Astr 102: Introduction to Astronomy

Fall Quarter 2009, University of Washington, Željko Ivezić

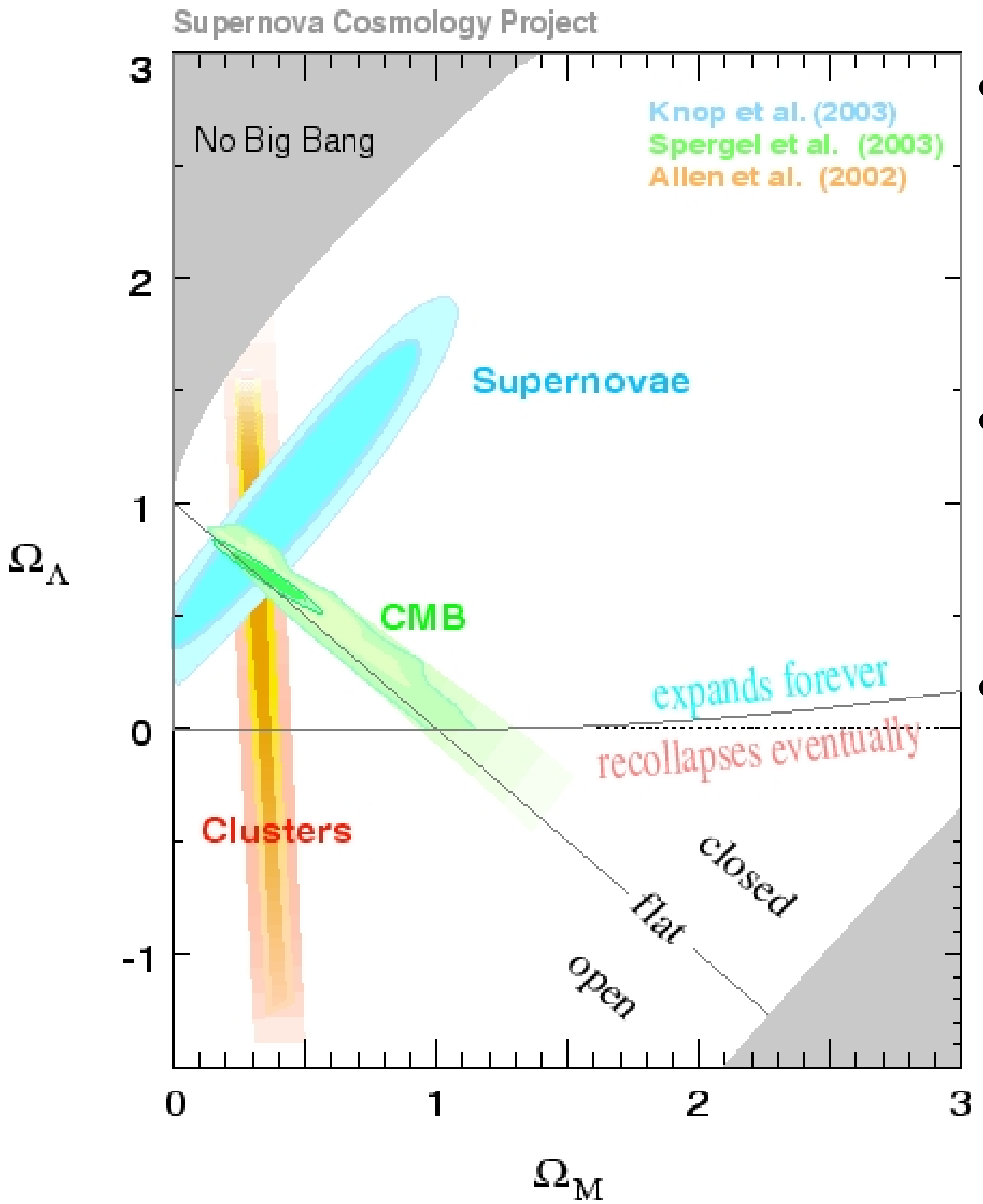
Lecture 17:

Dark Matter, Dark Energy and Cosmological Models

Outline

Observational Cosmology: observations that allow us to test our models for evolution of the whole Universe!

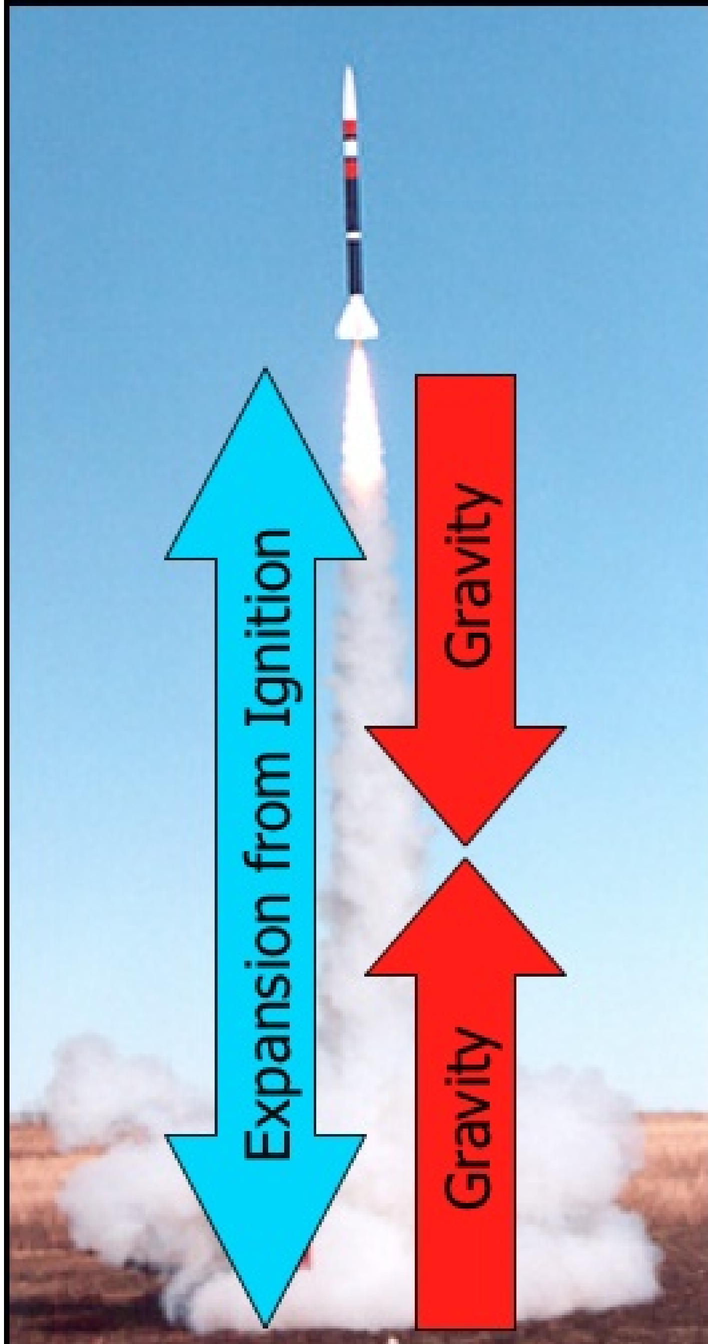
- Dark matter: rotation curves
- Dark matter: gravitational lensing
- Gamma-ray bursts
- Standard candles: supernovae (type Ia)
- Nucleosynthesis
- Cosmic microwave background
- **Cosmological models**



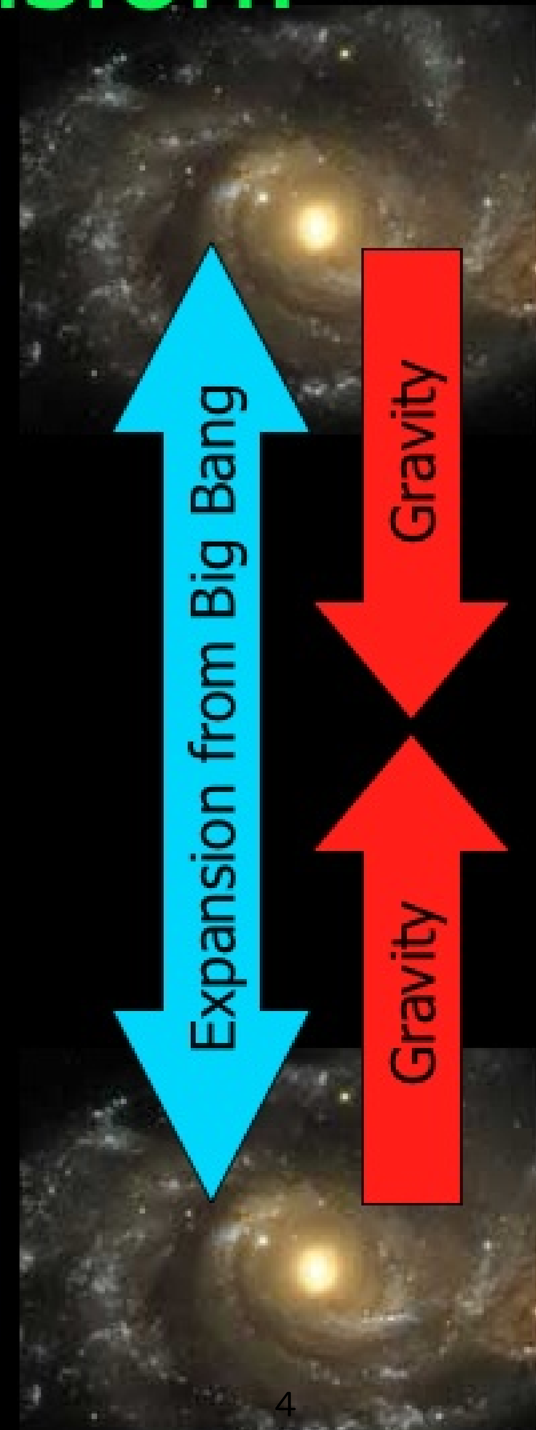
The Cosmological Concordance Model

- A large number of fundamentally different observations are explained with the same model: the expansion of the Universe after the Big Bang
- There is no other theory except the Big Bang that can explain all these observations **simultaneously**
- How do we combine very different observations, such as expansion of the Universe, the abundances of light elements, dark matter distribution, cosmic microwave radiation, and others, into a coherent model for evolution of the Universe?

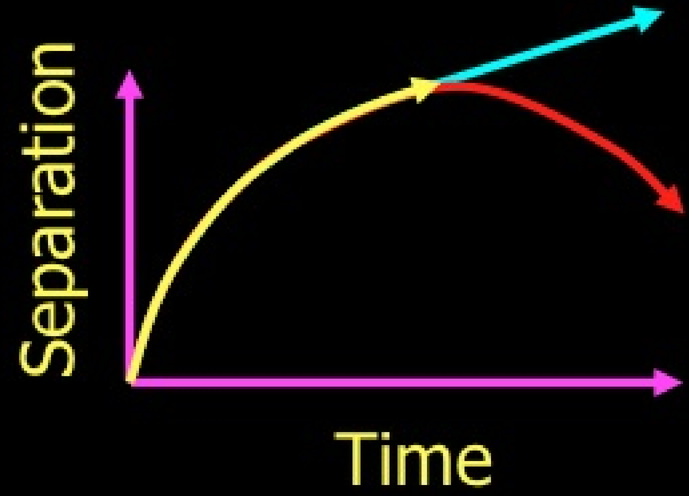
Gravity slows the expansion!



vs.



We need to know two numbers:



$V = H_0 D$

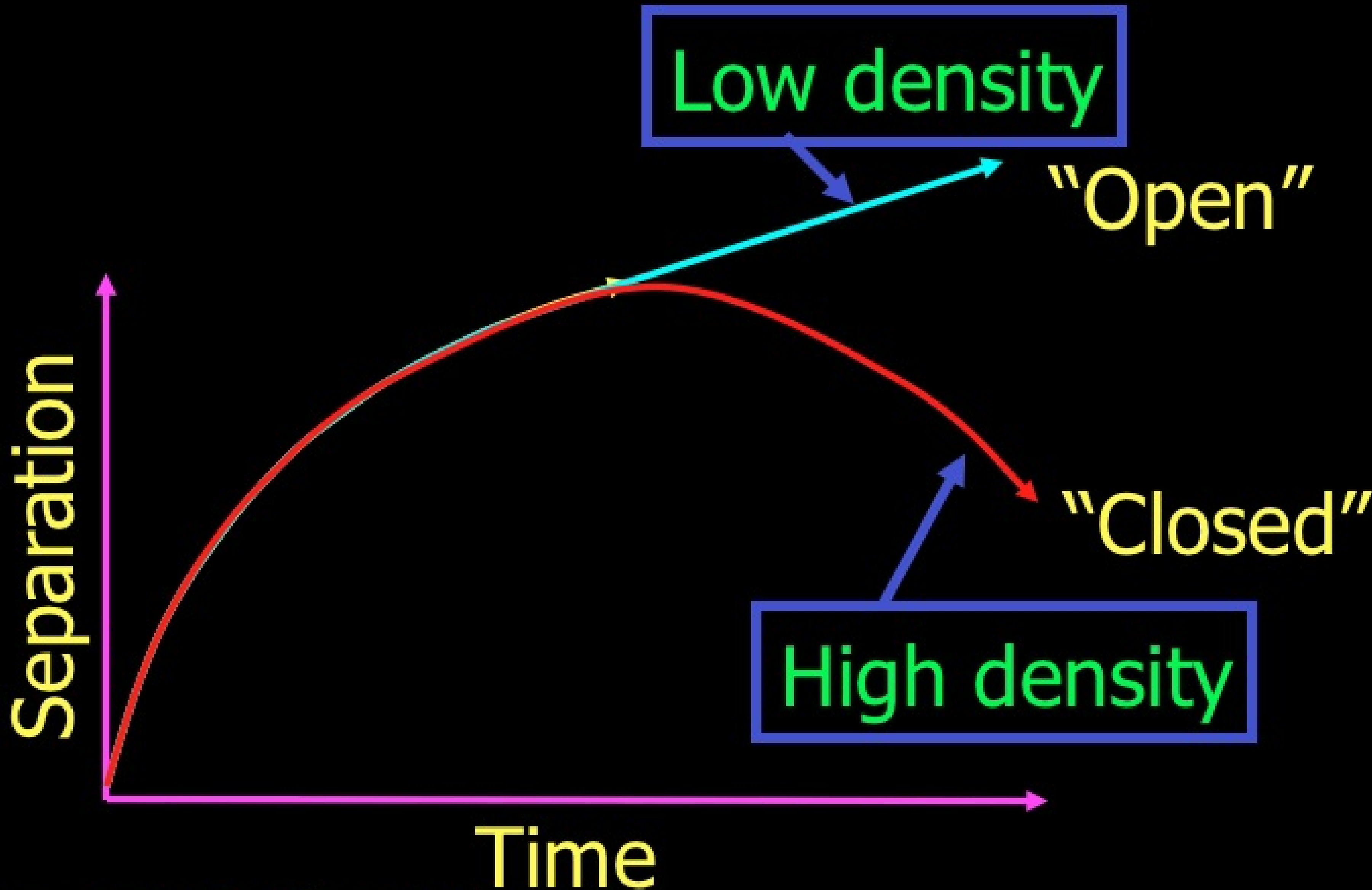
H_0

Depends on:

- The speed with which the separation is increasing
- The strength of gravity

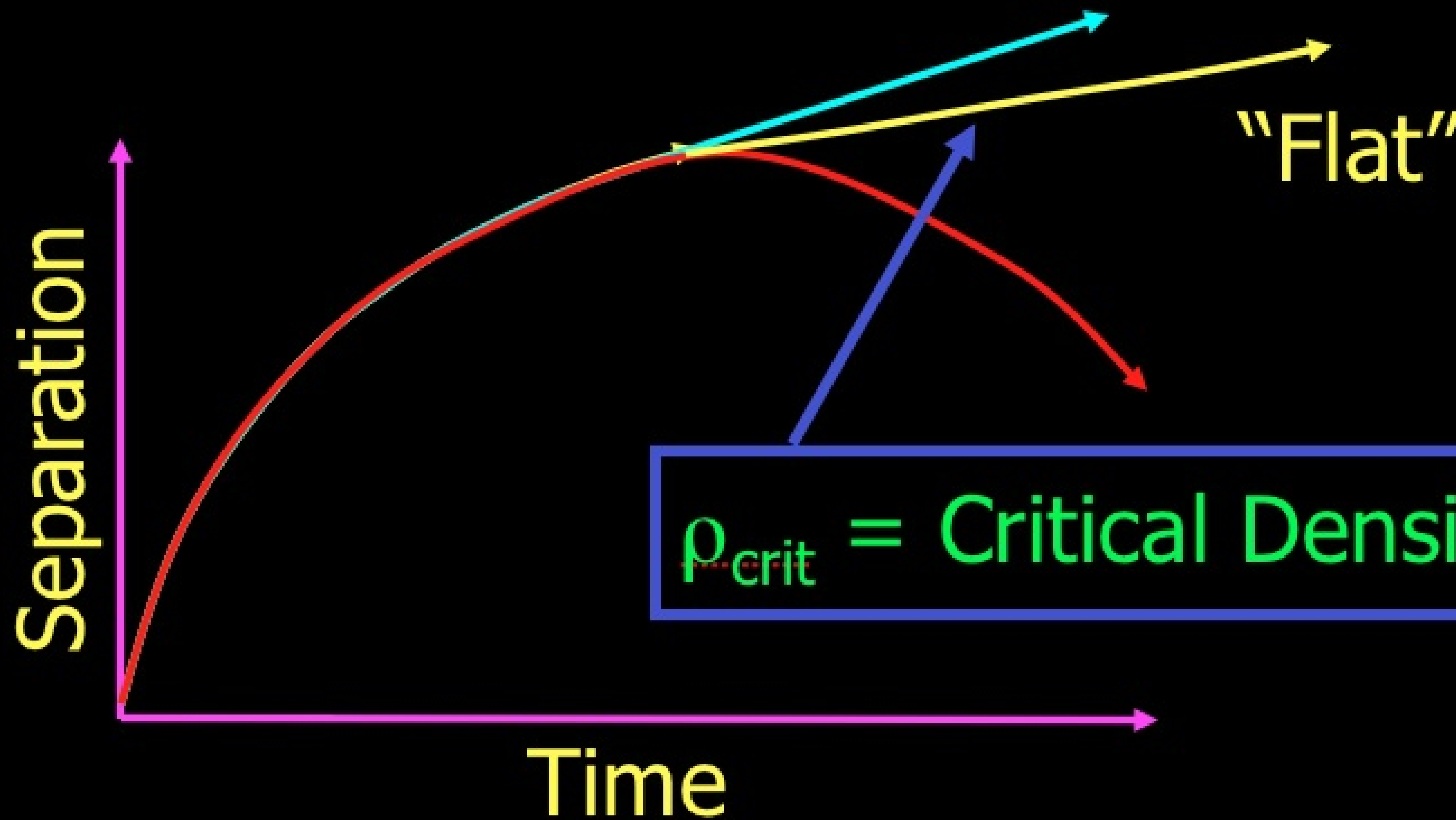
The average density of the Universe

The density determines if the universe will expand forever or will recollapse*



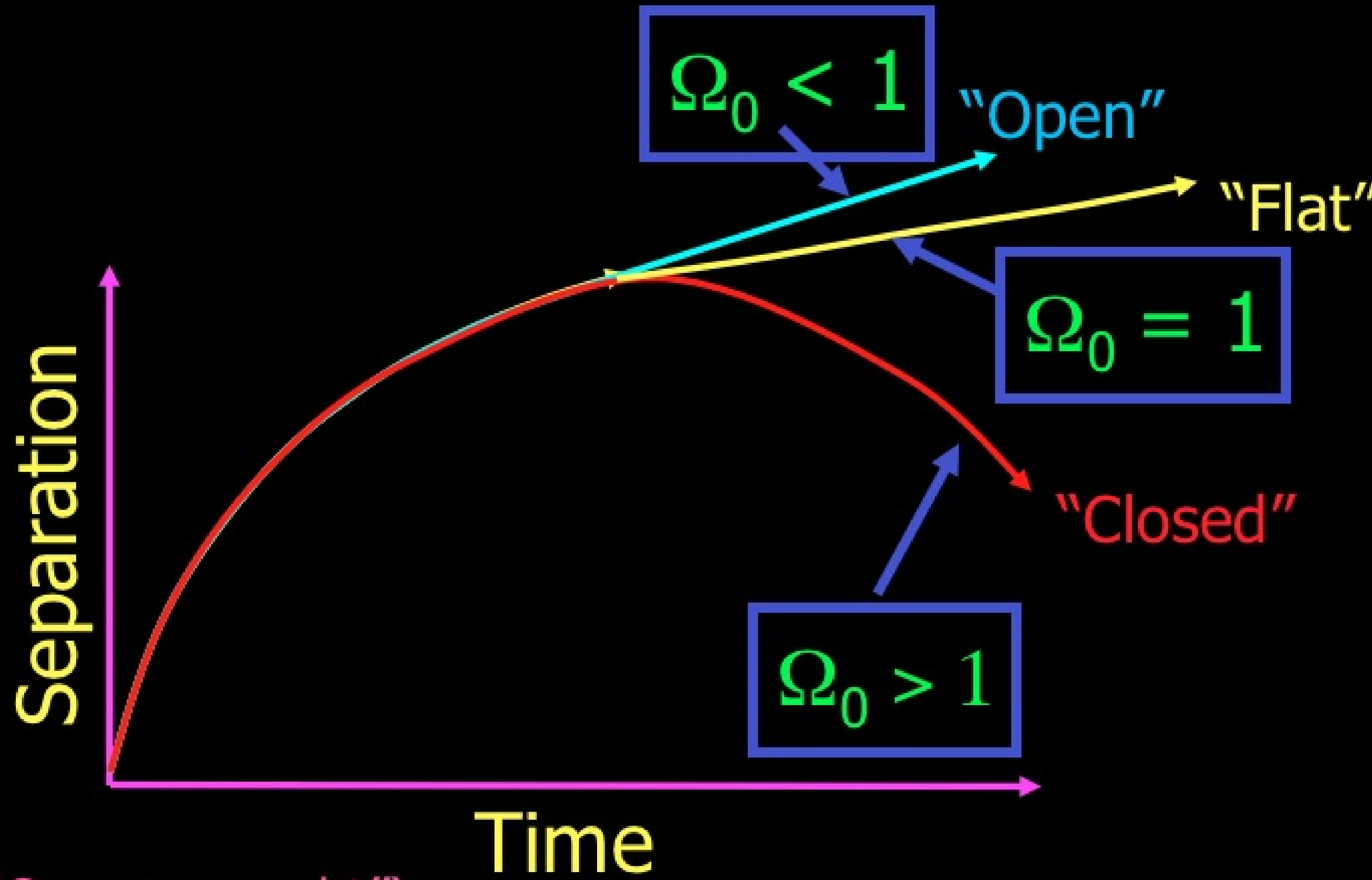
(*For a particular H_0)

There is a "critical density" which separates these two cases



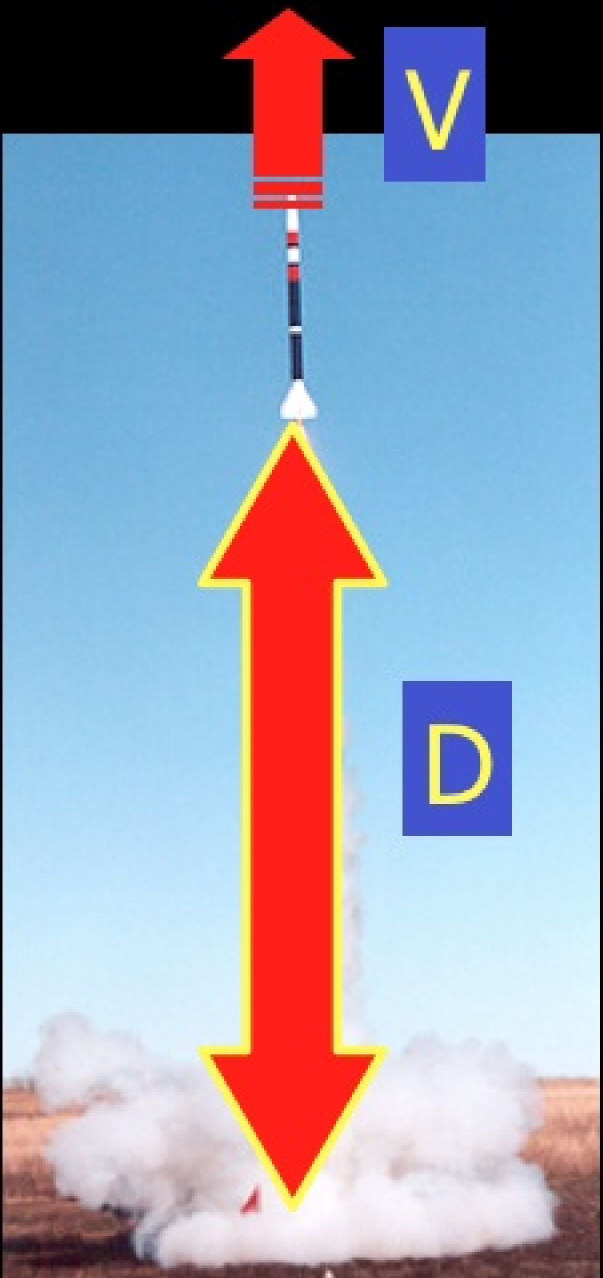
ρ_{crit} = Critical Density

We define $\Omega_0 = \rho/\rho_{crit}$ to be the density in terms of the critical density

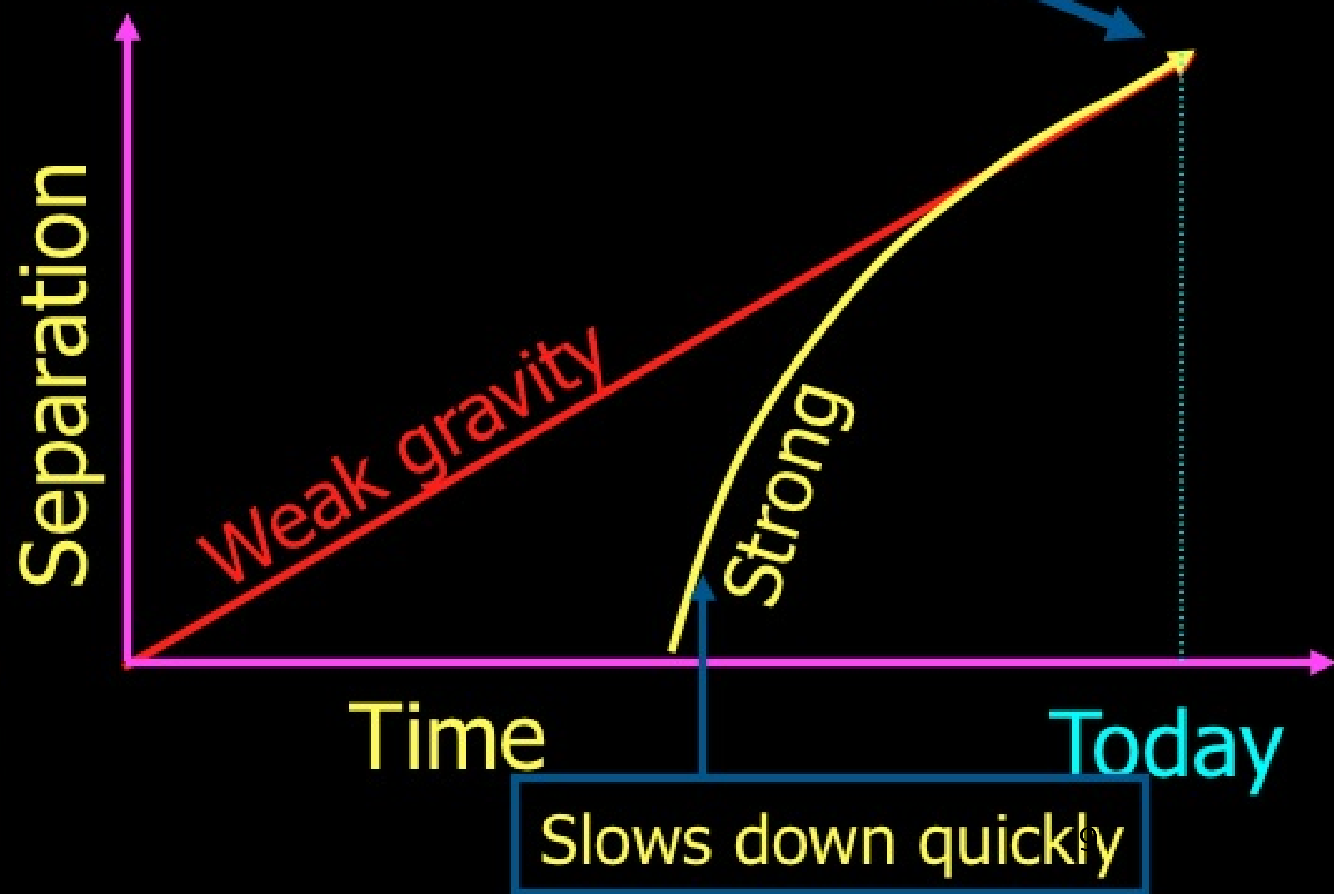


(say "Omega-nought")

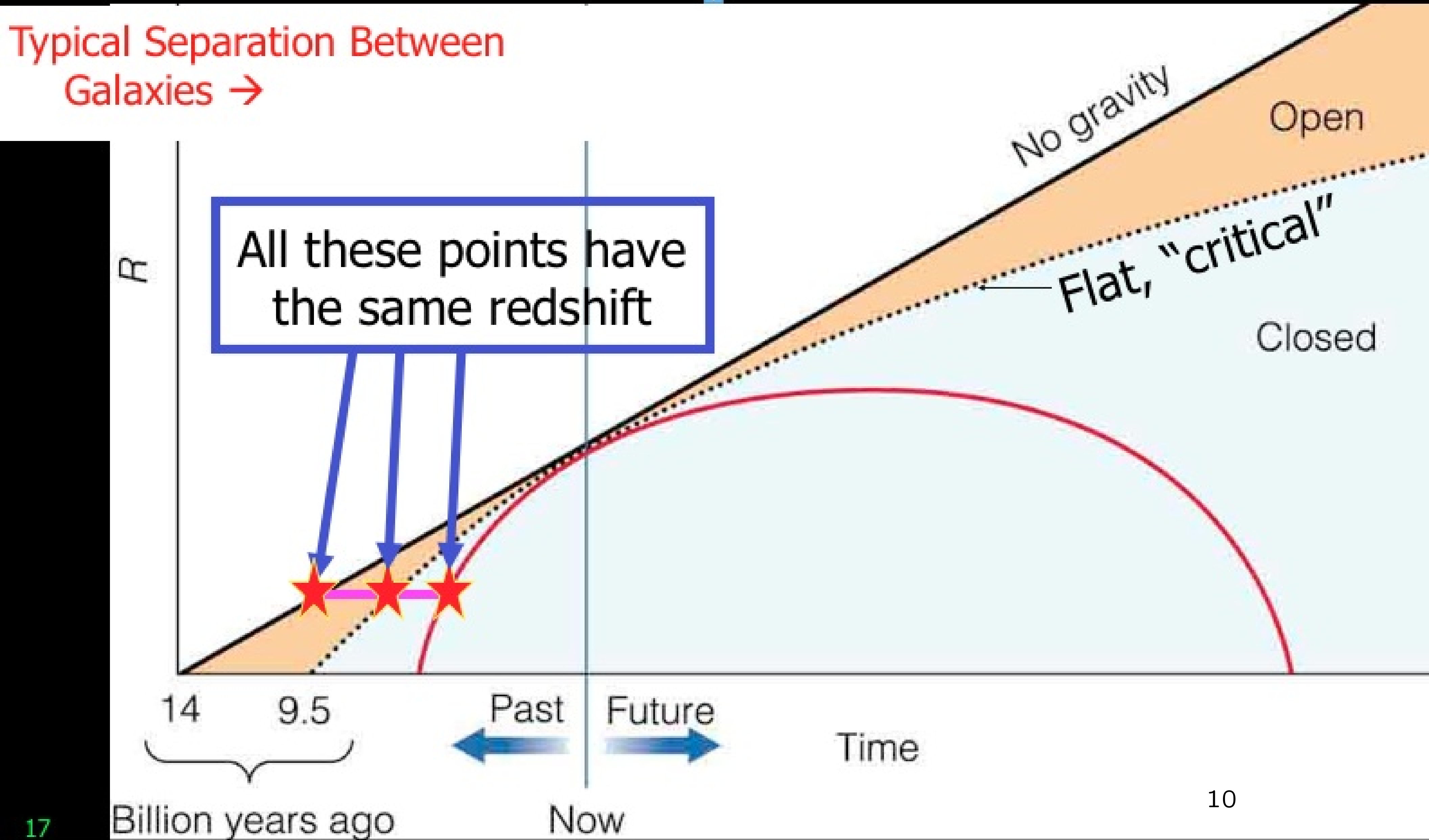
The strength of gravity affects our estimate of the duration



The separation and the rate at which the separation is increasing are <u>fixed</u> by current observation



The age of the Universe at a given redshift depends on H_0 & Ω_0



A bit more physics: just one stone, or the whole Universe!

- Lots of math – but can't have quantitative science without it, ey?

- Before we start thinking about the whole universe, let's first review the mechanics of a stone thrown vertically up.

- At some time t after it was thrown up, the stone of mass m is at height h away from the ground, and moving up with a speed v. Will it leave the Earth, or come back and fall on our head?

- As the stone moves up, its total energy $E = K + U$, doesn't change with time (neglect the deceleration by the atmosphere). However, its kinetic energy K must decrease because its potential energy U is increasing

$$E = \frac{1}{2}mv^2 - G\frac{M_E m}{R_E + h} \tag{1}$$

- Here M_E and R_E are the mass and radius of the Earth. Note that $R_E + h$ is simply the distance between the stone and the Earth's center. As h increases the negative potential energy becomes less negative, i.e. it increases (at the expense of kinetic energy – v becomes smaller, or the stone is decelerating). Note also that, as h goes to infinity, the potential energy goes to 0.

- The stone will reach infinity if its v is large enough so that there is enough kinetic energy to bring the potential energy from its negative level all the way to 0. In other words, E has to be positive (this is what happens with rockets). For a plain stone thrown up by a feeble astronomy professor, E is negative: the stone is *bound* and it eventually stops ($v = 0$) and then returns back.

- If a bystander sees a stone going up, (s)he can find out whether it is bound or not even if the initial act of stone being thrown up was not observed – simply evaluate (measure) kinetic and potential energy, add them up and thus get the total energy E; is it < 0 or > 0?

- Similar reasoning applies to the whole Universe: we measure its current kinetic and potential energy and try to understand its past and future: **observational cosmology**

- For the whole Universe, $E = 0$ if it's density, $\rho(t)$, is equal to **critical density**:

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

Evaluating this at the present time ($H_o = 70$ km/s/Mpc):

$$\rho_c(t_o) = 0.92 \times 10^{-29}\text{gcm}^{-3} \tag{3}$$

This corresponds to only about five hydrogen atoms per cubic meter! **A 'fate of the universe" question: what is $\rho(t_o)$?**

The density parameters Ω

- The ratio of the present density of the universe and the critical density determines the fate of the universe. Instead of working with numbers like 10^{-29}, it is convenient to define

$$\Omega(t) = \frac{\rho(t)}{\rho_c(t)} = \frac{8\pi G\rho(t)}{3H^2(t)} \tag{4}$$

which has the present value Ω_o. So, $\Omega = 1$ is the same condition as $\rho(t) = \rho_c(t)$.

- The contributions to Ω_o from baryons (a.k.a. "normal" matter): Ω_b, dark matter: Ω_{dm}, and dark energy: Ω_Λ, are treated separately.

- A model for a given choice of Ω_o, Ω_{dm}, and Ω_Λ can be compared to data and the free parameters refined until one gets satisfactory agreeement (so-called best-fit model)

Data vs. Model Comparison

In general, we use data (measurements or observations) to develop models that i) explain the data, ii) can be used to predict the behavior of new measurements.

In the context of cosmological models, we model the expansion (characteristic size) of the Universe as a function of time. The size vs. time relationship translates to distance vs. redshift relationship. The models include free parameters such as Ω_o, Ω_{dm}, and Ω_Λ. By measuring the distance vs. redshift relationship, we can constrain the values of these parameters. Once we know these values, we can use models to both predict the future evolution of the Universe, as well as reconstruct its past.

In addition to distance vs. redshift relationship (for example, measured using supernovae), we can also measure the growth of structure due to gravitation (via galaxy cluster counting and lensing measurements) which gives a very strong constraint on Ω_m. In addition, the measured properties of cosmic microwave background radiation give us another independent set of constraints (especially strong constraint for Ω_o).

- **The current best estimates** (from a combination of CMB measurements by WMAP and other data) are:

  - Only baryons: $\Omega_b = 0.043 \pm 0.002$

  - Total matter (baryons plus dark matter):
    $\Omega_m = \Omega_b + \Omega_{dm} = 0.260 \pm 0.002$

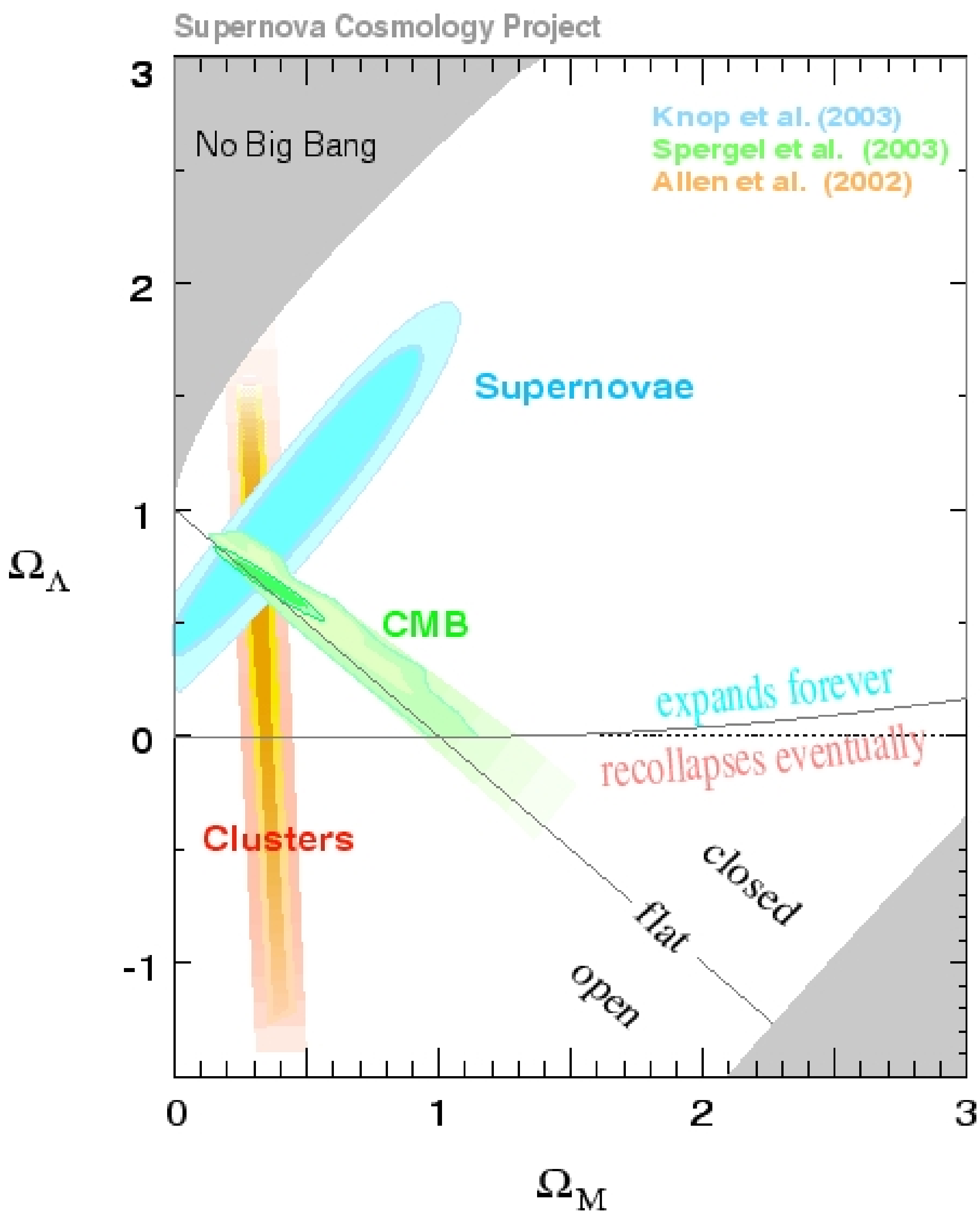
  - Total all: $\Omega_o = 1.02 \pm 0.02$

- The universe appears to have **density equal to critical density**, and its energy content is **NOT** dominated by matter.

- The difference between Ω_o and Ω_m is contributed to dark energy ($\Omega_m + \Omega_\Lambda = \Omega_o$), with $\Omega_\Lambda \sim 0.75$. Here,

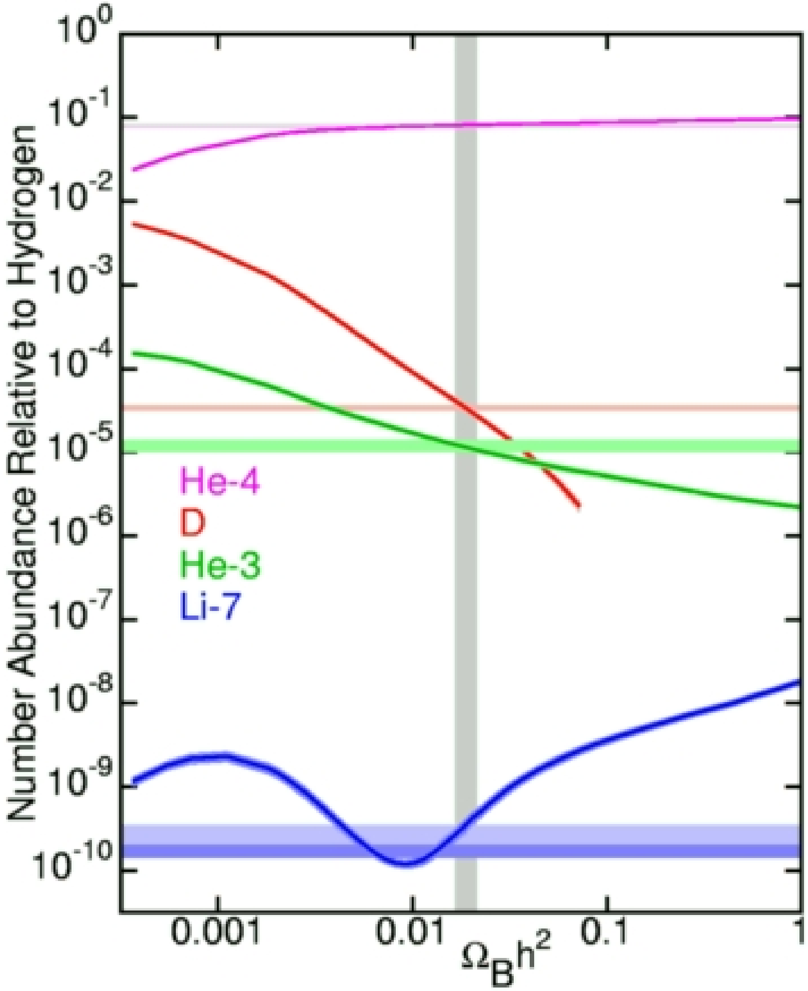
$$\Omega_\Lambda = \frac{\Lambda c^2}{3H^2(t)}, \tag{5}$$

where Λ is **the cosmological constant**, originally introduced by Einstein (which he called "his greatest blunder").



The Concordance Model

- Cosmic microwave background observations require $\Omega_o = 1$.
- The growth of structure measurements (galaxy clusters, gravitational lensing) give $\Omega_m = 0.3$.
- Supernovae Type Ia measurements are consistent with $\Omega_m = 0.3$ and $\Omega_o = 1$.
- Together, these measurements imply that $\Omega_\Lambda = \Omega_o - \Omega_m = 0.7$, where the $\Omega_\Lambda > 0$ result implies the existence of dark energy and current acceleration of the expansion of the Universe.
- This best-fit concordance model can also be used to compute the age of the Universe (13.7 billion years), as well as conditions (e.g. density and temperature) in the early Universe.



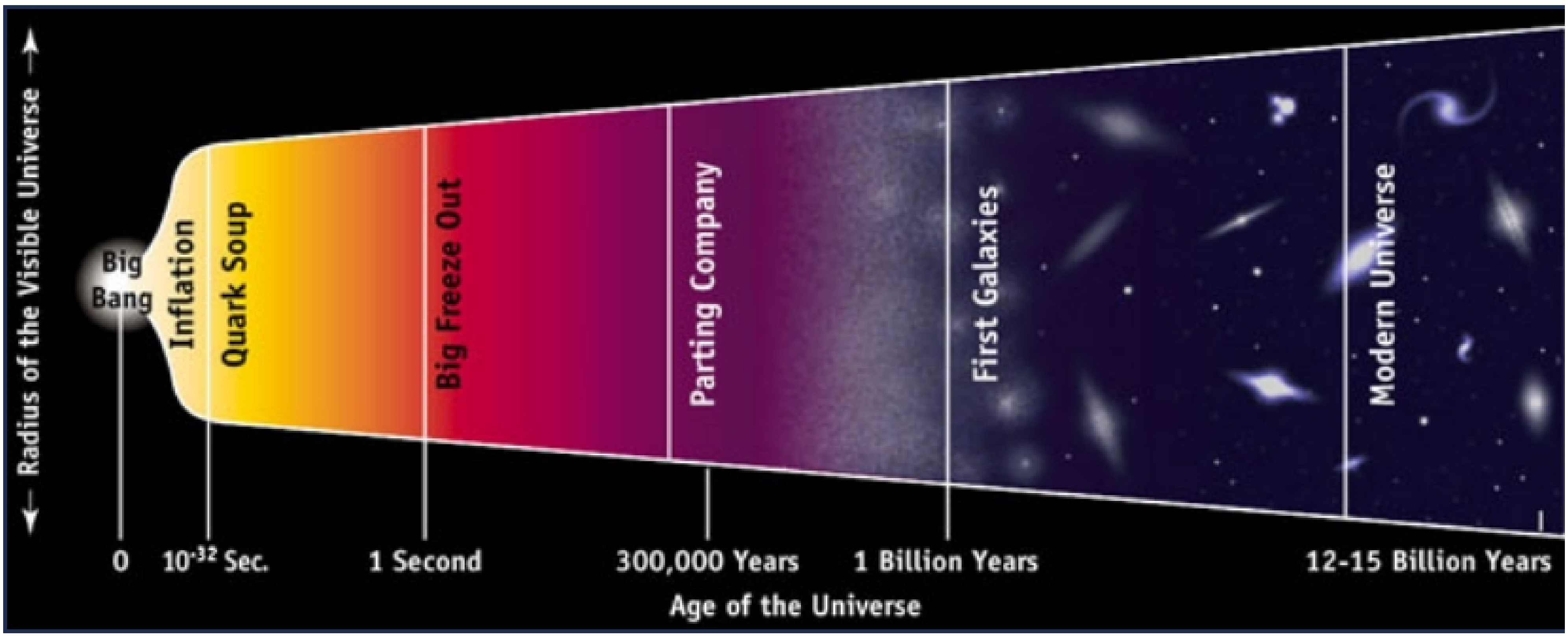
The graph shows the predicted abundance vs. baryon density for these light isotopes as curves, the observed abundances as horizontal stripes, and the derived baryon density as the vertical stripe.

The Light Element Abundance as a Cosmological Constraint

- The deuterium (H^2), He^3, He^4 and Li^7 abundances depend on the single parameter: the current density of ordinary matter made out of protons and neutrons (baryonic matter), often expressed as the fraction of the total matter/energy density, Ω_b (more about this next time).
- A single value of the baryon density Ω_b fits 4 abundances simultaneously.
- This value (~ 0.04) is much smaller than $\Omega_{matter} \sim 0.25$ measured by other means (CMB, SNe, dynamical methods). Hence, most of matter is in non-baryonic form. Candidates are massive neutrinos, WIMPS (weakly interacting massive particles), axions, etc.

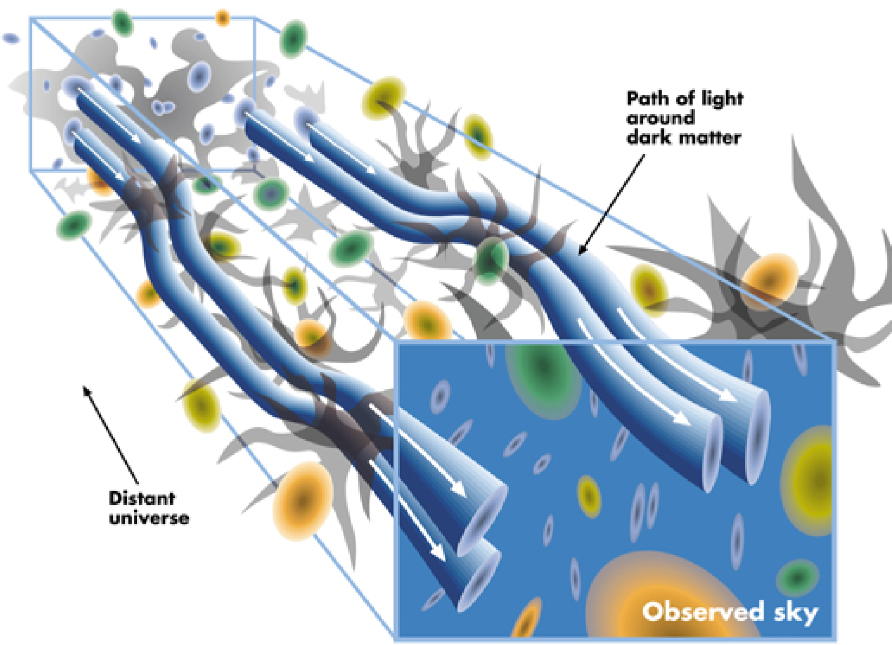
Early Universe and Inflation

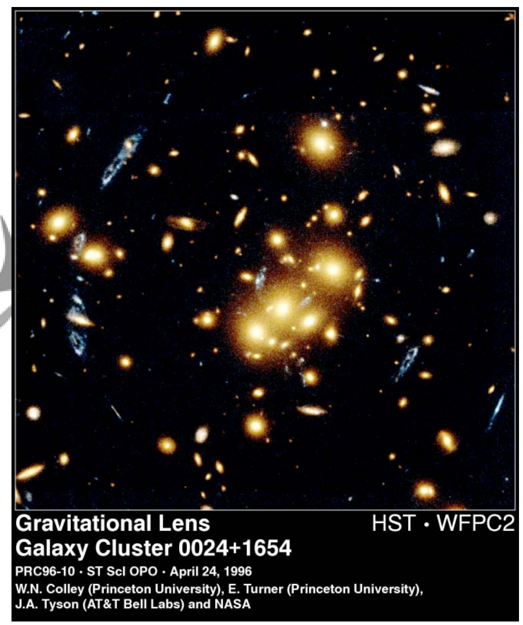
- The best-fit concordance model can also be used to compute thermodynamical conditions in the early Universe.
- How far back can we extrapolate our knowledge of physics?

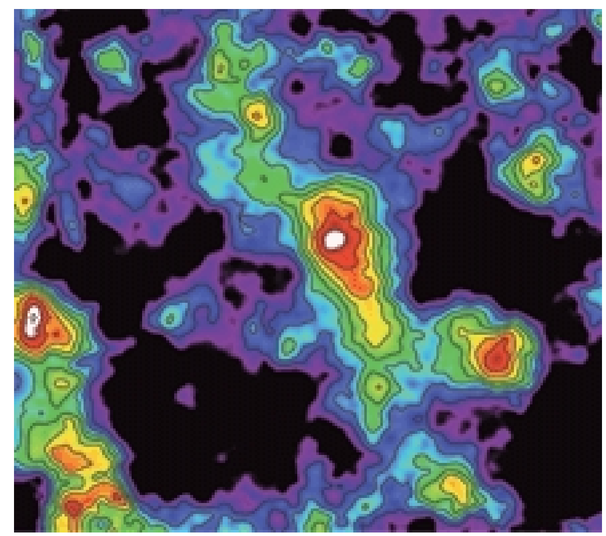


Cosmology with LSST

- **Goal:**
  use a variety of probes and techniques in synergy to fundamentally test our cosmological assumptions and gravity theories:
  1. **Weak Lensing:** growth of structure
  2. **Galaxy Clusters:** growth of structure
  3. **Supernovae:** standard candle
  4. **Baryon Acoustic Oscillations:** standard ruler

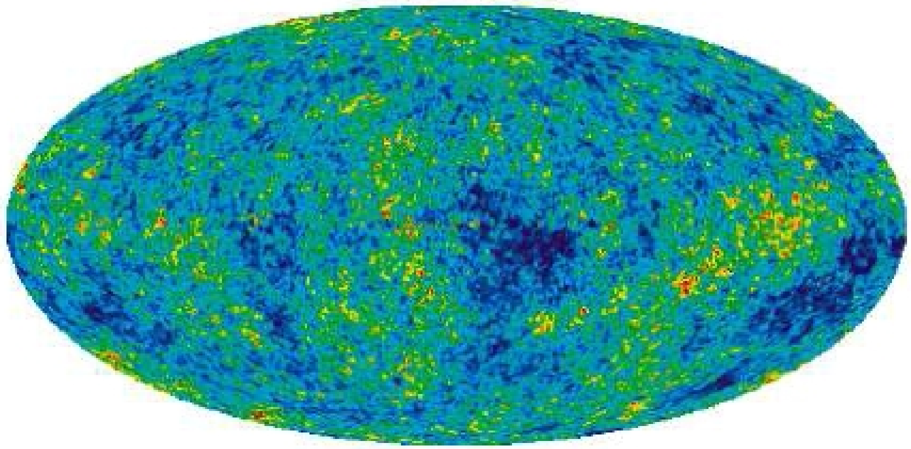


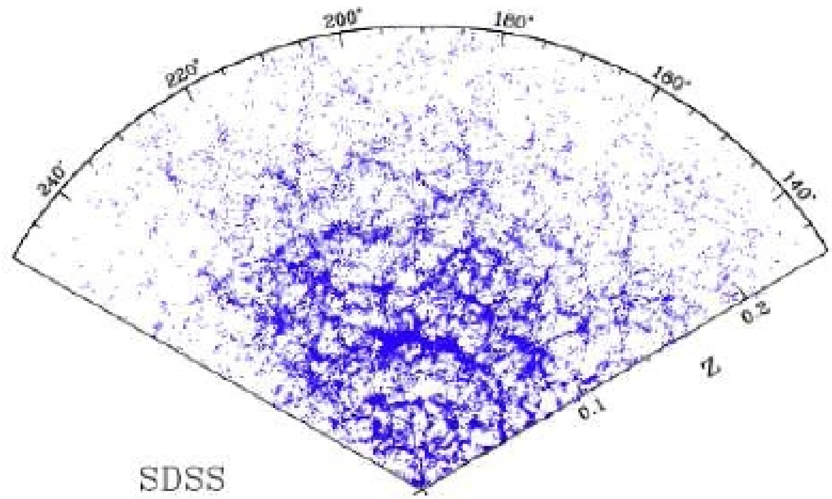


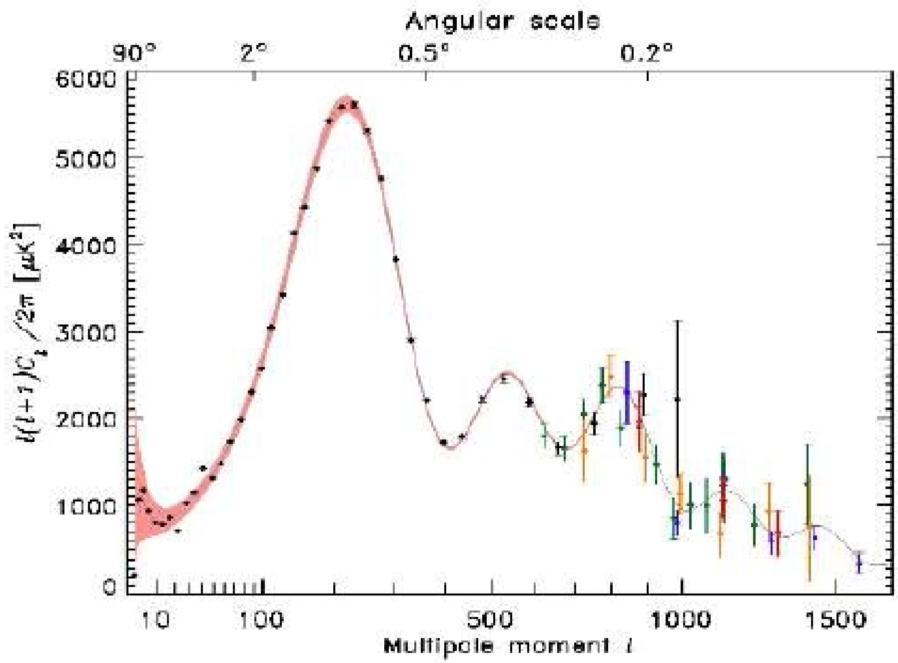


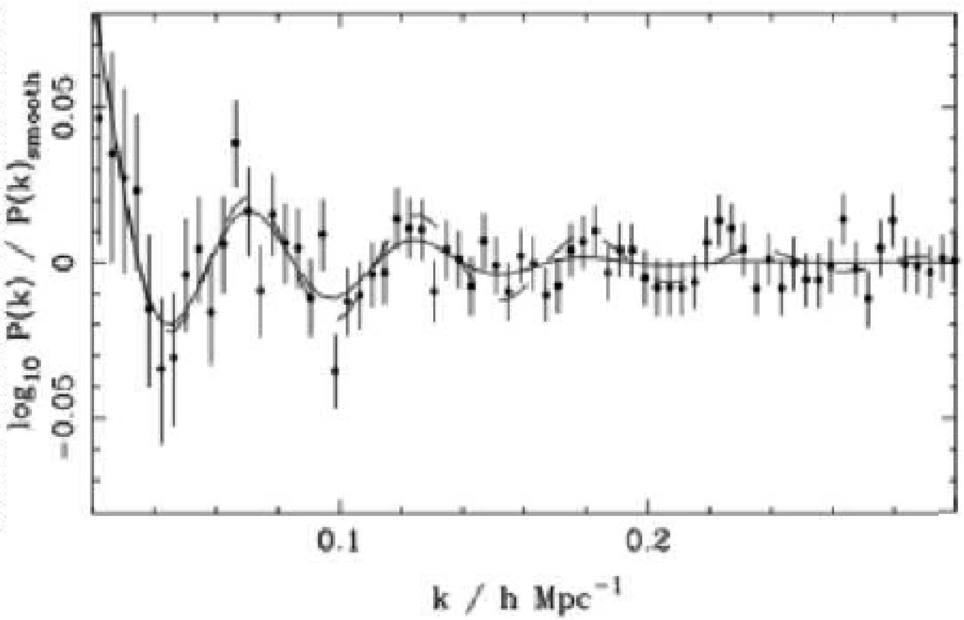
About a hundred-to-thousand-fold increase in precision over precursor experiments: the key is multiple probes!

CMB **Galaxies**









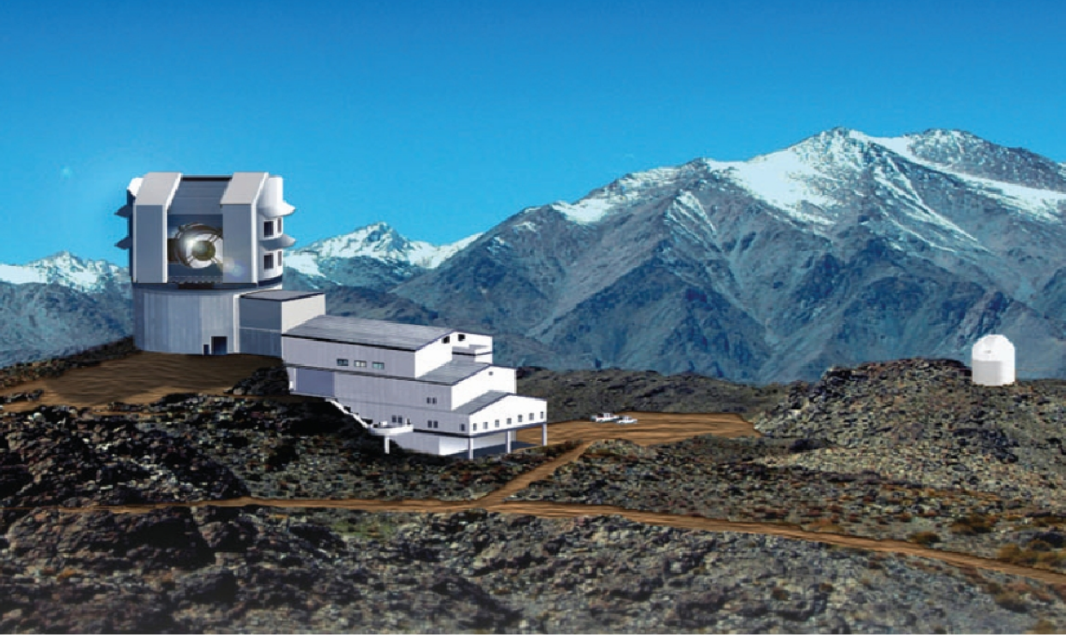
Baryon acoustic oscillations: standard ruler – new cosmological tool

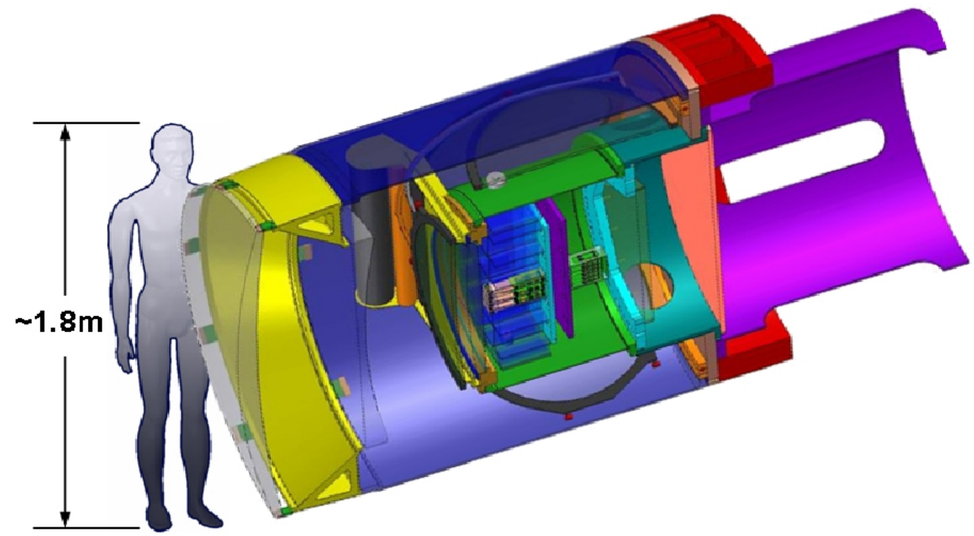
The LSST Concept: Deep, Wide, Fast

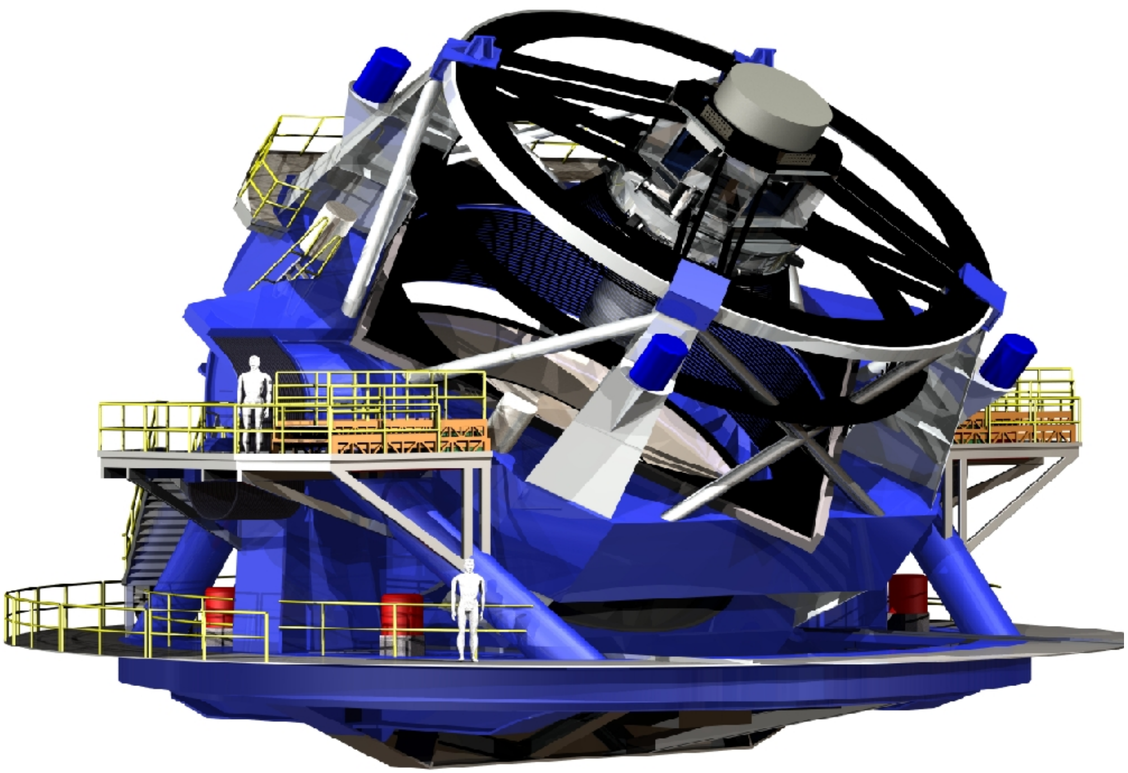
- **The Greatest Movie of All Time:** digital images of the entire observable sky every three nights, night after night, for 10 years (11 months to "view" it)
- **The Best Sky Image Ever:** 60 petabytes of astronomical image data (resolution equal to 3 million HDTV sets)
- **The Largest Astronomical Catalog:** 20 billion sources (for the first time more than living people)

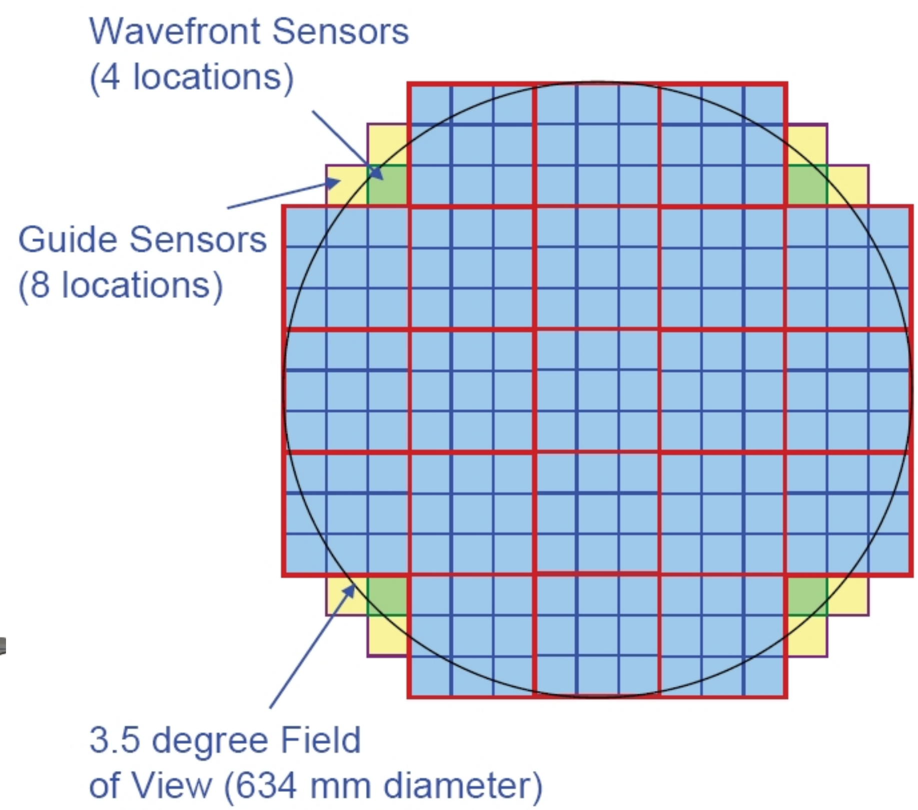
Science Drivers

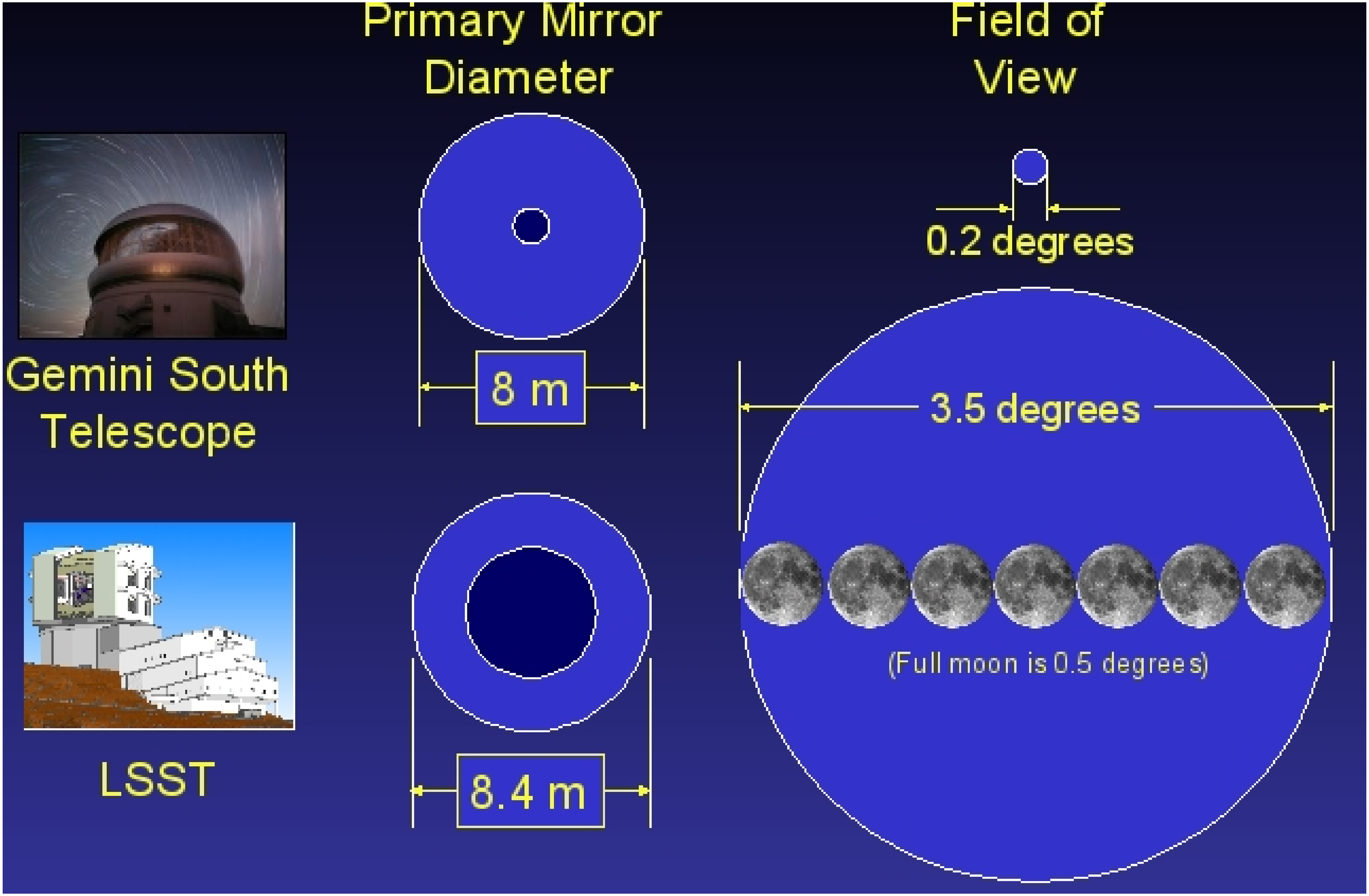
1. The Fate of the Universe: Dark Energy and Matter
2. Taking an Inventory of the Solar System
3. Exploring the Unknown: Time Domain
4. Deciphering the Past: mapping the Milky Way

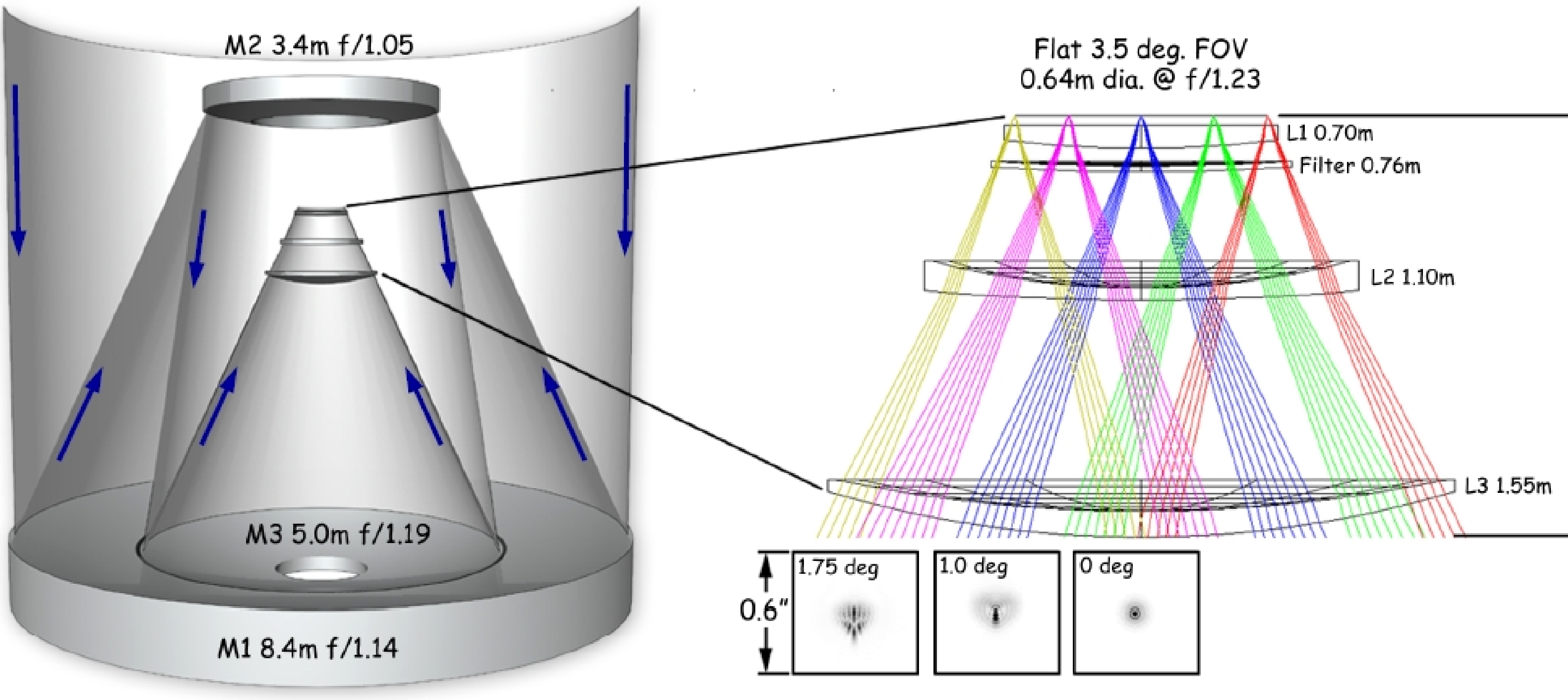



~1.8m



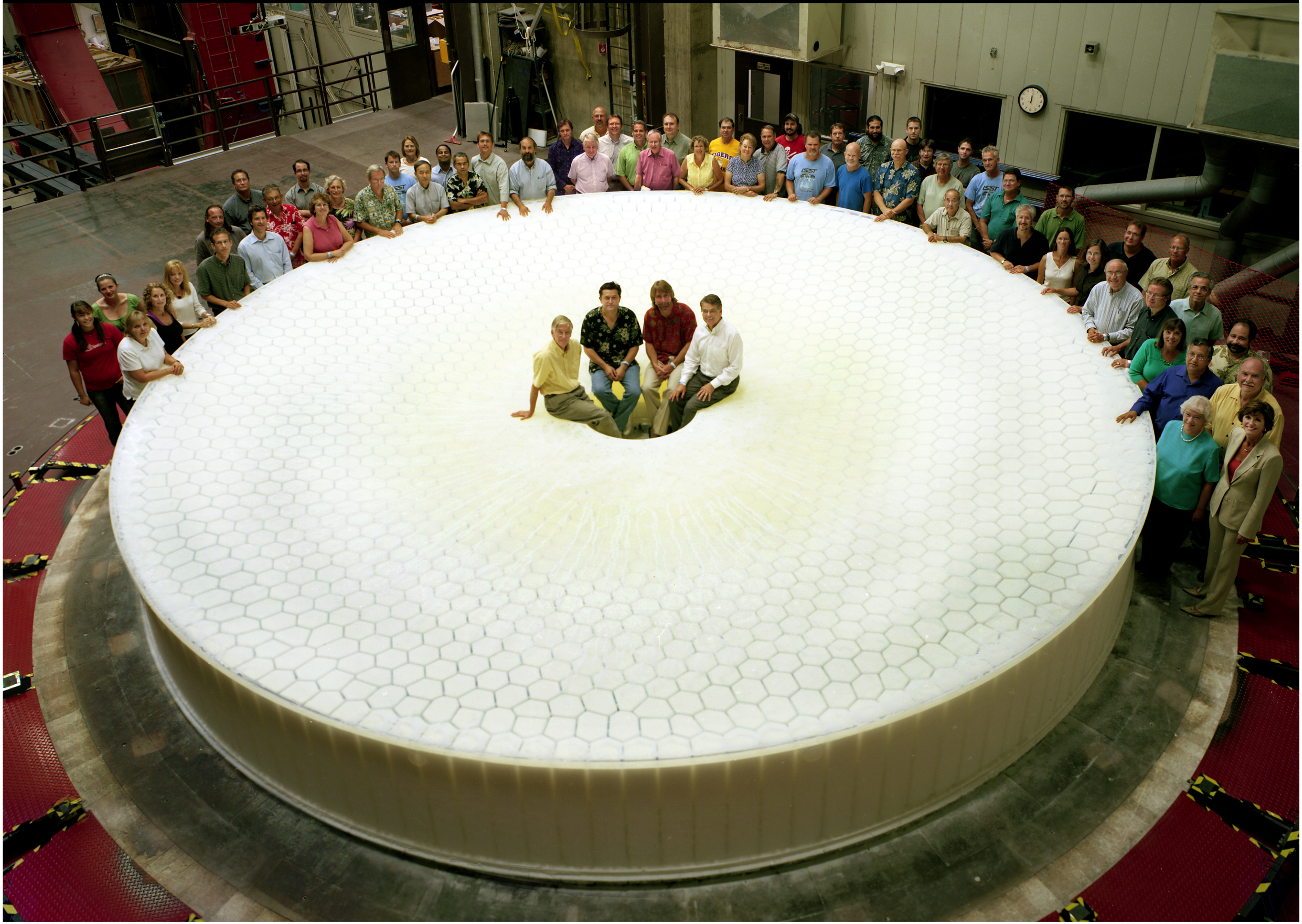

Wavefront Sensors
(4 locations)
Guide Sensors
(8 locations)
3.5 degree Field
of View (634 mm diameter)


Primary Mirror Diameter
Field of View
Gemini South Telescope
8 m
0.2 degrees
LSST
8.4 m
3.5 degrees
(Full moon is 0.5 degrees)



M2 3.4m f/1.05
M3 5.0m f/1.19
M1 8.4m f/1.14
Flat 3.5 deg. FOV
0.64m dia. @ f/1.23
L1 0.70m
Filter 0.76m
L2 1.10m
L3 1.55m
0.6"
1.75 deg
1.0 deg
0 deg

Large Synoptic Survey Telescope



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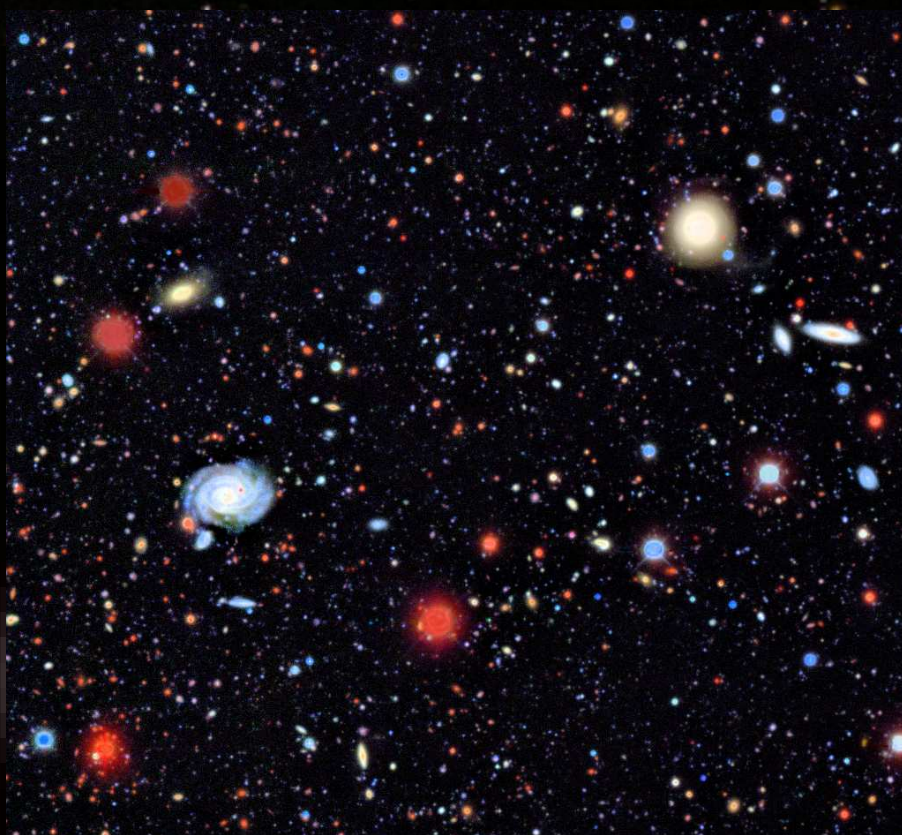
LSST Primary/Tertiary Mirror Blank

August 11, 2008, Steward Observatory Mirror Lab, Tucson, Arizona



SDSS: one US Library of Congress worth of data

LSST: one SDSS per night, or all the words ever printed!