

# **The Path to Measuring an Accelerating Universe**

**2011 Nobel Prize Lecture in Physics**

**BRIAN P. SCHMIDT**



**ANU**

THE AUSTRALIAN NATIONAL UNIVERSITY

**THE RESEARCH SCHOOL OF ASTRONOMY &  
ASTROPHYSICS  
MOUNT STROMLO AND SIDING SPRING  
OBSERVATORIES**





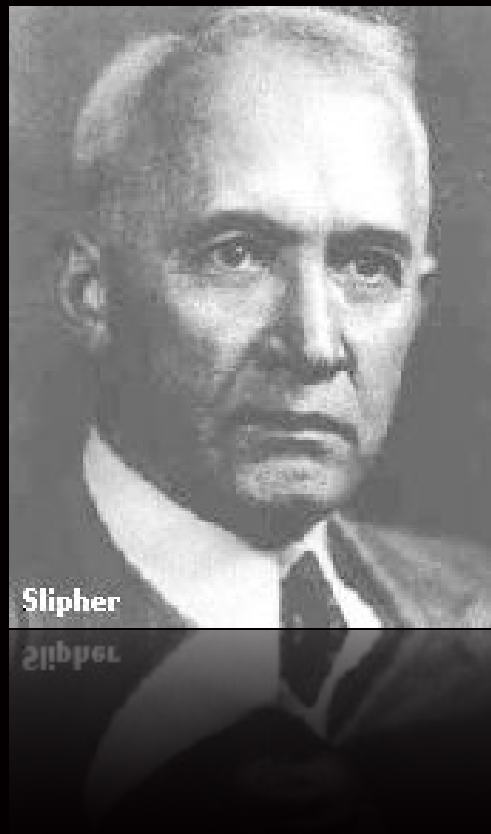
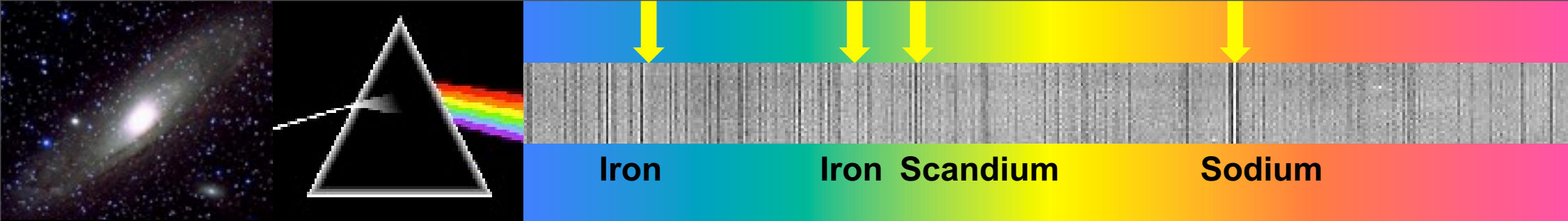
Slipher

Slipher

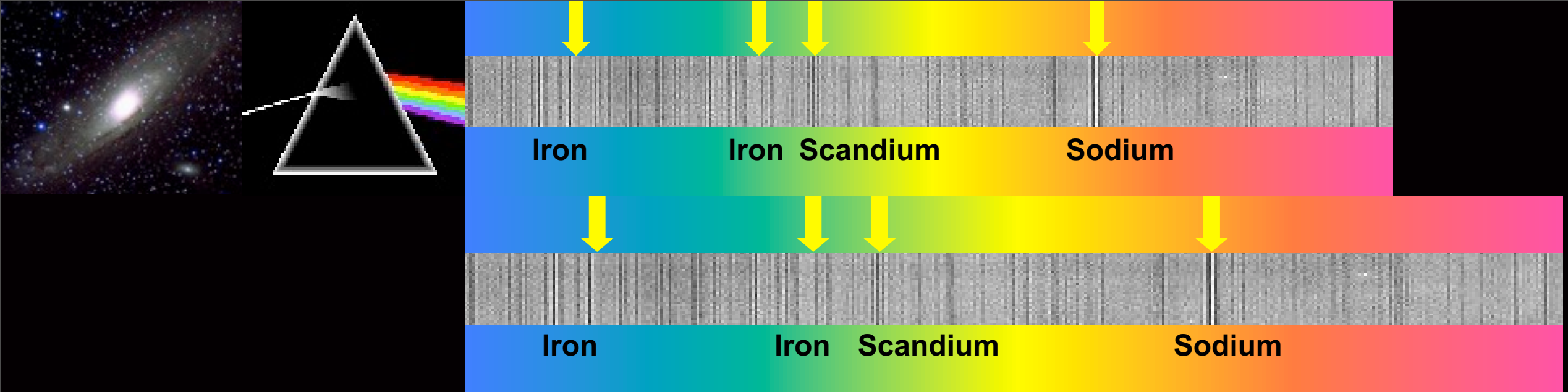


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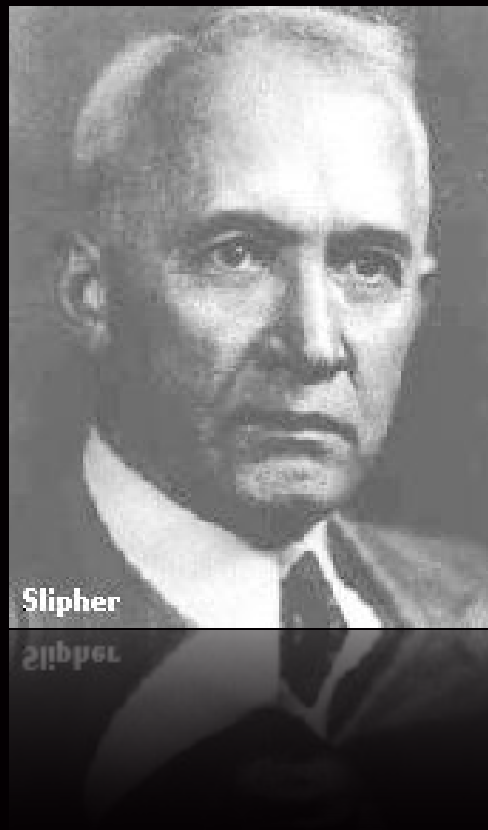
Slipher



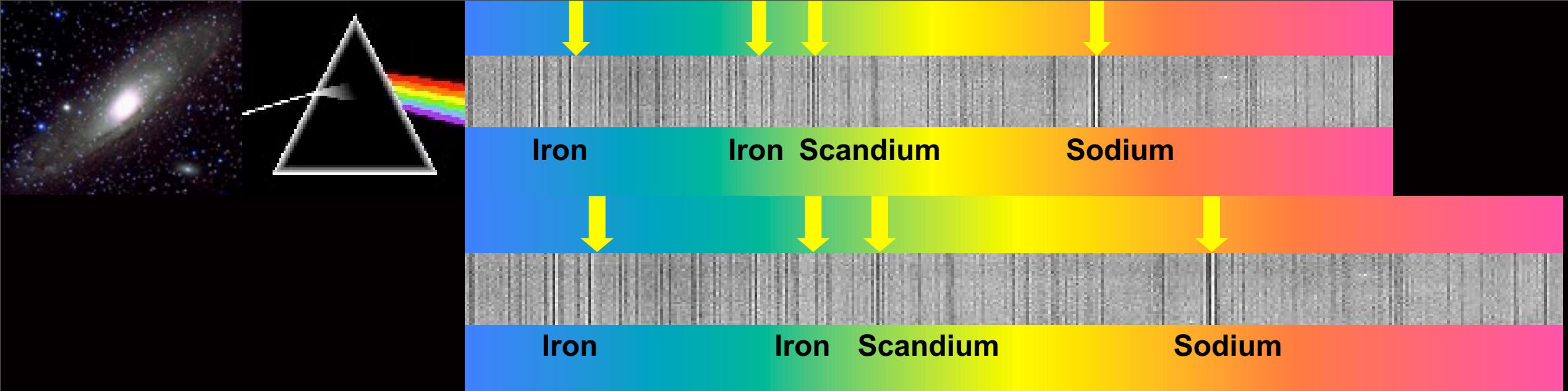




## Doppler Shift Gives Velocity of Galaxy





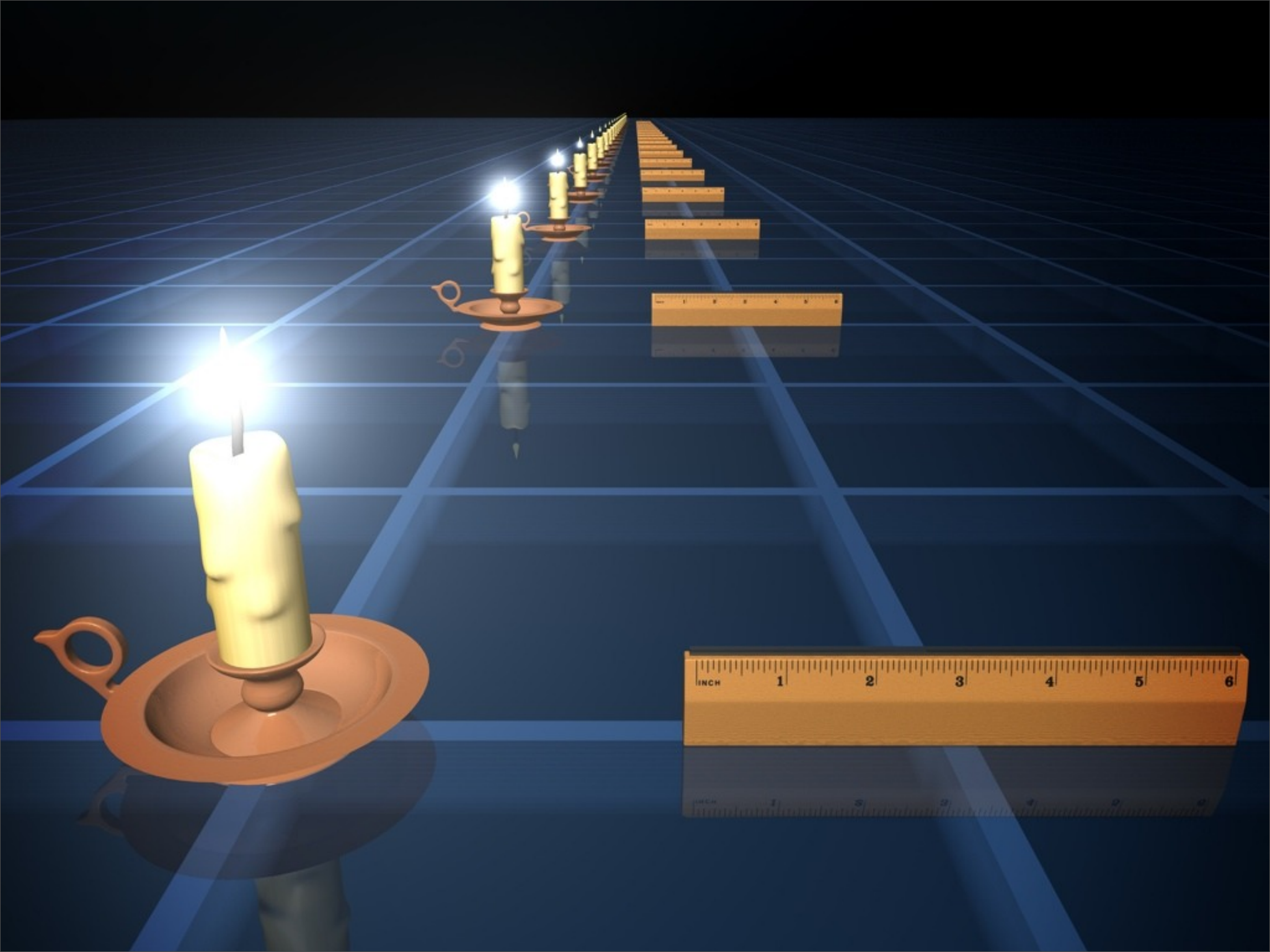


## **Doppler Shift Gives Velocity of Galaxy**

**In 1916 Vesto Slipher  
measured  
velocities to nearby  
galaxies, and discovered  
they were all moving  
away from us.**

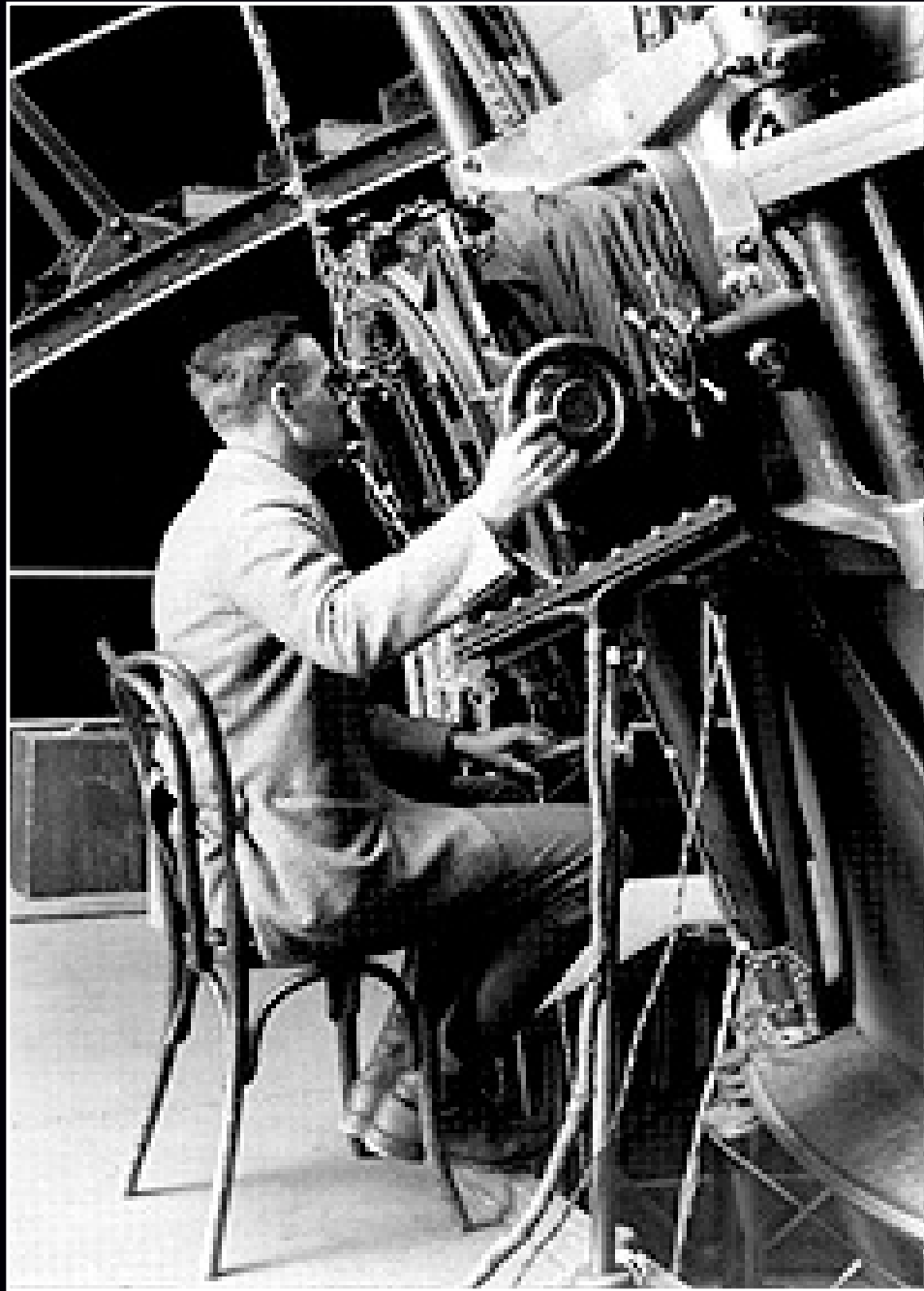


Slipher





*1929, Hubble uses brightest stars  
to measure the  
distances to the  
nearest galaxies.*



*He assumes the  
brightest stars are  
all the same  
brightness.*

*The faster the galaxy was moving,  
the fainter the stars!*





**The  
Universe is  
Expanding**

# Hubble's Data

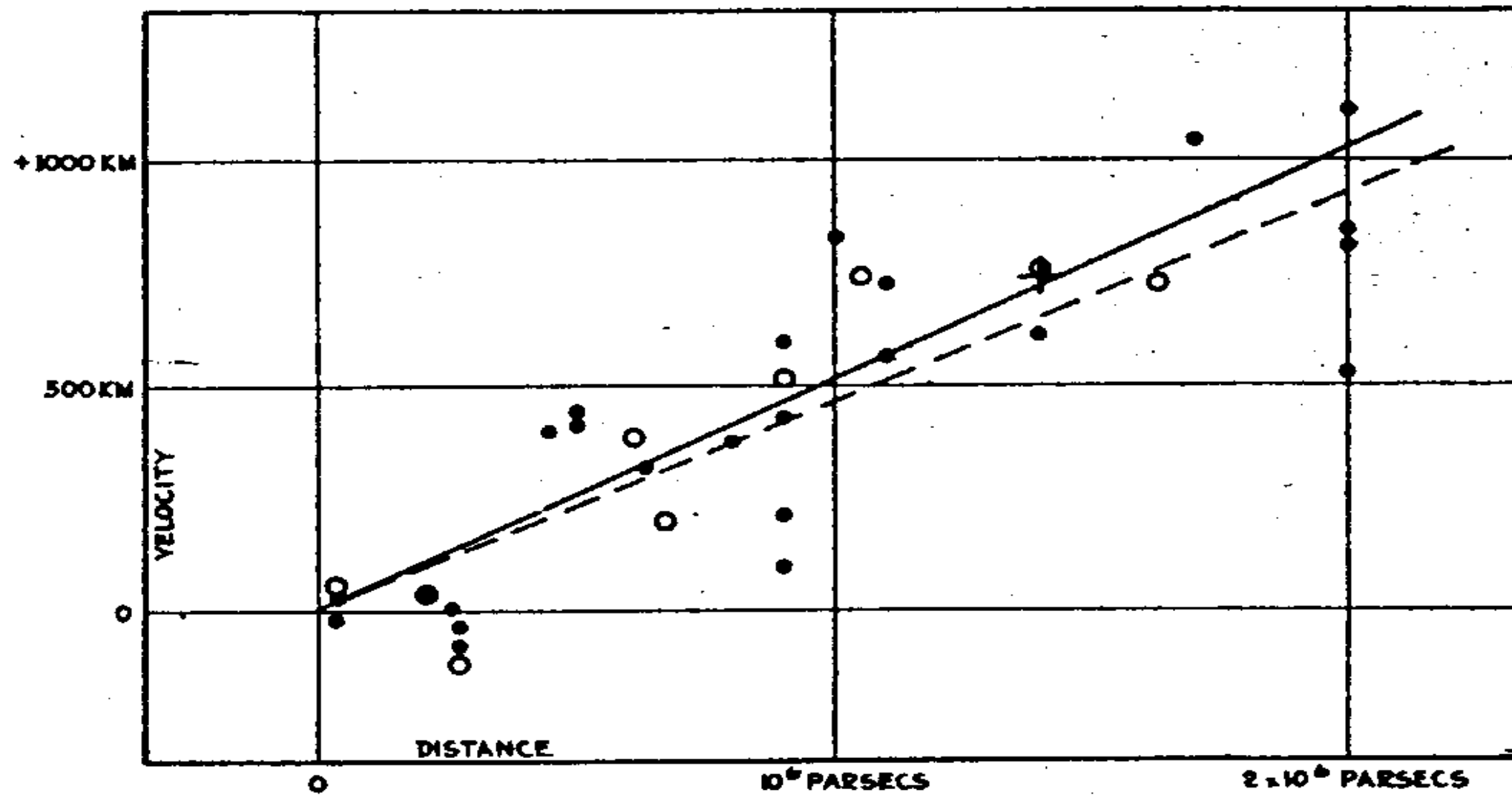


FIGURE 1



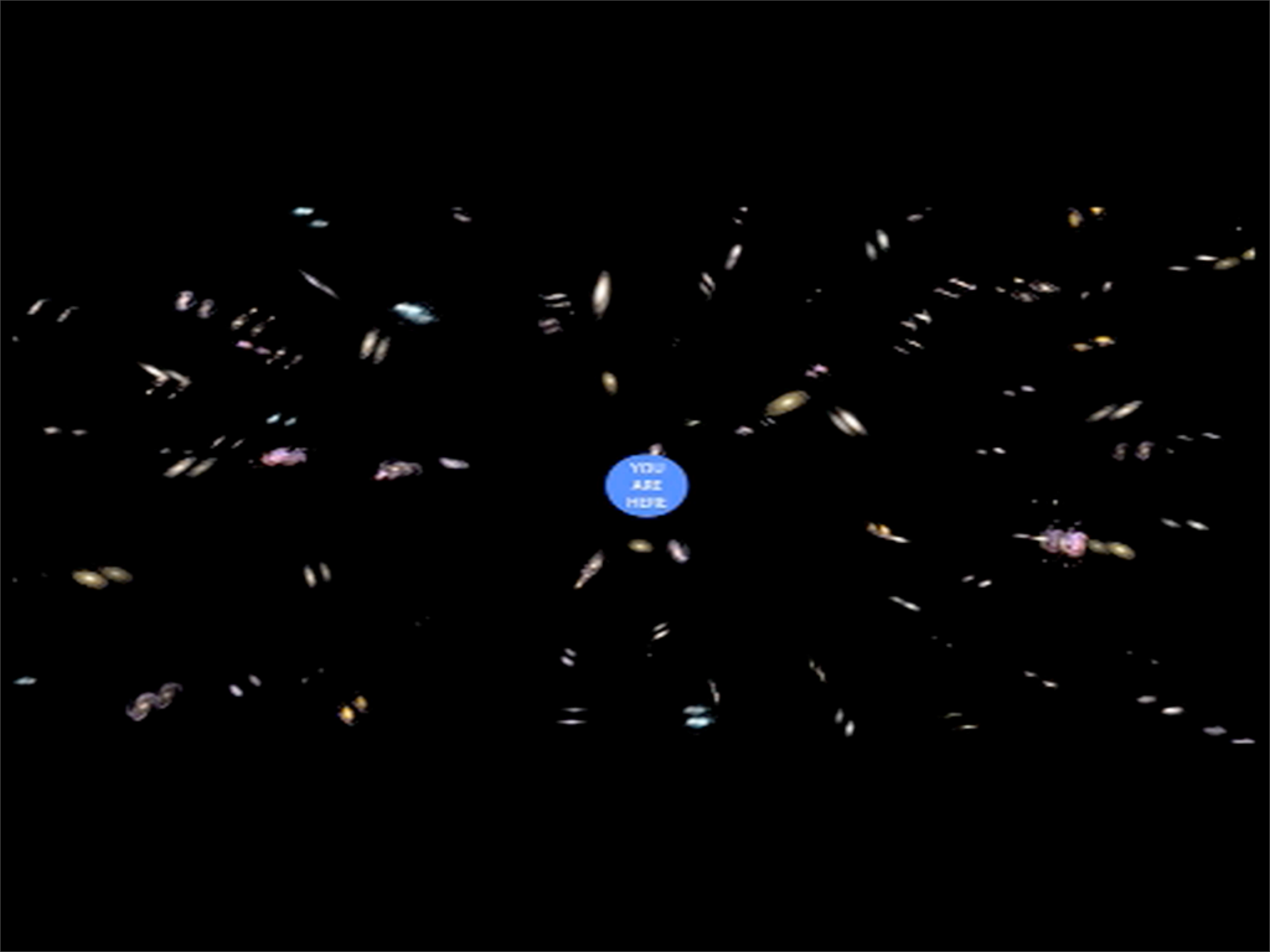


# Hubble's Law



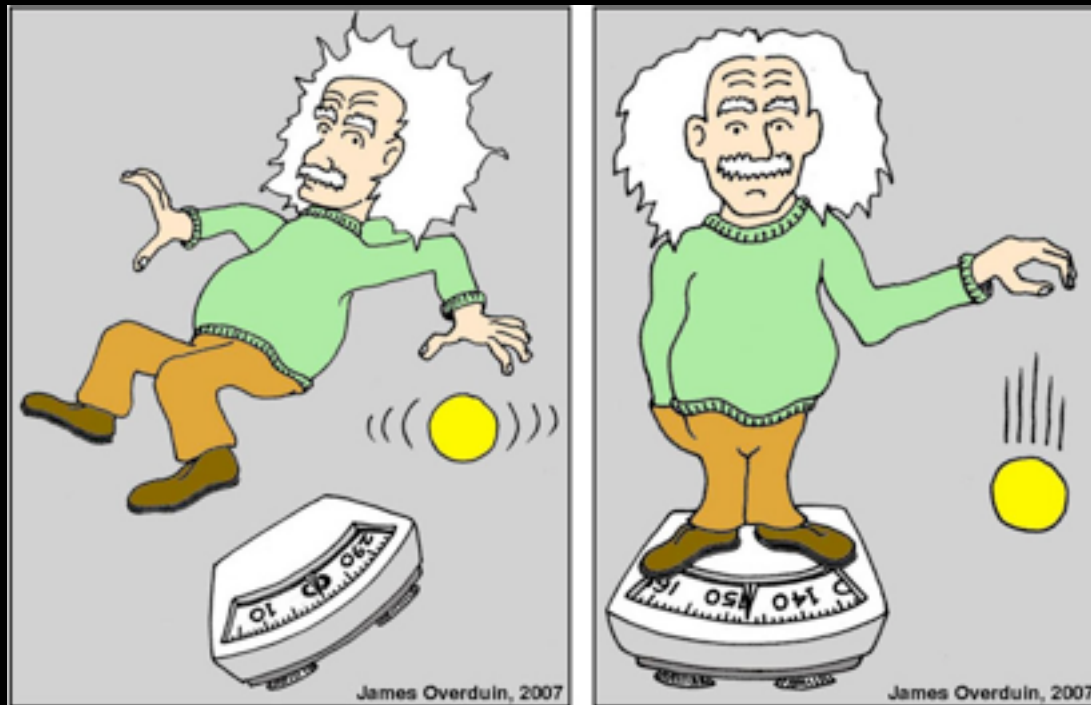
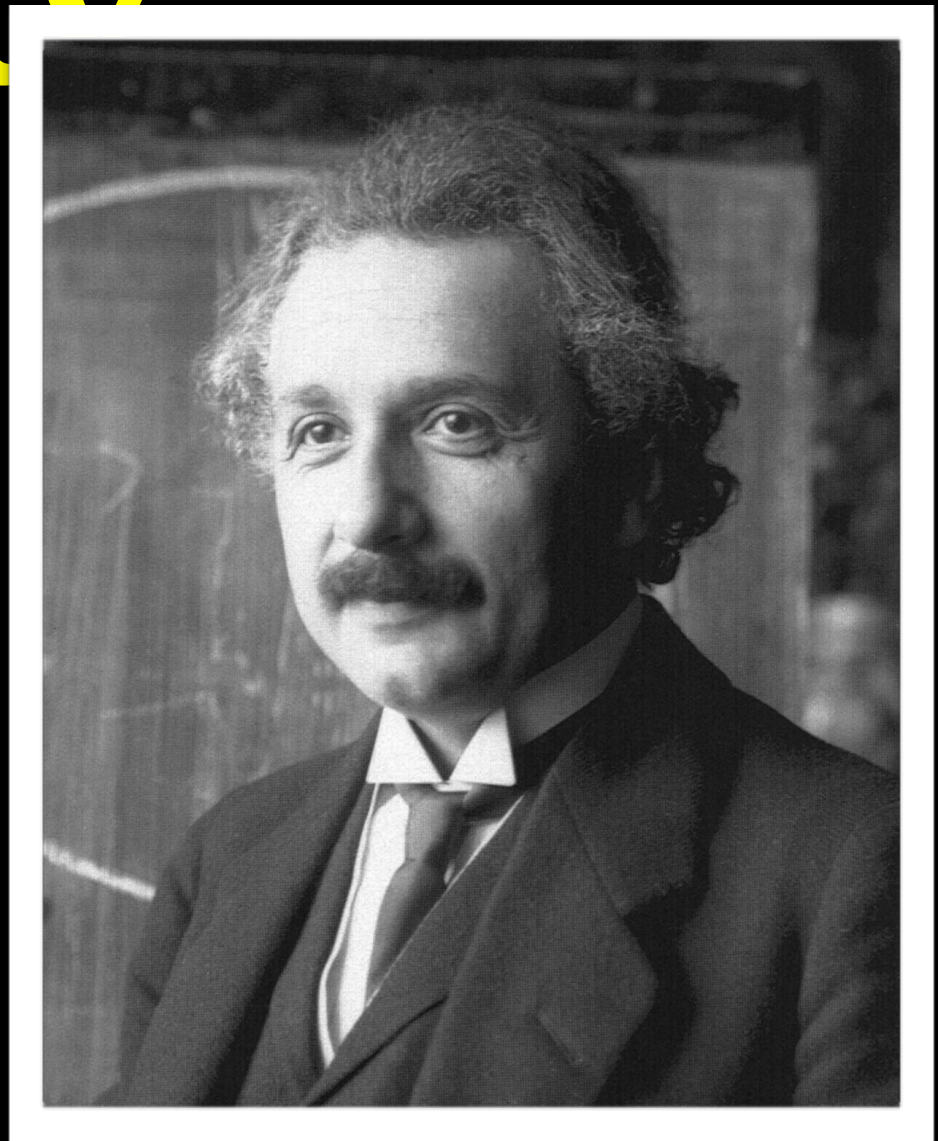
# Hubble's Law





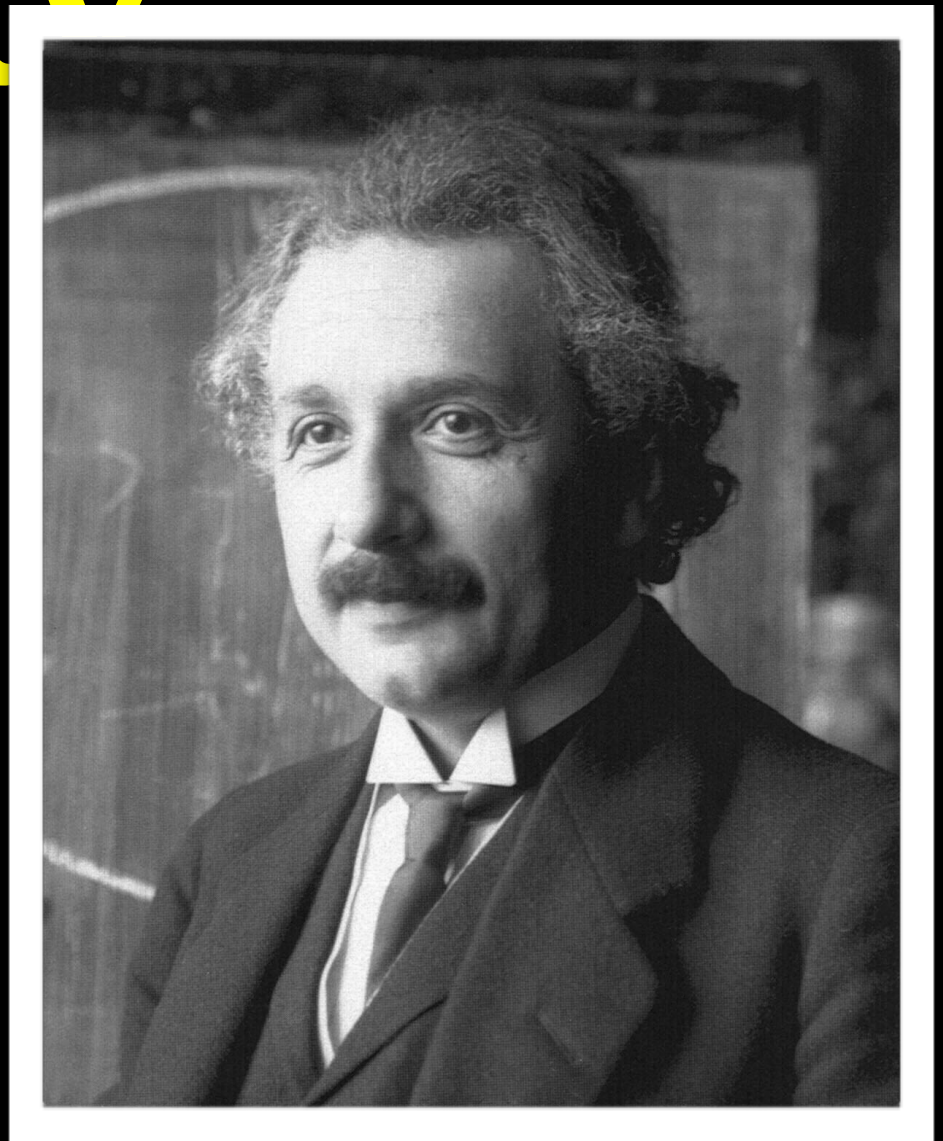
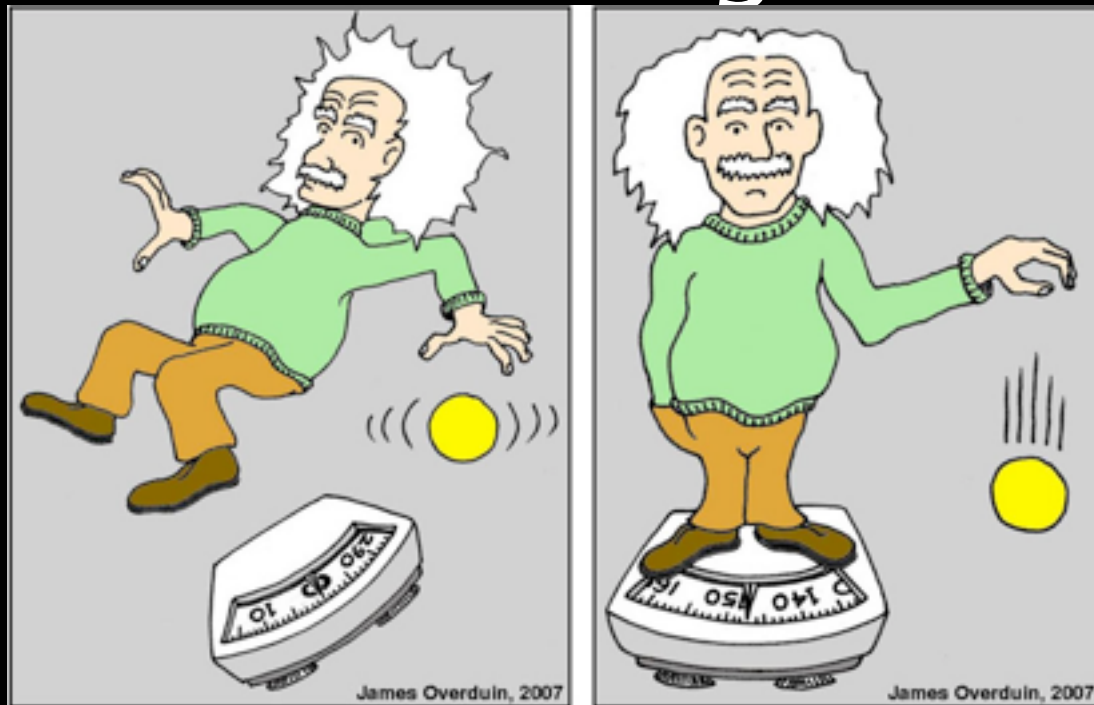


# Einstein's Theory of Gravity



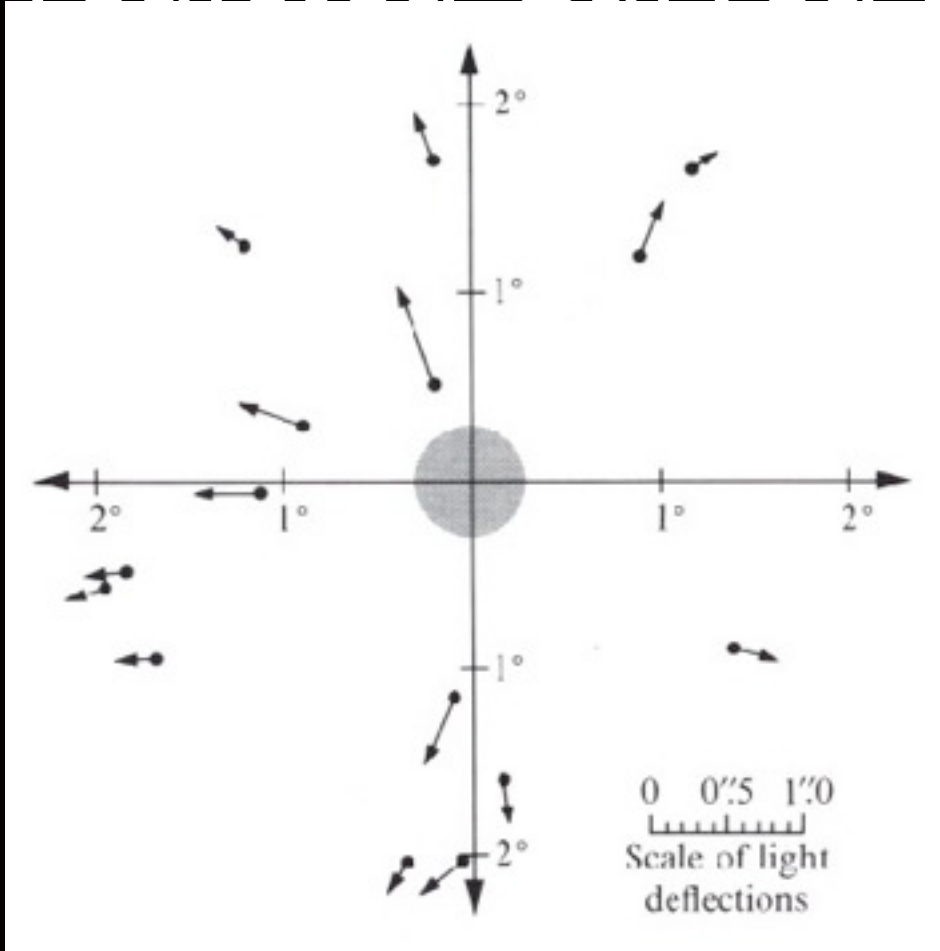
# Einstein's Theory of Gravity

- In 1907 Einstein had a revelation that acceleration and gravity were indistinguishable.



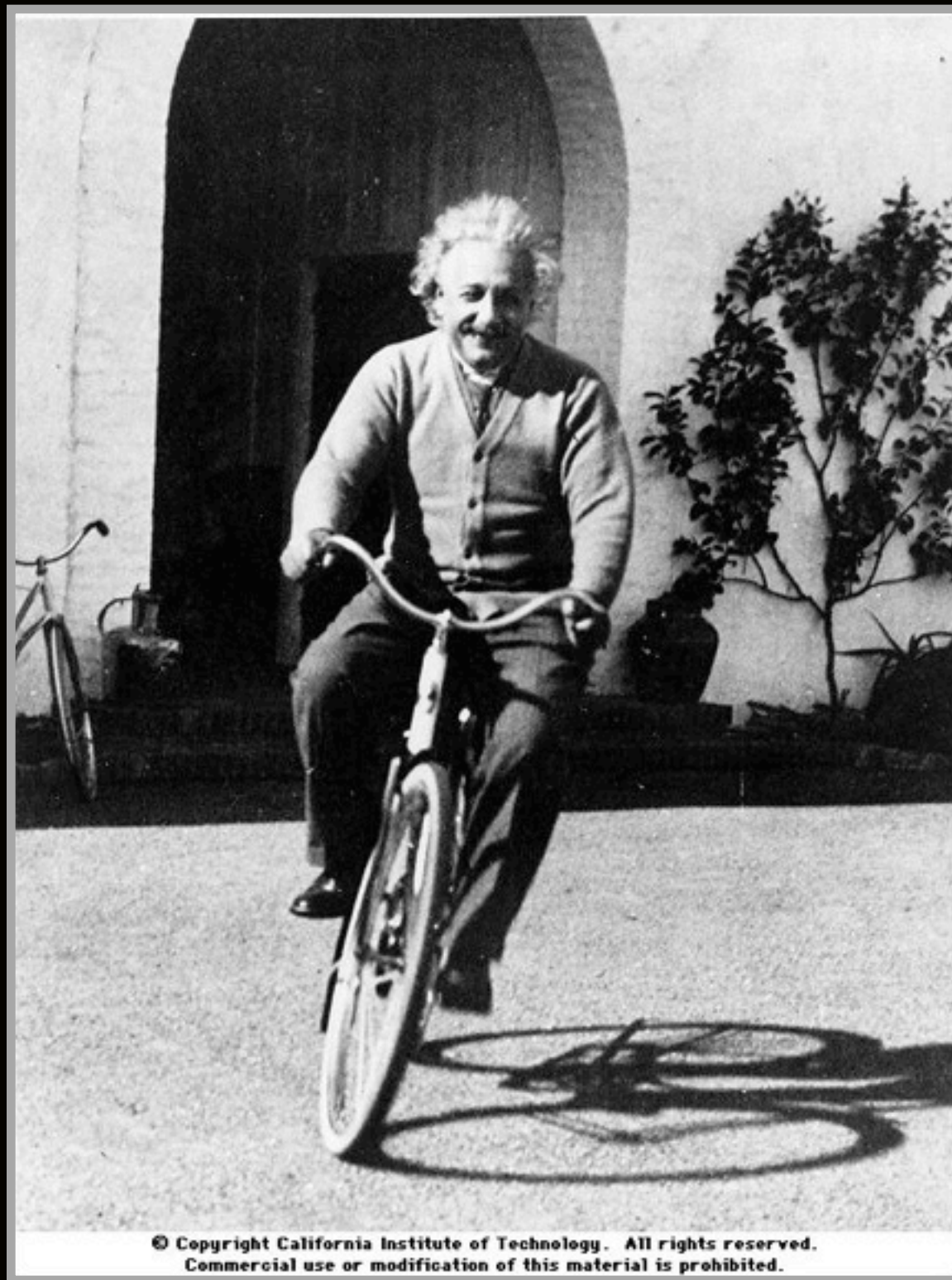
1915...Equations of General Relativity

# Predicted Curved Space



Allowed one to  
Solve  
Cosmology... But  
solutions were  
dynamic –  
Universe should





**The Cosmological Constant**  
Originally proposed by  
Einstein to counteract the  
Universe's gravitational  
attraction – it makes  
Gravity Push rather than  
Pull.

Later “retracted” once the  
expansion was discovered

It represents the energy of  
the vacuum (What is there  
when there is nothing  
there!)



# Our View of the Expanding Universe

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# Our View of the Expanding Universe

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Close,  
Recent

Far,  
Ancient

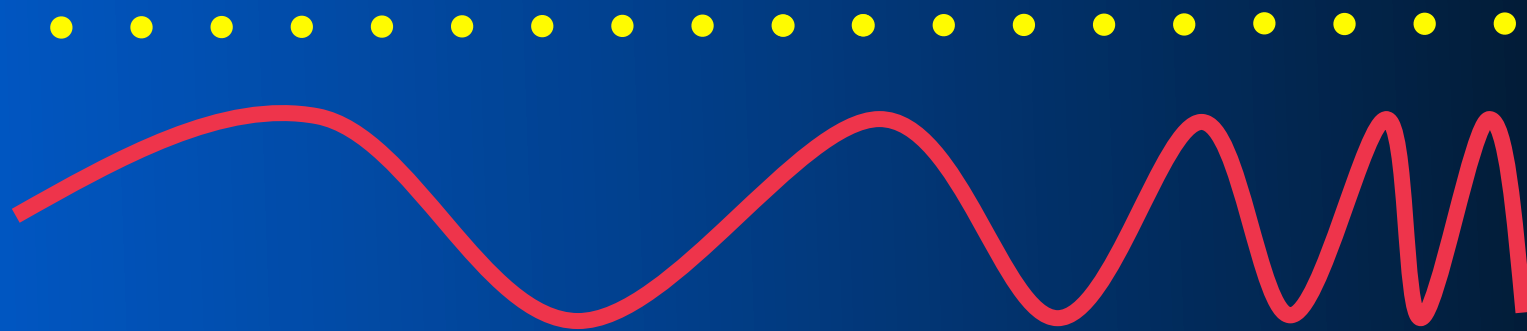


# Our View of the Expanding Universe

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Ancient

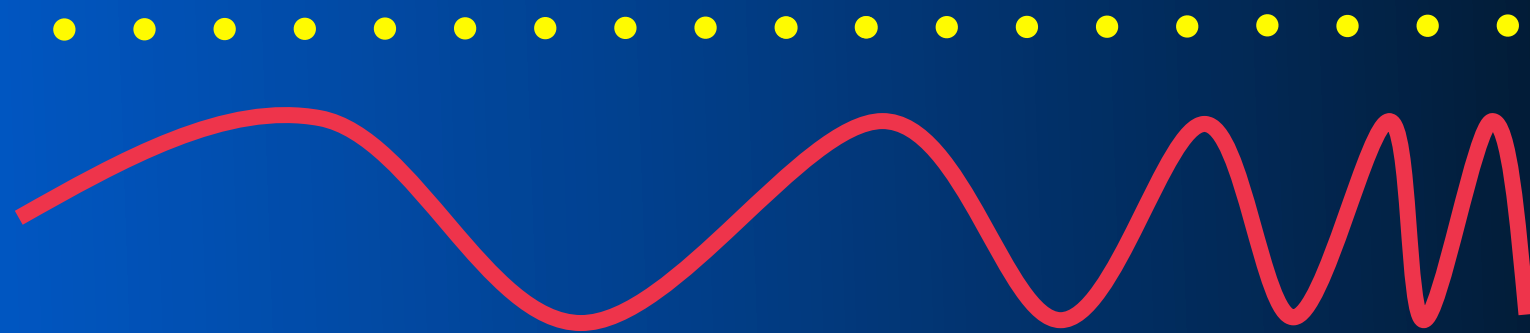


# Our View of the Expanding Universe

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Close,  
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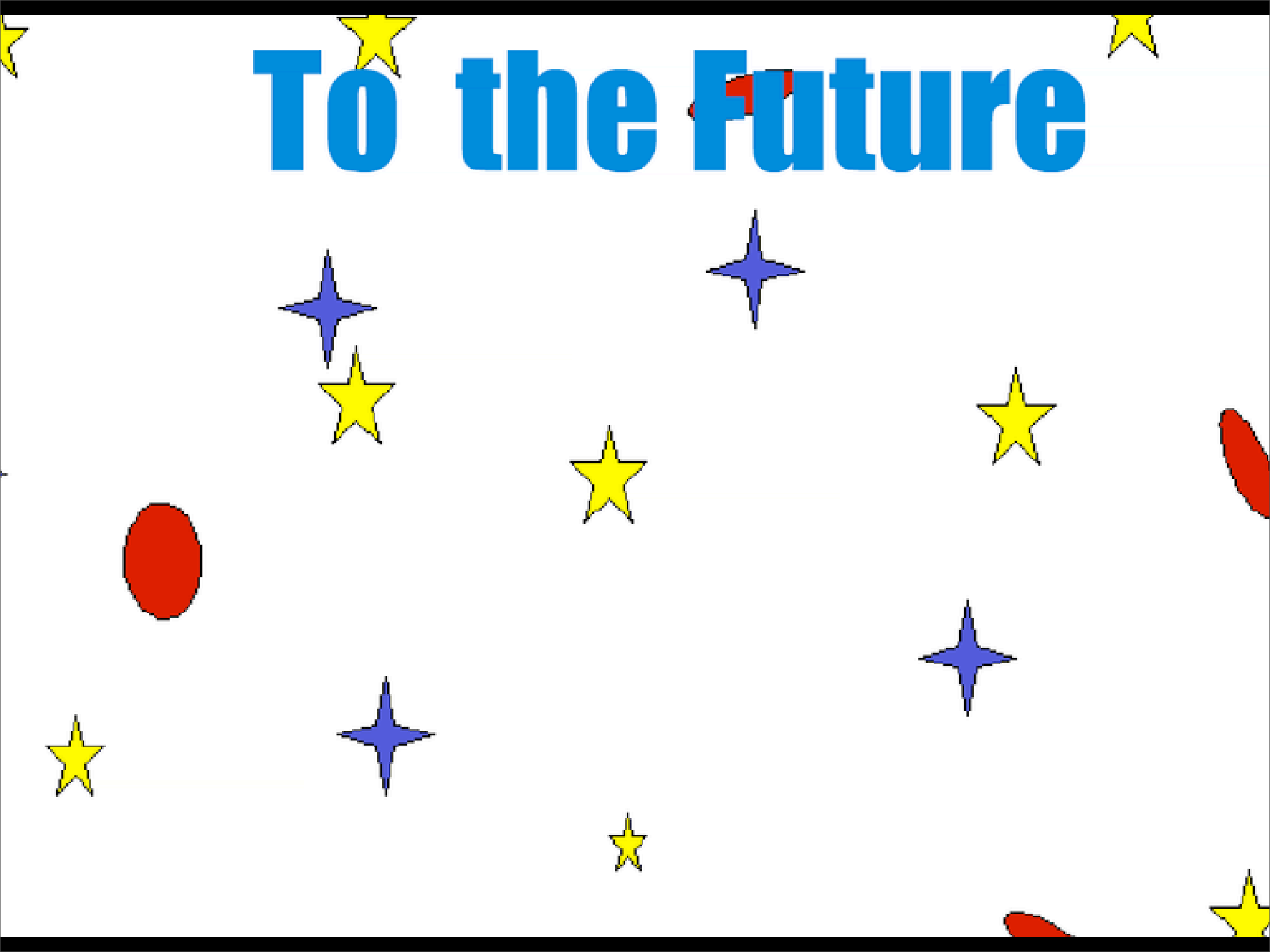
Light is stretched as the Universe expands,

The Further an object is away, the more the Universe has expanded, so the more the light is stretched to the Red - Redshift





# To the Future



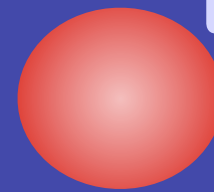
# The Distance Between Two Galaxies

Separation

Time

# The Distance Between Two Galaxies

Separation



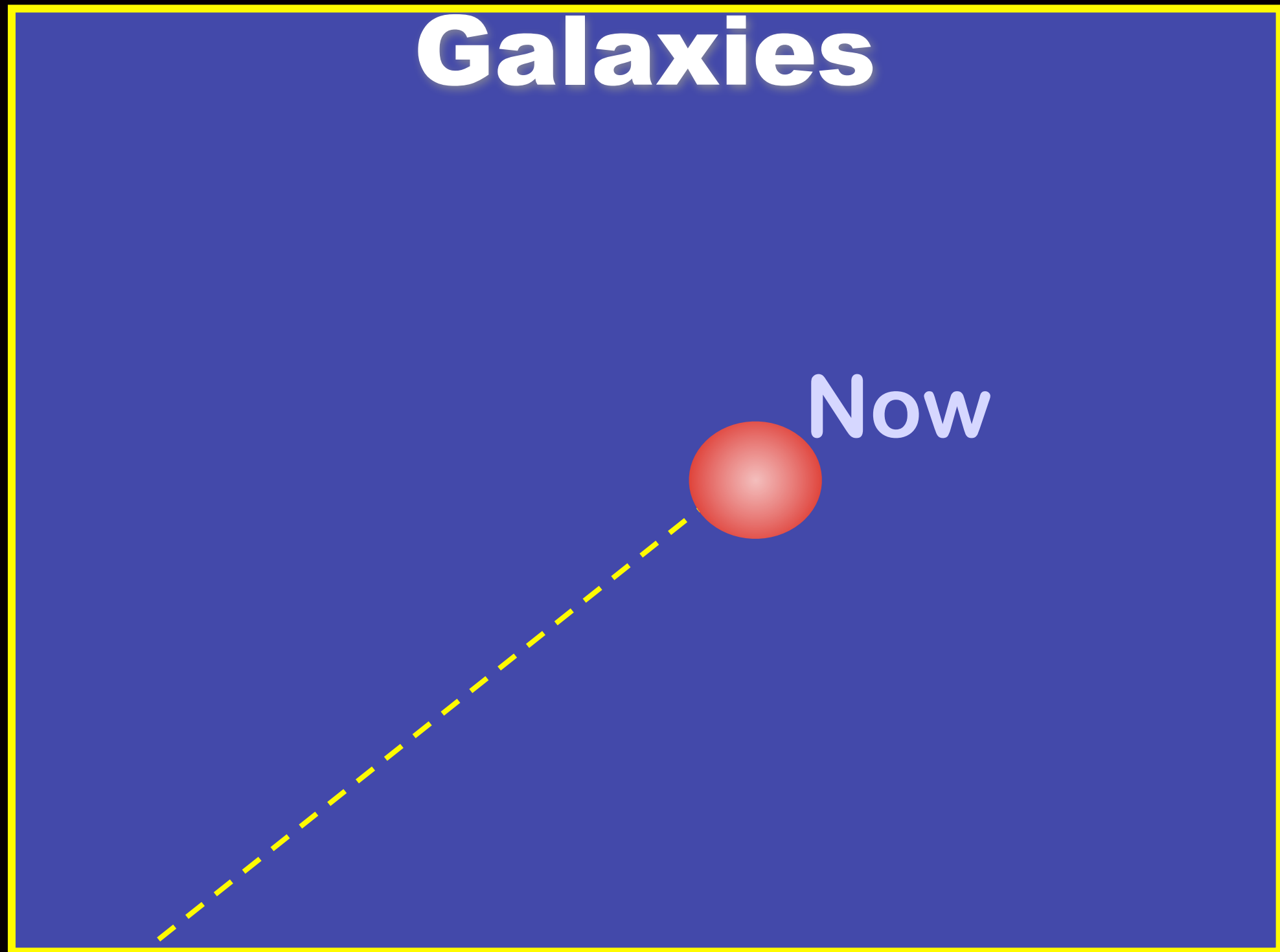
Now

Time



# The Distance Between Two Galaxies

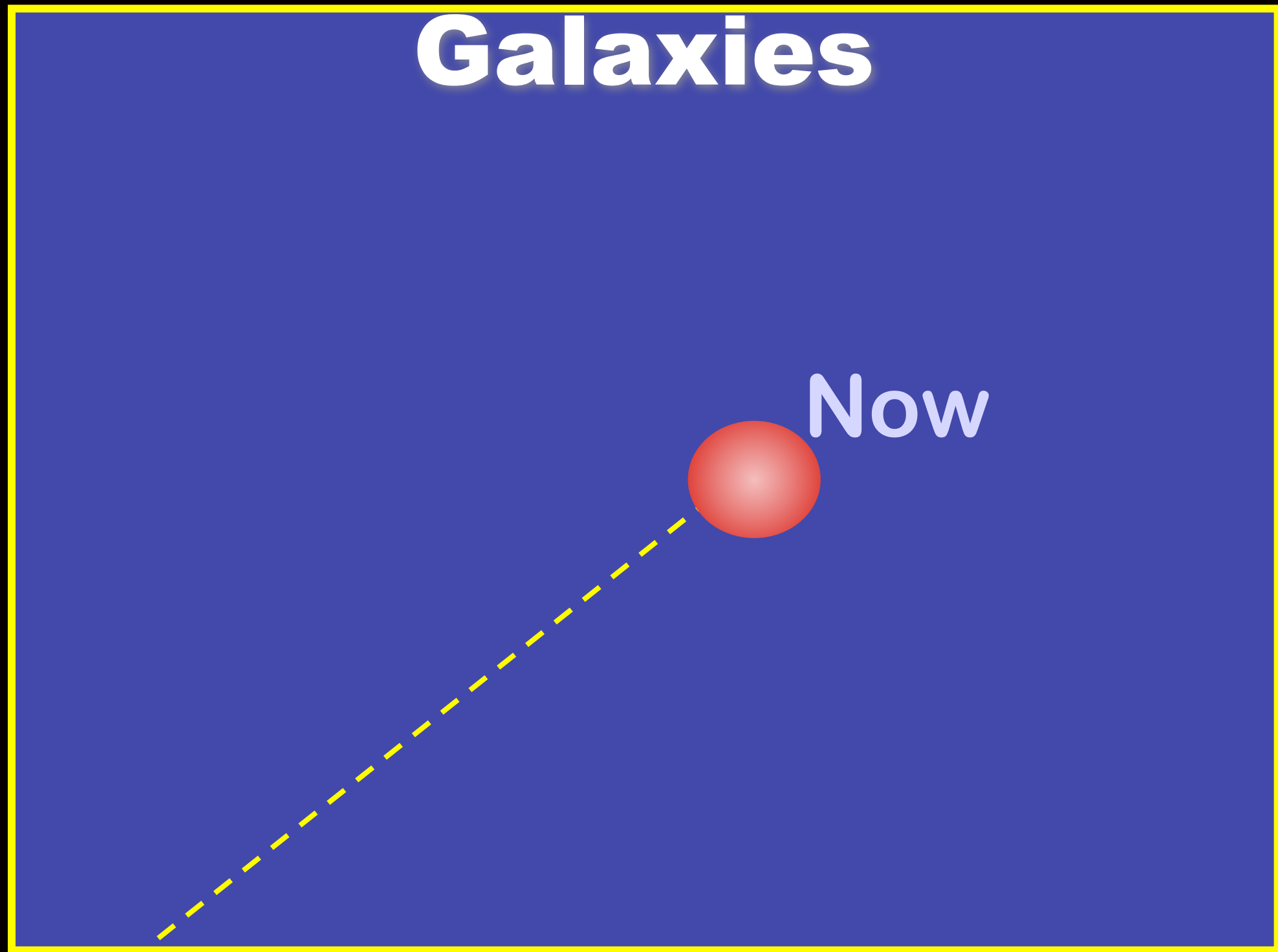
Separation



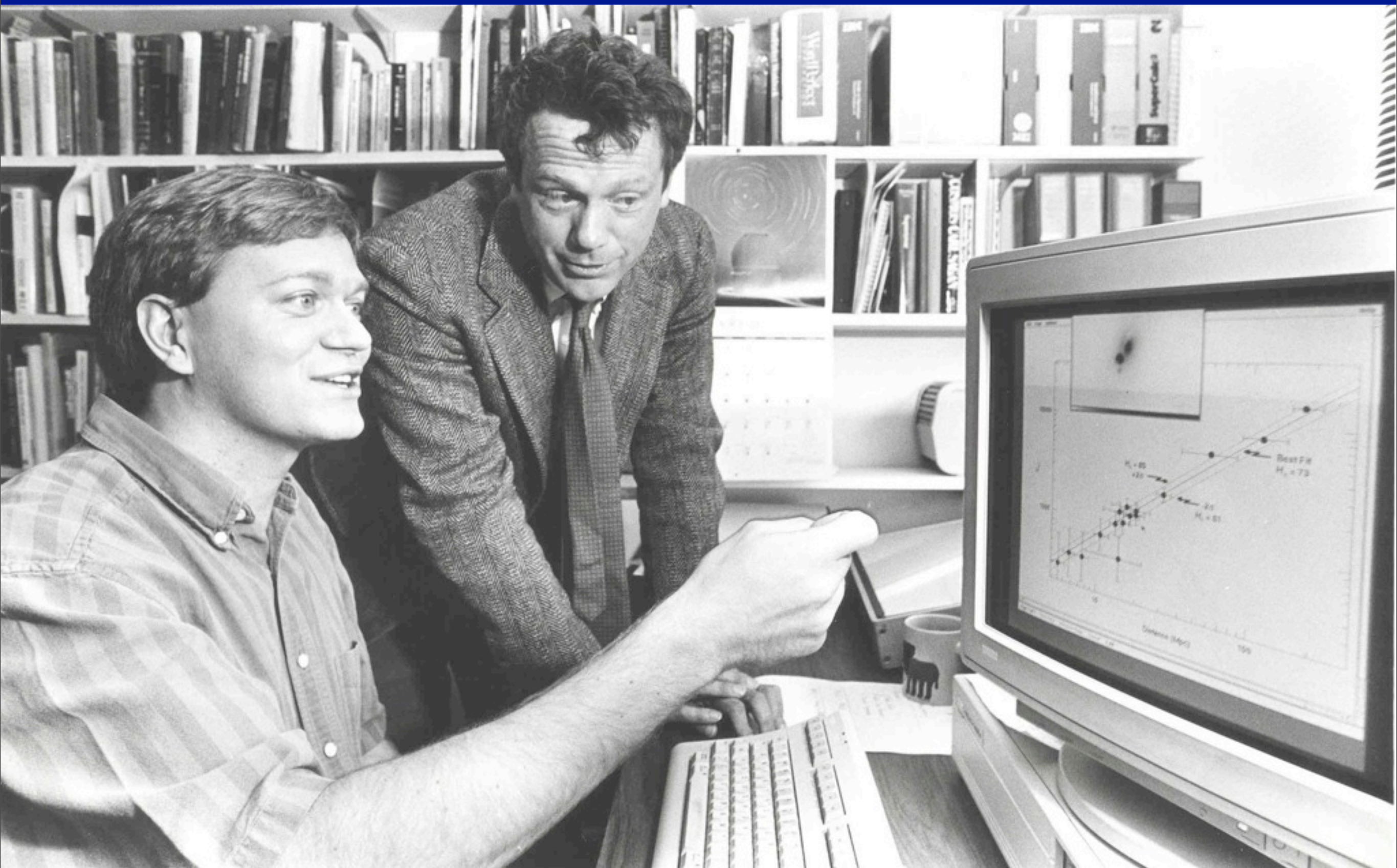
Time

# The Distance Between Two Galaxies

Separation



Time



**The Hubble Constant Tells us  
the age of the Universe...**

# The Hubble Constant Tells us the age of the Universe...

$H_0=50$     $t=19.6$  Billion Years

$H_0=60$     $t=16.3$  Billion Years

$H_0=70$     $t=14.0$  Billion Years

$H_0=80$     $t=12.3$  Billion Years

$H_0=90$     $t=10.9$  Billion Years

$H_0=100$     $t=9.8$  Billion Years



# The Hubble Constant Tells us the age of the Universe...

$$H_0 = 70 \quad t = 14.0 \text{ Billion Years}$$

**So how fast the Universe is  
expanding tells us about how  
old the Universe is...But...**

**So how fast the Universe is  
expanding tells us about how  
old the Universe is...But...**

**Gravity pulls on the Universe as it  
expands, slowing it down over  
time**

# The Distance Between Two Galaxies

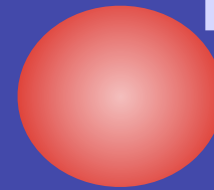
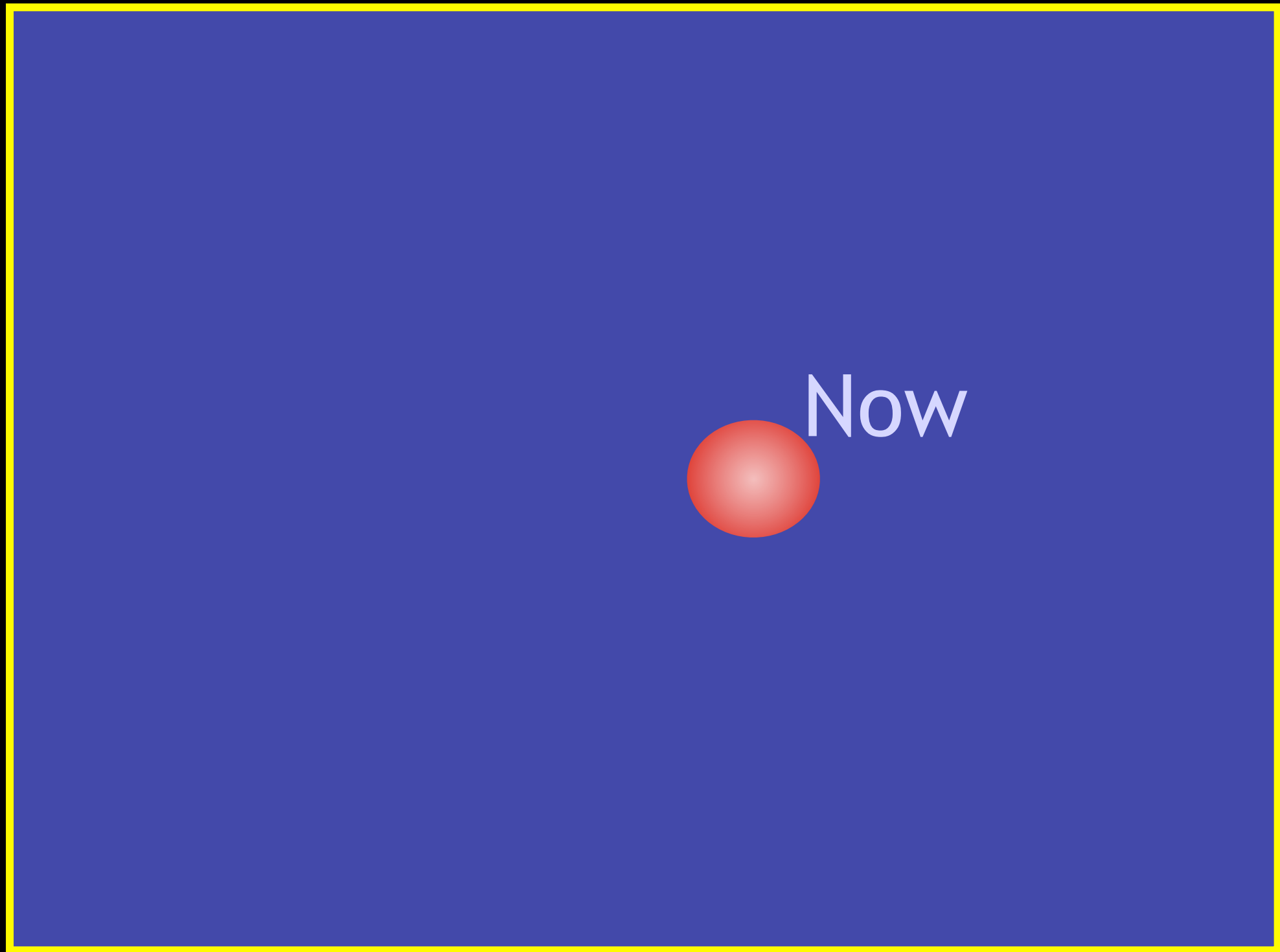
Separation



Time

# The Distance Between Two Galaxies

Separation

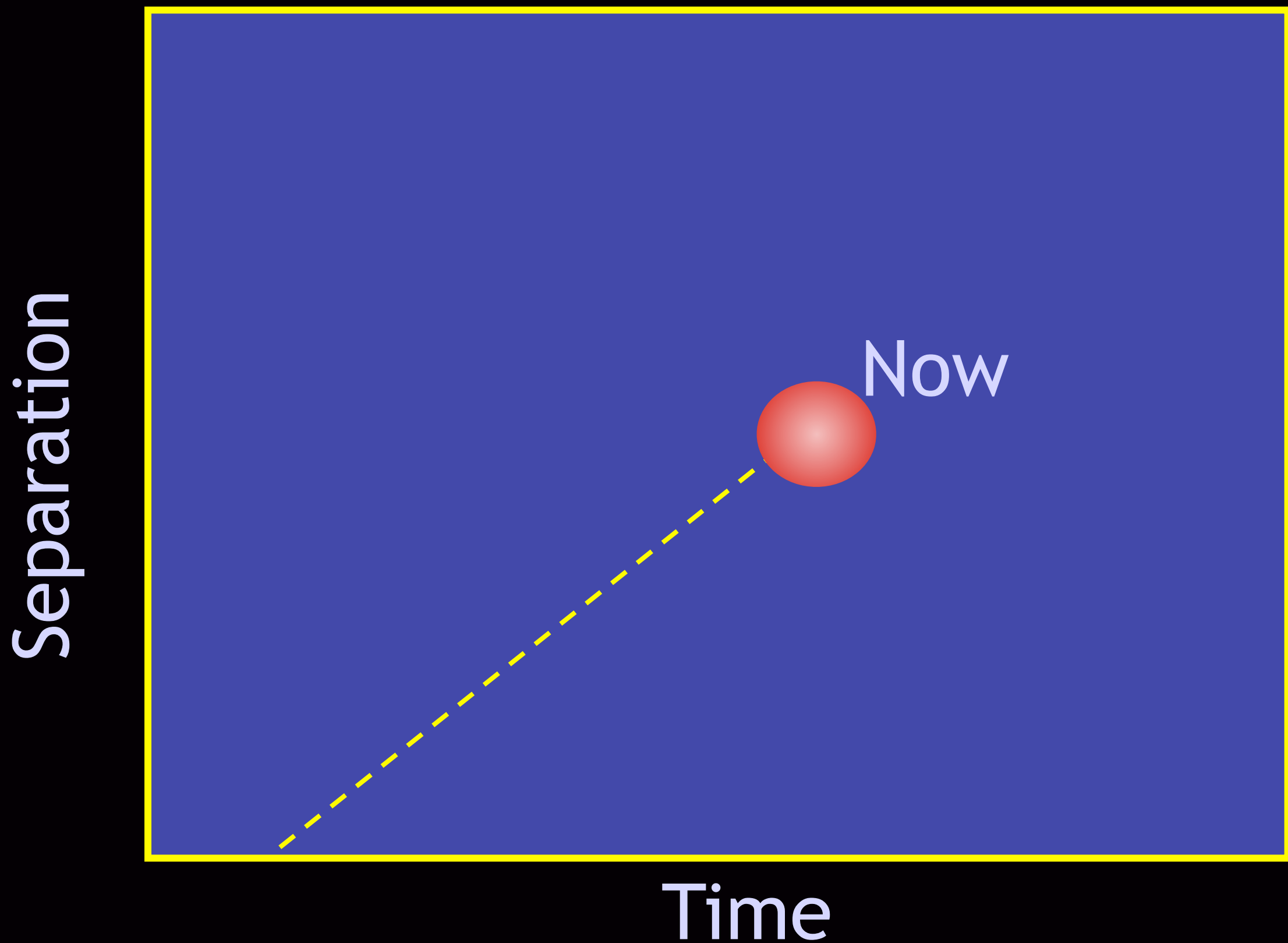


Now

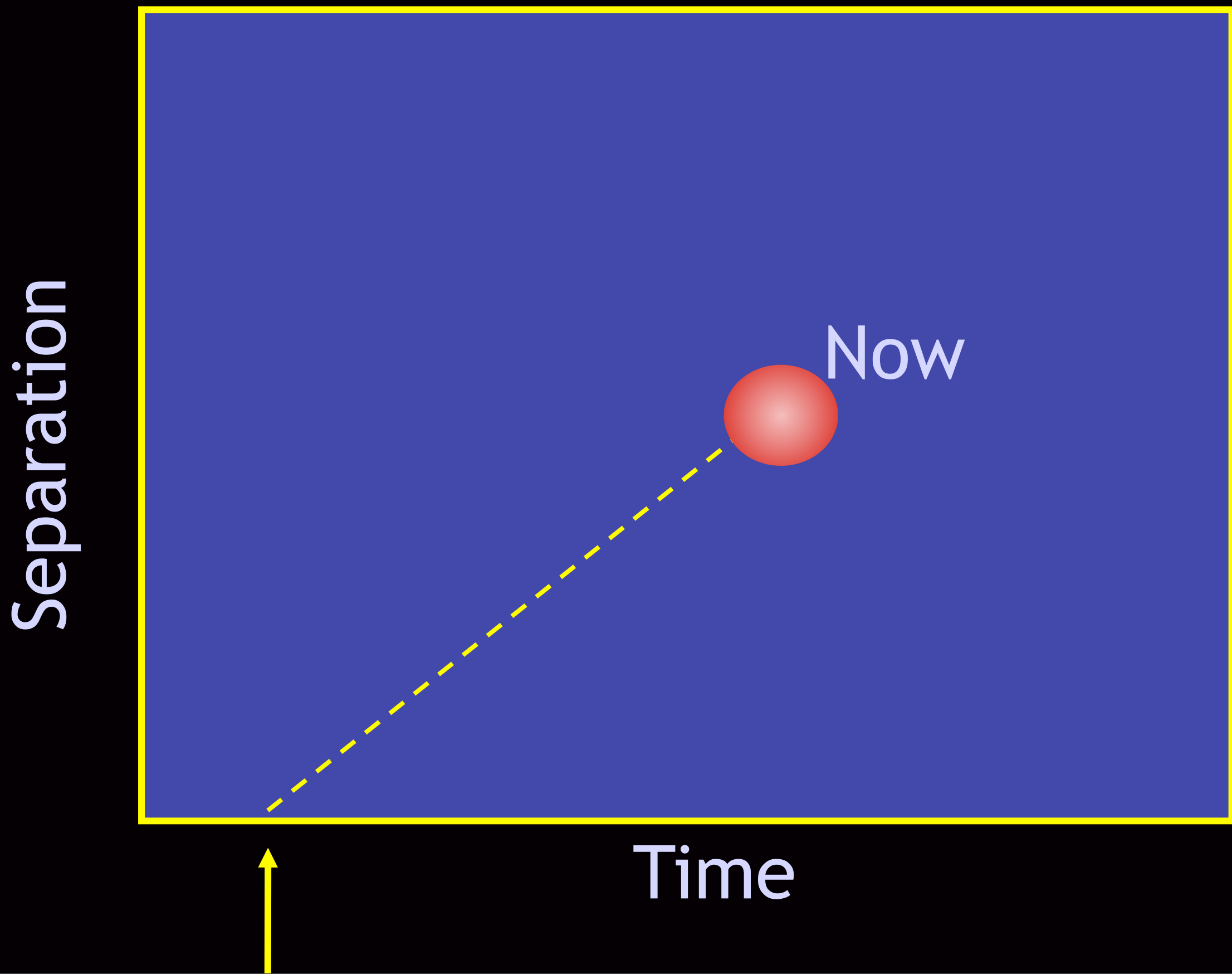
Time



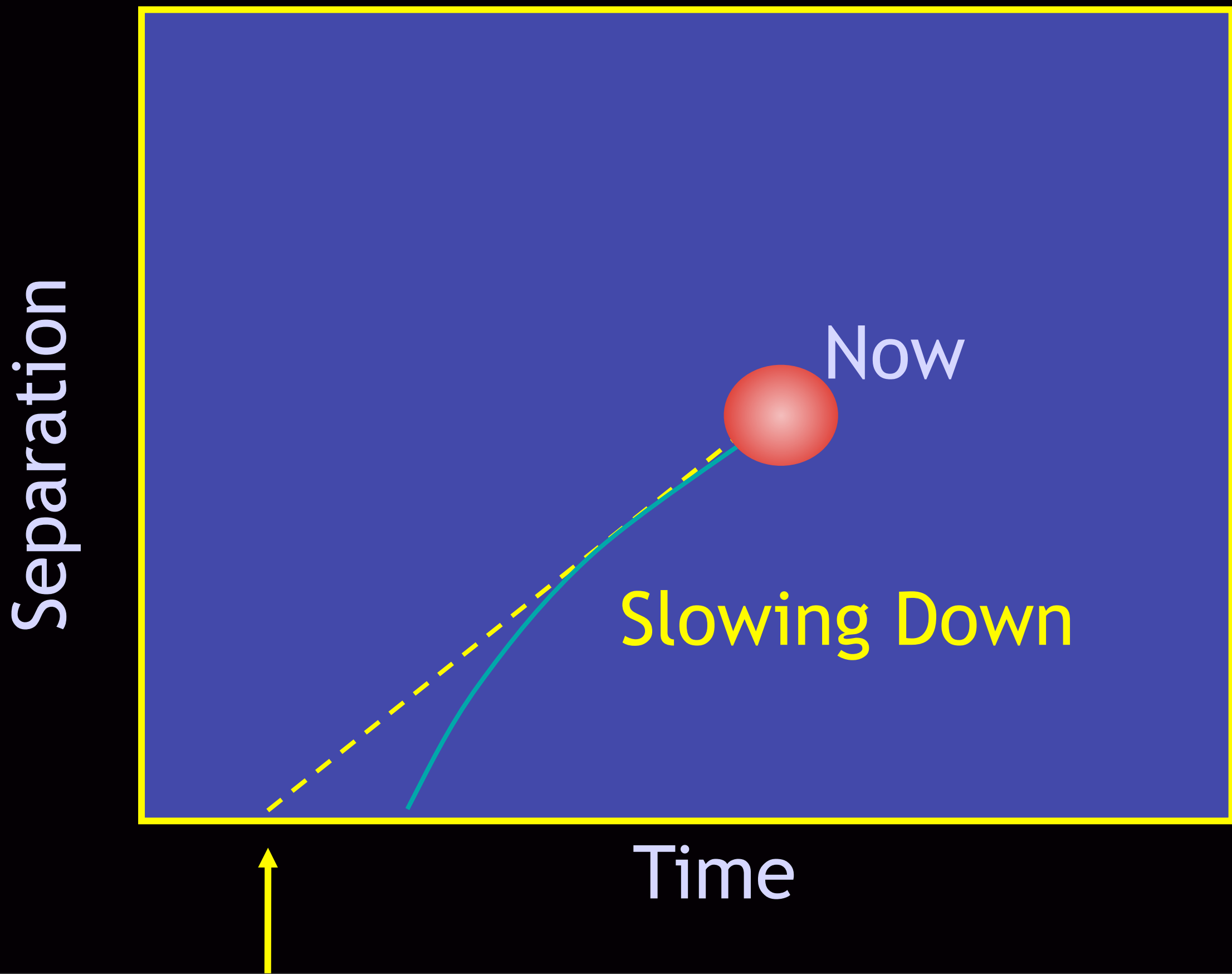
# The Distance Between Two Galaxies



# The Distance Between Two Galaxies



# The Distance Between Two Galaxies



# Looking towards the Future

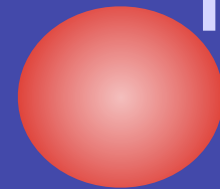
Separation



Time

# Looking towards the Future

Separation

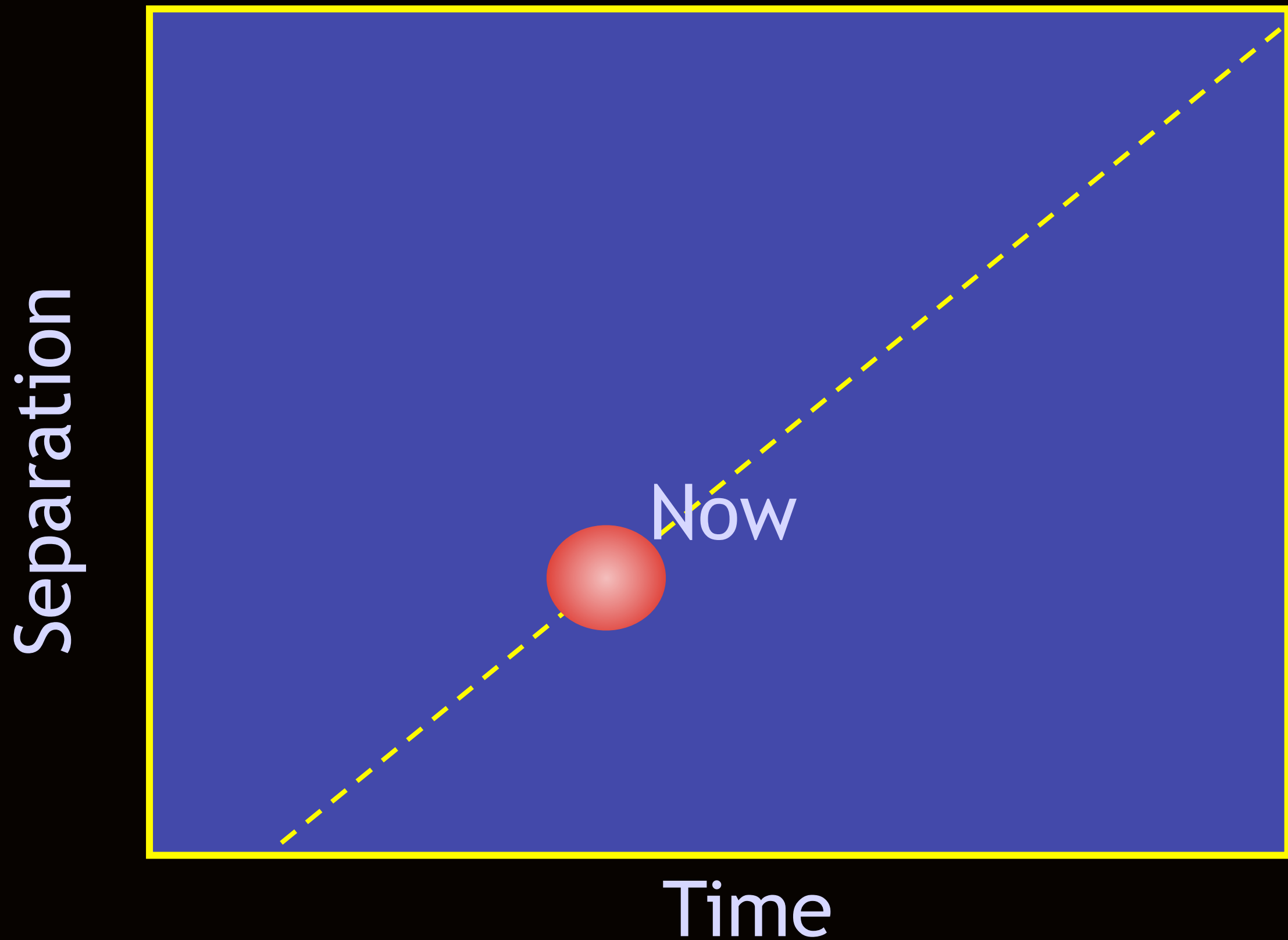


Now

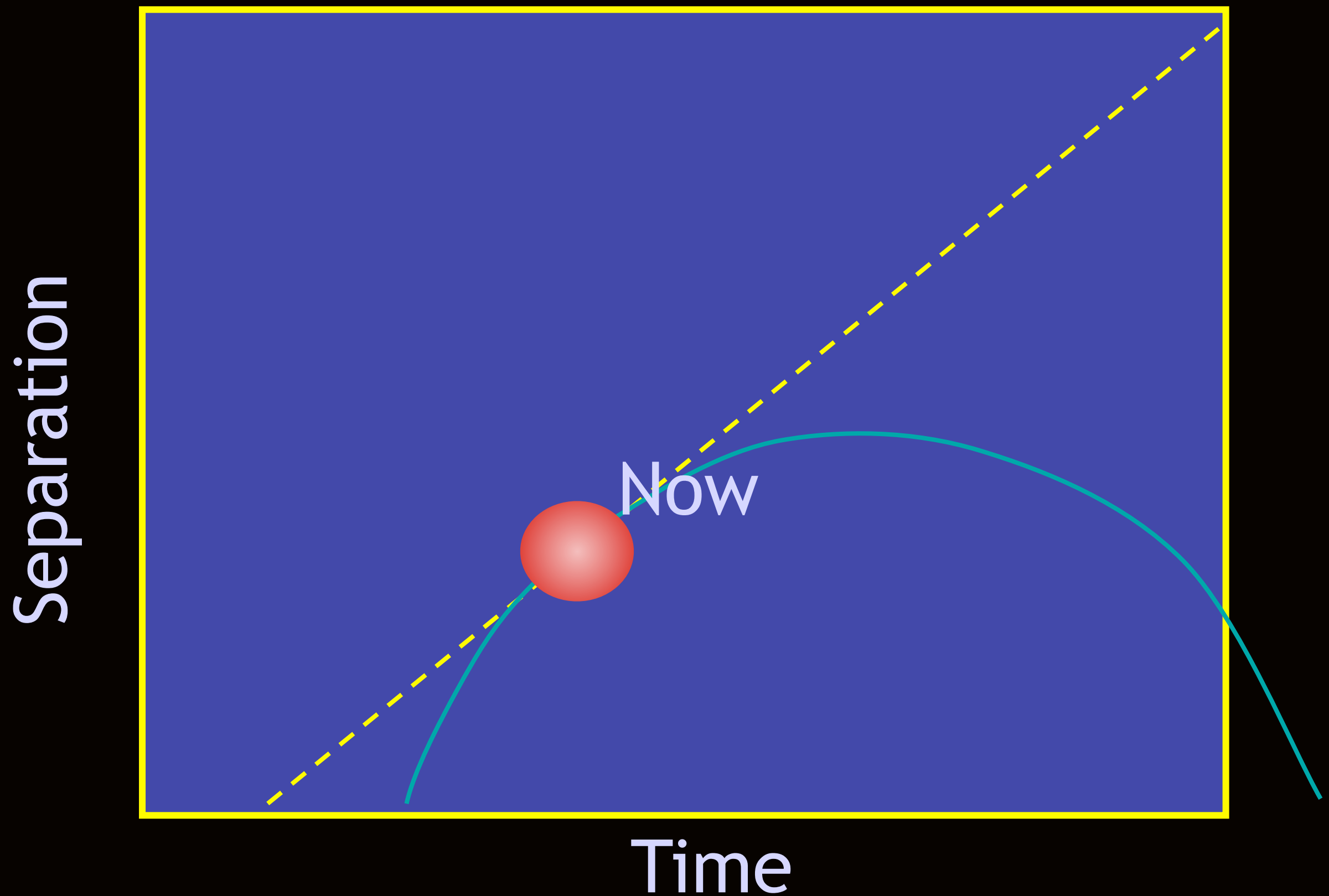
Time



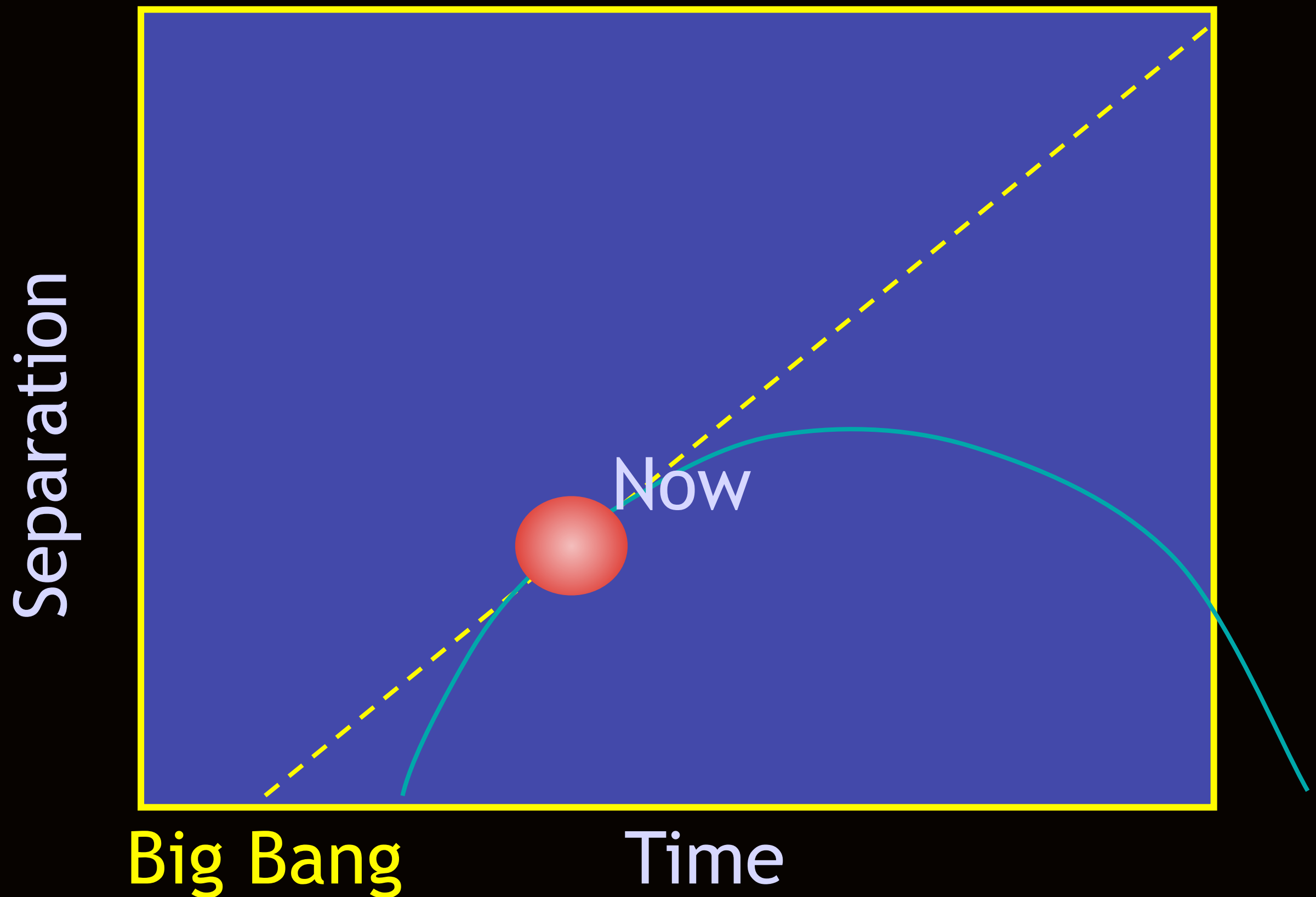
# Looking towards the Future



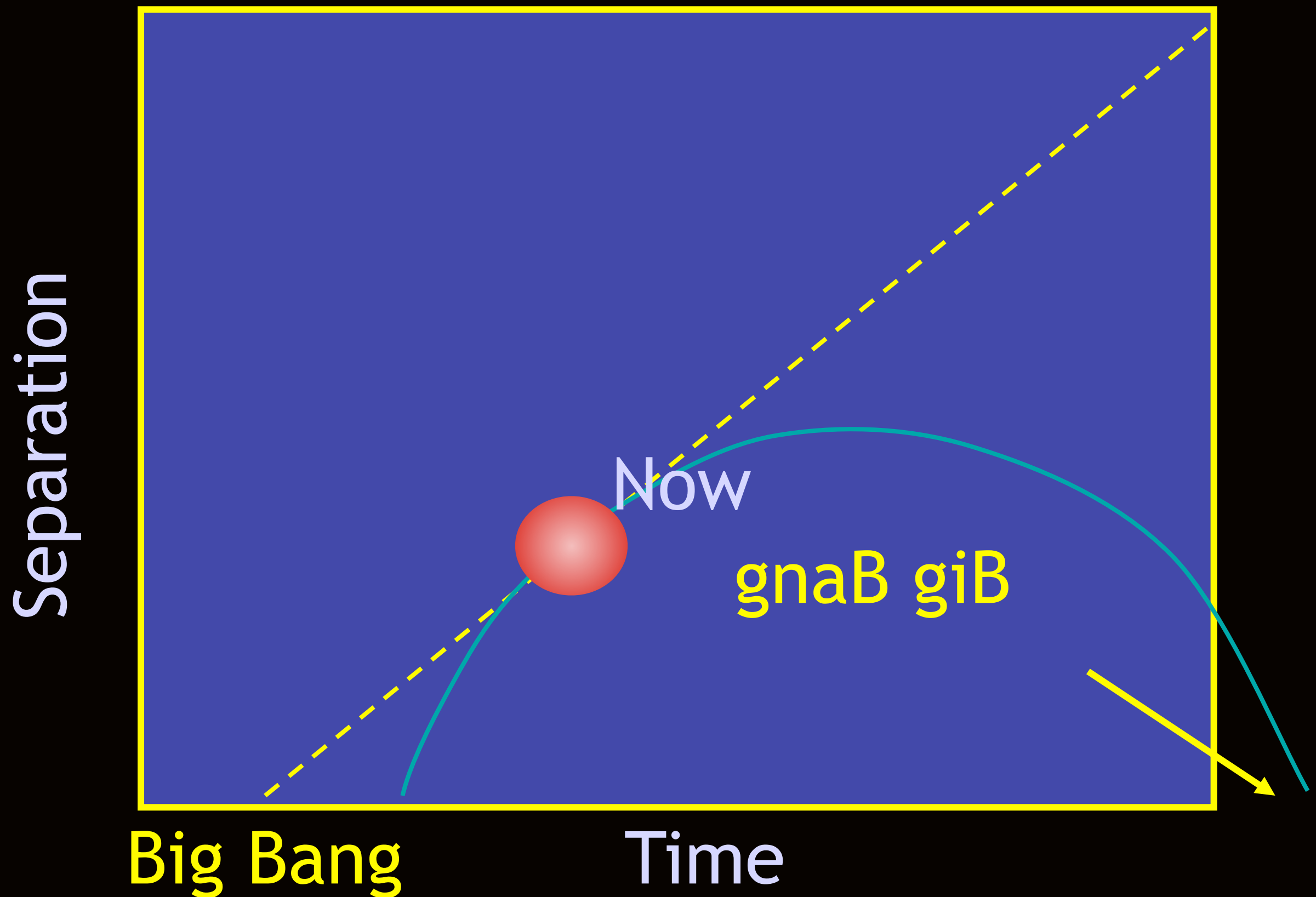
# Looking towards the Future



# Looking towards the Future



# Looking towards the Future



# Measure Universe's Past

Now

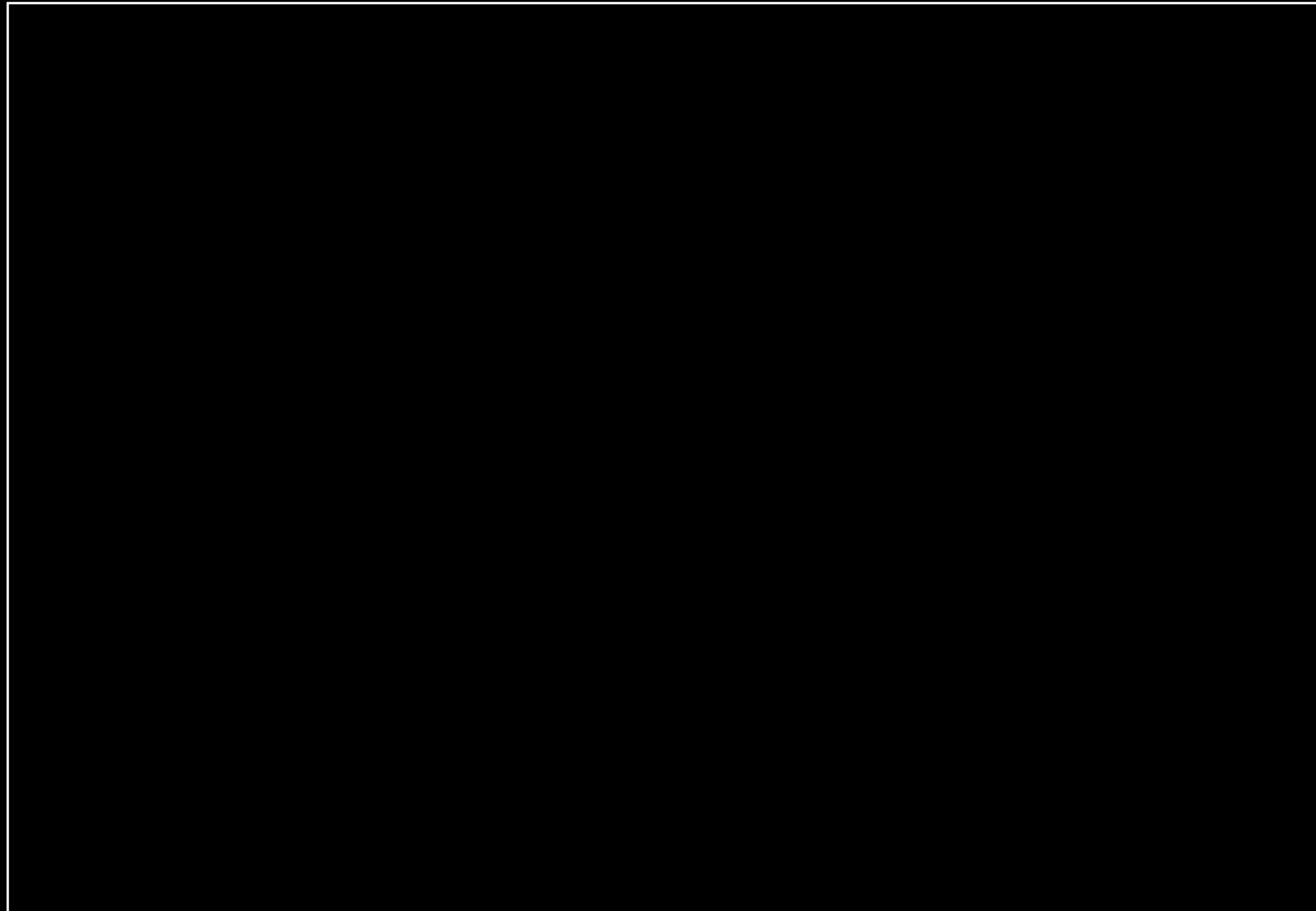
Time

Long Ago

Slow

Expansion Rate

Fast



# Measure Universe's Past

Now

Time

Long Ago

Slow

Expansion Rate

Fast

No Change



# Measure Universe's Past

Now

Time

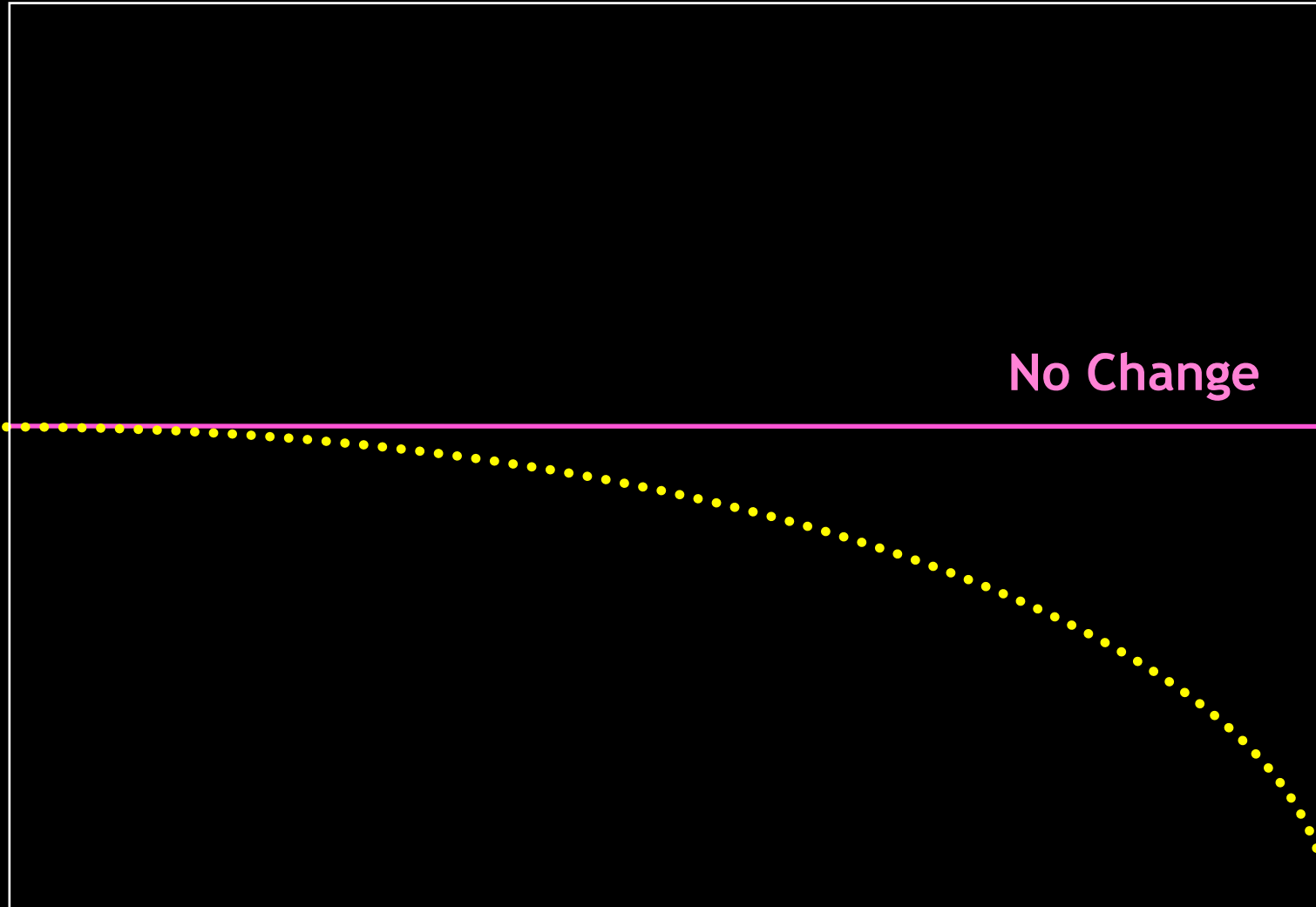
Long Ago

Slow

Expansion Rate

No Change

Fast



# Measure Universe's Past

Now

Time

Long Ago

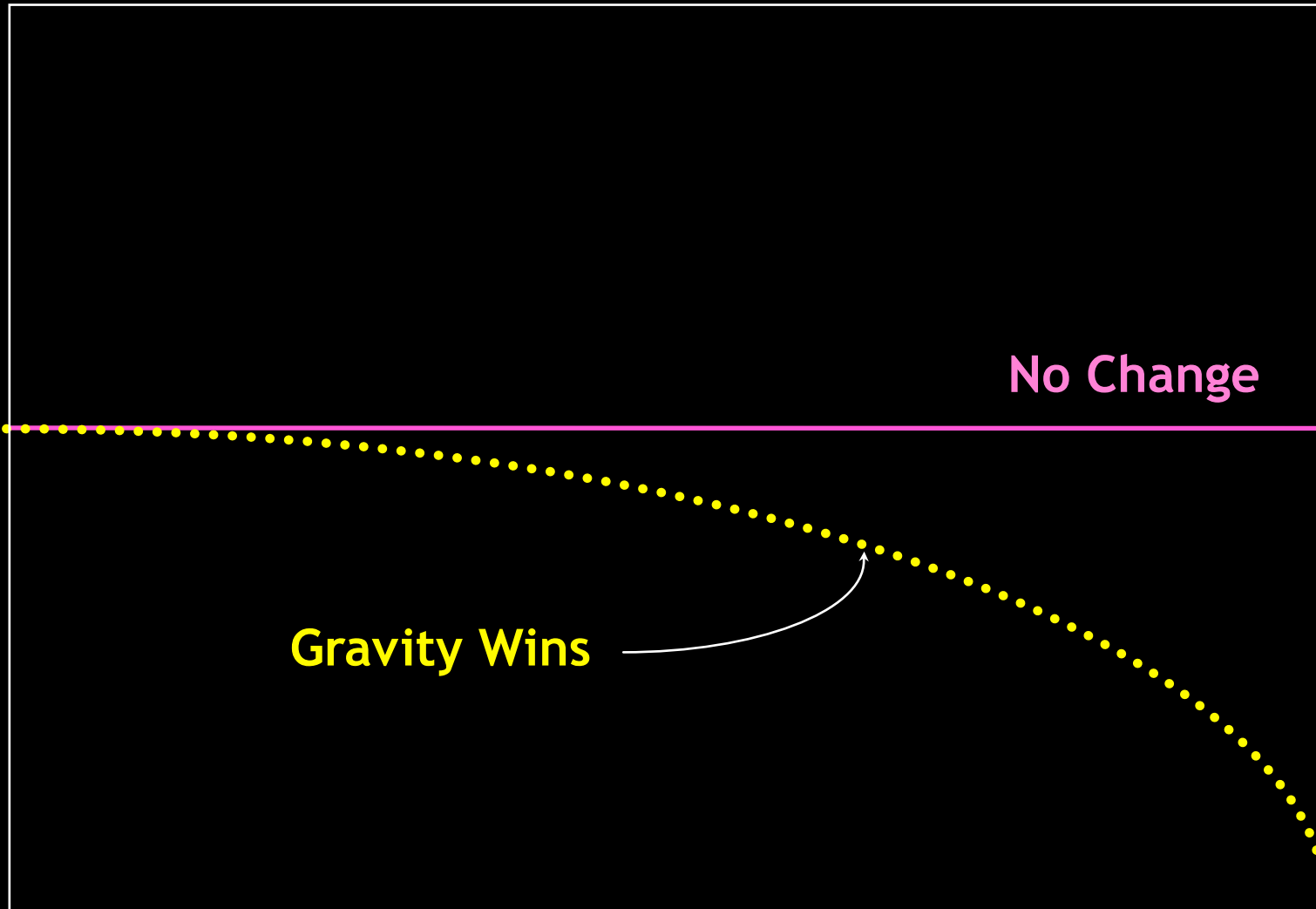
Slow

Expansion Rate

No Change

Gravity Wins

Fast

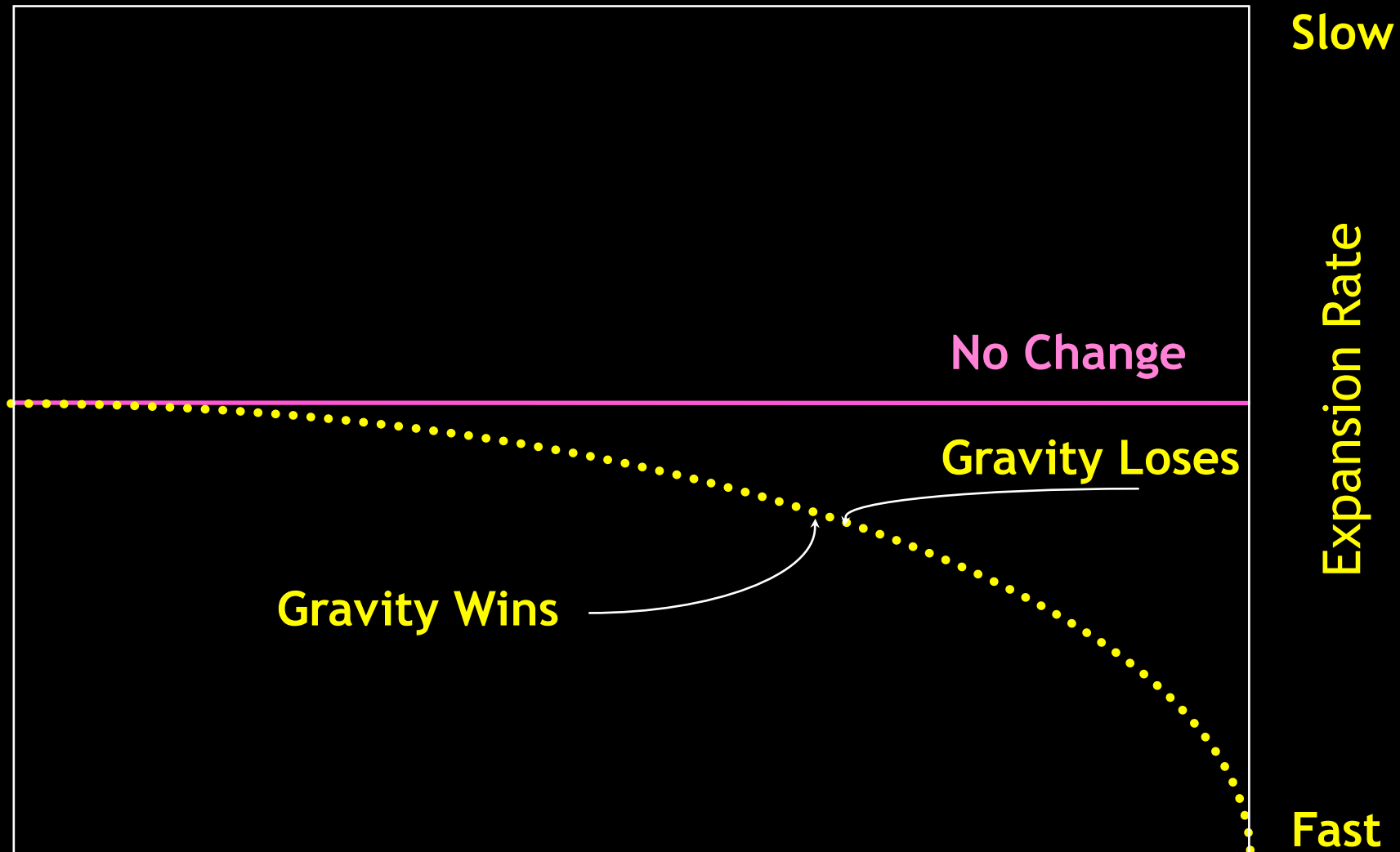


# Measure Universe's Past

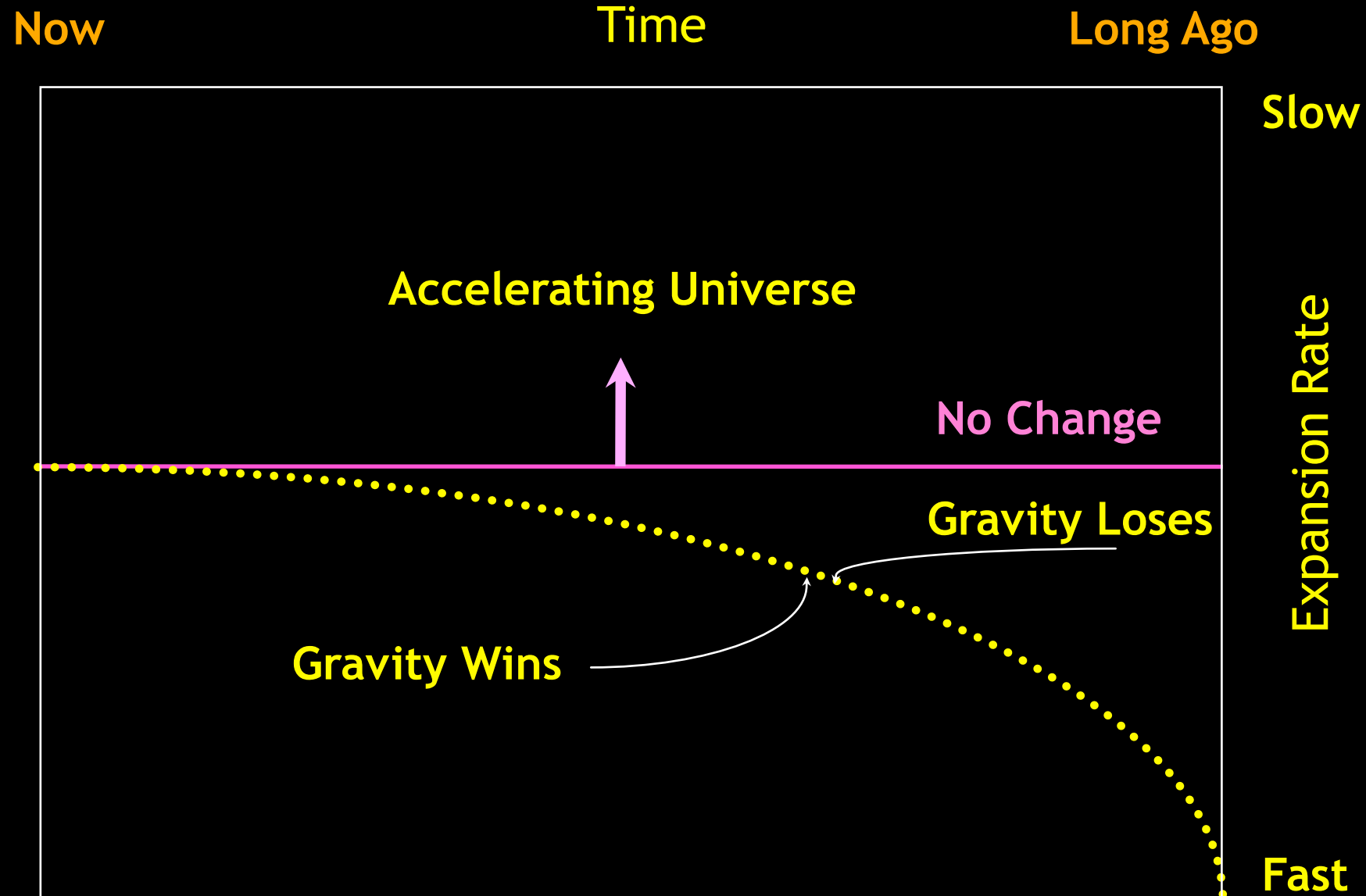
Now

Time

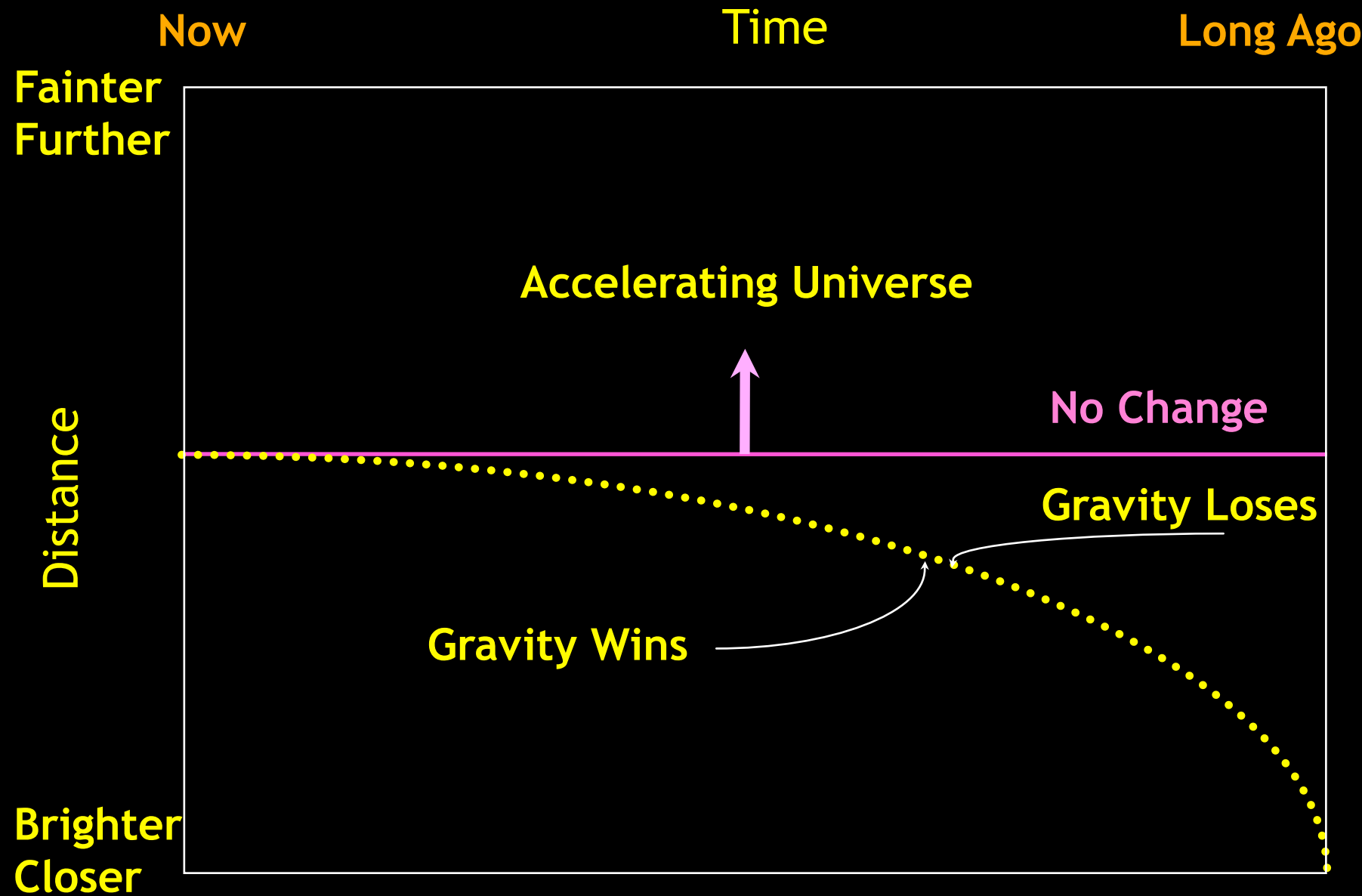
Long Ago



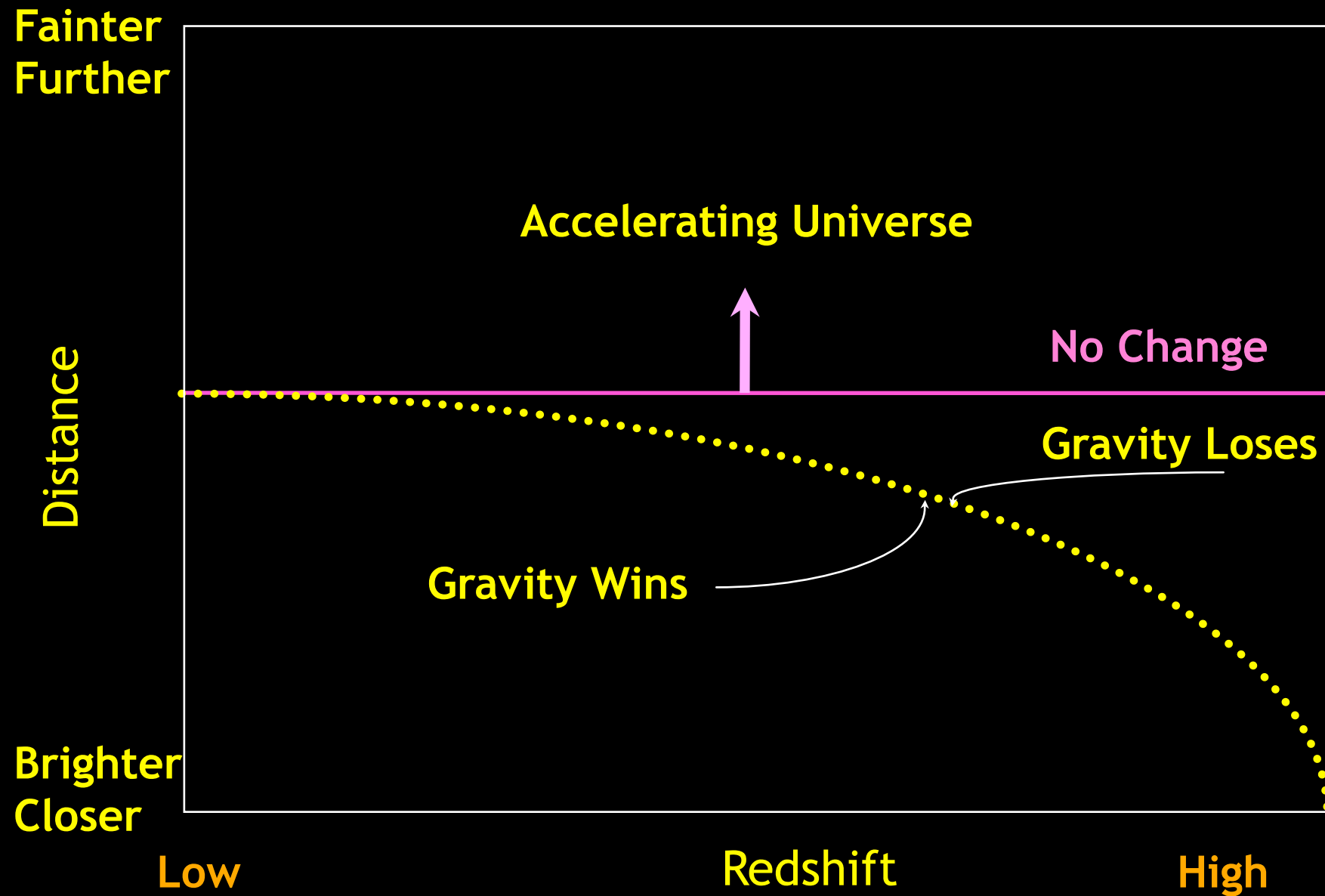
# Measure Universe's Past



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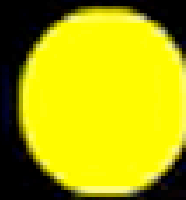


# Type Ia Supernovae





# Sun Earth (10 billion years)





0 days



# First use of Supernovae to Measure Distances

Fritz Zwicky

Charlie Kowal 1968



18in Schmidt Telescope

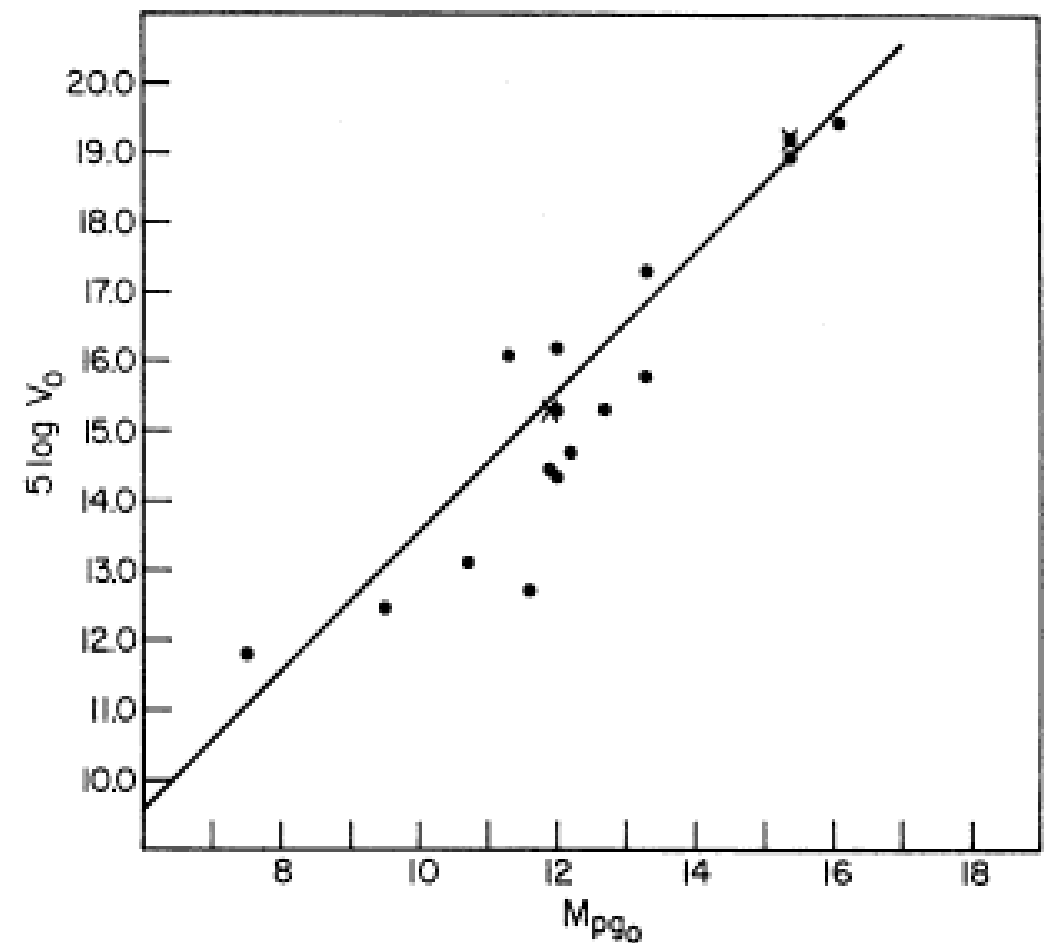


FIG. 1. The redshift-magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

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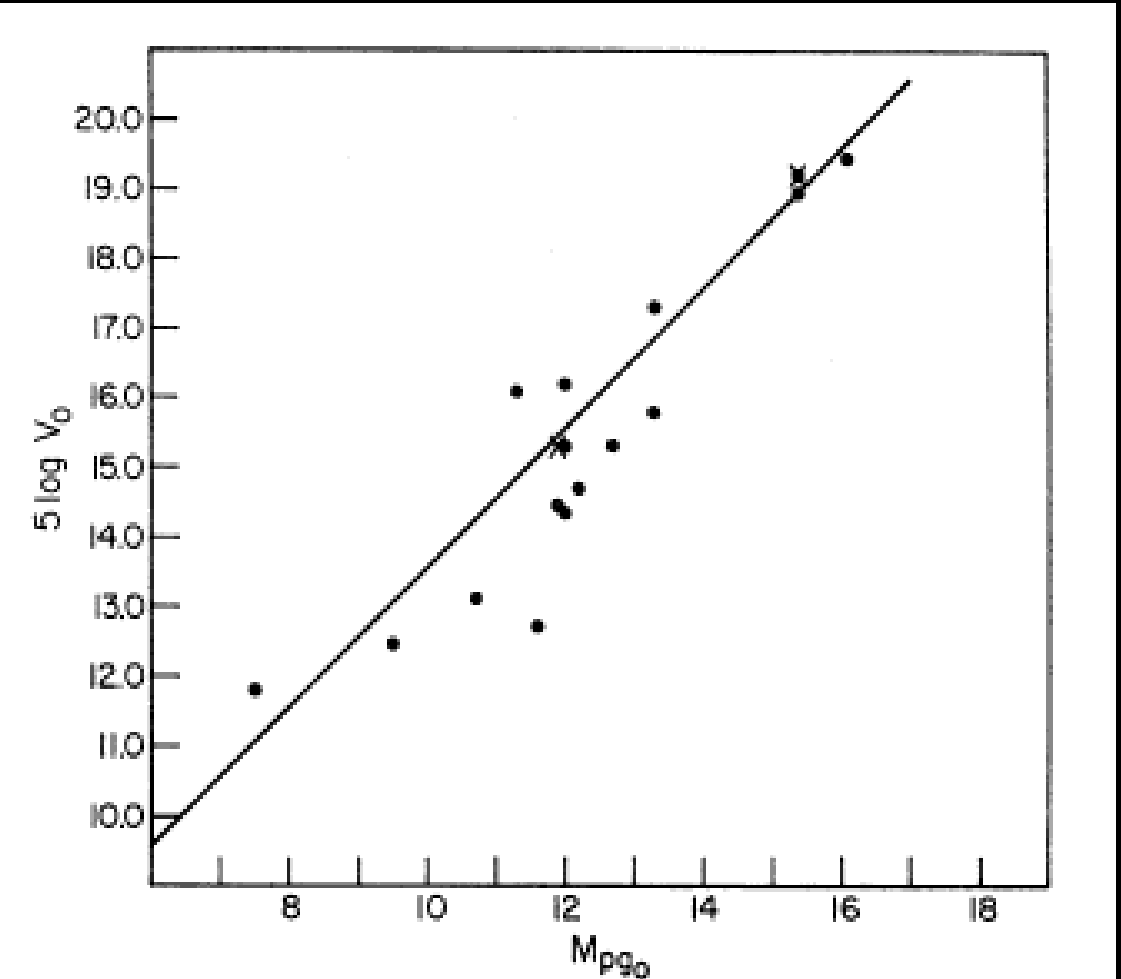


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First Distant SN detected in 1988 by Danish Team



HAMUY



SUNTZEFF SCHOMMER



PHILLIPS



ANTEZANA



MAZA



SMITH



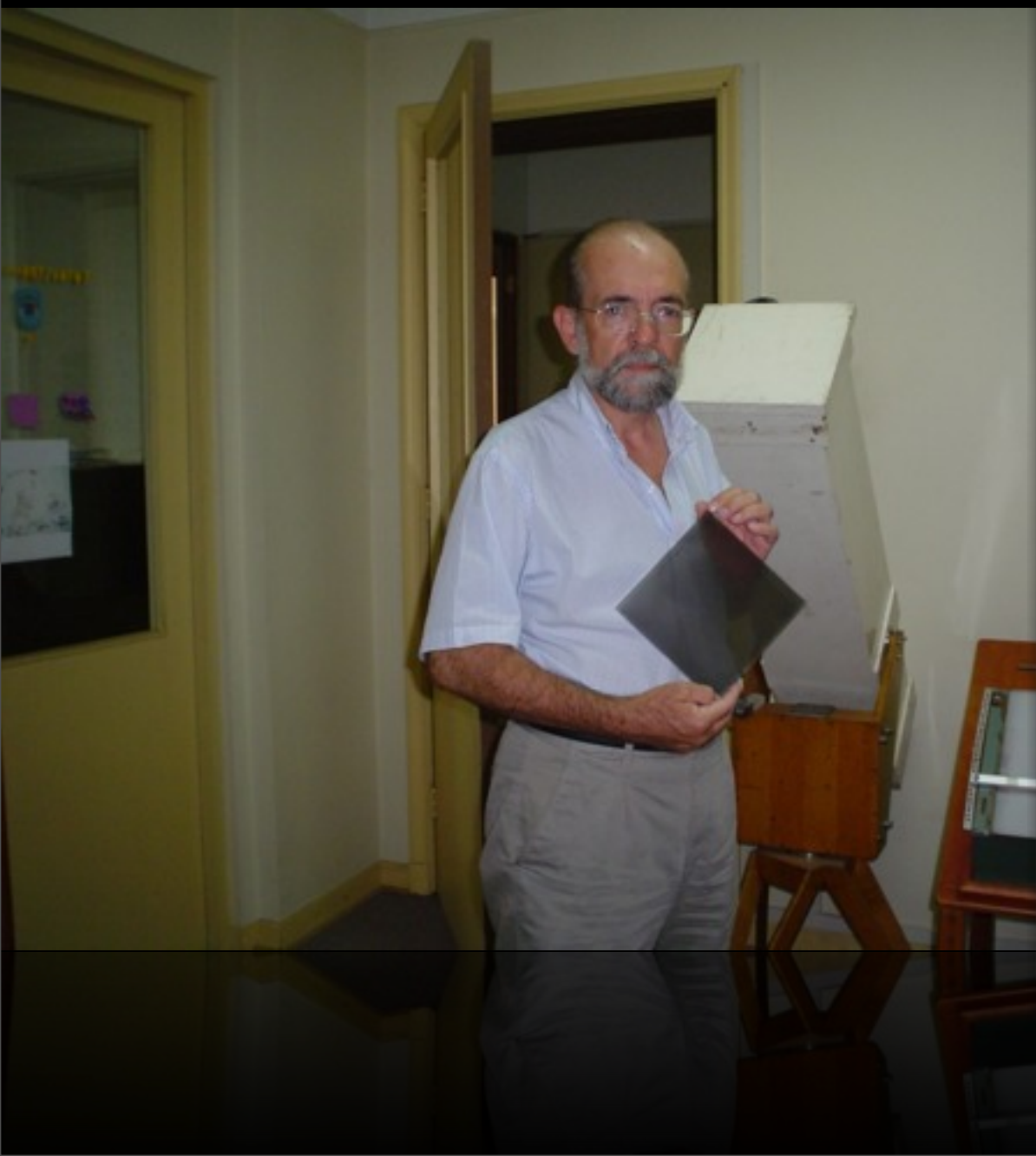
AVILES

WISCHNJEWSKY



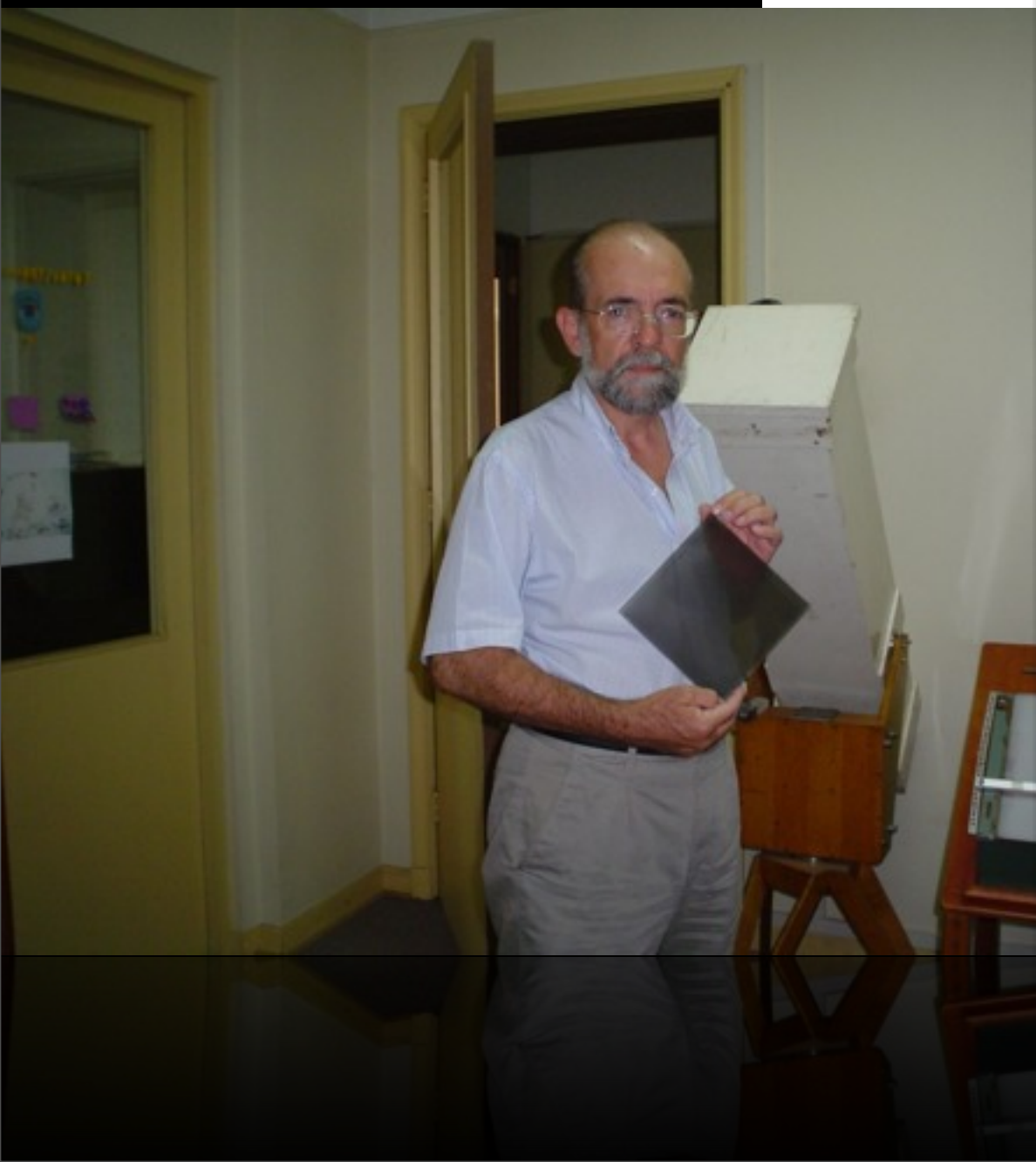
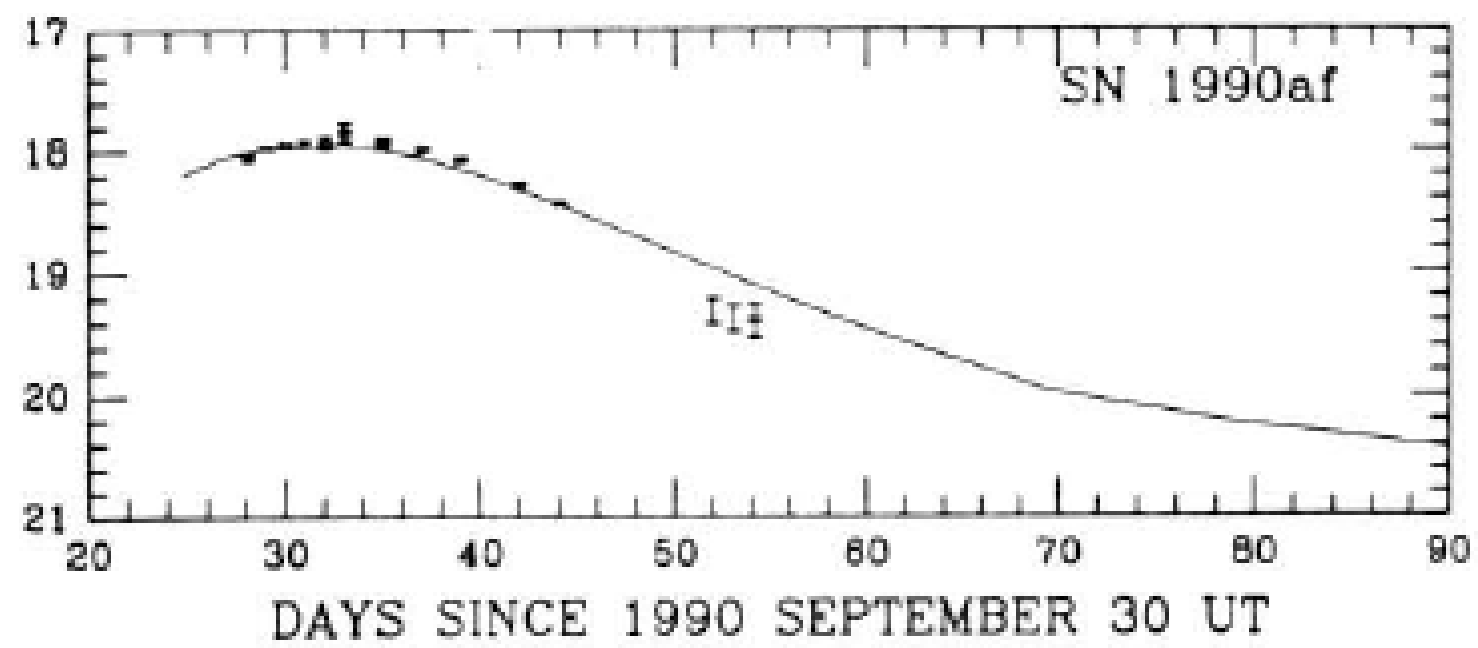
**Calan-Tololo  
SN Search**



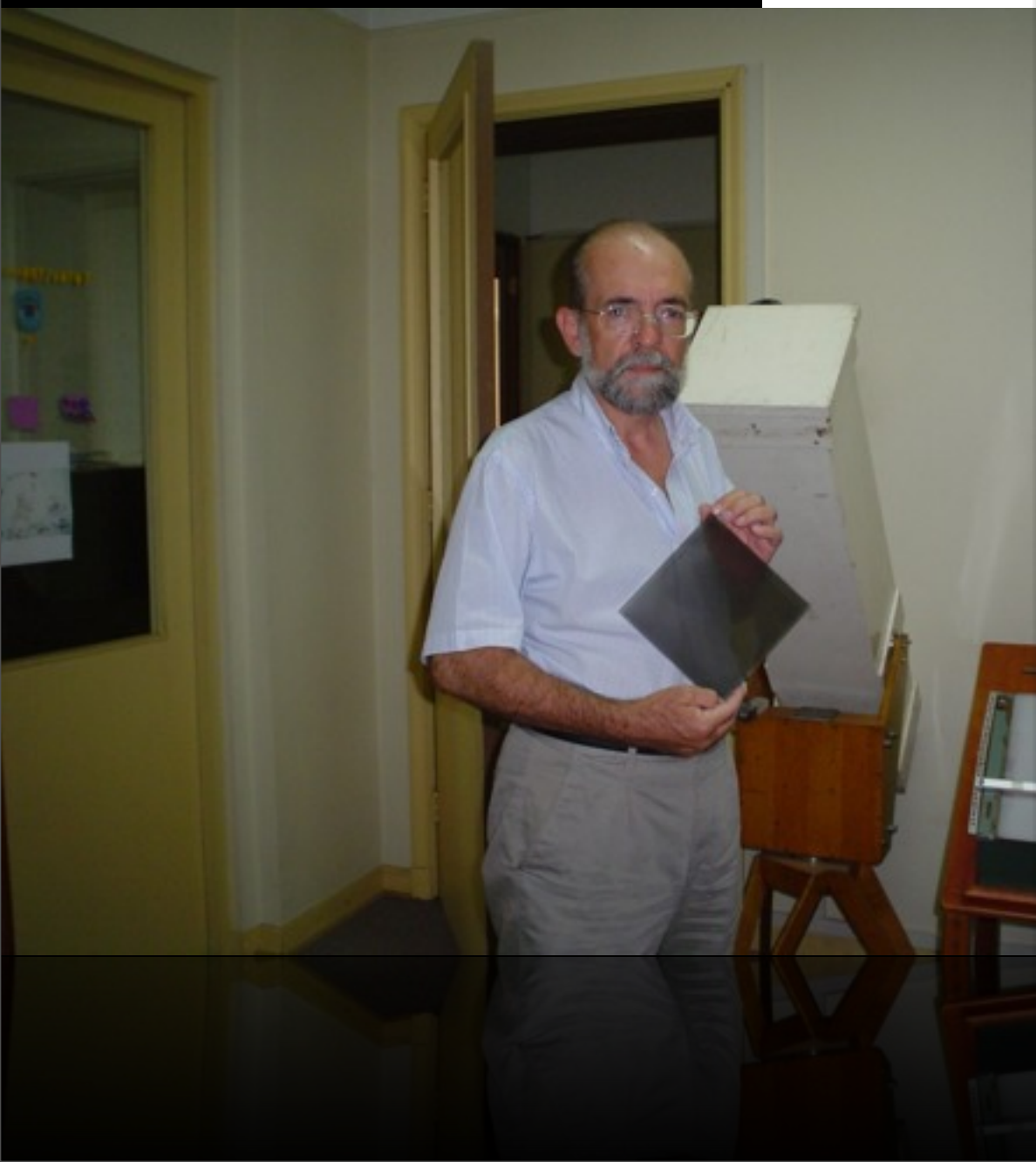
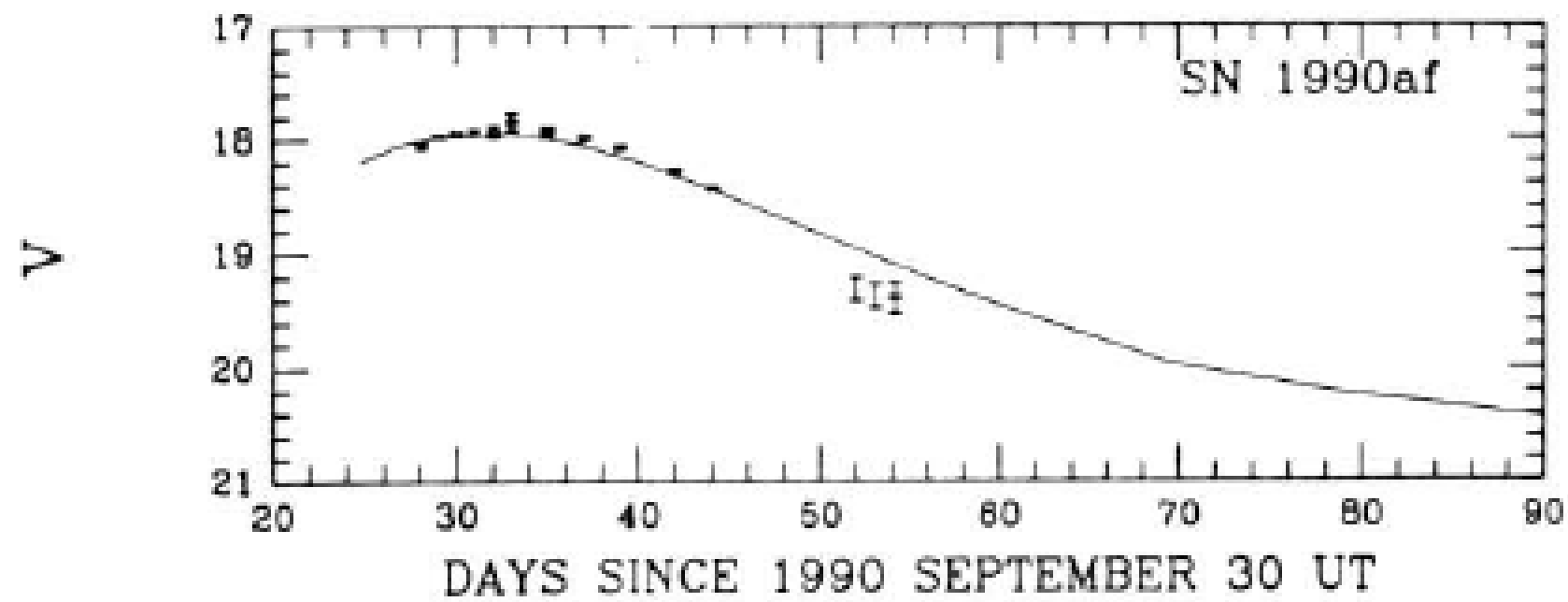




V



SN 1990af: faded  
quickly  
and was fainter  
than  
normal



# Refining Type Ia Distances

**MARK PHILLIPS (1993)**

HOW FAST A SUPERNOVA  
FADES IS RELATED TO ITS  
INTRINSIC BRIGHTNESS.

Three stylized supernova light curves are shown, each consisting of a dotted yellow line forming a peak and a subsequent decline. Above each peak is a bright, multi-pointed starburst representing the supernova's maximum light. The curves are arranged horizontally, with the first being the smallest, the second medium, and the third the largest.

ADAM RIESS WILL EXPLAIN



1994 Visit to Harvard  
Mario Hamuy showed  
us this Diagram.

SN Ia are Precision  
Distance Indicators!

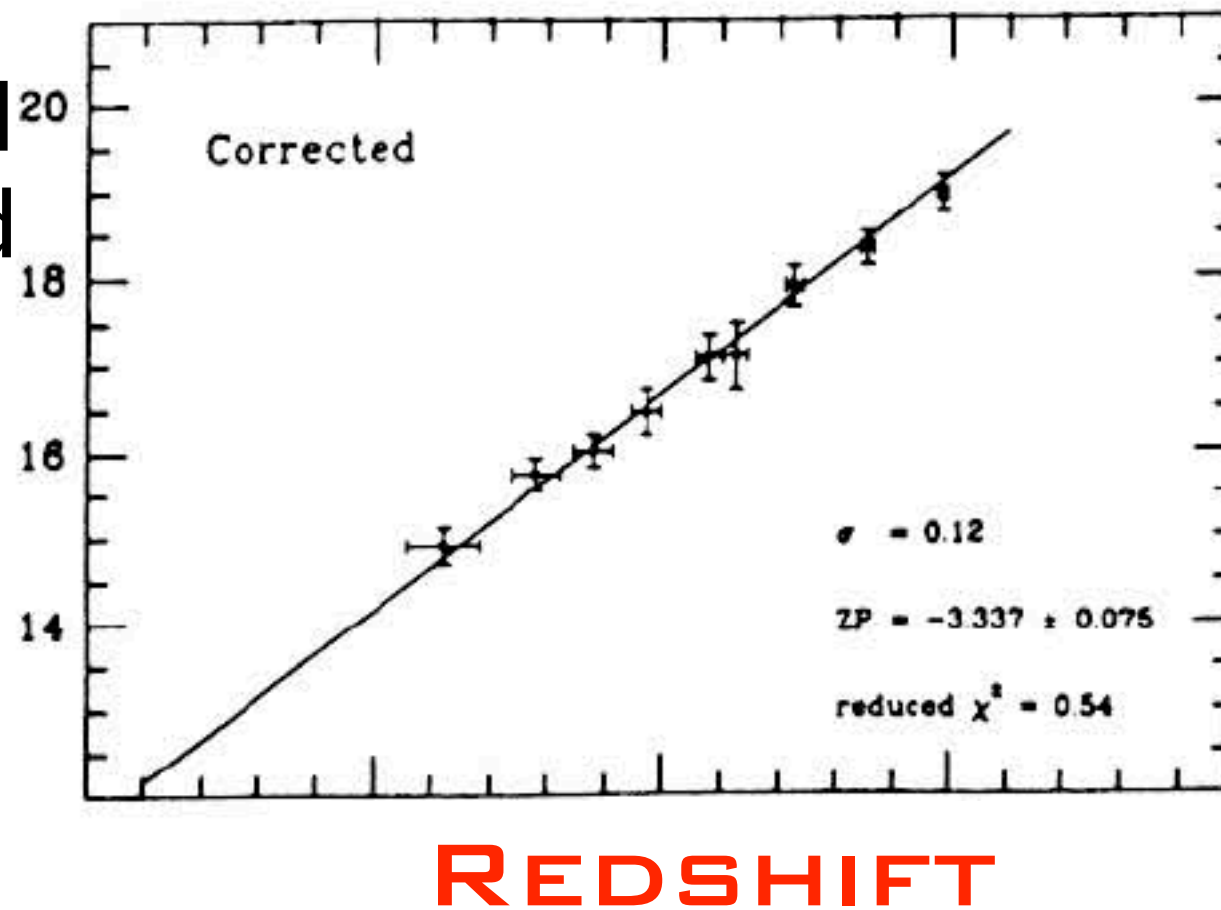


Figure 1: Hubble diagram of SNe Ia in the Calán/Tololo SN survey.

1994 Visit to Harvard  
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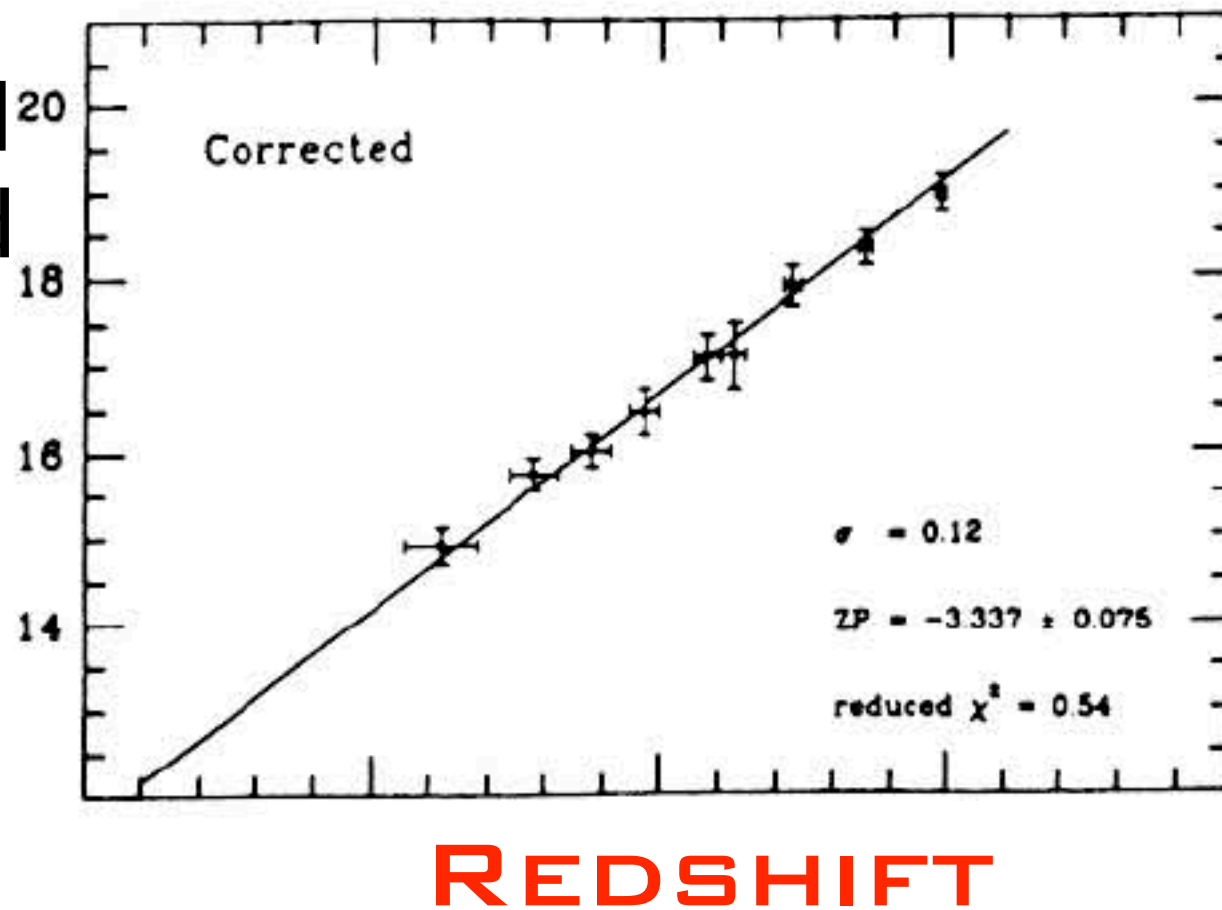


Figure 1: Hubble diagram of SNe Ia in the Calán/Tololo SN survey.

Eventually 29 Type Ia supernovae  
Provided the fundamental basis of  
using SN Ia as accurate distance  
indicators

# The Birth of the High-Z Team

- A month later, Saul Perlmutter asked us at Harvard to confirm a possible supernovae – we found it to be a distant SN

## **SUPERNOVAE 1994F, 1994G, 1994H**

S. Perlmutter, C. Pennypacker, G. Goldhaber, A. Goobar, R. Pain, B. Grossan, A. Kim, M. Kim, and I. Small, Lawrence Berkeley Laboratory and the Center for Particle Astrophysics, Berkeley, report three discoveries from a search for pre-maximum-light, high-redshift supernovae by themselves and R. McMahon, Institute of Astronomy, Cambridge; P. Bunclark, D. Carter, and M. Irwin, Royal Greenwich Observatory; M. Postman and W. Oegerle, Space Telescope Science Institute; T. Lauer, National Optical Astronomy Observatory; and J. Hoessel, University of Wisconsin. Following are given the designation, date of first detection, discovery magnitude and telescope (INT = 2.5-m Isaac Newton Telescope; KPNO = 4-m Kitt Peak telescope), supernova position for equinox 1950.0, offsets from the host galaxy's center, and date of the previous image of the galaxy not showing the supernova (to limiting mag about 24): SN 1994F, Jan. 9, R = 22.0, INT, R.A. = 11h47m25s.15, Decl. = +10o59'38".8, 1".1 west, 0".2 north, 1993 Dec. 22; SN 1994G, Feb. 13, I = 21.8, KPNO, R.A. = 10h16m17s.38, Decl. = +51o07'23".5, 1".4 east, 0".1 north, 1994 Jan. 16; SN 1994H, Jan. 8, R = 21.9, INT, R.A. = 2h37m32s.22, Decl. = -1o46'57".5, 1".2 west, 0".1 south, 1993 Dec. 20. On Jan. 18, spectra of SN 1994F were obtained by J. B. Oke with the Keck Telescope Low Resolution Imaging Spectrograph; the host galaxy redshift is 0.354, and the spectrum of SN 1994F matched that of a type-Ia supernova a week past maximum light. On Mar. 9 and 10, spectra of SN 1994G were obtained by A. Riess, P. Challis, and R. Kirshner at the Multiple Mirror Telescope, in which emission lines of [O II] and [O III] from the host galaxy give a redshift of  $z = 0.425$ ; the spectrum of the SN 1994G, though noisy, is consistent with a type-I supernova about a week past maximum light. SN 1994H was observed on numerous nights from Jan. 10 to Feb. 16 at the INT, at Kitt Peak by G. Jacoby and others, at the European Southern Observatory by M. Turrato, and at Siding Spring Observatory by M. Dopita; the resulting photometry is consistent with a type-Ia supernova at an implied redshift of about 0.32 (the host galaxy is on the periphery of a cluster with that redshift), with maximum light around Jan. 12.

# The Birth of the High-Z Team

- I was down visiting Nick Suntzeff in July 1994, and we discussed the idea of doing our own High-Z SN Ia



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## Observing Proposal Cerro Tololo Inter-American Observatory

Date: September 29, 1994

Proposal number:

**TITLE:** A Pilot Project to Search for Distant Type Ia Supernovae

**PI:** N. Suntzeff

CTIO, Casilla 603, La Serena Chile

Grad student? N

nsuntzeff@ctio.noao.edu

56-51-225415

**CoI:** B. Schmidt

CfA/MSSSO, 60 Garden St., Cambridge, MA 02138

Grad student? N

brian@cfanewton.harvard.edu

617 495 7390

**Other CoIs:** C. Smith, R. Schommer, M. Phillips, M. Hamuy, R. Aviles (CTIO); J. Maza (UCHile); A. Riess, R. Kirshner (Harvard); J. Spyromilio, B. Leibundgut (ESO)

### Abstract of Scientific Justification:

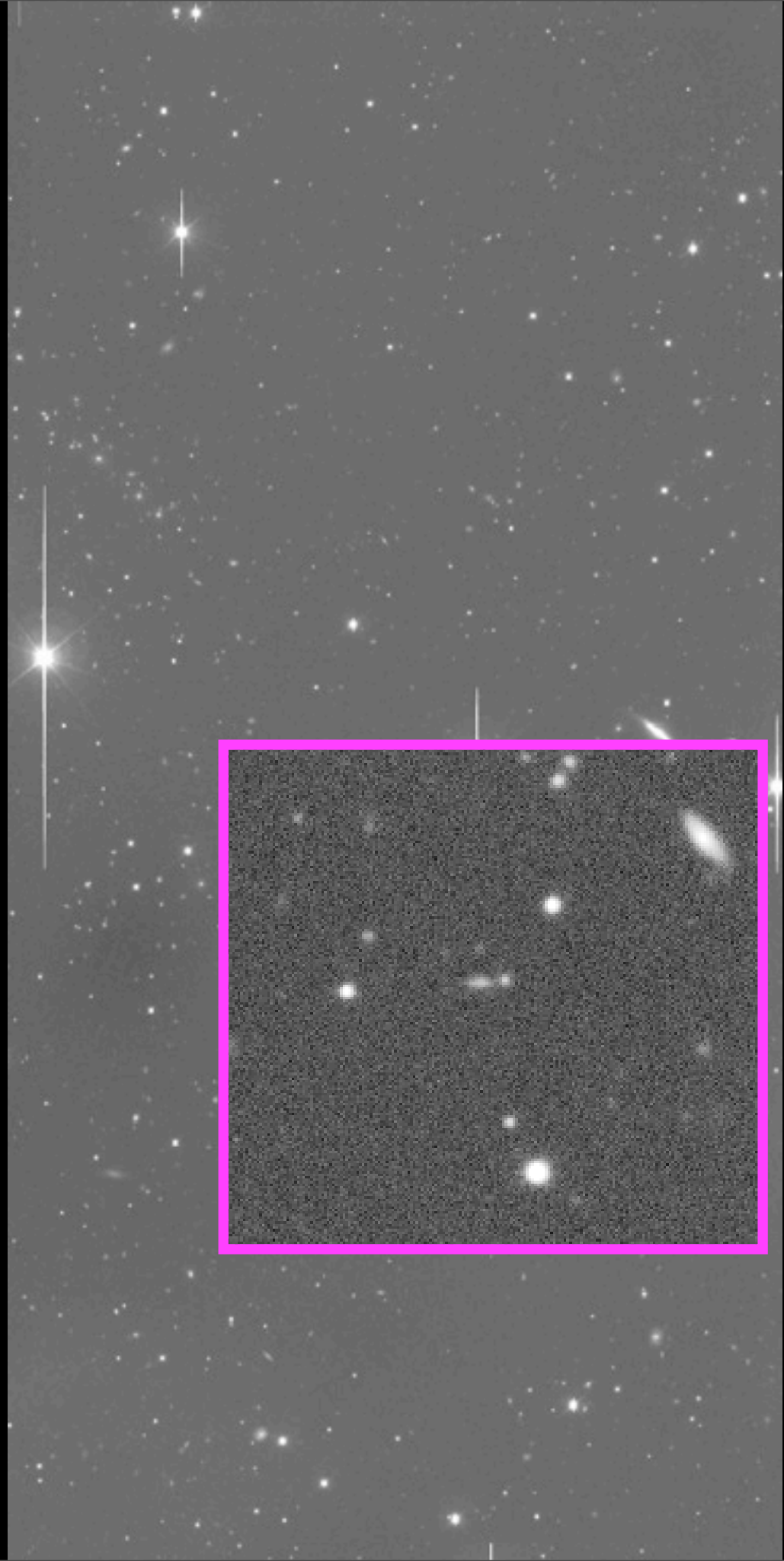
We propose to initiate a search for Type Ia supernovae at redshifts to  $z \sim 0.3 - 0.5$  in equatorial fields using the CTIO 4m telescope. This program is the next step in the Calán/Tololo SN survey, where we have found  $\sim 30$  Type Ia supernovae out to  $z \sim 0.1$ . The proposed program is a pilot project to discover fainter SN Ia's using multiple-epoch CCD images from the 4m telescope. We will follow up these discoveries with CCD photometry and spectroscopy both at CTIO and at several observatories in both hemispheres. With the spectral classification and light curve shapes, we can use our calibrations of the absolute magnitudes of SN Ia's from the Calán/Tololo survey to place stringent limits (Figure 2) on  $q_0$  in a reasonable time-frame. Based on the statistics of discovery from the Calán/Tololo SN survey, we can expect to find about 3 SNe Ia per month.

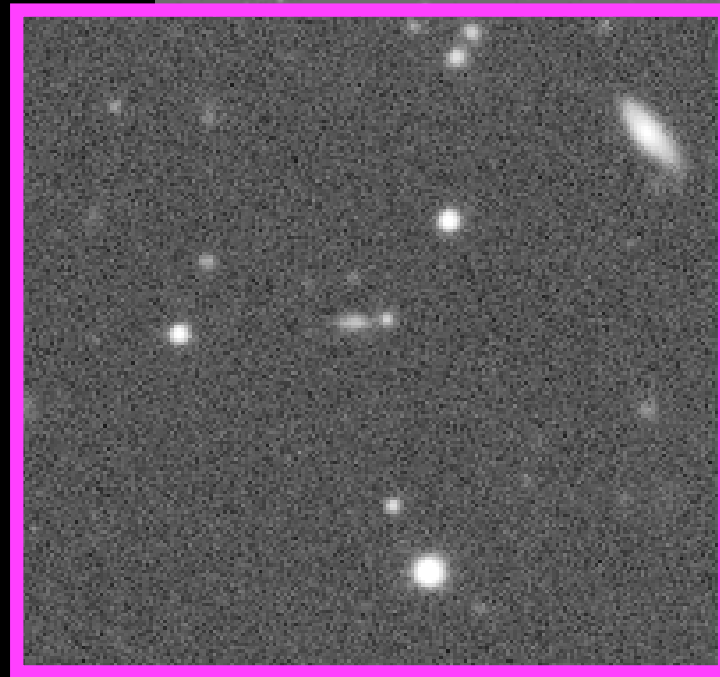
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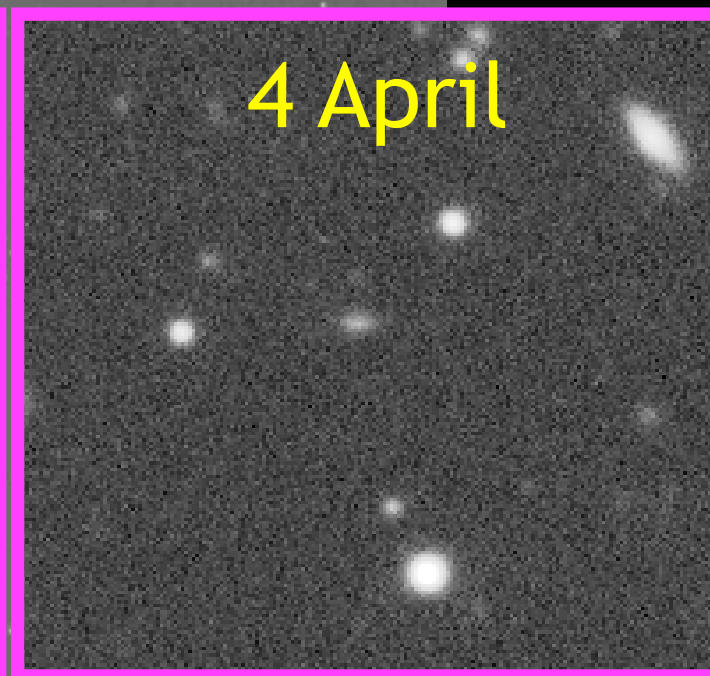
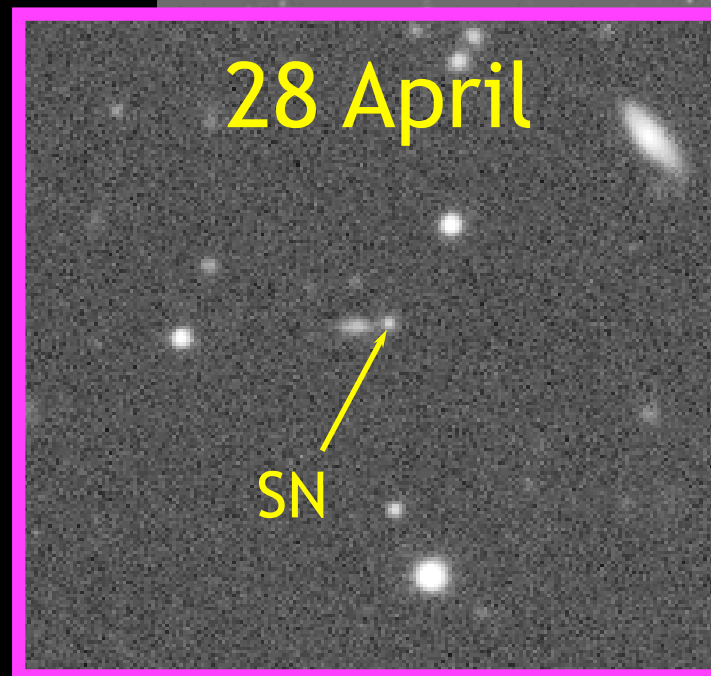
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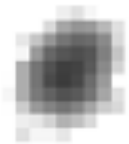






## A SN Ia at $z=0.48$

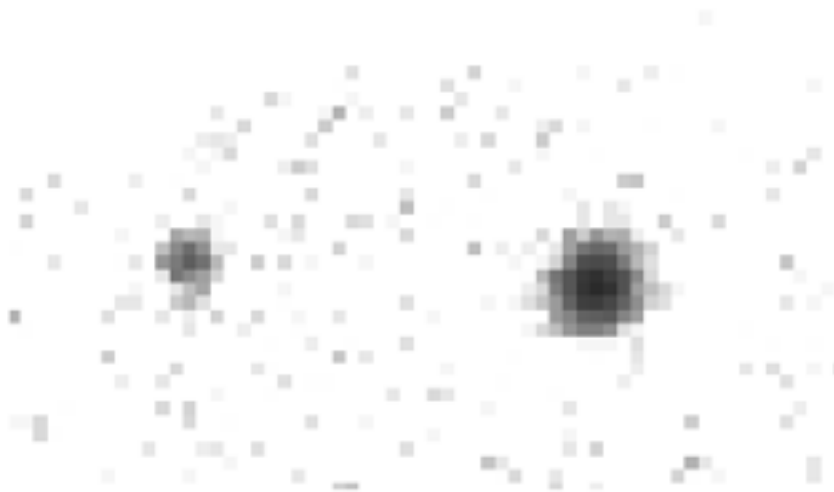
Raw Observation



Convolved Observation



Subtraced Image



Template Image



Subtraced Image



Template Image



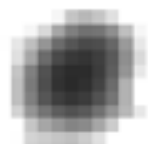
## Our First Supernova SN 1995K

# A SN Ia at $z=0.48$

Raw Observation



Convolved Observation



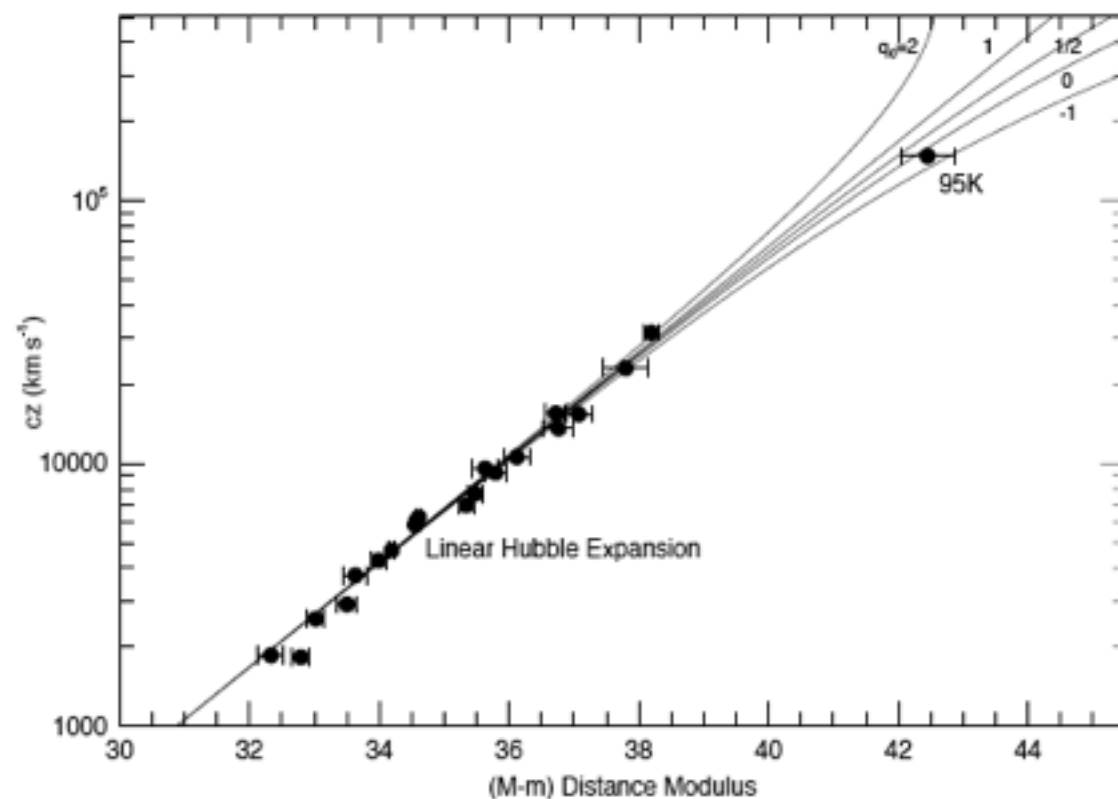
Subtraced Image



Template Image

## Our First Supernova SN 1995K

Hubble Diagram of SNe Ia



### Observing Proposal Cerro Tololo Inter-American Observatory

Date: September 30, 1995

Proposal number:

**TITLE:** A Search for Distant Type Ia Supernovae to Measure  $q_0$

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Time (Billions of Years)

.1

1.5

8

Fainter  
Further

Relative Distance

Brighter  
Closer

