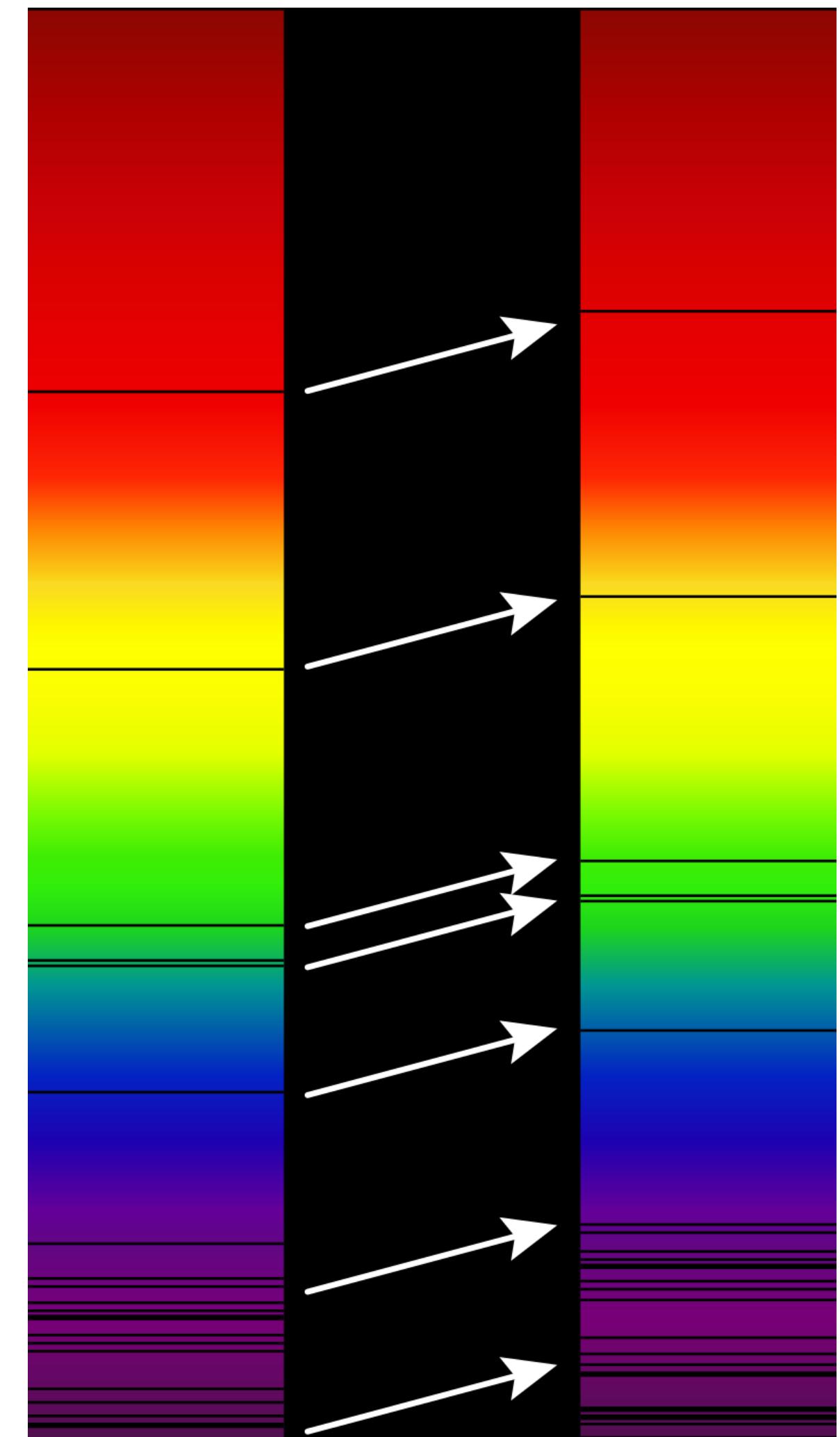

Hubble Constant

25.05.27

Redshift

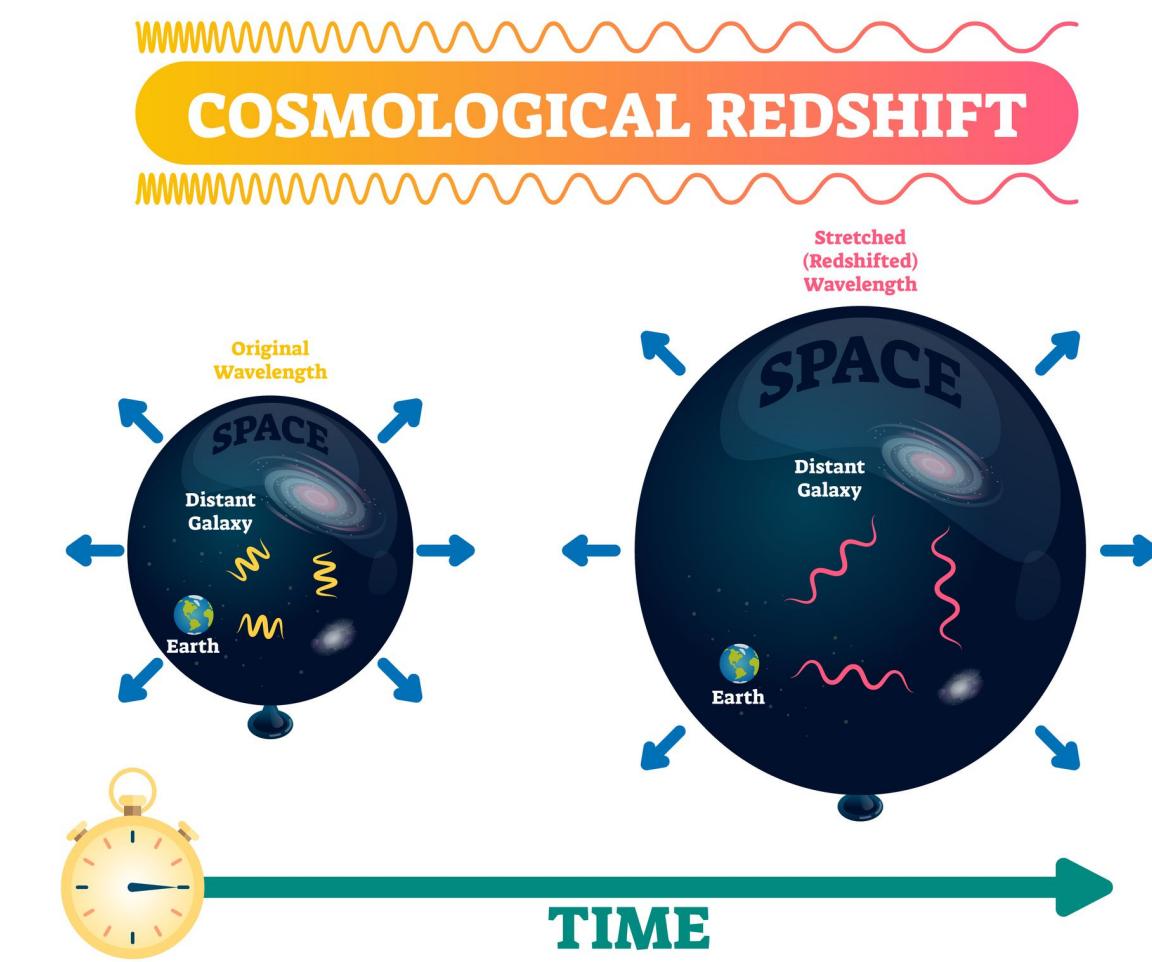
- Spectroscopy can give us redshift
- We can measure radial velocity with redshift
- $v = cz$

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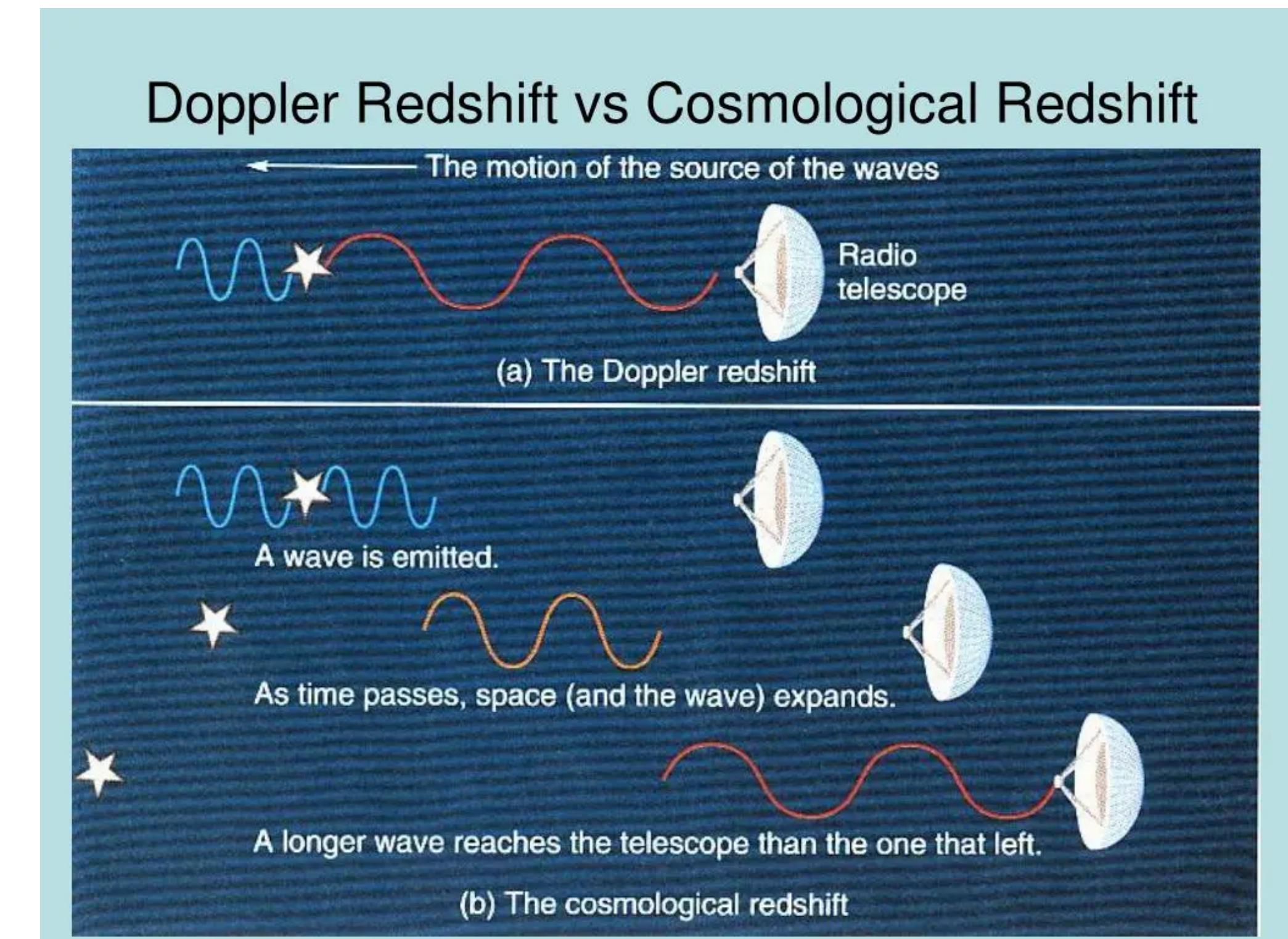
Cosmological redshift

- Cosmological redshift: resulted from cosmic expansion
 - Is cosmological redshift caused by doppler shift?



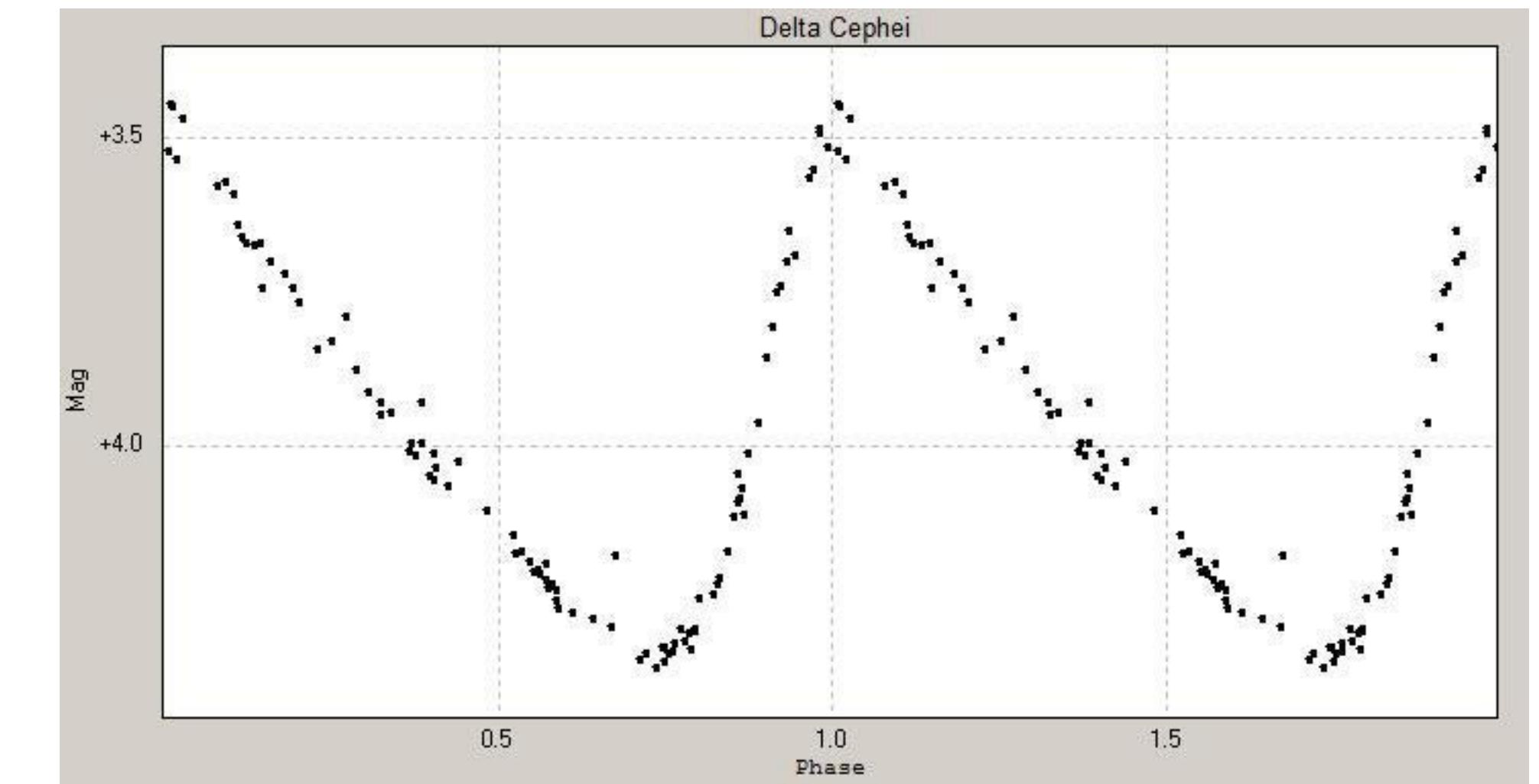
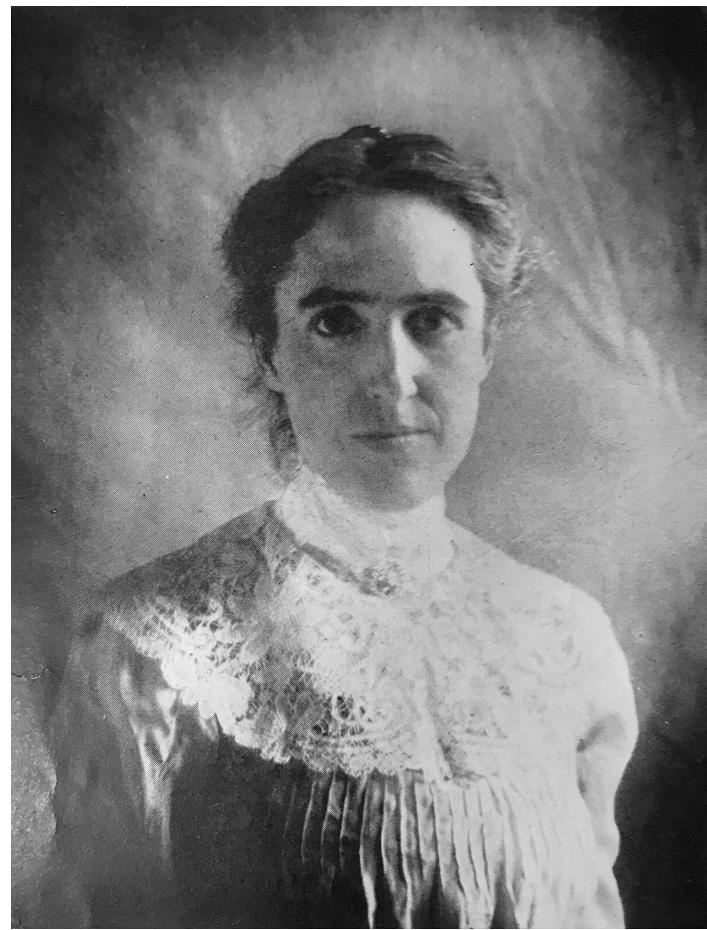
Cosmological redshift

- Cosmological redshift: resulted from cosmic expansion
 - Is cosmological redshift caused by doppler shift?
 - **No**



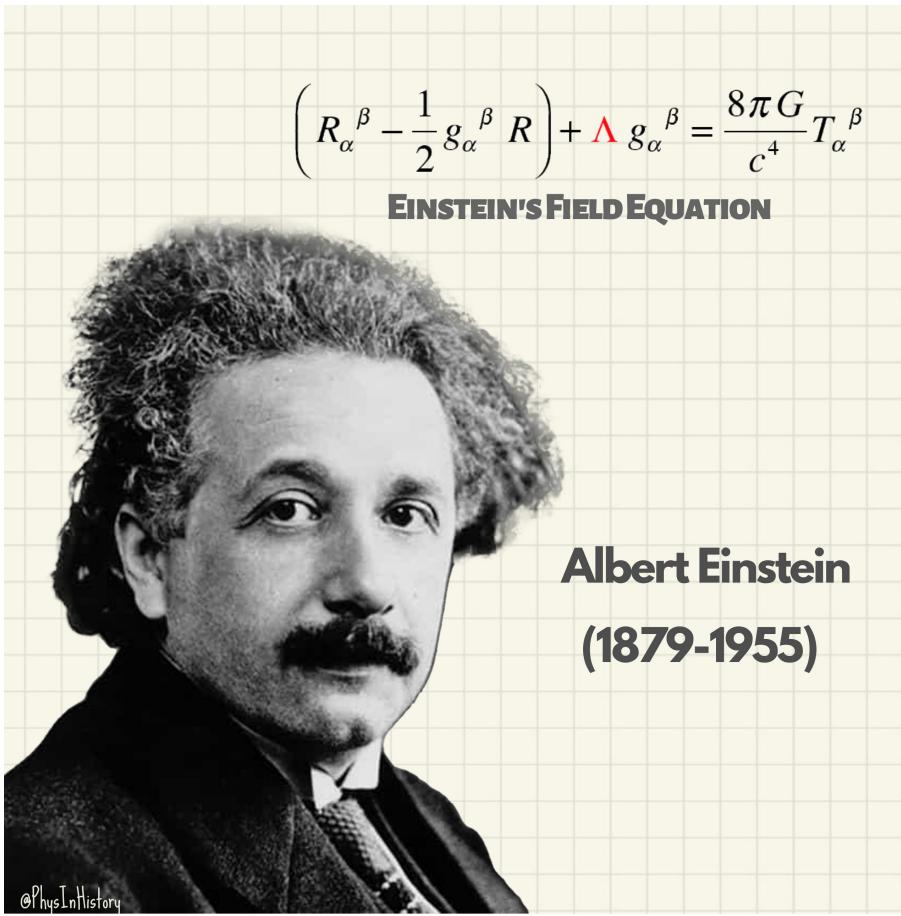
Distance

- Hubble measured distance with Cepheid variables in extragalactic galaxies.
- Henrietta Swan Leavitt found luminosity - period relation of Cepheid variables.



Hubble-Lemaître Law

- Question from General Relativity theory : Our universe is static or not?
 - Einstein claimed the Cosmological constant (Λ) to ‘make’ universe static
 - Lemaître claimed ‘expanding’ universe, known as ‘Big Bang theory’



Hubble-Lemaître Law

- Edwin Hubble, measured radial velocity and distance of some ‘Extragalactic galaxies’
- Hubble compares velocity and distance
 - He constructed linear regression
- The Hubble-Lemaître law: $v = H_0 d$
 - H_0 : Hubble constant

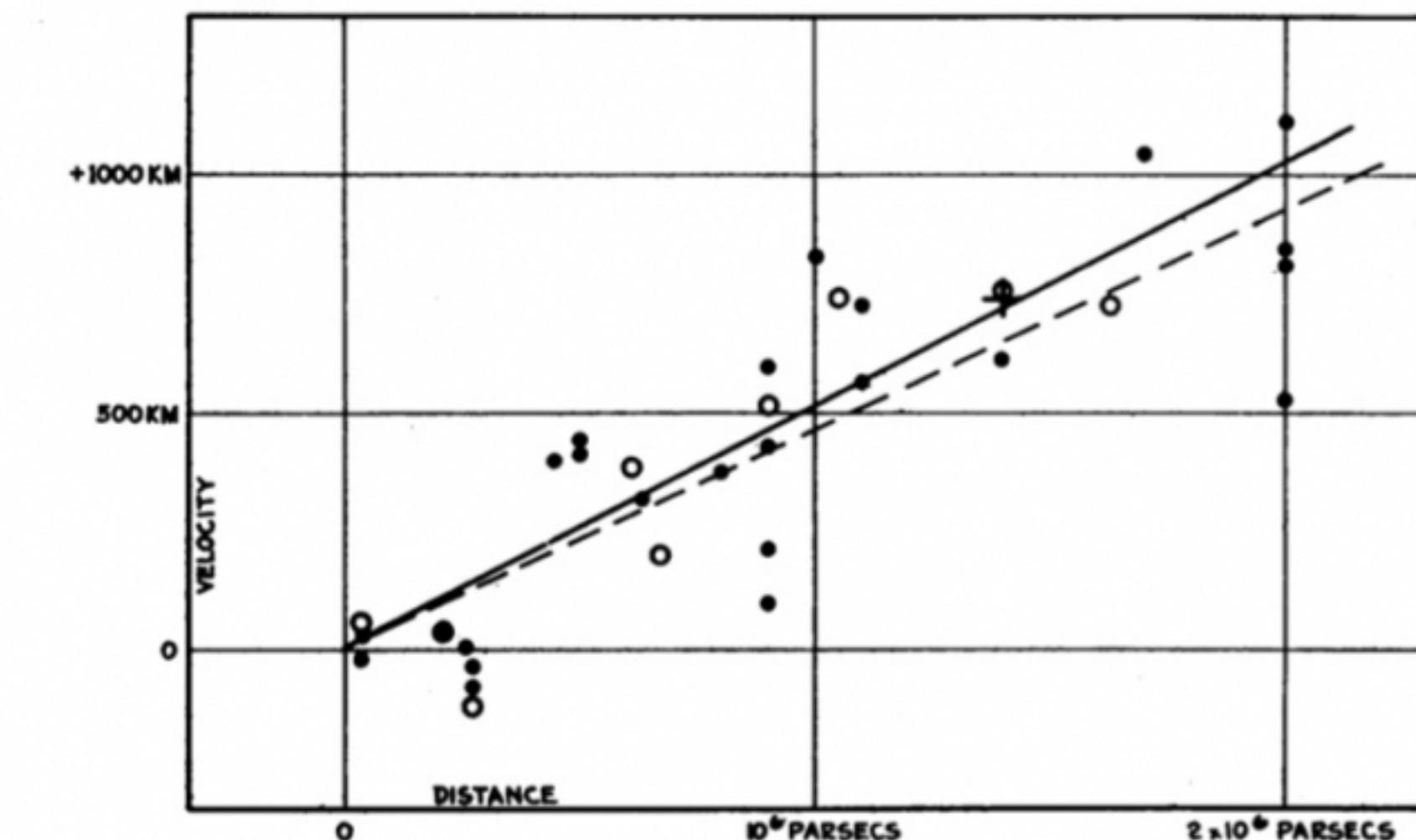


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

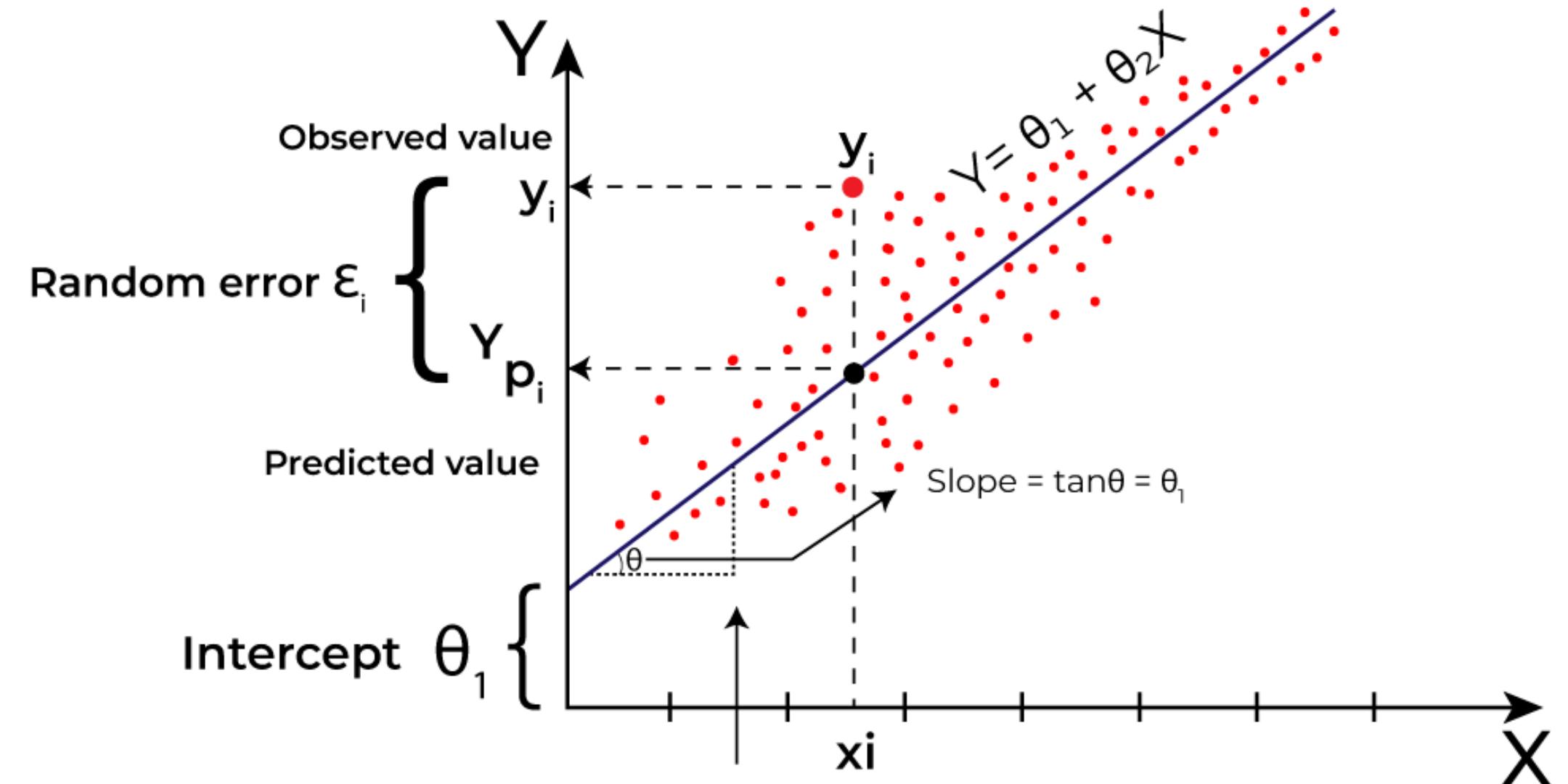


Linear Regression

- The Hubble-Lemaitre law: $v = H_0 d$

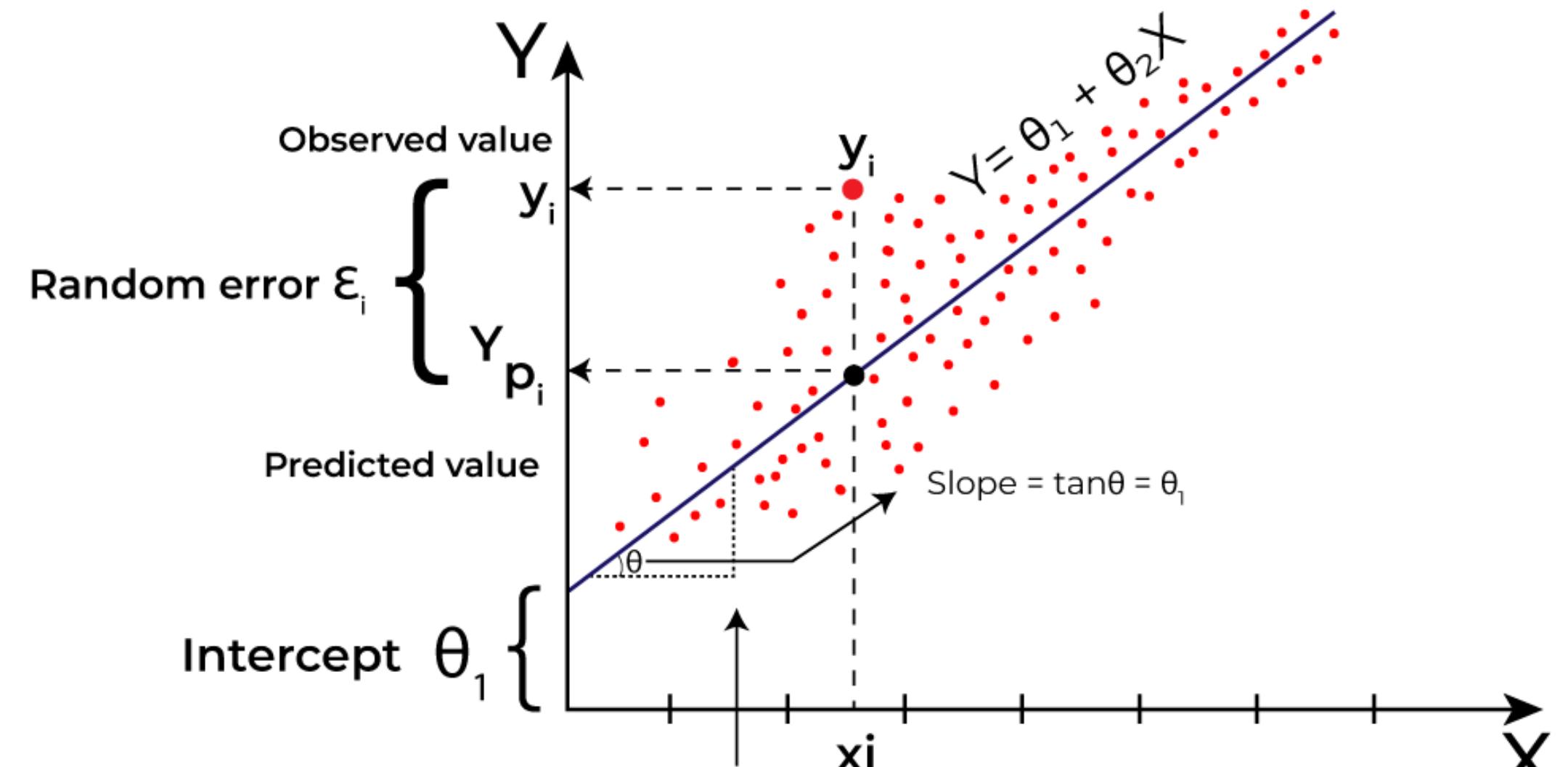
- H_0 : Hubble constant

- How can we estimate Hubble constant from distance - velocity data with random error?
 - We need to apply linear regression



Linear Regression

- $Y = \theta_1 + \theta_2 X$
- We need to know the parameters (θ_1, θ_2)
 - θ_1 : Intercept (Y-절편)
 - θ_2 : slope (기울기)
- Data contain random error -> The difference between predicted value and observed value
 - Residual for ith data point: $Y_i - \bar{Y}_i$ (Y_i : Observed value, \bar{Y}_i : Predicted value)



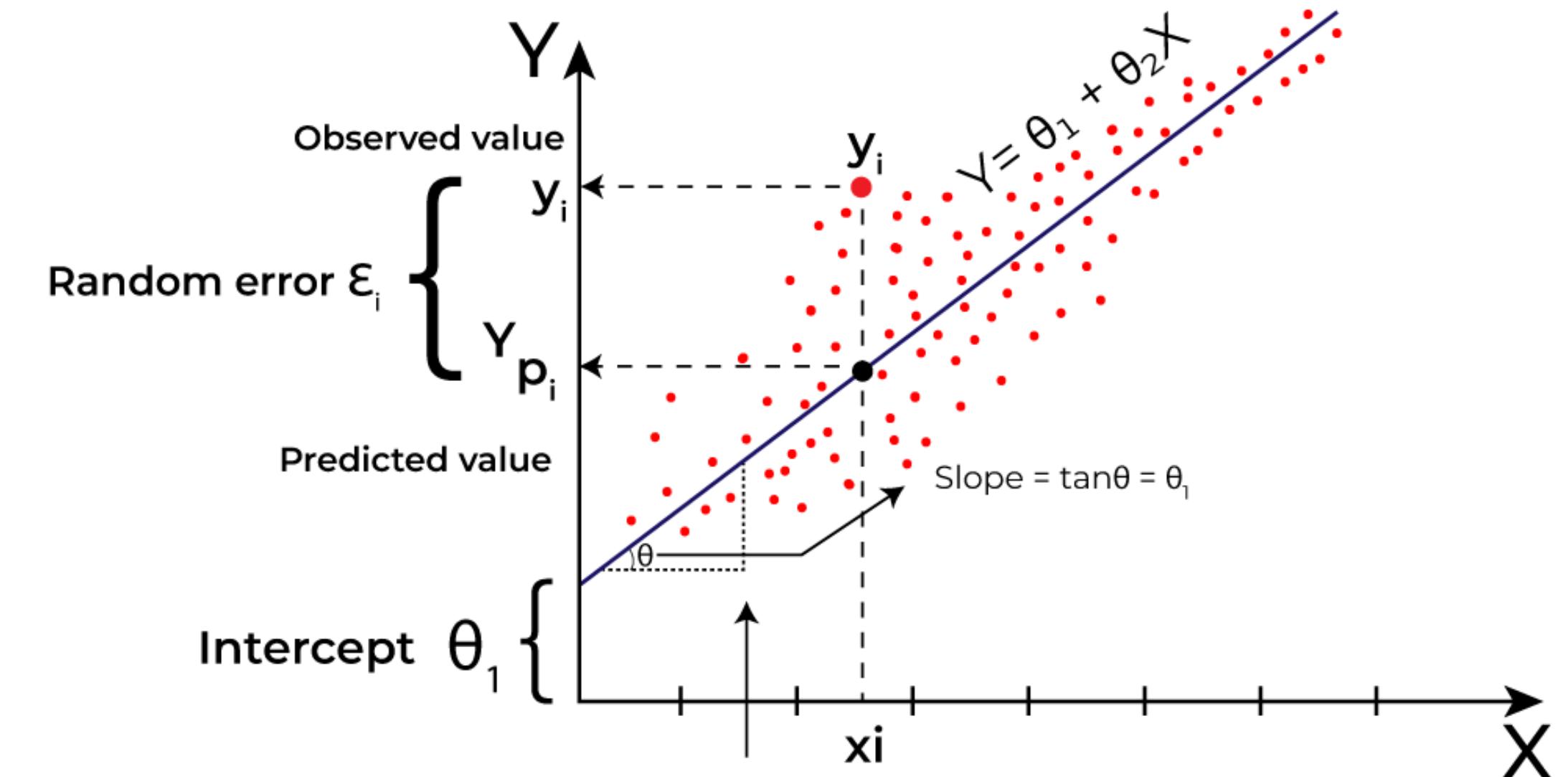
Linear Regression

- We should **minimize** the error

- Least Square Method: $Rss = \frac{1}{n} \sum_{i=1}^n (Y_i - \bar{Y}_i)^2$

- $\frac{\partial Rss}{\partial \theta_2} = \frac{2}{n} \sum_{i=1}^n (Y_i - \bar{Y}_i) \frac{\partial(-\bar{Y}_i)}{\partial \theta_2} = \frac{2}{n} \sum_{i=1}^n (Y_i - \bar{Y}_i)(-X_i) = 0 \rightarrow \theta_1 n + \theta_2 \sum_{i=1}^n X_i = \sum_{i=1}^n Y_i$

- $\frac{\partial Rss}{\partial \theta_1} = \frac{2}{n} \sum_{i=1}^n (Y_i - \bar{Y}_i) \frac{\partial(-\bar{Y}_i)}{\partial \theta_1} = \frac{2}{n} \sum_{i=1}^n (Y_i - \bar{Y}_i)(-1) = 0 \rightarrow \theta_1 \sum_{i=1}^n X_i + \theta_2 \sum_{i=1}^n X_i^2 = \sum_{i=1}^n X_i Y_i$

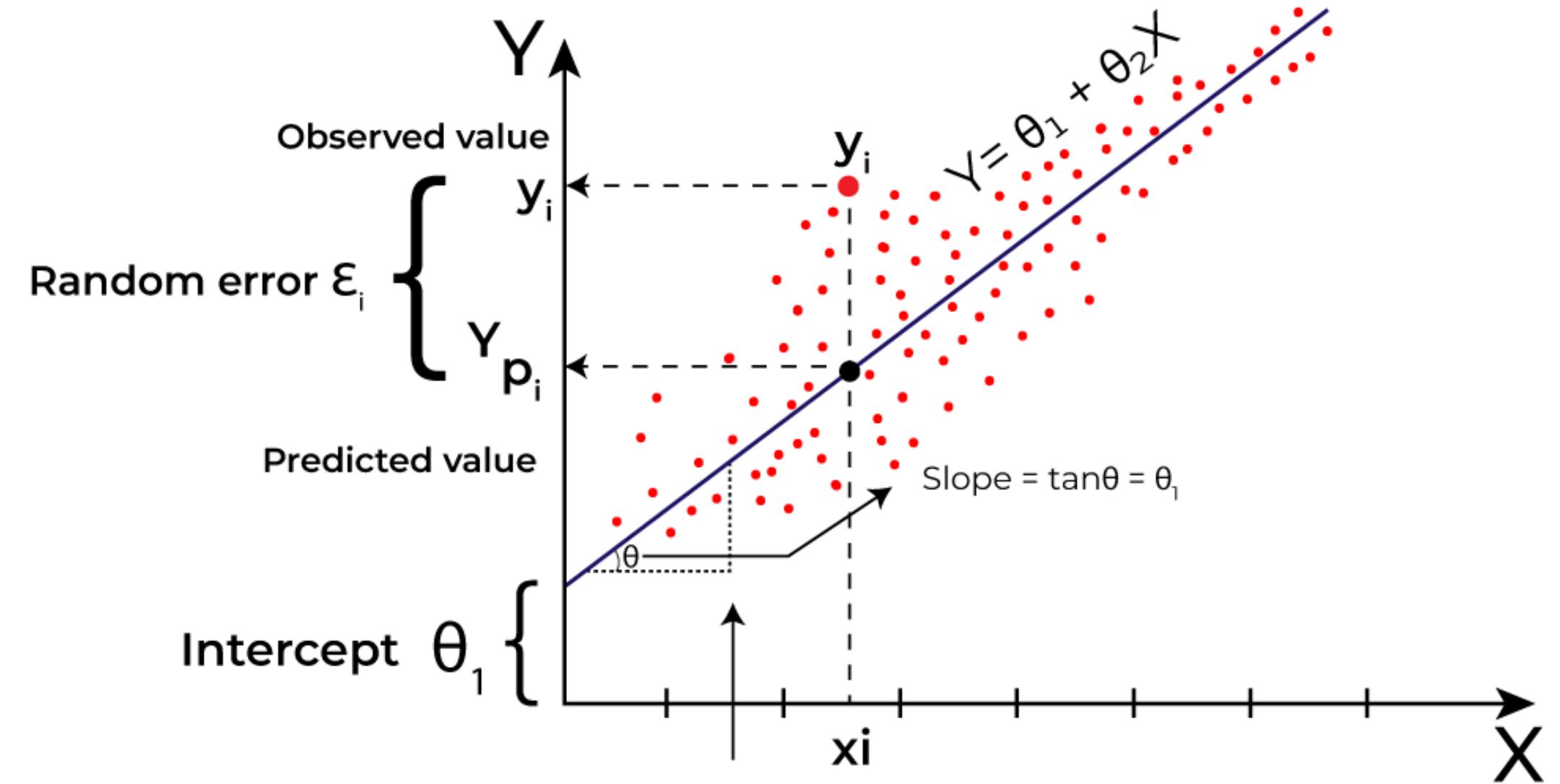


Linear Regression

$$\theta_1 n + \theta_2 \sum_{i=1}^n X_i = \sum_{i=1}^n Y_i$$

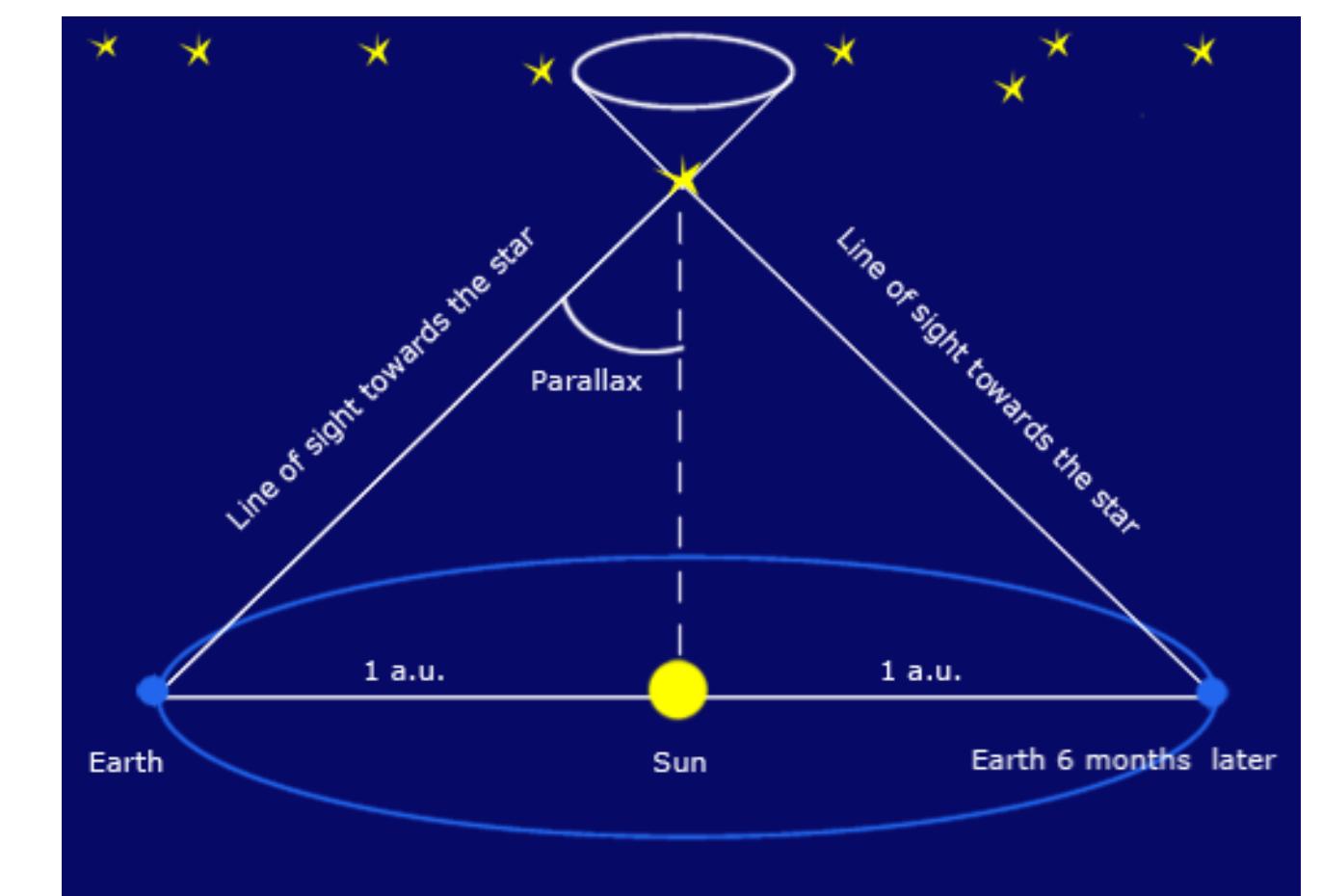
$$\theta_1 \sum_{i=1}^n X_i + \theta_2 \sum_{i=1}^n X_i^2 = \sum_{i=1}^n X_i Y_i$$

$$\begin{aligned}\theta_2 &= \frac{\sum_{i=1}^n X_i Y_i - \sum_{i=1}^n X_i \sum_{i=1}^n Y_i / n}{\sum_{i=1}^n X_i^2 - (\sum_{i=1}^n X_i)^2 / n} = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^n (X_i - \bar{X})^2} \\ \theta_1 &= \bar{Y} - \theta_2 \bar{X}\end{aligned}$$



Distance ladder

- How did Henrietta Swan Leavitt find luminosity - period relation of Cepheid variables?
 - She used actual distance to Cepheid variables in Magellanic Cloud
 - We know distance to Magellanic Cloud with 'stellar parallax'
- We know luminosity - period relation of Cepheid by stellar parallax
 - Can we know other distance measuring method by Cepheid?



Distance ladder

- Several distance measuring methods are linked
- Cosmicflow-4: Measure distance and redshift
 - Construct map of universe

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Cosmicflows-4

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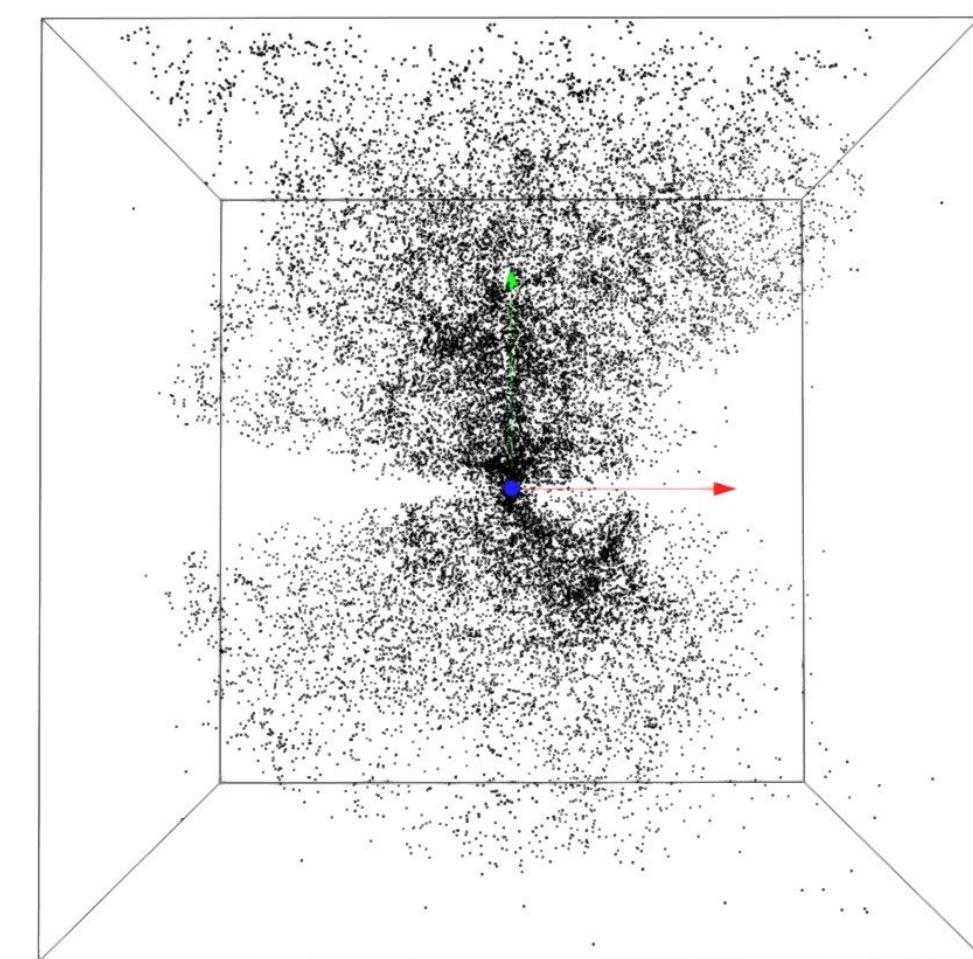
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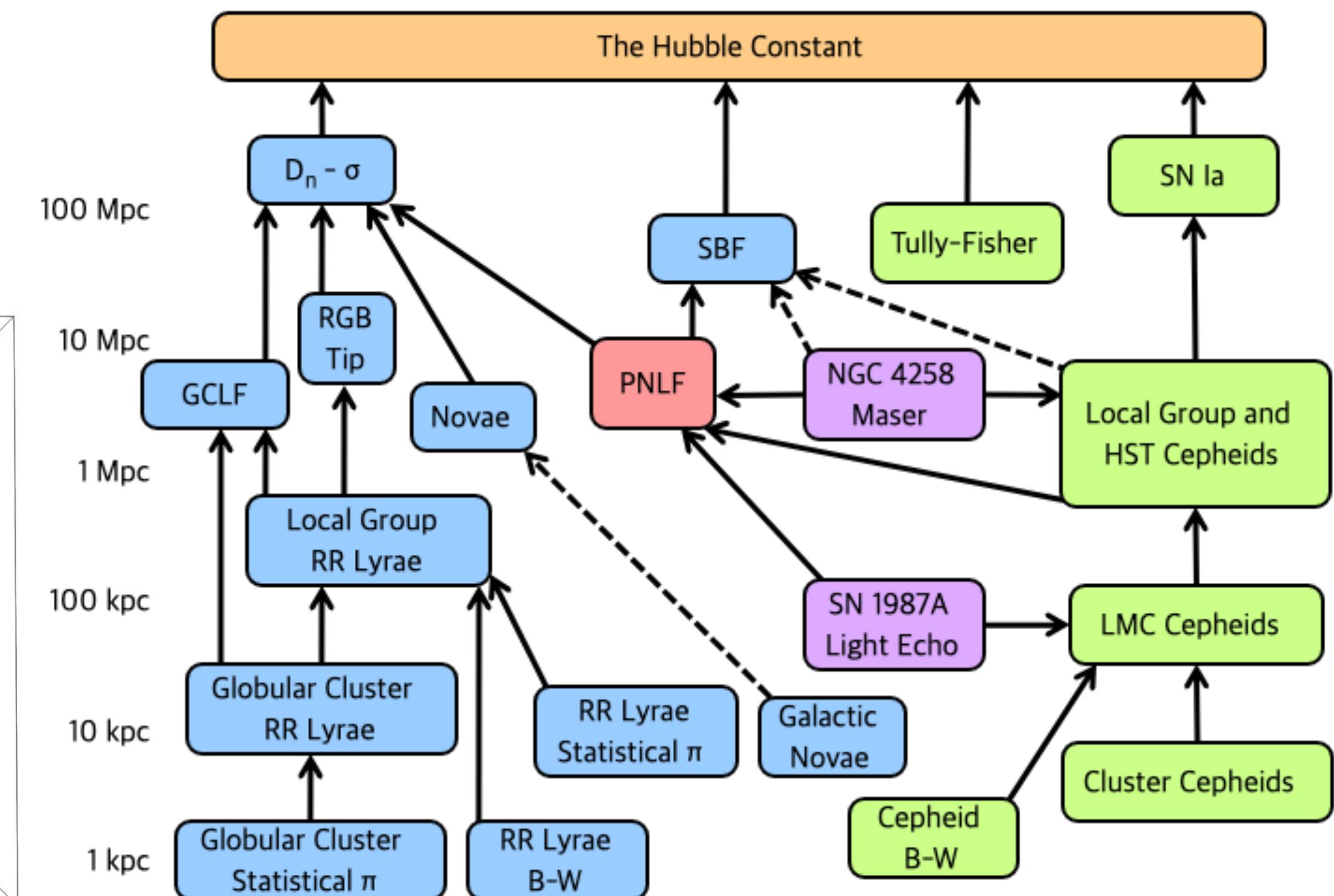
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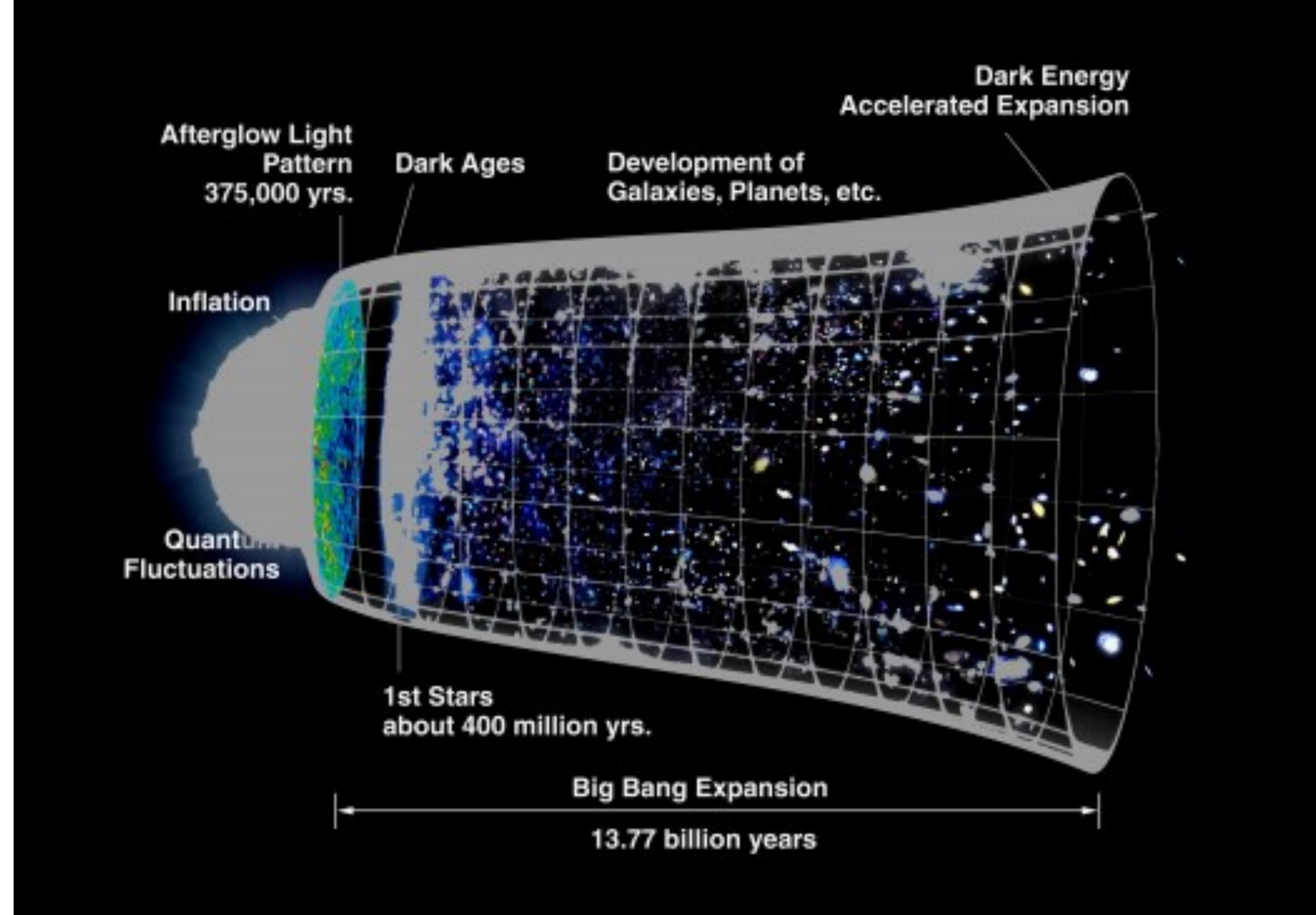
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Extragalactic Distance Ladder

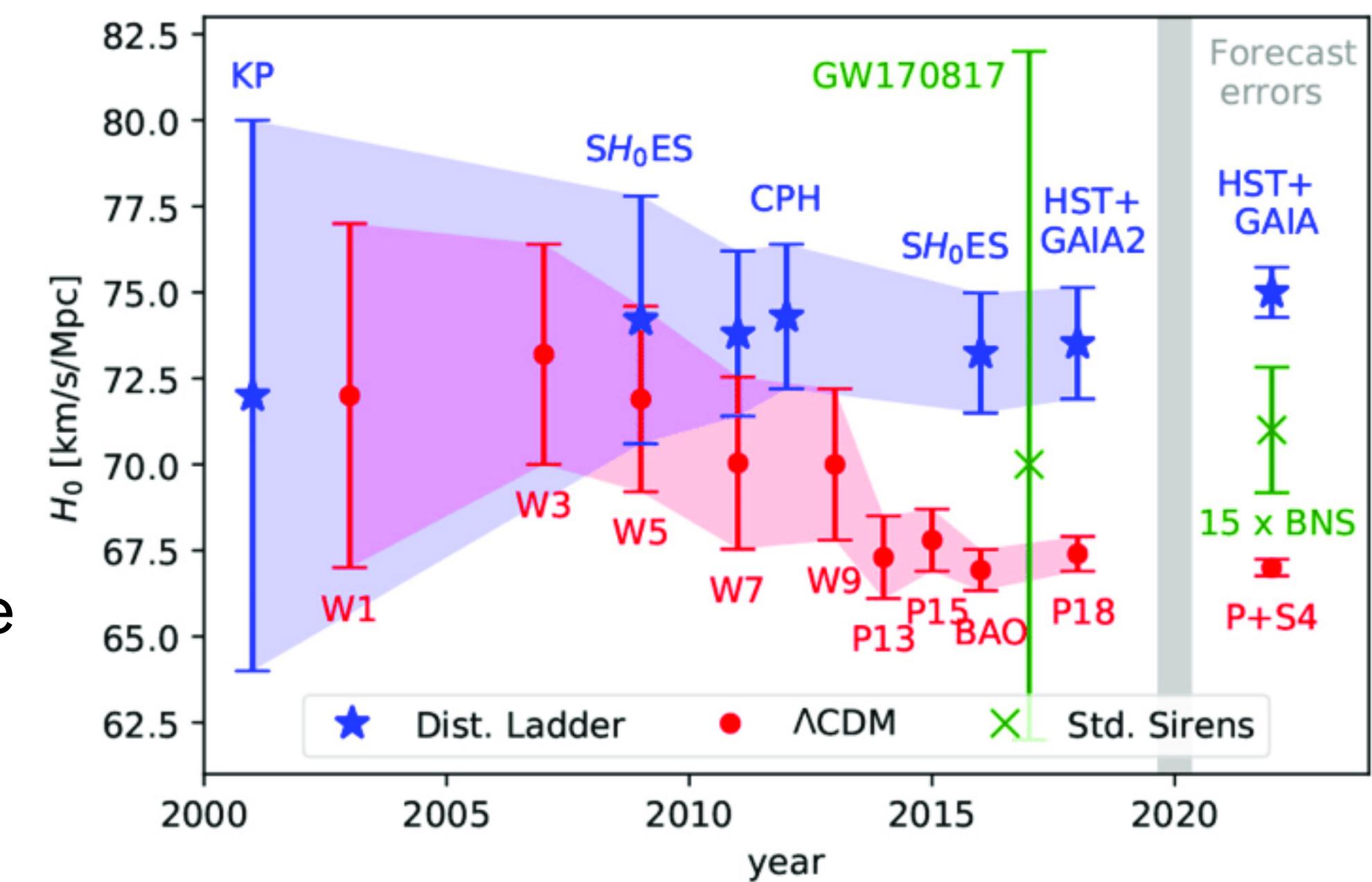


Why should we measure Hubble constant?



Hubble tension

- Today, astrophysicists try to measure Hubble constant with several methods
 - Distance ladder
 - CMB (Λ CDM)
 - Gravitational waves (Standard Sirens)
- The each result doesn't match in appropriate error range



HW

- Estimate the redshift at least 20 given galaxies (last lecture)
- Calculate Hubble constant with given velocity and distance data (using redshift you estimate)
- If you want, you can choose additional galaxies from ‘allCF4individual.txt’