Dark Energy

- In 1997, astronomers discovered that *distant* supernovae were dimmer than expected.

- The favored interpretation is that the expansion of our universe is accelerating.

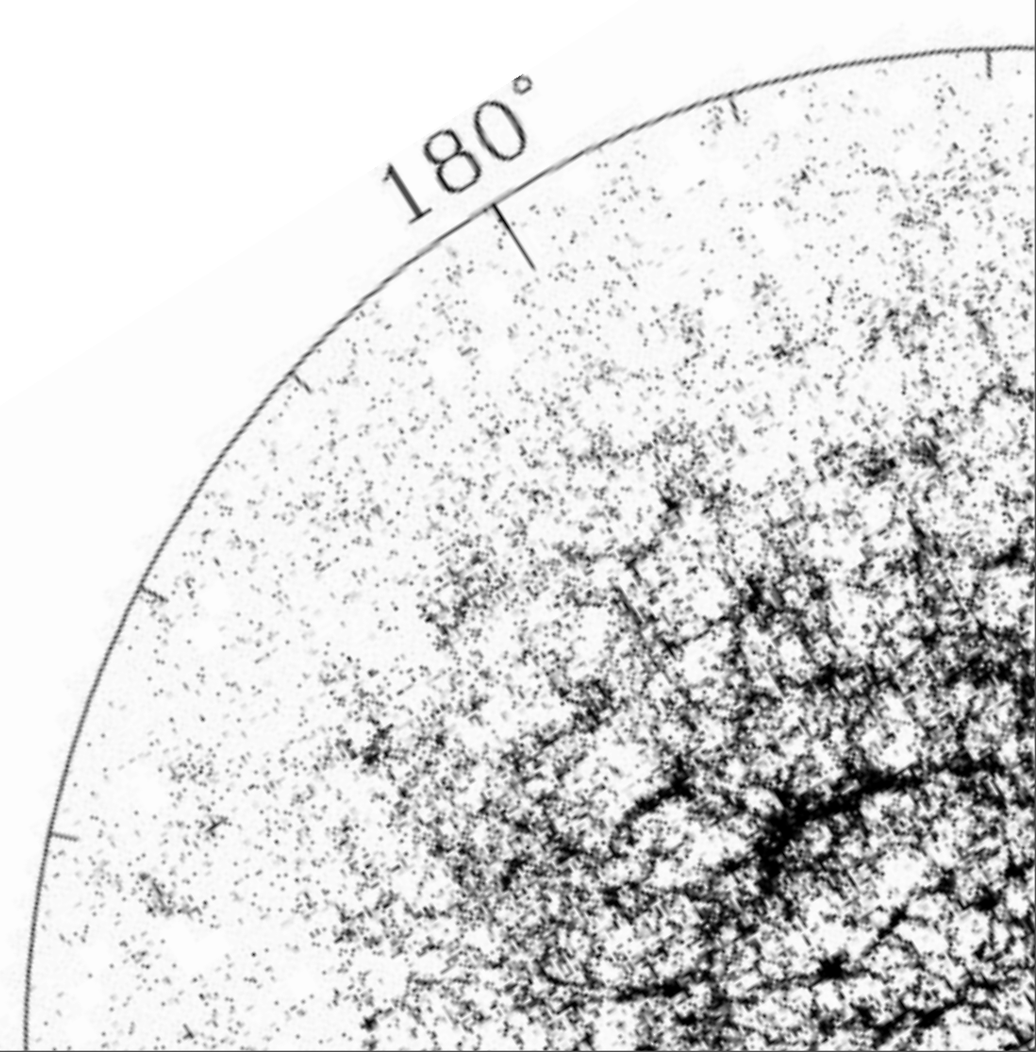
- The term "Dark Energy" is just shorthand for "whatever could cause acceleration"

- What is the evidence and how can we learn more?

The High-Z Supernova Search Team

How dim *should* the supernovae have been?

It has been known for nearly a century that distant galaxies are receding from us, and from each other (Hubble)



The Hubble Law:

Recession Velocity is Proportional to Distance

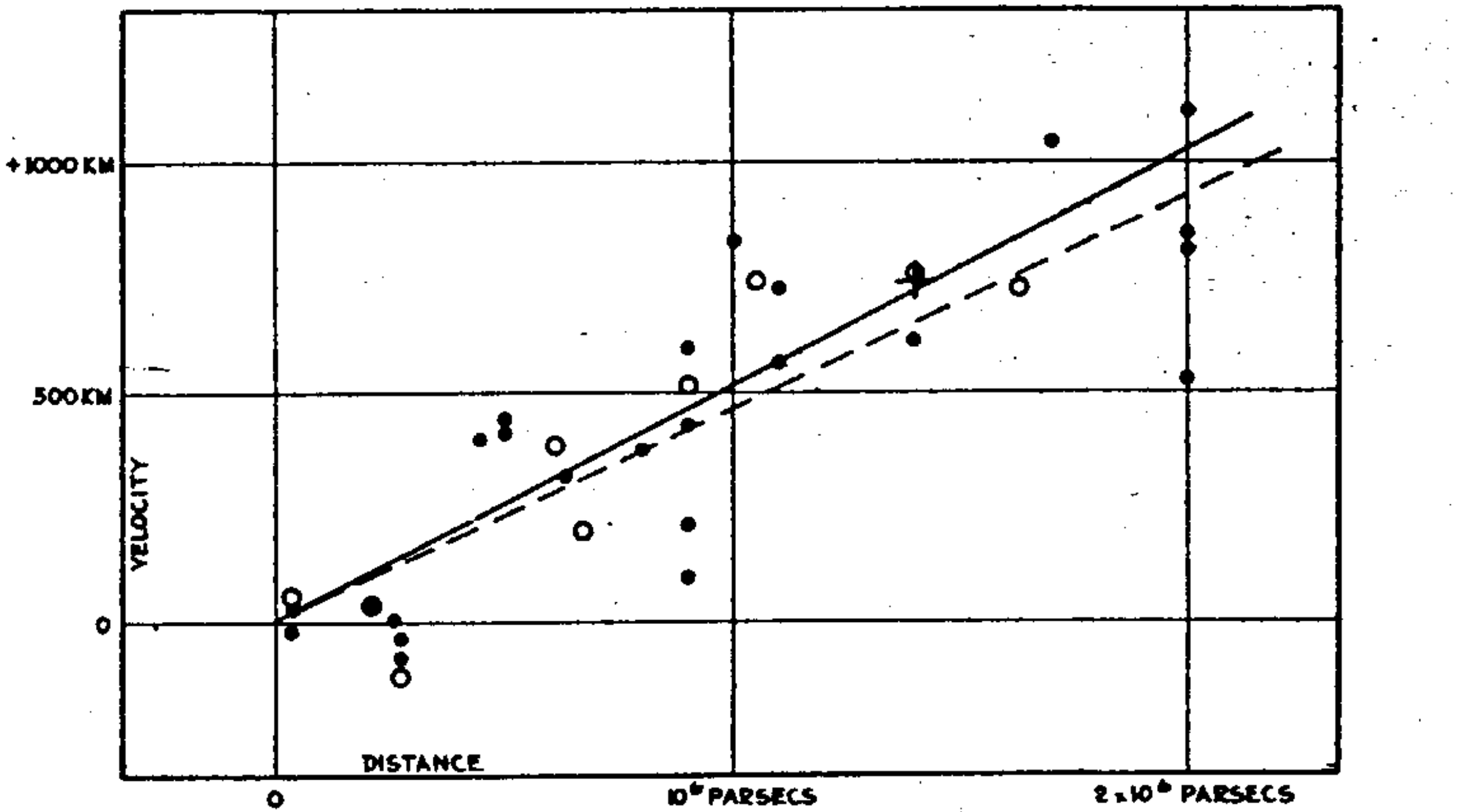


FIGURE 1

Blueberry Muffin

- Galaxies are like blueberries in a muffin

- As the muffin dough expands uniformly between the blueberries, the berries move apart

- Blueberries that began close together recede less during cooking than those that began farther apart

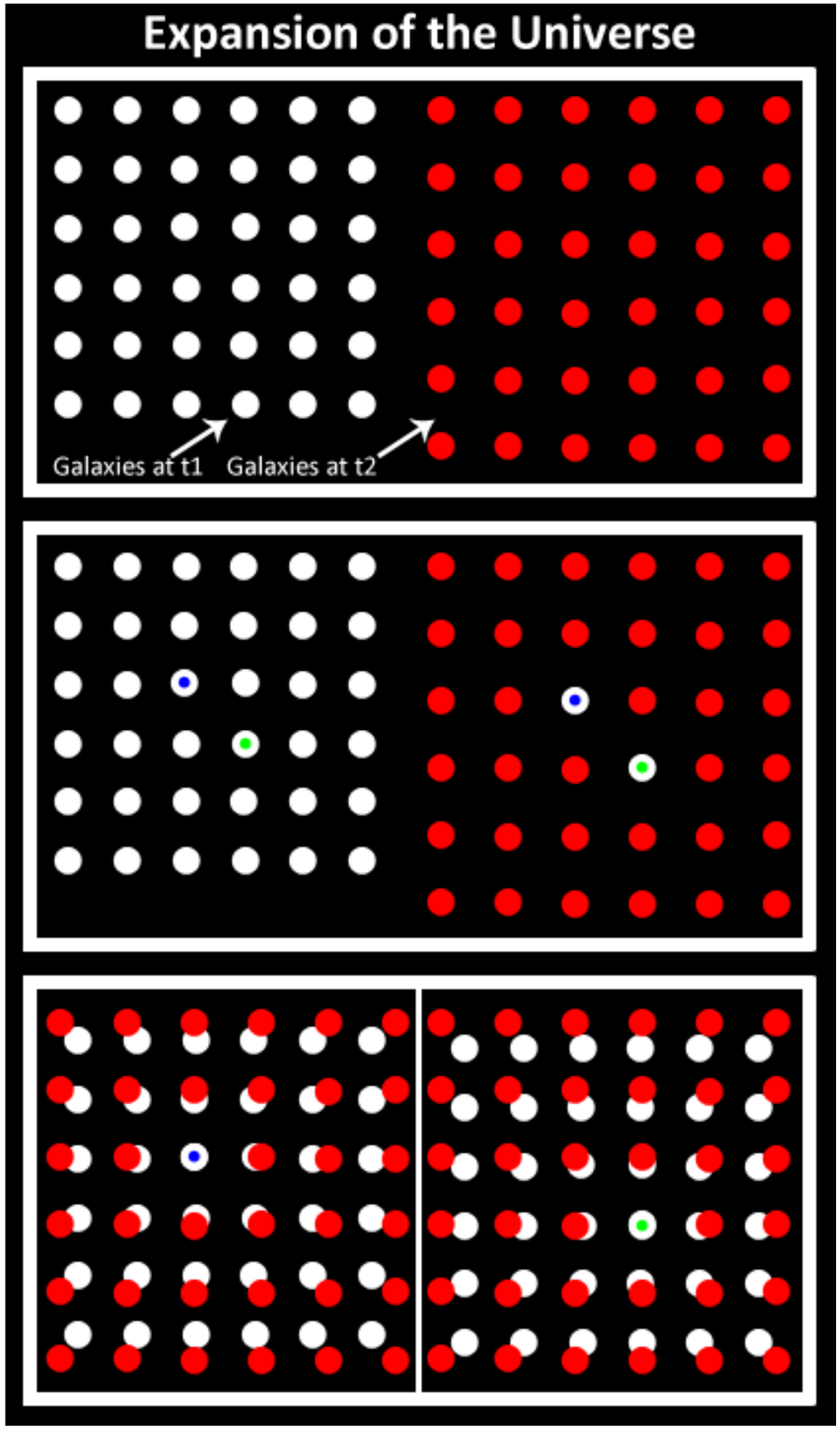
- Doppler shifts will be observed: Observers see "redshift" of the light: blueberries look a little redder

$$z = \Delta\lambda/\lambda$$

Blueberry Muffin Model

Velocity proportional to distance is a direct consequence of uniform expansion

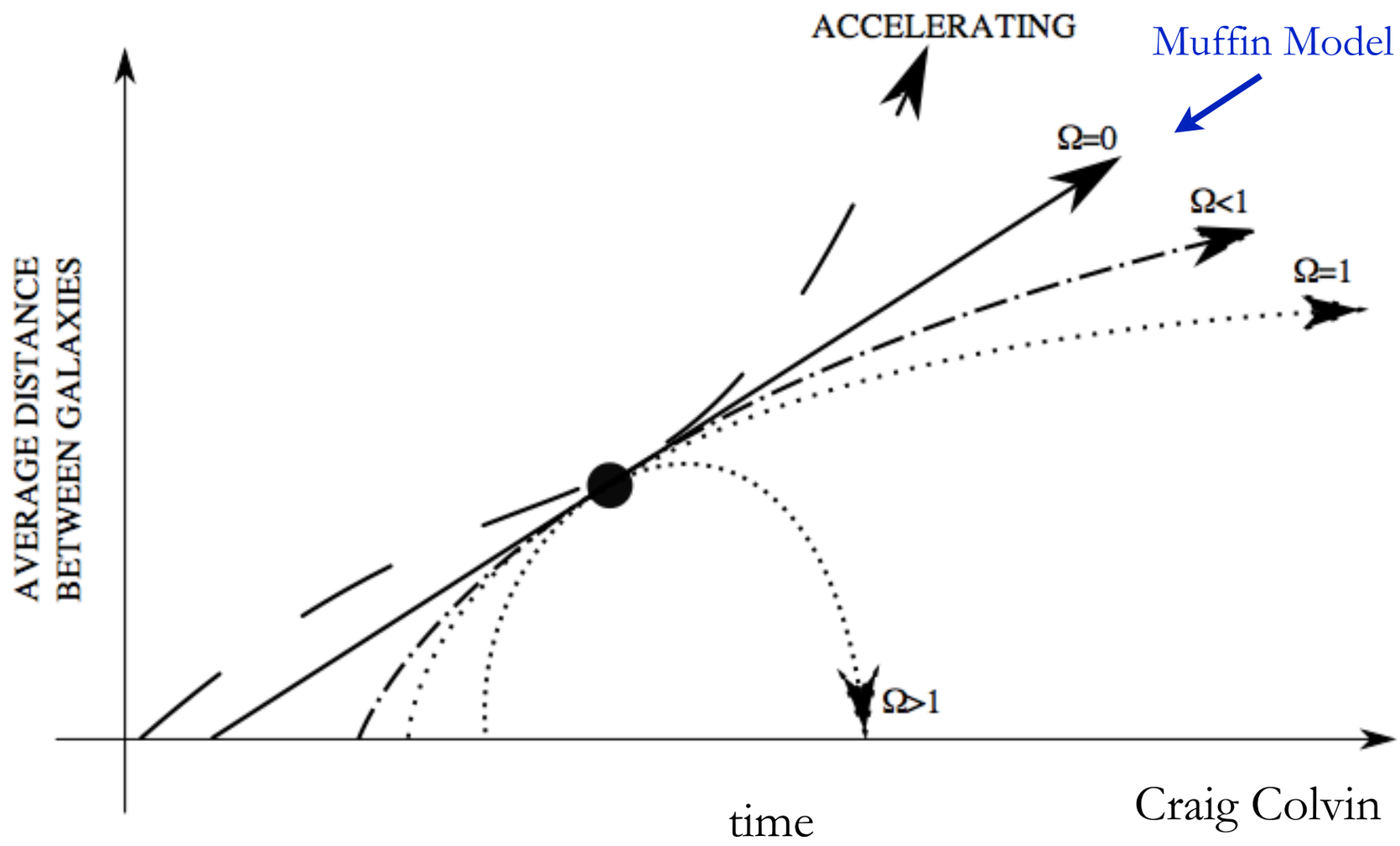
(However, redshift is a little subtler than simple doppler shift...)



Craig Colvin

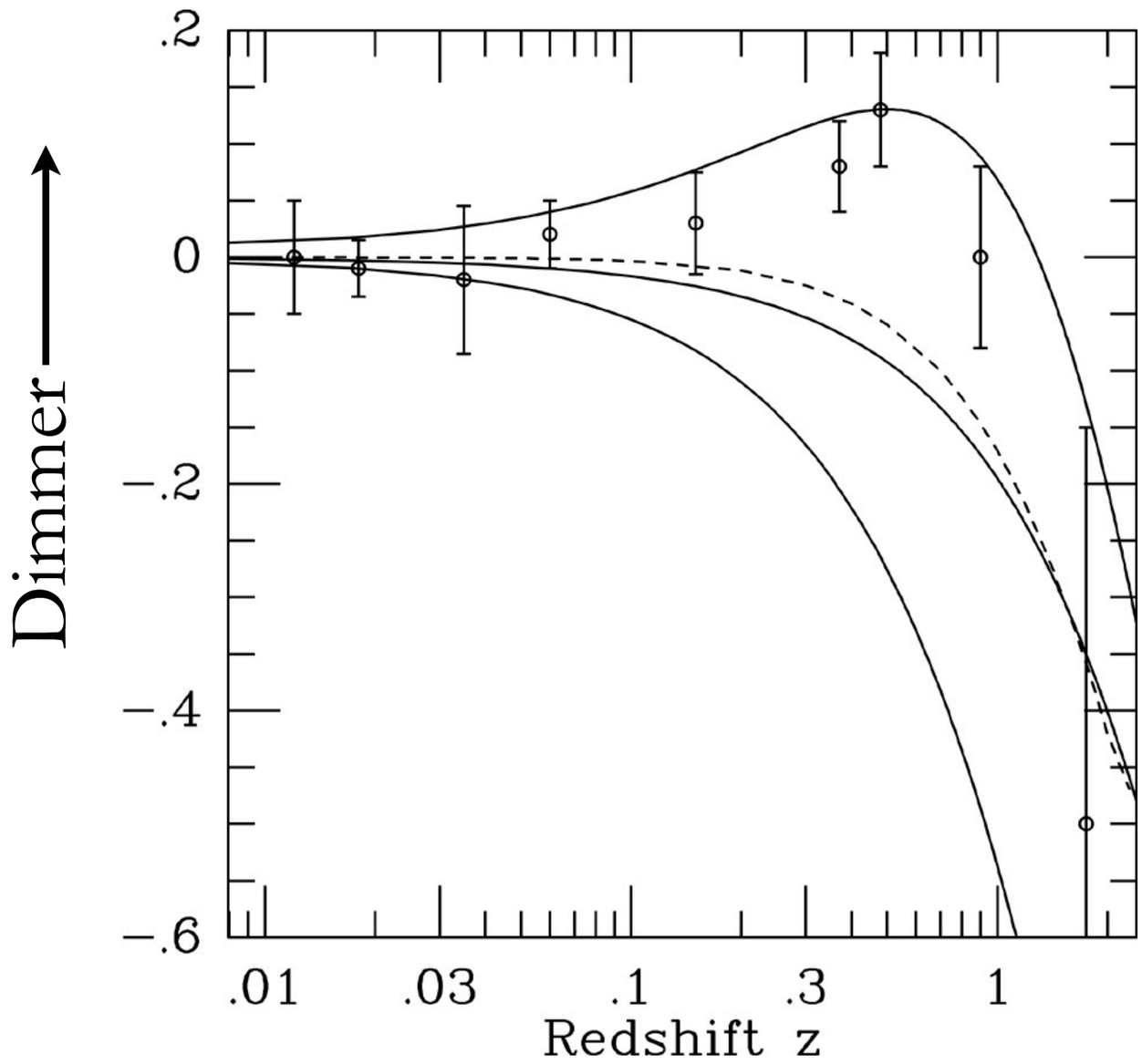
Scale of the Universe over Time

- With no mass to slow us down we coast like the muffin model (Omega=0)
- Adding any matter causes deceleration.
- Acceleration can only happen under bizarre circumstances



Supernova Data

- Supernovae look too dim.
- The "normal" models with only mass cannot fit the data.
- If we postulate acceleration we get fainter supernova and fit the data perfectly.
- Numerous other probes also indicate acceleration: Cosmic Microwave Background, Lensing, Baryon Acoustic Feature, Cluster Counts.....



What Are These Bizarre Circumstances?

- Cosmological Constant? You can add any constant to Einstein's Equations: If you give it the right sign it is like having a repulsive force everywhere in the universe.

- Problems: *Its constant energy density...even though the universe is expanding! *Although the CC is a classical concept, one may attempt to interpret it as a quantum mechanical vacuum energy. But the current calculations predict a value 120 orders of magnitude too big!

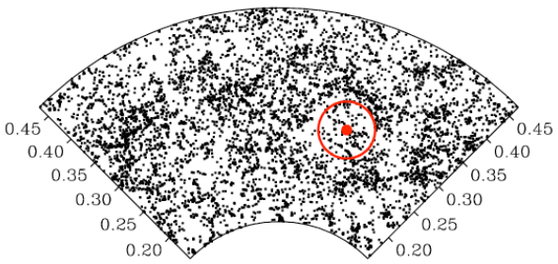
- Maybe we don't understand gravity on large scales.

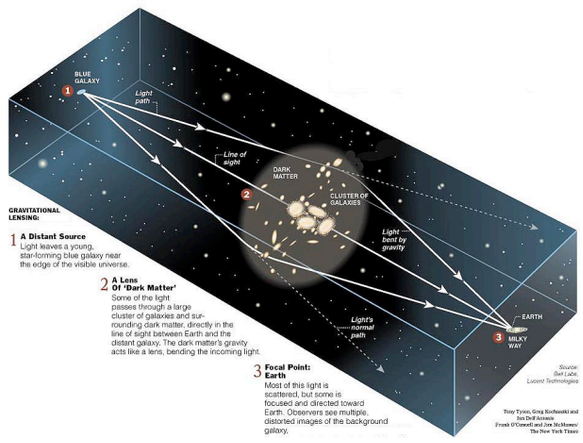
- Or maybe it's an exotic field? Cook up whatever you like!

- The bottom line: We need more data!

Astronomical Surveys

- We need surveys of the sky to implement probes.
- Probes of expansion and geometry
- Standard candles: Supernovae. Need better statistics and samples farther back in time.
- Standard rulers: The Baryon Acoustic feature.
- Gravitational lensing: measure the geometry directly





Gravitational Lensing

Abell 1689
Hubble Space Telescope

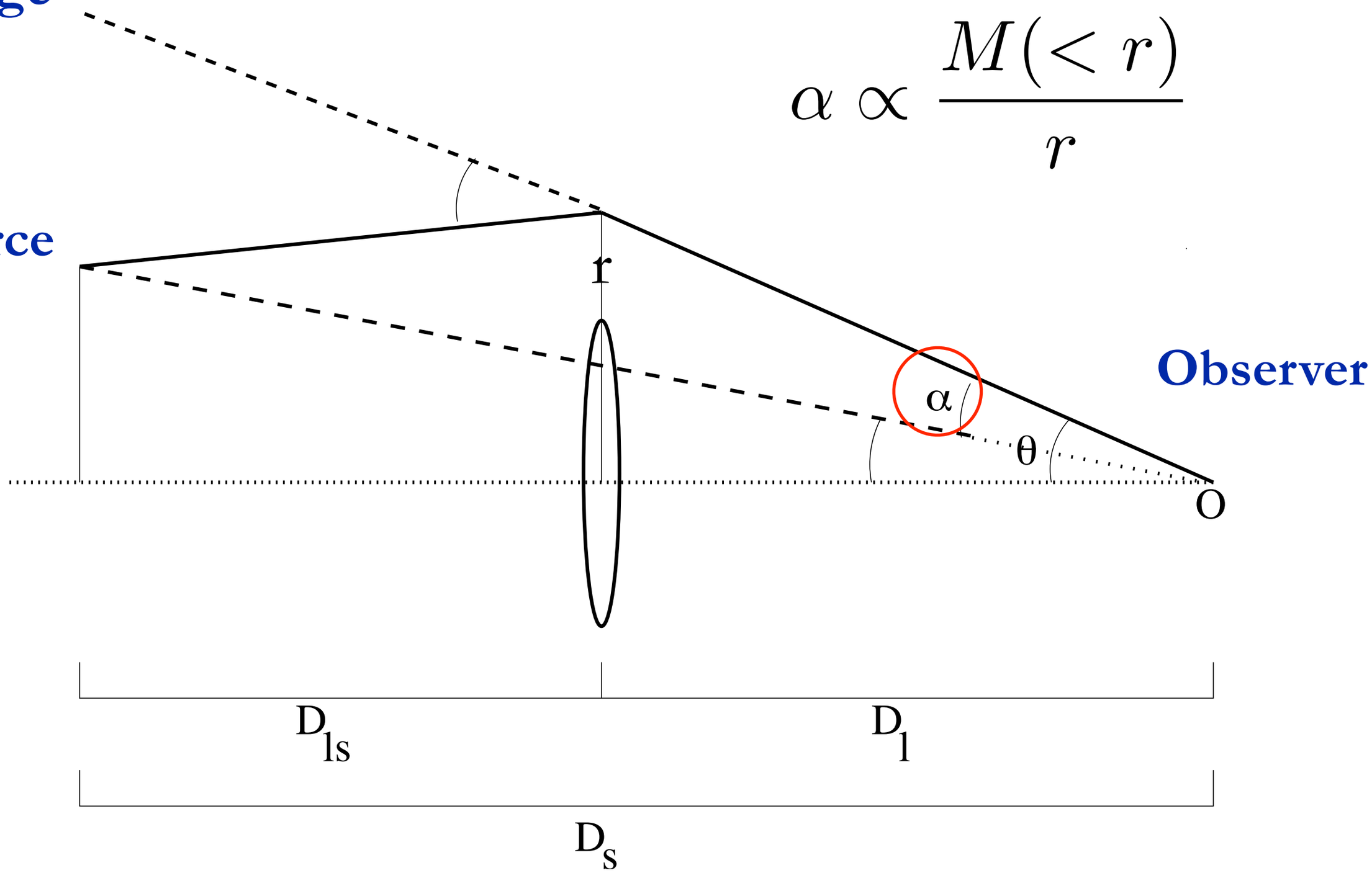
Galaxy Cluster Abell 1689 Details

Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI),
G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA • STScI-PRC03-01b

Gravitational Lensing

$$\alpha \propto \frac{M(<r)}{r}$$



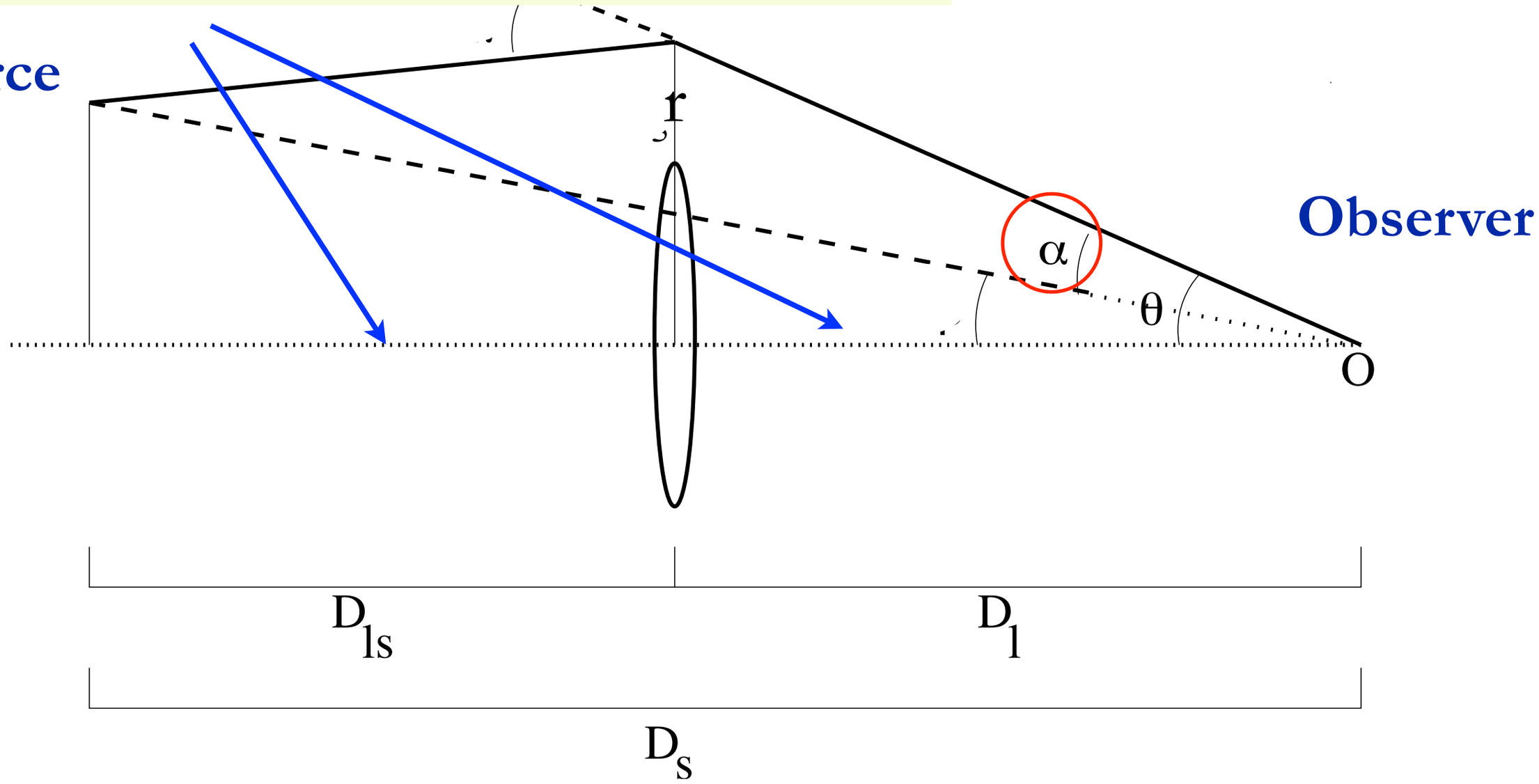
Gravitational Lensing

Image

Depends on all the *distances*
Measure different sources to probe acceleration

$$\propto \frac{M(<r)}{r}$$

Source

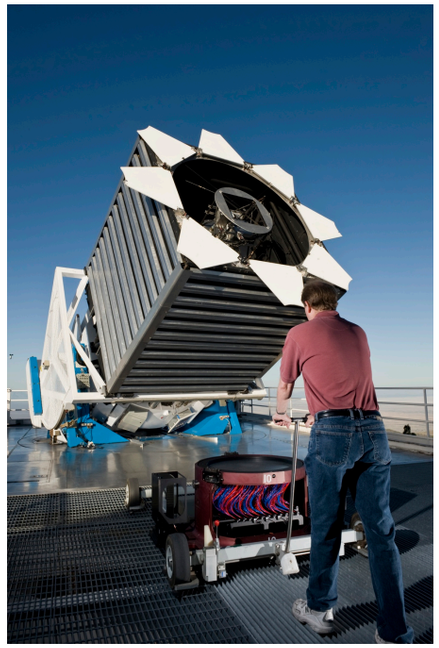


BNL Involvement in Surveys

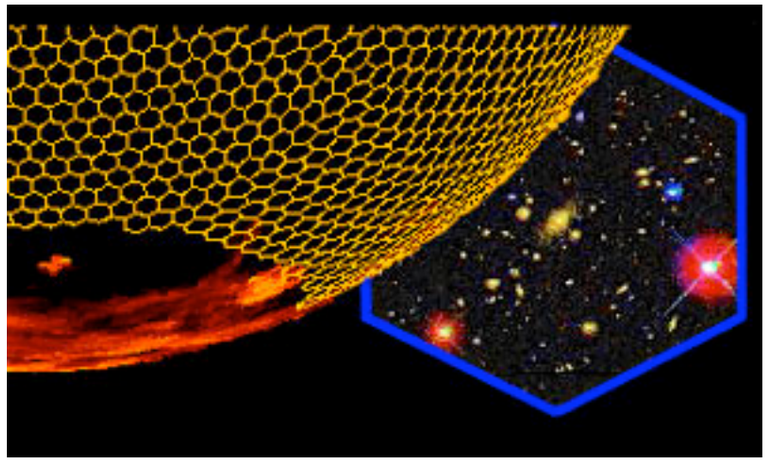
- BOSS: Baryon Oscillation Spectroscopic Survey. Measurement of a standard ruler. Fall 2009-2014

- DES: Dark Energy Survey. Supernovae, Lensing, Standard Ruler. Decrease uncertainties by factor of a few. 2011-2016

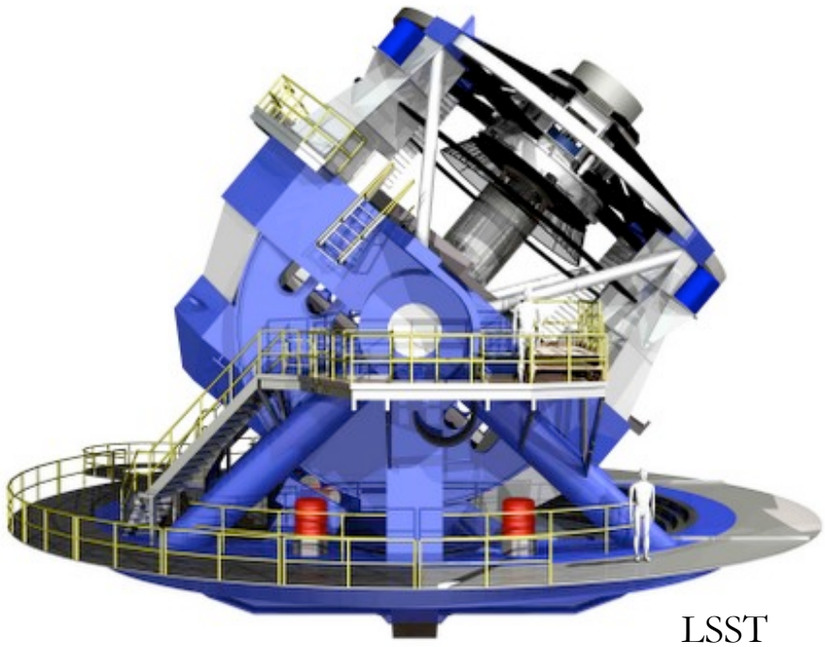
- LSST. Large Synoptic Survey Telescope: Supernovae, Lensing, Standard Rulers, Killer Asteroids. ~2015



BOSS



DES



LSST

DES

- Currently, combining all sources of data we cannot rule out a Cosmological Constant.
- Lensing in DES alone will decrease the uncertainties by a factor of a few.
- Lensing + BAO + Supernovae + galaxy clusters will provide many cross checks

BNL Scientists and Current Projects

- Erin Sheldon: In charge of target selection for BOSS. Developing software pipeline to study Lensing in DES.
  - Postdoc Zhaoming Ma: For DES, leading study of an important Lensing systematic: the point spread function of the telescope.
- Anze Slosar: Convener of the LyA working group in BOSS, measure standard ruler using quasar absorption lines.