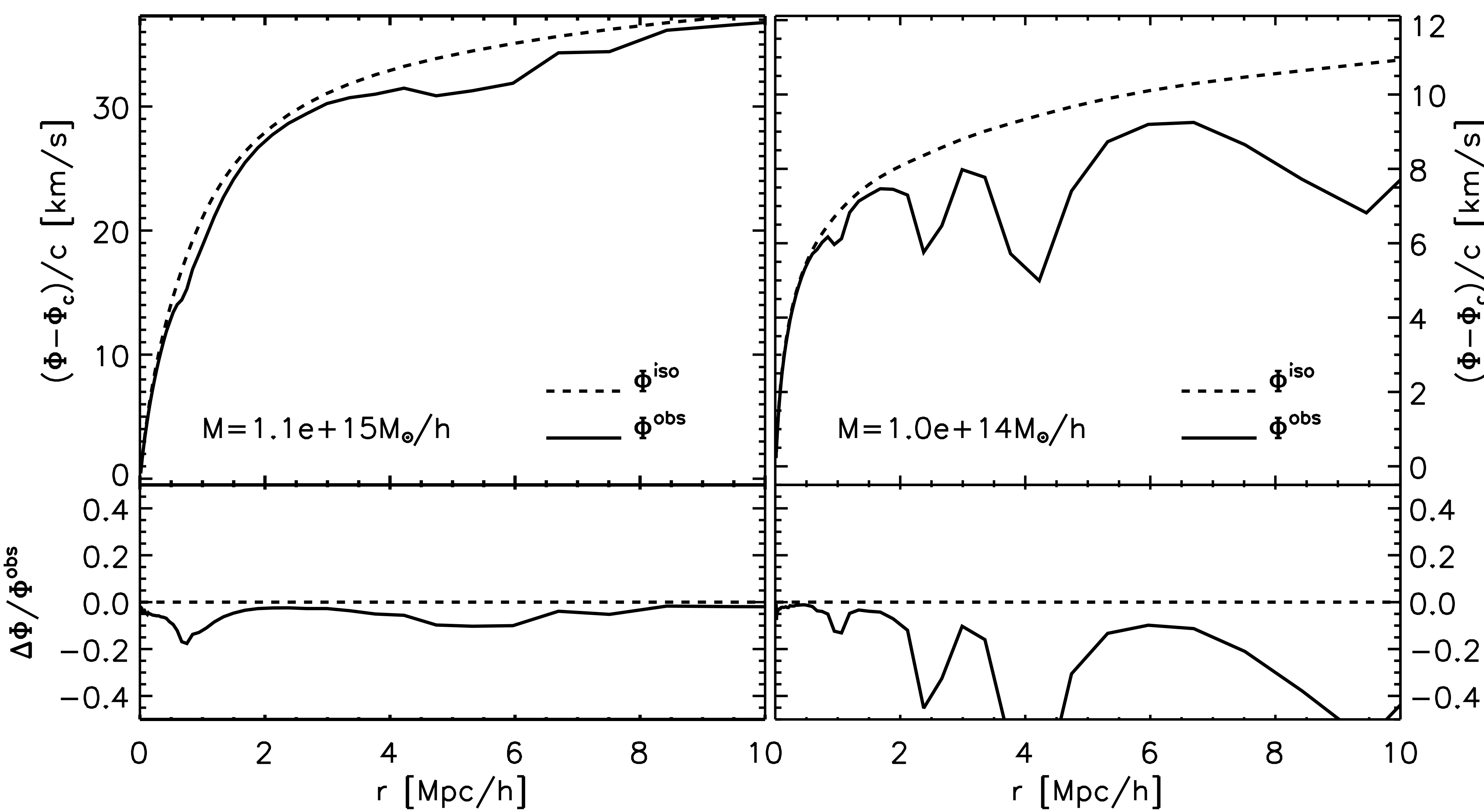
Gravitational redshift & uRS.



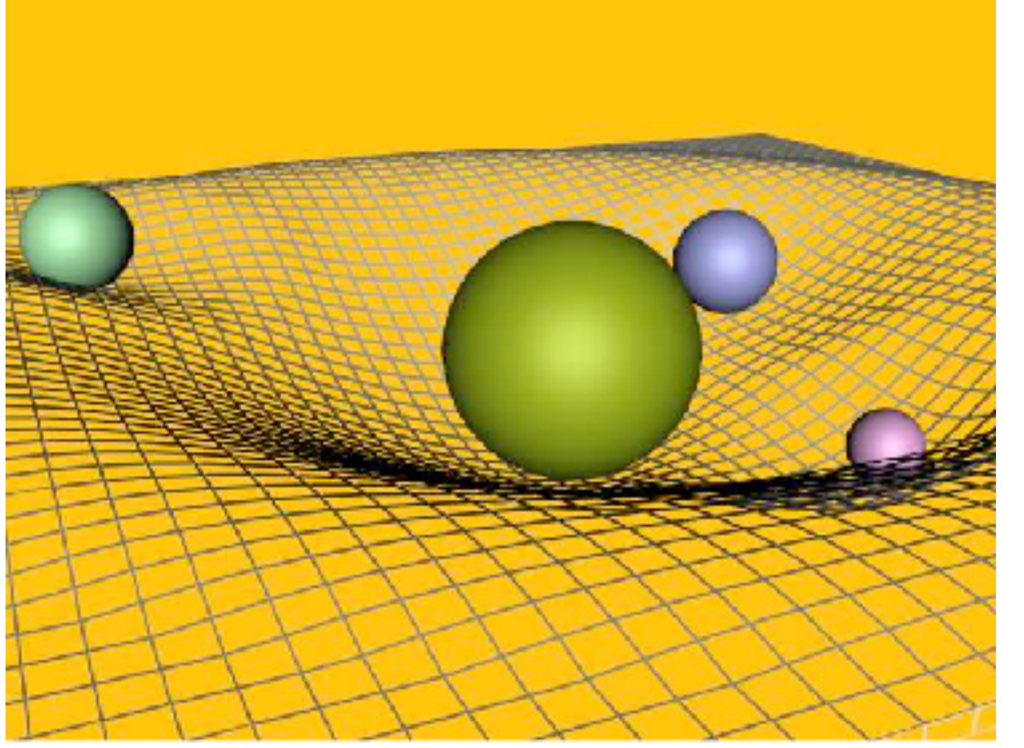
Modelling gravitational-z in simulations (Cai+'06)

Formalism: mapping from x to v (2nd order)

$$cz = Hx + v_x + v^2/2c - \Phi/c$$
$$\quad - xg_x + Hxv_x/c + \left[H^2 - \ddot{a}/(2a^2)\right] x^2/c,$$



Is it useful?



- 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}
  - both measure the "curvature of time"
- It is really a test of the equivalence principle
  - 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

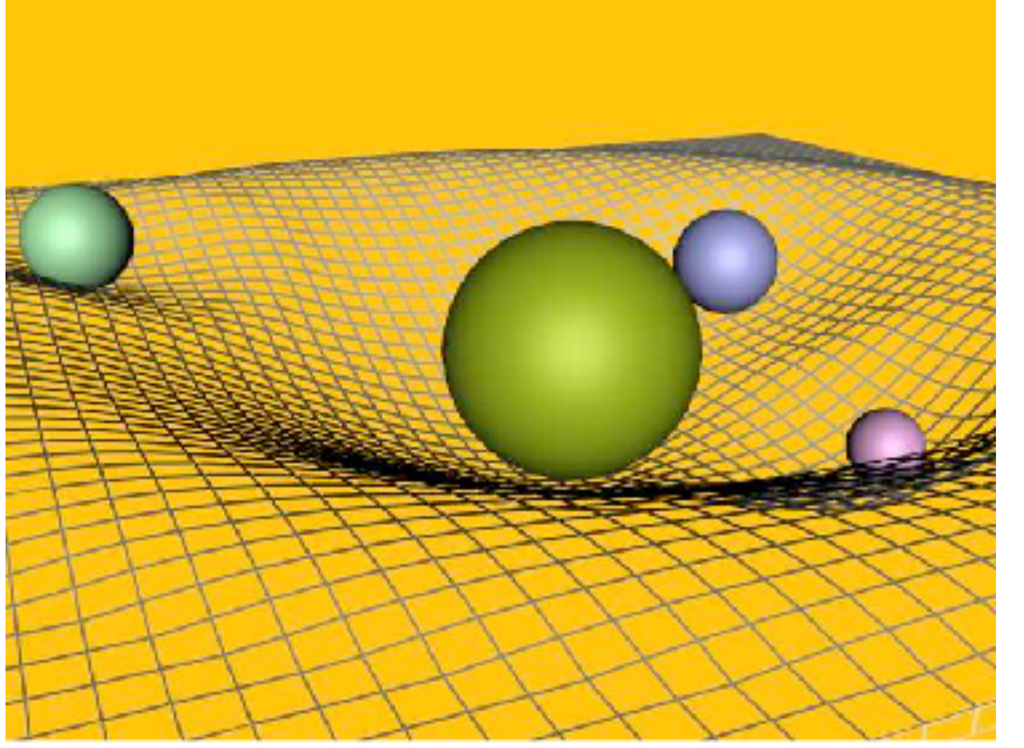
Redshifts in homogeneous FRW models

- λ scales with proper separation
- *analogous* to EM waves in an expanding cavity
- stretching of λ is *caused* by the expansion of space
- that this should be so is *obvious*
- expansion of space *causes* damping in Maxwell's equations
- cosmological redshifts do not obey special relativity
- z is a combination of SR Doppler shift + gravitational z
  - at low-z at least (Bondi 1947)
- overall frequency shift is the product of little Doppler shifts
  - Peebles

Redshifts in general

- all redshifts are Doppler shifts
  - Riemann tensor $R_{\alpha\beta\psi\delta}$ does not appear in the formula
- acceleration and gravity are the same thing
  - principle of equivalence
- acceleration *creates* gravity
- Pound and Rebka measured a *gravitational* redshift
- redshifts can be considered as either gravitational or Doppler
  - simply a difference of coordinate systems
- all redshifts can (and should) be considered to be Doppler
- all redshifts are kinematic in nature
  - the only way to measure velocity is through redshift

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 equivalence principle
- Provides a test of theories with 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.... and (maybe) f(R) gravity.
  - though such theories are already constrained by X-ray temp. vs galaxy motions in clusters....

Scalar fields, "Fifth forces" & Violation of the EP

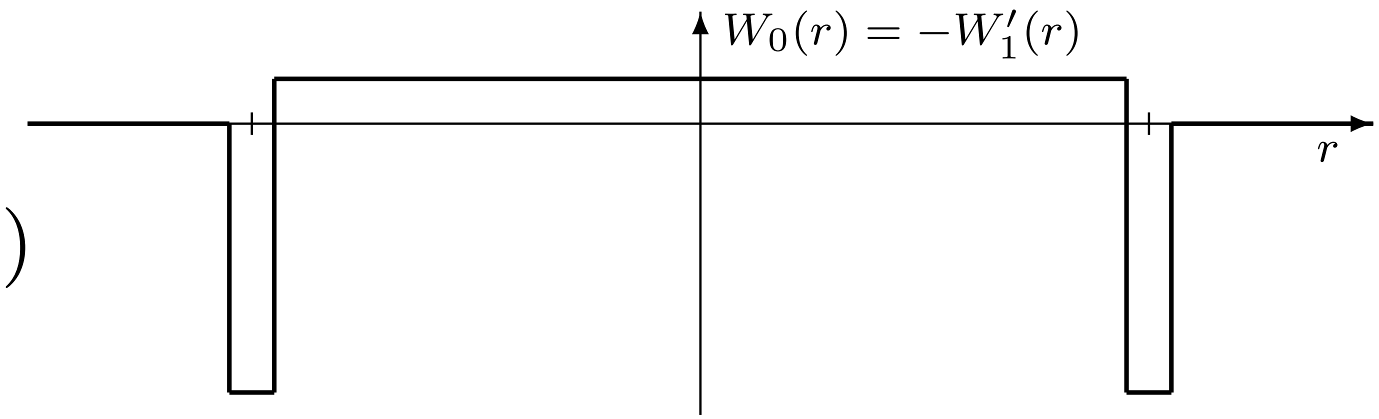
- a common feature of modified gravity theories
  - string theory inspired: dilaton field - couples to matter
  - also <u>interacting DE & DM</u> models where $m = m(\phi)$
  - f(R) gravity etc. etc.
- extra long-range (1/r potential) force augmenting gravity
  - must be suppressed/small on solar system scale
  - or only coupling to DM
- Violations of the <u>Equivalence Principle</u> (foundation of GR)
  - interesting - and testable - consequences
  - lensing - galaxy clustering - gravitational redshifts - BHs see different **g** - dynamics in clusters (gas vs *s vs DM)

Subtracting (1) - (2) gives

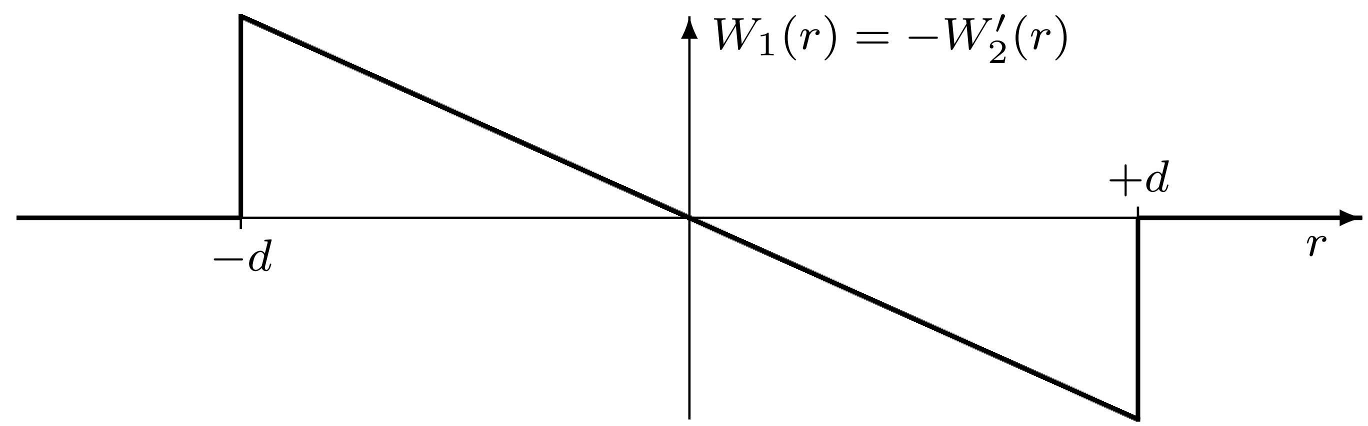
$$\Delta \log(\lambda/D) = \frac{1}{c^2}\left(d\ \mathbf{n}\cdot(\mathbf{g}_1+\mathbf{g}_2) - \int d\mathbf{r}\cdot\mathbf{g}\right)$$

or

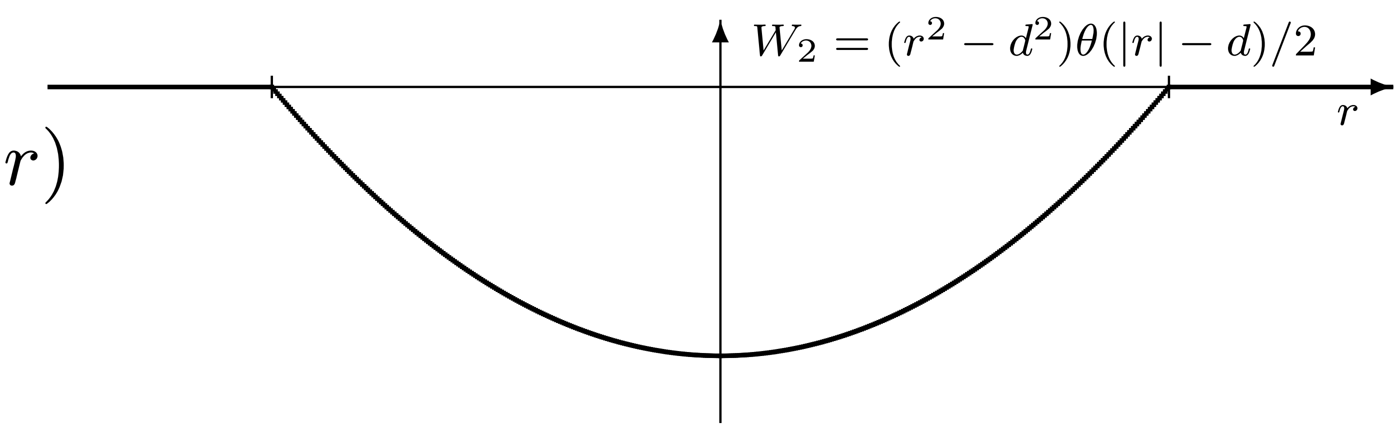
$$\Delta \log(\lambda/D) = \frac{1}{c^2}\int dr\ W_0(r)\phi'(r)$$



$$\Delta \log(\lambda/D) = \frac{1}{c^2}\int dr\ W_1(r)\phi''(r)$$



$$\Delta \log(\lambda/D) = \frac{1}{c^2}\int dr\ W_2(r)\phi'''(r)$$



There is a non-kinematic component of the redshift: it is a measurement of the gradient of the tide

More implications of the transverse Doppler red/ blue-shift dichotomy

- Contribution to cluster grav-Z from motions of stars in the BCG
  - velocity dispersions are smaller than in cluster, but not negligible
  - stars are unresolved so we get a transverse Doppler <u>blue-shift</u>
- 21cm radio observations of galaxies
  - sees mostly galaxies falling into cluster for first time as gas is stripped within virial region
  - should have a large potential difference relative to BCG
  - but the prediction for δZ is highly dependent on whether one makes unresolved single dish (e.g. Aricebo) measurements or resolved (e.g. Westerbork, ASKAP)

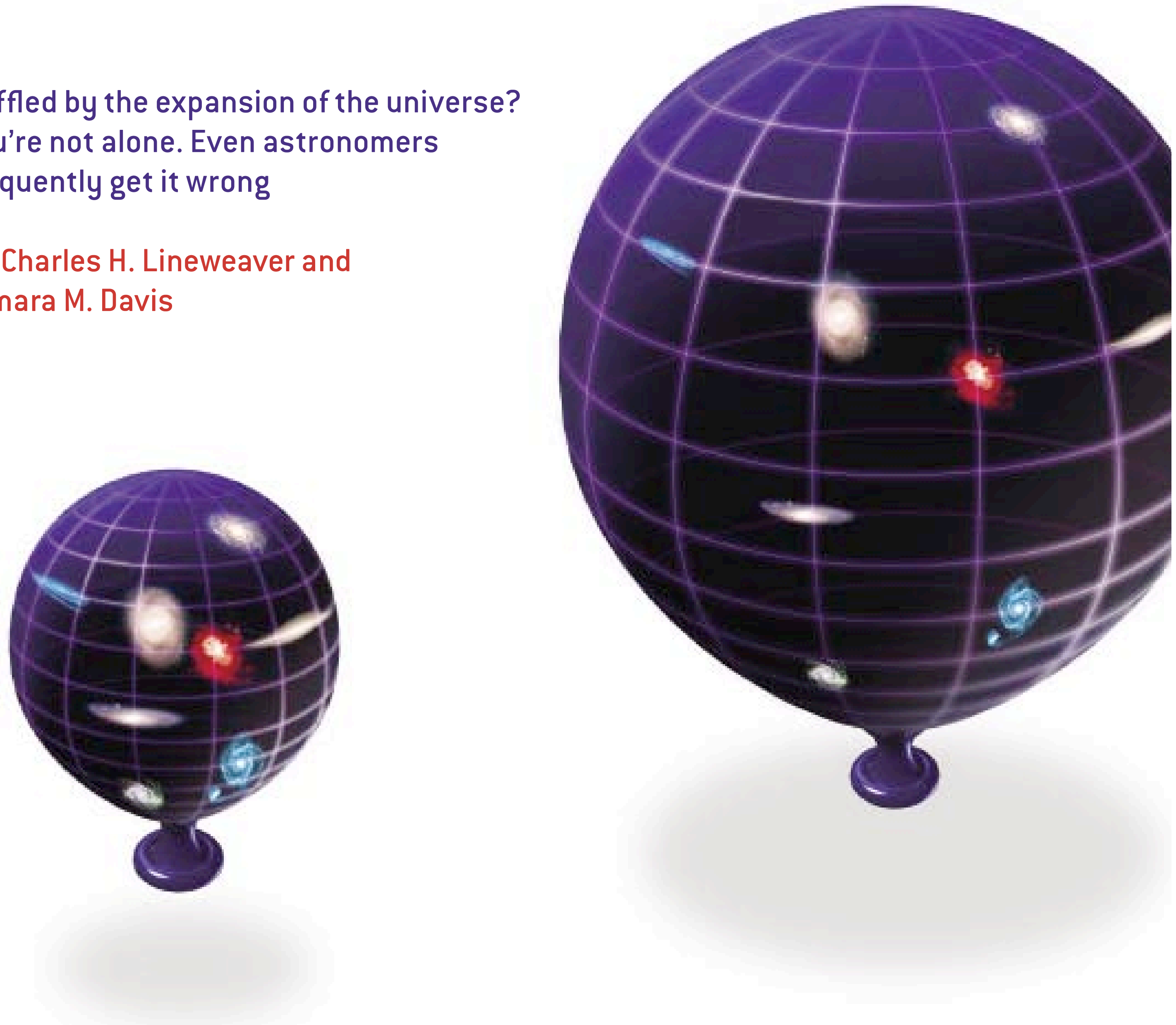
Future prospects...

- Can expect immediate improvements in measurement
  - 3x increase in number of redshifts available (BOSS)
  - and more to come:
    - optical: big-BOSS
    - radio: FAST, ASKAP-Wallaby+WNSHS
    - interesting to compare unresolved radio and optical
- Extension to larger scales. Bright-faint cross correlation Gaztanaga++2015, Alam++2016..
- Lots of rich material in the front-back asymmetry of the galaxy correlation function.
- Lots of interesting scope for modelling:

MISCONCEPTIONS ABOUT THE BIG BANG

Baffled by the expansion of the universe? You're not alone. Even astronomers frequently get it wrong

By Charles H. Lineweaver and Tamara M. Davis



Stretching and Cooling

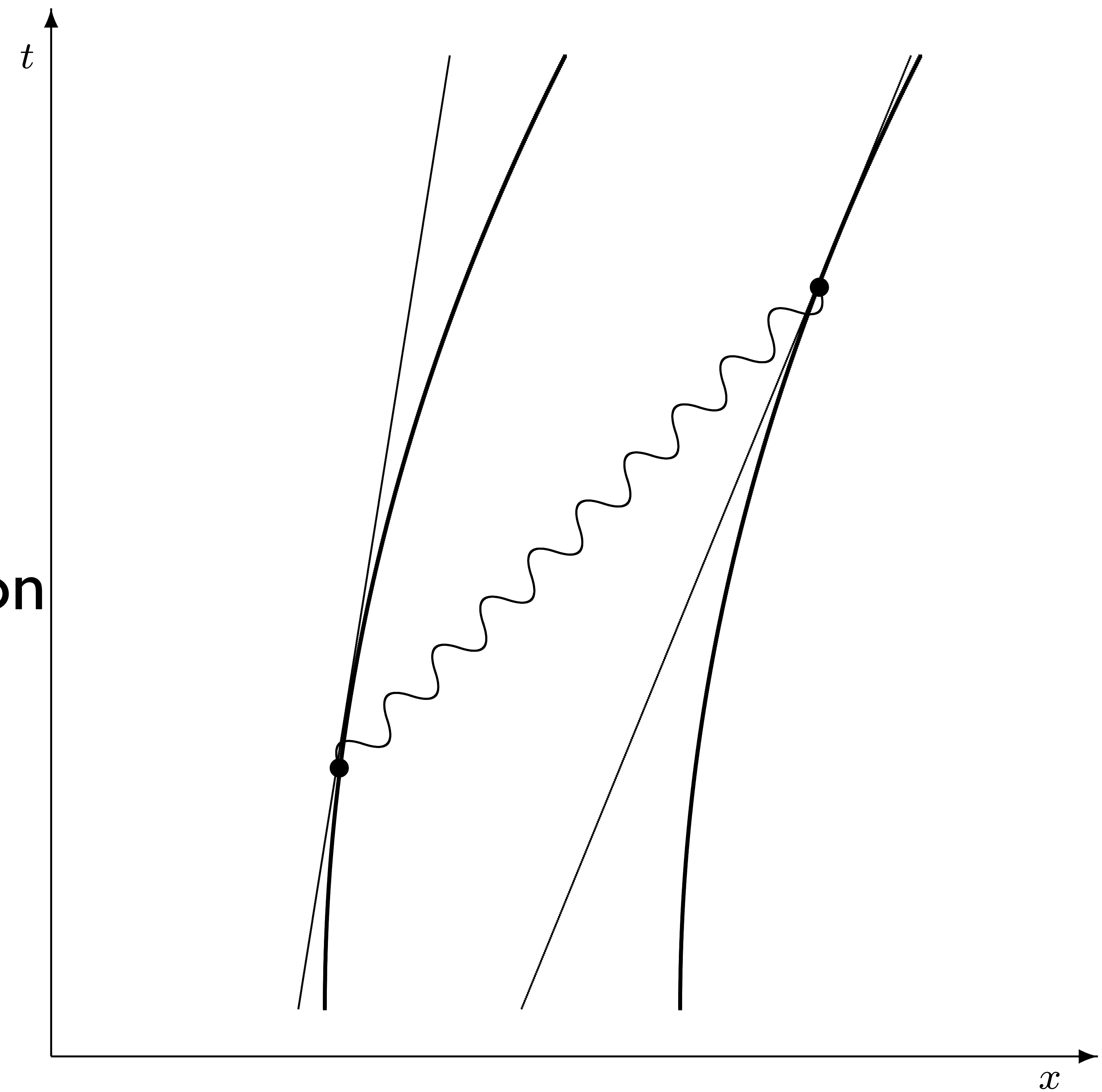
THE PRIMARY OBSERVATION that the universe is expanding emerged between 1910 and 1930. Atoms emit and absorb light of specific wavelengths, as measured in laboratory experiments. The same patterns show up in the light from distant galaxies, except that the patterns have been shifted to longer wavelengths. Astronomers say that the galactic light has been redshifted. The explanation is straightforward: As space expands, light waves get stretched. If the universe doubles in size during the waves' journey, their wavelengths double and their energy is halved.

This process can be described in terms of temperature. The photons emitted by a body collectively have a temperature—a certain distribution of energy that reflects how hot the body is. As the photons travel through expanding space, they lose energy and their temperature decreases. In this way, the universe cools as it expands, much as compressed air in a scuba tank cools when it is released and allowed to expand. For example, the microwave background radiation currently has a temperature of about three kelvins, whereas the process that released the radiation occurred at a temperature of about 3,000 kelvins. Since the time of the emission of this radiation, the universe has increased in size by a factor of 1,000, so the temperature of the photons has decreased by the same factor. By observing the gas in distant galaxies, astronomers have directly measured the temperature of the radiation in the distant past. These measurements confirm that the universe has been cooling with time.

Misunderstandings about the relation between redshift and velocity abound. The redshift caused by the expansion is often confused with the more familiar redshift generated by the Doppler effect. The normal Doppler effect causes sound

Are gravitational and Doppler shifts the same?

- Heavy lines are pair of accelerated observers
  - with same constant acceleration
- Light lines are a pair of freely falling observers
- These pairs perceive the same redshift for the photon (wiggly line)
- Redshift only depends on instantaneous velocity, not on the path before or after the interaction event.
- But is this gravity?

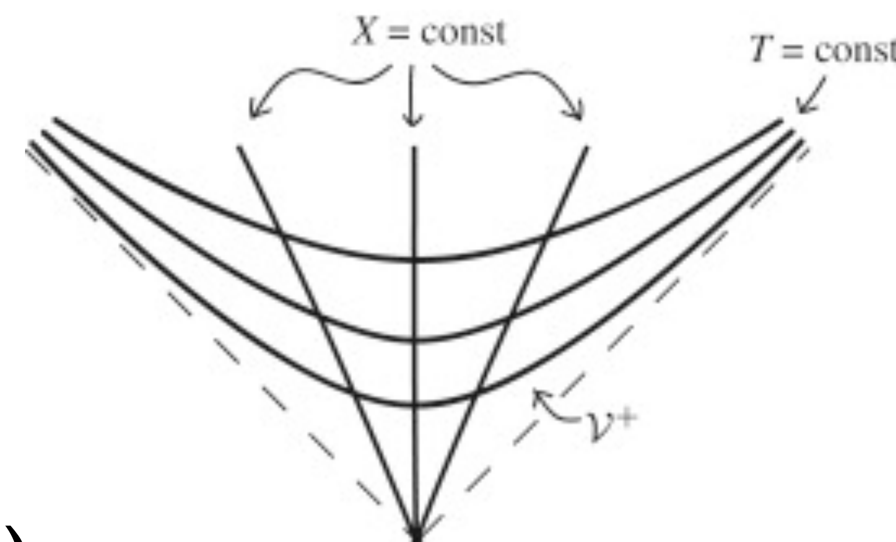


What does it all mean?

- Effect is very small - and hard to measure
  - measuring 10km/s mean offset with 600km/s velocity dispersion is truly impressive
  - requires careful modeling of background & cluster velocity distribution function f(v)
  - and predicting potential from kinematics is not trivial
    - rather sensitive to assumed velocity distribution for the brightest cluster galaxies (BCGs) used as centres
  - but it probably is a real measurement of gravitational redshift (+ special relativistic nuisance factors)

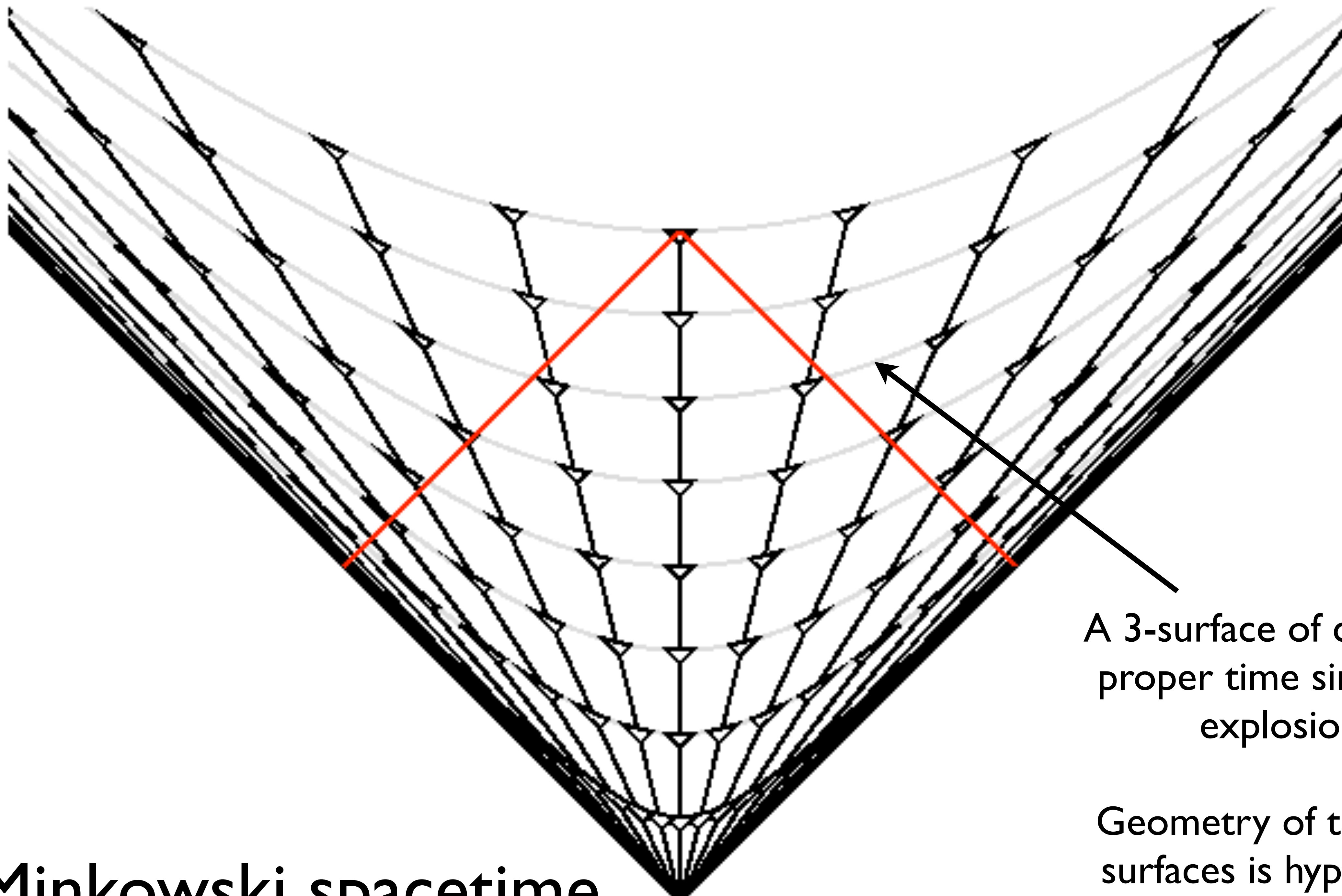
Arguments against "expanding space"

- Space-time is locally flat (a.k.a. 'Minkowskian')
  - Whiting, 2004; Peacock, 2009; Bunn & Hogg 2009, Chodorowski, 2007, 2011, Rees & Weinberg....
- Writing $\partial_t^2\varphi - \nabla_x^2\varphi = 0$ in re-scaled coordinates does not change the local physics.
  - despite apparent <u>damping</u> term



- Example: the Milne model
  - Limiting case of $\Omega \rightarrow 0$ FRW model
  - Different families of FOs → *different* a(t)
  - → Red-shifting or blue-shifting fireball solutions
  - multiple families of uniformly expanding (or contracting) observers and radiation fields - even in same region of space
- The expansion rate H is defined by the radiation <u>itself</u>!
- Determined by the initial conditions.

Observers and photon paths in the Milne Model



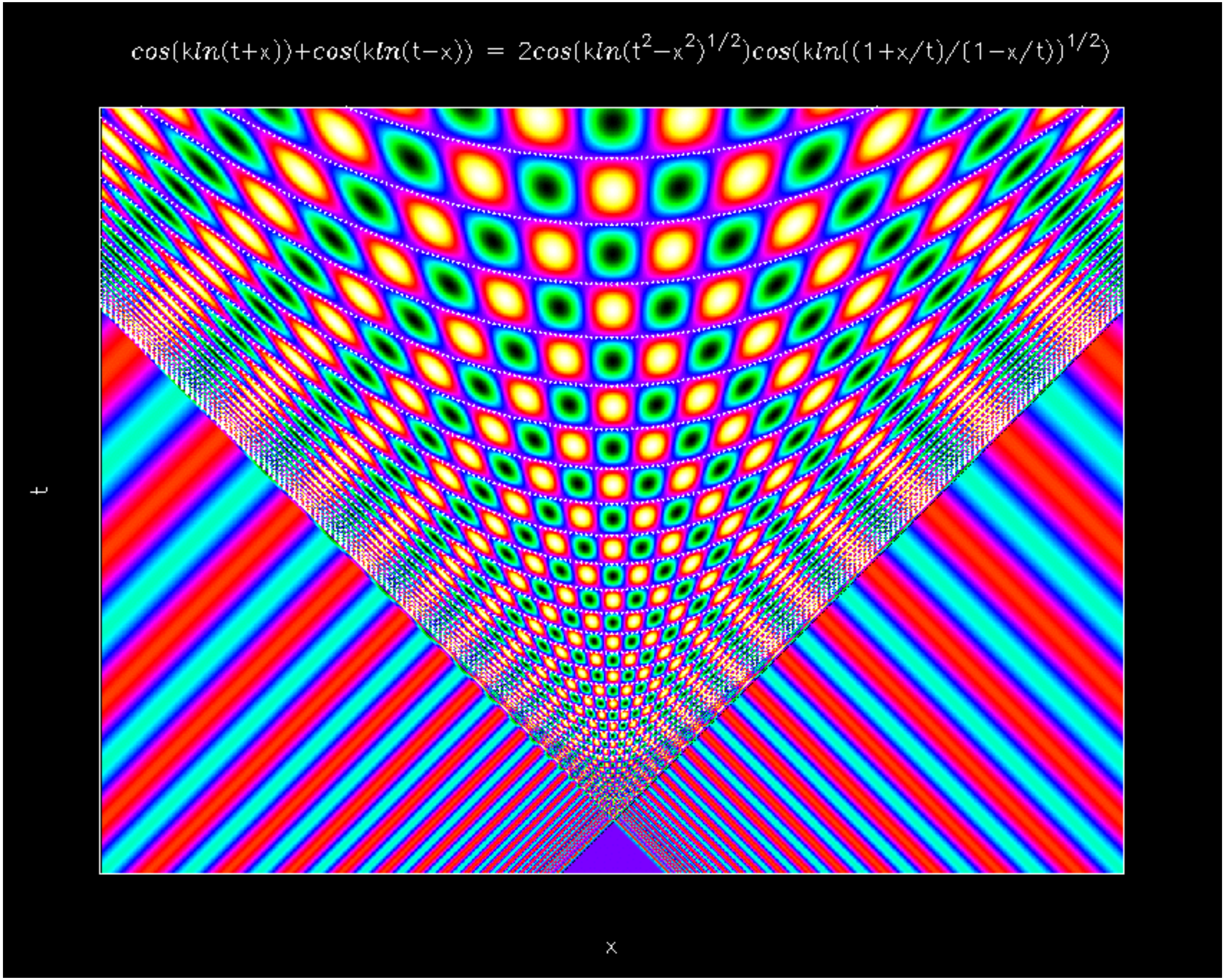
Minkowski spacetime

A 3-surface of constant proper time since the explosion

Geometry of these 3-surfaces is hyperbolic

Same as open FRW models

Standing waves (in expanding coords) in Milne's model



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 $T = \gamma\, T(\text{rest frame})$
- 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 (*).

T. W. B. KIBBLE

Department of Physics, Imperial College - London

(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

(*) The Research reported in this document has been sponsored in part by the Air Force Office of Scientific Research OAR through the European Office Aerospace Research, United States Air Force.

(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. 134.
(4) H. OTT: *Zeits. f. Phys.*, **175**, 70 (1963).
(5) H. ARZELIÈS: *Nuovo Cimento*, **35**, 783 (1965).
(6) See for example R. C. TOLMAN: *Relativity, Thermodynamics and Cosmology* (Oxford, 1950), p. 79.

Biro & Van 2010

ABOUT THE TEMPERATURE OF MOVING BODIES

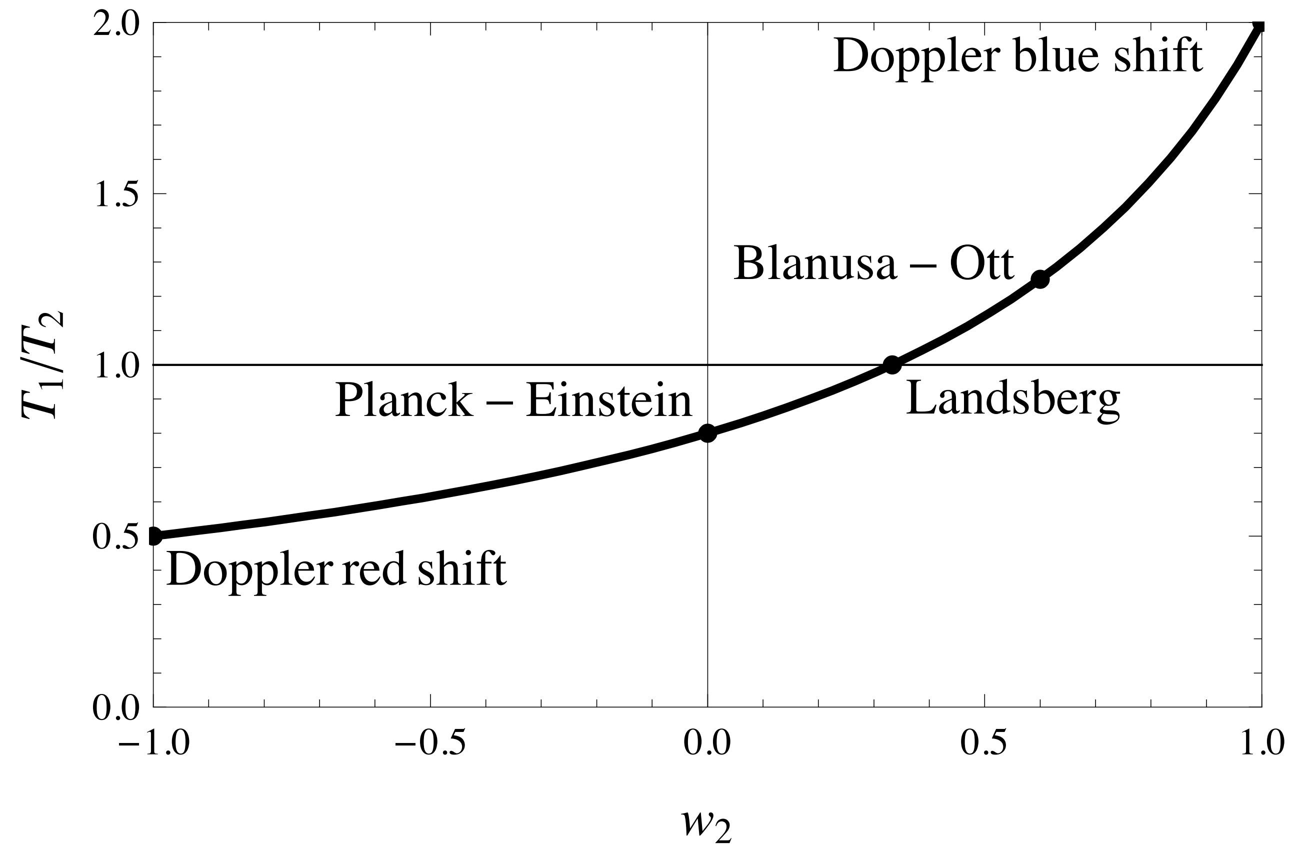


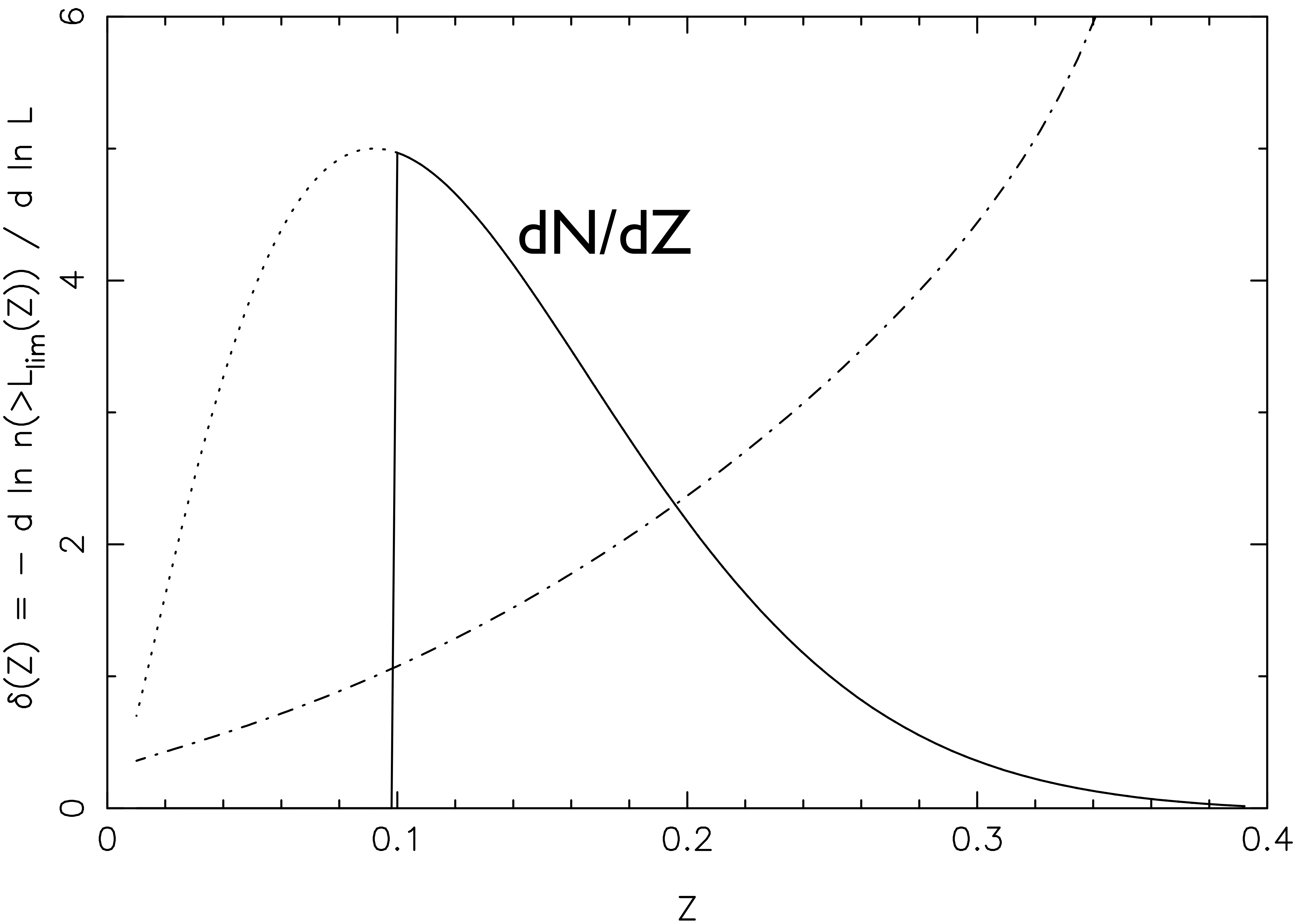
FIGURE 1. Ratio of the temperatures of the observed body in its rest frame, T_2 to that shown by an ideal thermometer, T_1 as a function of the the speed of the heat current in the body, w_2 while approaching with the relative velocity $v = -0.6$.

Conclusions: 1) redshifts in general

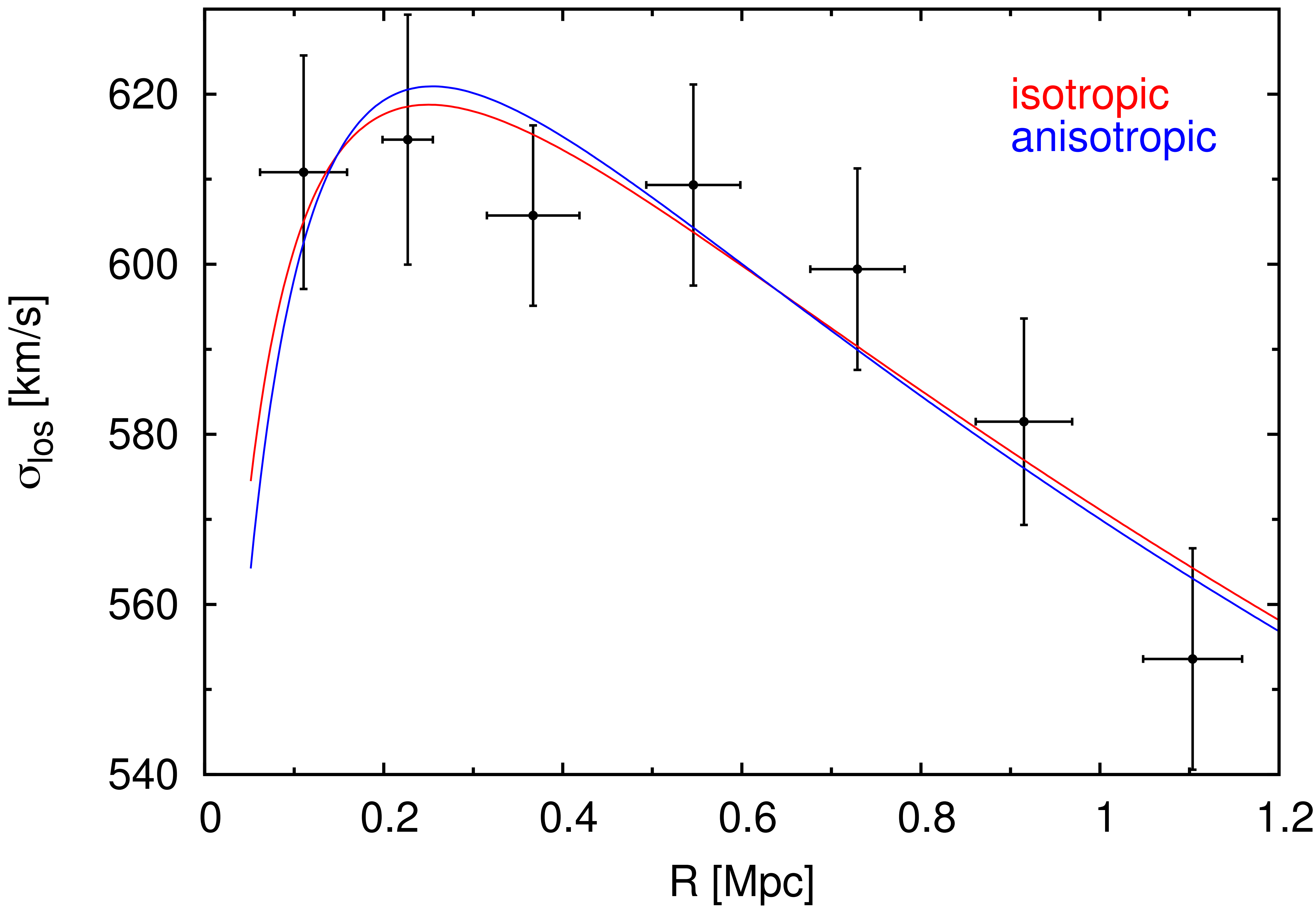
- Redshifts in FRW are <u>not</u> caused by the expansion of space
  - both changes in wavelength and changes in the space between observers are 'caused' by the initial relative velocities and the tidal field in which the observers and photon move.
  - In homogeneous models they happen to be equal because a constant tide stretches λ the same way it stretches D
- But neither can they be thought of as being essentially kinematic, or Doppler, in nature in presence of inhomogeneity
  - that gives the wrong answer for the gravitational redshift component of the redshift
  - which is an integral of the *gradient of the tide* along the photon path
  - Allowance for this largely reconciles conventional view with direct calculation (modulu kinematic TD, LC, SB effects)

Conclusions: 2) cluster gravitational-Z

- 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



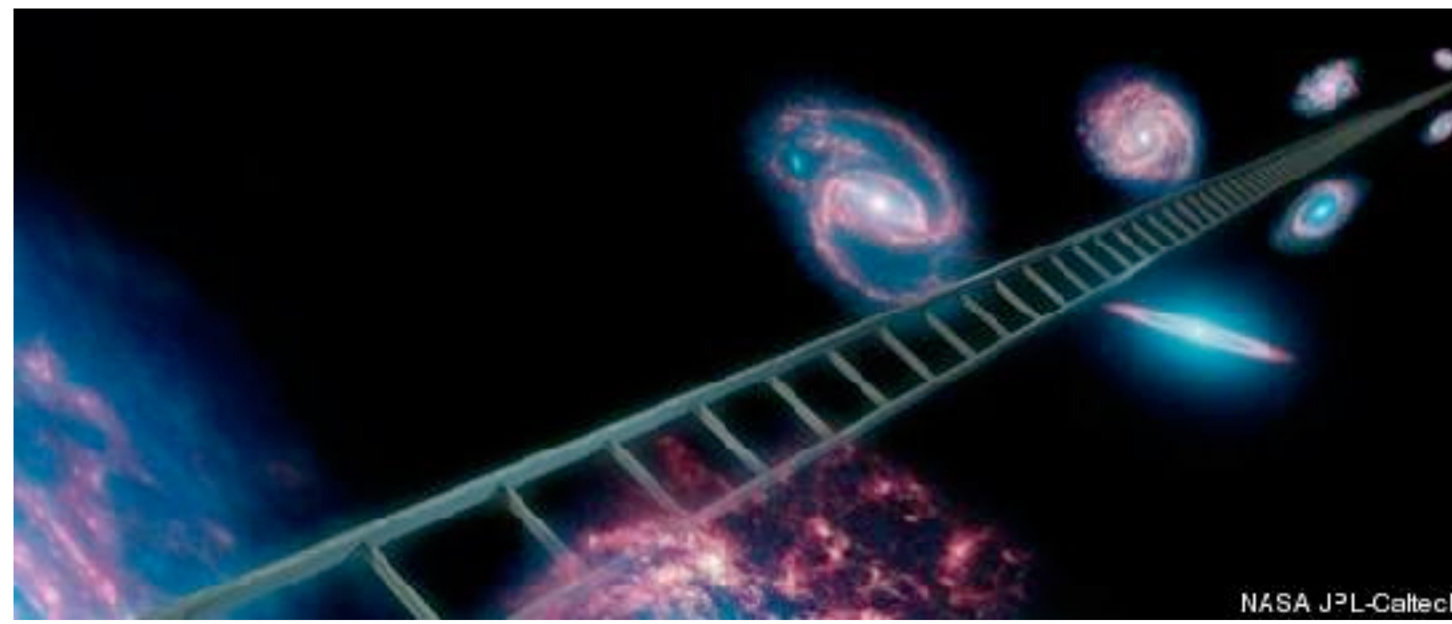
dN/dZ
δ(Z) = − d ln n(>L_lim(Z)) / d ln L
Z
0
0.1
0.2
0.3
0.4
0
2
4
6



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]

Is the 'kinematic' picture correct?

- B&H (and many others) say that the only way to compare velocities of separated objects is *via* parallel transport
  - But that would mean the only way to measure the relative velocity is via redshifts. But then saying 'redshift is a velocity effect' is circular
- But there are other ways:
  - this is how we think about measuring geodesic deviation (and hence the gravitational field)



- It *not* vacuous to say that redshifts in flat space-time are 'Doppler because the velocity that gives the redshift really is the same as the rate of change of proper separation.
- Same is true for FOs in FRW, and many other situations
- Key question: is this a general law? Seems plausible, right?

Application to gravitational redshifts in clusters

- WHH experiment measures the redshift of the general galaxy population relative to the BCG
  - In equilibrium, their mean separation D is unchanging
  - So the 1st order Doppler effect averages to zero.
  - What is the residual (2nd order effect)?
- Conventional view: The relative redshift is just the mean gravitational potential difference.
  - Just as in Pound and Rebka. But doesn't it matter that the galaxies are in free fall?
- Kinematic picture: D is unchanging, so redshift vanishes?
- Or alternatively, one might imagine that the redshift between a pair of galaxies would not be sensitive to the first order potential difference $\delta\varphi \sim \mathbf{D}.\mathbf{g}$ (EP: gravity **g** is "transformed away" in free fall) but would see higher order effects (i.e. tidal field to lowest order).
- Several plausible pictures - which is right?

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?
  - Does their motion induce a red-shift? If so, how is can that be compatible with energy conservation?
    - Note: 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

- Objects will appear red-shifted (on average at least)
  - And a swarm of objects will have an additional red-shift from their motions (light-cone effect)
- But photons from an object 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 radiating isotropically in the observer (or lab) frame
- It is a mild relativistic beaming 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:

What went wrong with the argument about little Doppler shifts?

- We break the null path into a set of segments with a family of observers
- Each can be assumed to be turning around as photon passes
- But Δv is in rest-frame of the pairs
- Generally these don't add up to the rate of change of separation of end-points
- but in constant tidal field they do

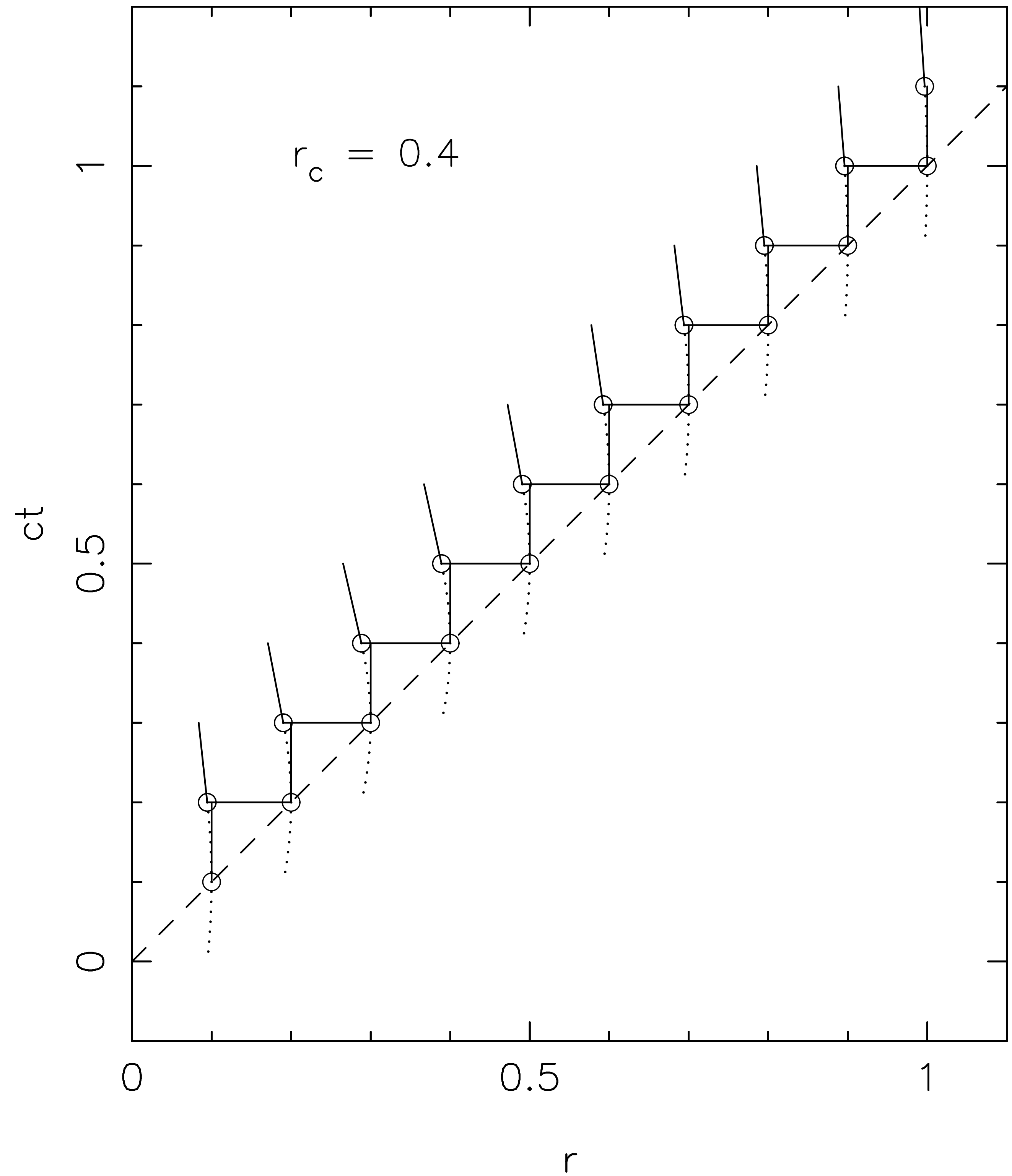


Figure 1. Illustration of the example described in the text. Here we have a potential with gravity $g \sim r/(r^3 + r_c^3)$ which is like that for a uniform density sphere at $r \ll r_c$ and is Keplerian at $r \gg r_c$. The redshift between an emitter at $r = 0$ and a distant

Bunn & Hogg

II. REDSHIFTS OF NEARBY GALAXIES ARE DOPPLER SHIFTS

We begin by returning to the parable of the speeding ticket, mentioned in Sec. I.

> "A driver is pulled over for speeding. The police officer says to the driver, 'According to the Doppler shift of the radar signal I bounced off your car, you were traveling faster than the speed limit.'
>
> "The driver replies, 'In certain coordinate systems, the distance between us remained constant during the time the radar signal was propagating. In such a coordinate system, our relative velocity is zero, and the observed wavelength shift was not a Doppler shift. So you can't give me a ticket.' "

If you believe that the driver has a legitimate argument, then you have our permission to believe that cosmological redshifts are not really Doppler shifts. If, on the other hand, you think that the officer is right, and the redshift can legitimately be interpreted as a Doppler shift, then you should believe the same thing about redshifts of nearby galaxies in the expanding universe.

Why is the police officer right and the driver wrong? Assuming the officer majored in physics, he might explain the situation like this: "Spacetime in my neighborhood is very close to flat. That means that I can lay down space and time coordinates in my neighborhood such that, to an excellent approximation, the rules of special relativity hold. Using those coordinates, I can interpret the observed redshift as a Doppler shift (because there is no gravitational redshift in flat spacetime) and calculate your coordinate velocity relative to me. The errors in this method are of the same order as the departures from flatness in the spacetime in a neighborhood containing both me and you. As long as I'm willing to put up with that very small level of inaccuracy, I can interpret that coordinate velocity as your actual velocity relative to me."

The principle underlying the officer's reasoning is uncontroversial. It is no different from the principle that lets football referees ignore the curvature of Earth and use a flat coordinate grid in describing a football field.

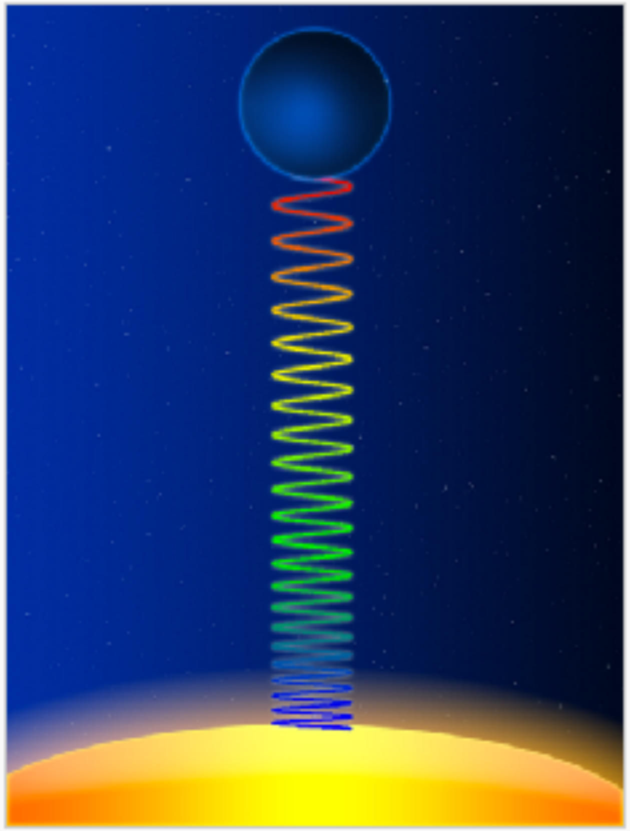
The gravitational redshift according to wikipedia

Gravitational redshift

From Wikipedia, the free encyclopedia

In astrophysics, **gravitational redshift** or **Einstein shift** is the process by which electromagnetic radiation originating from a source that is in a gravitational field is reduced in frequency, or redshifted, when observed in a region of a weaker gravitational field. This is a direct result of gravitational time dilation - as one moves away from a source of gravitational field, the rate at which time passes is increased relative to the case when one is near the source. As frequency is inverse of time (specifically, time required for completing one wave oscillation), frequency of the electromagnetic radiation is reduced in an area of a lower gravitational field (i.e., a higher gravitational potential). There is a corresponding reduction in energy when electromagnetic radiation is red-shifted, as given by Planck's relation, due to the electromagnetic radiation propagating in opposition to the gravitational gradient. There also exists a corresponding blueshift when electromagnetic radiation propagates from an area of a weaker gravitational field to an area of a stronger gravitational field.

If applied to optical wavelengths, this manifests itself as a change in the colour of visible light as the wavelength of the light is increased toward the red part of the light spectrum. Since frequency and wavelength are inversely proportional, this is equivalent to saying that the frequency of the light is reduced towards the red part of the light spectrum, giving this phenomenon the name redshift.



The gravitational redshift of a light wave as it moves upwards against a gravitational field (produced by the yellow star below). The effect is greatly exaggerated in this diagram.

Contents [hide]

The nature of astronomical redshifts - prologue

- For photons exchanged between fundamental observers in FRW λ increases with the scale-factor a(t)
  - Equivalently, wavelength changes in proportion to the emitter-receiver proper separation D so $\Delta \ln(\lambda/D) = 0$
  - Just as for a pair of observers in flat space-time
- Widely accepted, but there has been much debate as to *why*?
- There has been a shift away from describing redshifts as being *caused* by the 'expansion of space' and towards a `kinematic' description in which redshifts --- and perhaps all redshifts --- are thought of as essentially Doppler-like, or 'kinematic' in nature.
- Here I will review the old picture and the arguments against it, and the arguments for the kinematic picture
  - but both lead to wrong expectations for cluster grav-Z
- Calculation: the intrinsically gravitational component of Z

The kinematic origin of the cosmological redshift

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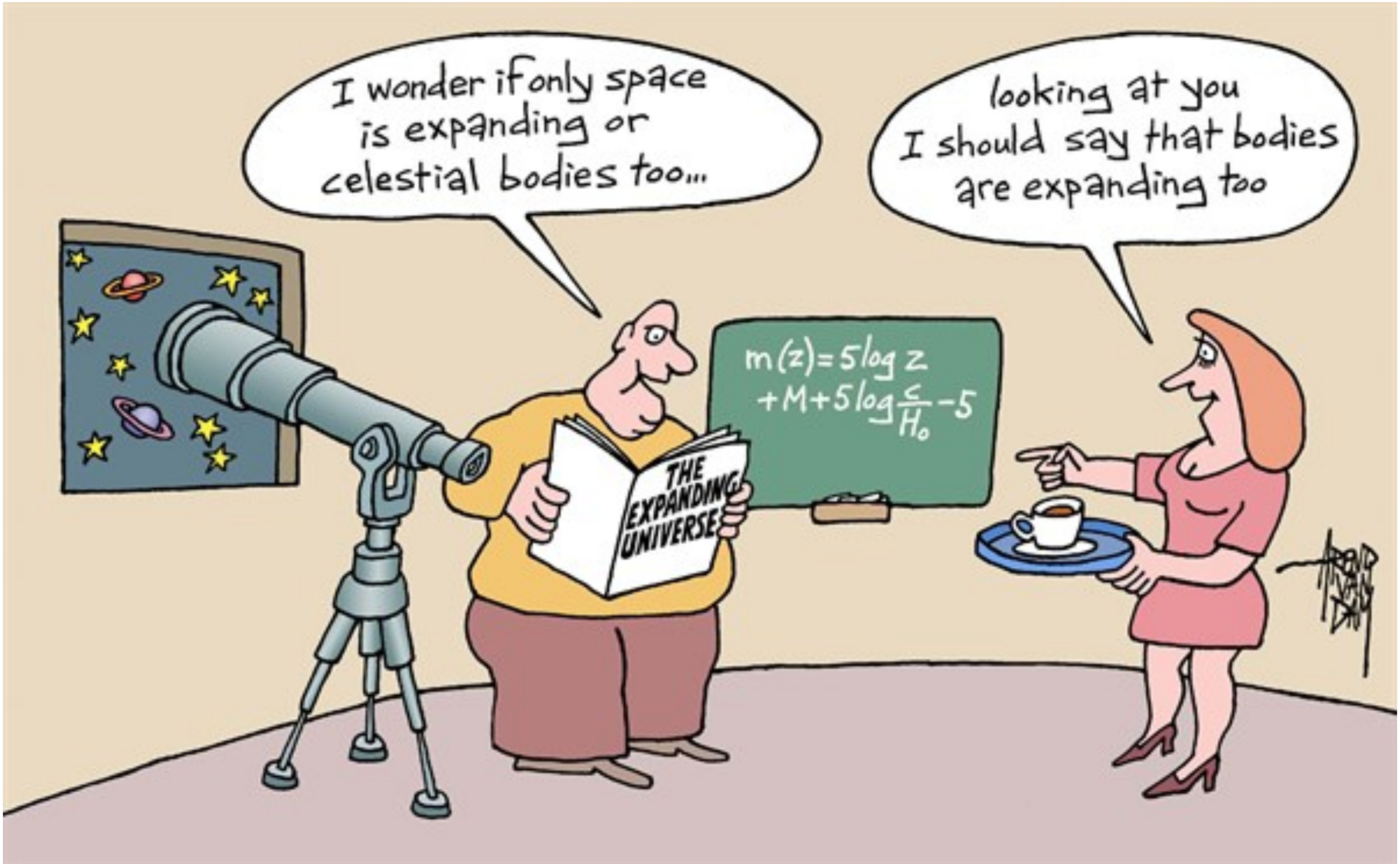
A common belief about big-bang cosmology is that the cosmological redshift cannot be properly viewed as a Doppler shift (that is, as evidence for a recession velocity), but must be viewed in terms of the stretching of space. We argue that, contrary to this view, the most natural interpretation of the redshift is as a Doppler shift, or rather as the accumulation of many infinitesimal Doppler shifts. The stretching-of-space interpretation obscures a central idea of relativity, namely that it is always valid to choose a coordinate system that is locally Minkowskian. We show that an observed frequency shift in any spacetime can be interpreted either as a kinematic (Doppler) shift or a gravitational shift by imagining a suitable family of observers along the photon's path. In the context of the expanding universe the kinematic interpretation corresponds to a family of comoving observers and hence is more natural.

either the observations or the general-relativistic equations that successfully explain them. Rather, our focus is on the interpretation: given that a photon does not arrive at the observer conveniently labeled "Doppler shift," "gravitational shift," or "stretching of space," when can or should we apply these labels?

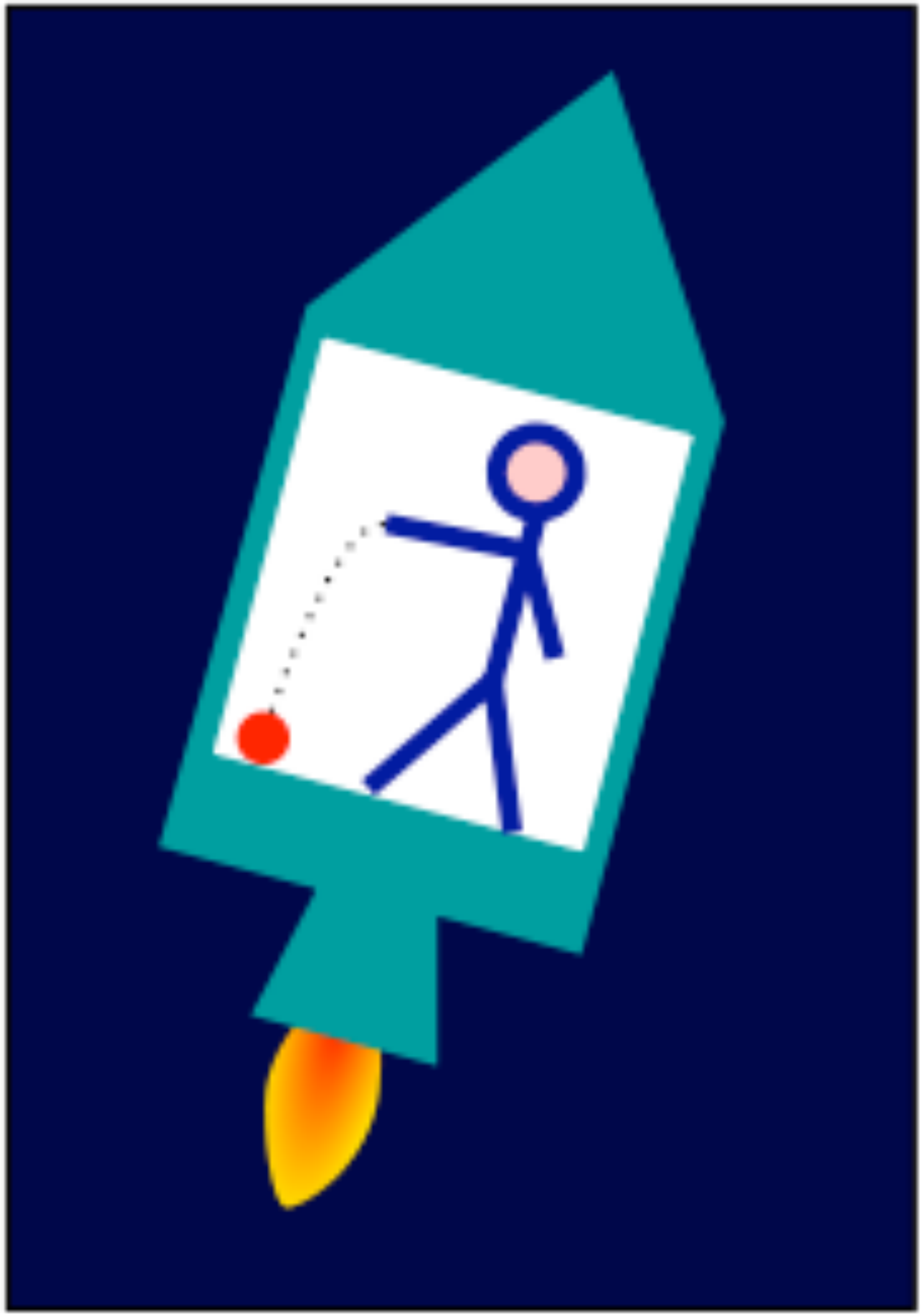
Arguably an enlightened cosmologist never asks this question. In the curved spacetime of general relativity, there is no unique way to compare vectors at widely separated spacetime points, and hence the notion of the relative velocity of a distant galaxy is almost meaningless. Indeed, the inability to compare vectors at different points is the definition of a curved spacetime.[1,2,3,4] In practice, however, the enlightened view is far from universal. The view presented

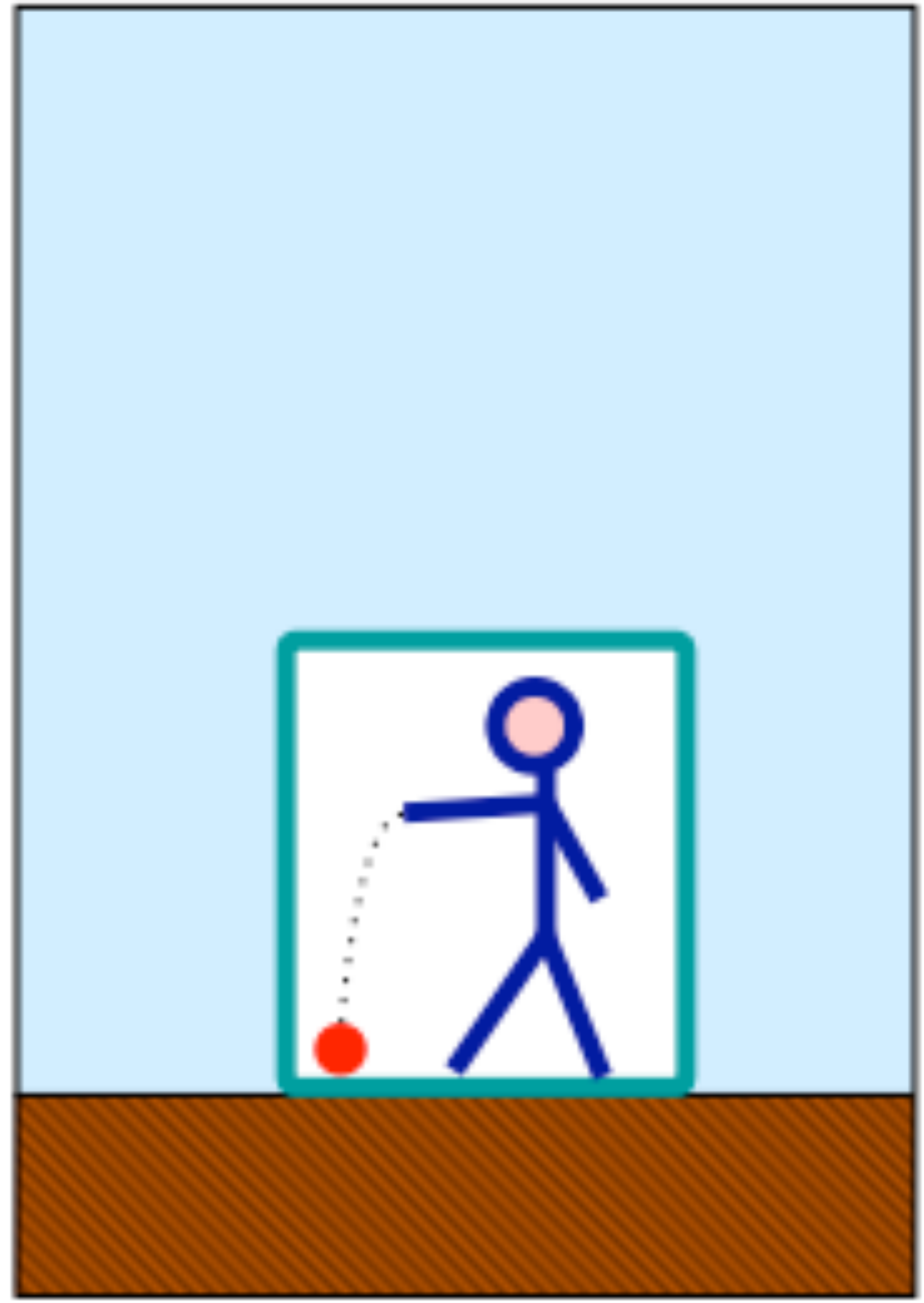

I wonder if only space is expanding or celestial bodies too...
looking at you I should say that bodies are expanding too
m(z)=5 log z +M+5 log c/H0 -5
THE EXPANDING UNIVERSE

My thoughts on P&R, B&H, Synge, Rindler

- B&H argument that gravitational and Doppler redshifts are in some way equivalent is misleading.
    - Accelerated observers *know* that they are accelerated
        - So when they allow for this they agree that the redshift measured by the cop was a Doppler shift cause by δv
    - An acceleration *does not* create gravity ($R_{\alpha\beta\gamma\delta} = 0$)
    - Pound and Rebka *did not measure* a gravitational redshift
        - they measured a redshift caused by the *non-gravitational* acceleration that their apparatus experienced
- Synge is right: gravity = *curvature* (or *tidal* field)
    - Pound & Rebka too insensitivite to measure tidal effects
- But Synge is wrong to say that redshift is just Doppler
    - parallel transport of photon involved the *connection*
- Most redshifts are mostly Doppler - but there is an intrinsically gravitational component - it is the *gradient* of the tide

equivalence principle





What is the equivalence principle?

- Synge:

Perhaps they speak of the Principle of Equivalence. If so, it is my turn to have a blank mind, for I have never been able to understand this Principle. Does it mean that the signature of the space-time metric is + 2 (or − 2 if you prefer the other convention)? If so, it is important, but hardly a Principle. Does it mean that the effects of a gravitational field are indistinguishable from the effects of an observer's acceleration? If so, it is false. In Einstein's theory, either there is a gravitational field or there is none, according as the Riemann tensor does not or does vanish. This is an absolute property; it has nothing to do with any observer's world-line. Space-time is either flat or curved, and in several places in the book I have been at considerable pains to separate truly gravitational effects due to curvature of space-time from those due to curvature of the observer's world-line (in most ordinary cases the latter predominate).

- Rindler:

As a consequence of the equivalence principle, not only can we *eliminate* gravity by free fall, we can also *create* it by acceleration.

version of the EP is directly supported by Mach's principle. The rocket in outer space sees the universe accelerate past it. The accelerating universe creates a gravitational field inside the rocket.

Possible resolution of static and “kinematic” view?

- Consider particles in equilibrium in potential well
- photon emitted by “cold” particle at bottom of potential well and received by randomly chosen “hot” particle at larger radius
- particles were lower when the photon was emitted
- together with tidal gradient term this exactly reproduces the naive P&R effect
- plus TD, LC, SB ....

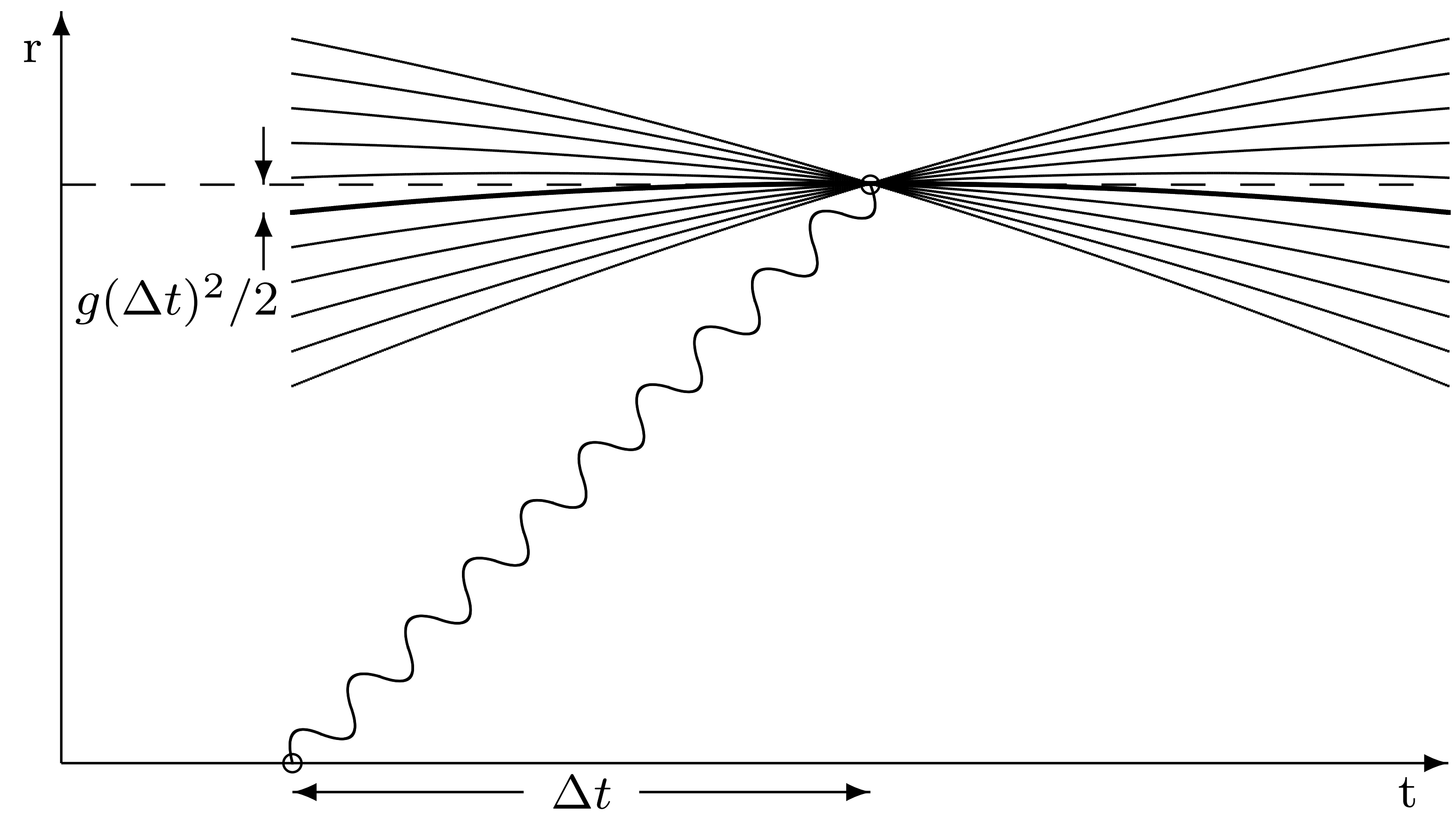


Figure 2. Illustration of situation described in text where a photon is emitted by a ‘cold’ particles near the centre of a smooth potential well and is received by a randomly chosen ‘hot’ particle at large distance. A sample of orbits from the distribution of velocities – here a simple box-car – is shown as curves. The orbit for the average velocity particle is shown as the heavy curve. The average radial velocity is zero at the time of reception, but the average velocity over the time-of-flight of the photon is $-g\Delta t/2$ and, for a parabolic potential, this velocity, in units of c is equal to the gravitational redshift. It is tantalising to think that a generalisation of this reconciles the GR kinematic view of redshifts with more conventional view of gravitational redshifts.

So why does λ scale with a(t) in cosmology?

- 1) Thermodynamics plus photons as quanta:
  - lst law of thermodynamics: $dE = pdV$ (or $T^{0\mu}{}_{;\mu} = 0$)
    - with pressure $P = \rho c^2/3$
    - and $E = mc^2$
    - implies $\rho_{rad} \sim a^{-4}$
      - same as $T^{0\mu}{}_{;\mu} = 0$
  - plus conservation of photon number (or entropy)
    - $n \sim a^{-3}$
- With $E_\gamma = h\nu$ gives $\lambda \sim a$

Radiation in the expanding Universe

- Thermodynamics and photons as quanta:
  - 1st law of thermodynamics (dE = pdV)
    - and E = mc2 => $\rho \sim a^{-4}$
  - plus conservation of photon number (or entropy)
    - $n \sim a^{-3}$
- Classical wave mechanics (Maxwell's equations):
  - "damping" term in the wave equation
    - $\rho \sim a^{-4}$
  - and for $\omega \ll H$ there is an extra conserved quantity
    - $\omega P_\varphi(\underline{k}) \sim a^{-3}$ is an adiabatic invariant
- Peebles's argument (photon, wave packet, whatever ....)
- All give $\lambda \sim a(t)$
  - (though see Bassett et al 2013 etc on "z-remapping")

Front-back asymmetry effects in LSS-RSD

- Extension to larger scales.
  - Bright-faint cross correlation
    - e.g. Croft et al...
  - Boss survey:
    - Gaztanaga+2015 (no significant effect)
    - Alam+2016..
- Lots of rich material in the front-back asymmetry of the galaxy correlation function.
- Lots of interesting scope for modelling
  - e.g. beyond 1st order....

Transverse Doppler Effect: Blue is the new Red

- Moving *objects* appear redshifted on average
- But moving objects have more energy per unit mass (in the observer frame)
- So *photons* must be blue-shifted on average
- same magnitude effect - opposite sign

How do we resolve this?

Light-cone effect - more particles moving away!