L'Energie Noire

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Expansion of the universe:
The groups of galaxies are moving away from each other.

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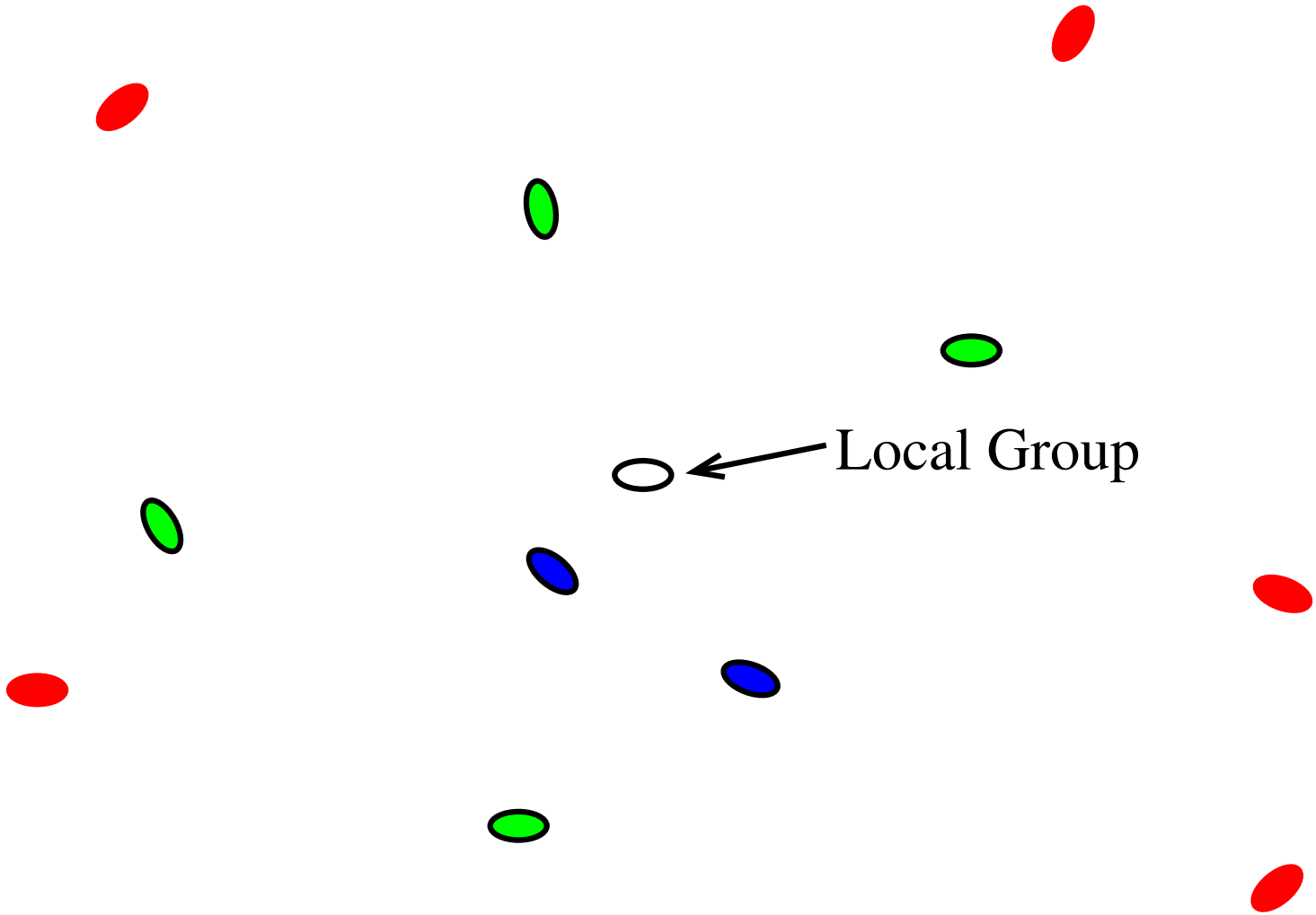
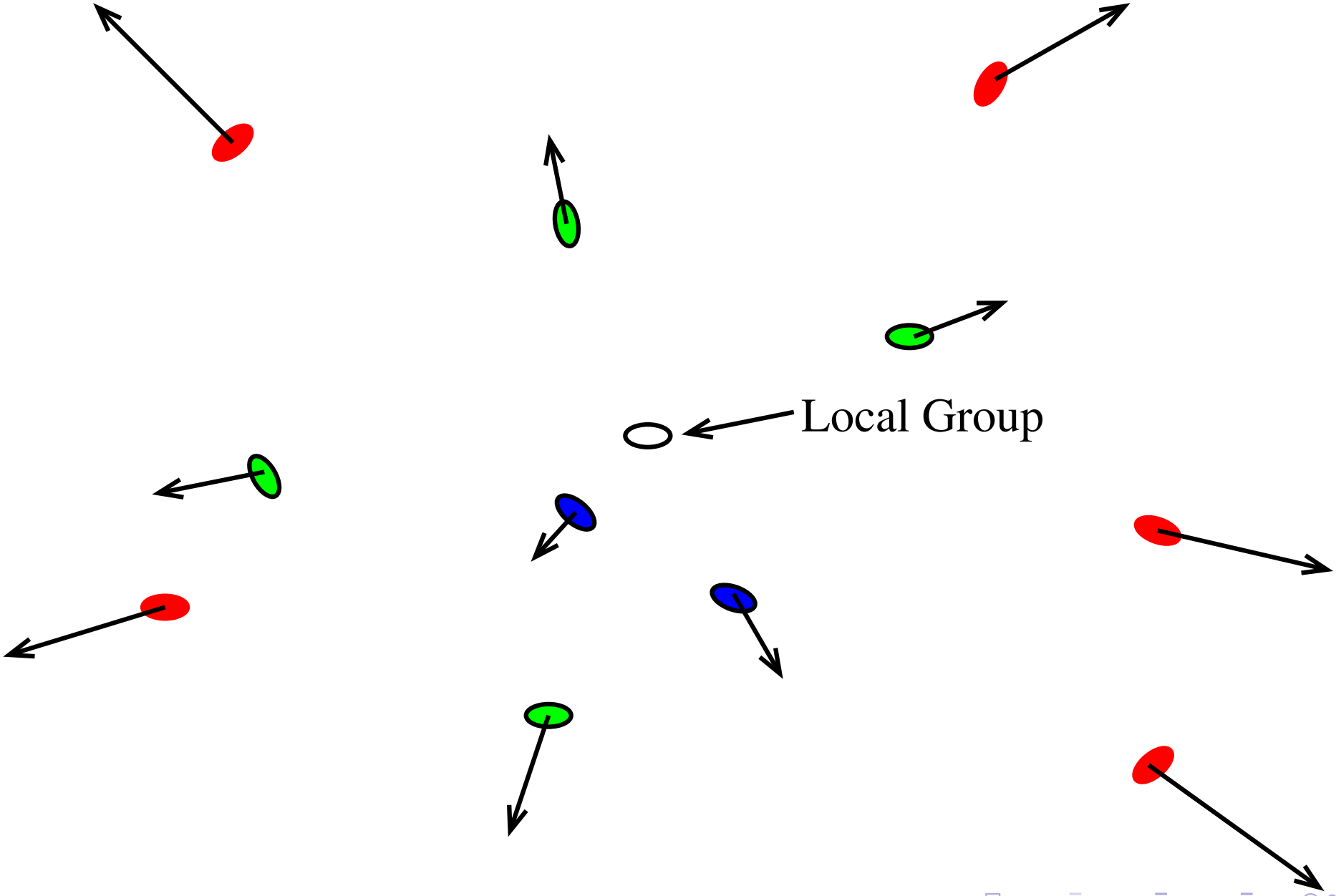
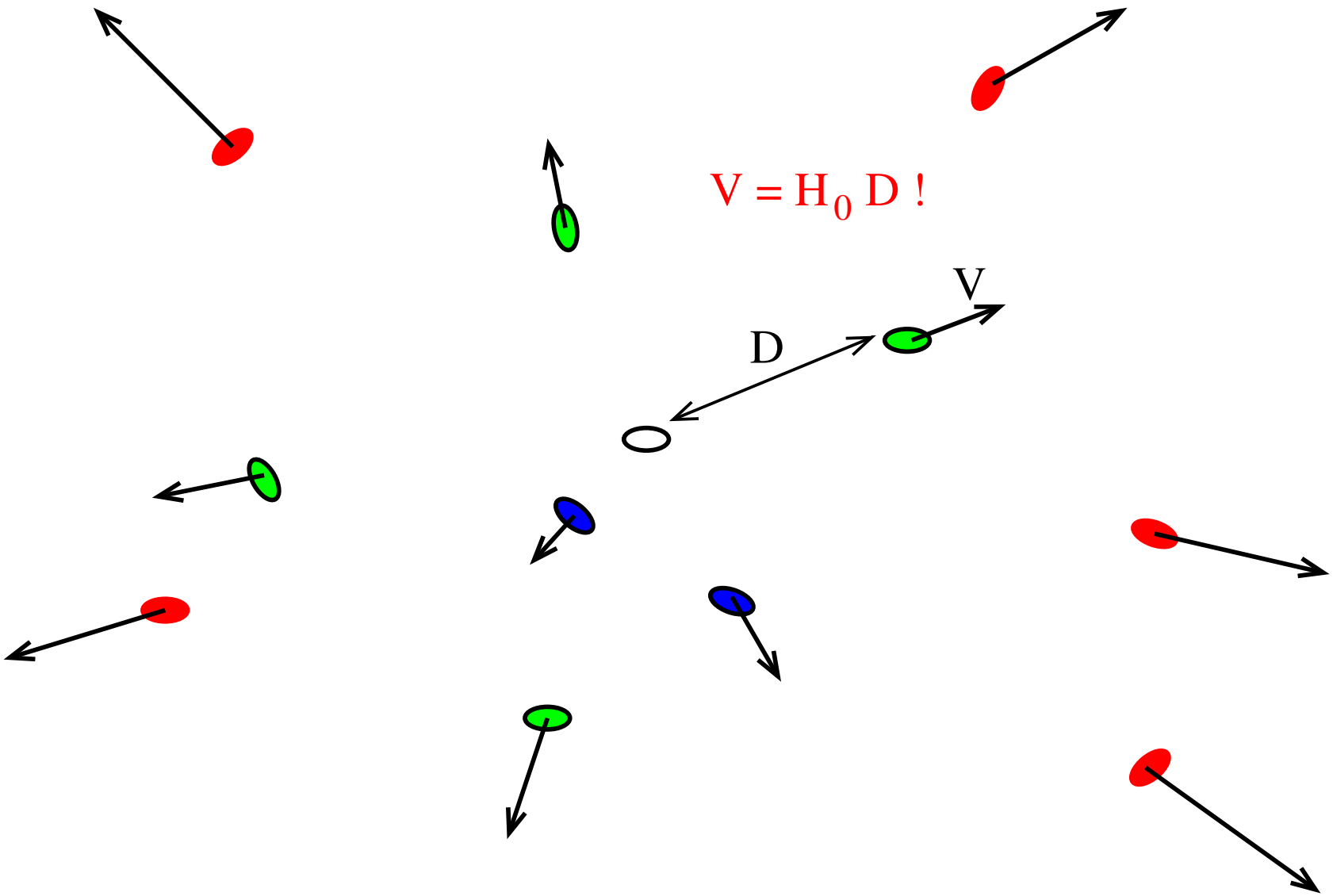


Expansion of the Universe?



Expansion of the Universe: $V = H_0 D$



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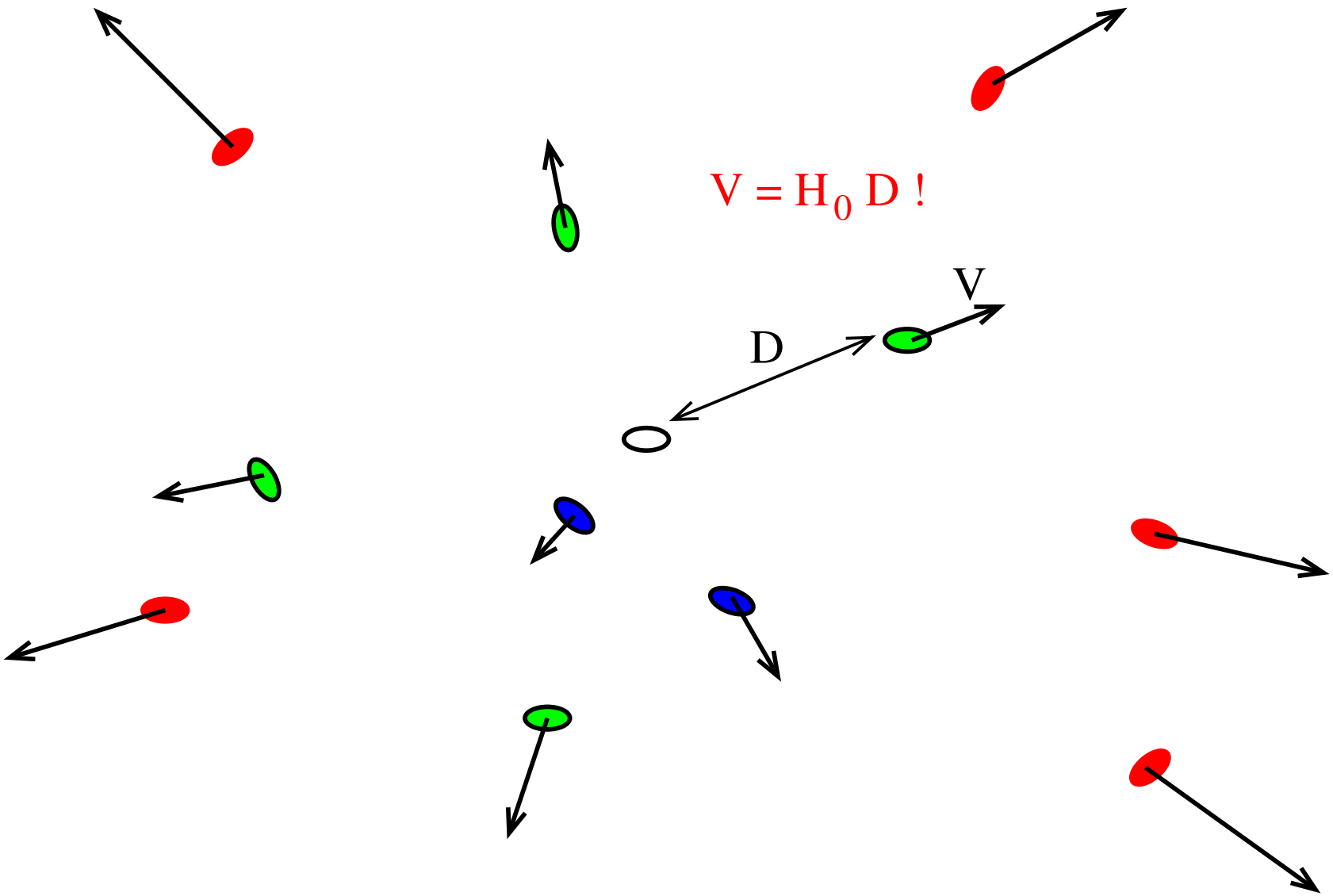

$V = H_0 D$ makes all groups recede from each other!

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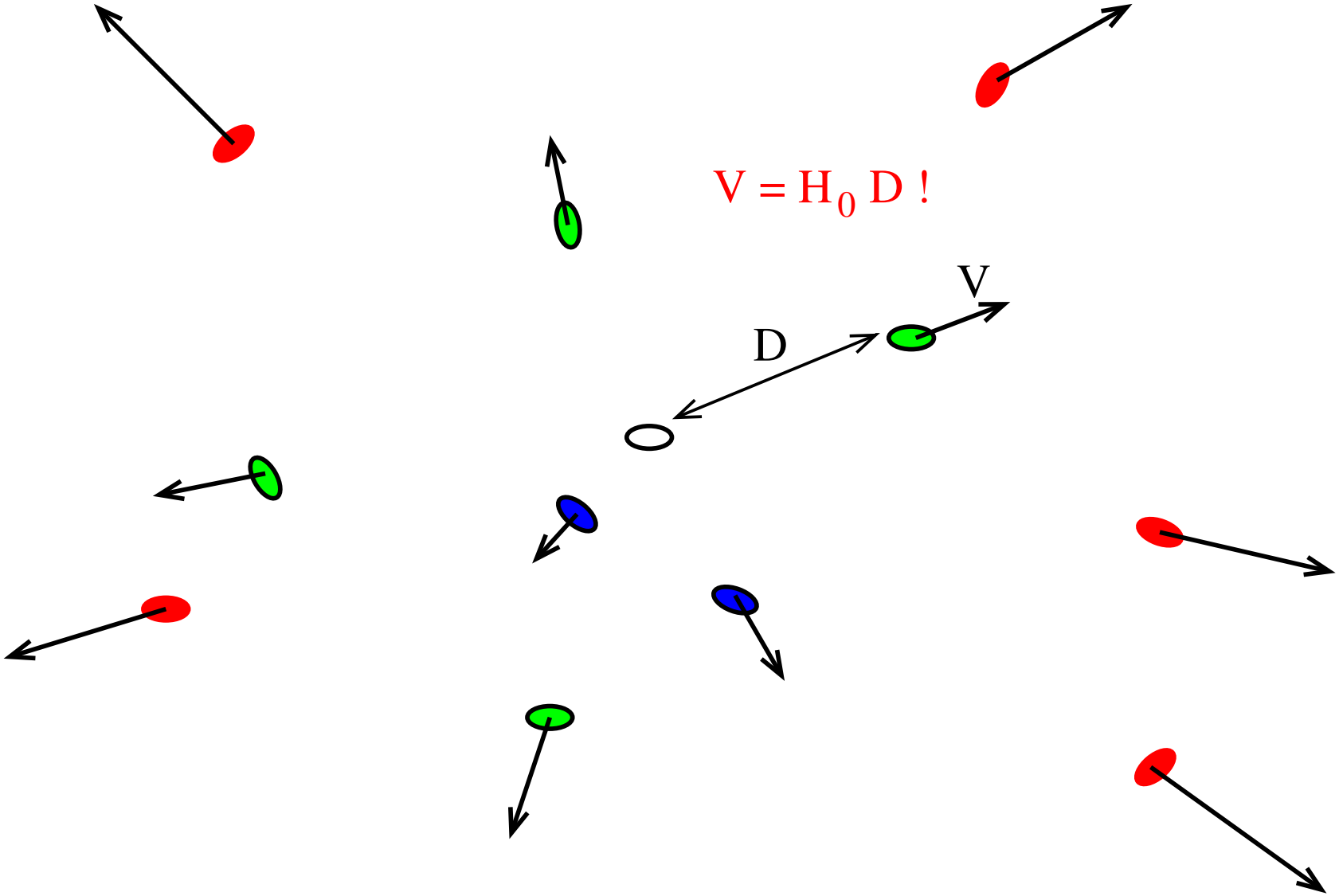

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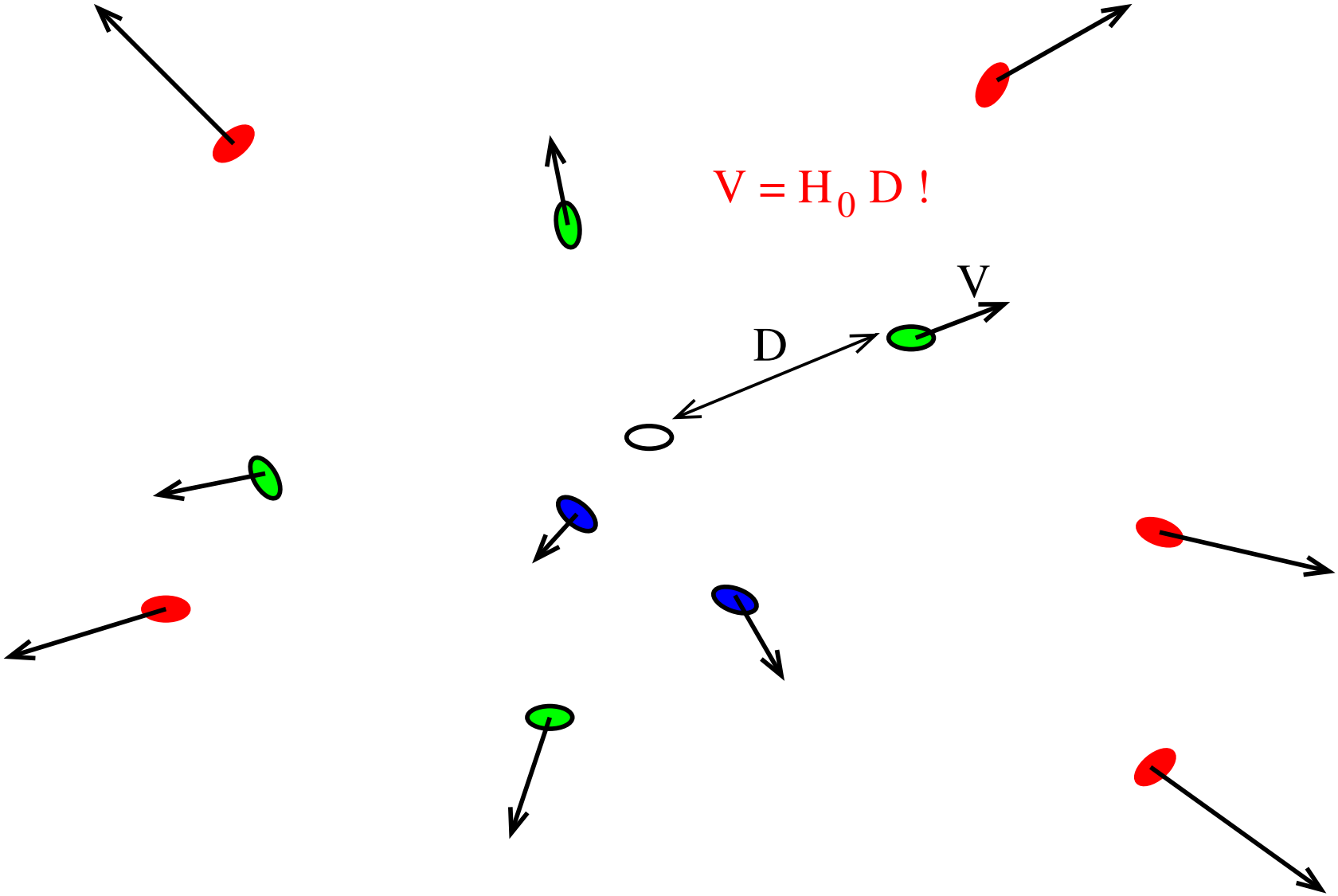
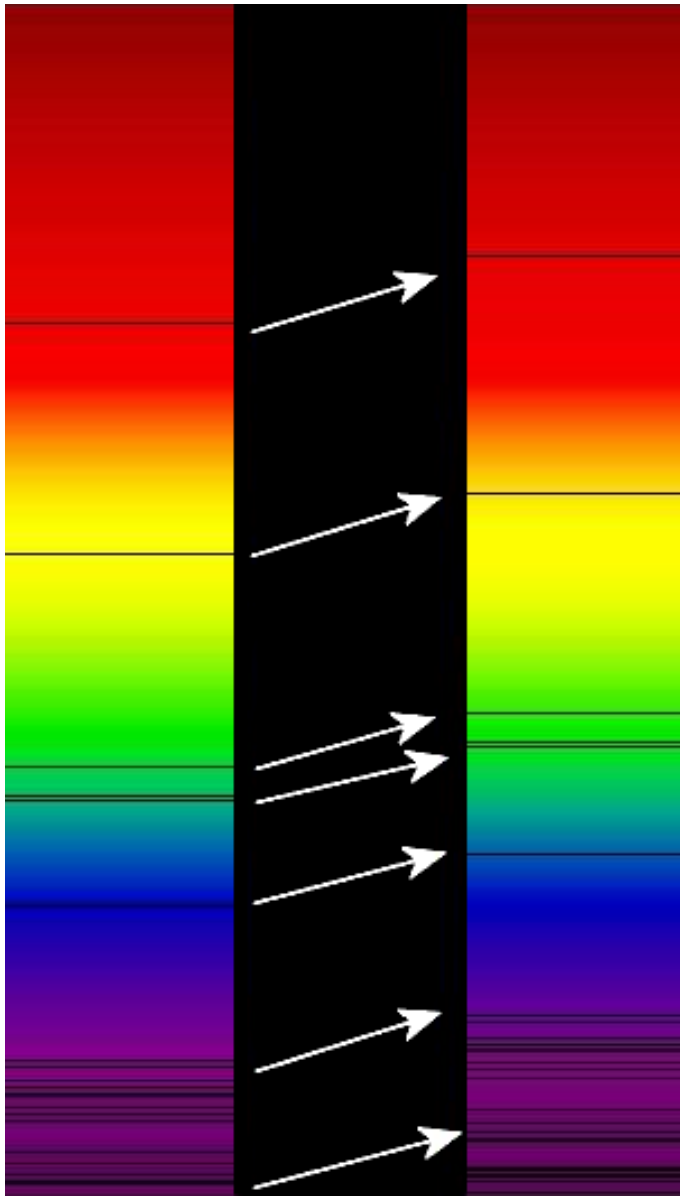


Need to measure V and D!

Measure V with Doppler shift

solar spectrum with "absorption lines" due to specific atoms



galaxy spectrum $v \sim 0.1c$ (same lines but redshifted)

Measure D: it's really hard!

- Sun: looks big and bright!
- Stars: look small and faint!

$$\frac{Brightness\ of\ sun}{Brightness\ of\ sun'} = \frac{D^2_{sun'}}{D^2_{sun}}$$

sun' is a star "like" the sun.

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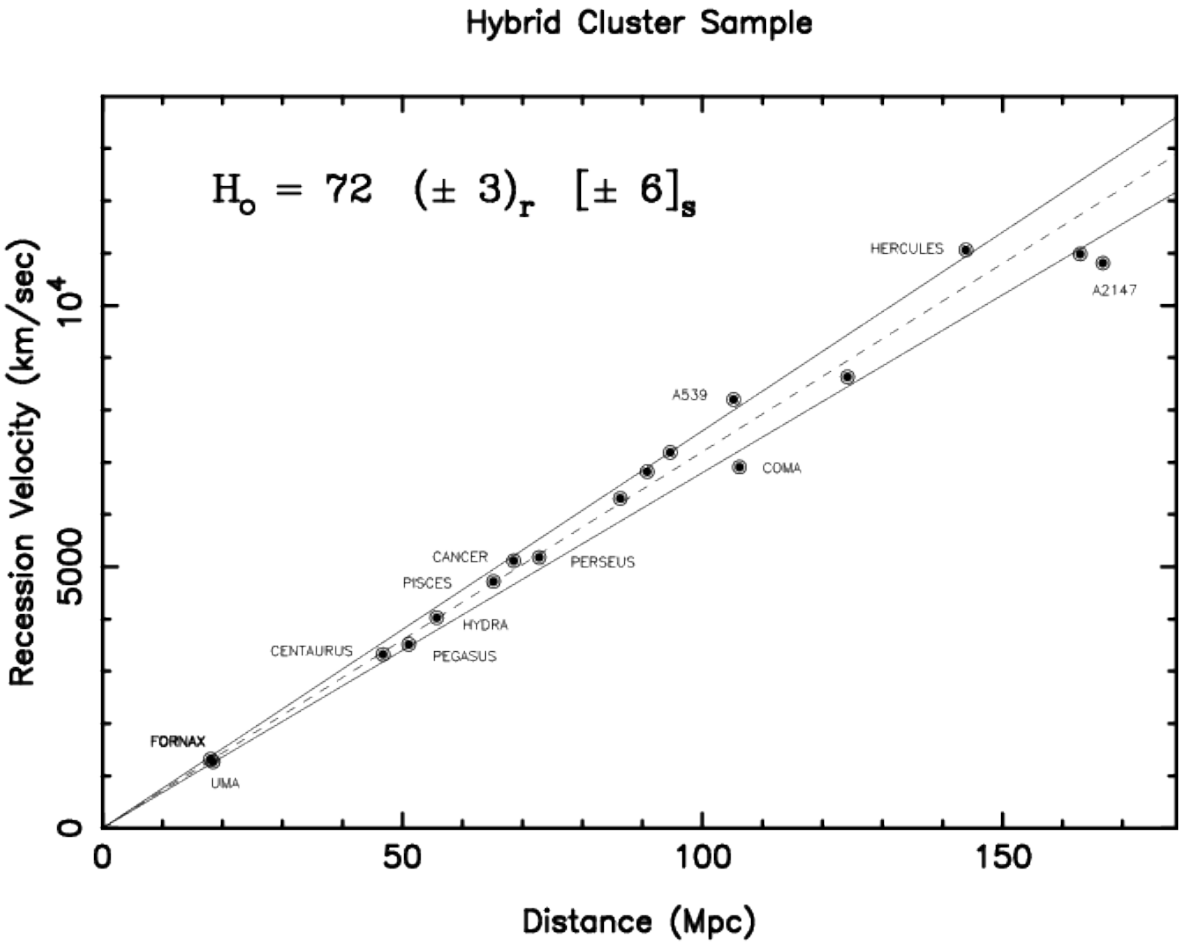
Problem: Sun not bright enough to be seen in distant galaxies

$\Rightarrow$ Use exploding stars (supernovae)

(Type Ia) Supernovae: Best Candle in the Universe

- explosion of a star at the end of its life
- visible for $\sim$ 1month
- Luminosity known to $\sim$ 10% and calibrated by observing supernovae in galaxies of known distance (!)

A Hubble diagram: $v = H_0 D$



- v from Doppler shift
- D from standard candles (e.g. supernovae)

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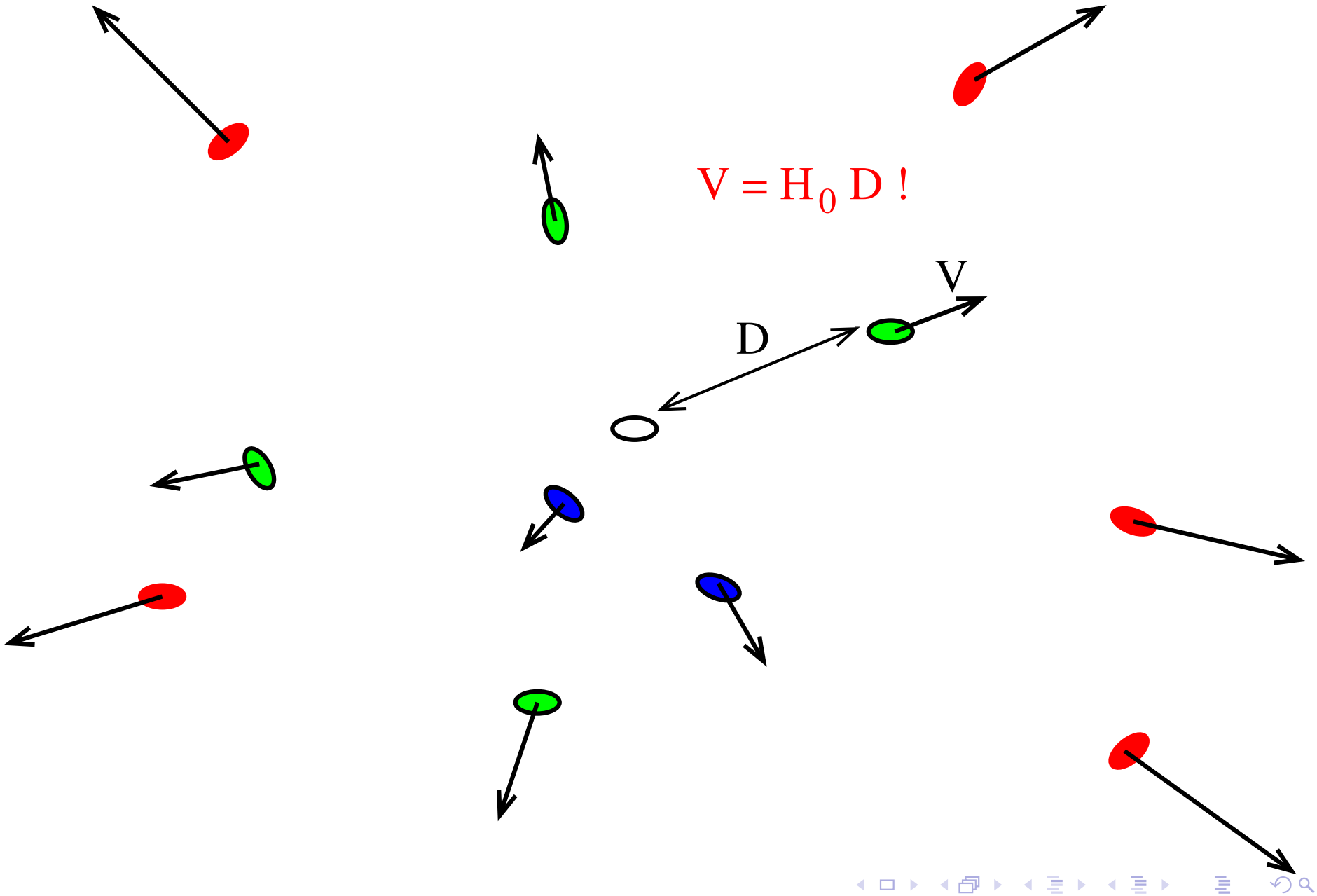
Acceleration $\Rightarrow$ all V's smaller in past



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How can we know that velocities were smaller in the past and will be faster in the future?

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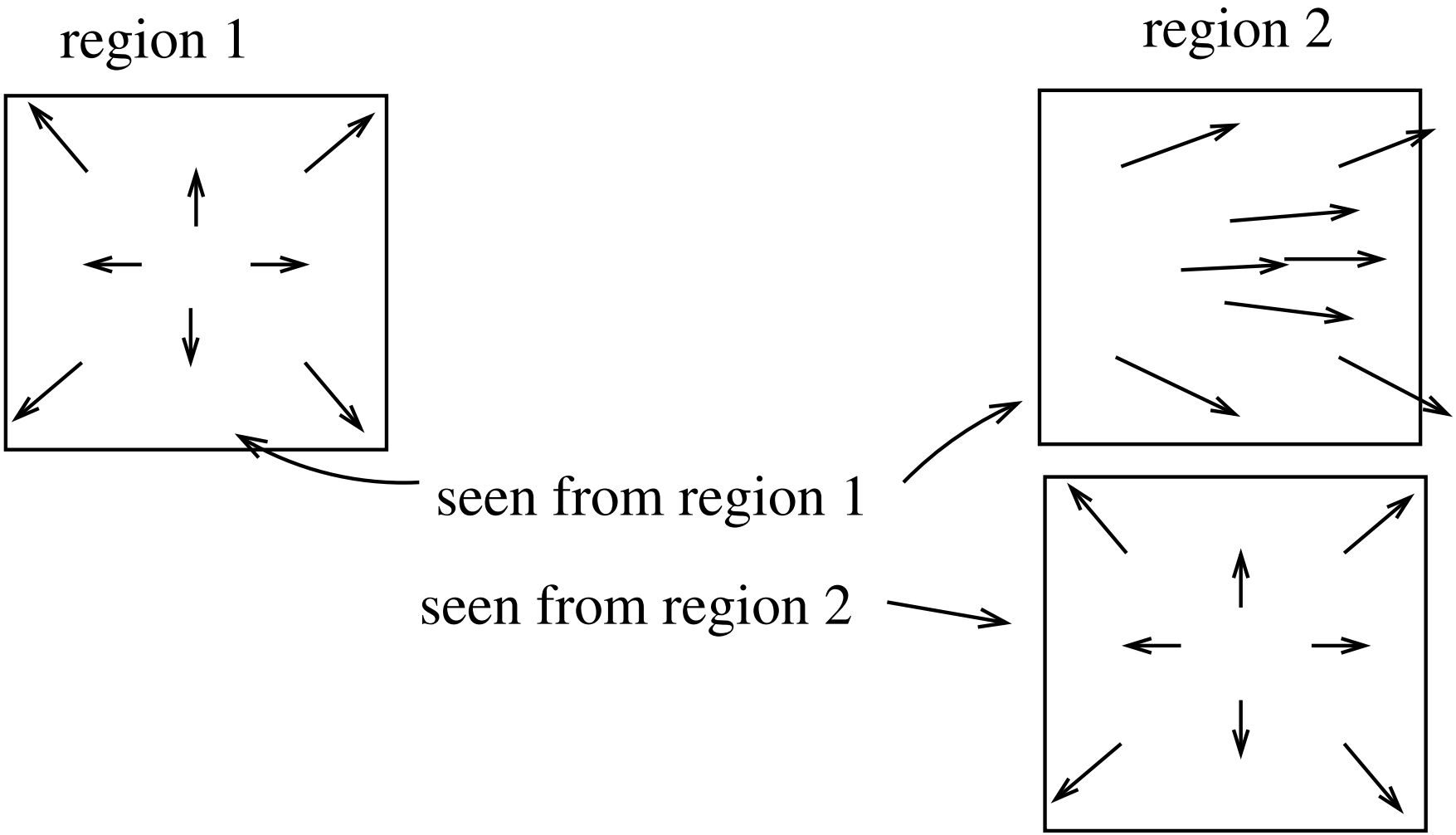
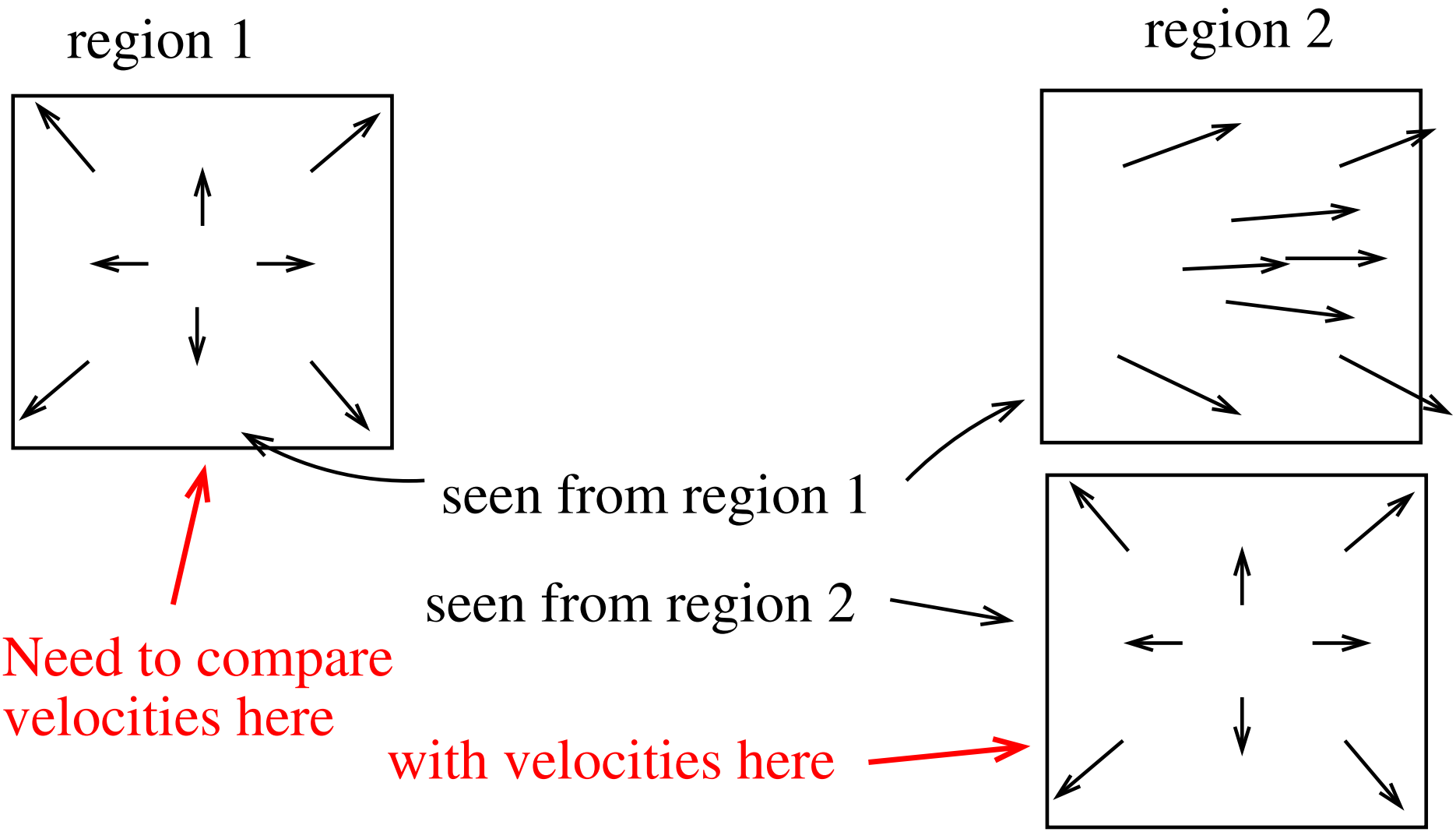
We can't measure future velocities.....

but we can measure past velocities!

Region 1 sees Region 2.....in the past



To distinguish acceleration from deceleration



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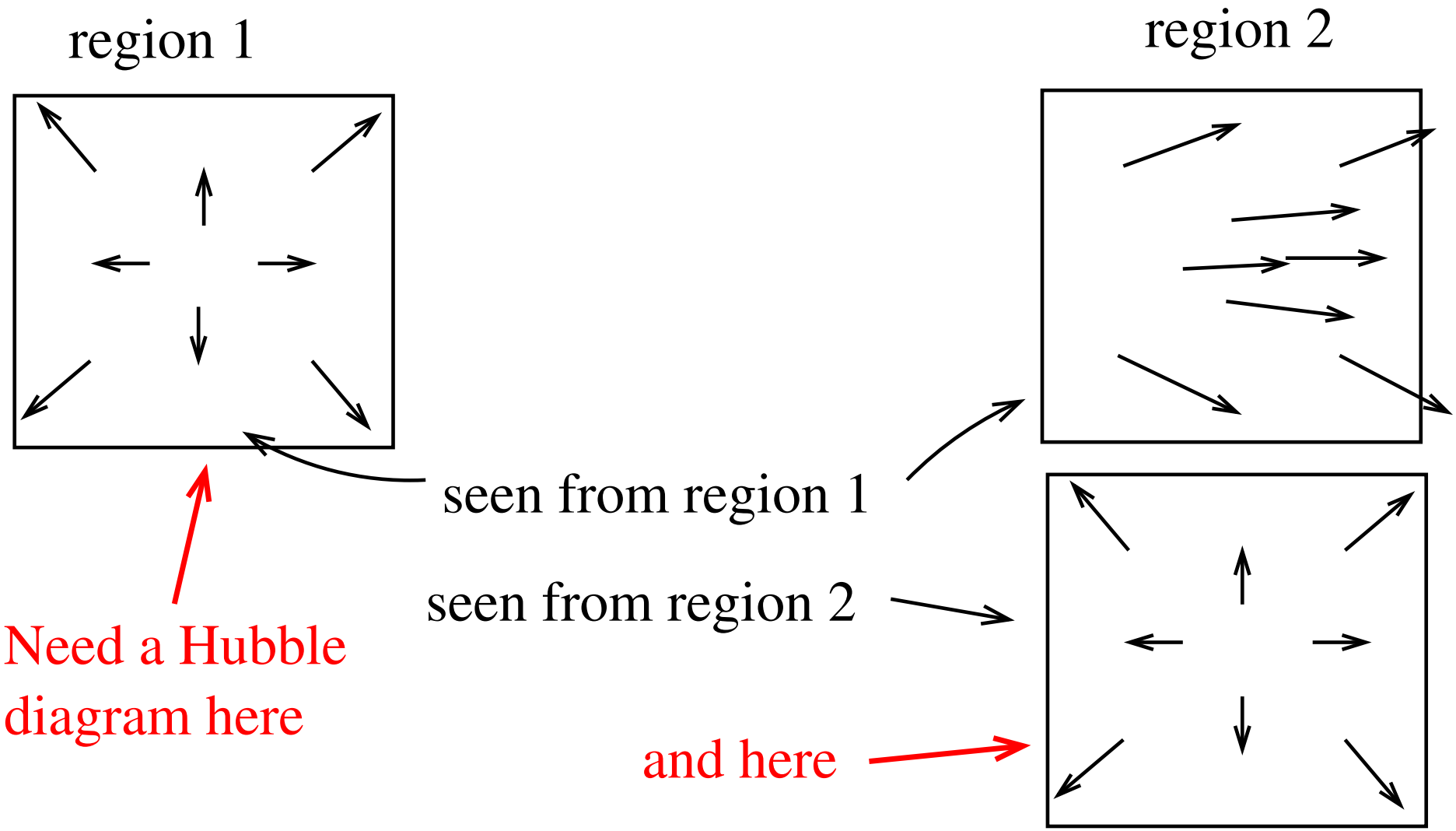
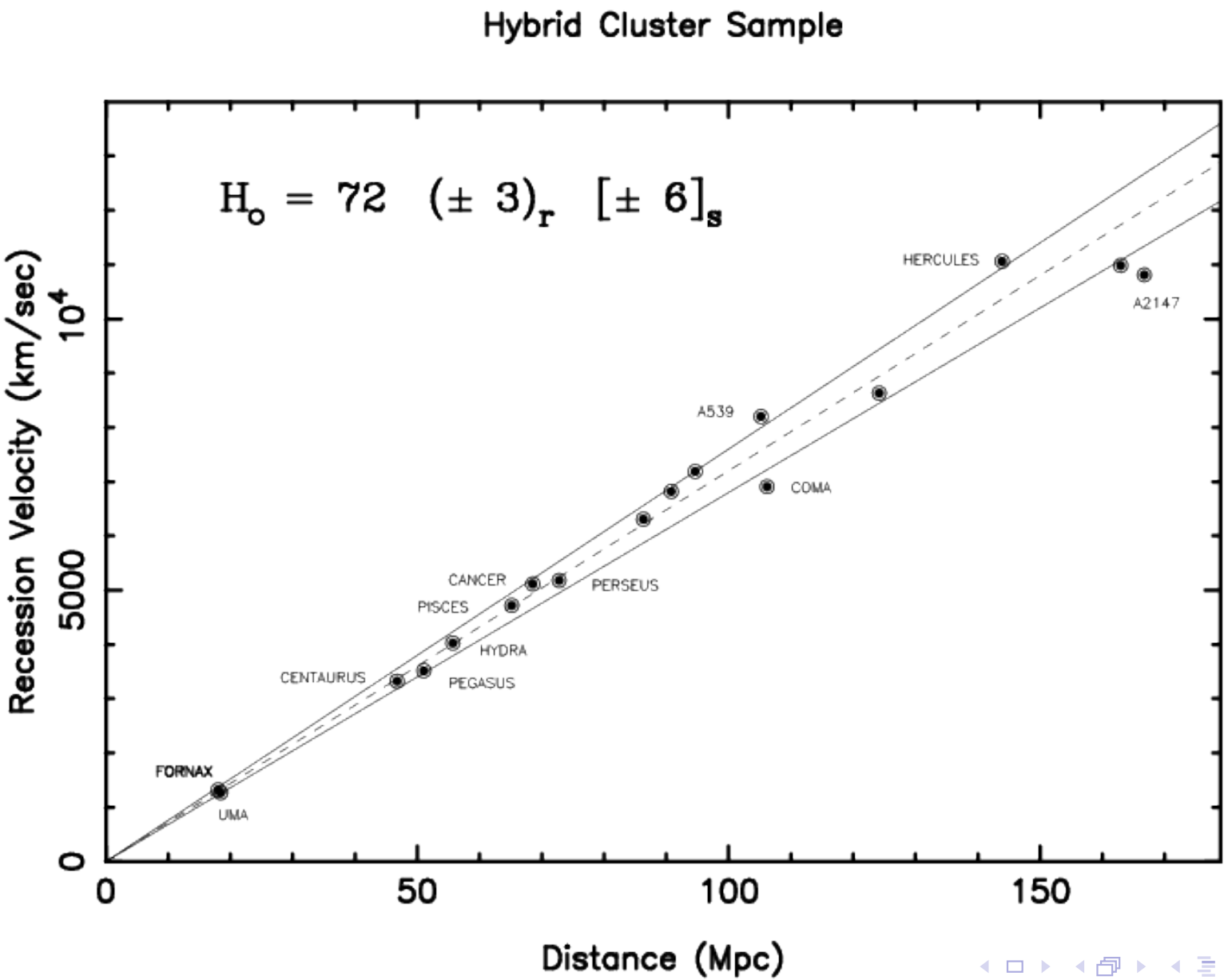
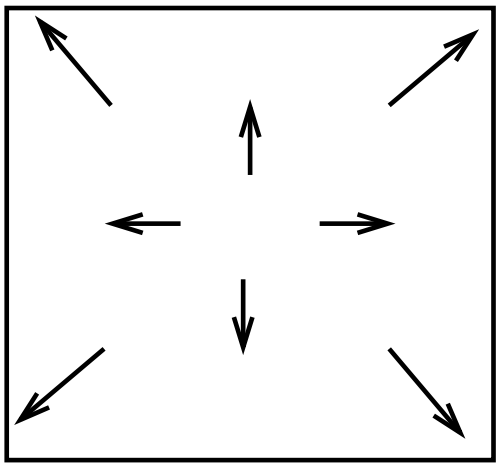


A Hubble diagram (here)



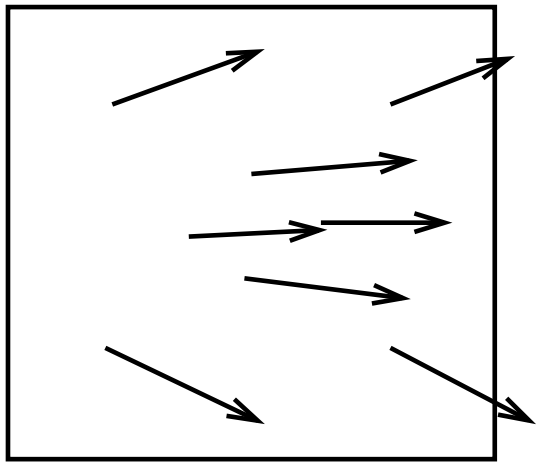
Not easy to measure $V = HD$ in region 2!

region 1



$V=H_0D$

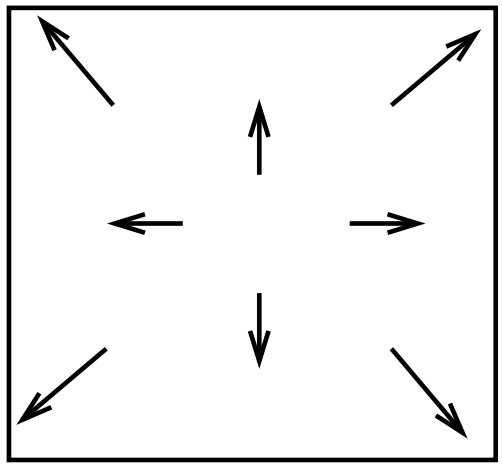
region 2



V=HD here

V's from relative Doppler shifts

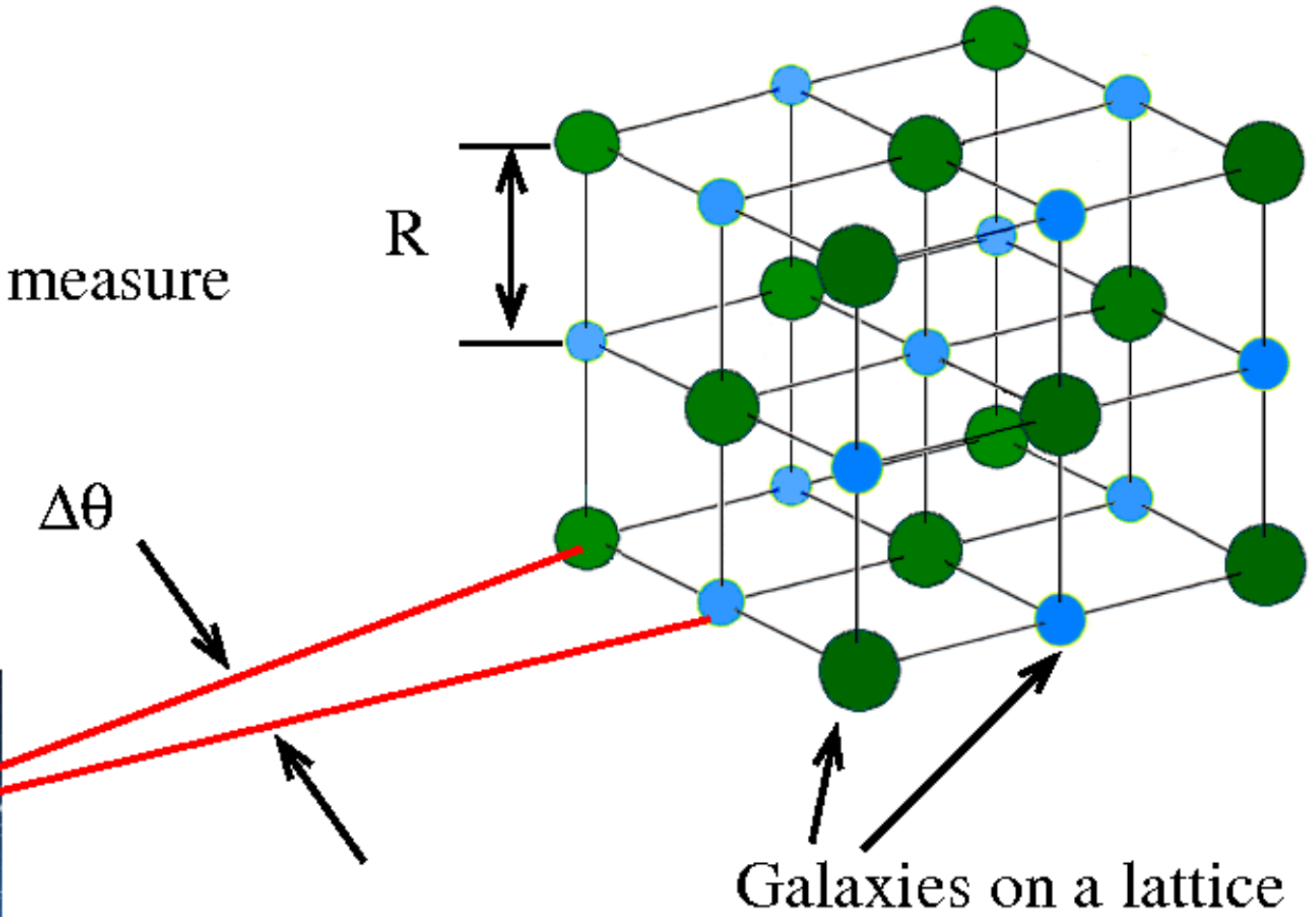
D's from ''BAO correlations''



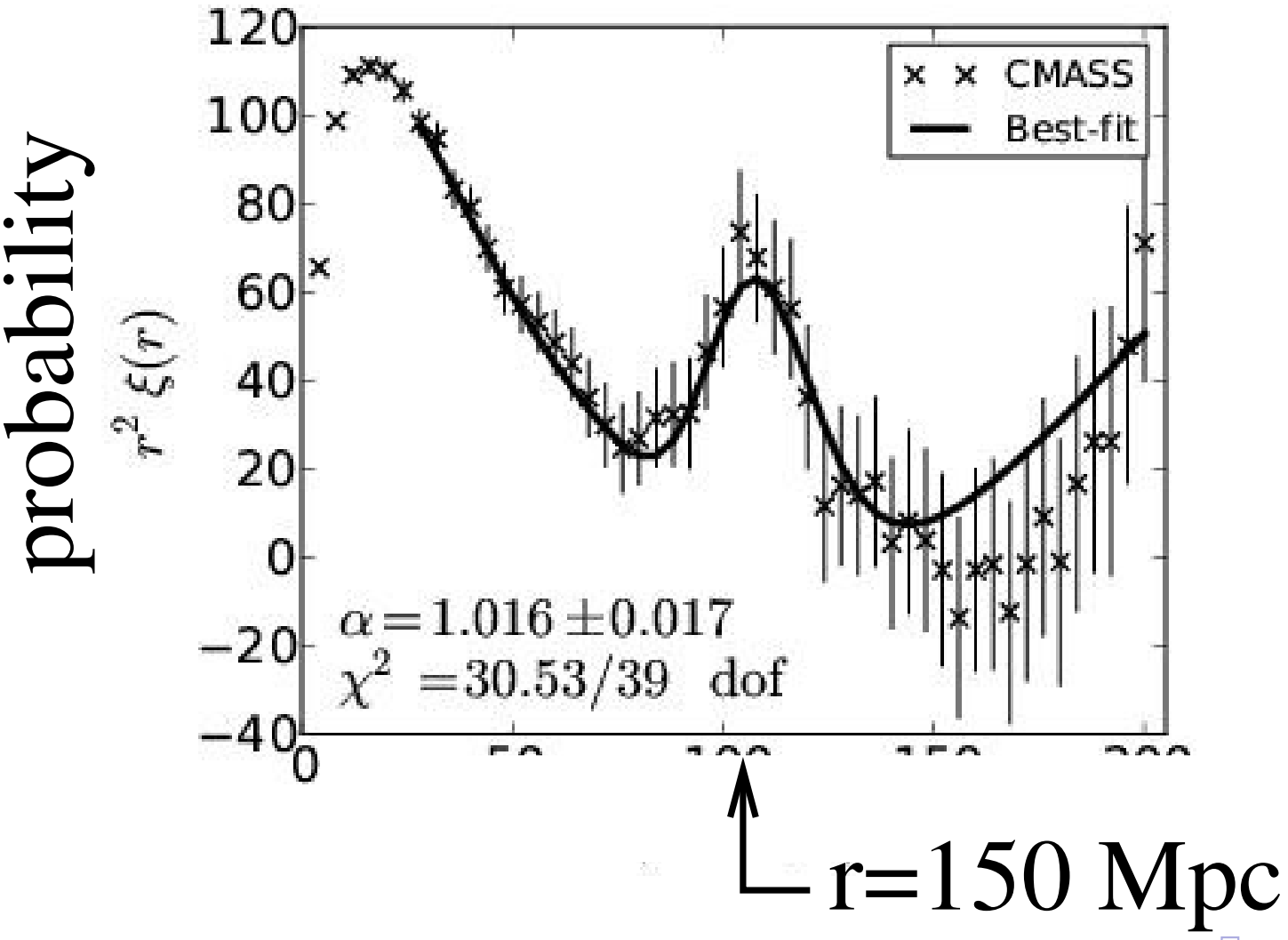
Measuring D would be easy in this universe!

$$D = R / \Delta\theta$$

Distance easy to measure



BAO correlations: galaxy pairs have a slight tendency to be separated by 150Mpc!



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150Mpc is the distance a sound wave can travel between the big bang and "recombination" (the epoch when atoms were first formed.)

(If a galaxy is formed where the wave originated, another galaxy has an enhanced probability to be formed where the wave stopped!)

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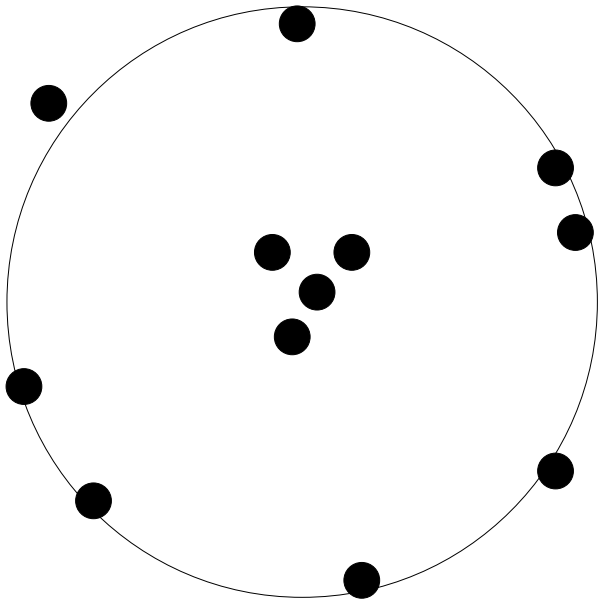
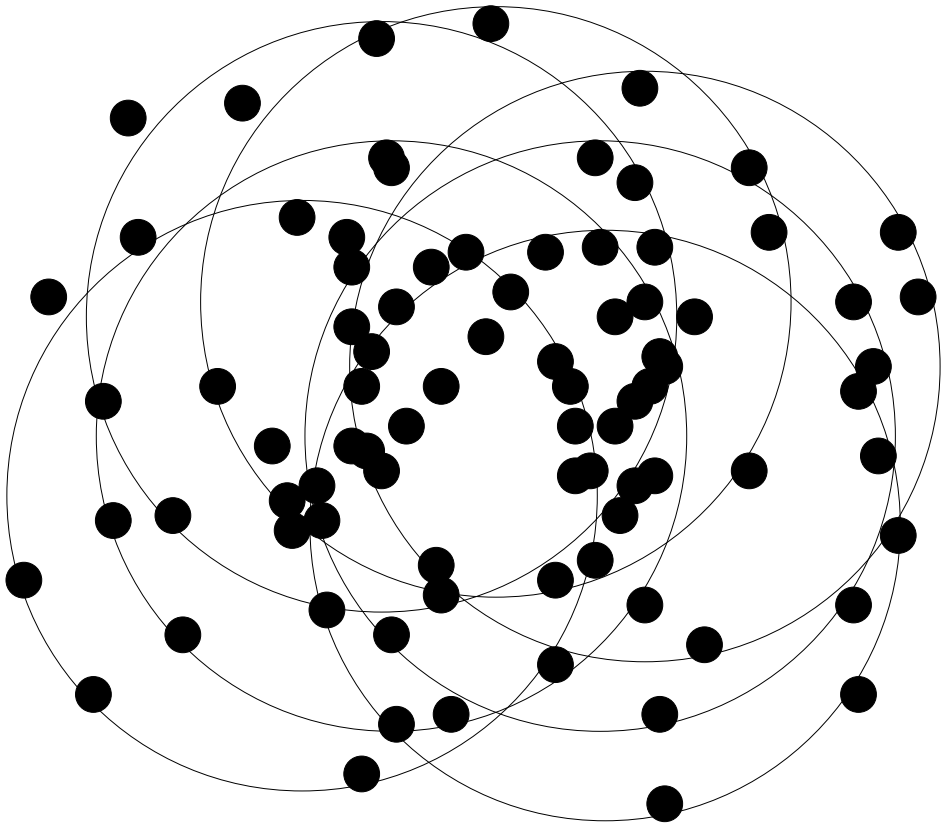
Almost too good to be true!!

A ridiculously simple region of the sky



The “150Mpc” is visible

A slightly more realistic region of the sky

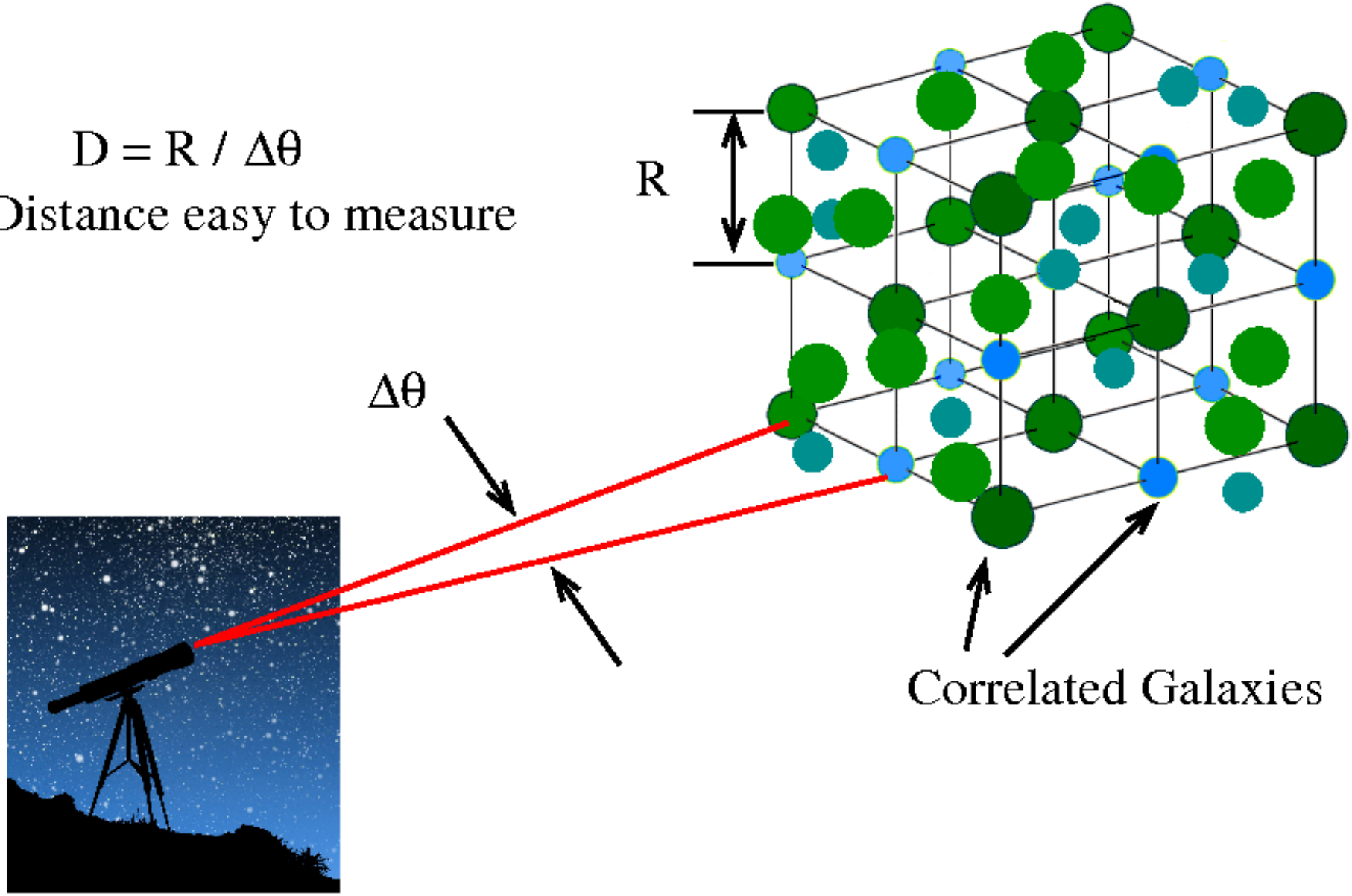


The “150Mpc” can be found statistically

Use BAO correlation to measure distances

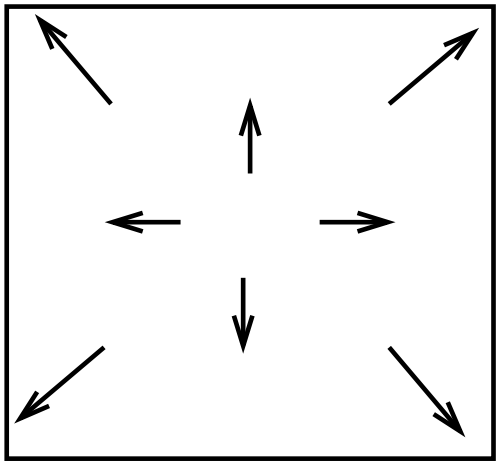
$D = R / \Delta\theta$

Distance easy to measure



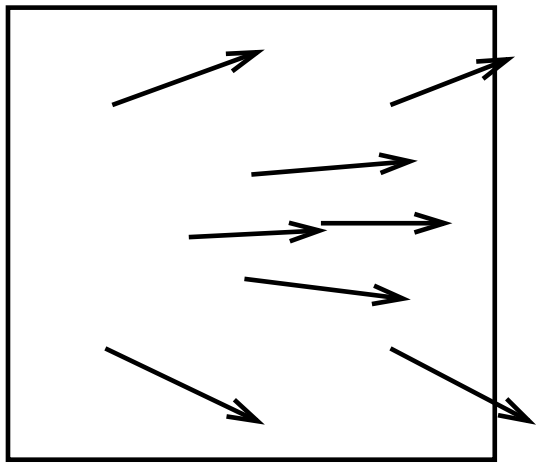
Measure $V = HD$ in region 2 with BAO correlations!

region 1



$V=H_0D$

region 2



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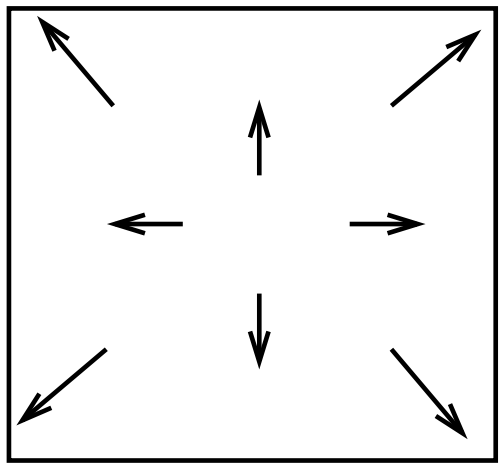
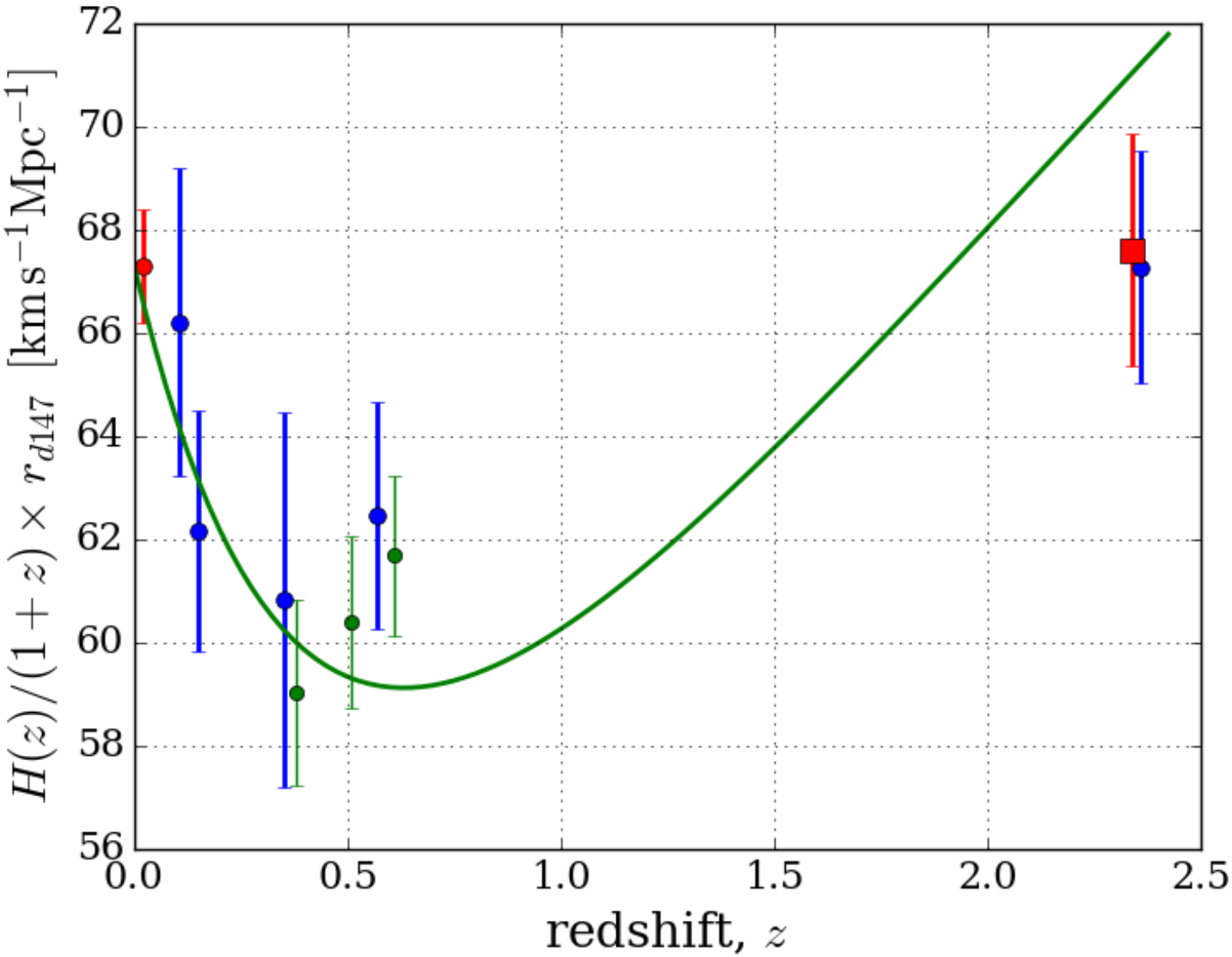
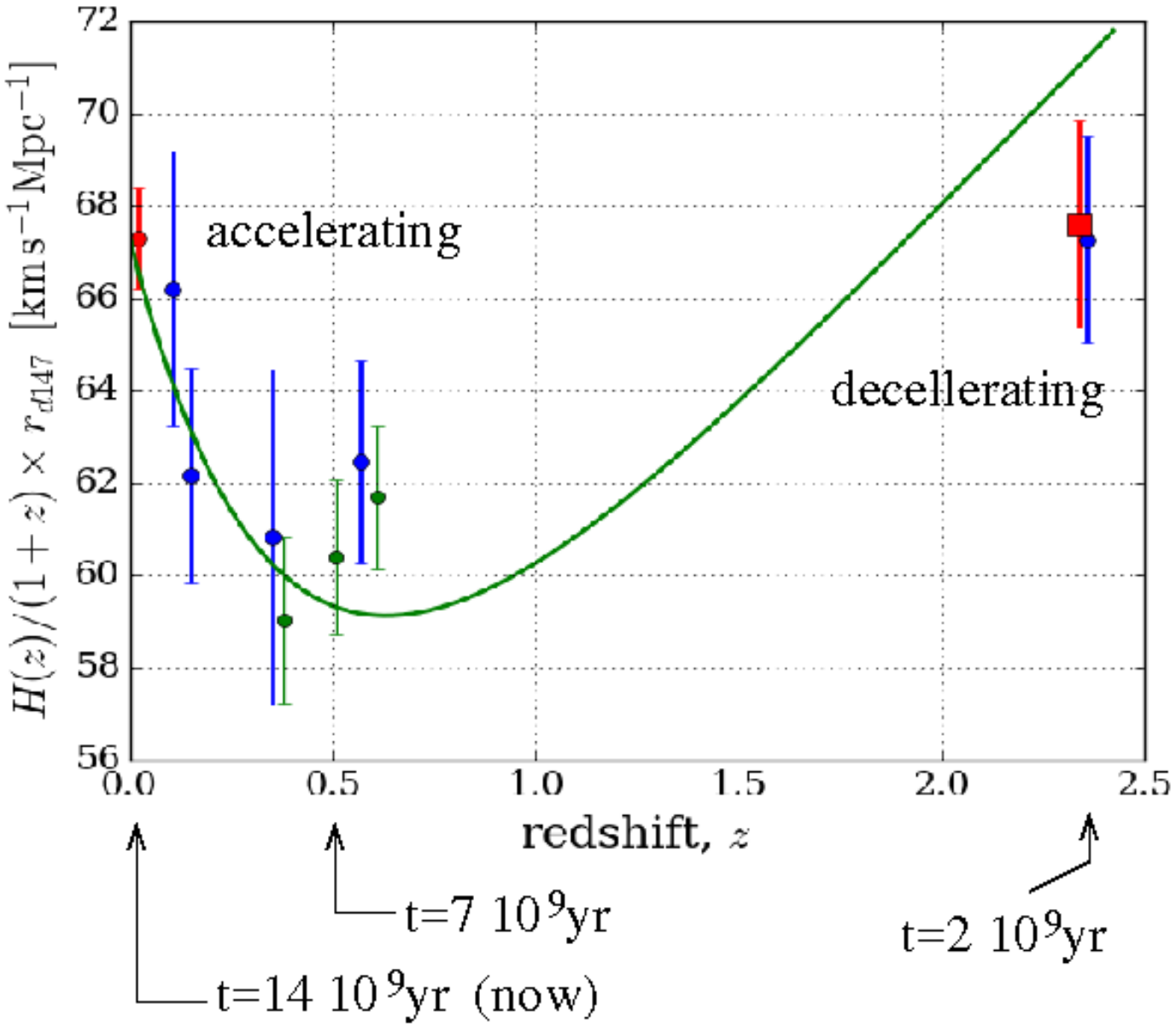


$H(z)/(1+z)$ (velocity at fixed distance)



The expansion decelerated then accelerated



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Dark energy is a "substance" filling all space that somehow reverses the expected deceleration"

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  Answer: Positive pressure (thermal energy) increases gravitation ($E = mc^2$!). A negative pressure decreases gravitation. If the pressure is sufficiently negative it over-cancels the attraction between galaxies, causing acceleration.

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  Nothing! Substances with positive pressure do work during the expansion, causing the density of energy to decrease with time. Dark energy, has just the right amount of negative pressure to keep the density (of dark energy) constant over time.

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Energy was mostly matter in the past (deceleration) and is mostly dark energy now and in the future (acceleration).

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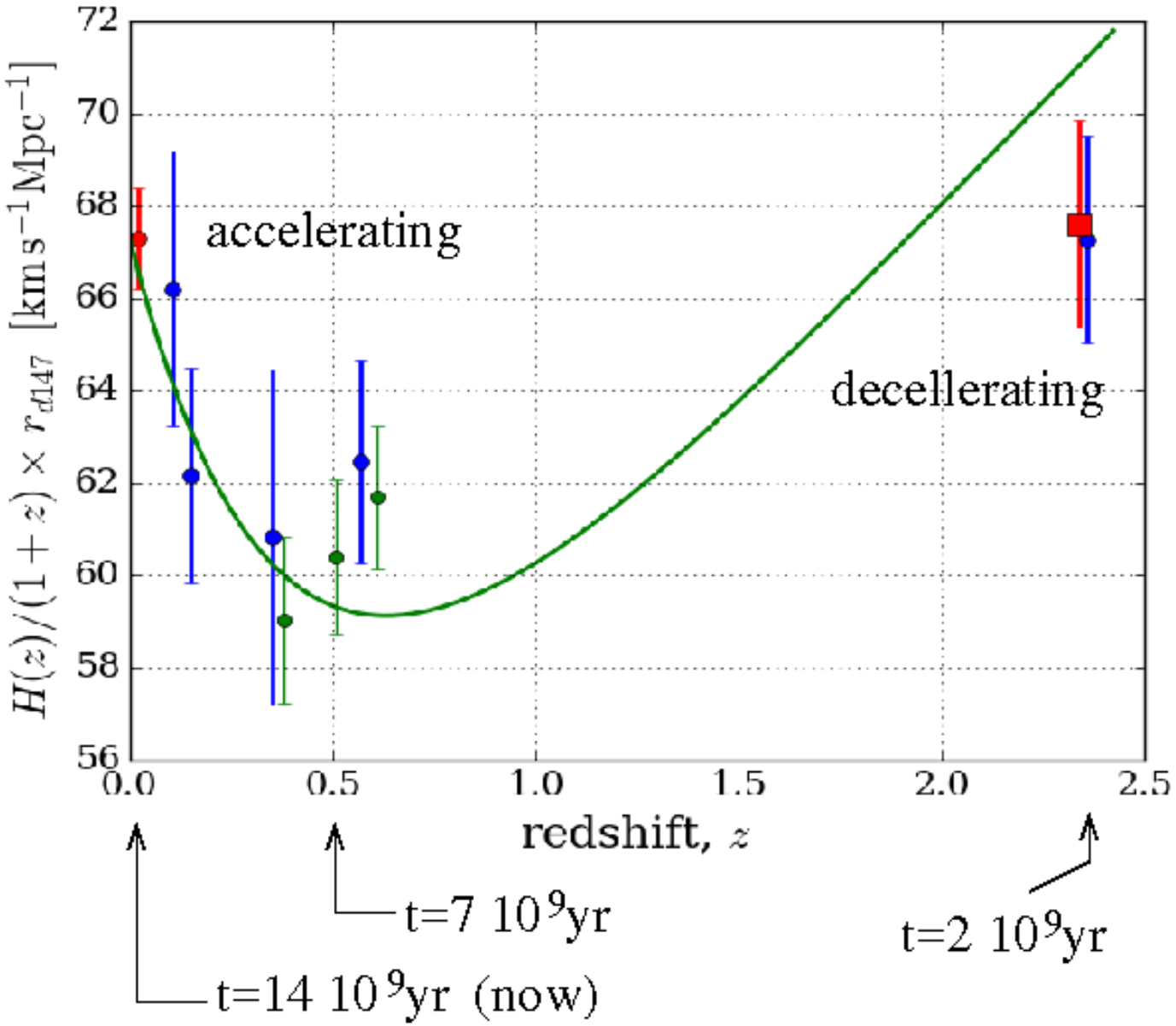
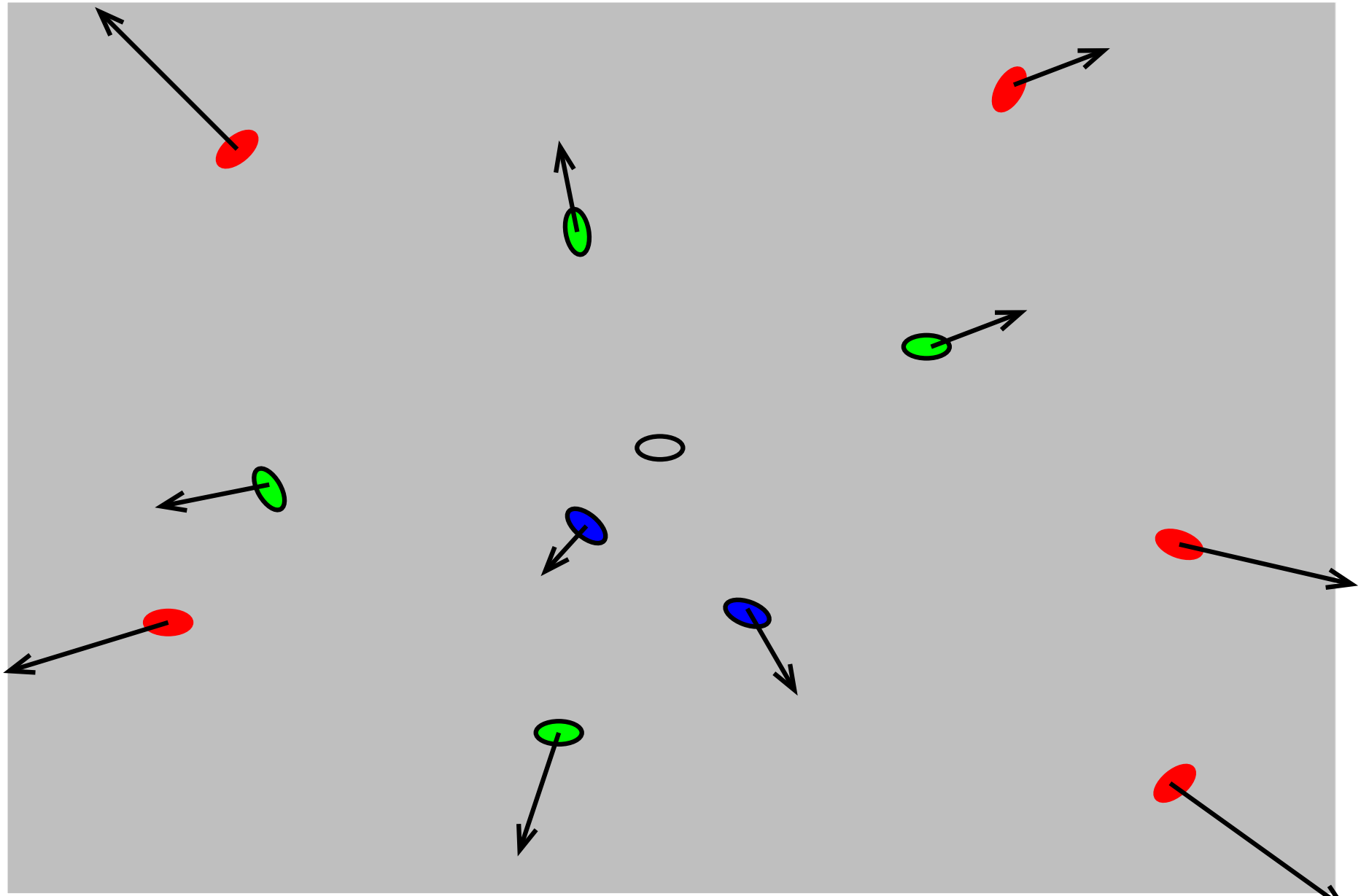


The universe: matter and dark energy



The future: dark energy