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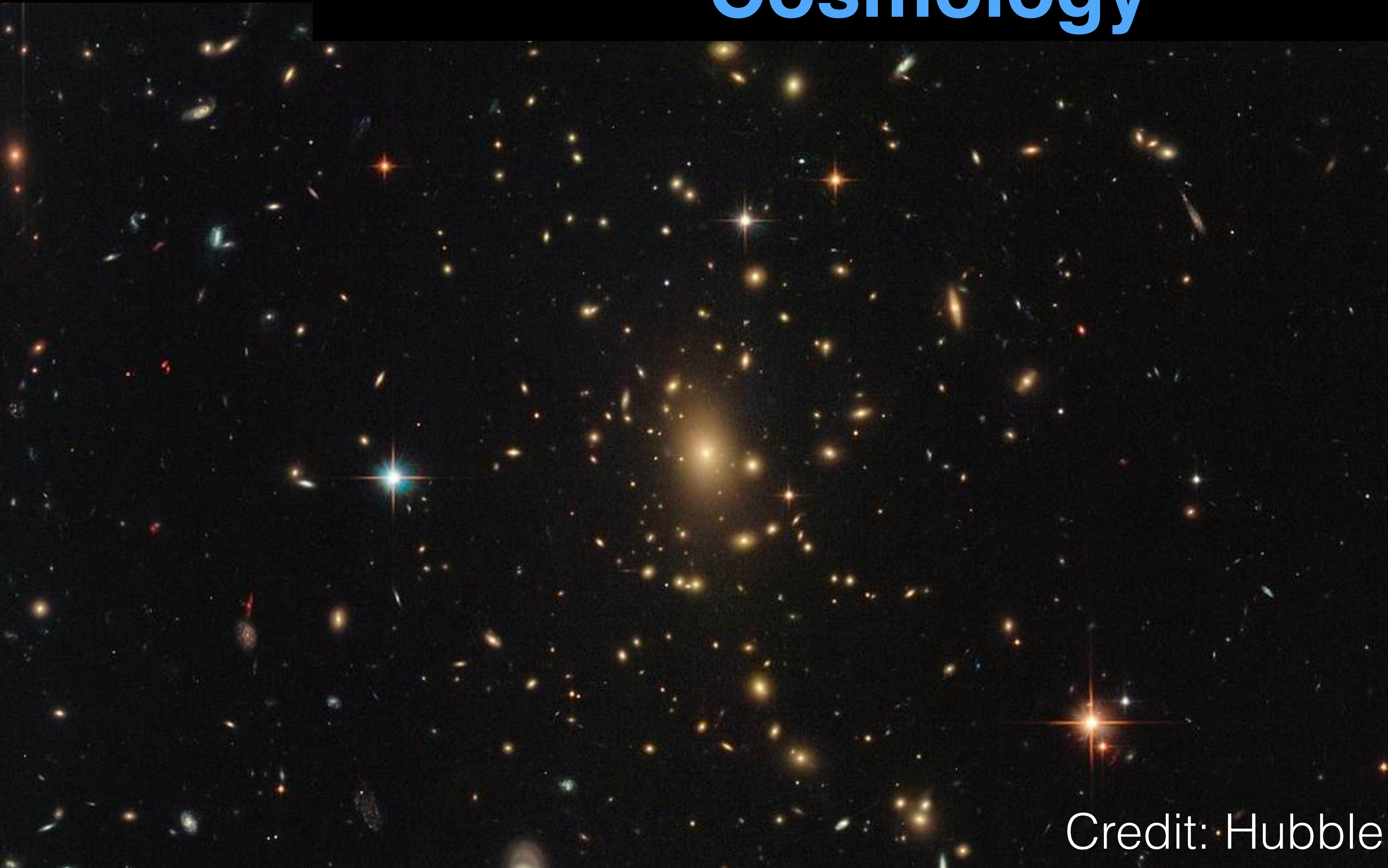
2025 U.Oregon Quarknet

Intro to Early Universe Cosmology

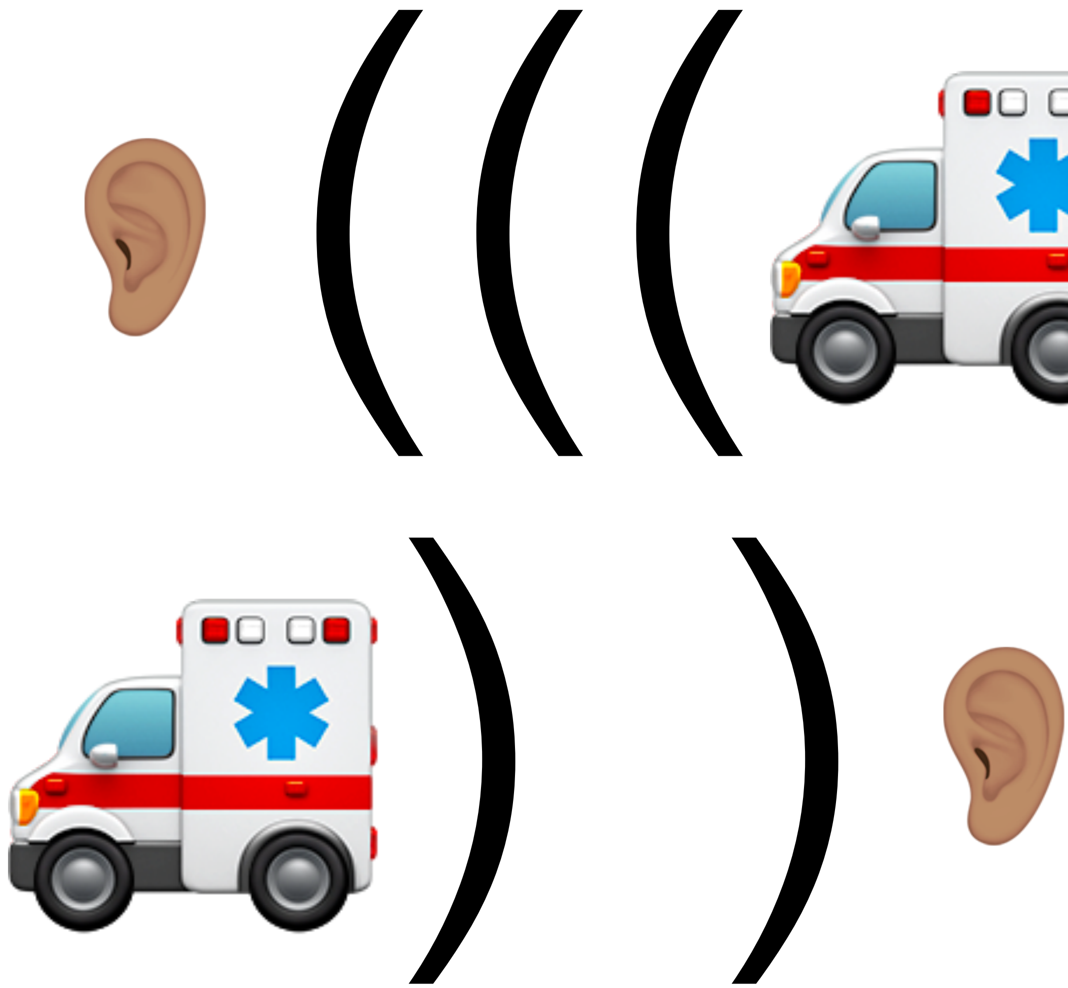


Credit: Hubble

Outline

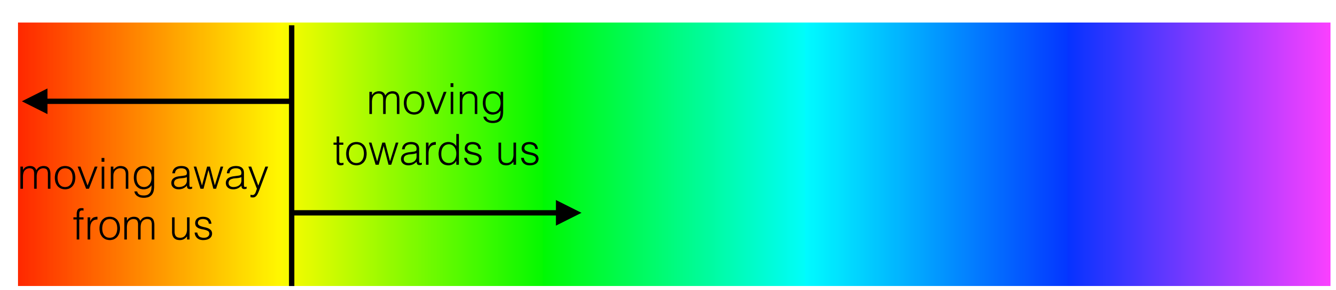
- Evidence for an expanding universe (Hubble's Law)
- Hubble's law implies universe is homogeneous and isotropic
- Possible energy content and effect on expansion (Big Bang and future)
- Overview of recent hot topics in cosmology in these directions

Doppler Effect



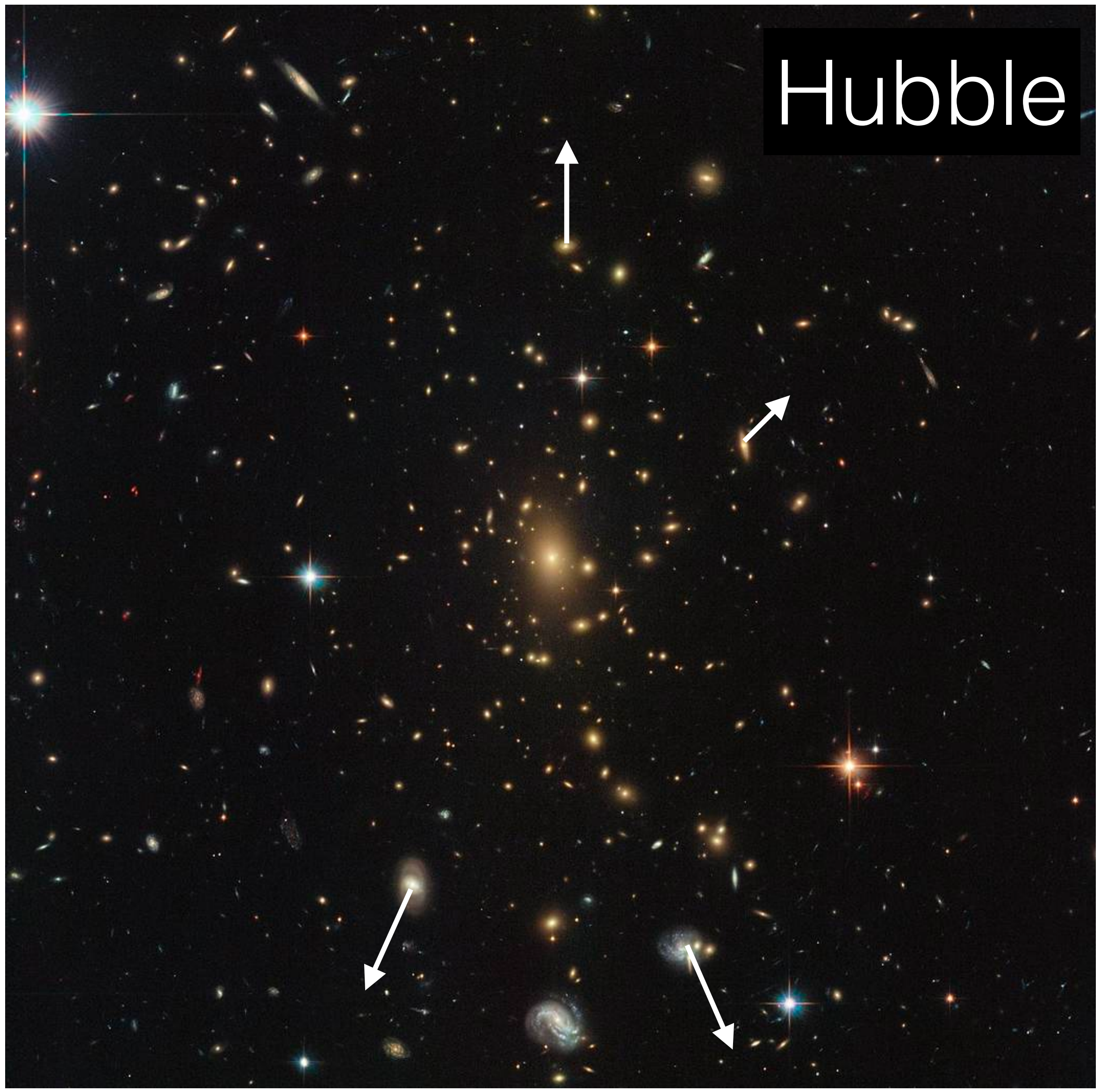
An ambulance's siren is higher pitch (frequency) when its coming towards you, lower frequency when going away

Can also be used to measure speed of ambulance

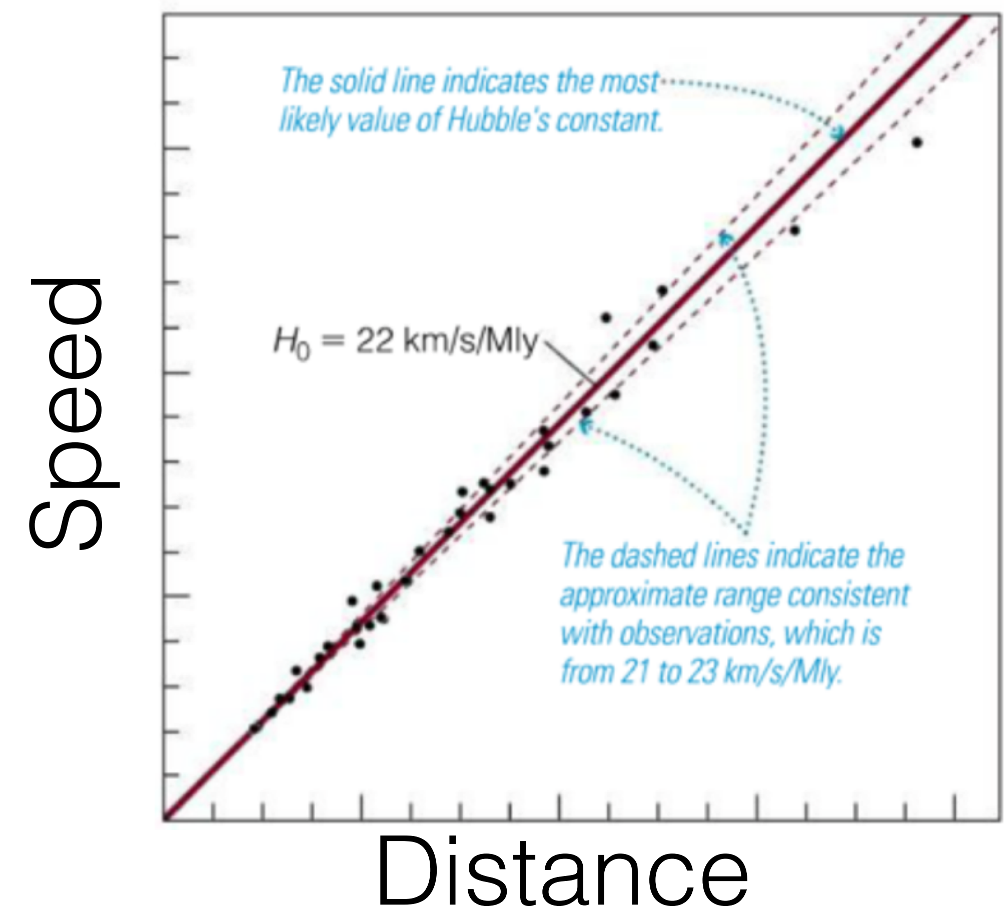


Similarly a light bulb will have a different color if it is moving toward or away from us (e.g. radar speed guns)

Galaxy Observations



From Doppler effect on light, one measures that other galaxies are moving away from us.
Is our galaxy a special place?

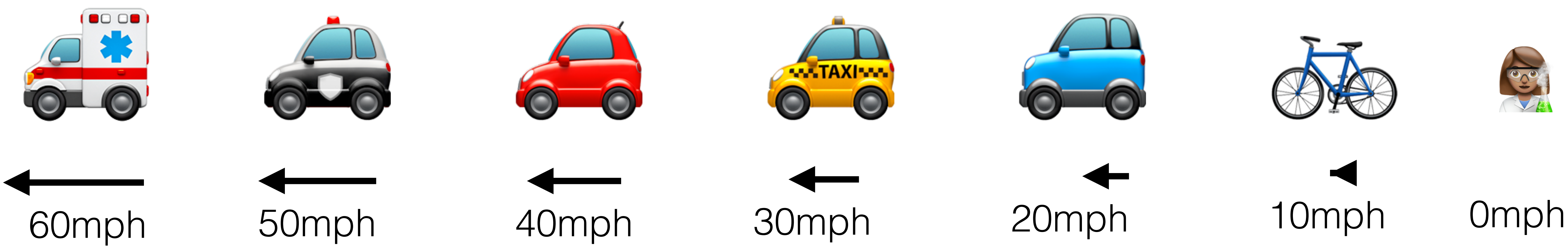


Credit: Pearson

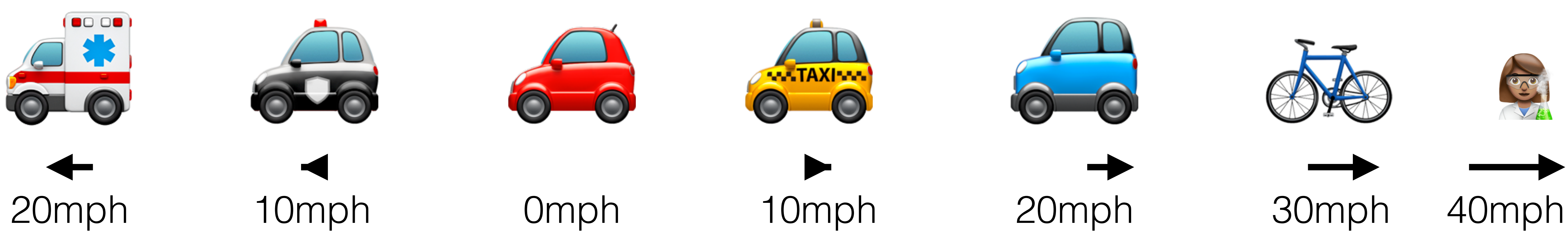
Naive conclusion is wrong, straight line in plot (Hubble's law) says all galaxies see other galaxies moving away

Highway Analogy

Equally spaced vehicles are going at speeds listed

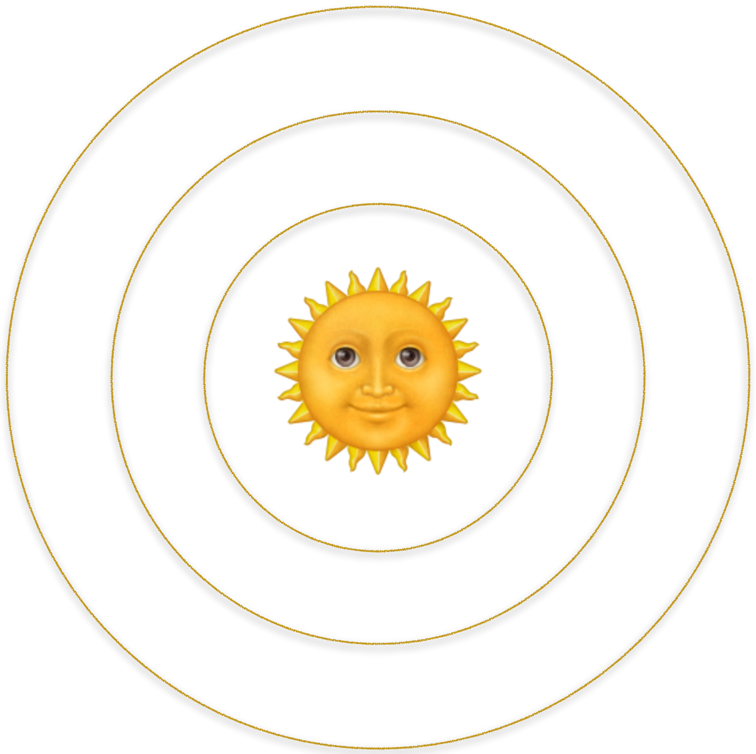


What does the car in red observe from their point of view?



Similarly each car observes a Hubble's law of other cars, so everybody observes the same thing (no point is special)!

Implications of Hubble's Law



Isotropic

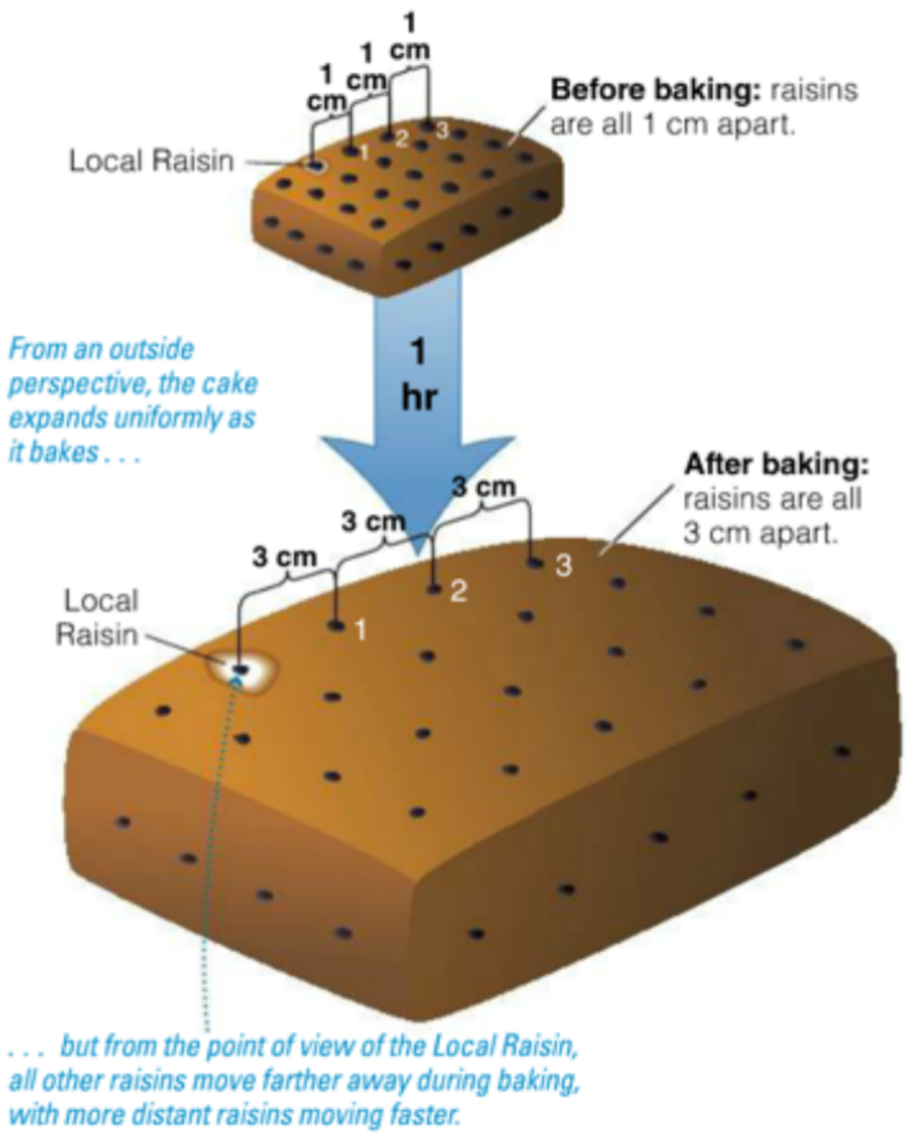
Since Hubble's law is not direction dependent, universe looks the same in all directions from our point of view

Homogeneous

Since Hubble's law is observed by all observers (highway analogy), universe appears to be the same at all points

Together, these completely invalidate the geocentric model

Universe Expansion



Distances and Speeds as Seen from the Local Raisin

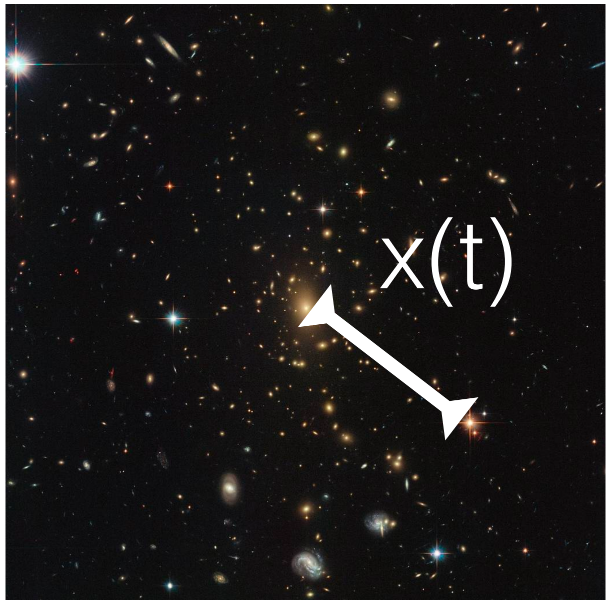
Raisin Number	Distance Before Baking	Distance After Baking (1 hour later)	Speed
1	1 cm	3 cm	2 cm/hr
2	2 cm	6 cm	4 cm/hr
3	3 cm	9 cm	6 cm/hr

FIGURE 12.10

Credit: Pearson

Raisin cake analogy
as cake (Universe) expands,
raisins (galaxies) move away
from each other just like
in Hubble's law, with a
speed that grows with distance

(Also google "Expanding
Universe Balloon Experiment")



Scale Factor

To treat expansion, we use a scale factor R which can change with time

$x(t) = R(t)\, x_0$

$$v(t) = \frac{dx(t)}{dt} = x_0 \frac{dR(t)}{dt}$$

$$= x_0 R(t) \left(\frac{dR(t)/dt}{R(t)} \right) = \frac{dR/dt}{R} x(t) = H(t) x(t)$$

If dR/dt > 0, universe is expanding leading to a positive Hubble "constant" H(t) = (dR/dt)/R

Evolution of R, depends on the energy content of the universe

Energy Density ρ change w/ R

1) Matter
(e.g. protons, electrons, dark matter)
$\rho \sim 1/R^3$
# of particles is fixed, but density dilutes w/ volume

2) Radiation
(e.g. photons, neutrinos)
$\rho \sim 1/R^4$
energy of each particle also drops as 1/R

3) Vacuum energy
(e.g. cosmological constant, dark energy)
$\rho \sim 1$
Energy density doesn't change

Friedmann Equation

$$H(t)^2 = \frac{8\pi G}{3}\rho$$

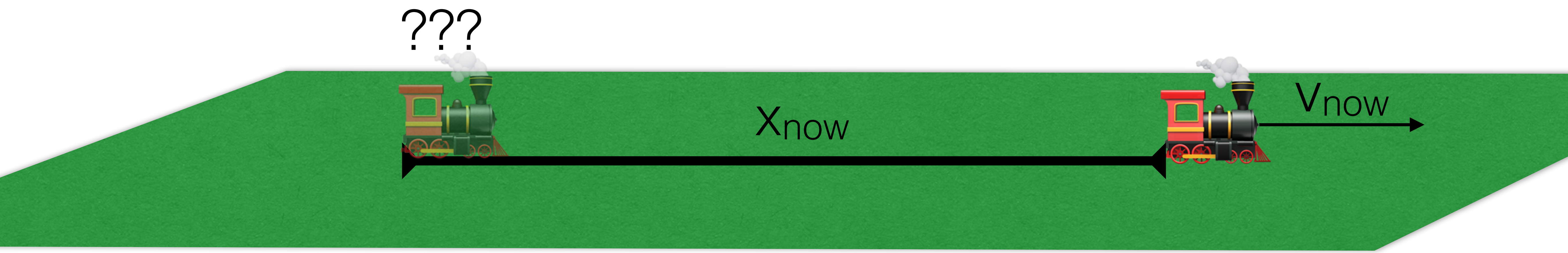
where G is Newton's gravitational constant

$\boxed{\text{With this equation, we can prove the existence of a big bang if we only have matter and radiation!}}$

$$\left(\frac{dR}{dt}\right)^2 = \frac{8\pi G}{3}\rho R^2$$

For matter and radiation energy
right hand side falls with R,
so expansion in past was faster

Big Bang



If you see a train and it is going at speed v_{now}
and you know it has been slowing down all this time,
do you know if it has been at the original point on the left?

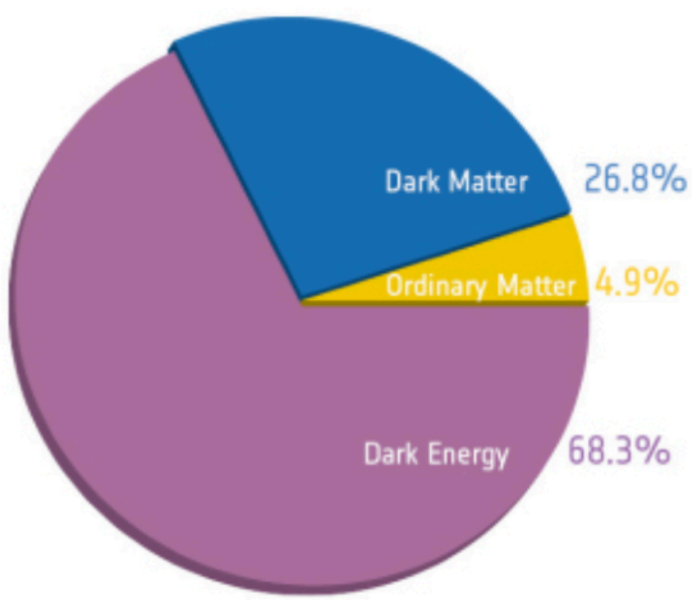
Yes, because it took at most time x_{now}/v_{now}
to move from the left to the right if it has been slowing down

By analogy, with radiation and matter only, the universe's expansion is slowing down and thus it had R = 0 a finite time in the past. R=0 is the big bang, where the universe was infinitely dense (not a point though)

Predicting Universe's Fate

We've ignored curvature of space so far,
if it is positively curved (like a sphere)
the universe might stop expanding and crunch

Density measurements



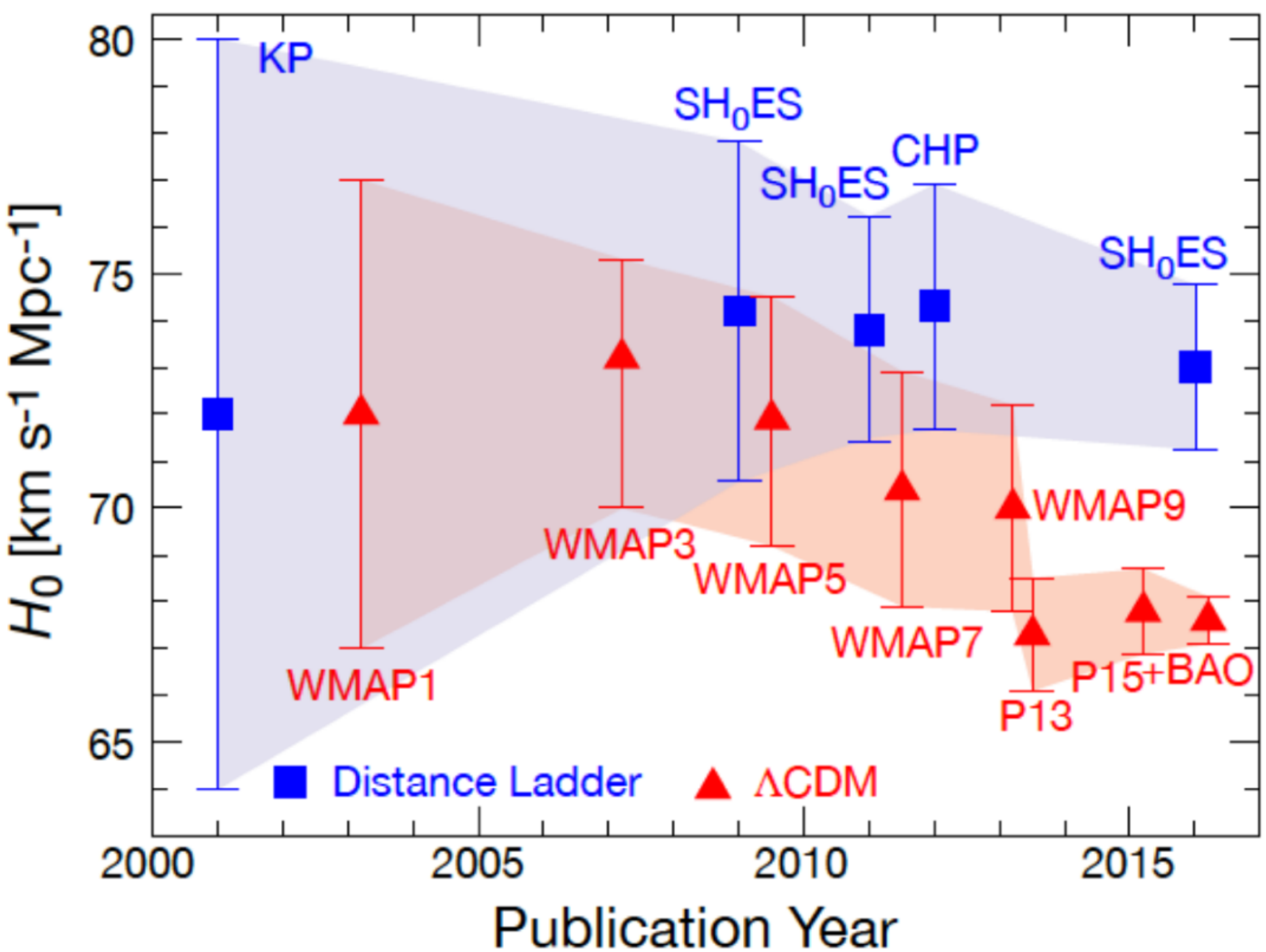
Recent determination of energy content
~30% matter
~70% dark energy

$$\left(\frac{dR}{dt}\right)^2 = \frac{8\pi G}{3}\rho R^2$$

If dark energy acts like vacuum energy leads to R growing exponentially with time, eventually other galaxies cannot be seen

Recent Trends in the Field

Hubble Tension



Credit: Freedman

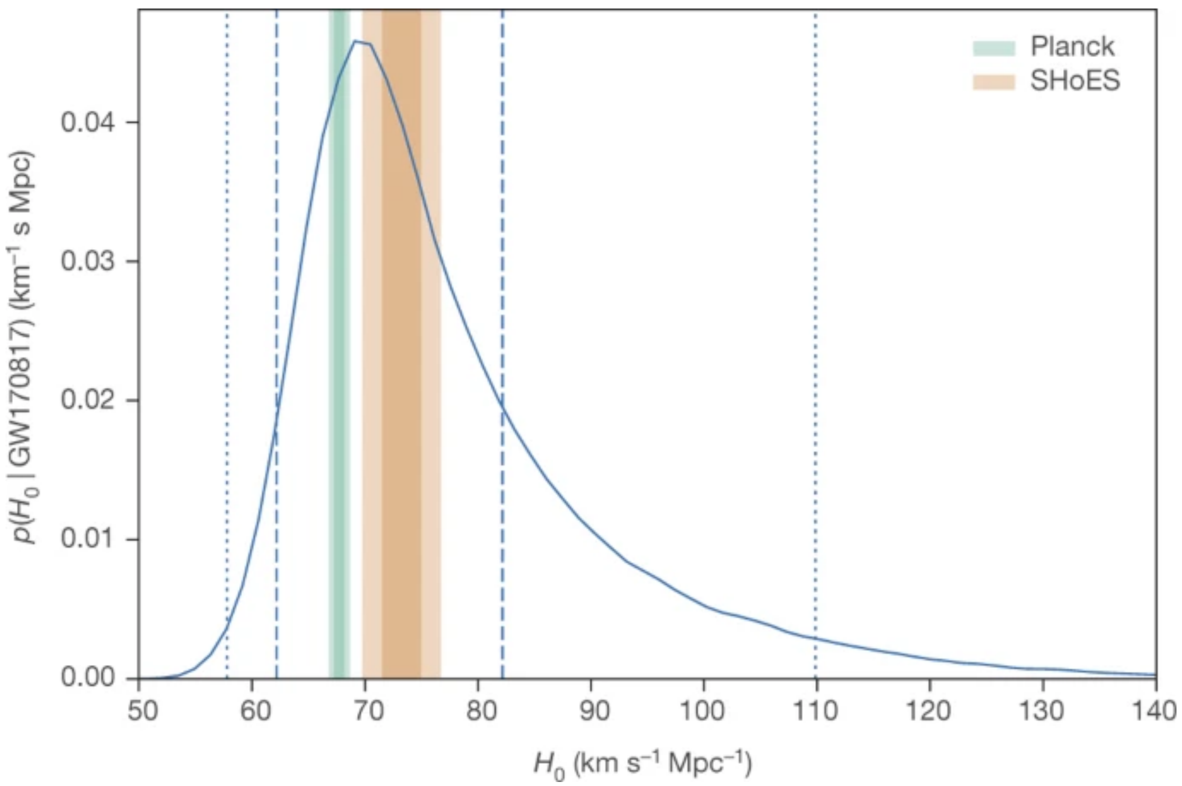
H(now) can be inferred in two ways

1) Measuring Hubble's law using supernova (blue)

2) Using indirect measurement from cosmic microwave background (red)

Disagreement between two values is either
1) new physics or 2) issue with measurements

LIGO Input



Gravity wave sources with an electromagnetic counterpart can independently measure Hubble constant

GW170817 was a binary neutron star merger seen in GWs and optically, which allows one to effectively measure distance and velocity

Only one observation so far, but future observations will help to resolve issue

Evolving Dark Energy?

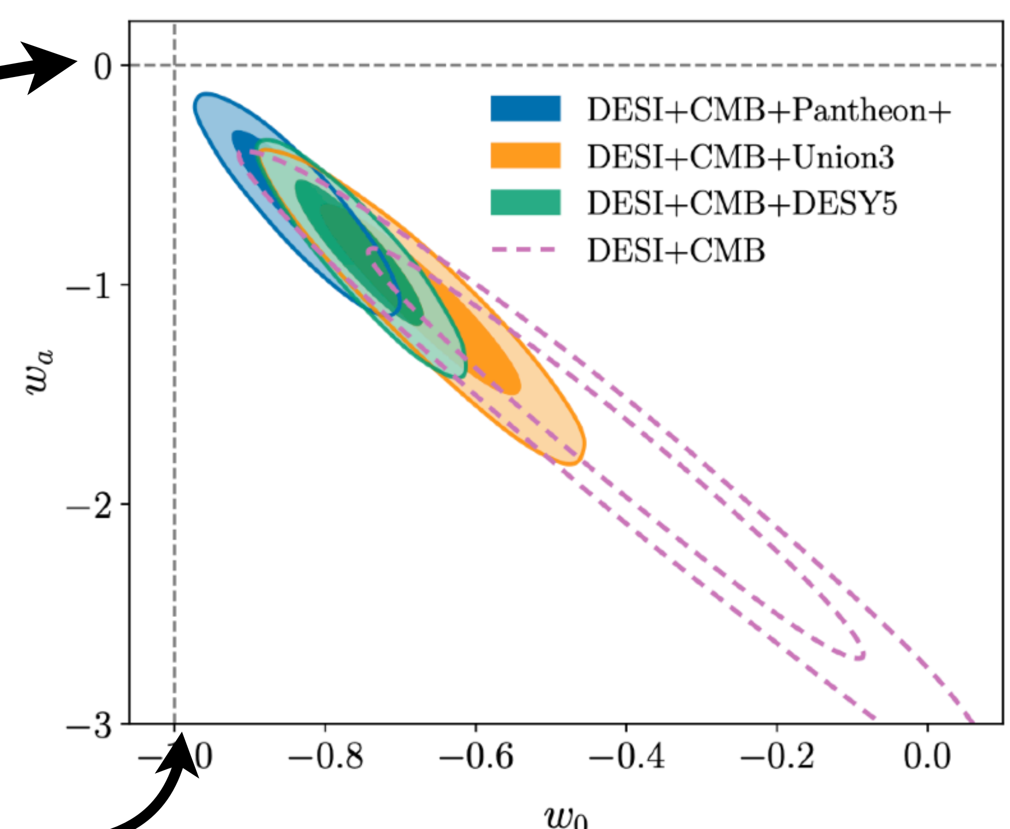
Dark Energy Spectroscopic Instrument (DESI)

DESI has made a 3d map of millions of galaxies and quasars

Looking at their distribution of them, they can test the expansion of the universe at different times in the past

no evolution

vacuum energy



Common Misconceptions People Have

- Hubble Law shows we are at a special place in Universe, but it shows opposite

- Big Bang occurred at a point, but all of space is there but it was infinitely dense

- Expansion only occurs between objects which aren't gravitationally bound. E.g. we aren't expanding, Milky Way isn't getting stretched…

Conclusion

- Cosmology is entering a precision era
- Complementary probe to particle colliders, becoming of interest to both particle theorists and experimentalists
- Field is extremely exciting with many experiments coming online (e.g. James Webb, Vera Rubin)

Thanks for your time!

Extra Slides

Doppler Effect for Light

$$\frac{\lambda_{\mathrm{receiver}}}{\lambda_{\mathrm{emitter}}} = \sqrt{\frac{1+\frac{v_{\mathrm{emitter}}}{c}}{1-\frac{v_{\mathrm{emitter}}}{c}}}$$

Right hand side > 1 if
emitter is moving away from you

Right hand side <1 if emitter
is moving towards you

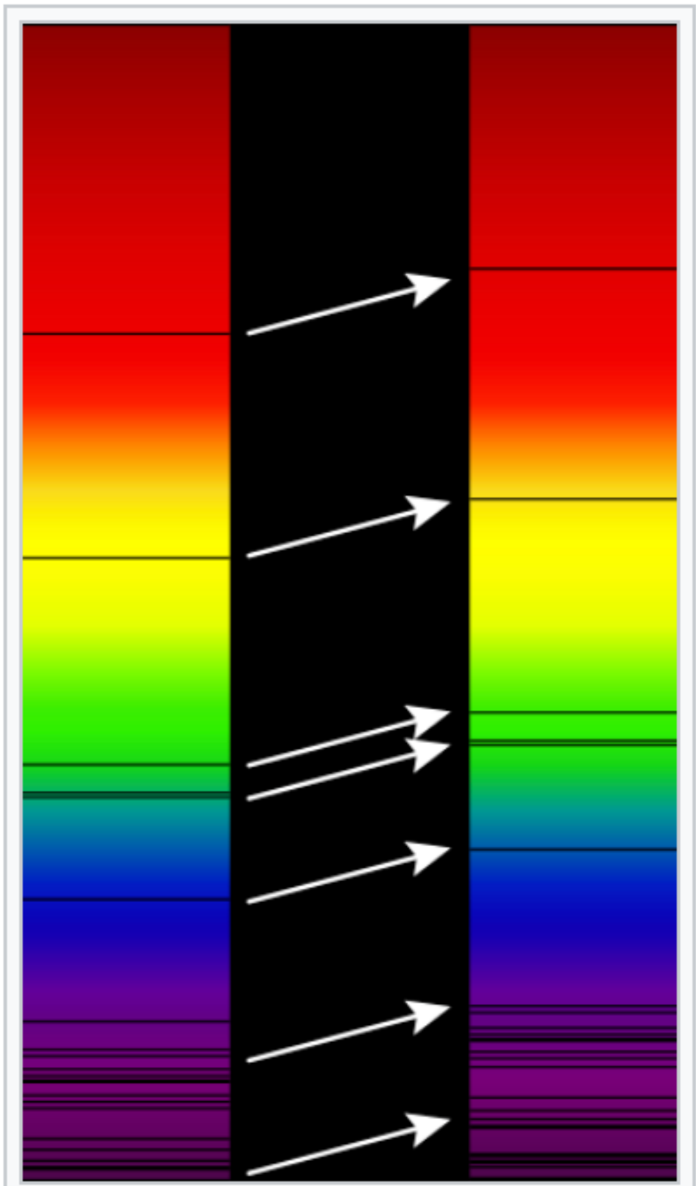
λ
is the light wavelength

c
is the speed of light
(186,000 miles/second)

v_{emitter}
is the speed of the
emitter in receiver's
frame

Measuring Speed

Credit:Wikipedia



Amount that the lines move to redder part of spectrum (longer wavelengths), the faster the object is moving away from of us