Dark Energy

Jim Rich

SPP-IRFU
CEA-Saclay
91191 Gif-sur-Yvette

james.rich@cea.fr

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Answer: The stuff that causes the expansion of the universe to accelerate!

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- What does "expansion of the universe" mean?
- How do we know the universe is expanding?
- What does "acceleration of expansion" mean?
- How do we know it is accelerating?
- How does dark energy cause the acceleration?

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- What does "expansion of the universe" mean?
- How do we know the universe is expanding?
- What does "acceleration of expansion" mean?
- How do we know it is accelerating?
- How does dark energy cause the acceleration?
- Why is there dark energy?
- Why is the universe expanding?

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Expansion of the Universe?

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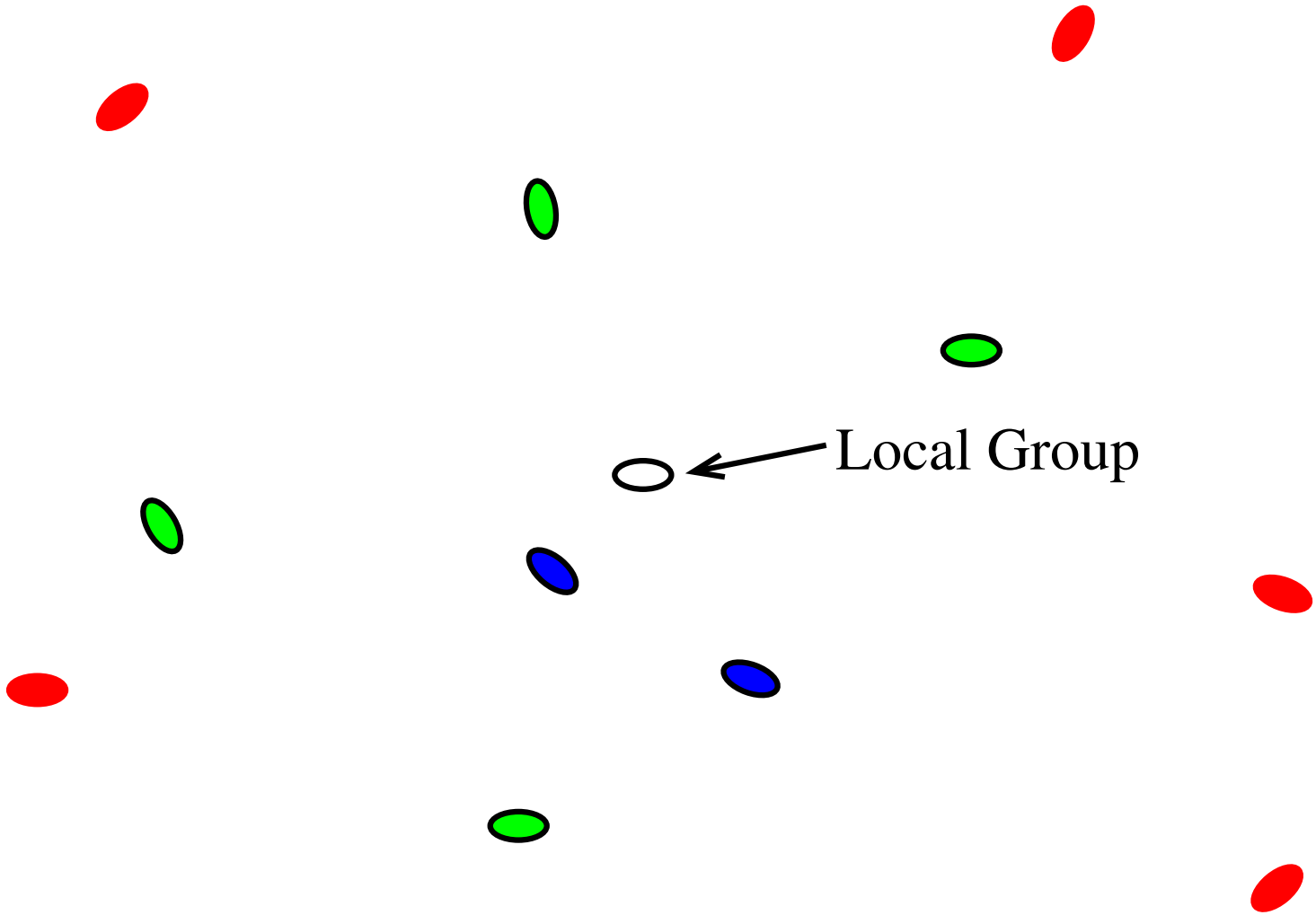
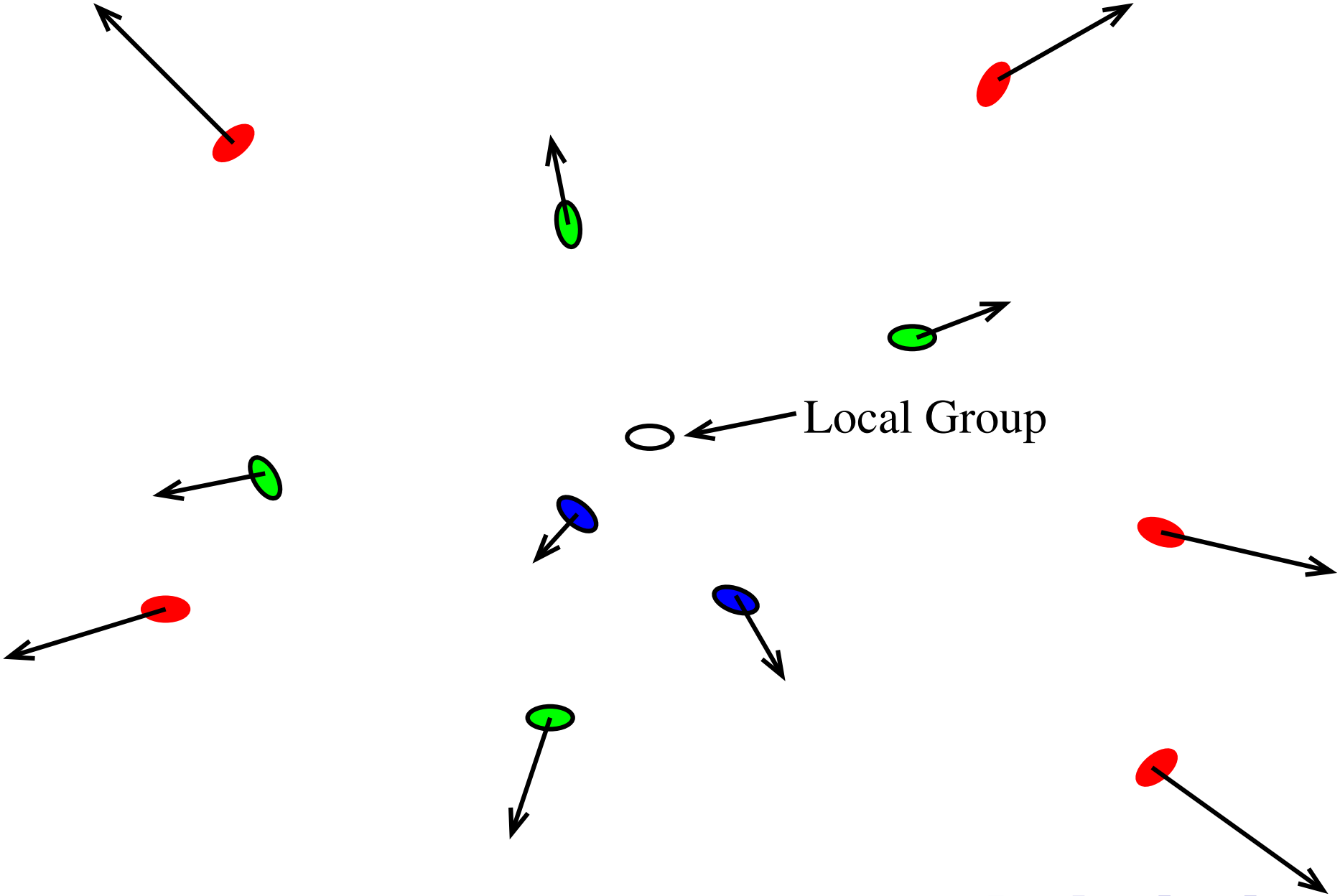
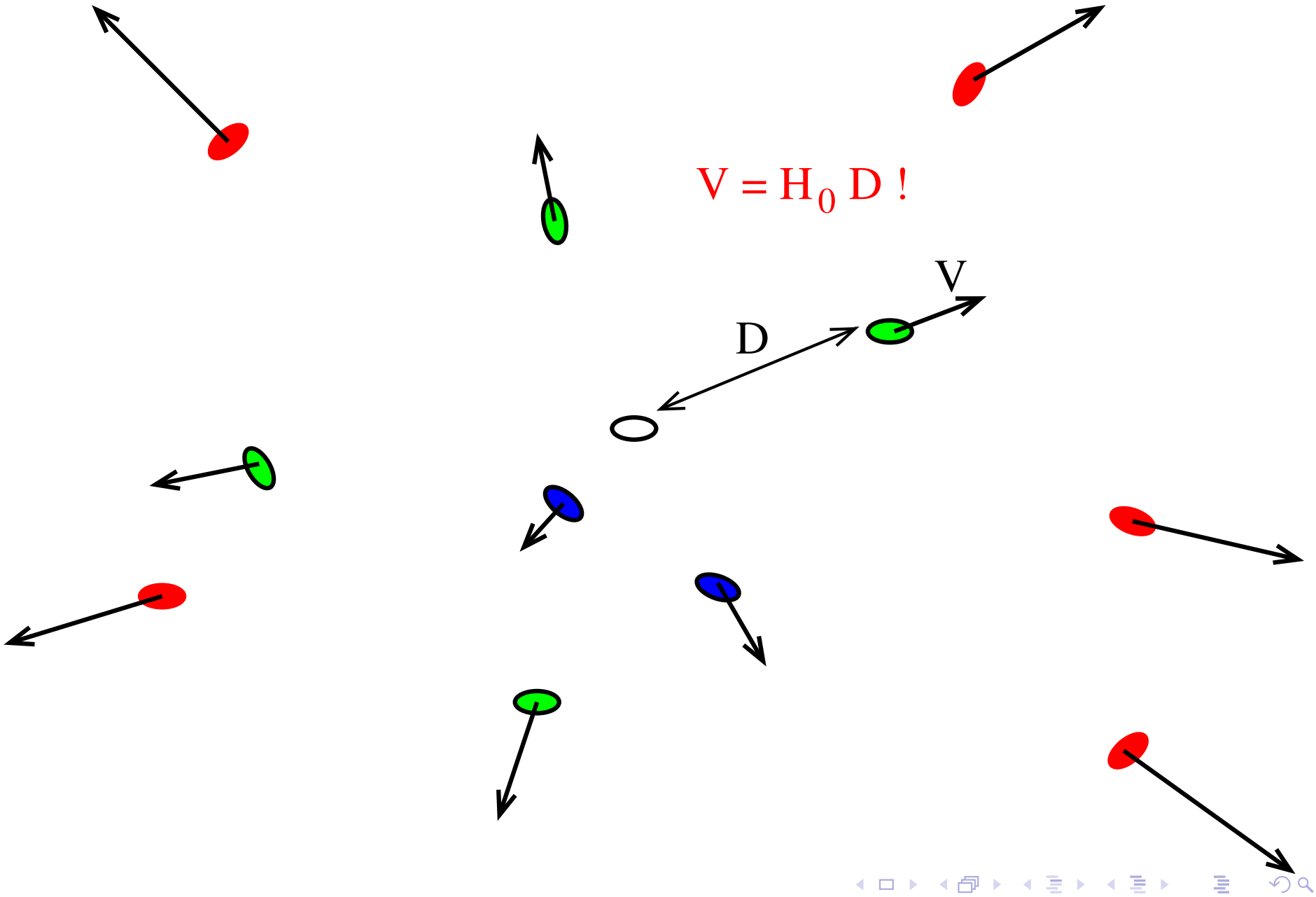


Expansion of the Universe?



Expansion of the Universe: $V = H_0 D$



A diversion: Why such grandiose language?

Why do we say

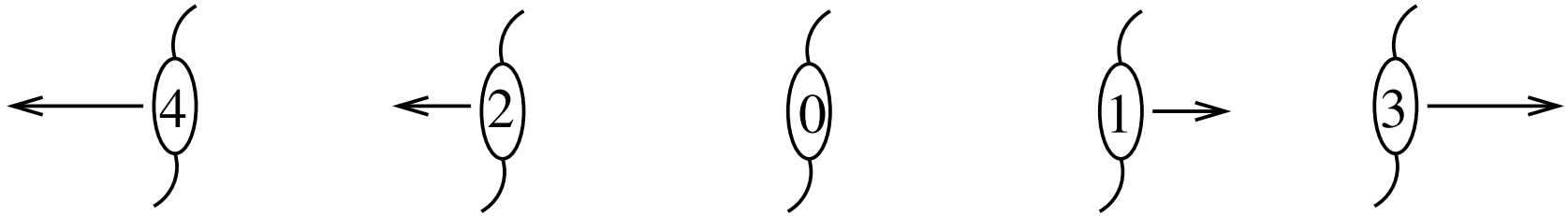
"The universe is expanding!"

instead of

"The other galaxies are running away from us!"

Answer: Everybody sees the same thing!

What galaxy 0 sees:



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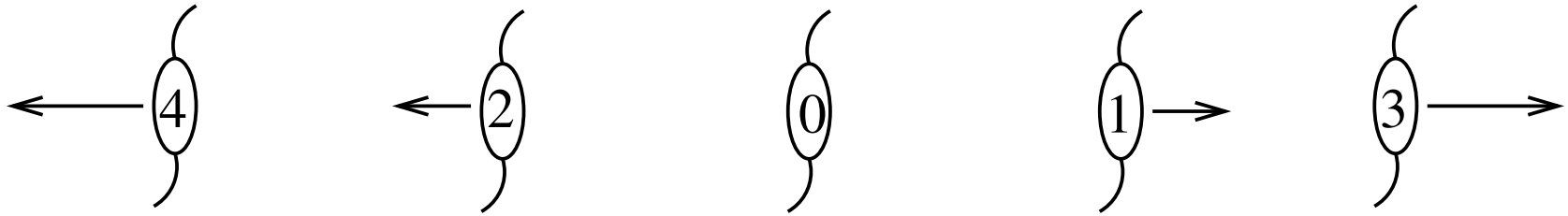
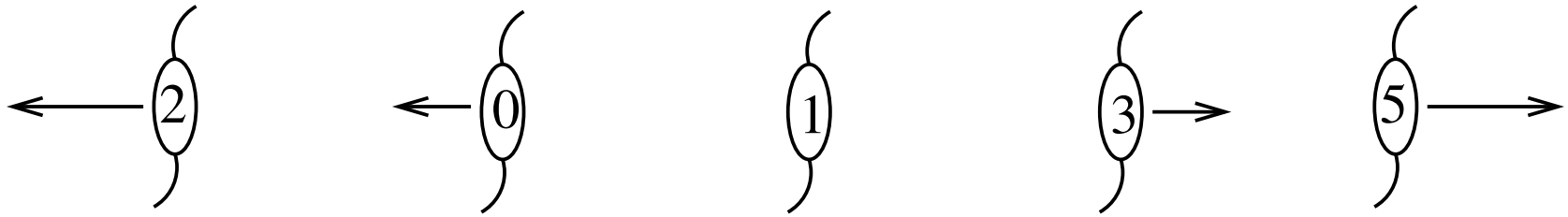


What galaxy 1 sees:



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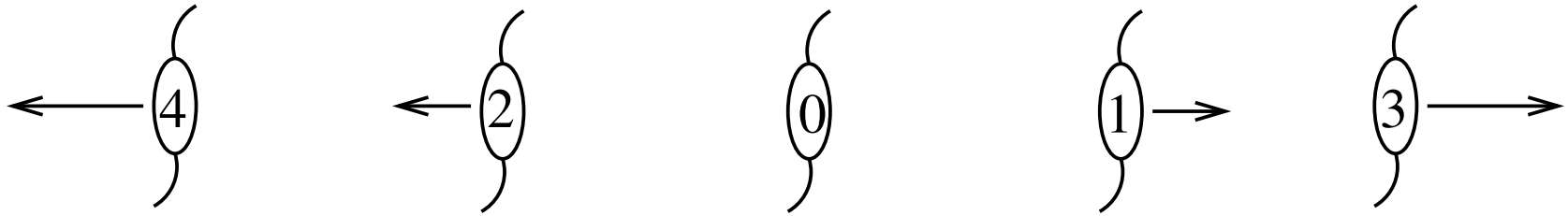

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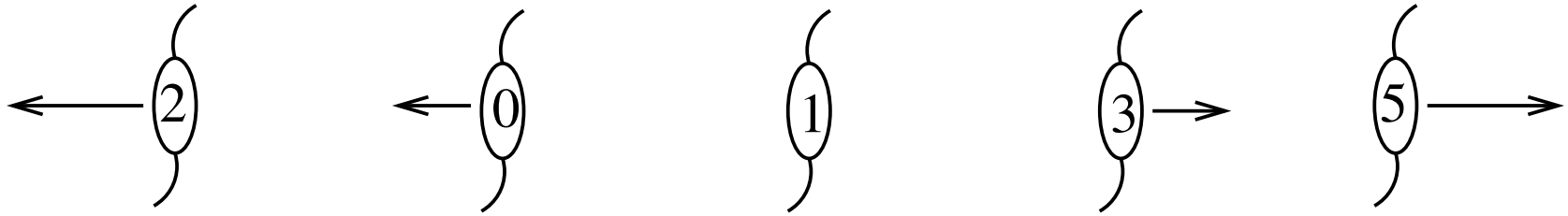

No "Center of the Universe" if $v = H_0 D$

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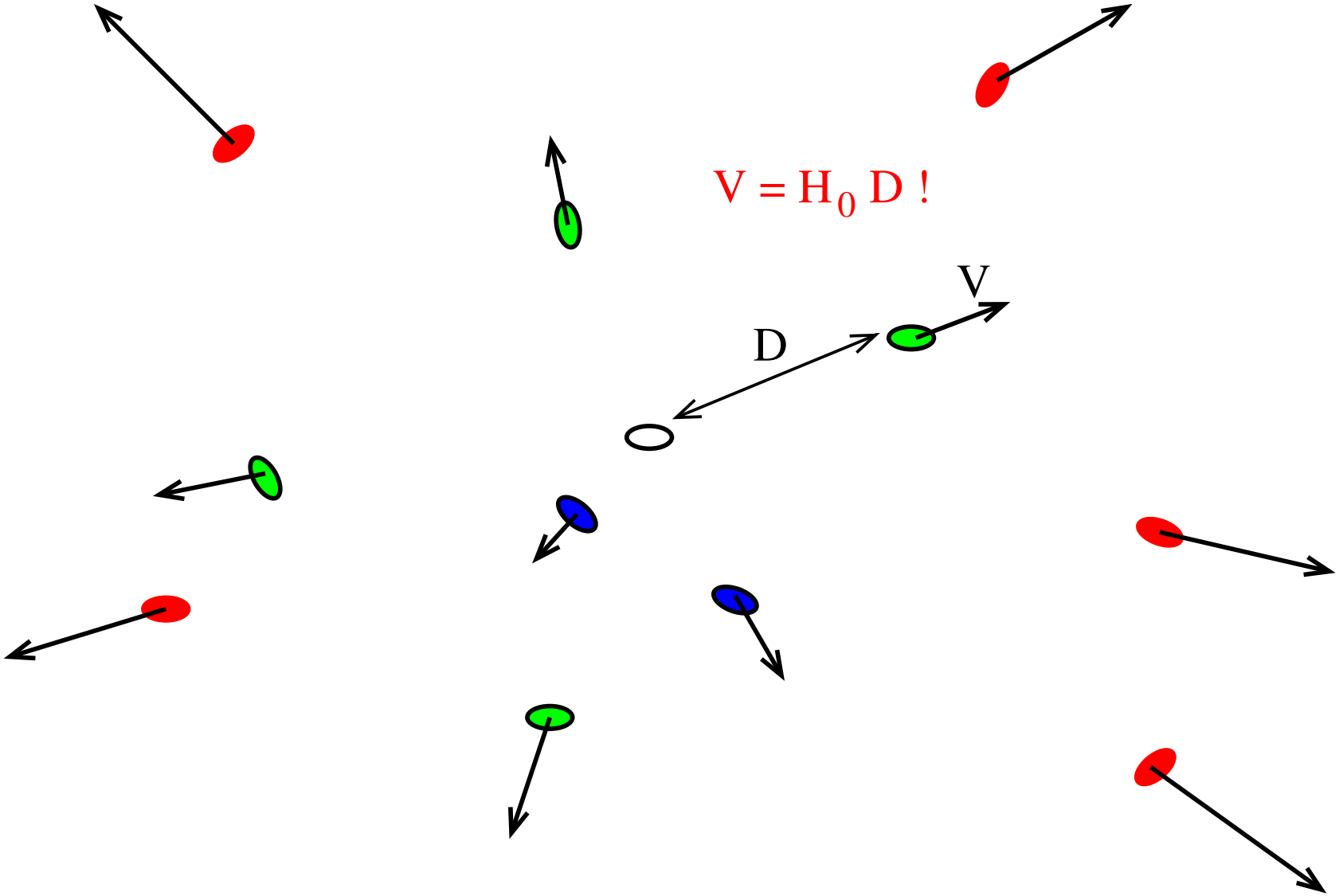
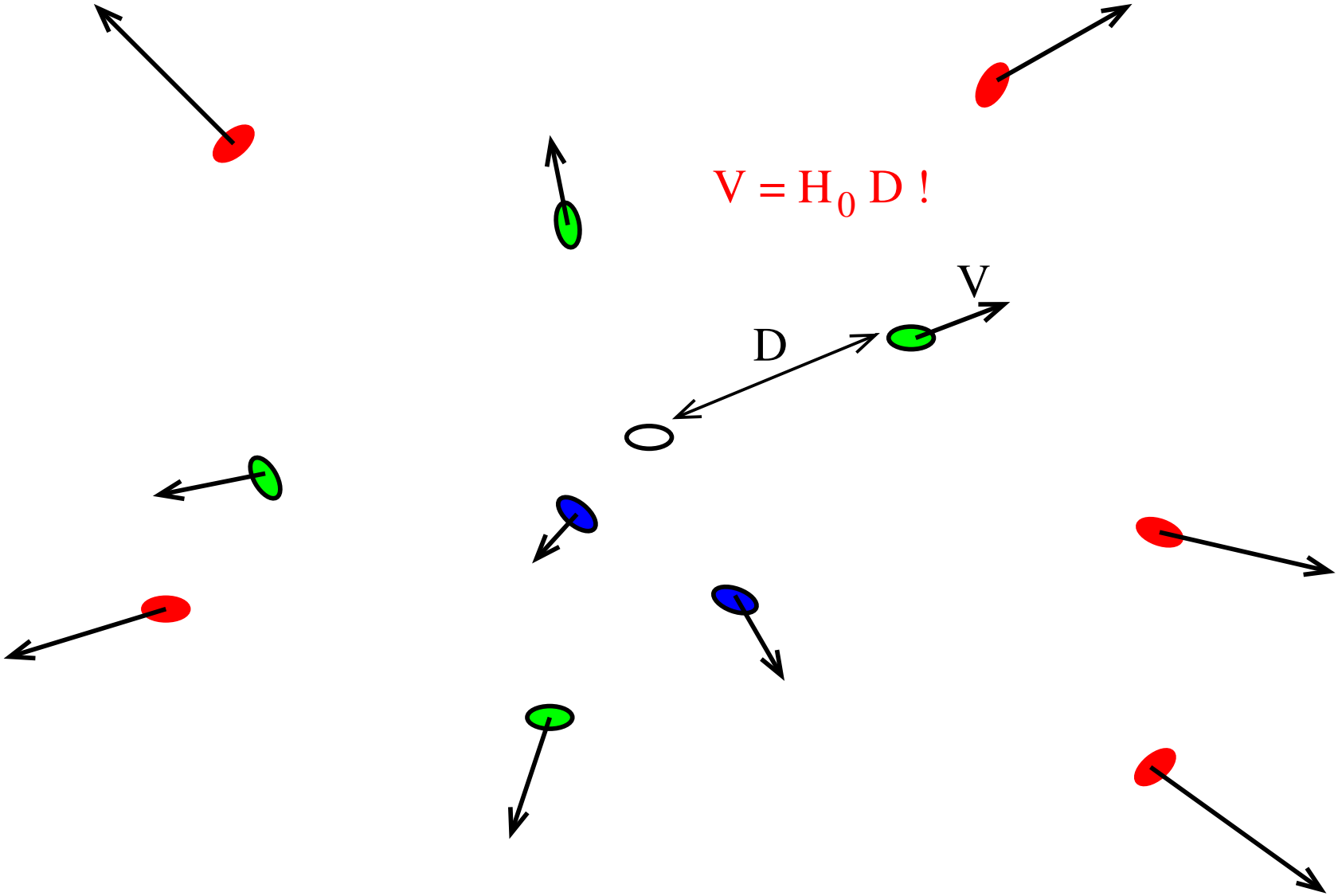
How to we know $V = H_0 D$?



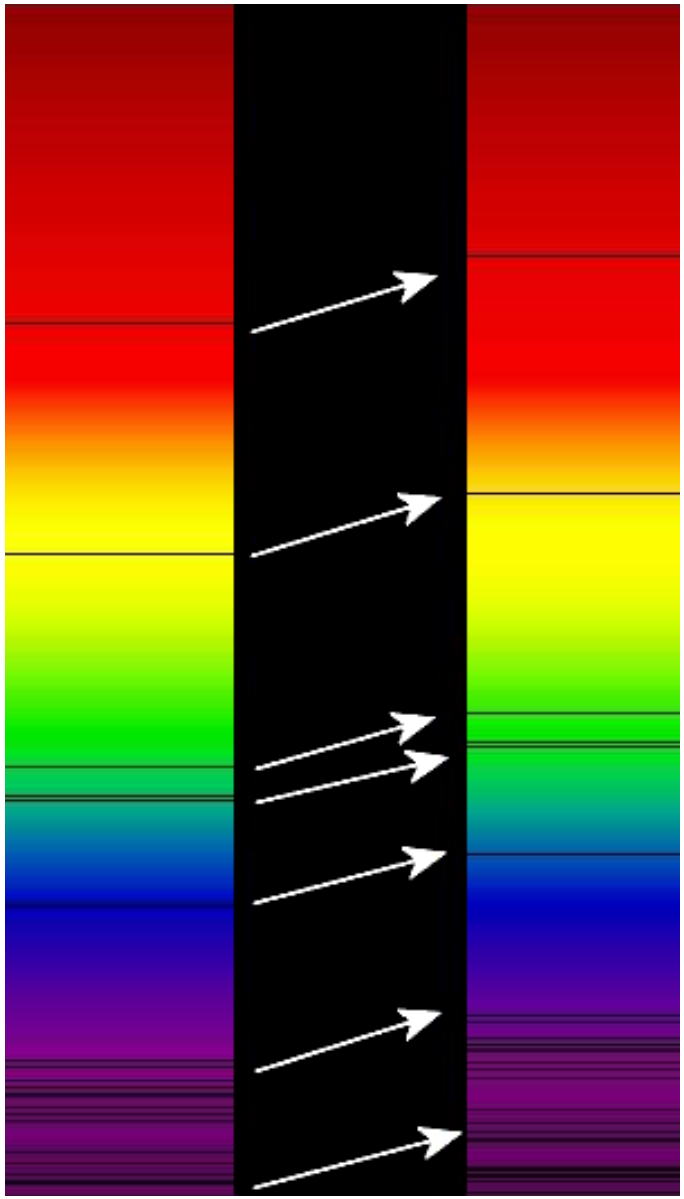
How to we know $V = H_0 D$?



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!

$\Rightarrow$ All other things being equal,
galaxies that are near look big and bright;
galaxies that are far look small and faint.

Which galaxies are nearest?

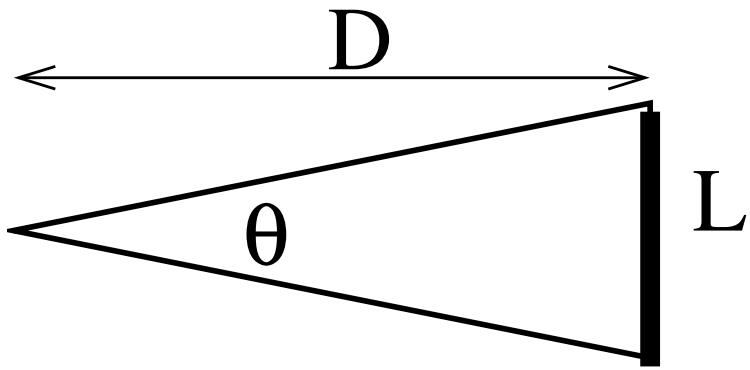
Hubble Deep Field

Quantitatively: standard rulers and candles

1. Measure angular size θ

of object of known size L

$\theta = L/D$

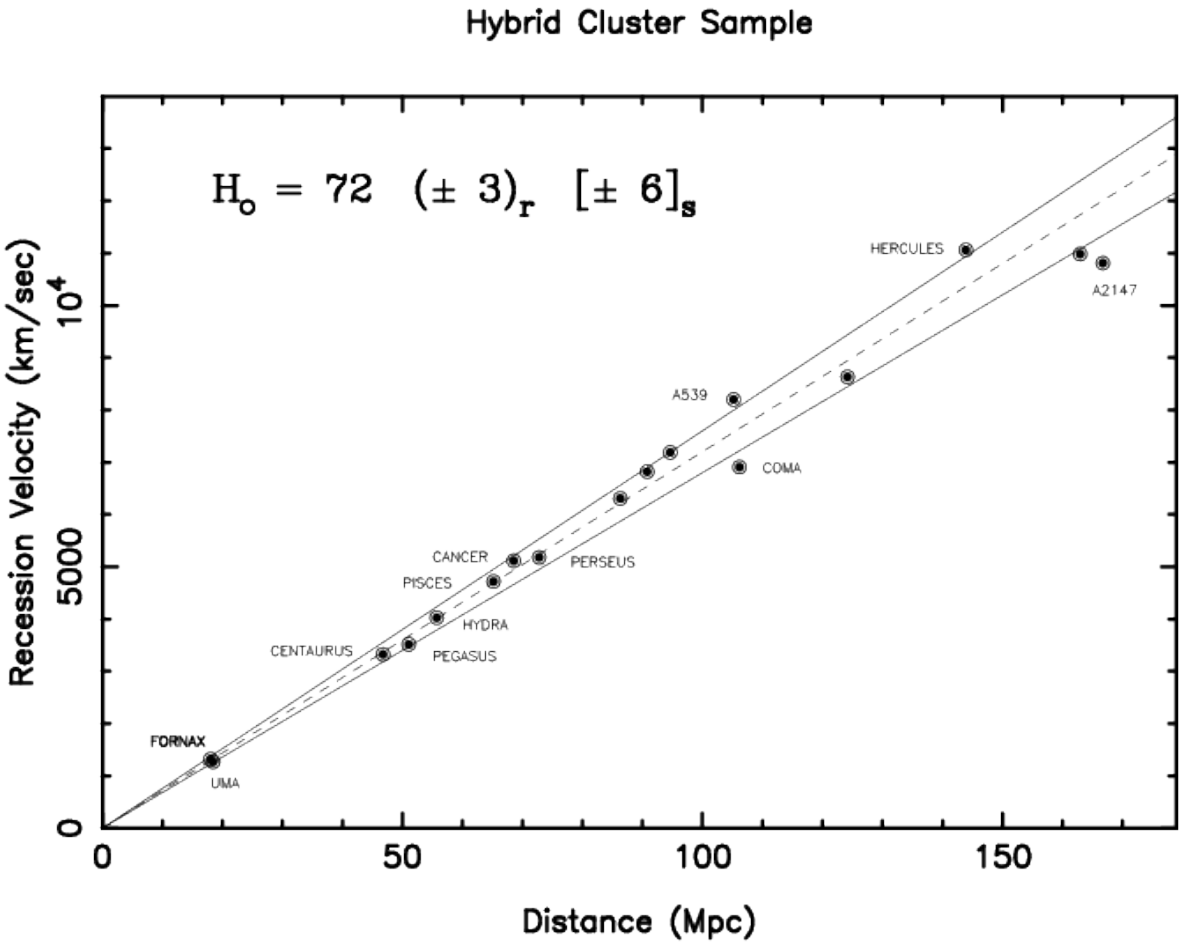


2. Measure Flux from object of known Luminosity

$F = L/4\pi D^2$

Problem: how to measure L or L?

A Hubble diagram: $v = H_0 D$



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

(Type Ia) Supernovae: Best Candle in the Universe

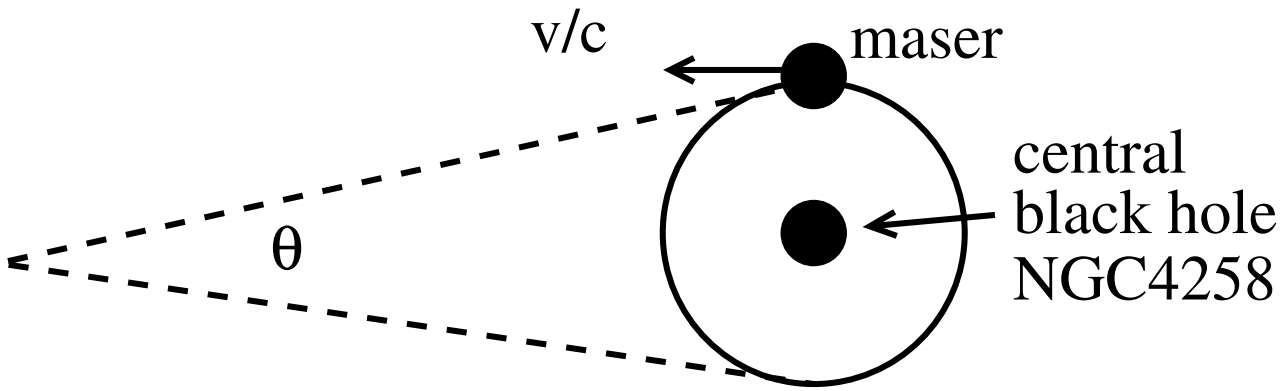
- explosion of a star at the end of its life
- visible for $\sim$ 1month
- Luminosity known to $\sim$ 10% and calibrated by observing supernovae in galaxies of known distance (!)

Distance Ladder (example)

- Determine distance to galaxy NGC4258 (next slide)
- Observe Cepheid variable stars in NGC4258 and determine their luminosity (from measured flux and known distance)
- Observe Cepheid variable stars in galaxies that had hosted type Ia supernovae and determine distance (from measured Cepheid flux and known Cephei luminosity.)
- Determine luminosity of type Ia supernovae (from measured flux and known distance.)
- Observe type Ia supernovae and determine distance from known luminosity; measure H_0.

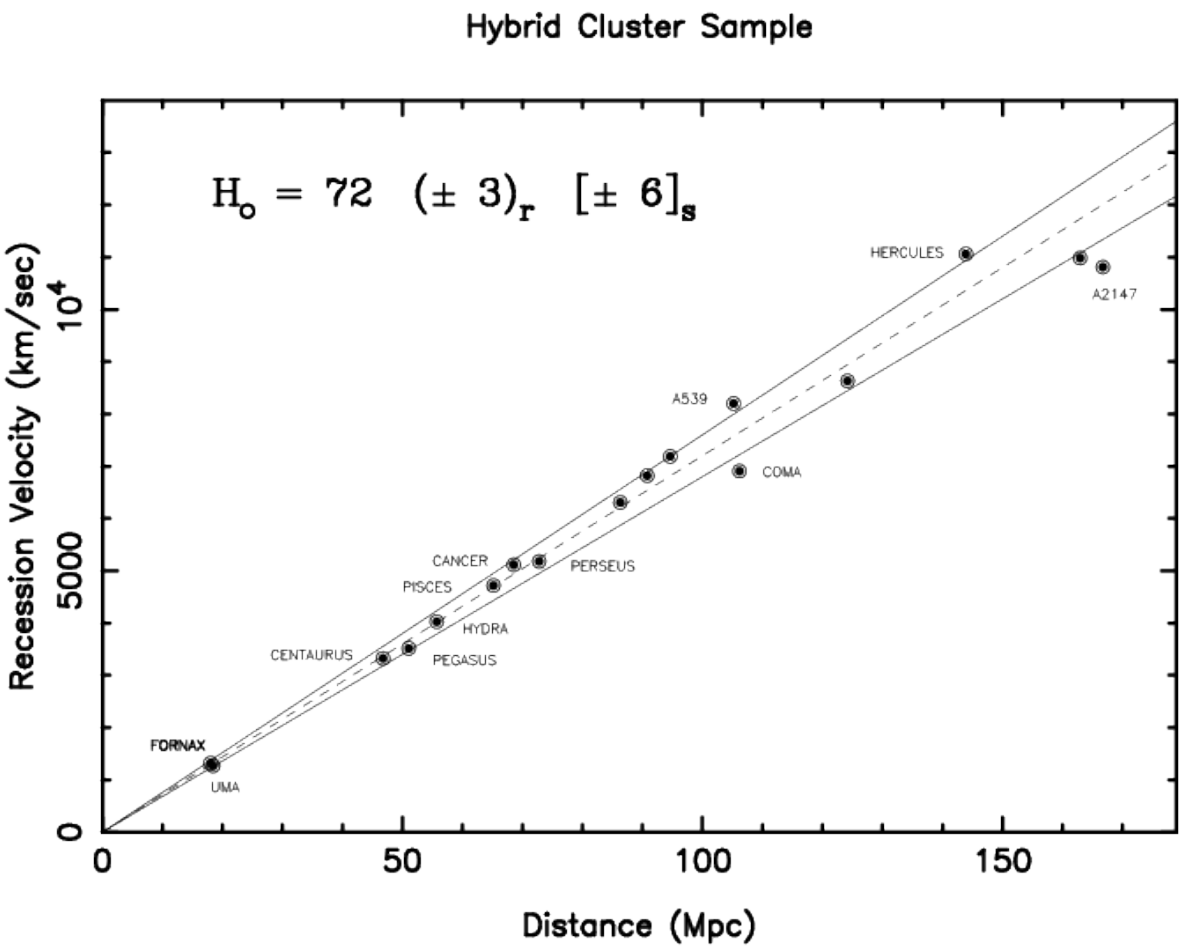
Distance of NCG4258

Maser (gas cloud with narrow emission lines) orbiting a black hole:



- v from Doppler shift (periodic).
- θ from periodically changing position on sky.
- T: orbital period
- r: orbital radius from $v = 2\pi r/T$
- D: distance from $\theta = 2r/D$

A Hubble diagram: $v = H_0 D$



- D from standard candles (e.g. supernovae)
- D(NGC4258)$\sim$ 5Mpc; D(Cepheids)$<$ 20Mpc (too near to measure H_0 precisely because of random (peculiar) velocities)

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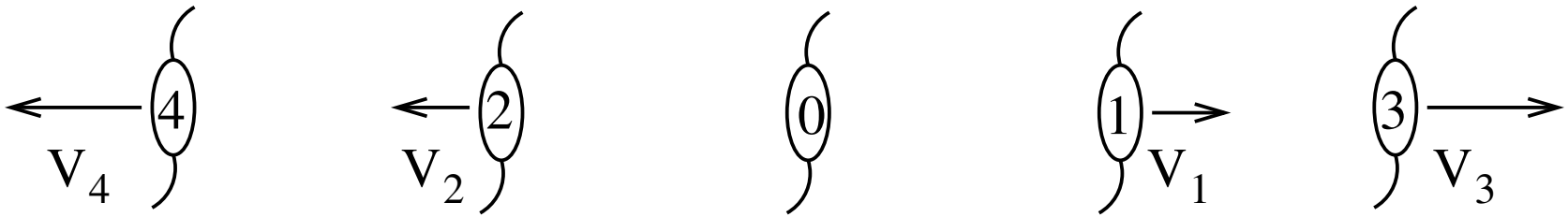
Expansion today and tomorrow

Today:



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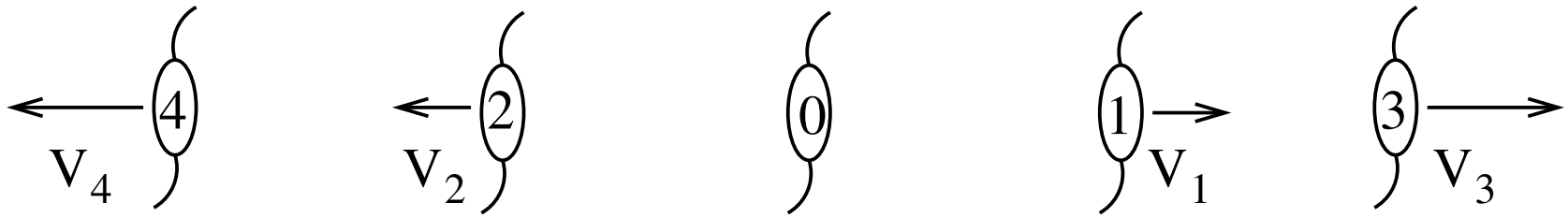
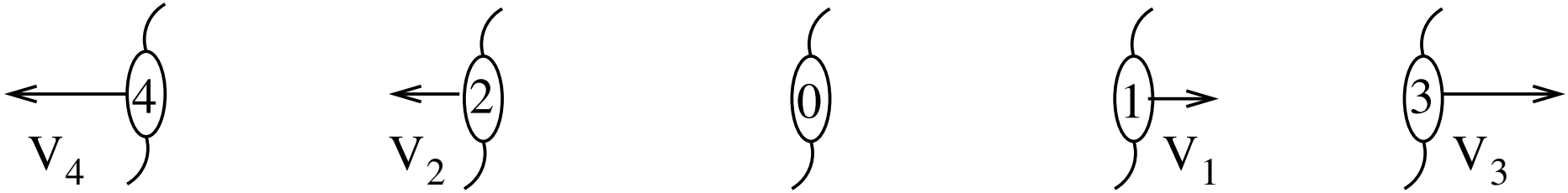


Tomorrow:



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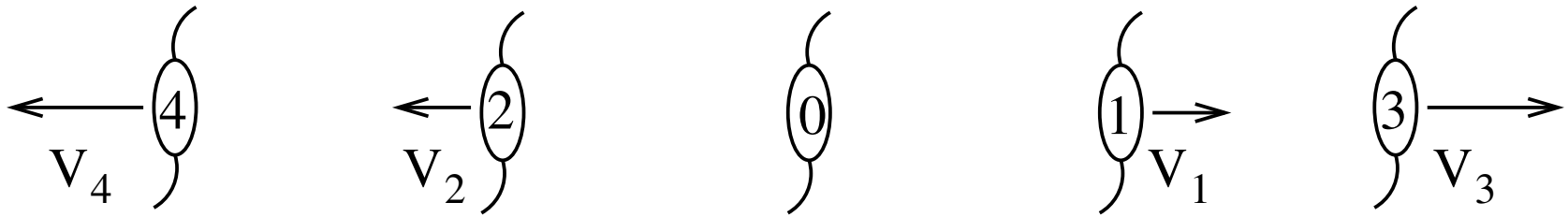

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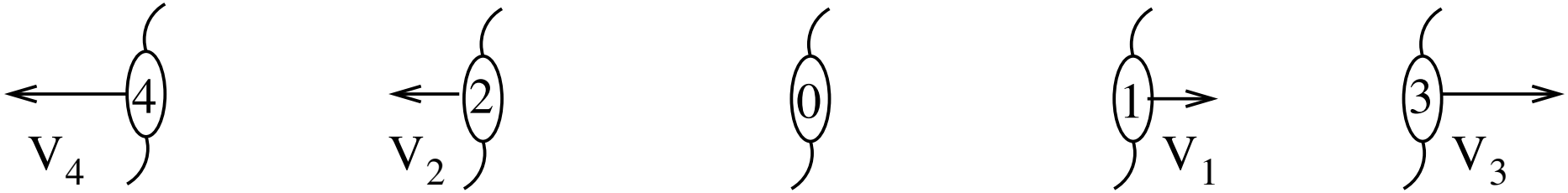

V_i(tomorrow)$<$ V_i(today): deceleration

Expansion today and tomorrow

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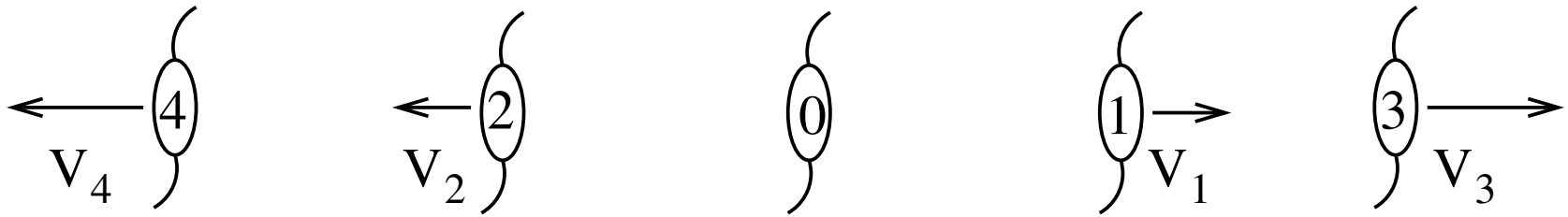

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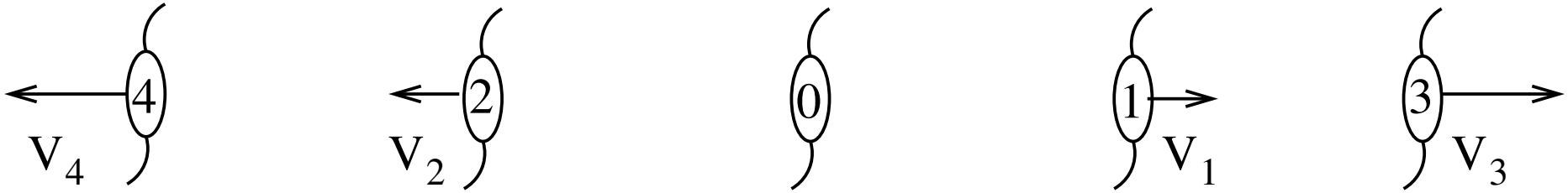
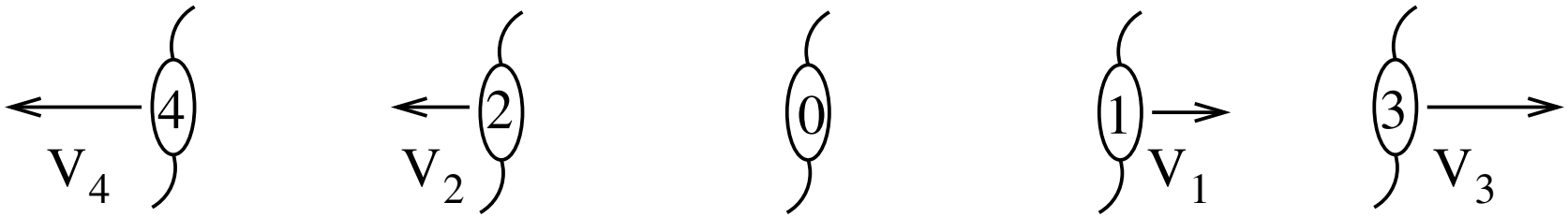


V_i(tomorrow)$<$ V_i(today): deceleration

V_i(tomorrow)$>$ V_i(today): acceleration

Better: Expansion yesterday and today

Yesterday:



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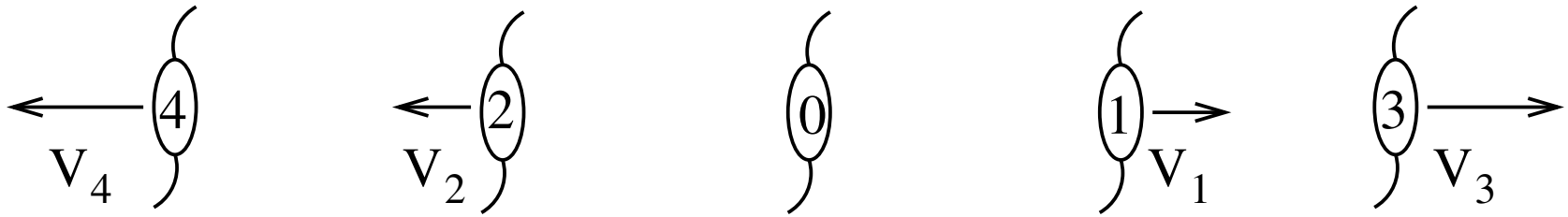

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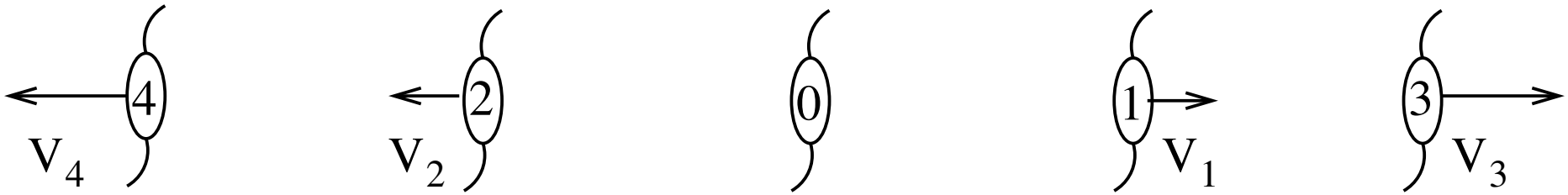

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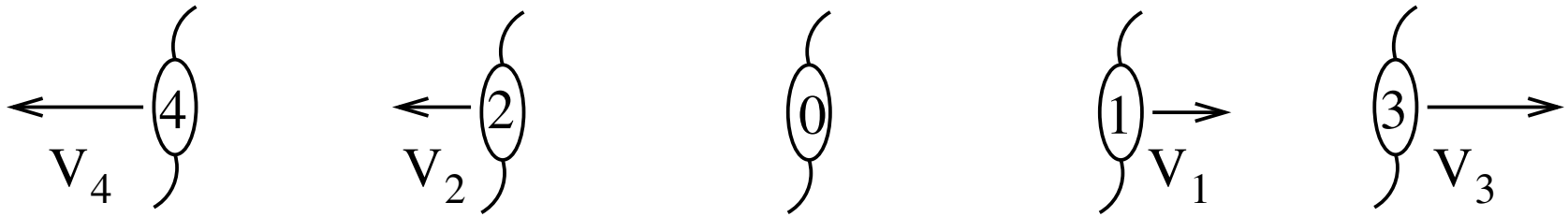

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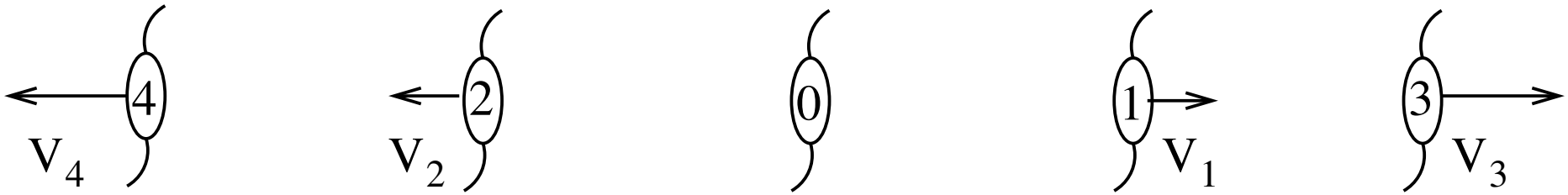

V_i(today)$<$ V_i(yesterday): deceleration
V_i(today)$>$ V_i(yesterday): acceleration

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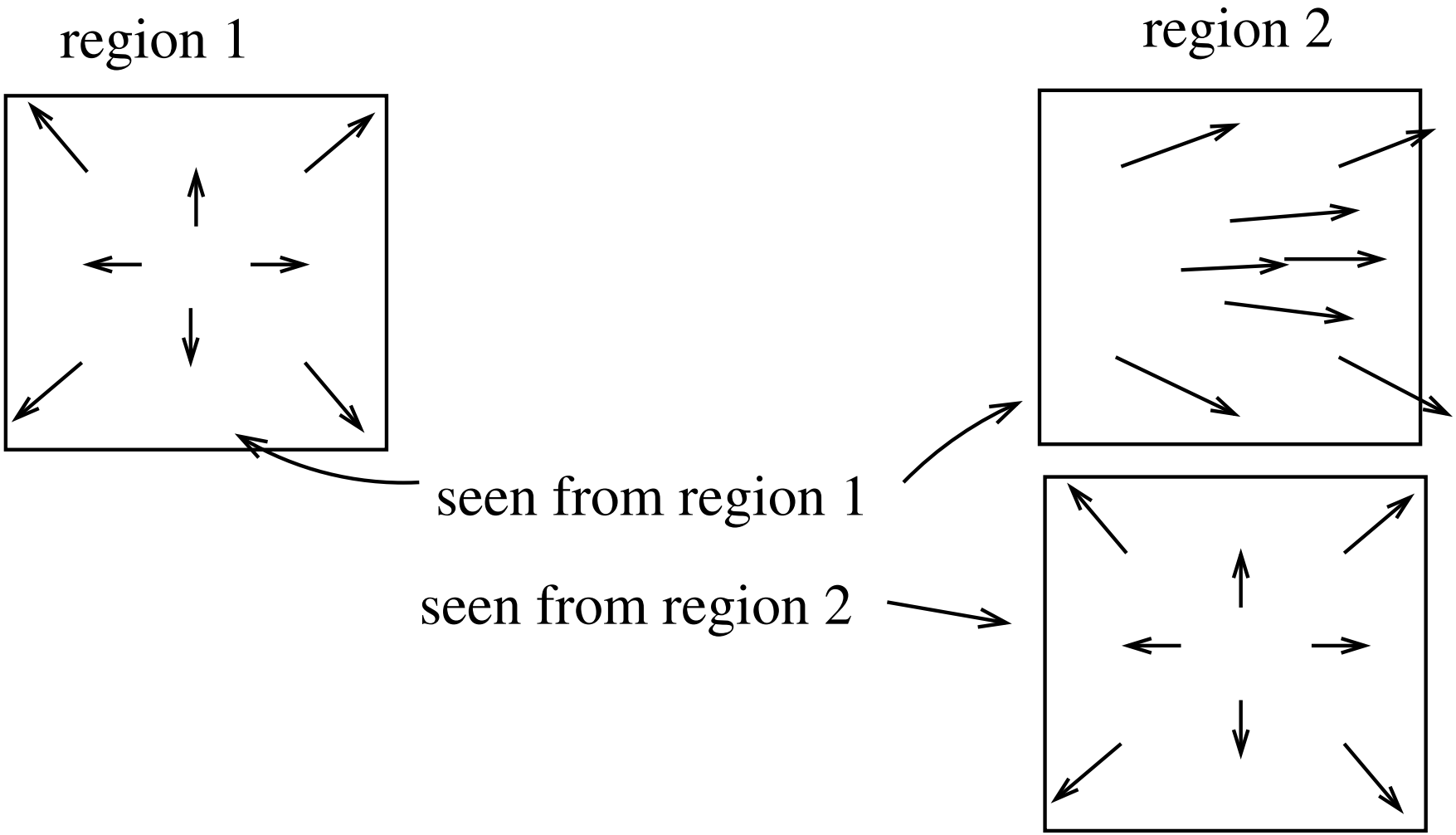
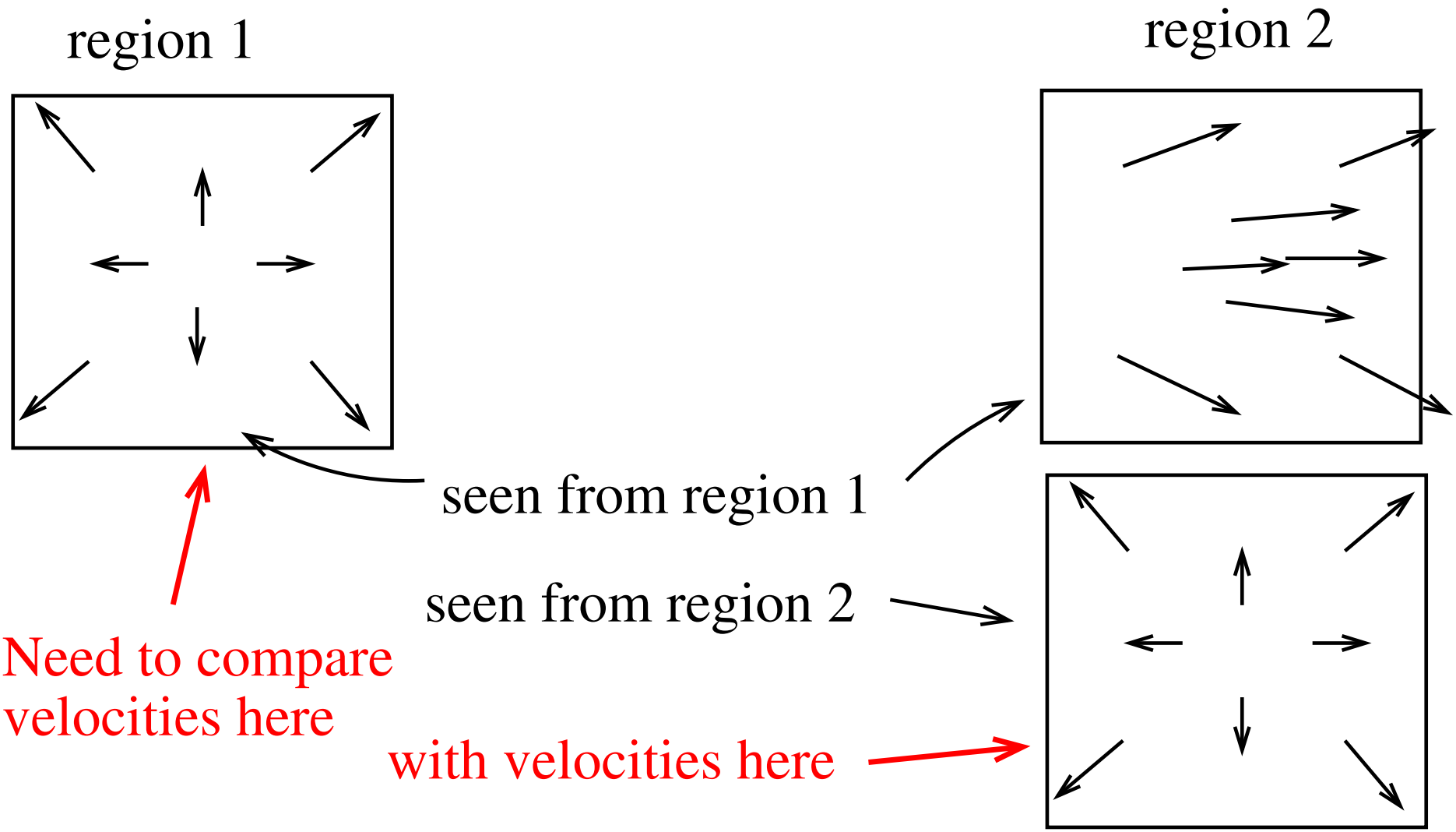
We can't measure future velocities.....

but we can measure past velocities!

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



To distinguish acceleration from deceleration



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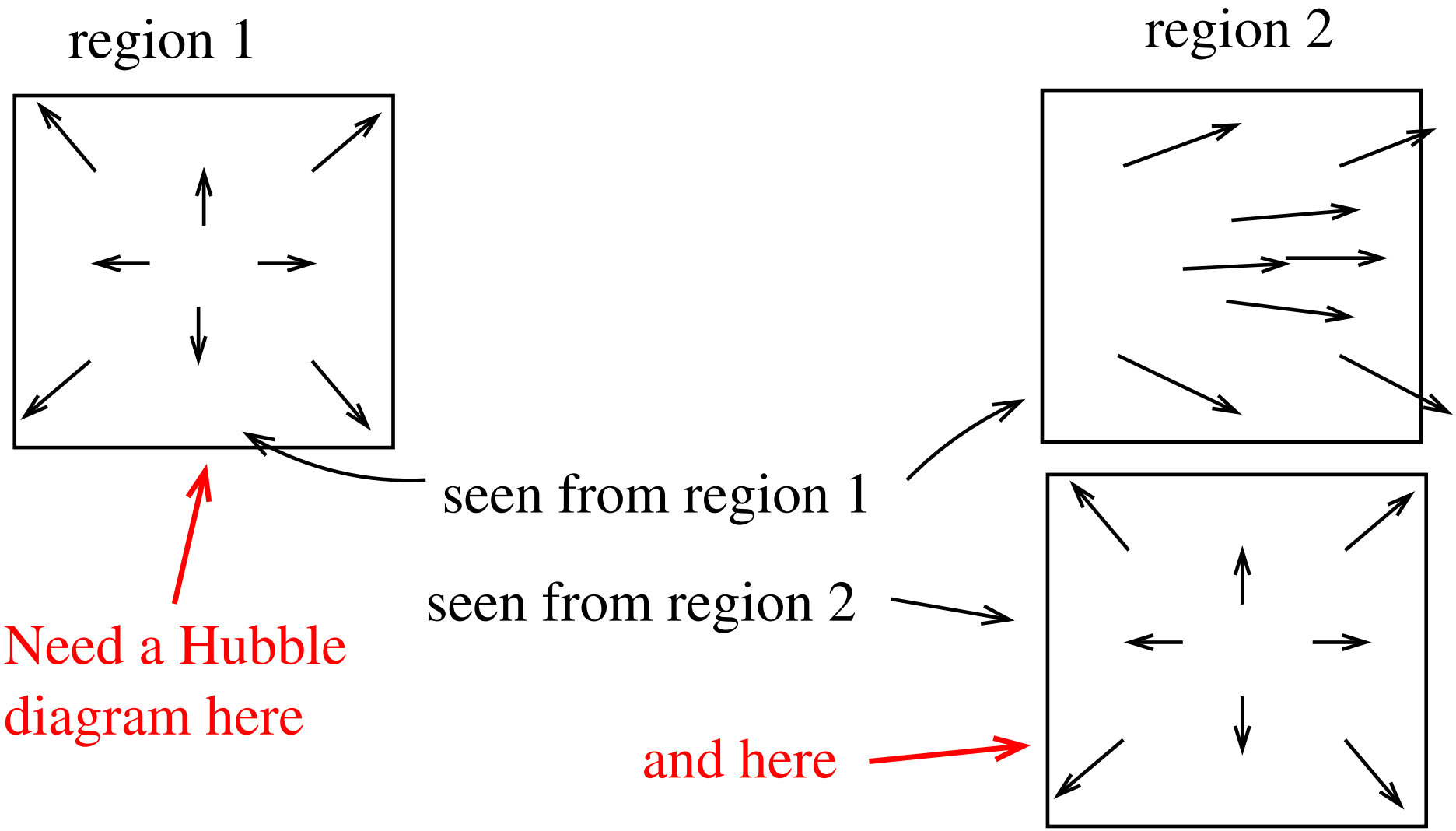
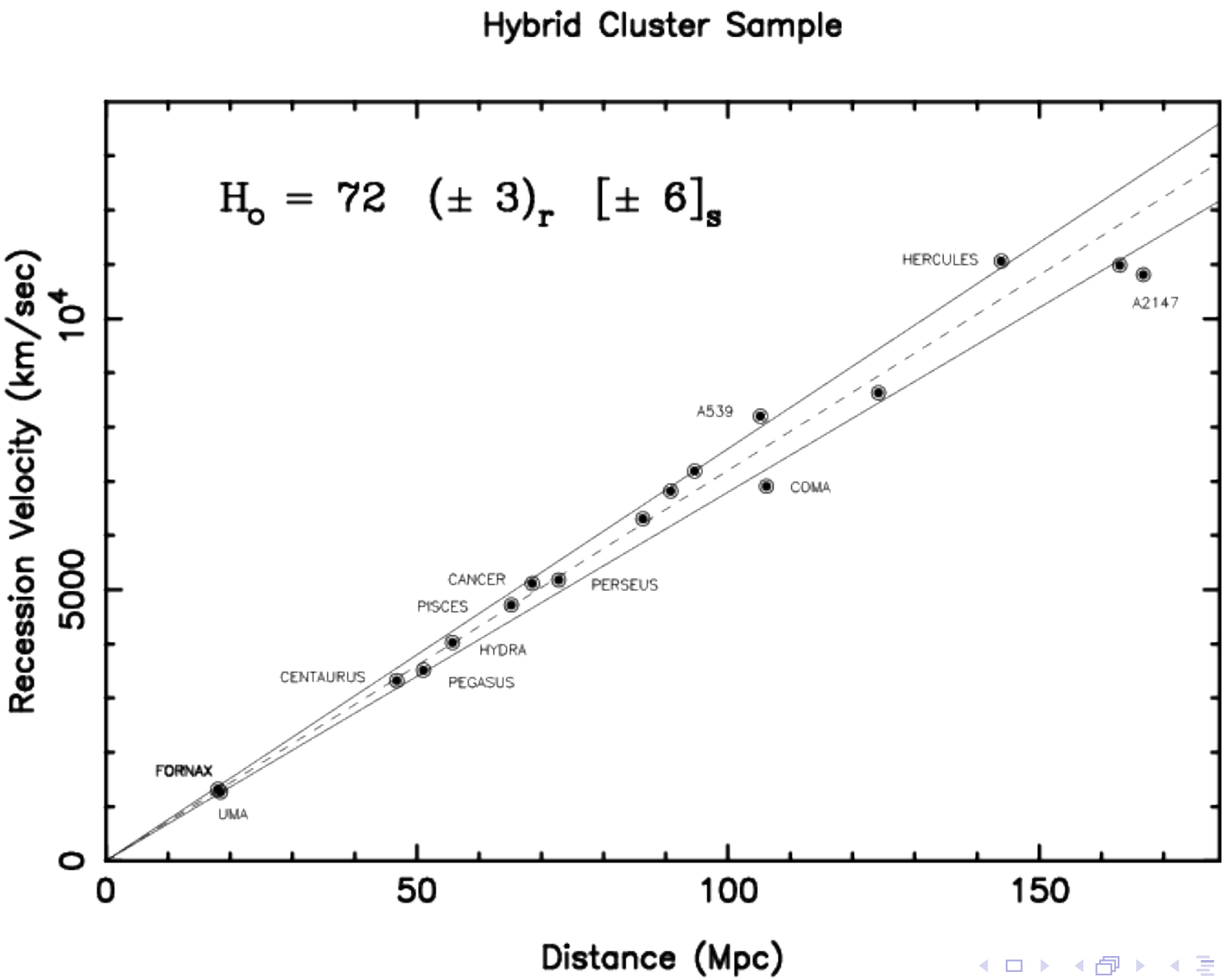
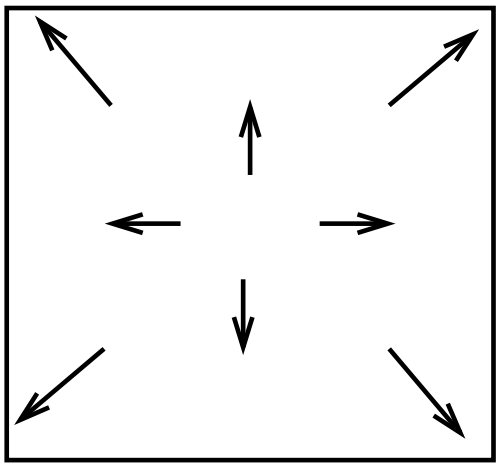


A Hubble diagram (here)



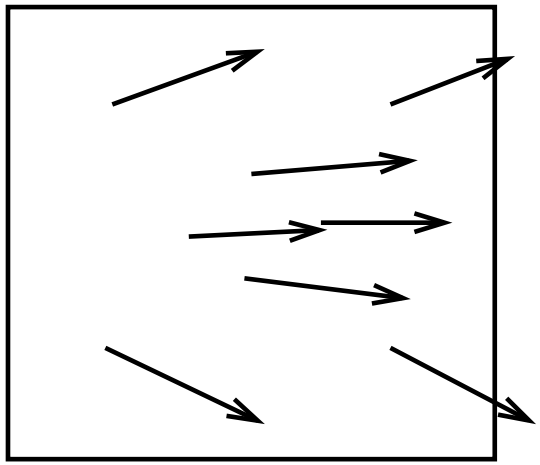
Not easy to measure $V = HD$ in region 2!

region 1



$V=H_0D$

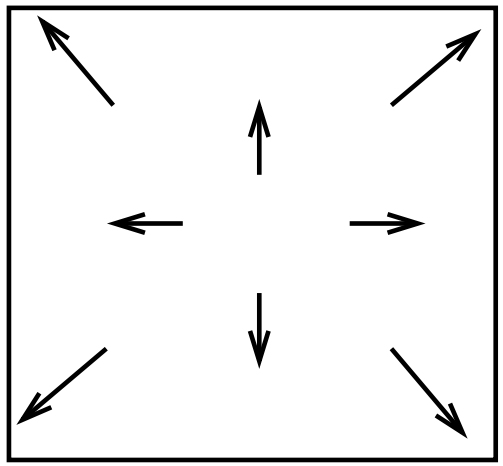
region 2



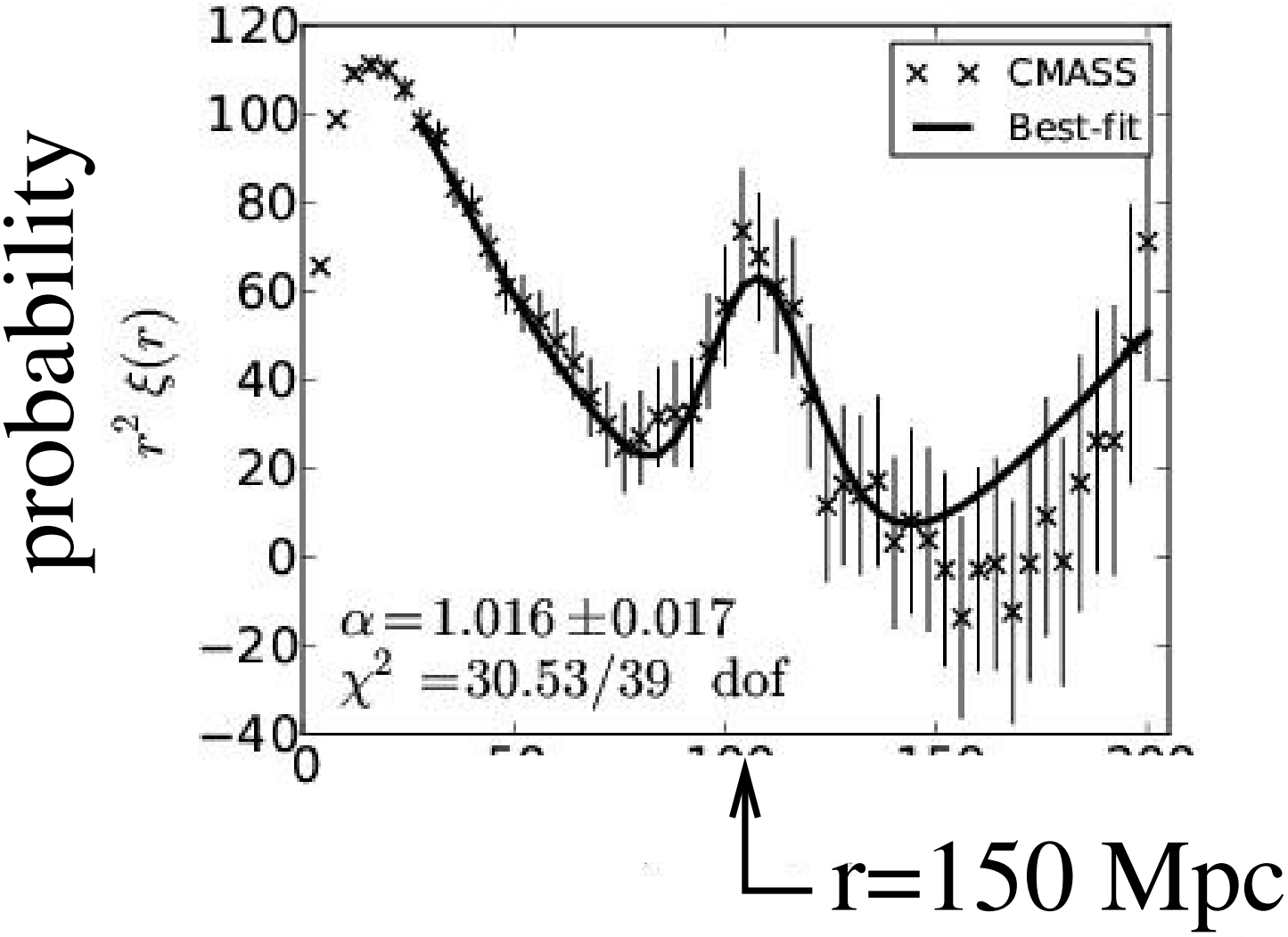
V=HD here

V's from relative Doppler shifts

D's from ''BAO correlations''



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



Where does the “150Mpc” come from?

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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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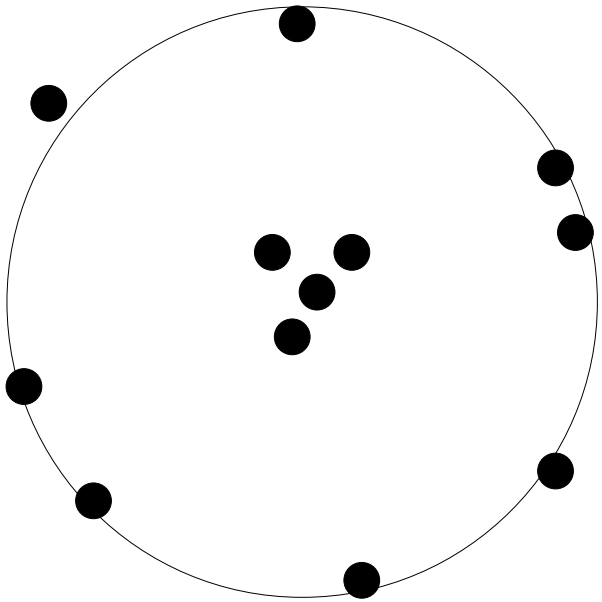
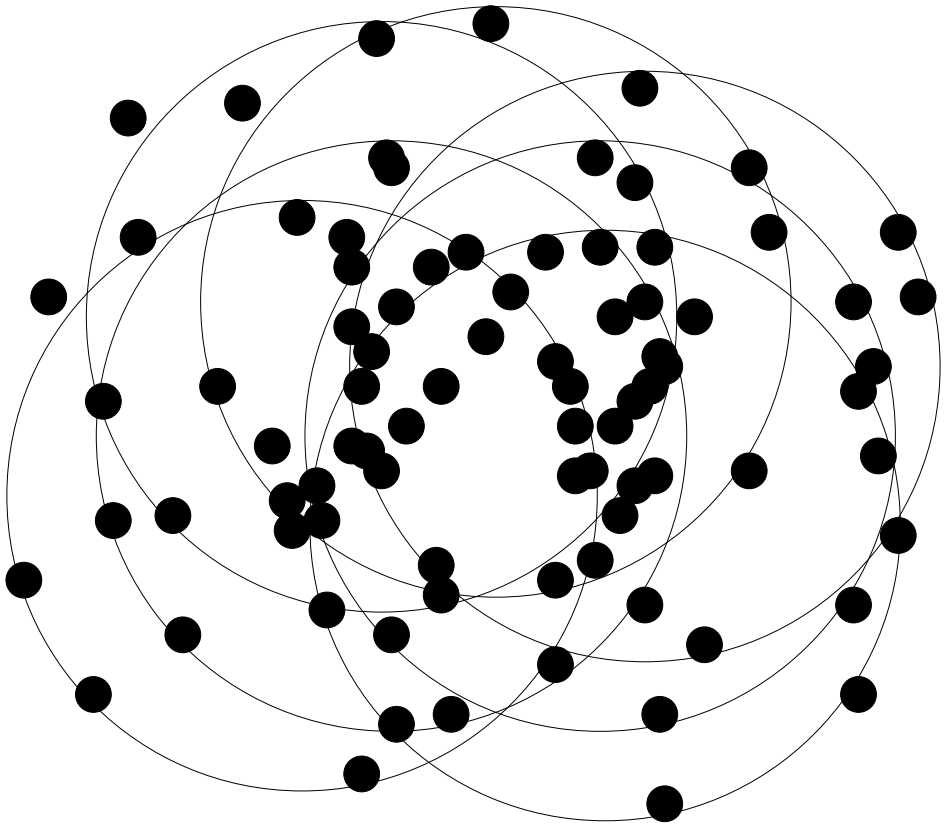
Almost too good to be true!!

A ridiculously simple region of the sky



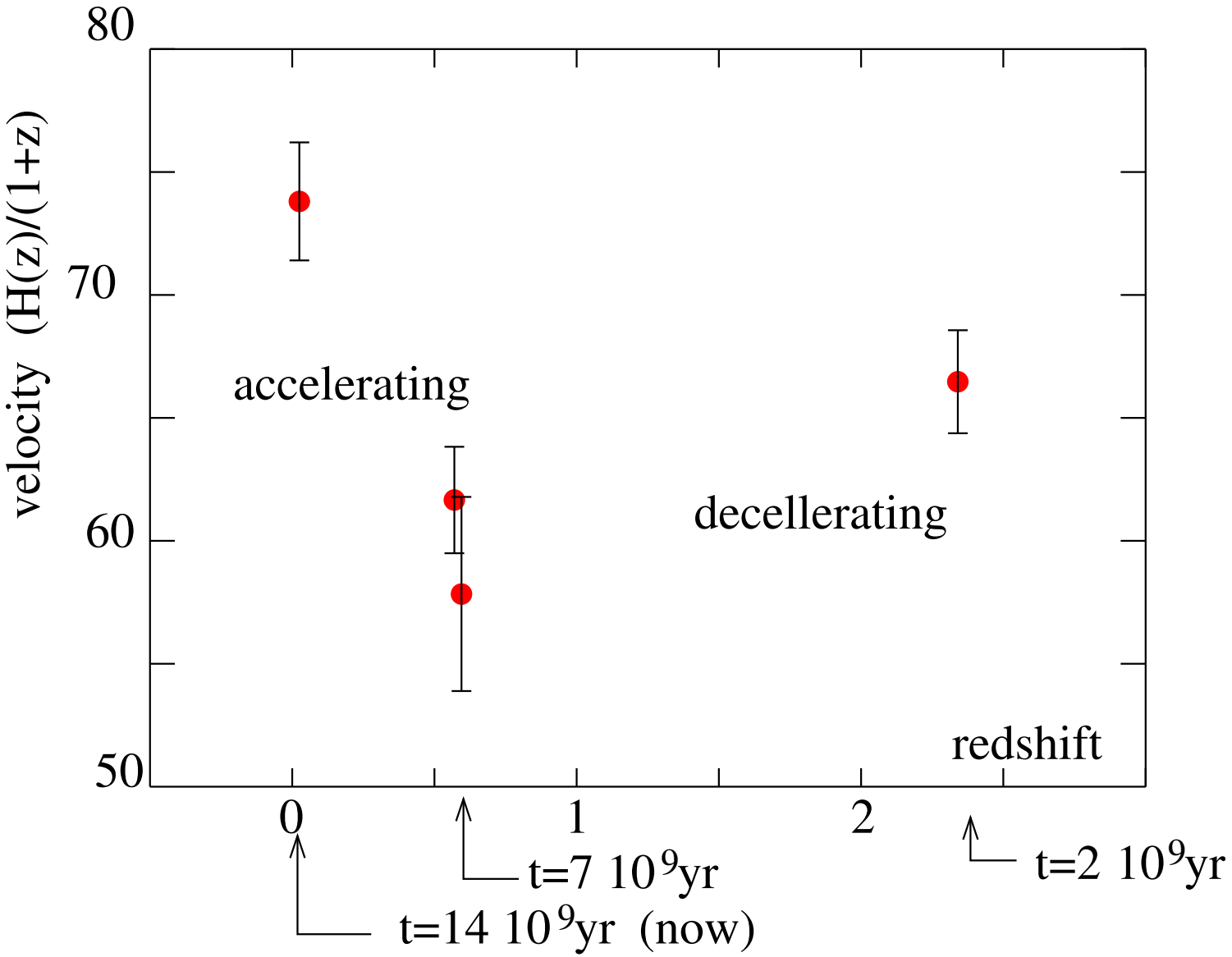
The "150Mpc" is visible

A slightly more realistic region of the sky



The “150Mpc” can be found statistically

The expansion decelerated then accelerated



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- How does a negative pressure cause acceleration?

  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.

- How does dark energy cause acceleration?

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- How does a negative pressure cause acceleration?

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- Besides causing the acceleration, what does dark energy do during the expansion?

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- Besides causing the acceleration, what does dark energy do during the expansion?

  Nothing! Substances with positive pressure due 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.

- How does dark energy cause acceleration?

  Answer: It has a negative pressure

- How does a negative pressure cause acceleration?

  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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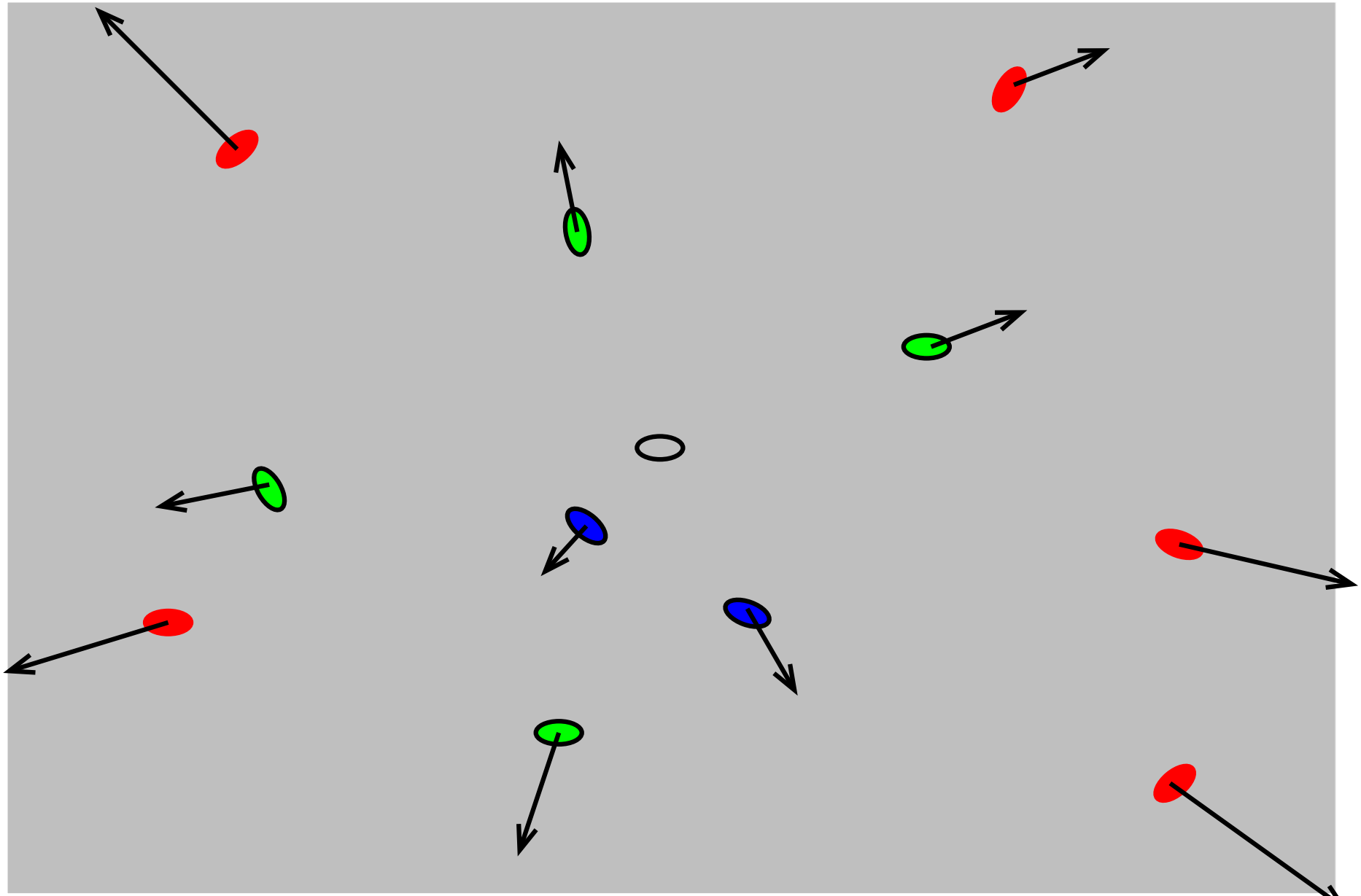
$\Rightarrow$ Energy density mostly matter in the past (decelleration) and is mostly dark energy now and in the future (acceleration).

The universe: matter and dark energy



The future: dark energy