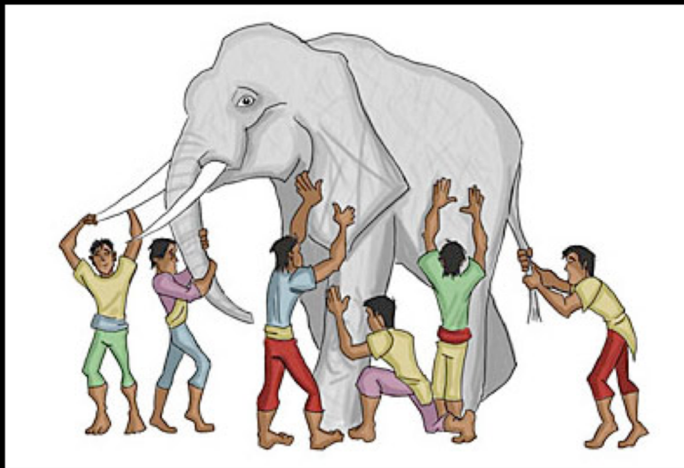
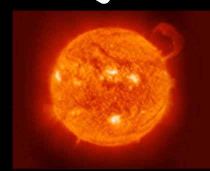


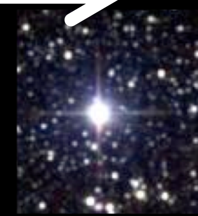
Analyzing data on a cosmic scale
Prof. Rachel Bean (Astronomy)

How big is our universe?

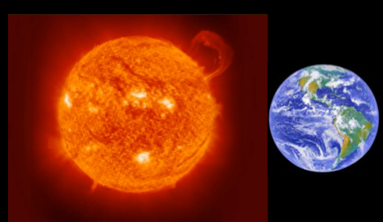
1 light second

4 light years





8 light minutes



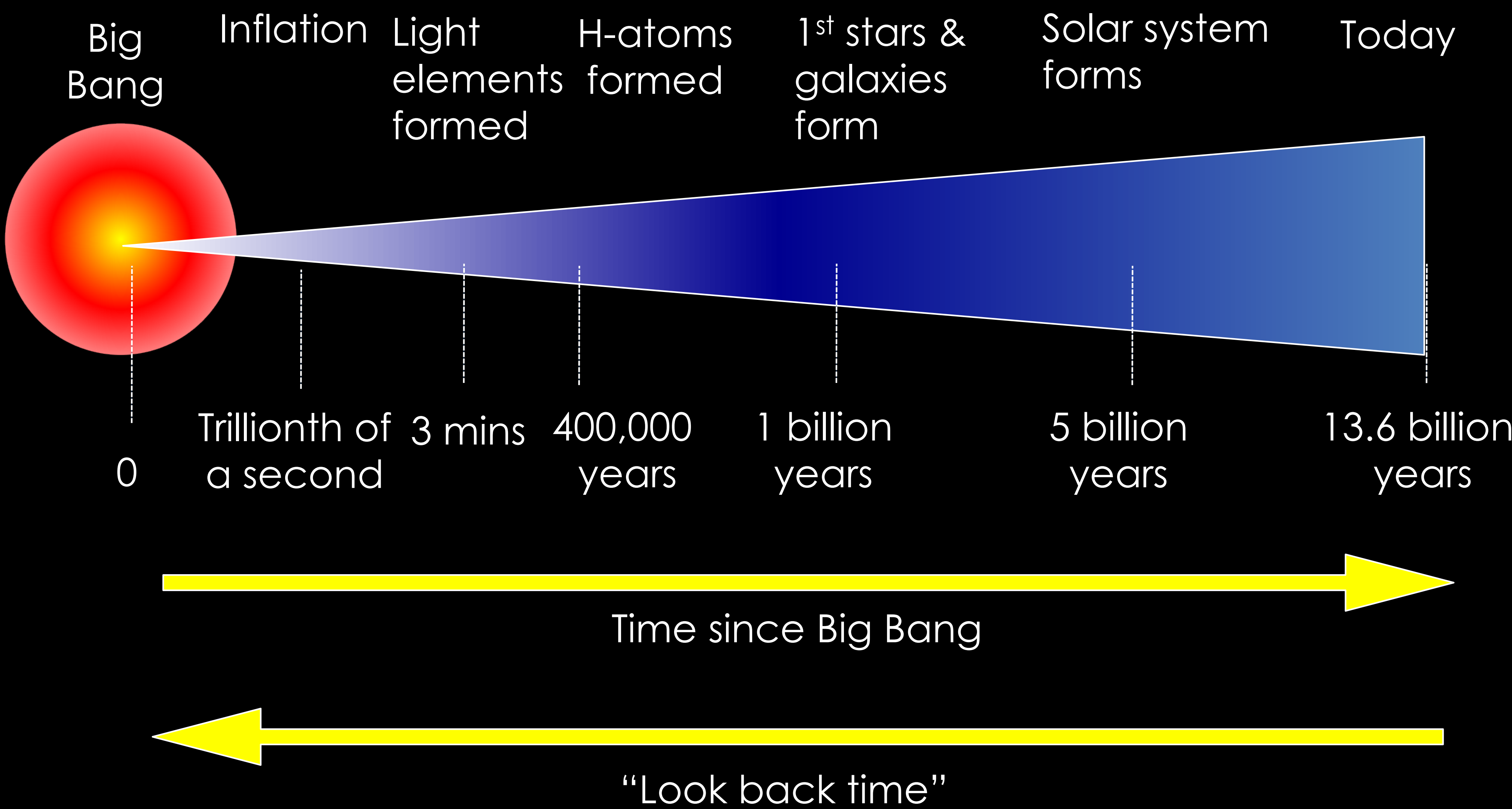
~100,000 light years

5 light hours

~million light years

Observable universe
~billion light years

Distant objects tell us about cosmic history



What type of data do we take?

Measure properties of luminous objects e.g. gas clumps, planets, stars, stellar remnants, galaxies, galaxy clusters

- Positions
- Temperatures/colors
- Brightness
- Images
- Spectra

How do we use the data?

- Use observations with known laws of physics to infer properties of the universe
  - Geometry
  - Size
  - Matter constituents
  - Origin and Evolution history
- Distances are critical, but are the hardest quantity to infer: obtained indirectly, using geometry

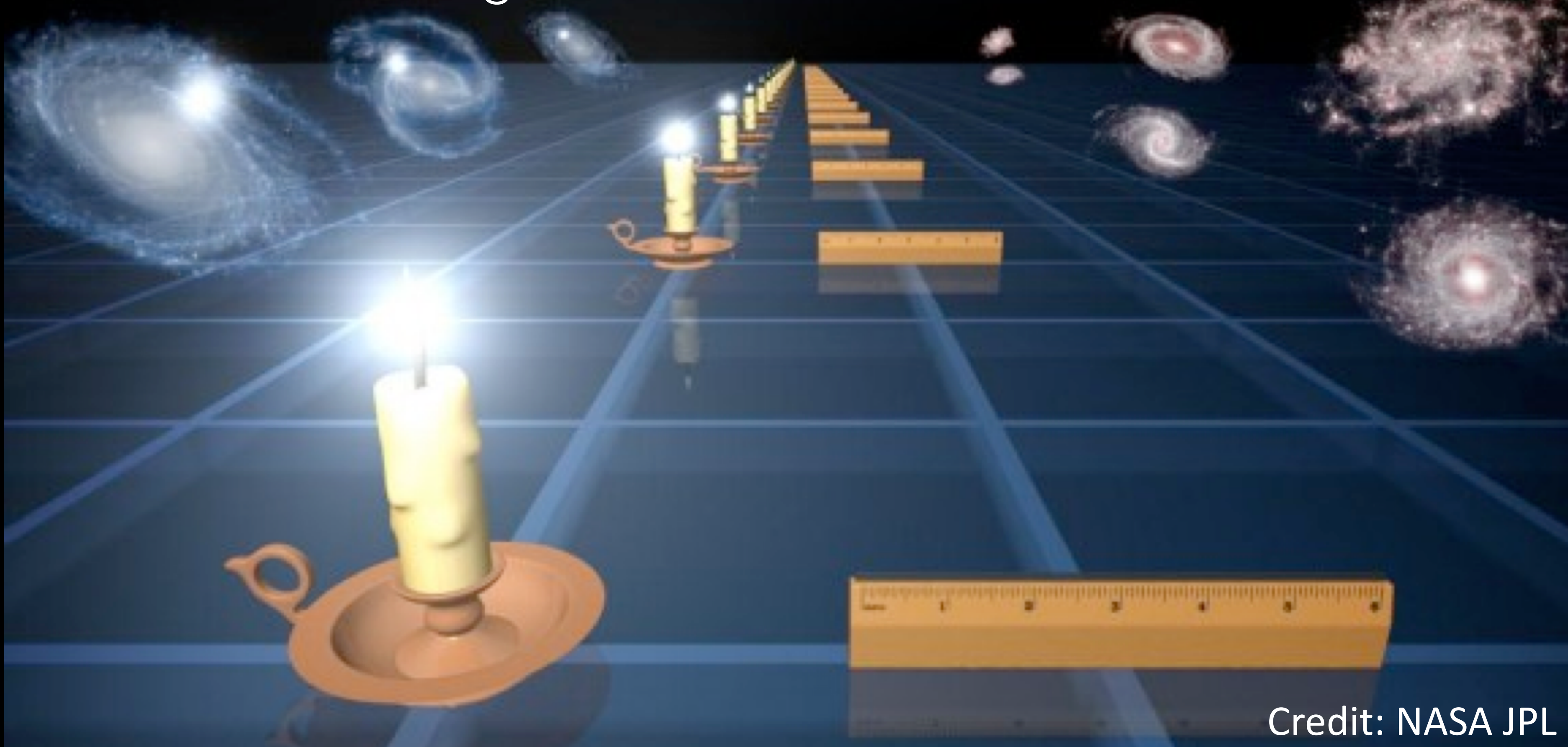
Cosmic Depth Perception

Standard Candles

Compare known intrinsic and observed brightness

Standard Rulers

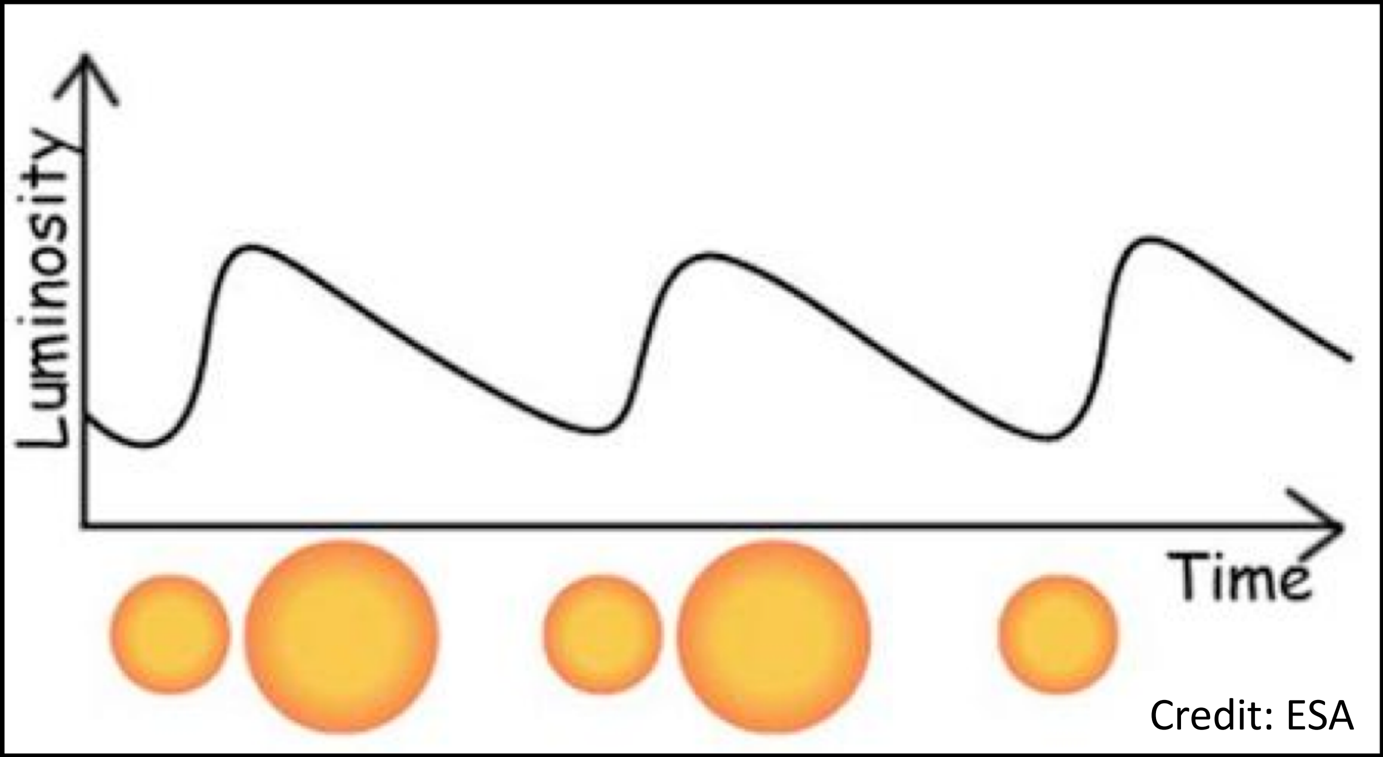
Compare known physical and observed size



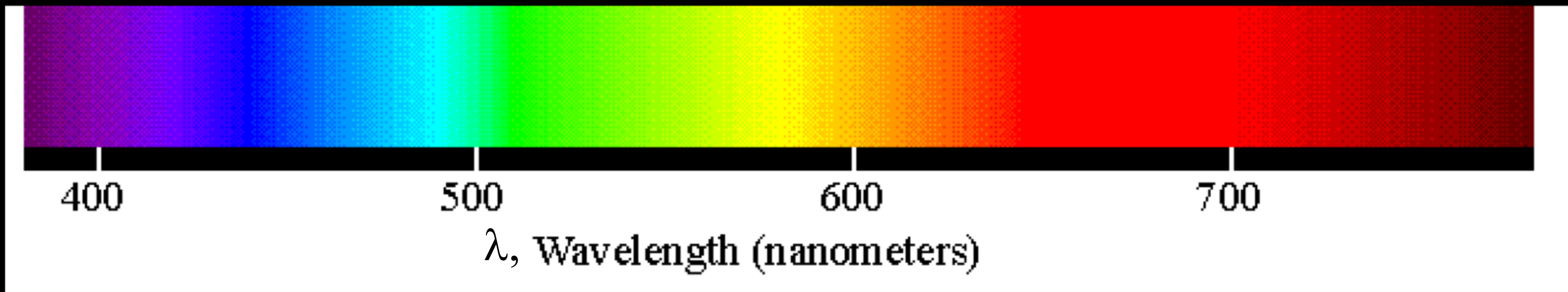
Credit: NASA JPL

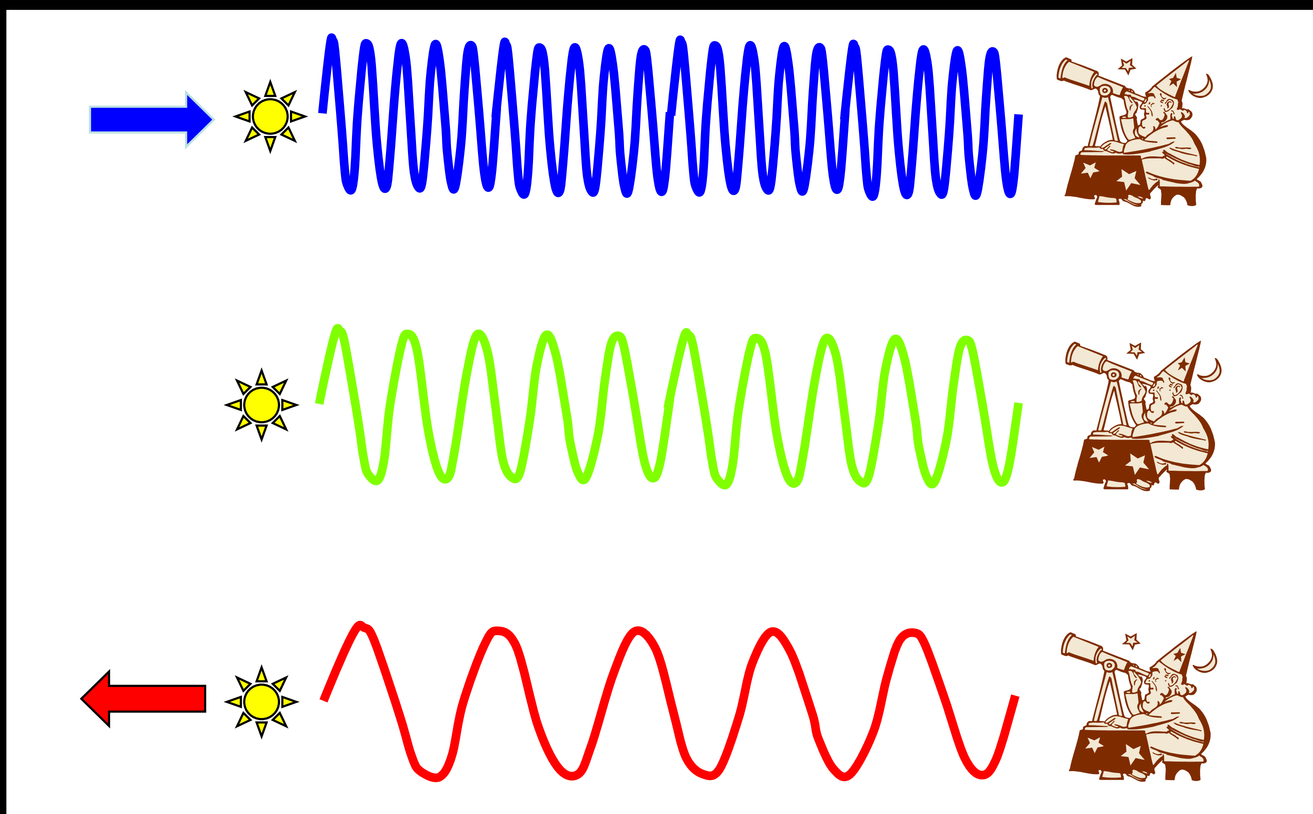
Standard candles: Cepheid Variable Stars

- [”Middle-aged" pulsating stars]
- Pulsation period directly related to their luminosity
- 100 x brighter than Sun (see ~million light yrs away)



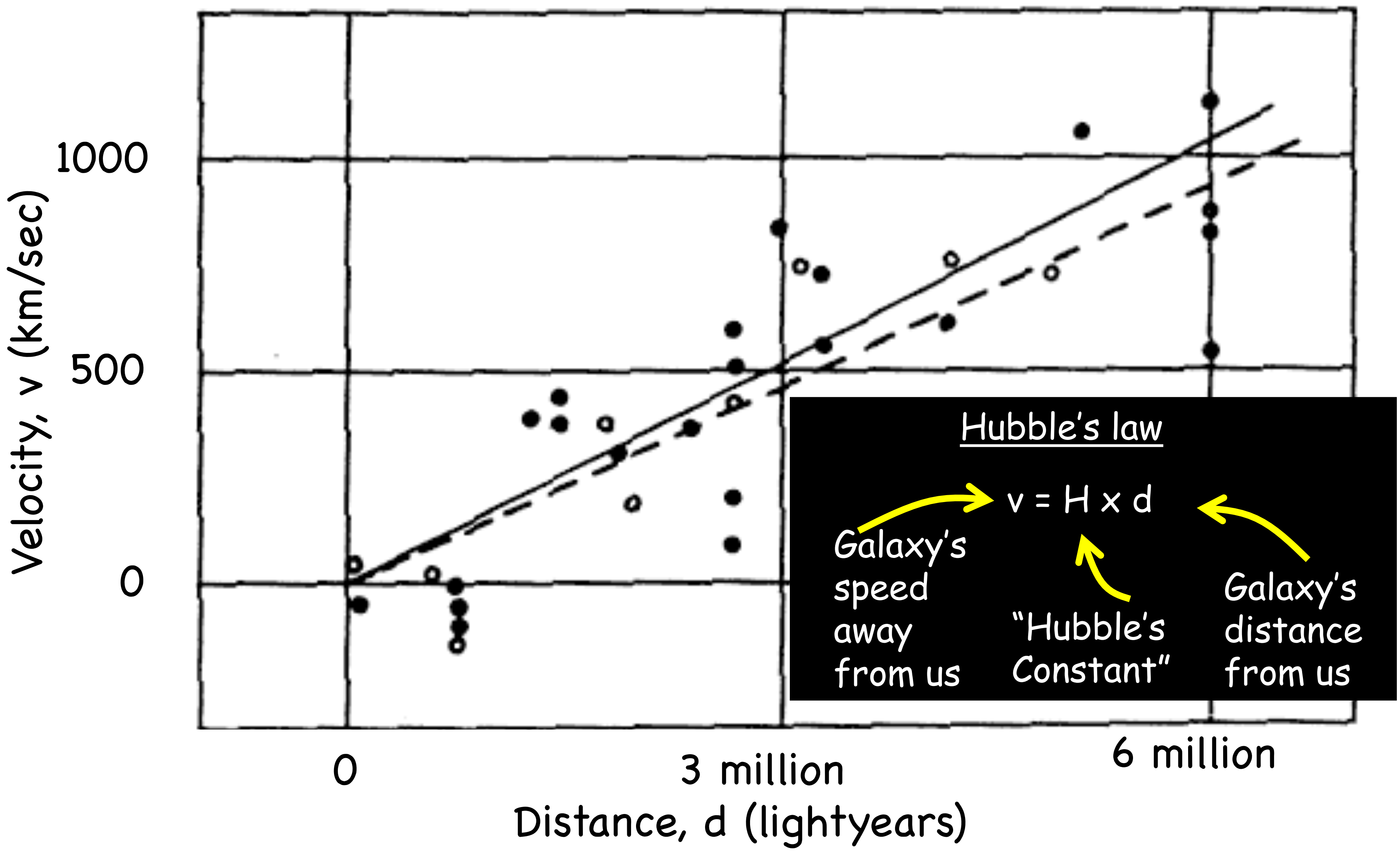
Use Doppler shift to measure cosmic motion





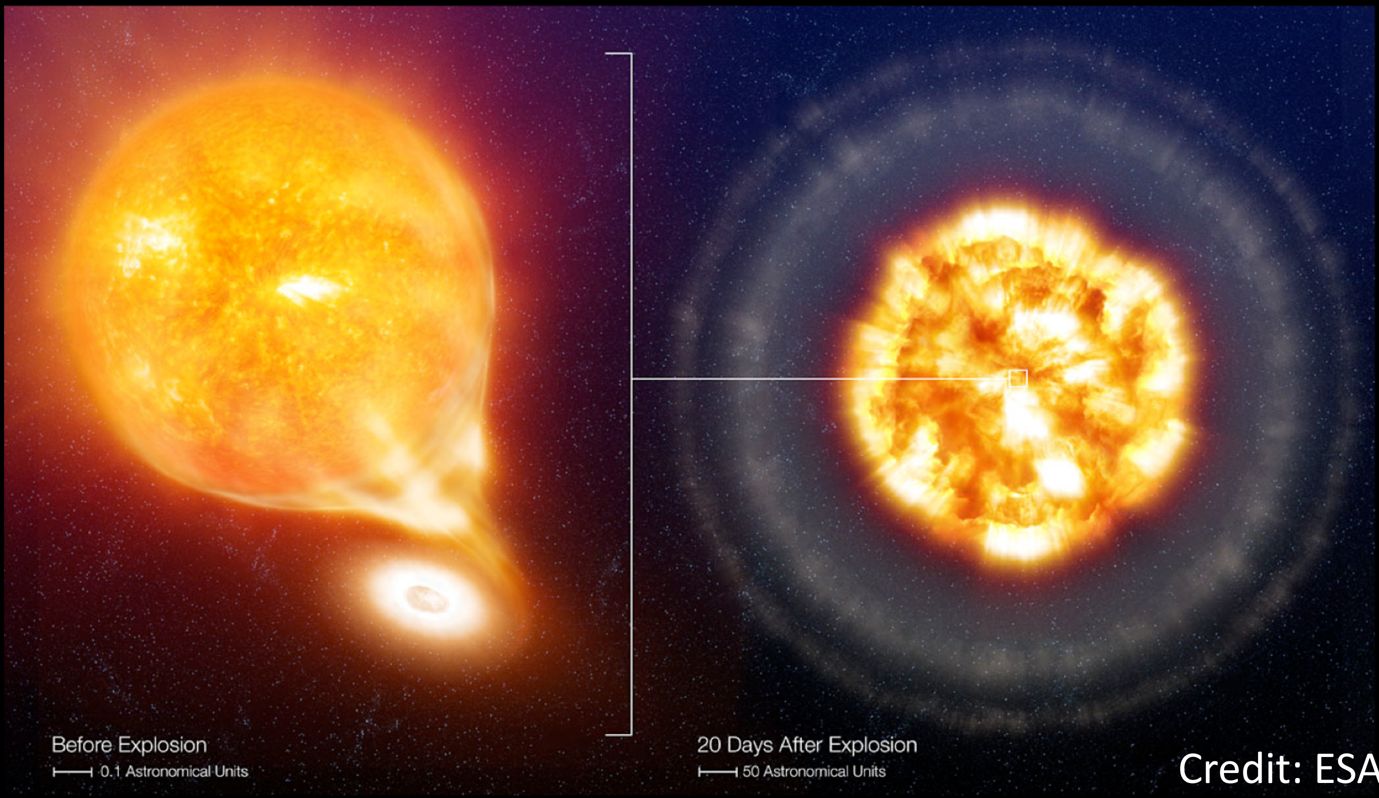
$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Hubble's Law (1929): Evidence for cosmic expansion

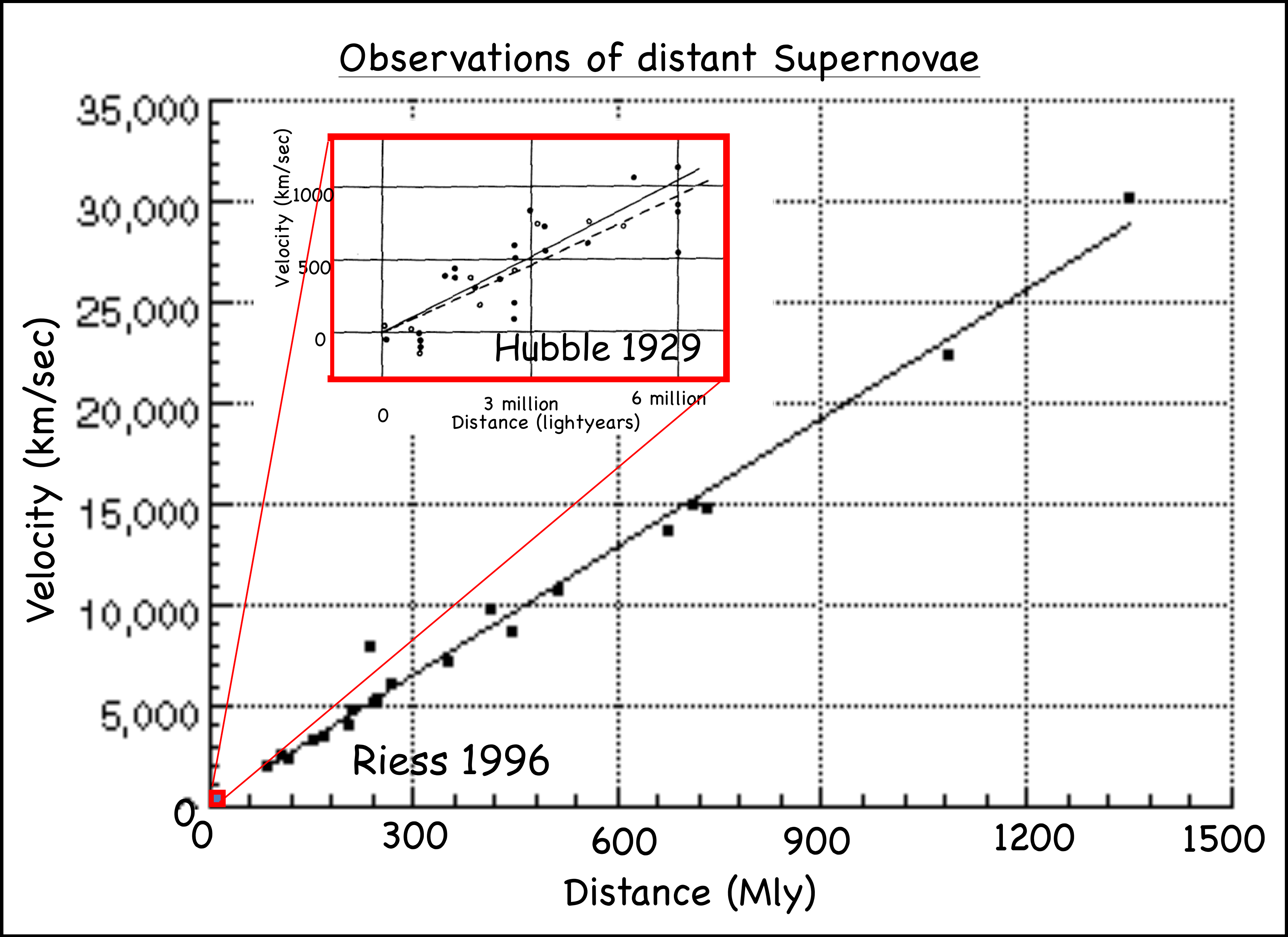


Standard candles: Type 1a Supernovae

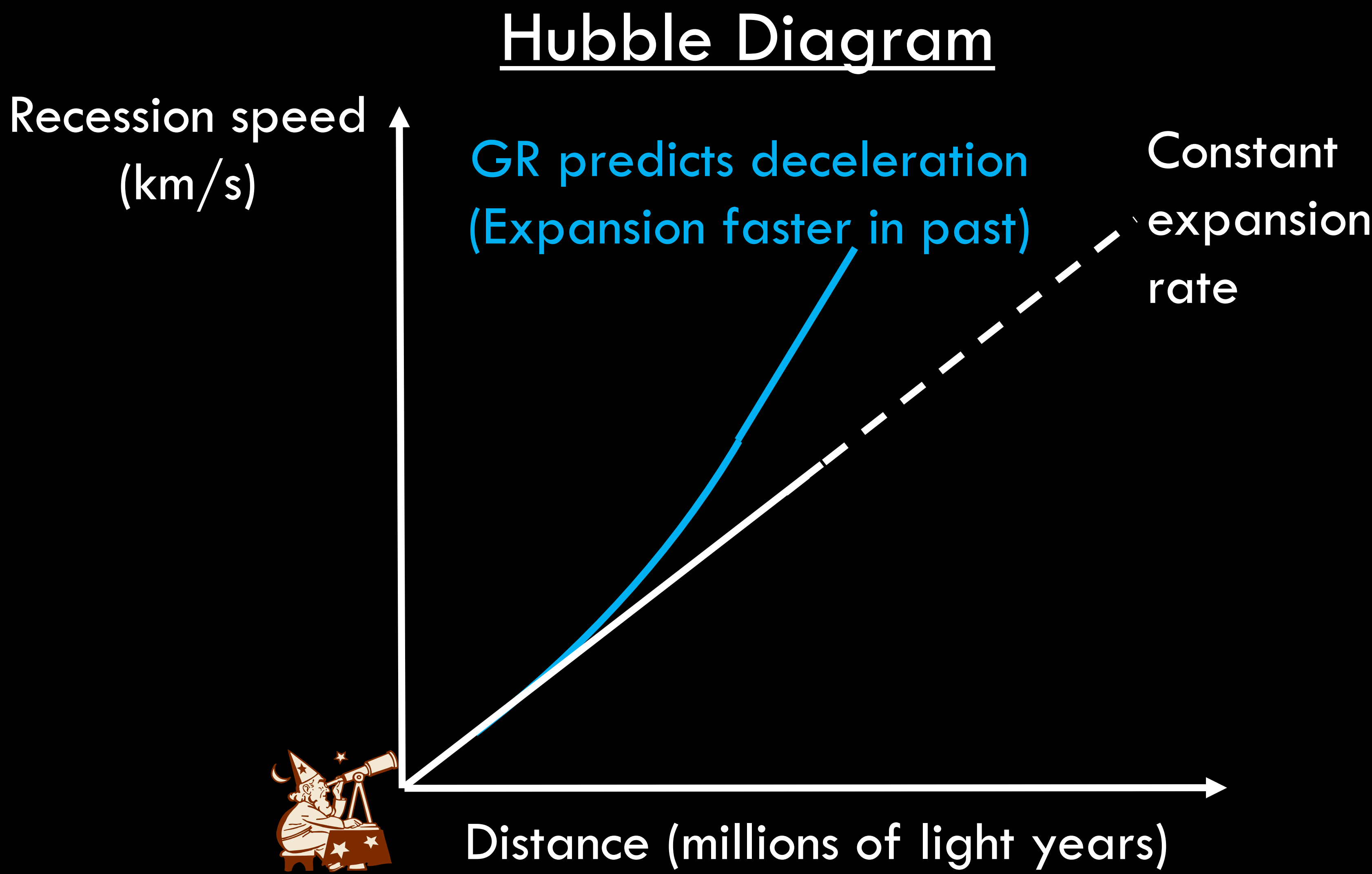
- Dead star accreting from its companion
- Rate of decline in brightness related to peak luminosity
- 5 billion x brighter than Sun (see billions light yrs away)



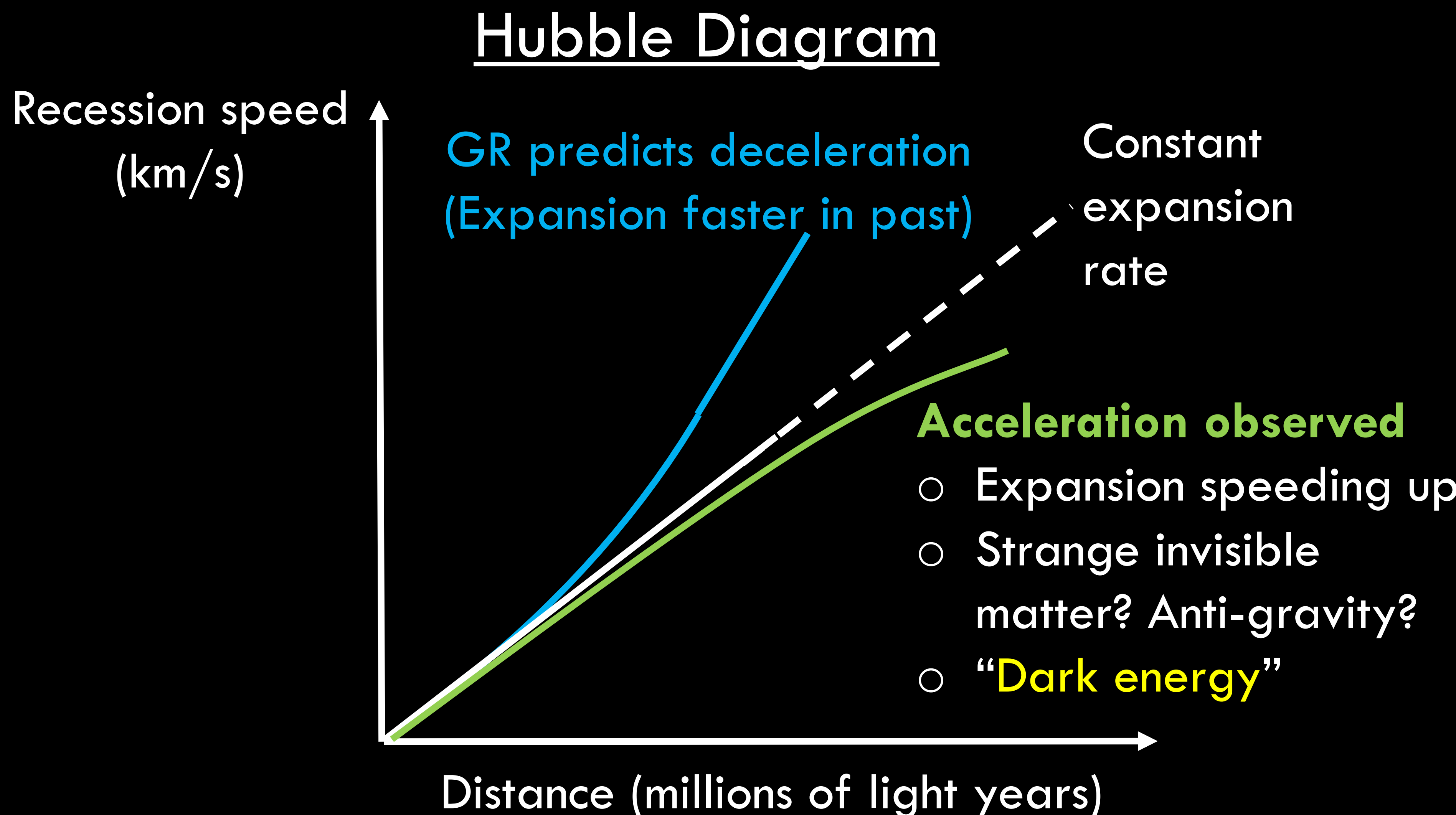
Hubble's law: the modern day version



Interpreting the cosmic expansion history



Interpreting the cosmic expansion history



Get more data, ask more questions…

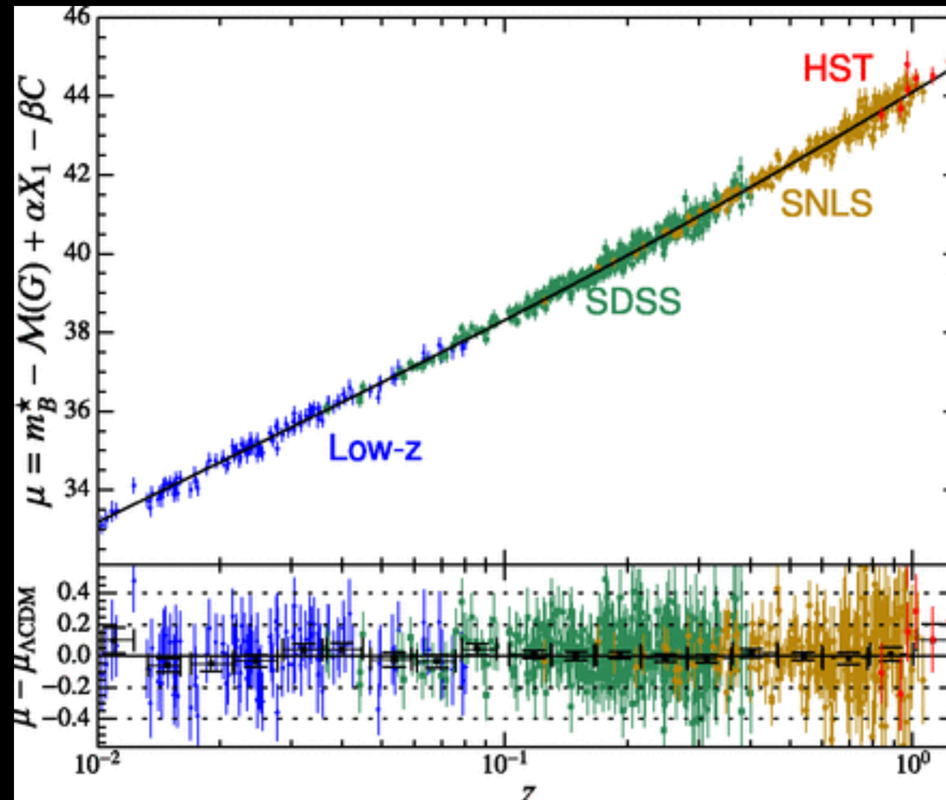
More data: More constraining power

Statistical uncertainties:

Random variations in sample

- Variance ~1/sample size
- Examples for SN1a:
  - Random instrument noise
  - Random variations in SN1a luminosity

Related to distance



Related to Speed

Credit: Betoule et al 2014
Astron Astrophys 568(A22):22–53

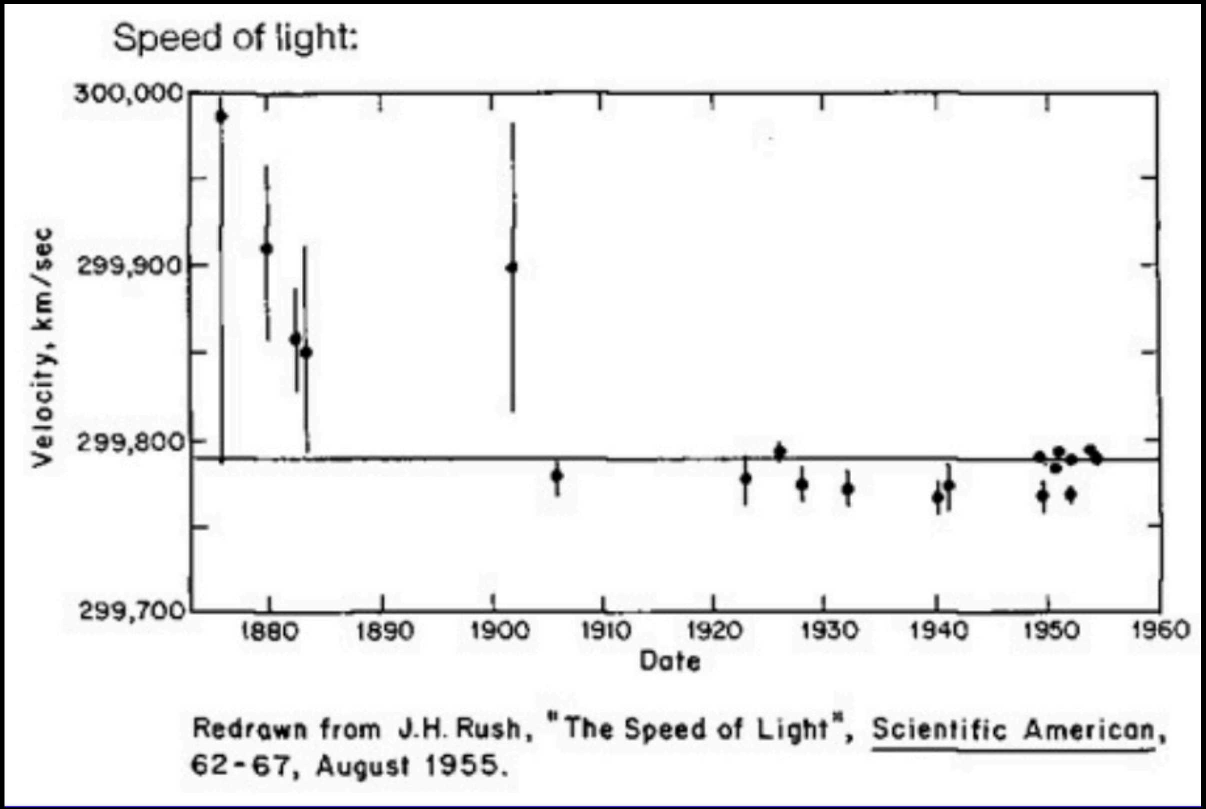
More data: More complexity

Systematic uncertainties: Non-random variations

- Errors persist as increase sample size
- Examples for SN1a:
  - Offsets/miscalibration in instrument response or between surveys
  - Survey selection biases
  - Light extinction by dust in the Milky Way
  - Contamination by misclassified non-SNIa events
- Approach
  - Conduct "null tests": tests that should be consistent with zero, independent of parameters for hypothesis you are testing
  - Model and remove systematic effects, where identified
  - "Marginalize" over "known unknowns" to include them in errors.

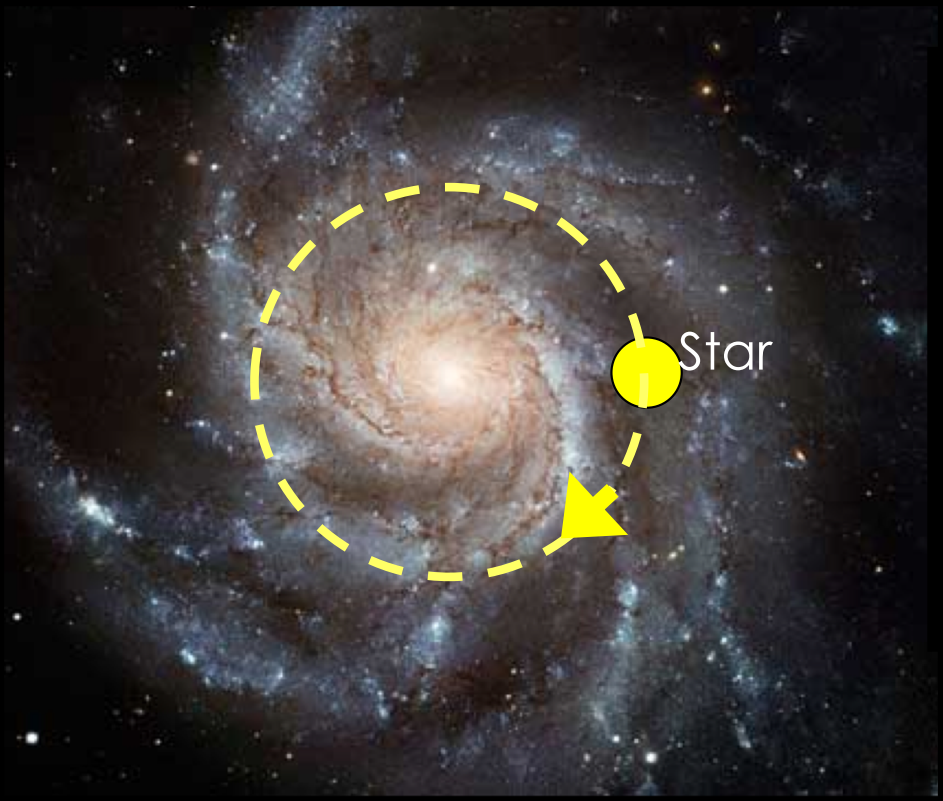
Another peril: Confirmation Bias

Presuming you know the answer when analyzing data.



Avoid by conducting a "blinded analysis" of the data

"Weighing" galaxies using galaxy rotation

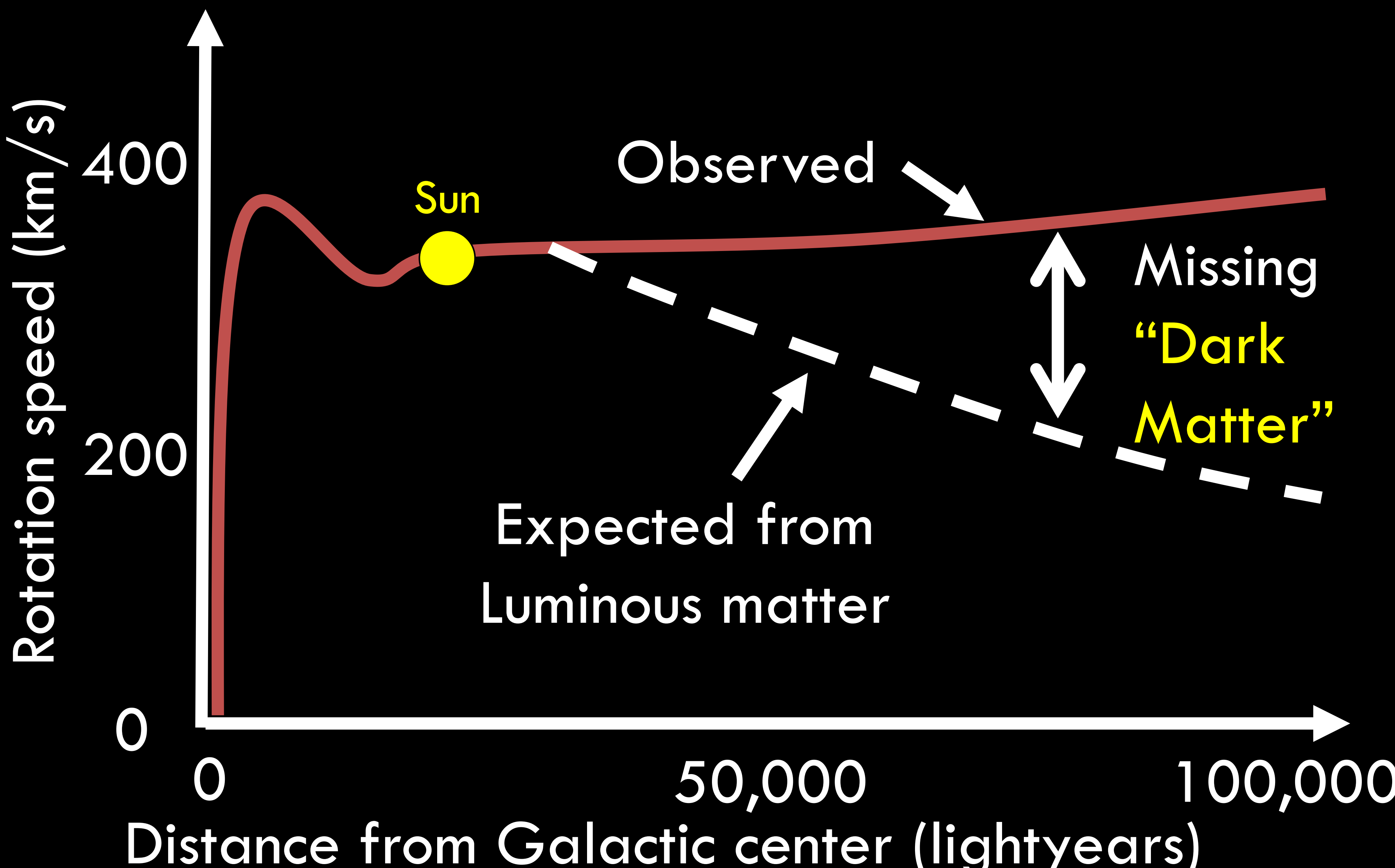


Newton's Law applies to stars in galaxy

$$v^2 \approx \frac{GM}{r}$$

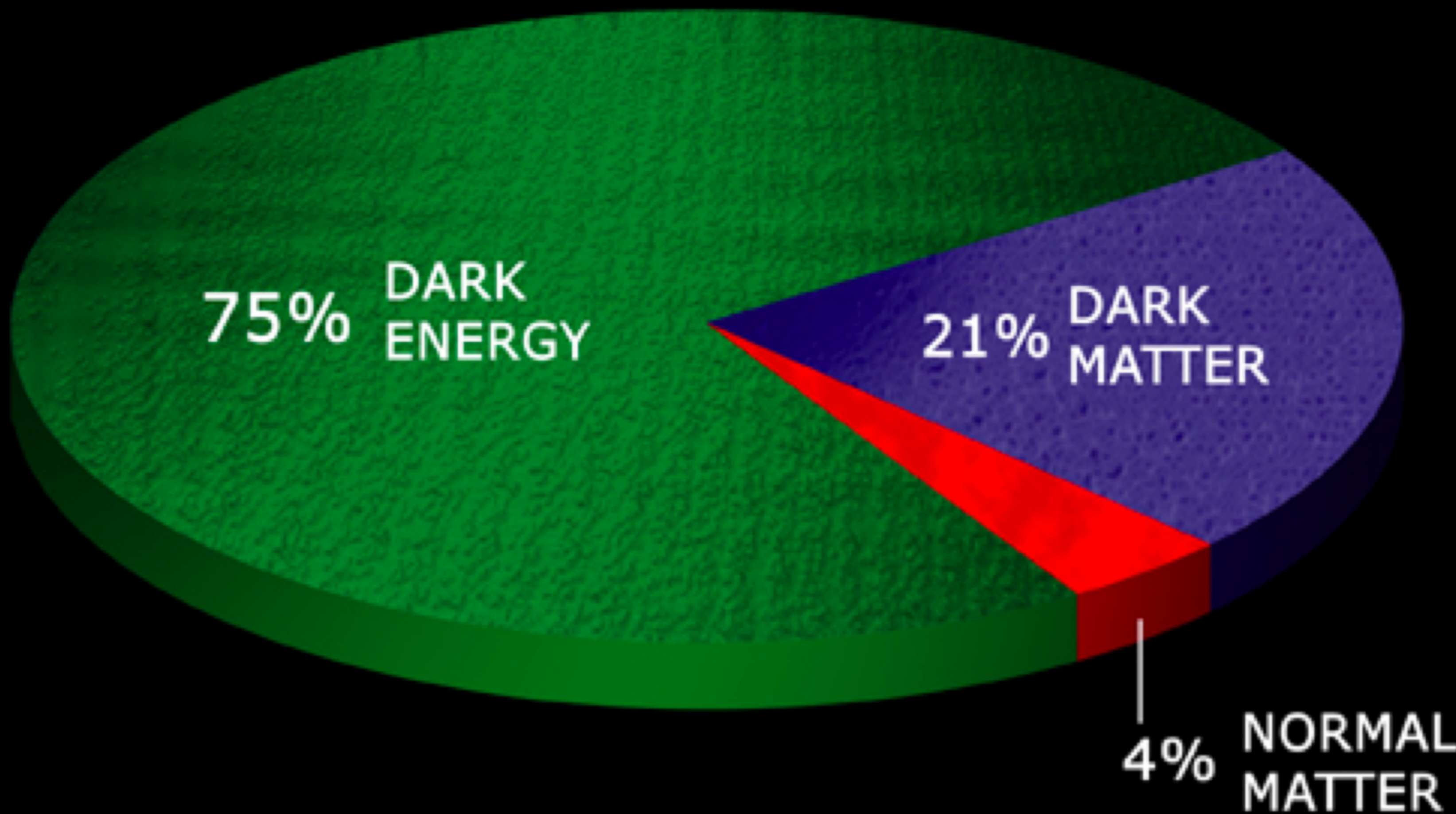
- Newton's constant → G
- Mass of Galaxy within orbit → M
- Star rotation speed → v
- Distance to galaxy center → r

Puzzling observations: Invisible matter?



The cosmic challenge

- 96% of universe's matter is unlike anything on Earth
- And/or we don't understand how gravity works



Large Synoptic Survey Telescope (LSST)

Optical telescope in Chile, "first light" in 2019

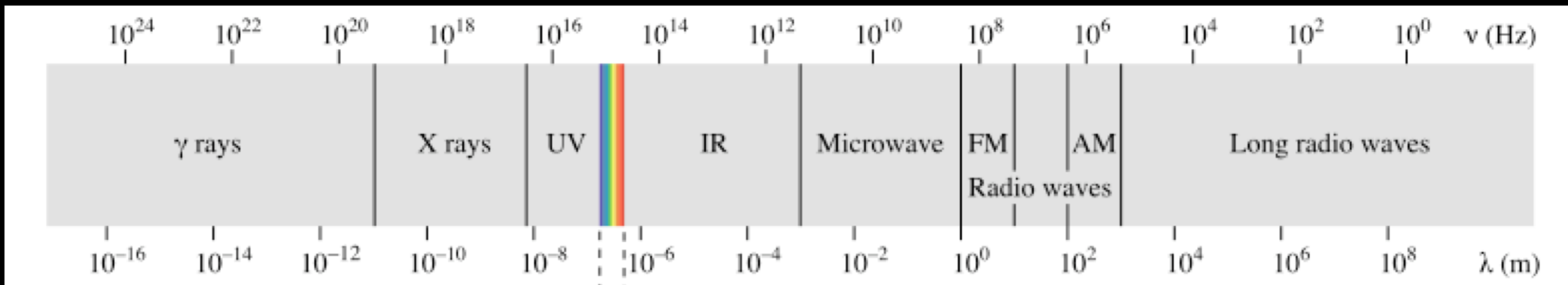
3D cosmic map over a billion lyrs

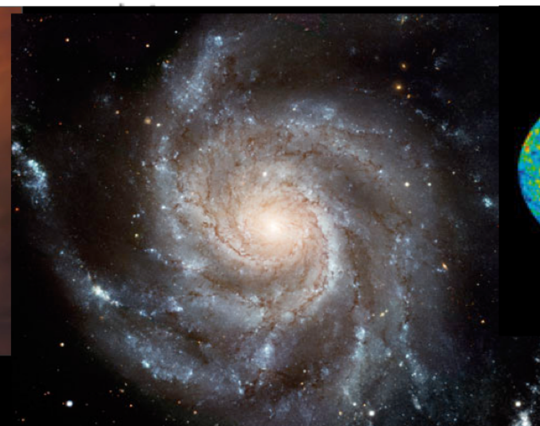
- 10 billion galaxies
- 10 billion stars with redshift
- 1 million supernovae

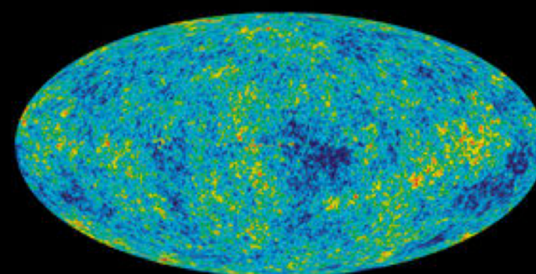
>10-fold improvement in dark energy & dark matter constraints

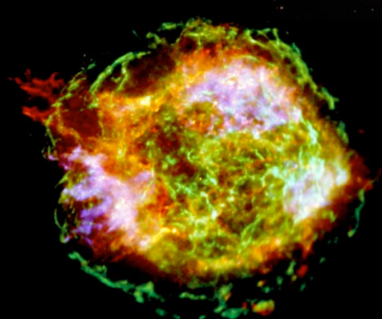
A data challenge both in size and complexity: Petabytes of data

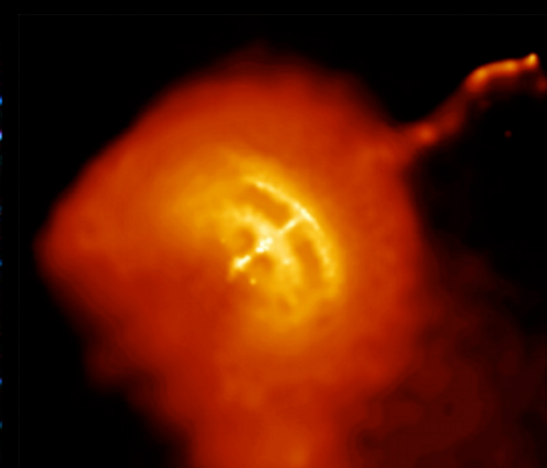
Different wavelengths probe very different cosmic environments



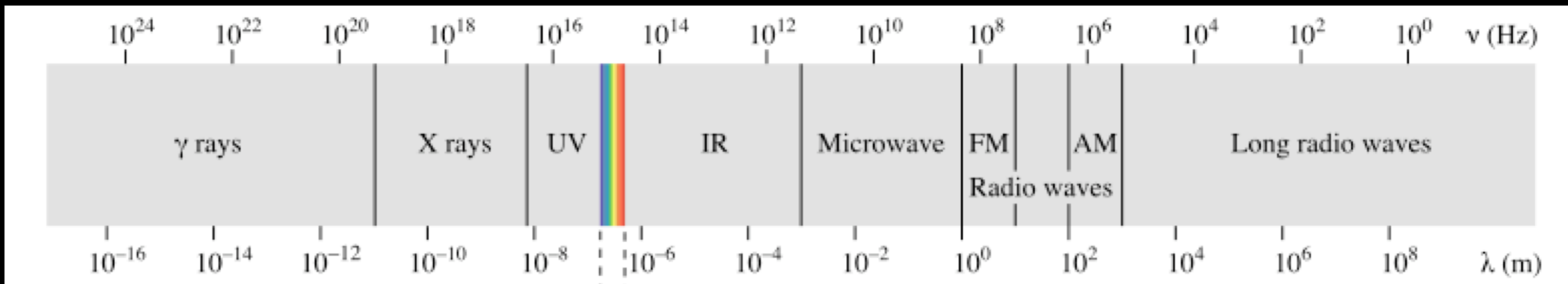


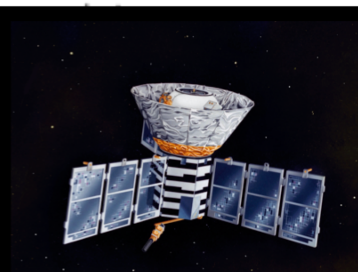




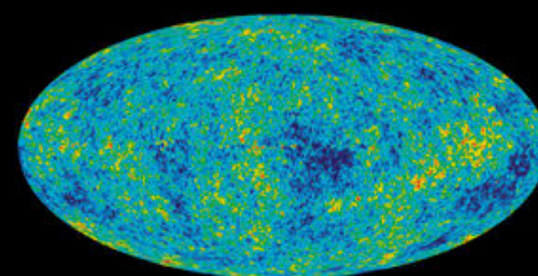


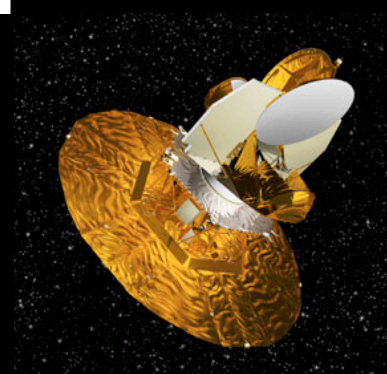
Different wavelengths probe very different cosmic environments





COBE 1989-93

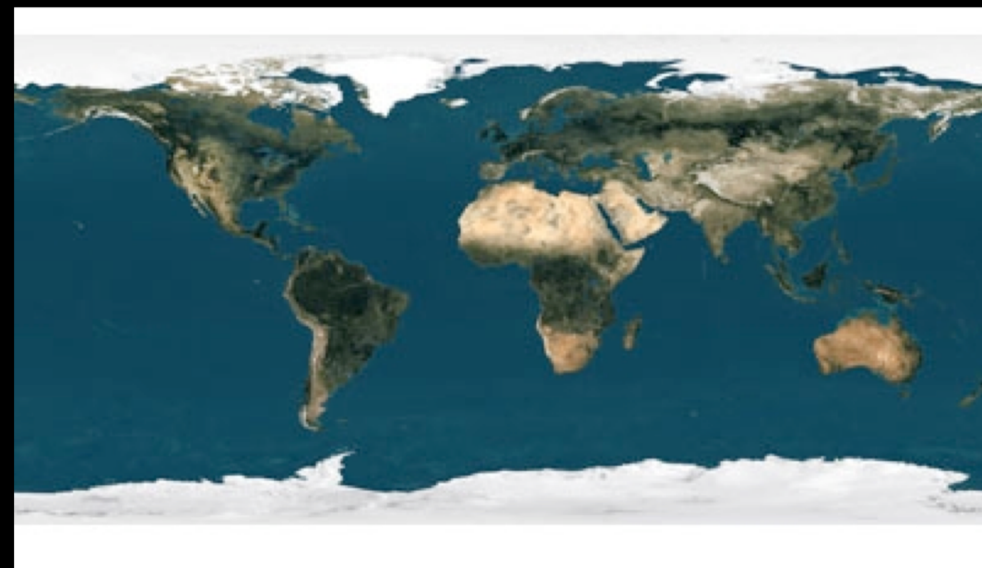


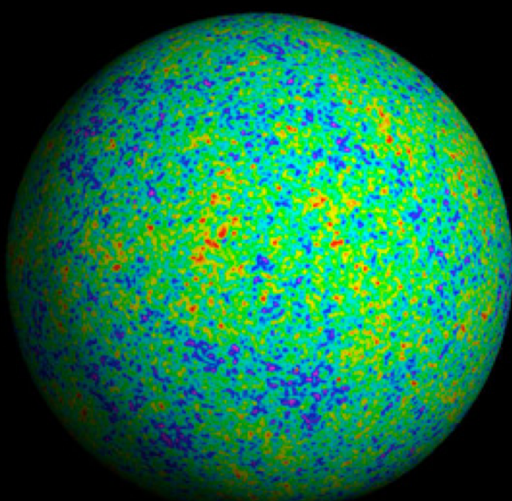


WMAP 2001–10

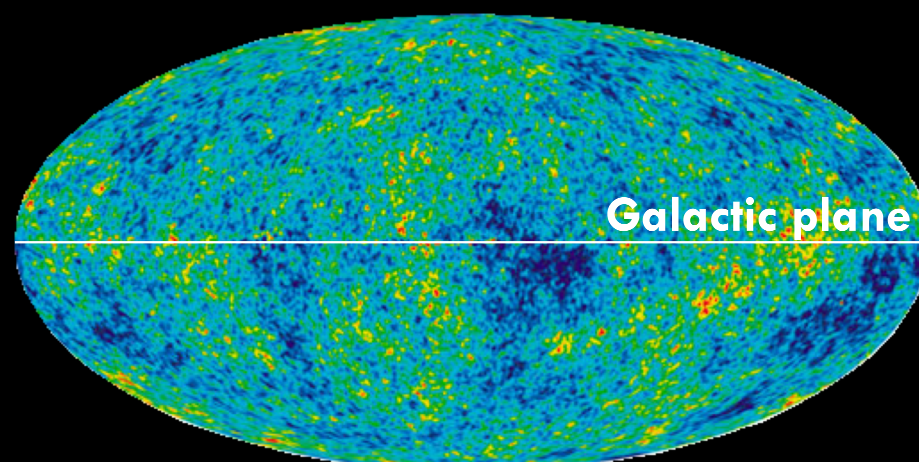
Planck 2009-13

Looking at the microwave sky map





Tegmark

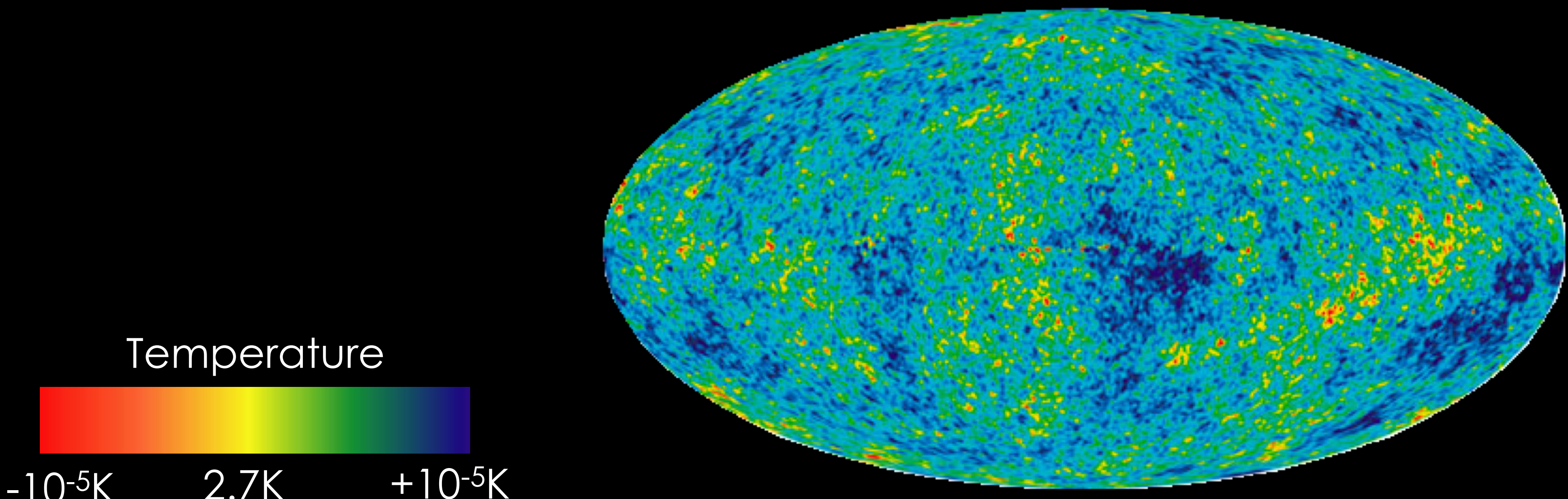


The Cosmic Microwave Background (CMB)

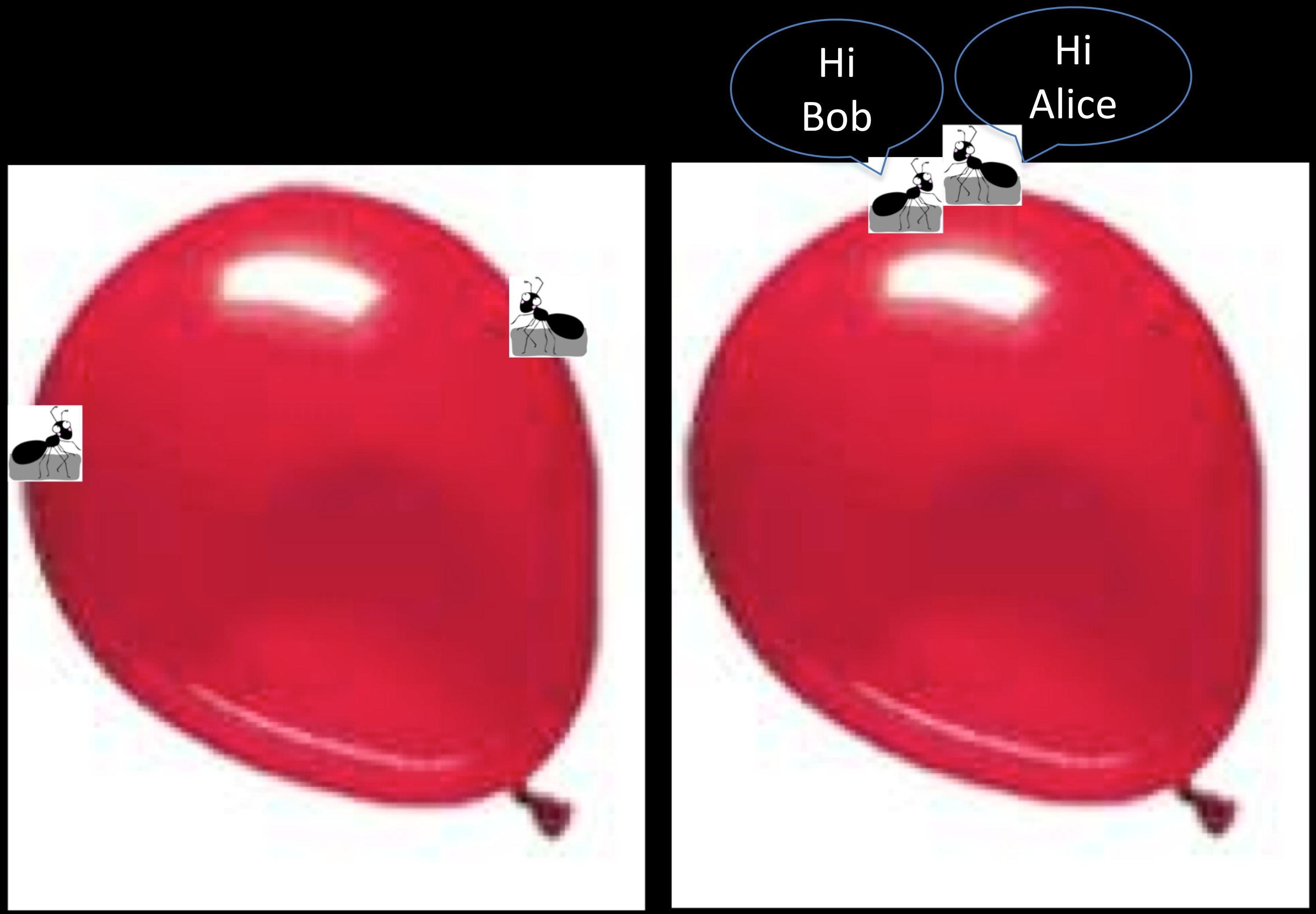
A fossil remnant, light emitted 400,000 yrs after the Big Bang

The light has the same temperature across the whole sky.

How can this be?? The "Horizon Problem".



An ant on a balloon analogy

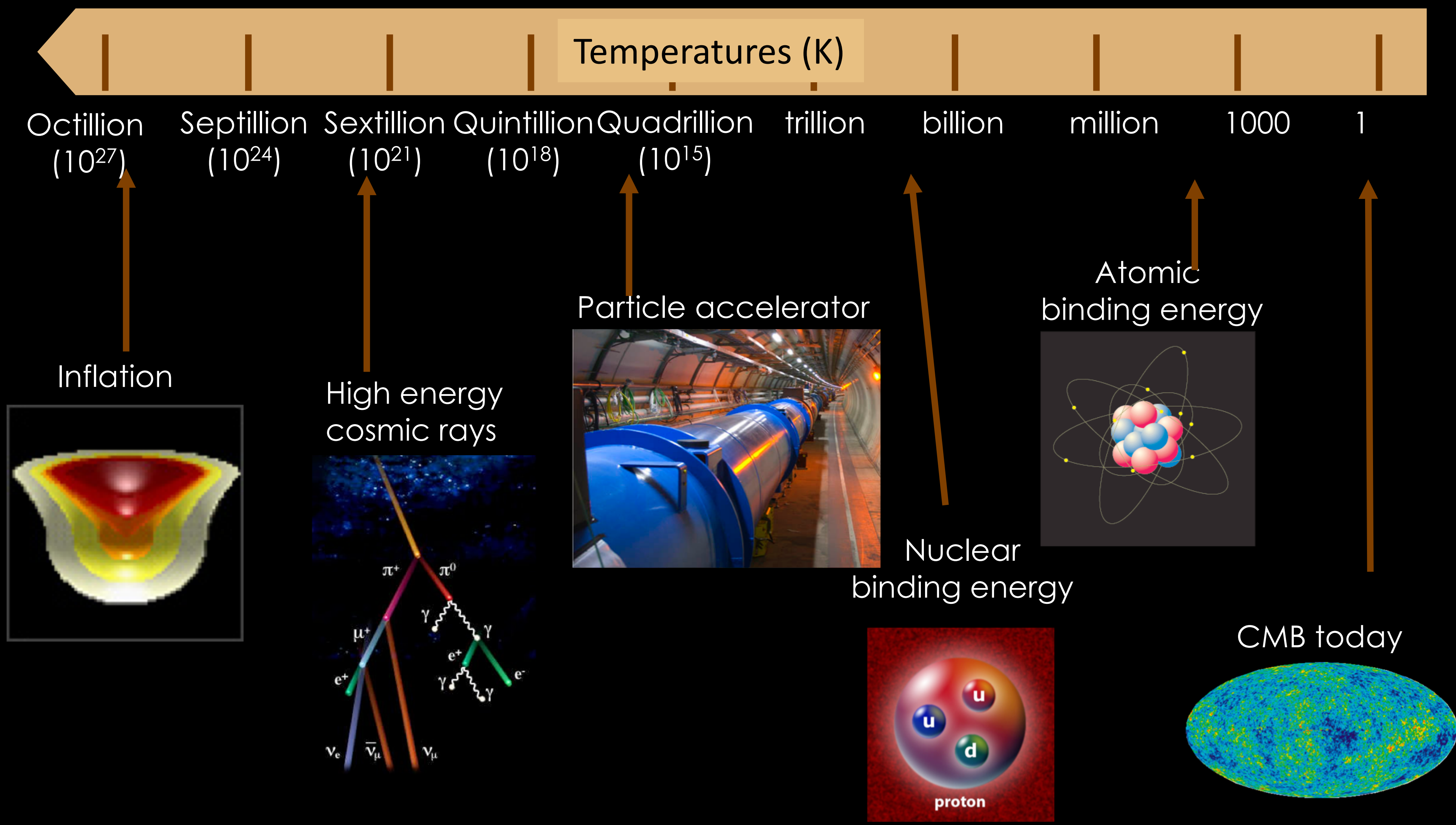


An ant on a balloon analogy

CMB data motivated new cosmological model:
Cosmic Inflation – superluminal expansion!!

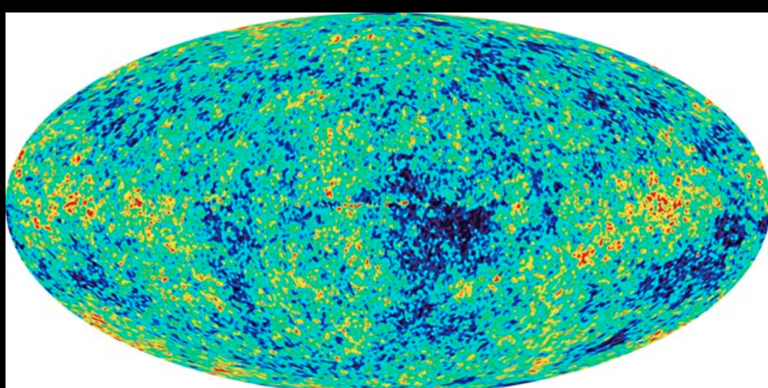
The Universe -the ultimate particle accelerator!

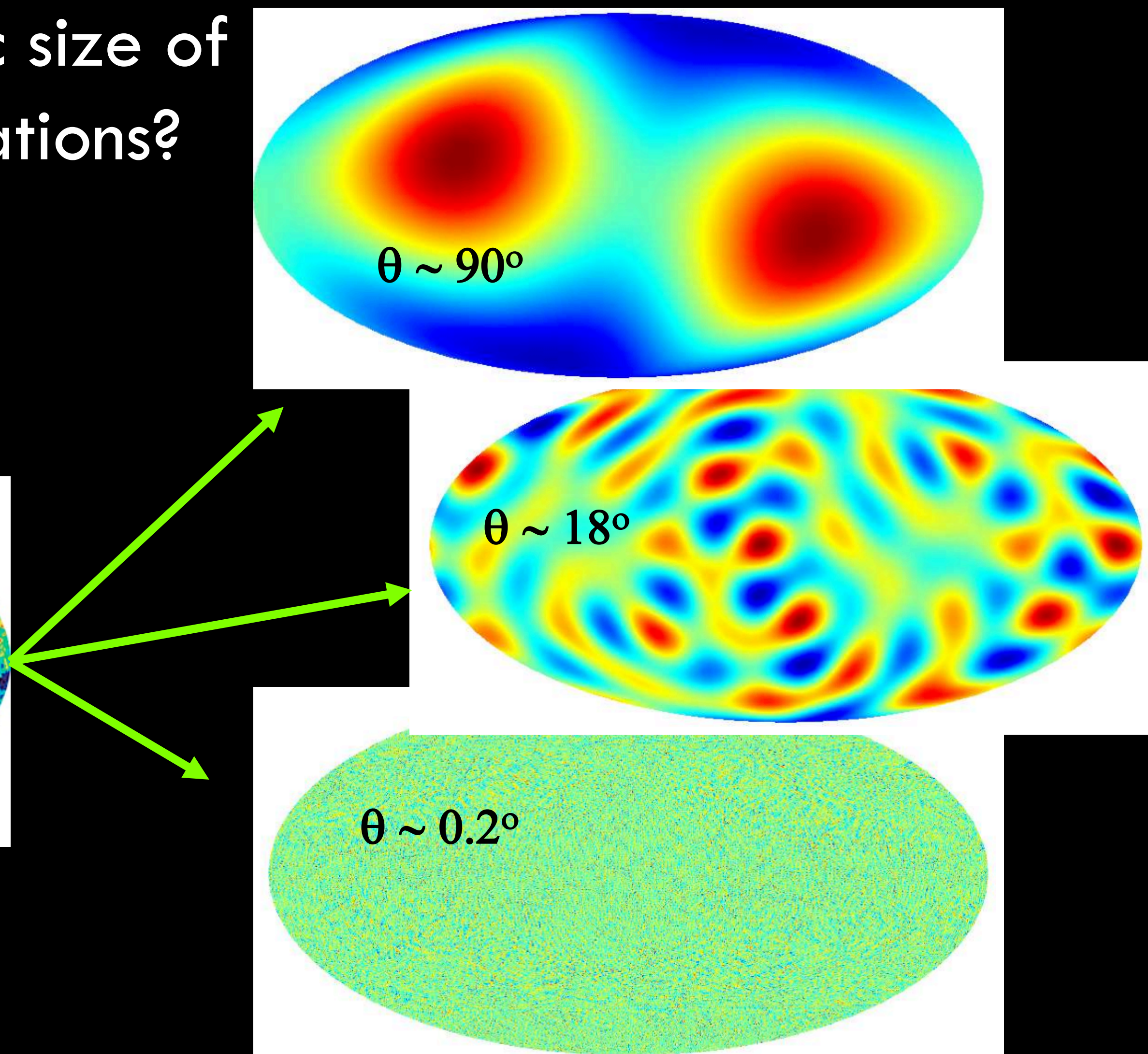
When the universe was smaller, it was hotter and denser



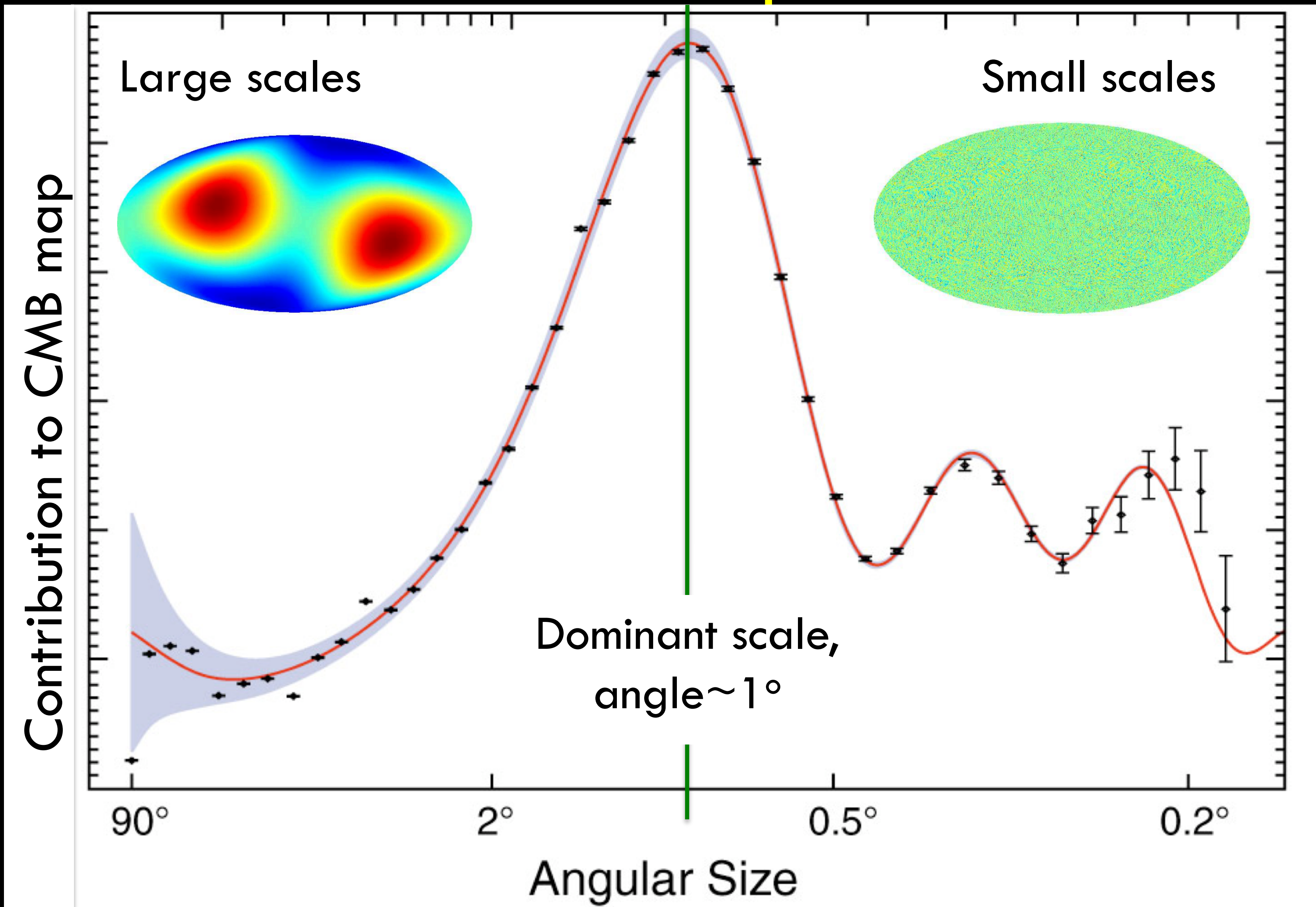
What's with the spots?

Is there a characteristic size of the temperature fluctuations?



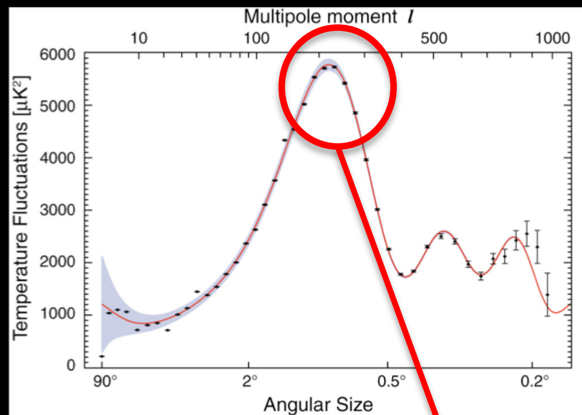


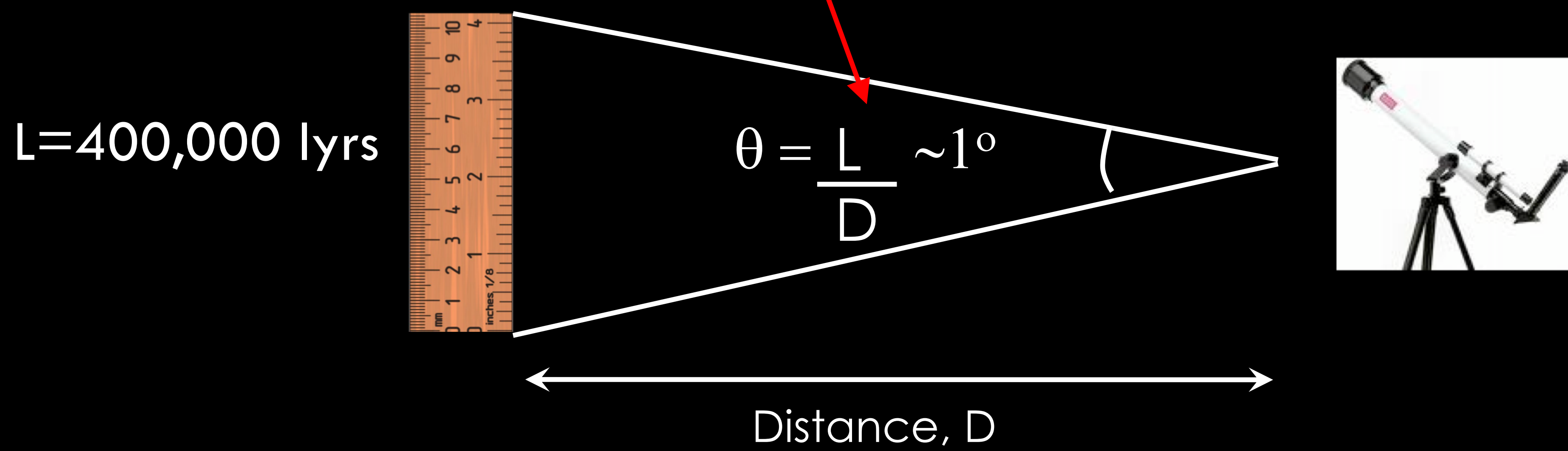
What's with the spots?
CMB "Power Spectrum"



What's with the spots?
Characteristic size = Standard Ruler

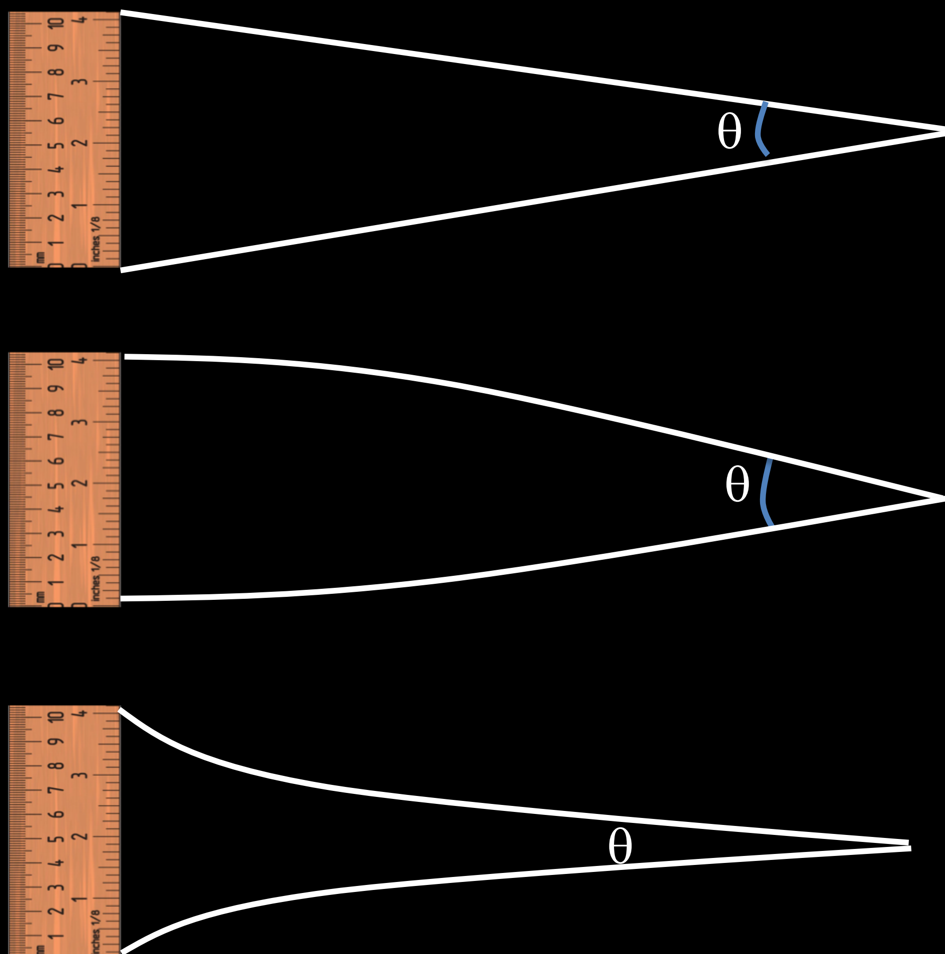
- Yay! A distance (to when CMB was formed).

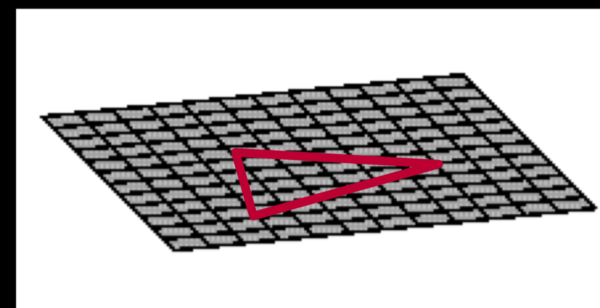


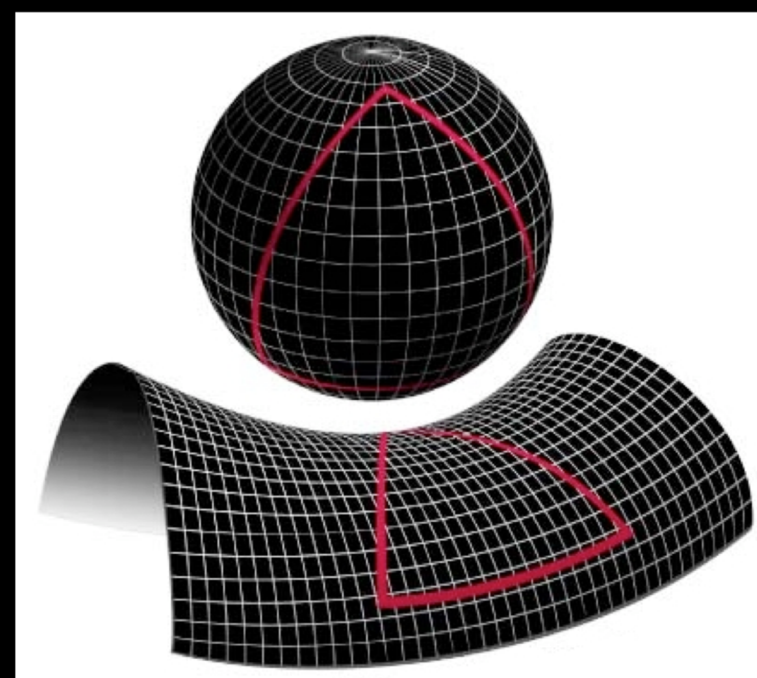


What's with the spots?
Tell us if space is curved

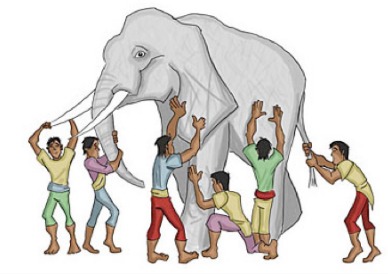
- CMB tells us universe is essentially flat







Parting thoughts



- Astrophysical data providing insights into the laws of nature at scales and densities inaccessible on earth
- Creating profound challenges for our theoretical understanding.
- Upcoming surveys will provide massive data sets from which we want to extract miniscule signals from competing noise.
- They will play a revolutionary role in answering key outstanding questions about the cosmos.
- This an amazing time to work in astrophysics!