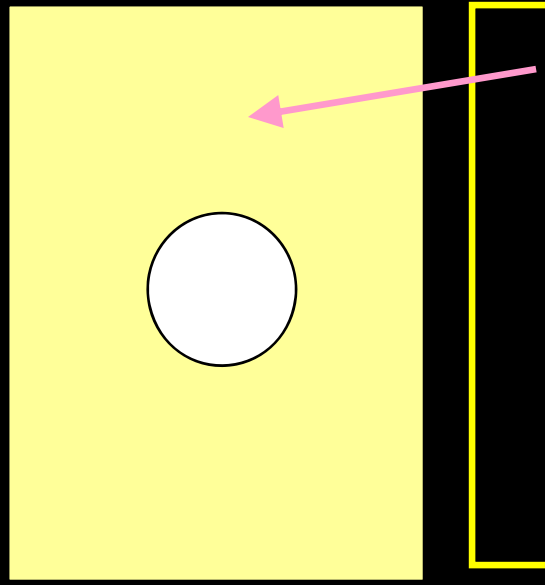
"The Dark Side of the Universe"

Wolfgang Lorenzon

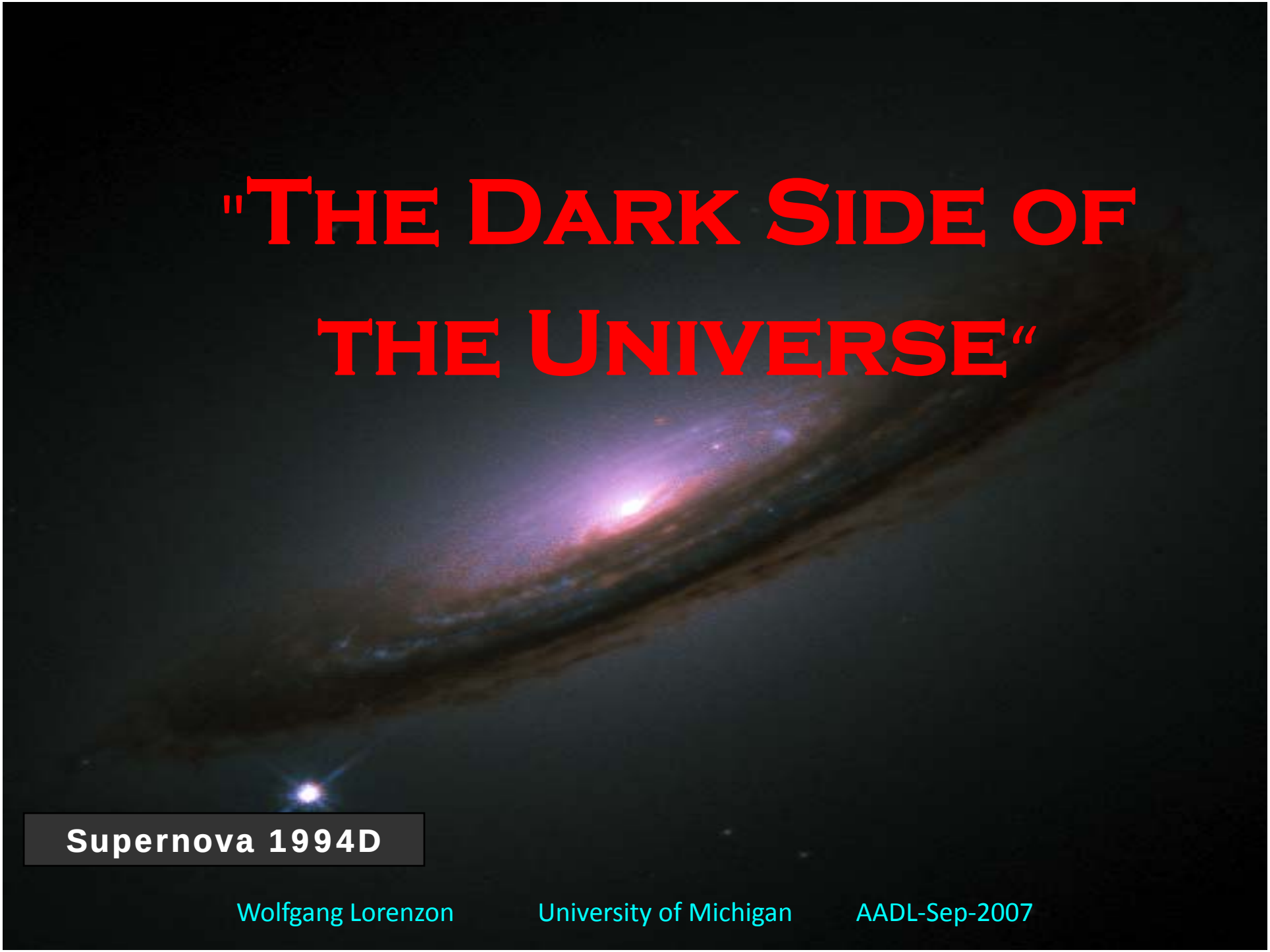


Please take a Diffraction Grating sheet.
We will need it for a demonstration.

Don't touch the plastic sheet in the center.

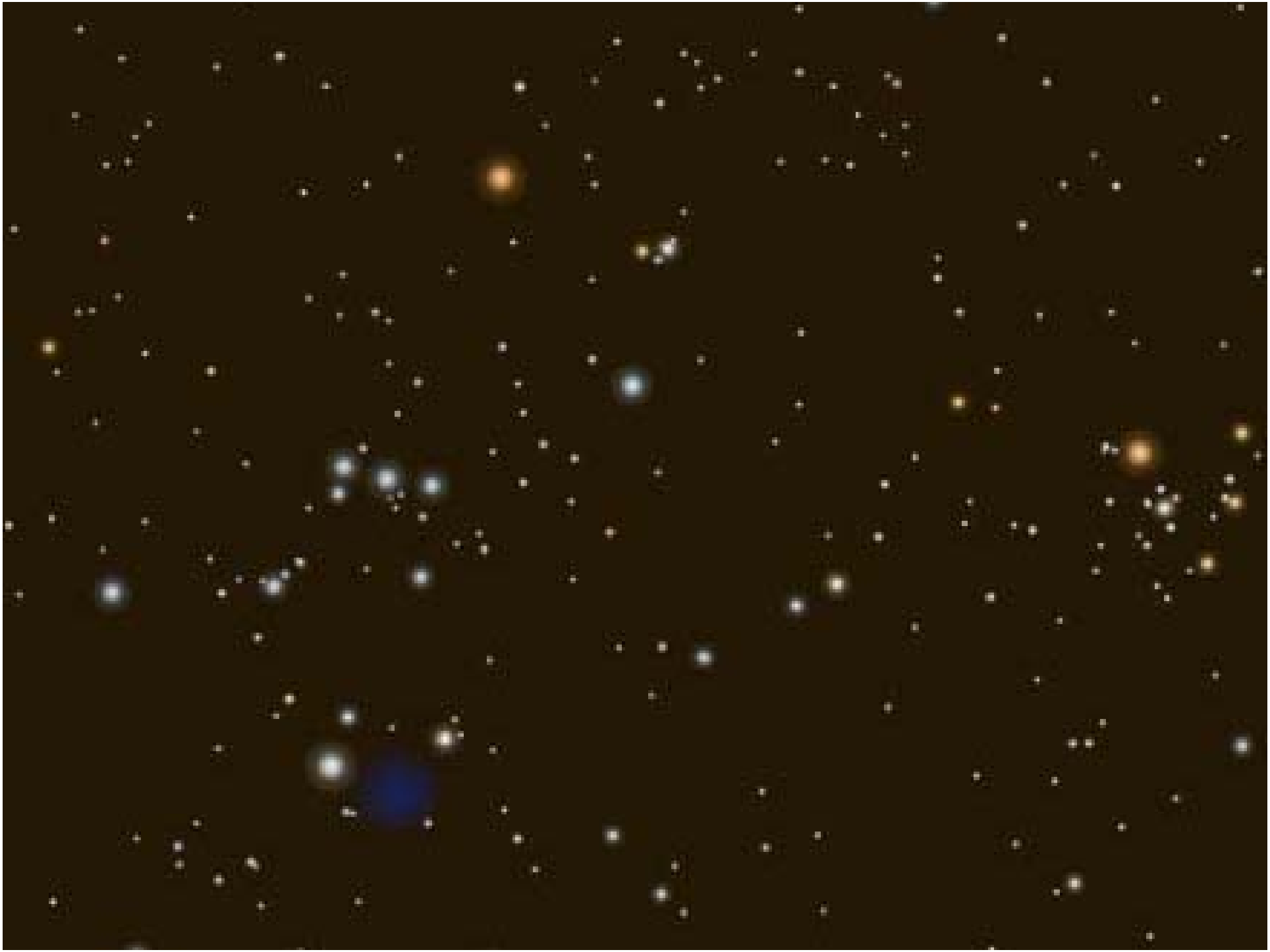
Return it at the end of the lecture.

"The Dark Side of the Universe"



Supernova 1994D

Wolfgang Lorenzon University of Michigan AADL-Sep-2007



Don't let the bright lights fool you

The DARK SIDE controls the UNIVERSE

Our Universe:	
Stars:	0.5%
Dark Matter:	25%
Dark Energy:	70%

Dark Matter holds it together

Dark Energy determines its destiny

What is Cosmology?

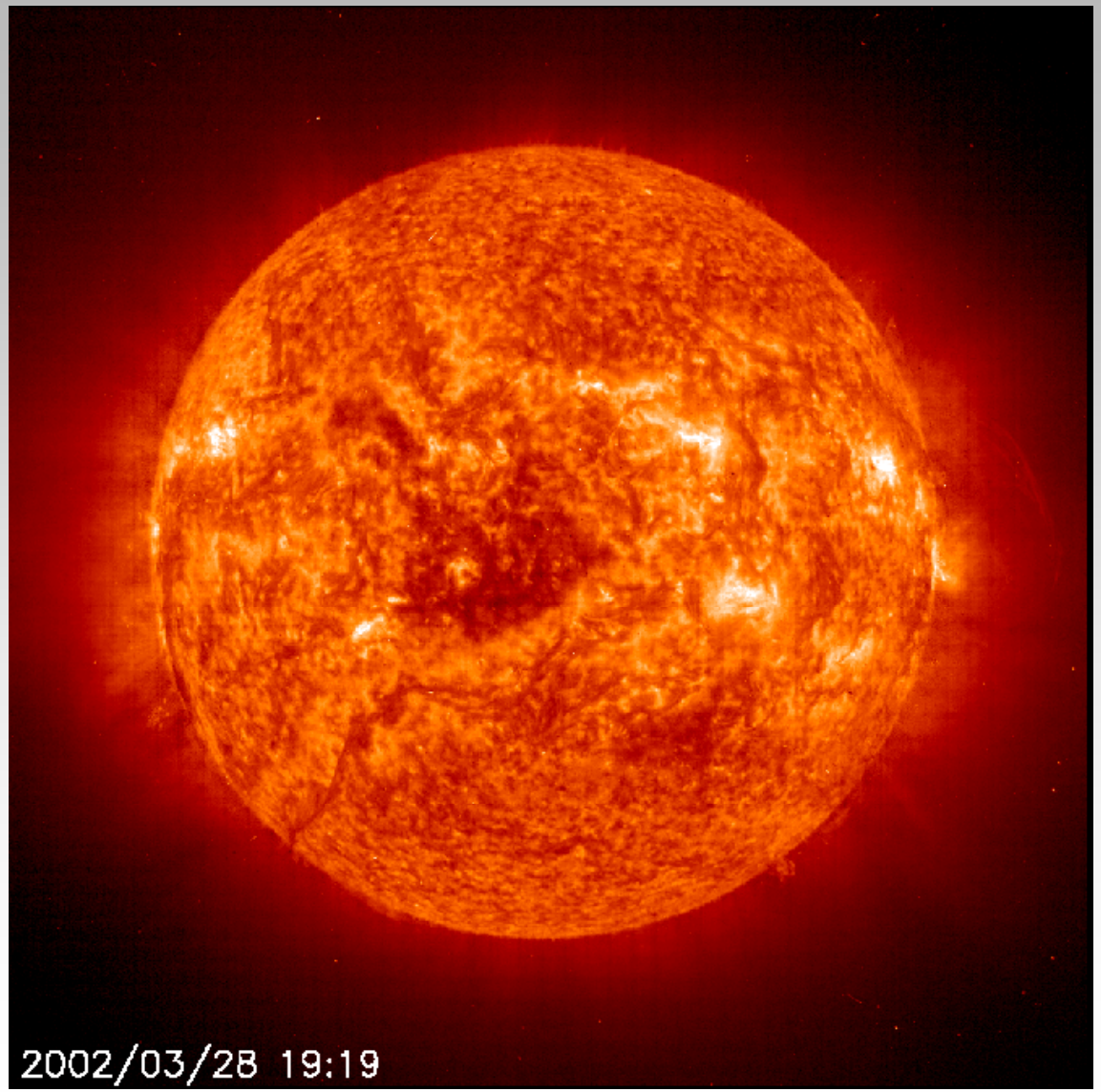
The attempt to understand the origin, composition and history of the Universe in which we find ourselves.

Basic Propositions of Cosmology

- Science works – we can understand the natural world using the process of testing theories against experiments.

- Experiments here on Earth are a valid guide – the behavior of material in the laboratory is the same as in distant reaches of the Universe, provided the conditions are the same.

Our Star: The SUN



Many Stars make a Galaxy

100-400 Billion stars/galaxy

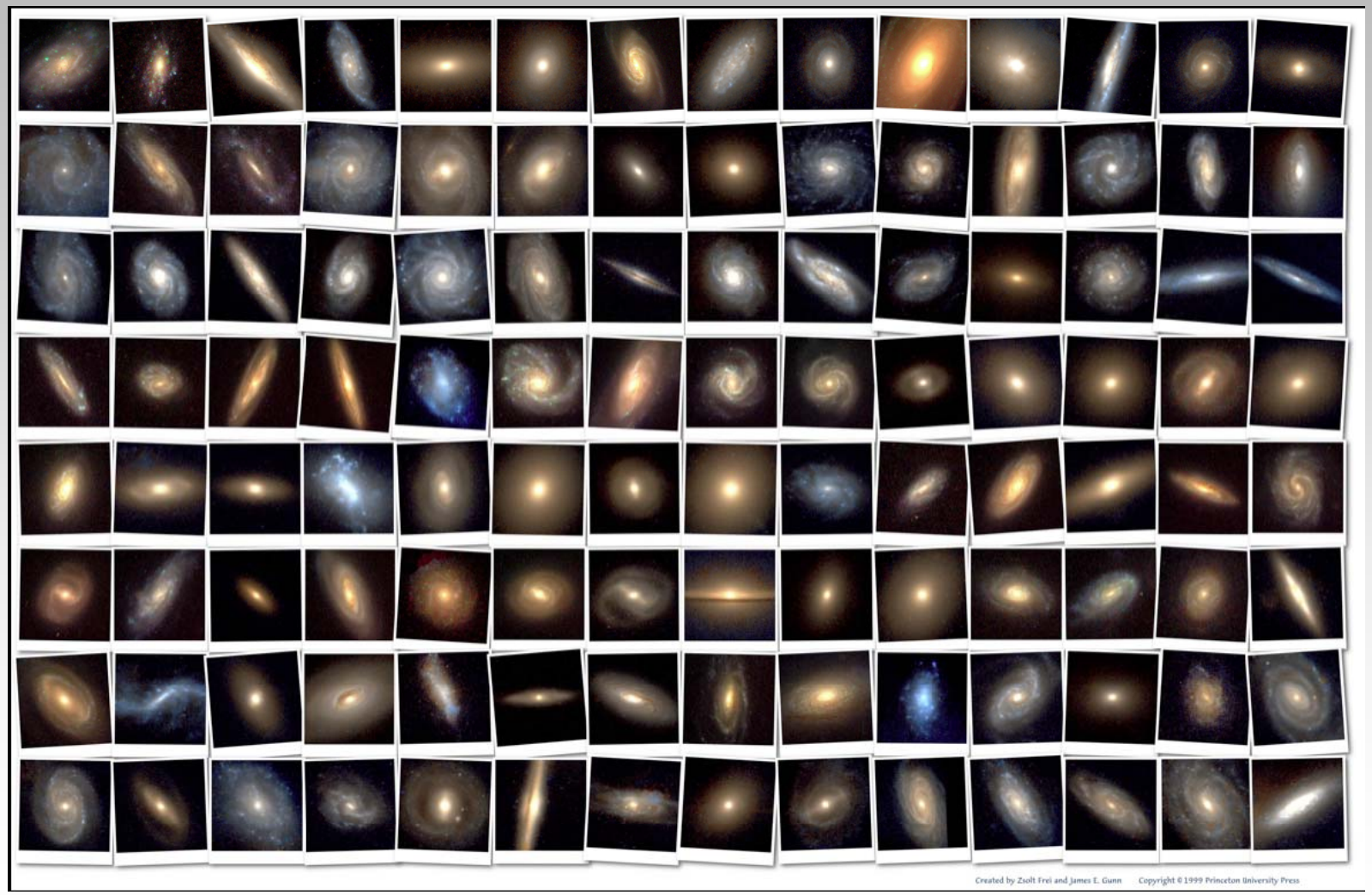
100,000 light years

Many Stars make a Galaxy

100-400 Billion stars/galaxy

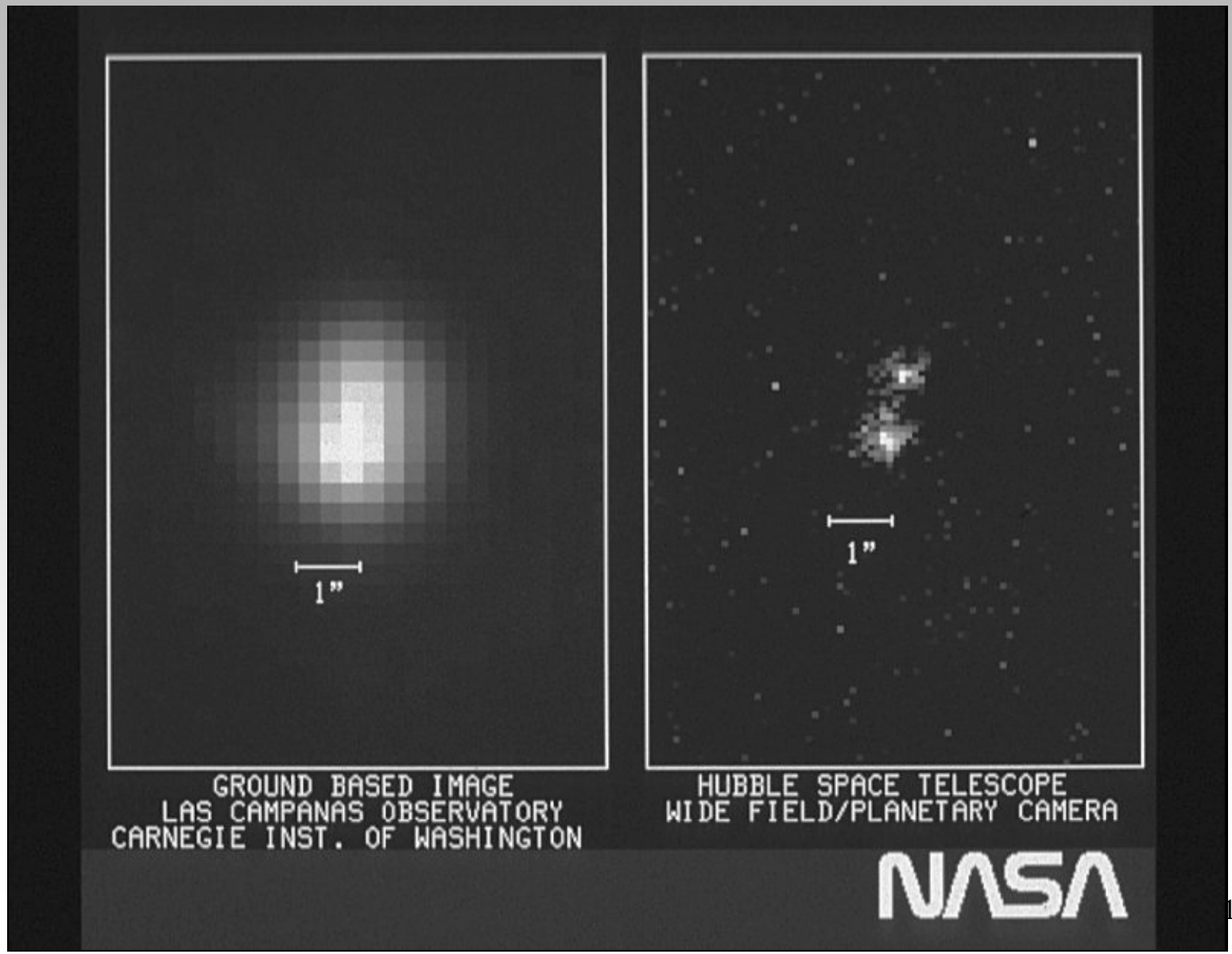
There are Many Galaxies…

100 Billion galaxies



Millions of light years

Seeing from Space



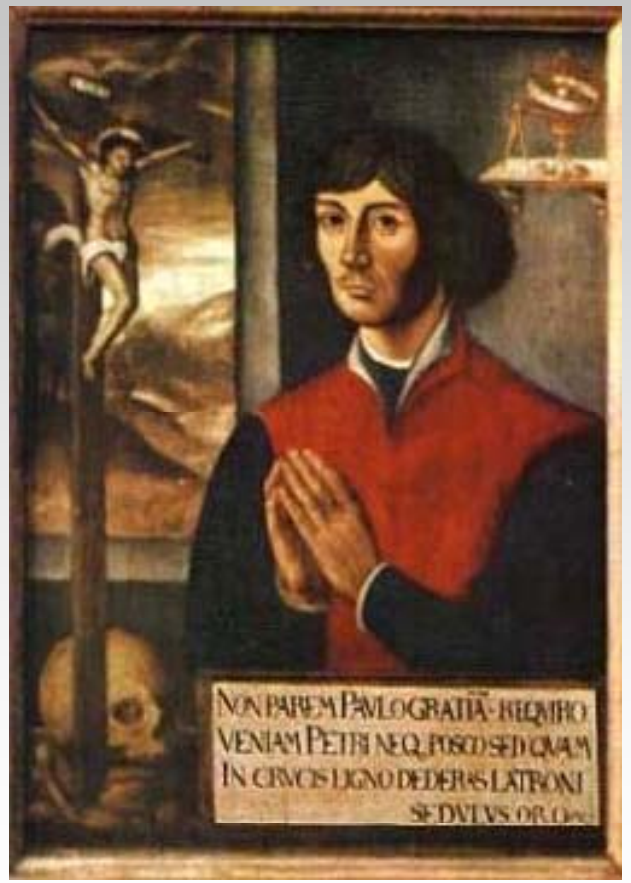
The Hubble Space Telescope

Big Questions

- What is our place in the Universe?
- What is it made of?
- How old is it?
- How has it developed?
- What is its ultimate fate?

What Copernicus "Knew"*

- "First of all, we must note that the universe is spherical."
  Elliptical orbits!
- Motions are centered on the sun
  Sun is at focus!
- Uniform velocities
  Equal areas in equal times!



Nicolaus Copernicus (1473 – 1543)
the sun — rather than the Earth — is at the center of the solar system. This is considered among the most important landmarks in the history of modern science.

It ain't what you don't know, it's what you know that ain't so!

What Kepler "Knew"*

- Gravity is an inverse-square law

  Kepler thought it was repulsive!

Johannes Kepler (1571 – 1630)
Kepler's laws provided one of the foundations for Isaac Newton's theory of universal gravitation.

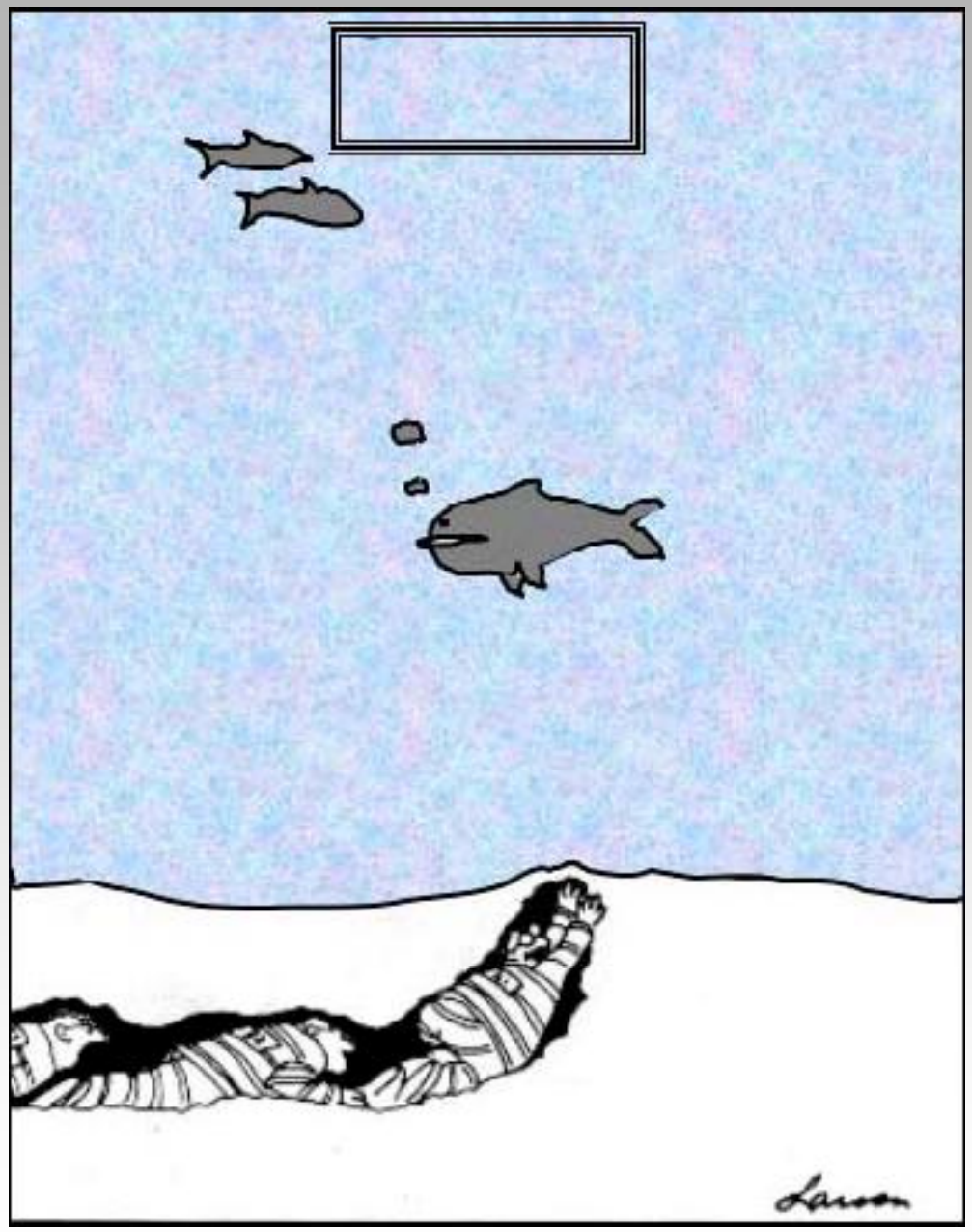
It ain't what you don't know, it's what you know that ain't so!

What We "Know"*

- Cold dark matter holds the Universe together
  we know nothing about it!

- The Universe is dominated by a cosmological term
  (Dark Energy, cosmological constant, …)
  we know less than nothing about it!

It ain't what you don't know, it's what you know that ain't so!



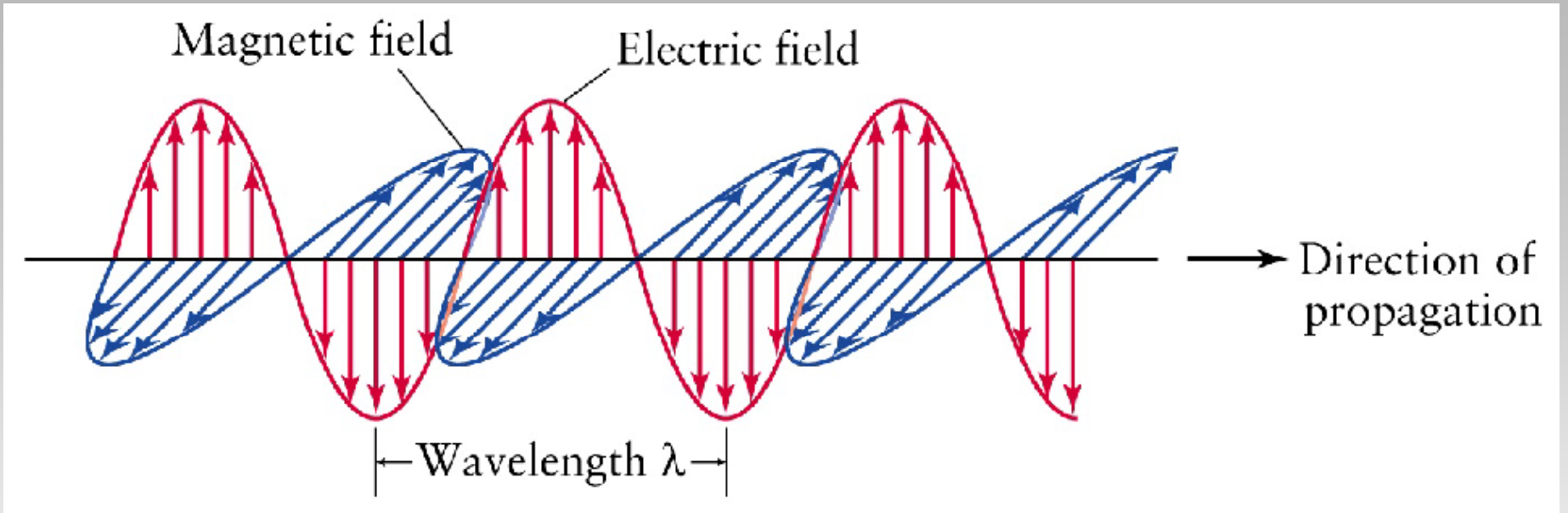
We’re almost free, I just felt the first drops of rain

Star Stuff

- We cannot go to stars and distant galaxies and take a sample.
- We can only “sit” here on Earth and receive the radiation which they send to us.
- Fortunately there is a wealth of information in the spectrum of their radiation.

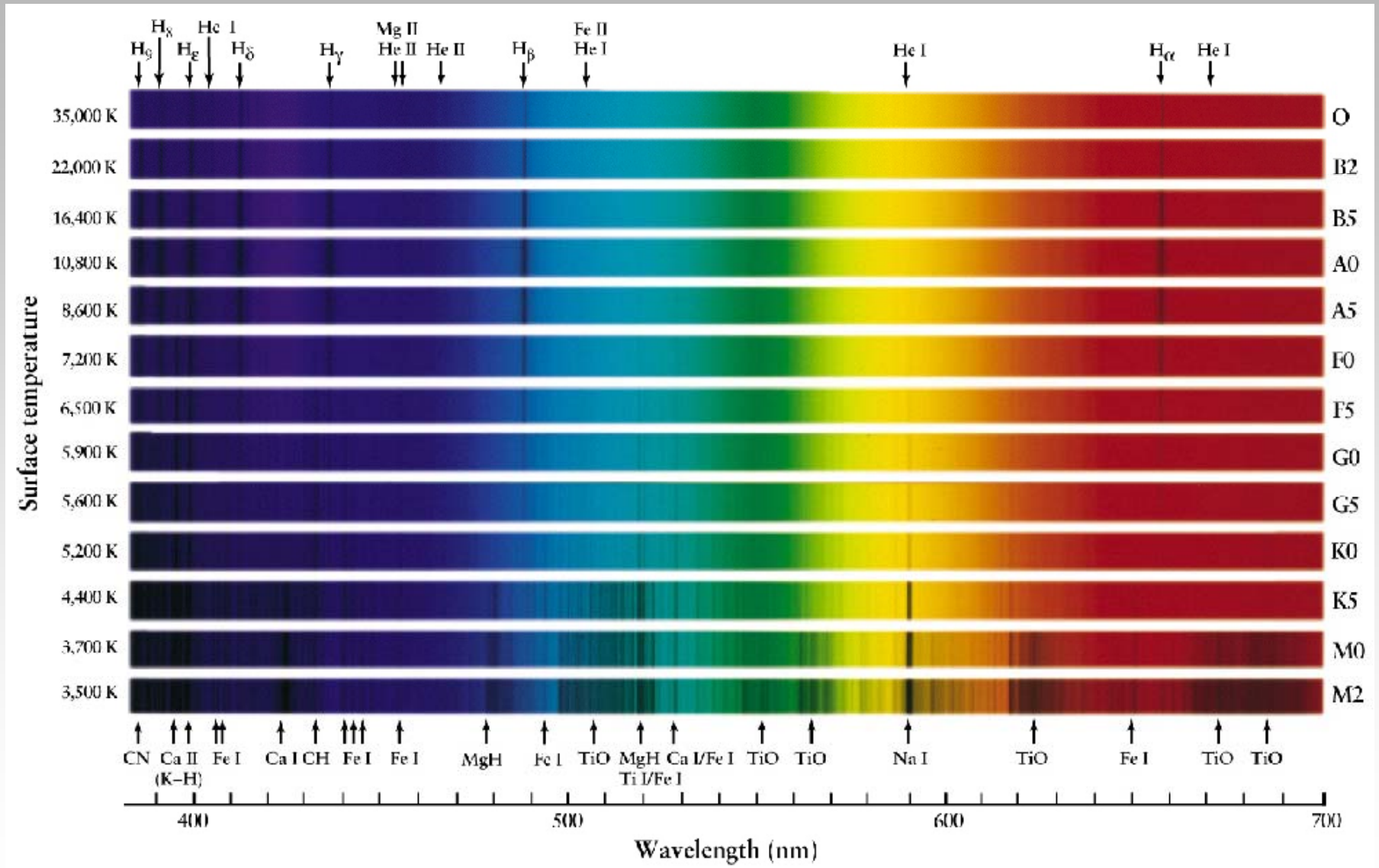
Sunlight is a Mixture of Colors

What is light?



- Light is an electromagnetic wave (for our discussion)
- It moves forward always at the same speed – 300,000 km/sec
  186,000 mi/sec
- The distance from one peak to the next is called the wavelength

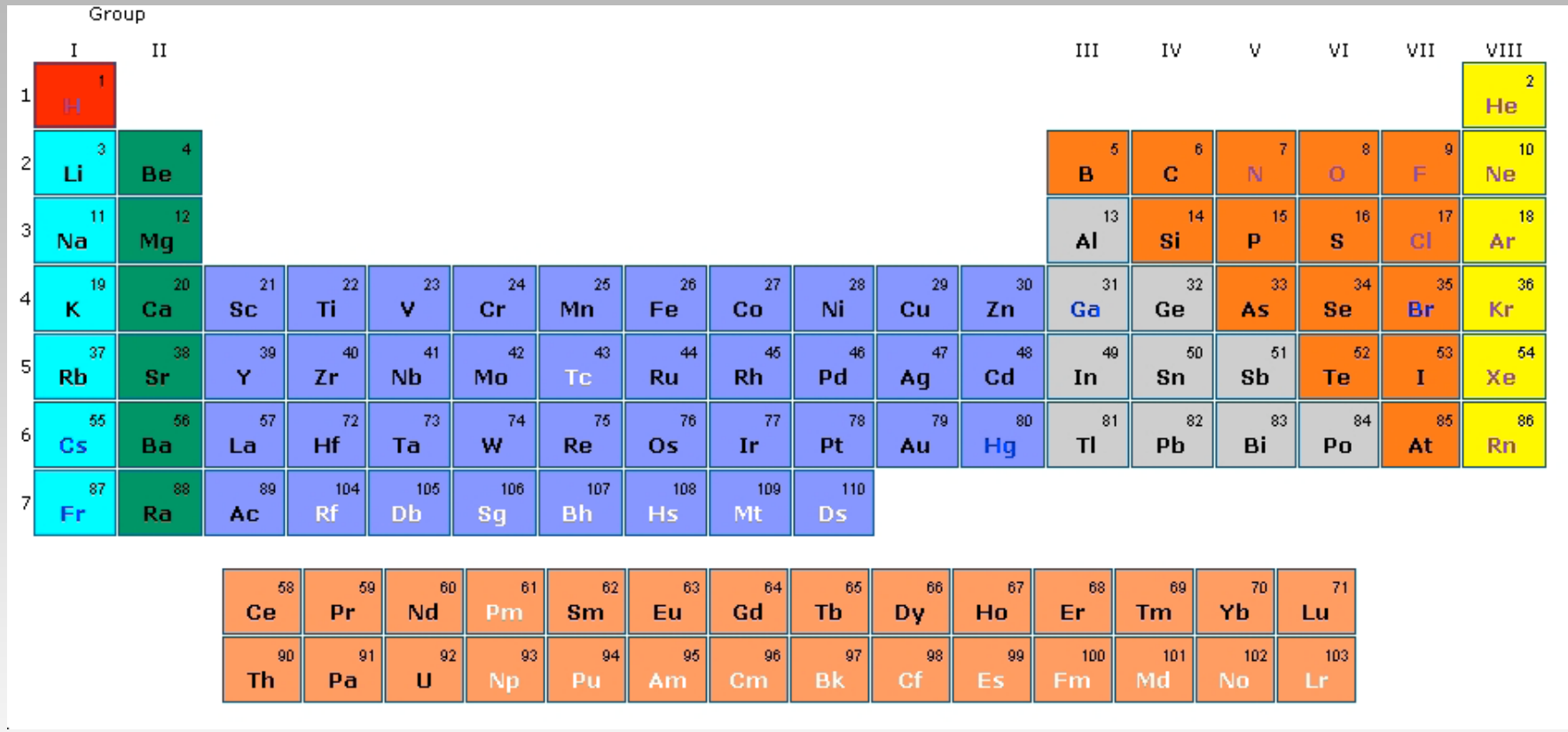
Stellar Spectra



Stellar Spectra

- Spectra of stars are very complicated (thousands of lines)
- Every single of them can be matched with an element (or compound) whose spectrum we measure here on Earth
- The obvious explanation is that stars are made of the same stuff we are … (although of course not in the same proportions)

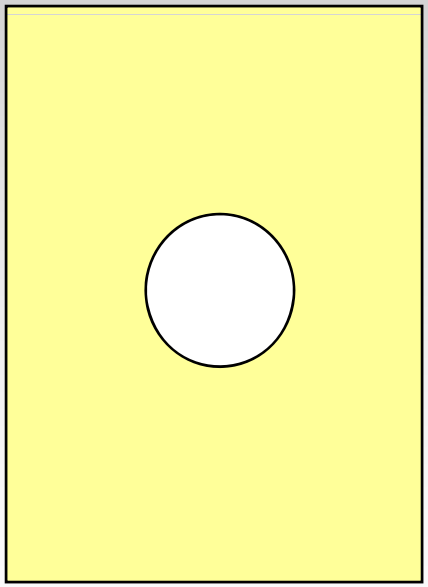
The Periodic Table of Elements



- All matter is composed of atoms
- Atoms come in a fixed range of types – The Elements

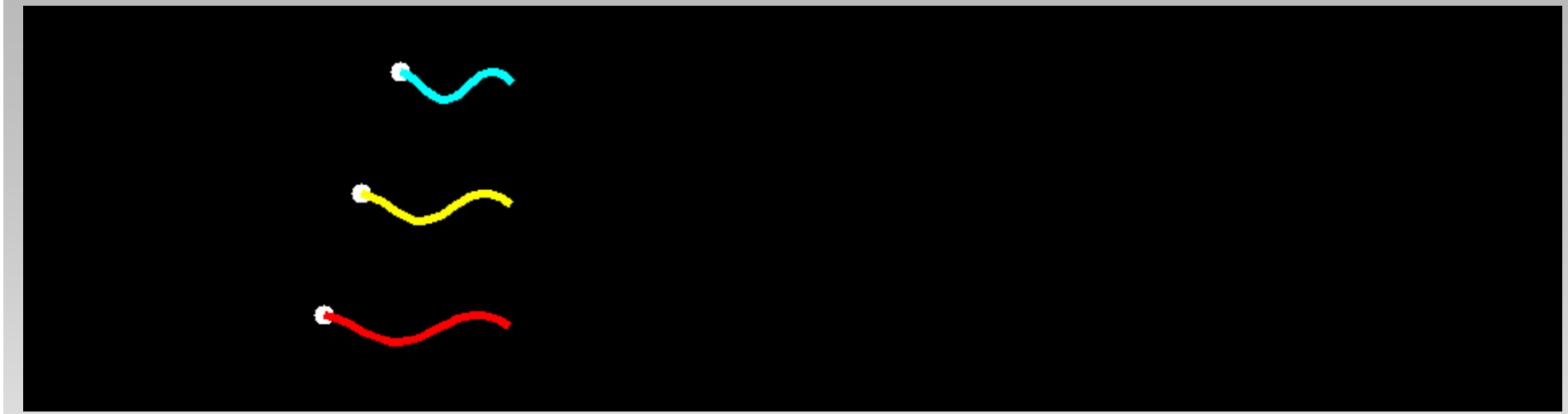
Each Element has a unique Fingerprint

Let's see that for ourselves



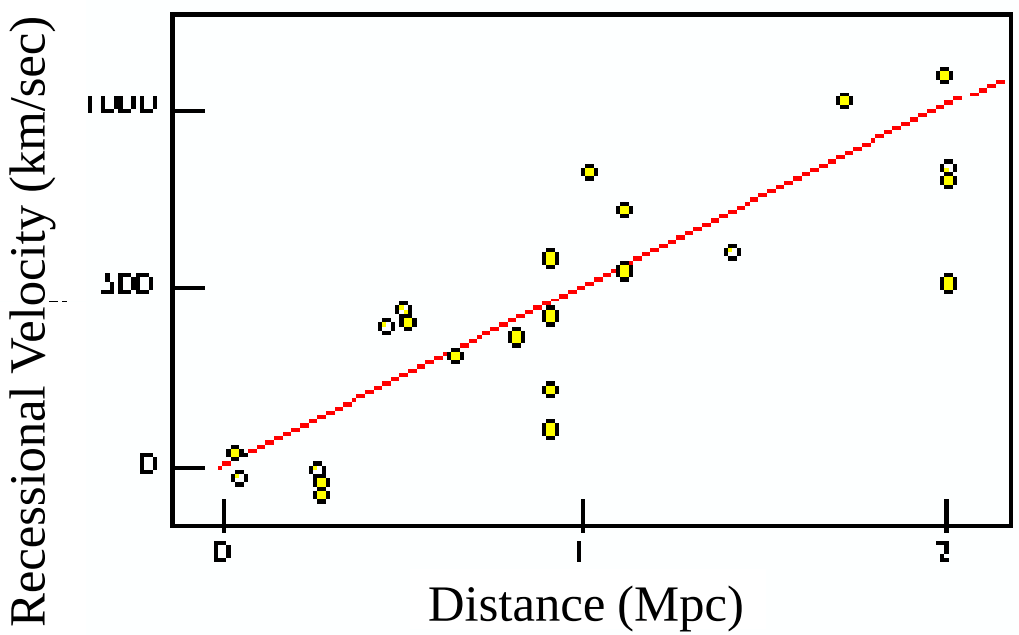
Pick up your diffraction grating sheets to view the demonstration.

Classic Doppler Effect



- Imagine three atoms emitting a ray of light of the same color (let's say yellow)
- One is stationary, one is moving towards us, one is moving away
  - moving towards → "compressed" → appears bluer
  - moving away → "stretched" → appears redder

Hubble's Great Discovery



- In 1929 Hubble measured the velocity of nearby galaxies and found that nearly all were moving away from us.
- He used Cepheid variable stars in these galaxies to measure distances.

$$\text{velocity} \propto \text{distance}$$

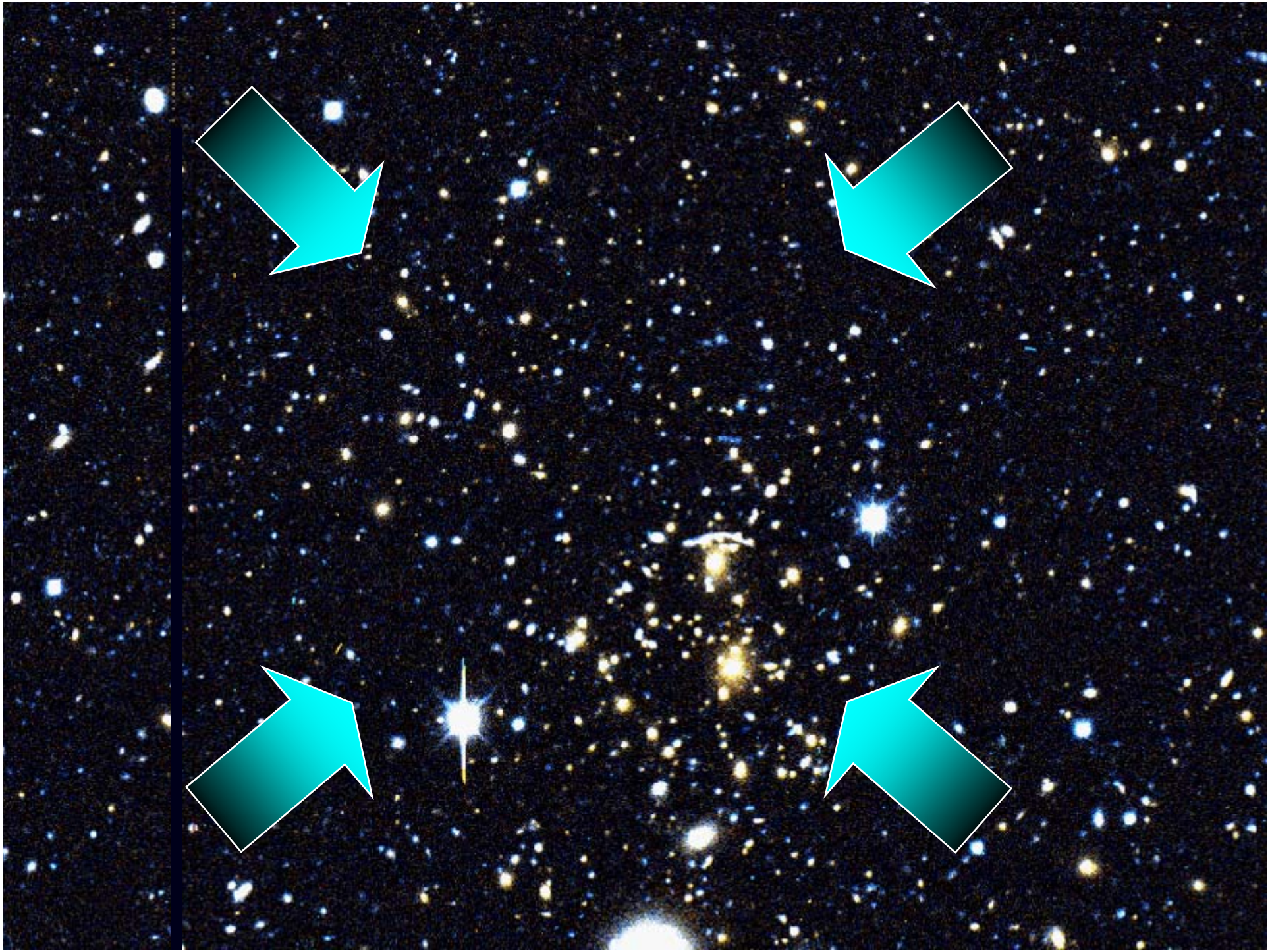
$$v = H_o r$$

- Result: The faster they are moving, the farther away they are.
- The Universe is not static – it is expanding!

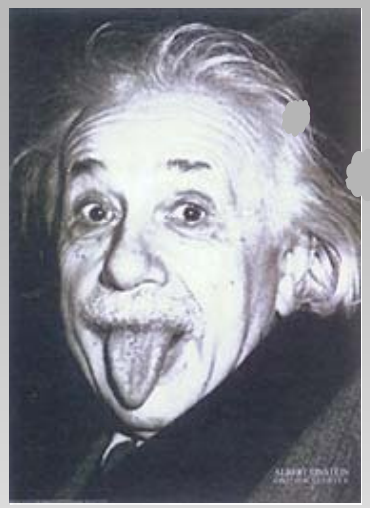
Pre 1920s: The Static Universe

$$H^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2}$$

- The widely-held belief was that we lived in a static, unchanging universe
- In 1916, Einstein develops a theory of gravity: General Relativity
- Problem! His equations predict that Gravity pulls things together

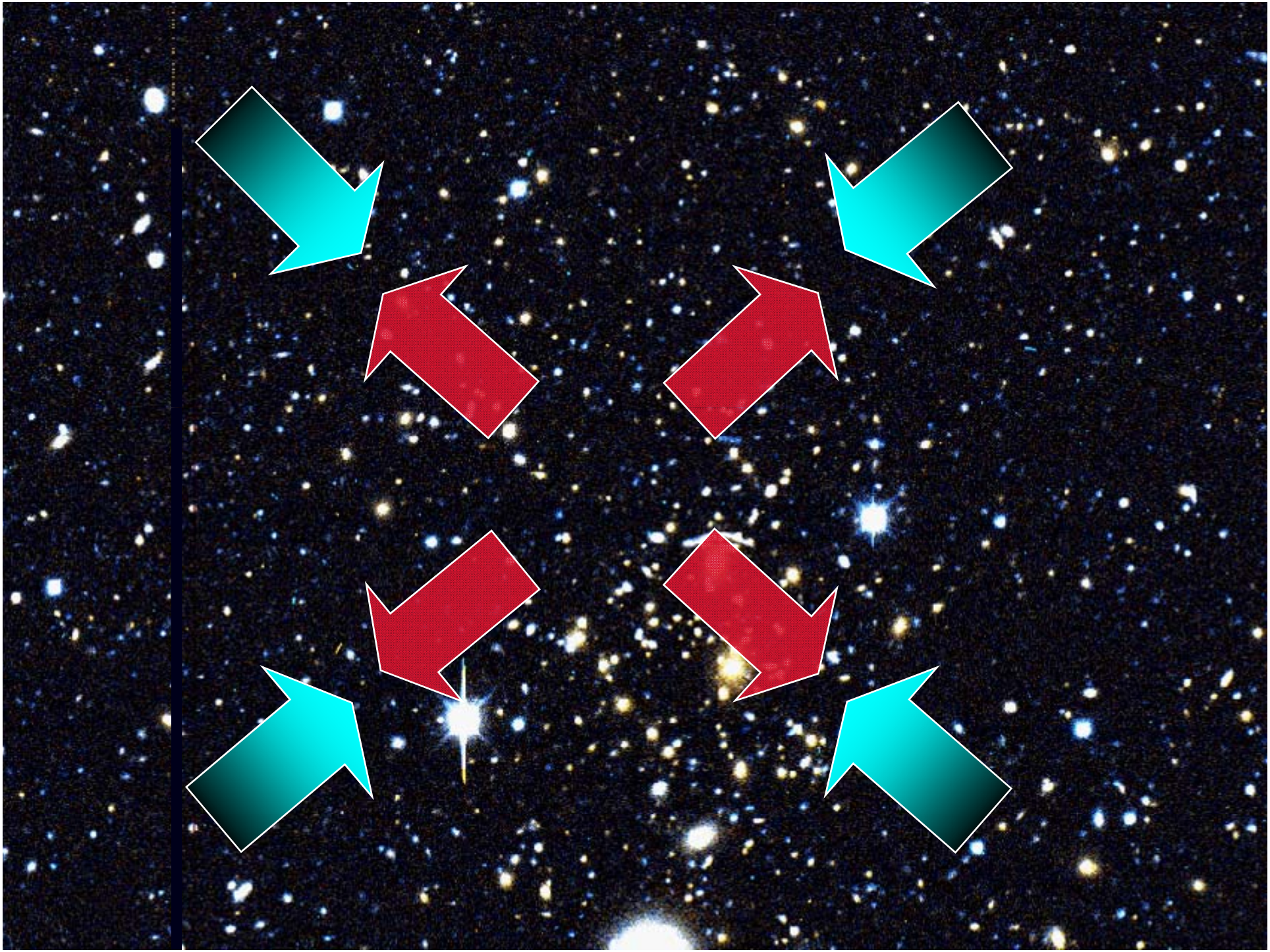


The Equation of the Universe



$$H^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

- So Einstein sought to modify the equation to fix this flaw and prevent gravitational collapse …
- Einstein introduced a cosmological constant Λ (vacuum energy) to ensure a static universe.
- By tuning Λ, attractive gravity due to matter can be balanced by the "repulsive" gravity of Λ.

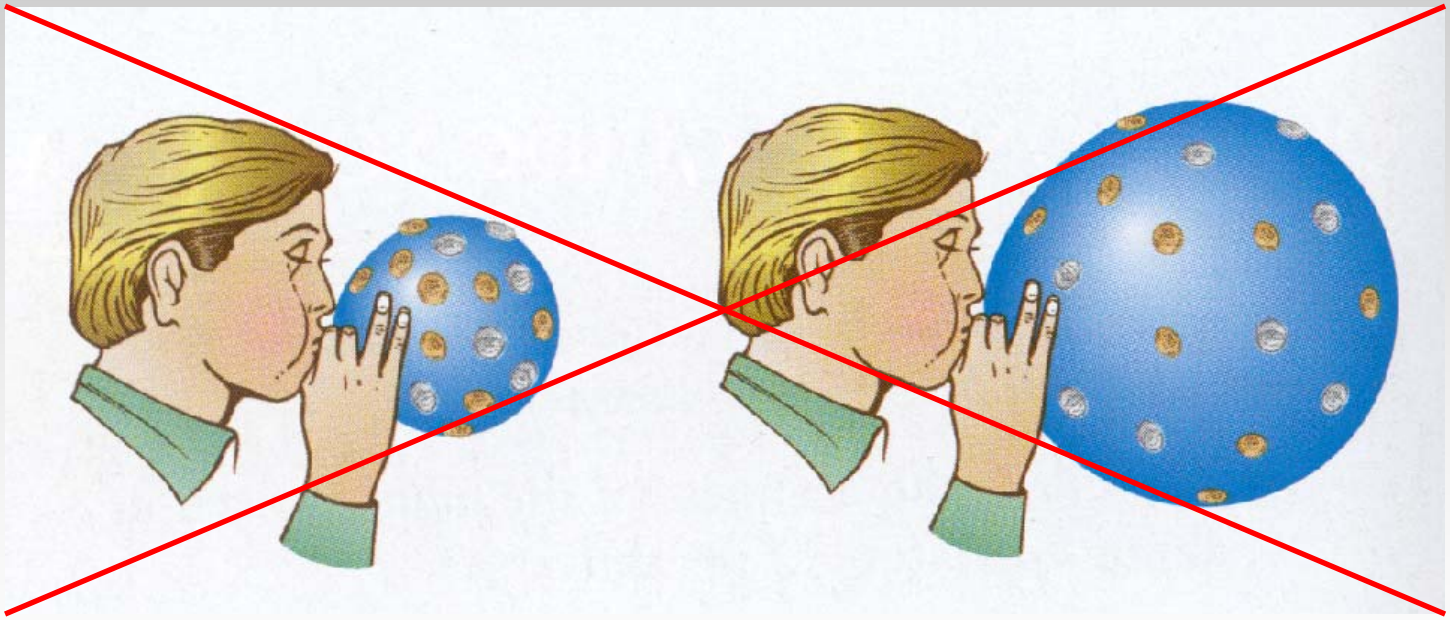


Einstein's "biggest blunder"

- The Universe is not static – it is expanding!
- Einstein is very upset!
- Einstein declares Λ his biggest blunder!

"Brooklyn is not expanding!"

- The expansion of the universe is an expansion of space itself. It is **not** an explosion with pieces flying out from a common center through space.
- Except for motion due to local gravity through space, each galaxy is at rest with the Hubble flow and "sees" the other galaxies moving away according to the Hubble law $v = H_0 r$.



- The universe is not expanding into anything. It is creating new space between the galaxies as it grows.

The Big Bang

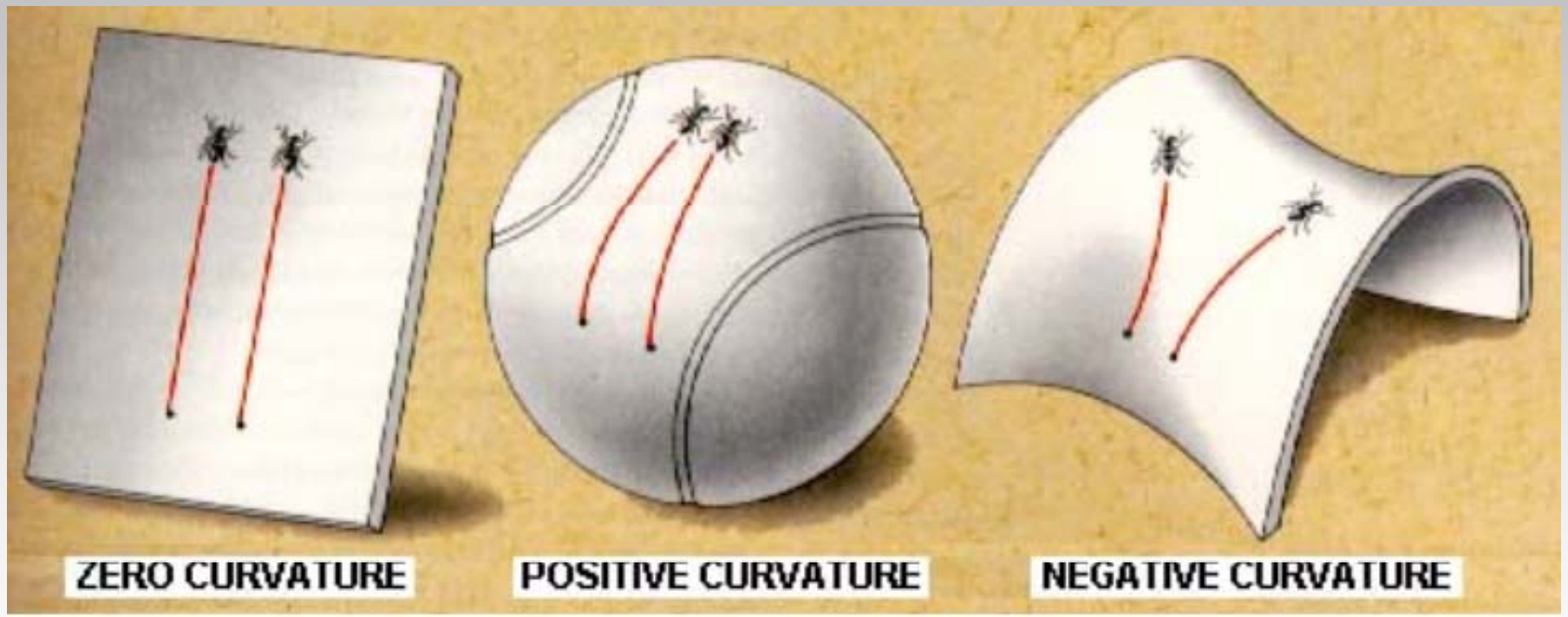
- If everything is moving away from us – are we at the center?
  - **No**: every place is the center
- If everything is moving away from everything else – some time ago in the past everything was on top of each other?
  - **Yes**: Winding the clock back, we reach a time of infinite density: the Big Bang!
- If the expansion rate is constant, then the age of the Universe is ~14 billion years (or $1/H_0$)

Is the Universe Slowing Down?

- As we look out into space we look back into time
- Telescopes = Time machines
  - We see nearby objects as they were recently
  - More distant objects we see as they were a long time ago
- What is the fate of the Universe?

Geometry vs Destiny

Einstein's General Relativity: Geometry ⇒ Destiny



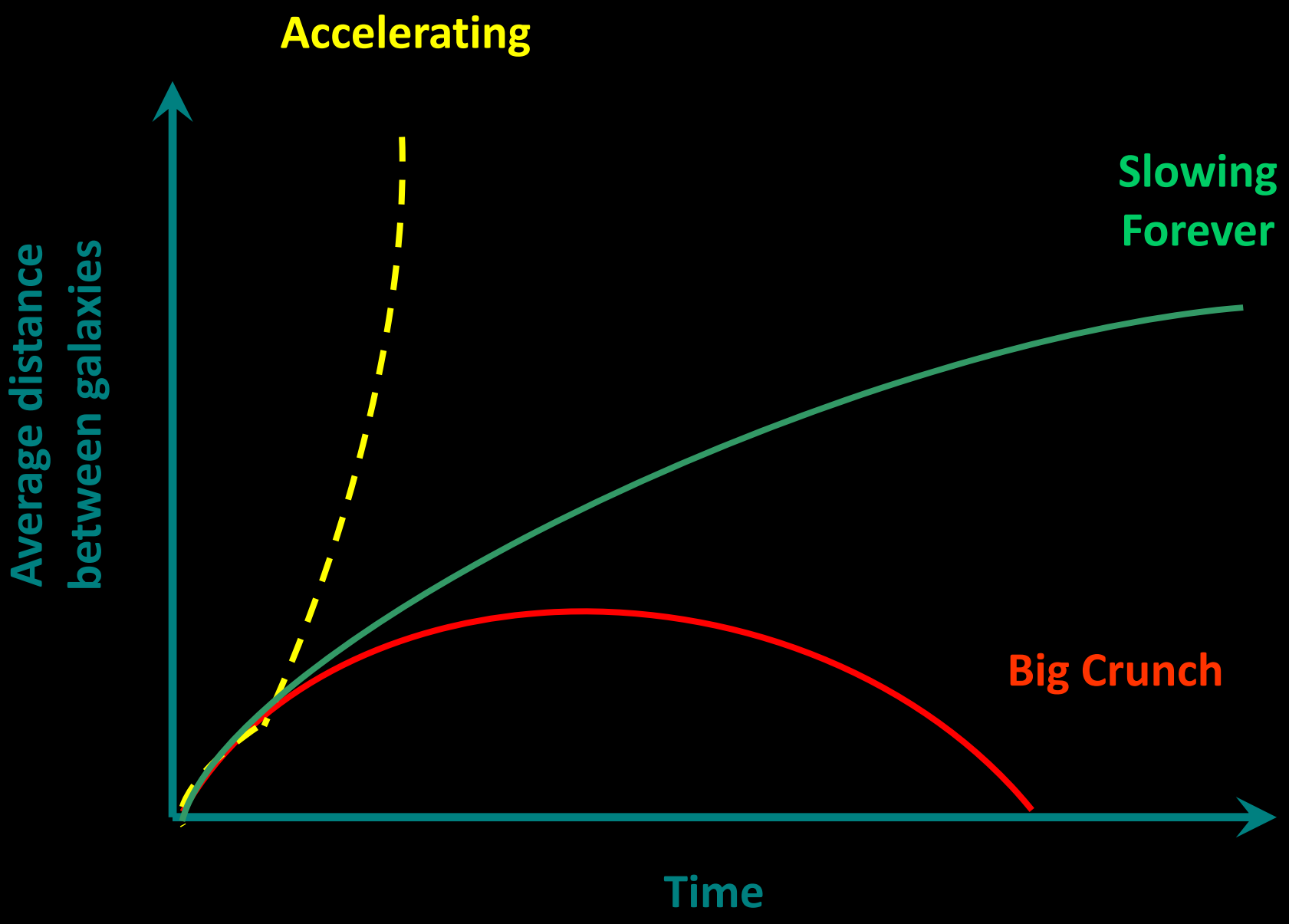
FLAT **SPHERICAL** **HYPERBOLIC**

open infinite universe ⇒ decelerates to rest

closed universe ⇒ eventual collapse

open infinite universe ⇒ expands forever

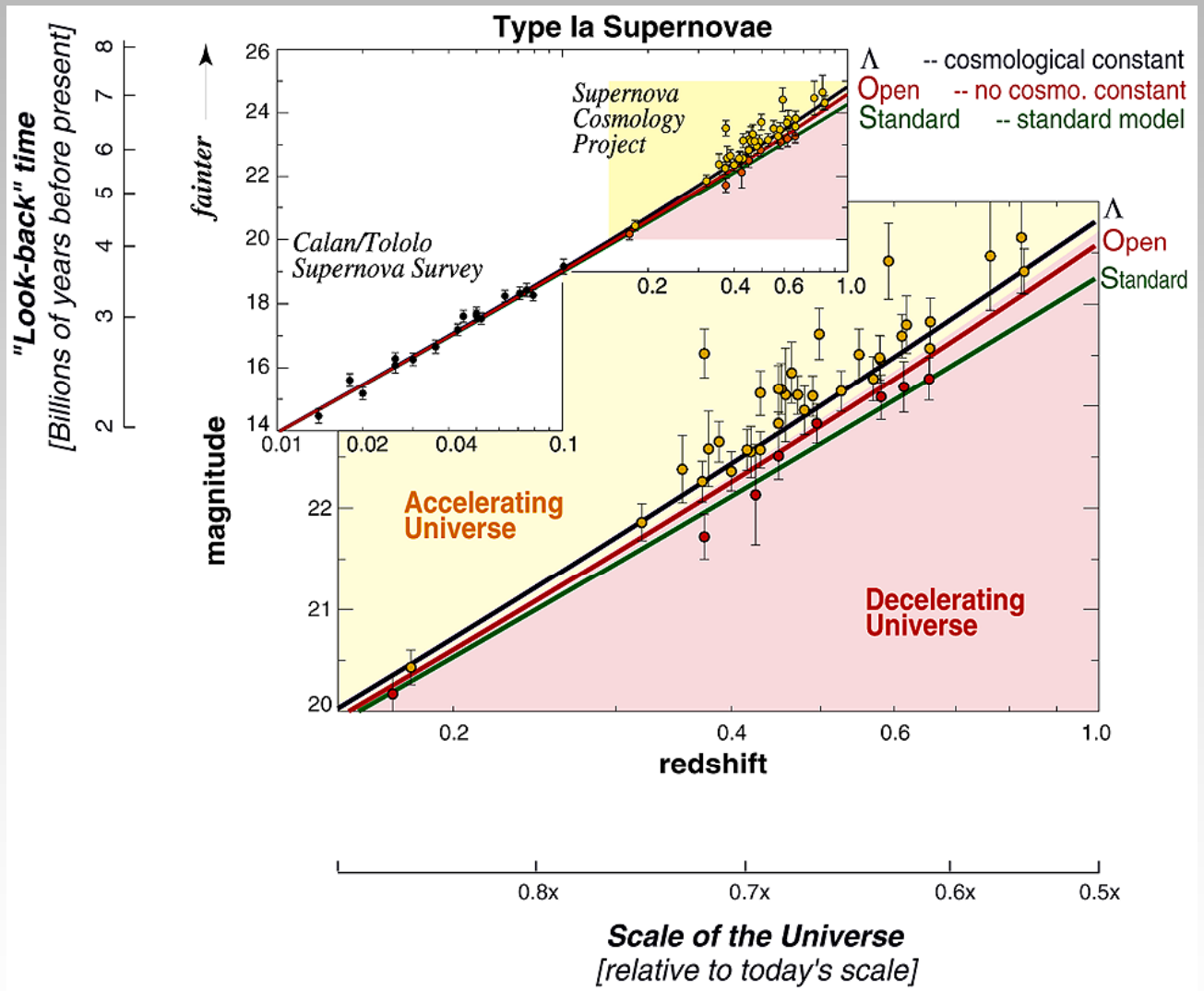
The Fate of the Universe



A Startling Discovery

- (1998) Supernova Cosmology Project and High-Z Supernova team construct a Hubble diagram using Type Ia supernovae looking back 7 Byr (1/2 the age of the universe).

- Both found that the Universe is speeding up, not slowing down!

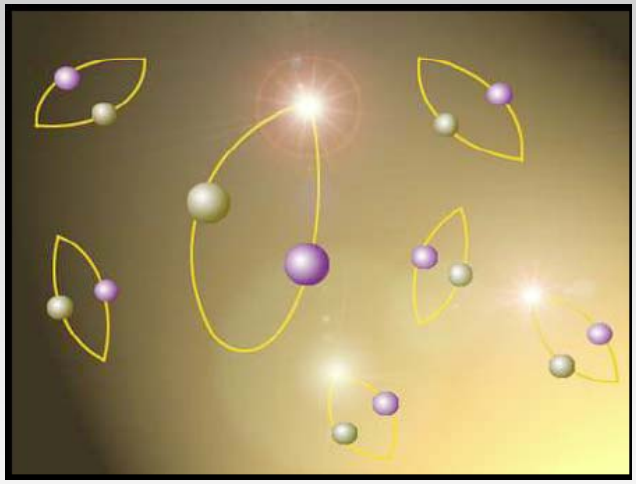


WHY??

Dark Energy

DARK ENERGY

- What is it?
  - It is a property if empty space itself
  - Vacuum Energy (Einstein's "biggest blunder")
  - Repulsive instead of attractive
  - Smoothly filling space
  - Constant or slowly changing
  - No one knows!
- It is a funny concept
  - Turns out nothing (the vacuum) has energy
  - Quantum fluctuations in the vacuum have energy
  - This energy is repulsive
- It causes the Universe to accelerate



Problem!
Theoretical calculations are off by 10^{120}

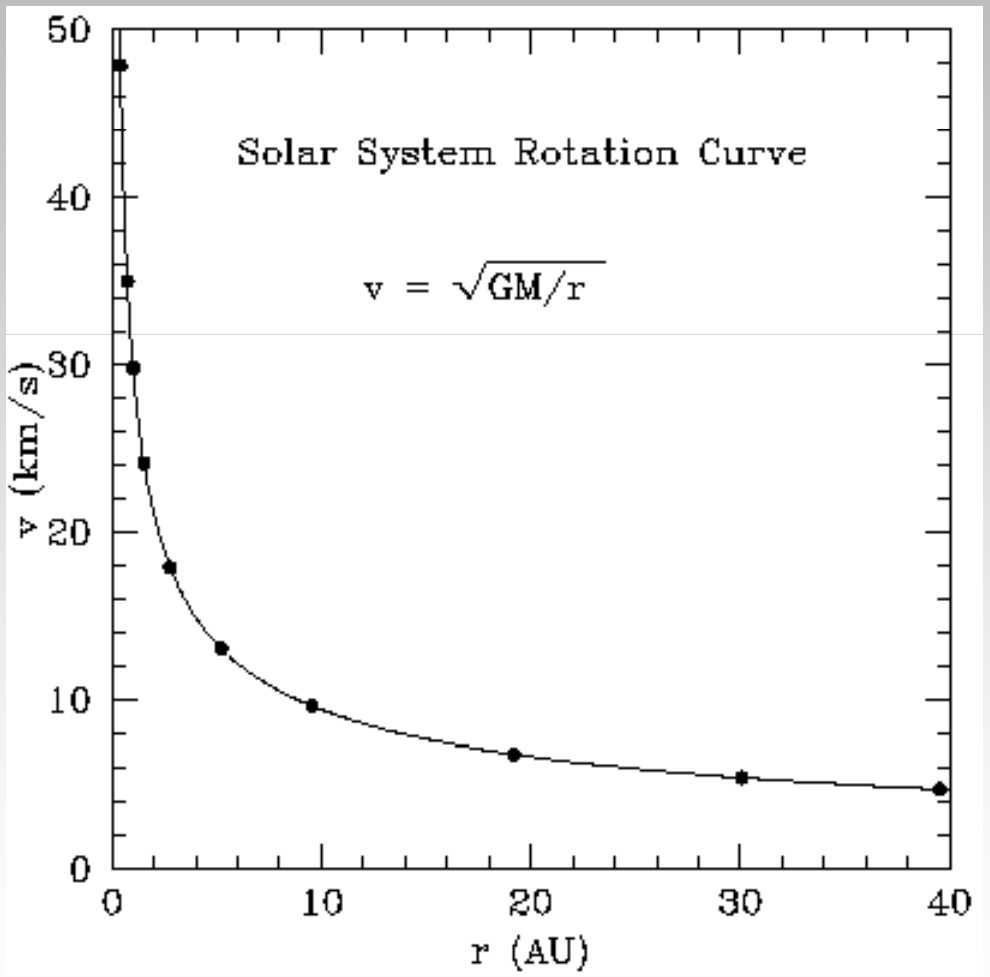
The Mysterious DARK Matter

- Observations indicate that there is matter out there which does not produce any kind of light
  - Does not appear to interact with ordinary matter or itself at all except through gravity!
- One type of evidence for this is the way stars and gas in galaxies move …

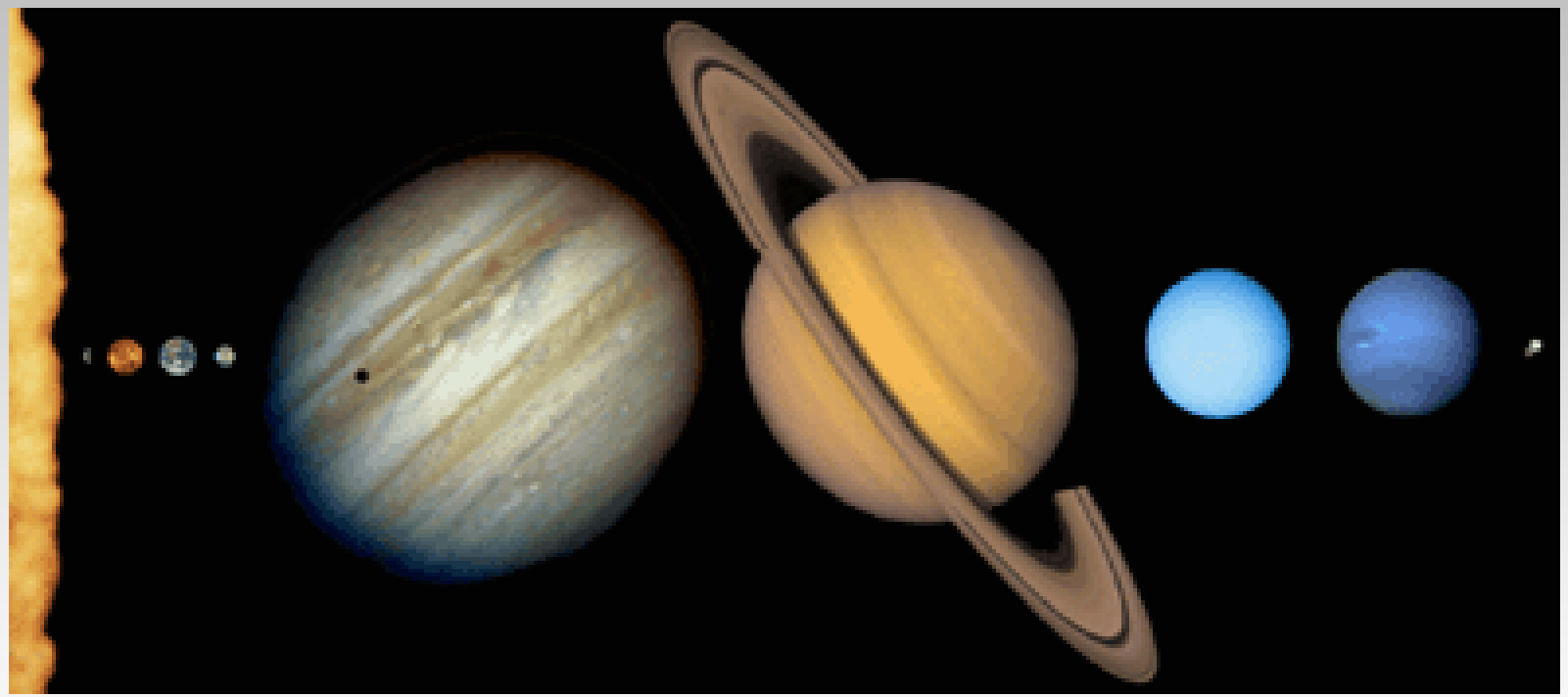
Solar System Rotation Curve

Average Speeds of the Planets

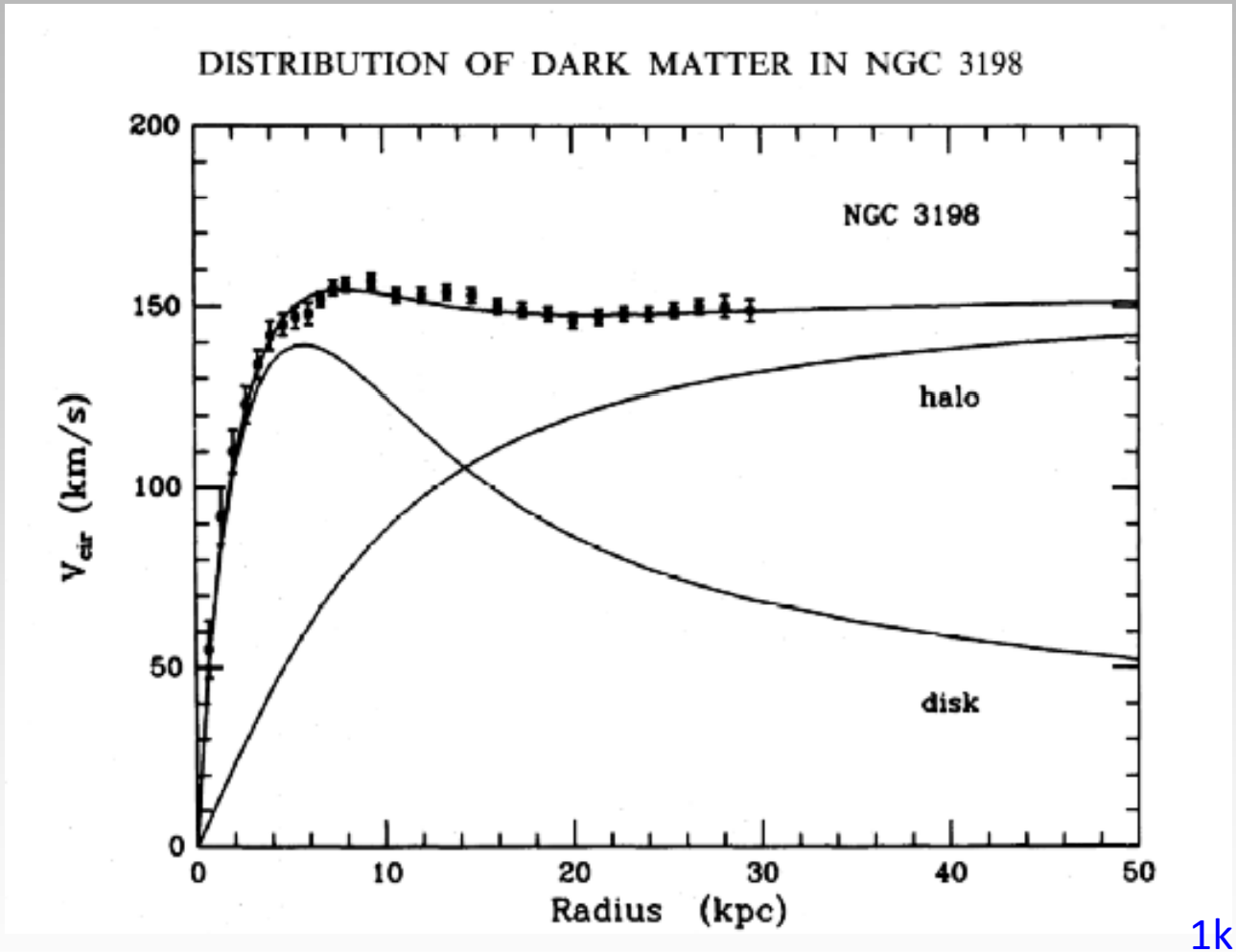
As you move out from the Sun, speeds of the planets drop.



Solar System



Rotation Curves of Galaxies



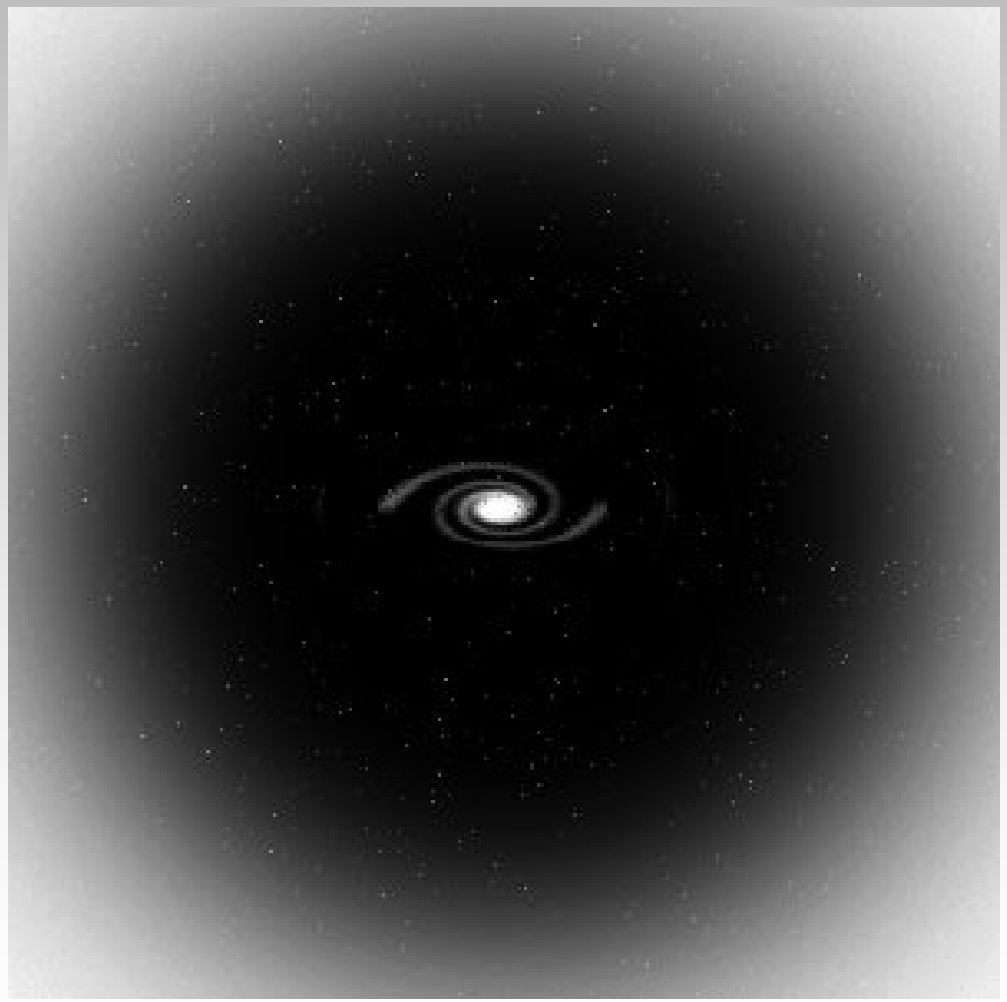
observed:
flat rotation
curve

expected
from stars

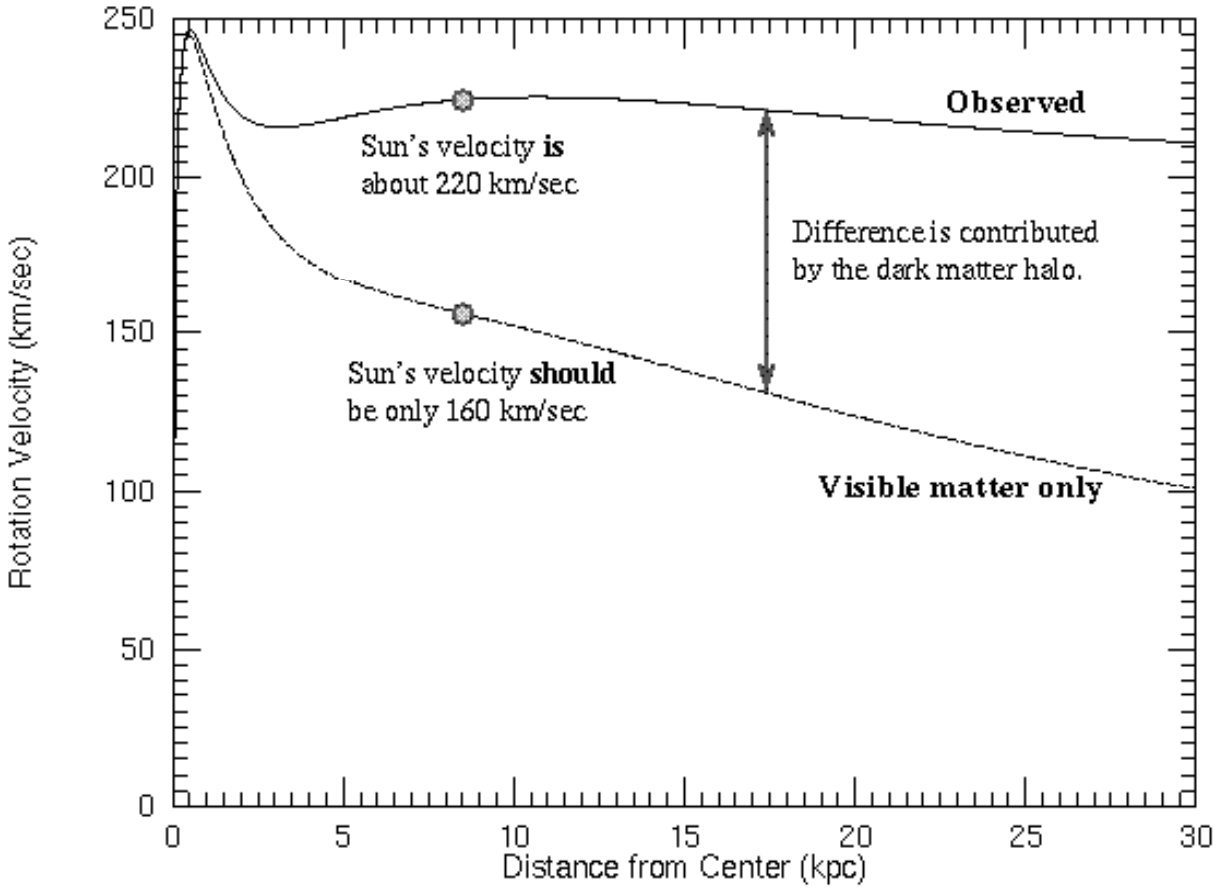
1kpc = 3,300 light years

95% of the mass in galaxies is made of an unknown dark matter component

Galaxies have Dark Matter Haloes



Sun's orbit is sped up by dark matter in the Milky Way

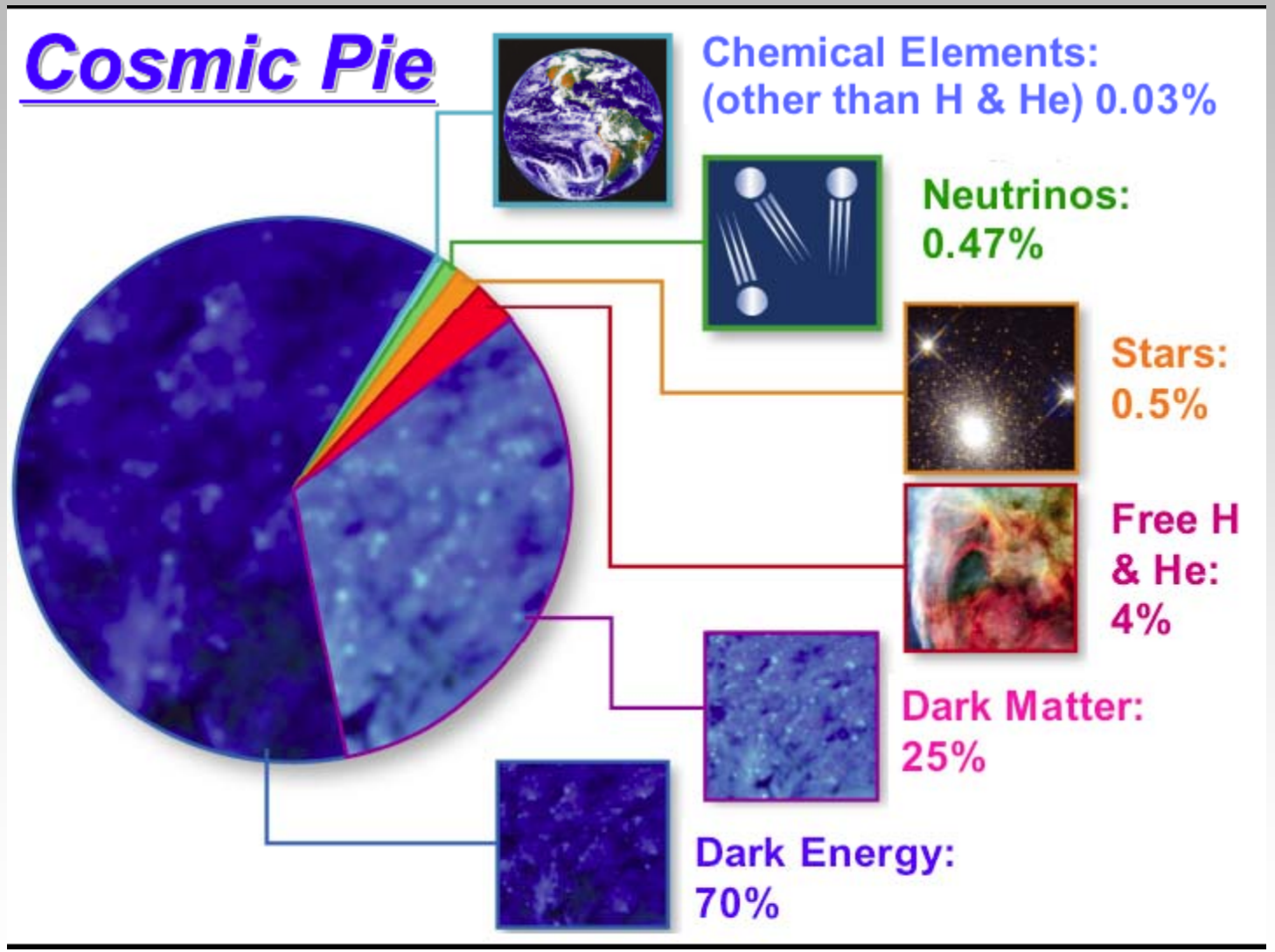


The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

What is Dark Matter?

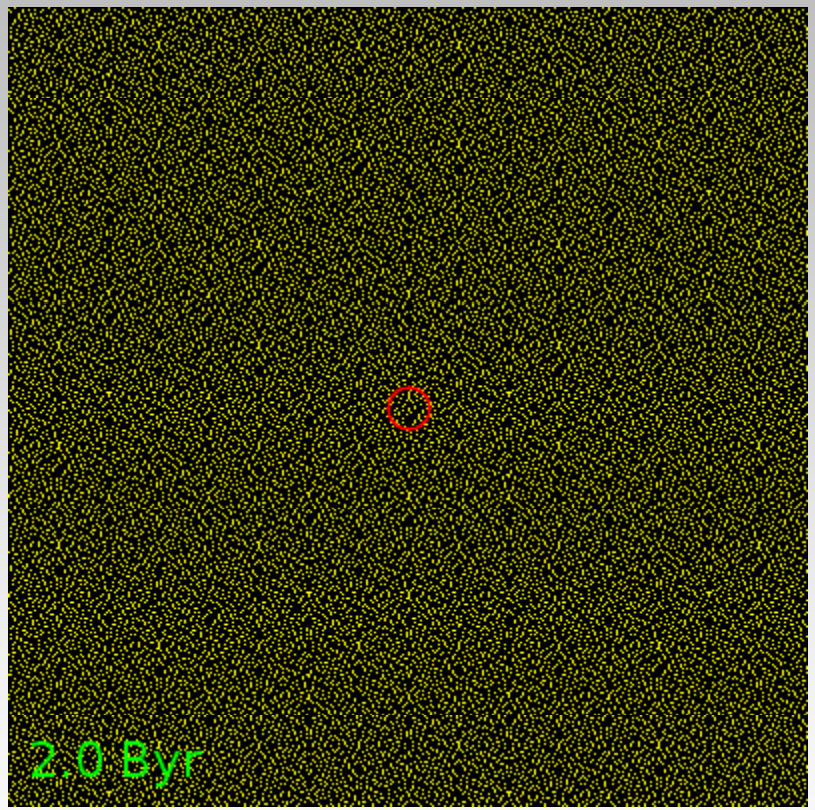
- Does not emit or absorb light in any wavelength
- Visible through gravitational effects only
- Normal stuff that does not emit light?
  - brown dwarfs or planets, white dwarfs, neutron stars, black holes, dark galaxies and clusters of galaxies?
- Exotic particles?
  - "Hot" Dark Matter: neutrinos?
  - "Cold" Dark Matter: Weakly Interacting Massive Particles? WIMPS are about 100 times as heavy as protons
- Incorrect law of gravity?

The contents of our Universe

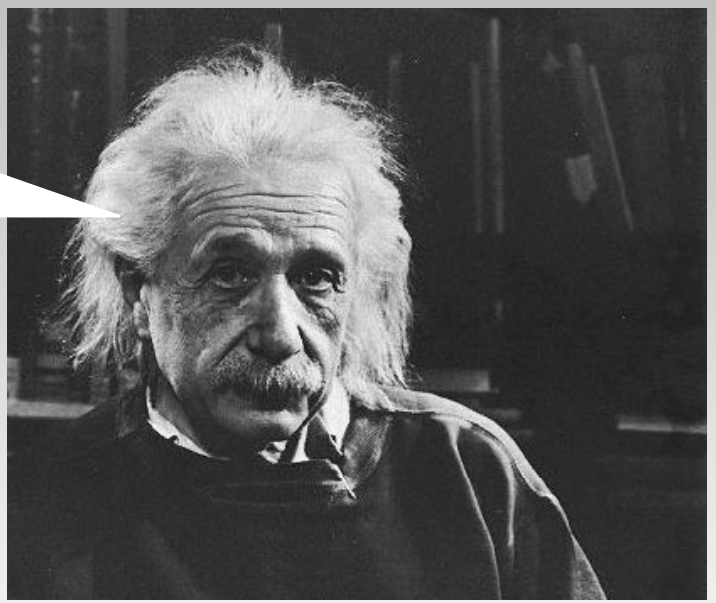


Implications of Cosmic Acceleration

- There is a previously unseen "dark energy" pervading all of space that is now accelerating the expansion of the universe.
- The expansion is NOT slowing to a halt and then collapsing (i.e., the universe is not "coming to an end"). In the simplest models, it will expand forever.
- In the not so distant past (> 5 Byr ago) the universe was dominated by matter and was decelerating. Larger and larger structures formed as each new scale entered the horizon.
- The formation of structure ended when dark energy prevailed over matter.
- The largest structures in the universes are now being accelerated beyond our horizon - e.g. Virgo Cluster will be leave our horizon in 118 billion years.


2.0 Byr

More than 380,000 light years in less than 380,000 years?



- …. for velocity <u>through</u> space
- no limit on expansion velocity <u>of</u> space
- “acausal” requires “accelerated” expansion

What we don't know

- Precisely how much mass density and dark energy density is there?
- What is the equation of state of the dark energy, the ratio of pressure to density $w = p/\rho$?
- how has it changed in time?

What is the "dark energy?" Theorists have proposed a number of possibilities each with its own unique features:

- Cosmological constant (Einstein).
- "Quintessence" models
- Supergravity models
- "Cardassian" expansion
- The "big rip" $w < -1$

…

Lots of theories, little data!

Dark Energy

Quintessence

Supergravity

Kessence

Cyclic Universe

Phantom Energy

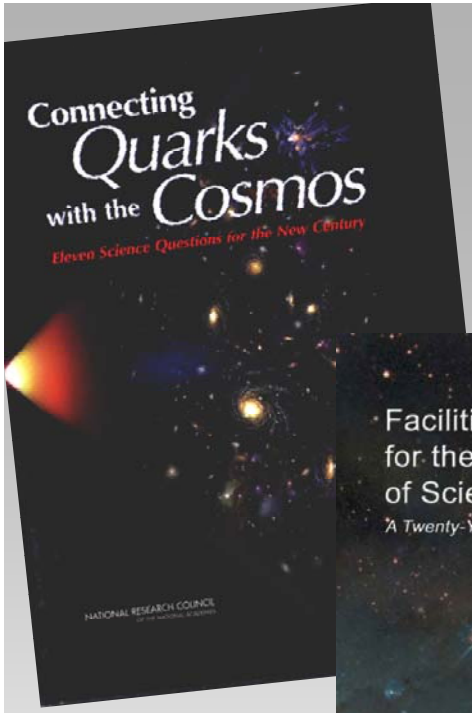
Extra Dimensions

Big Rip Cosmology

Ekpyrotic Universe

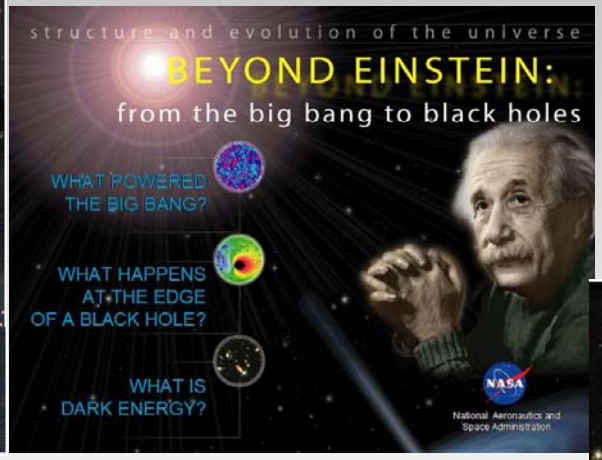
Photon axion oscillations

National Academy of Sciences

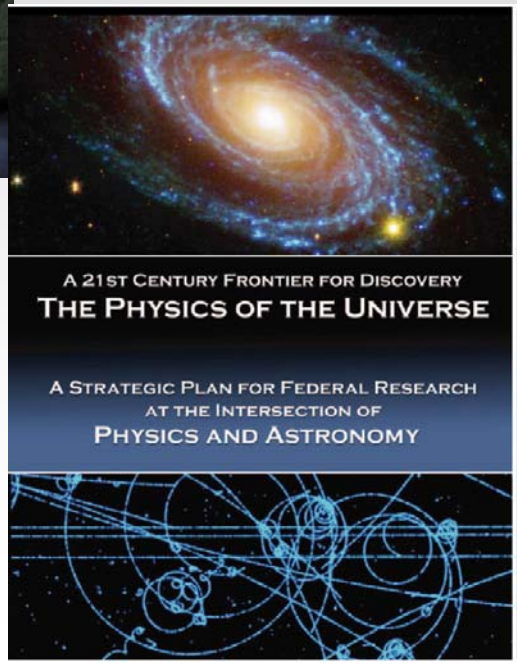


Department of Energy

NASA



OSTP



Dark Energy Task Force

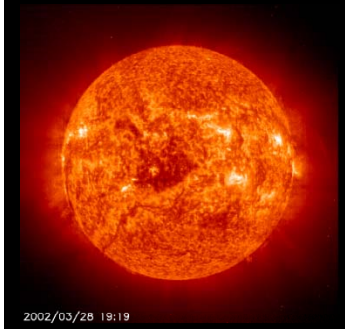
- DETF was jointly organized by 3 agencies: DOE, NSF and NASA
- Charged to "advise the agencies on the optimum near and intermediate-term programs to investigate dark energy and… to advance the justification, specification and optimization of LST and JDEM."
- "Prioritize approaches (not projects)"
- Findings from preliminary report highlighted four techniques:
  - **Baryon Acoustic Oscillations:** "only recently established. Less affected by astrophysical uncertainties than other techniques. "
  - **Galaxy Clusters:** "least developed. Eventual accuracy very difficult to predict."
  - **Type Ia Supernovae:** "presently most powerful and best proven technique. "
  - **Weak Lensing:** "also emerging technique… *If* the systematic errors are at or below the level proposed by the proponents, it is likely to be the most powerful individual technique and also the most powerful component in a multi-technique program."

A practical point:

Light takes time to travel.

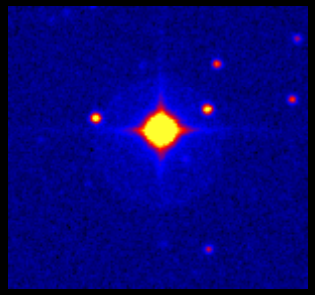
How long does light take to reach us from…

The Sun



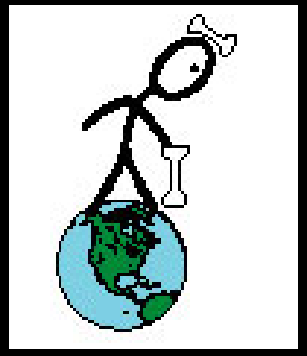
8 minutes

Nearest Star

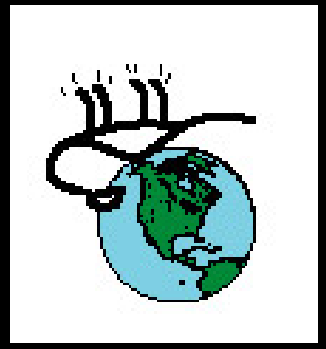


4 years

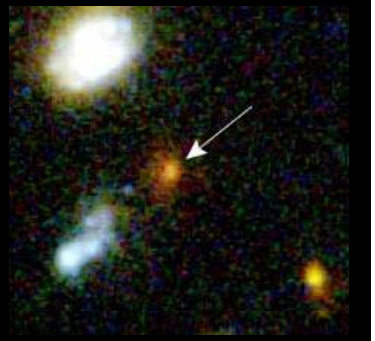
Nearest Galaxy



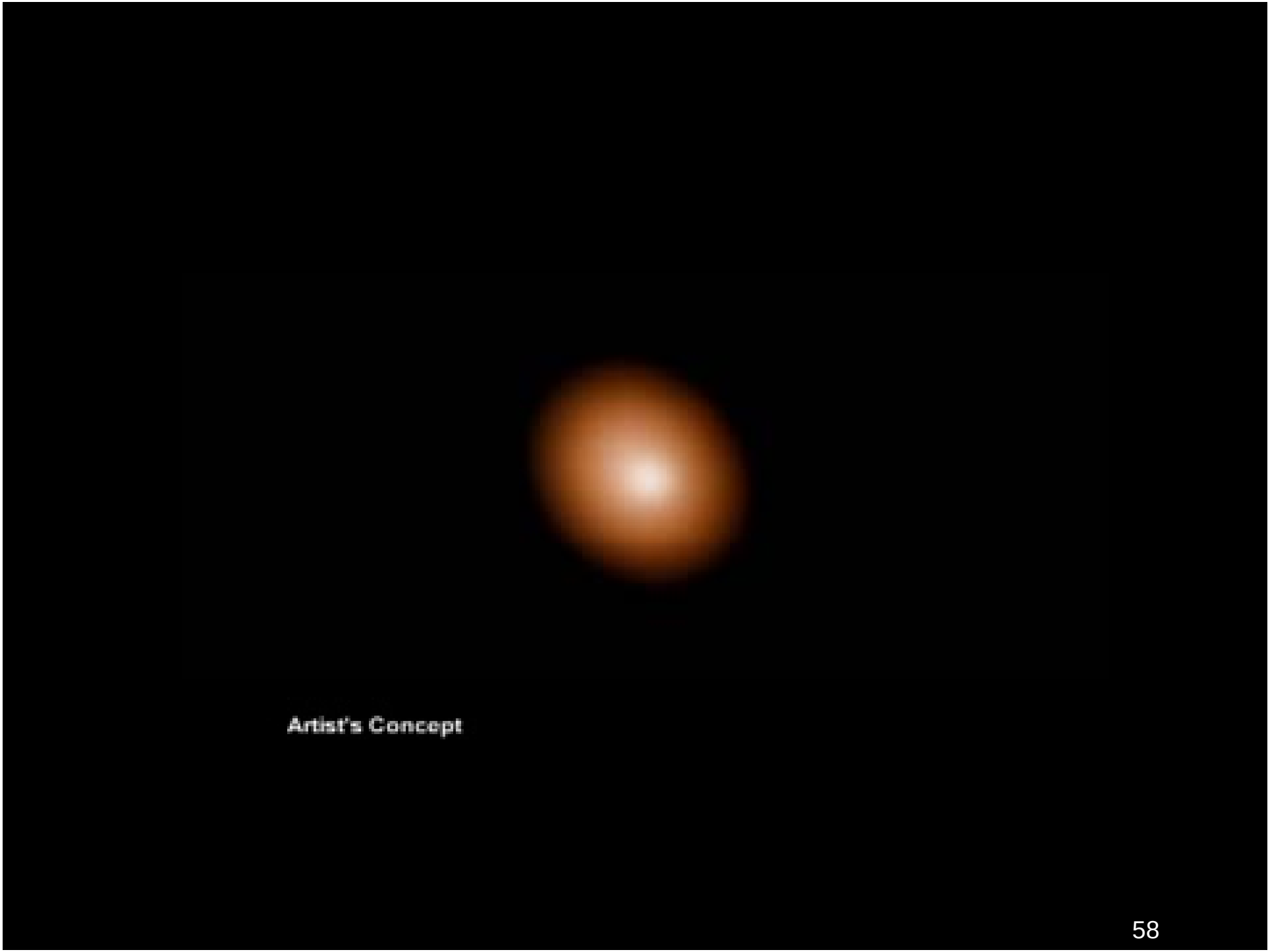
Nearest Galaxy Cluster



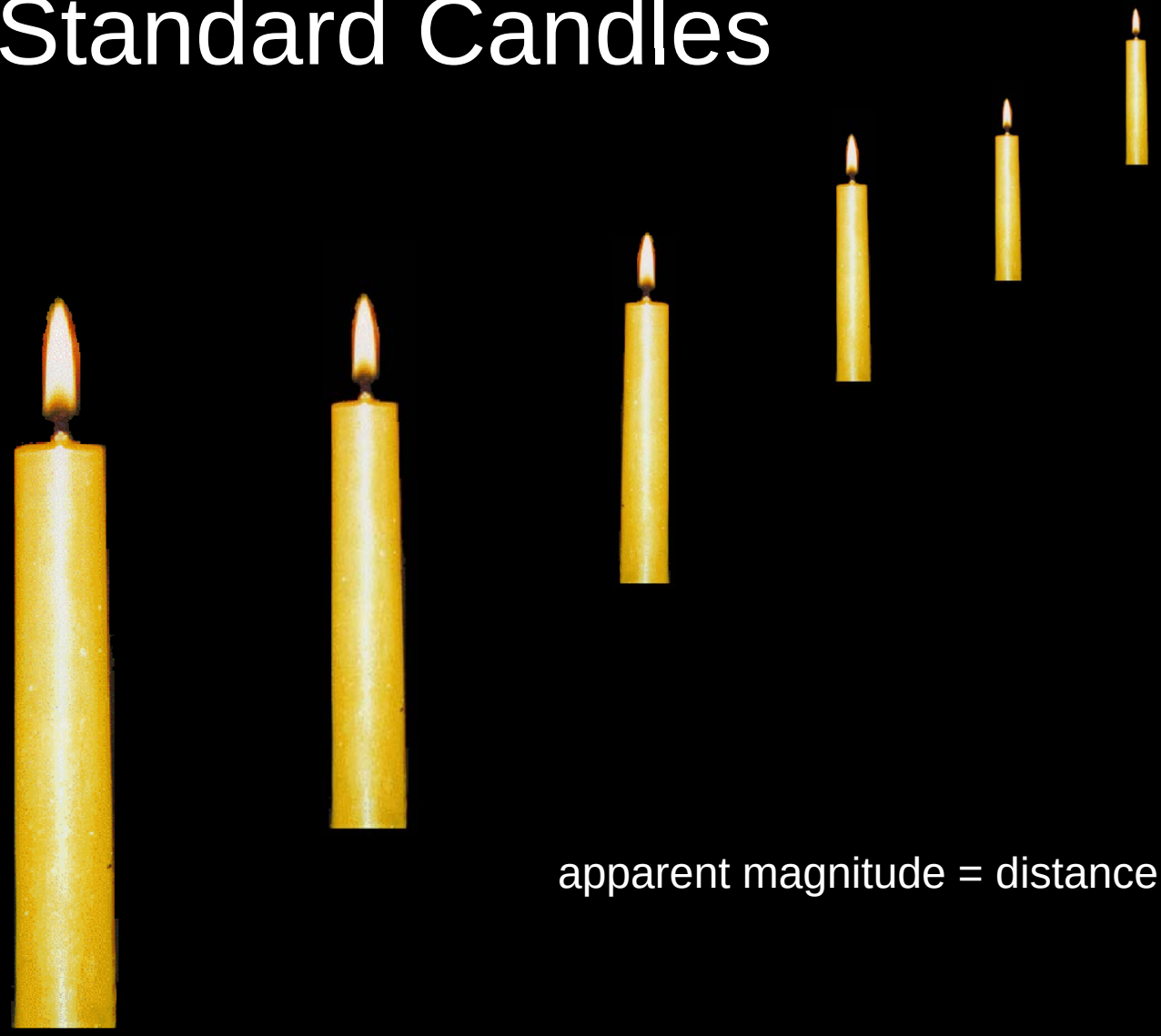
Supernova in Distant Galaxy



10 billion years

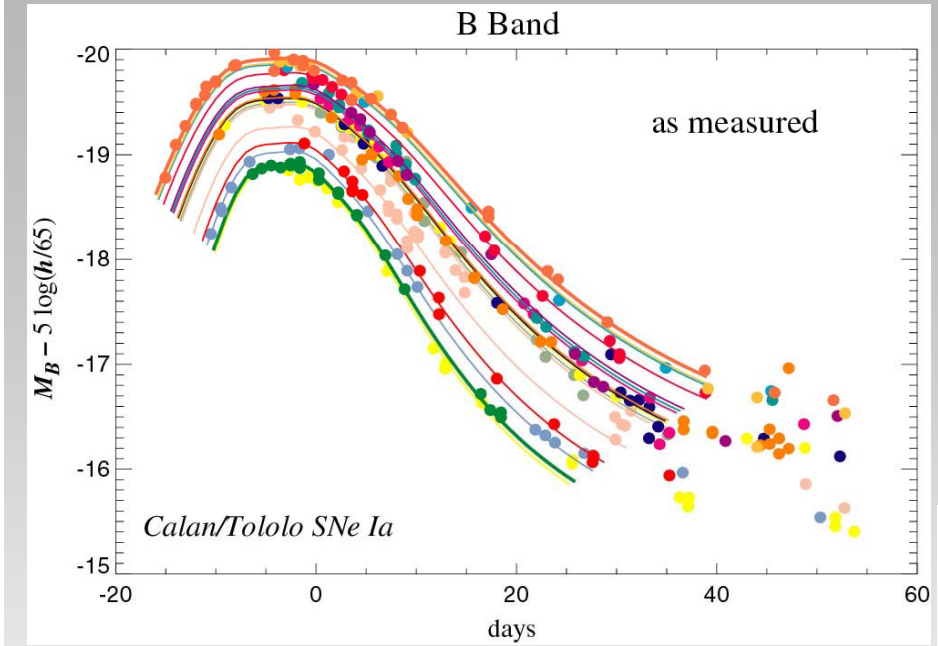

Artist's Concept

Type Ia SNe as Standard Candles



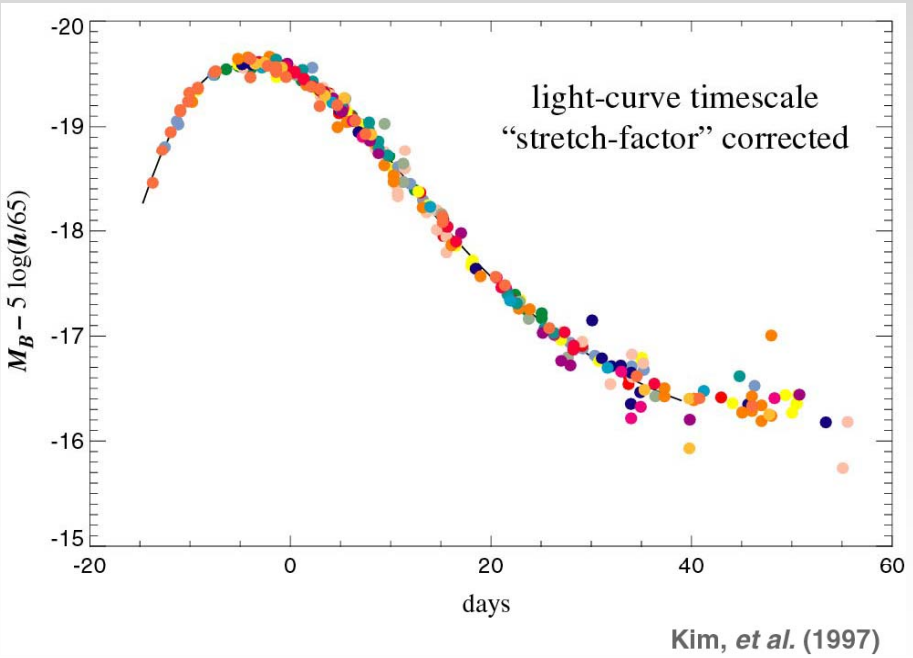
apparent magnitude = distance = time

"Standard-izable" Candles



- Nearby supernovae used to study SNe light curve (z<0.1)
- Brightness not quite standard
- Intrinsically brighter SNe last longer
- Correction factor needed

Peak-magnitude dispersion of 0.25 – 0.3 magnitudes

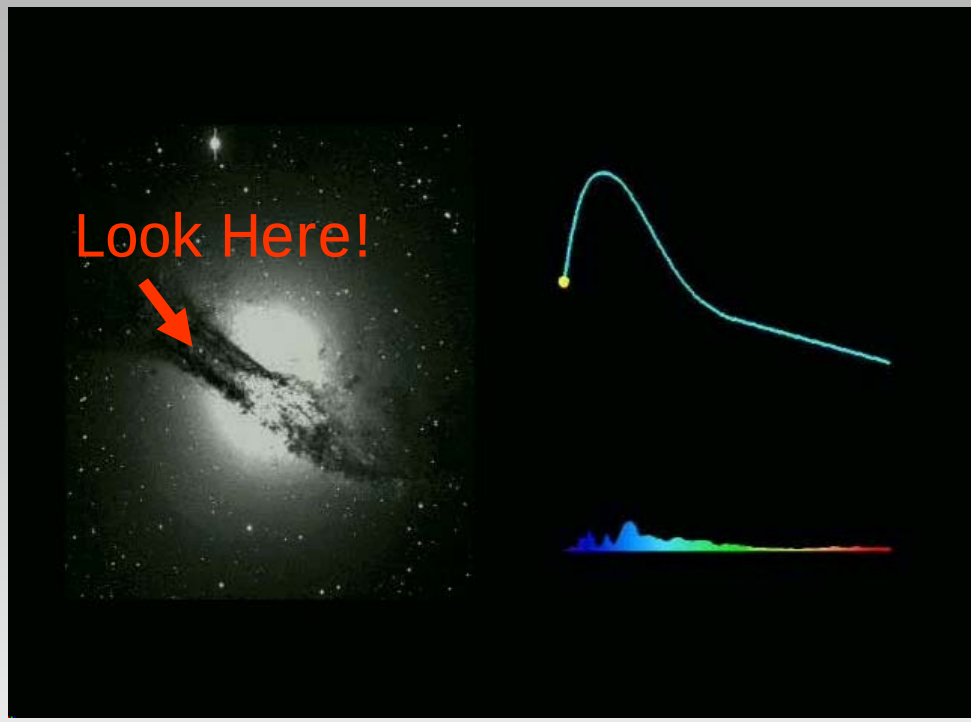


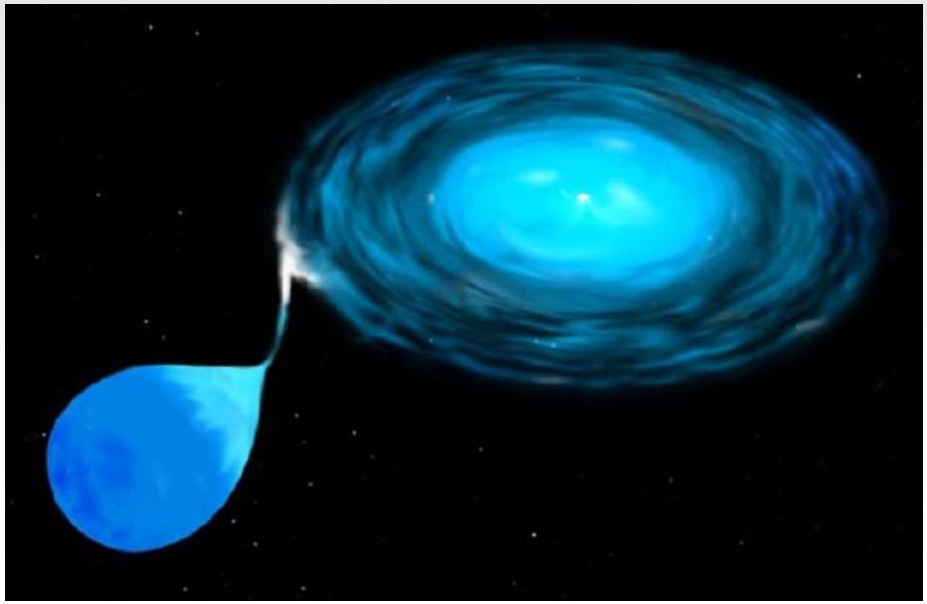
~0.15 magnitude dispersion

Kim, *et al.* (1997)

Type Ia SNe: The Best Tool

- Accretion sends mass of white dwarf star to Chandrasekhar limit leading to gravitational core collapse and a thermo-nuclear explosion of its outer layers.
- Each one is a strikingly similar explosion event with nearly the same peak intensity.
- Other types of supernovae exist but do not have same homogeneity in progenitor

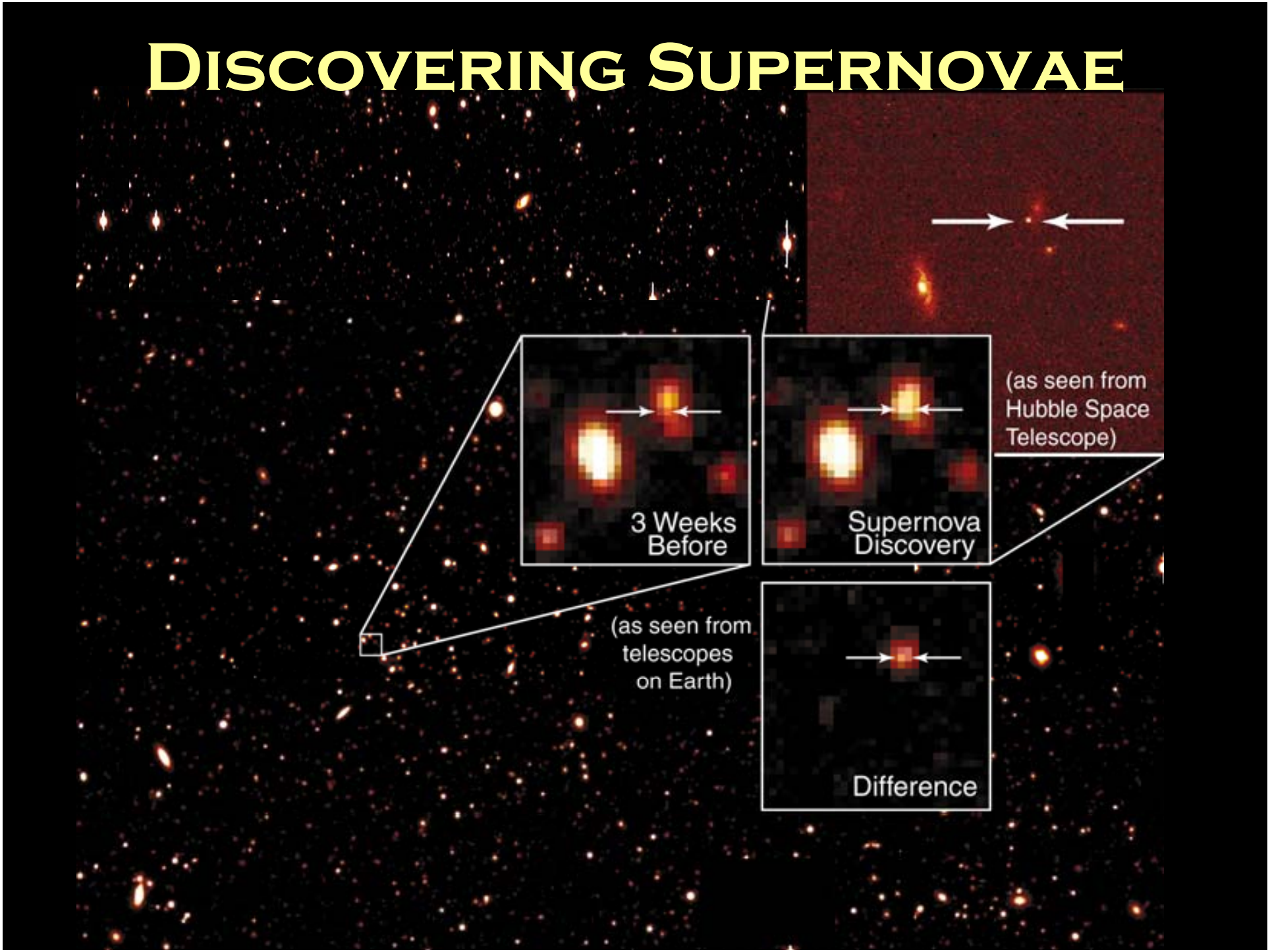




What makes the supernova measurement special?

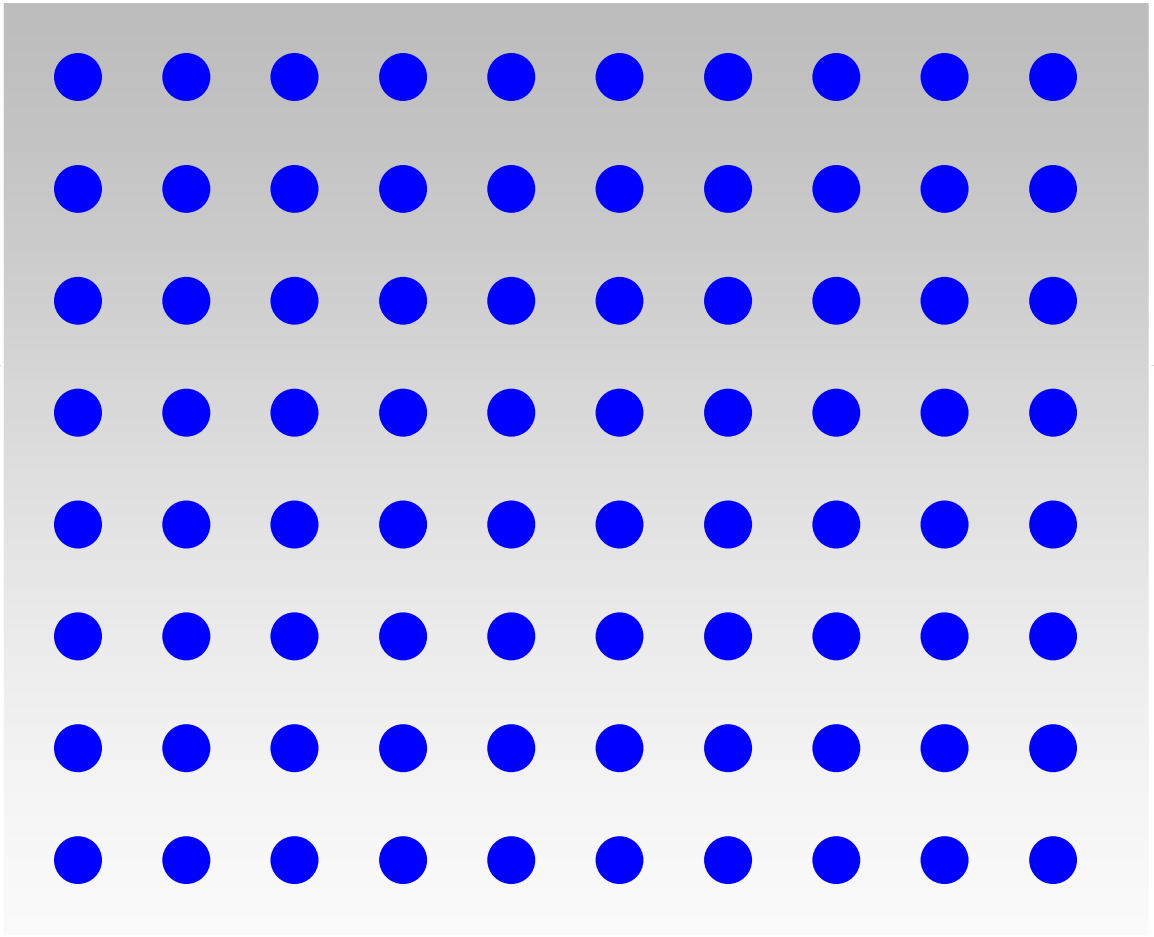
Can measure both intensity and spectra as the supernova brightens and fades over many days.

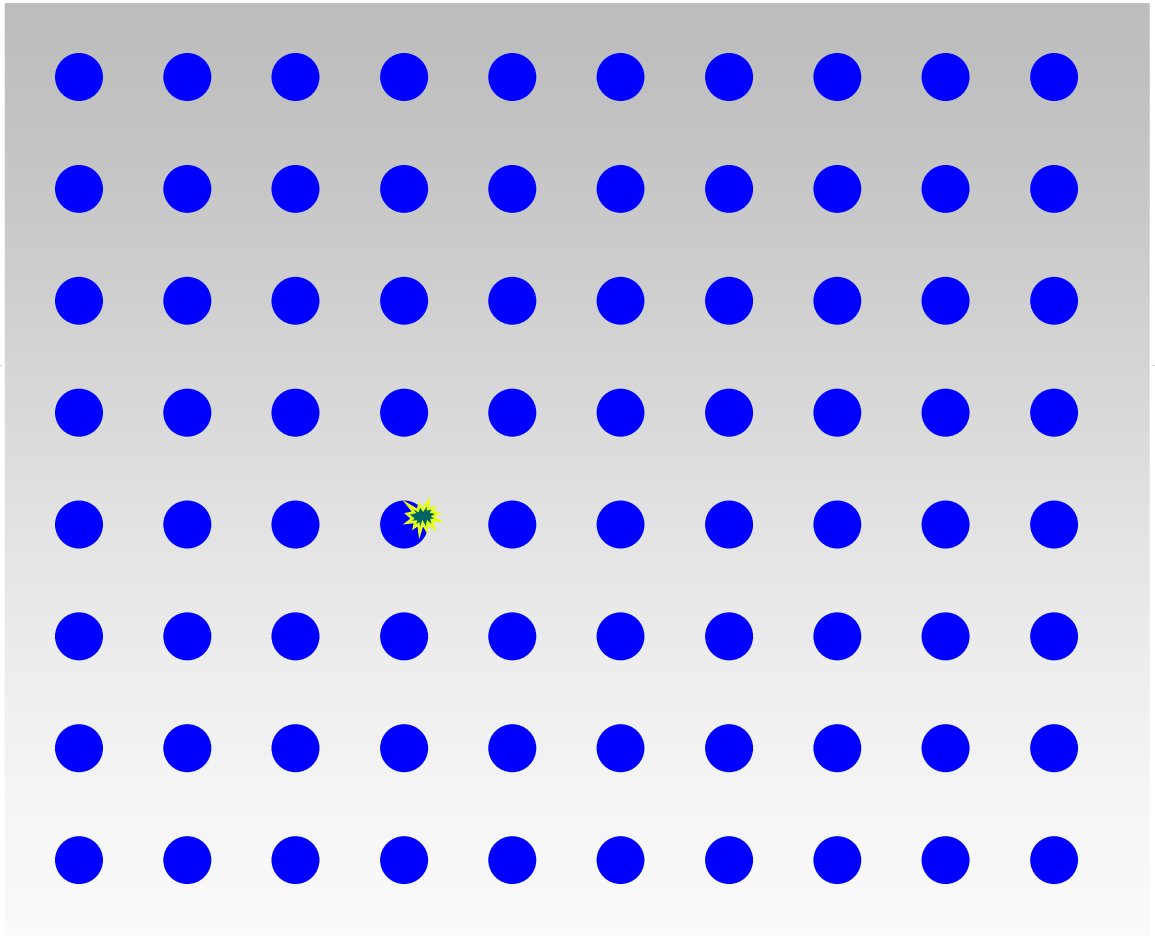
Discovering Supernovae

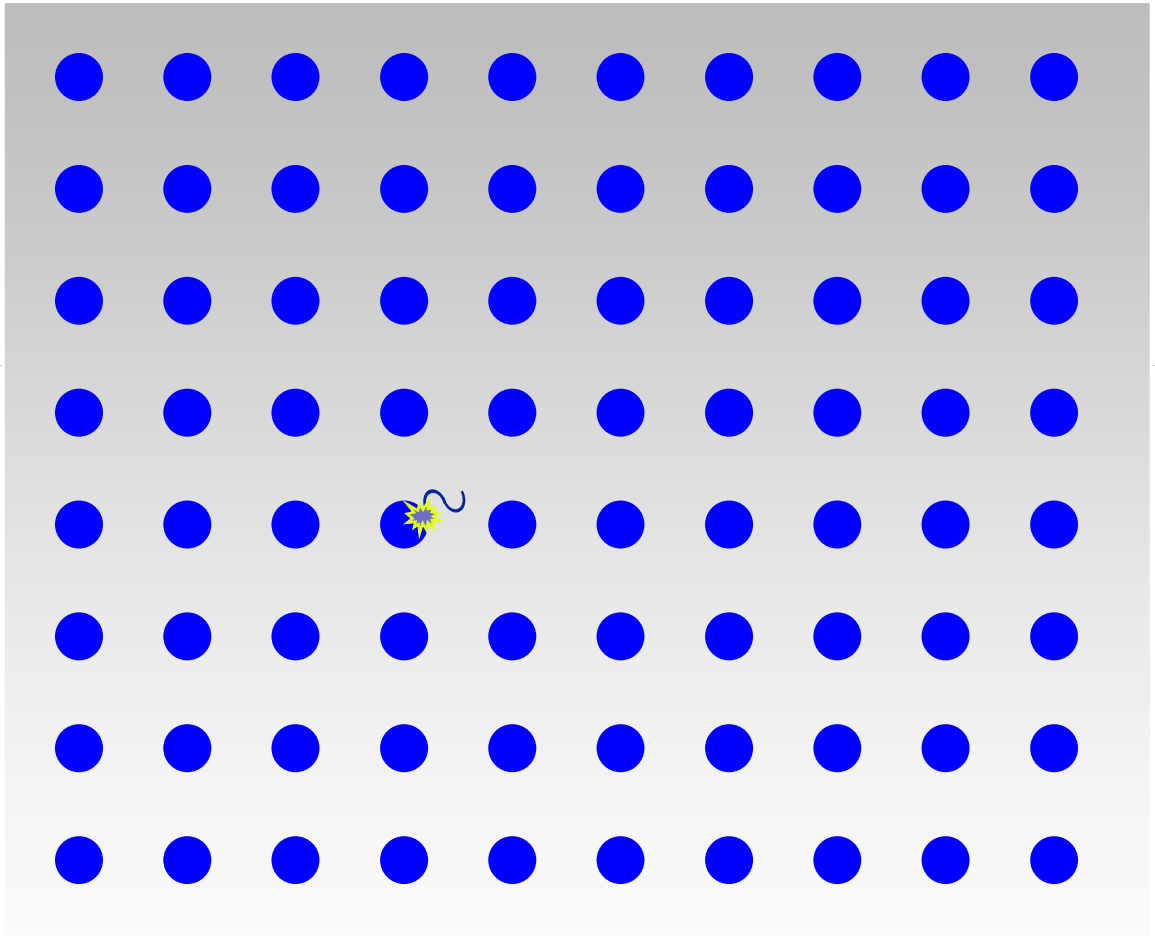


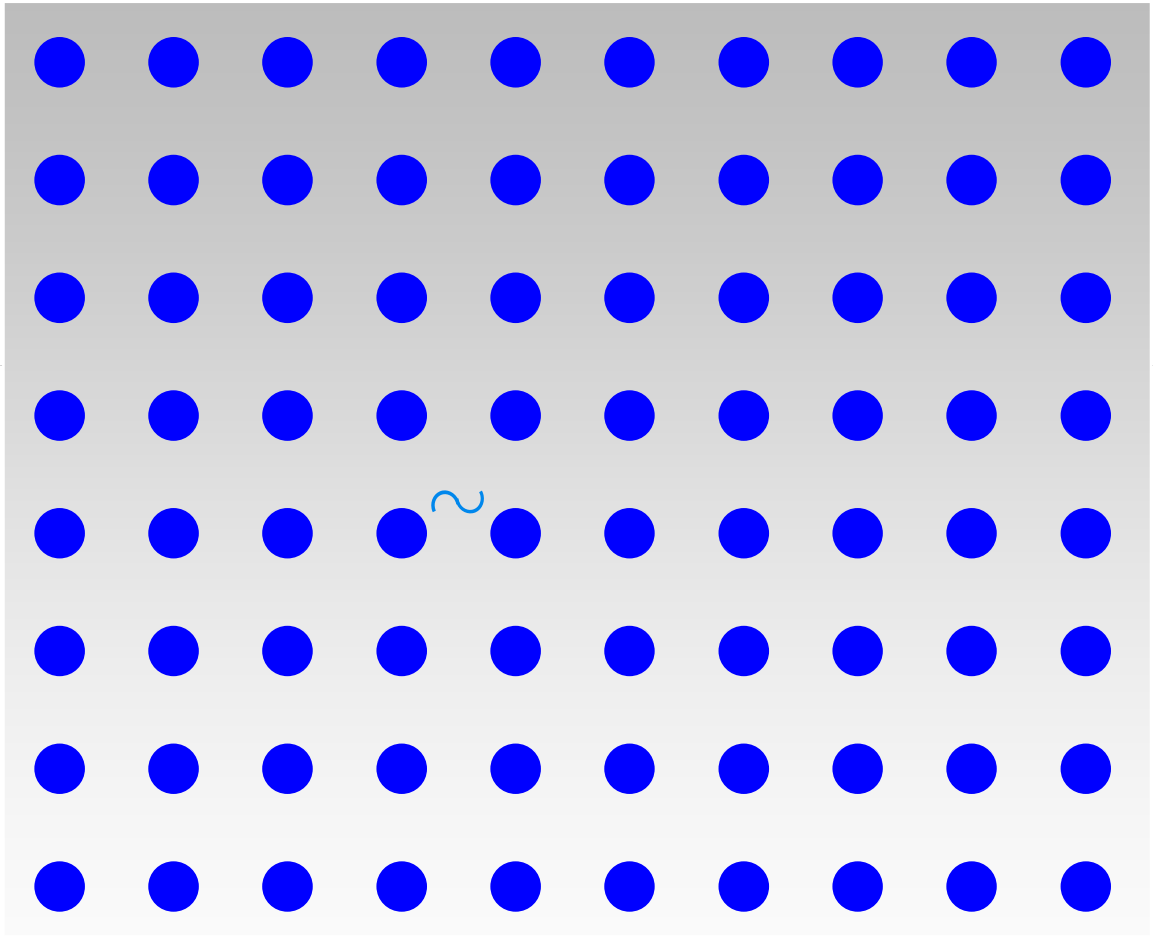
One amazing trick:

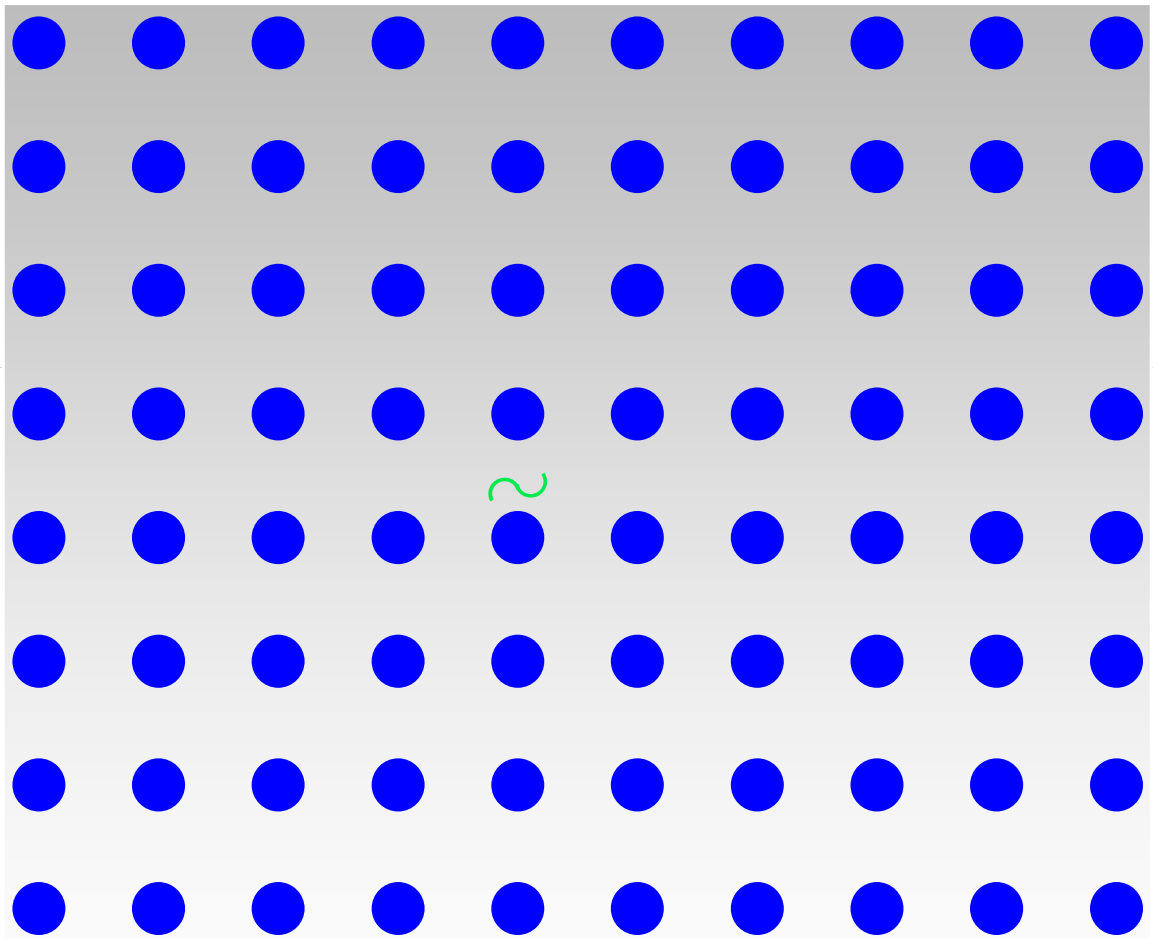
A supernova's "redshift" tells us *how much the universe has stretched* since the supernova exploded.







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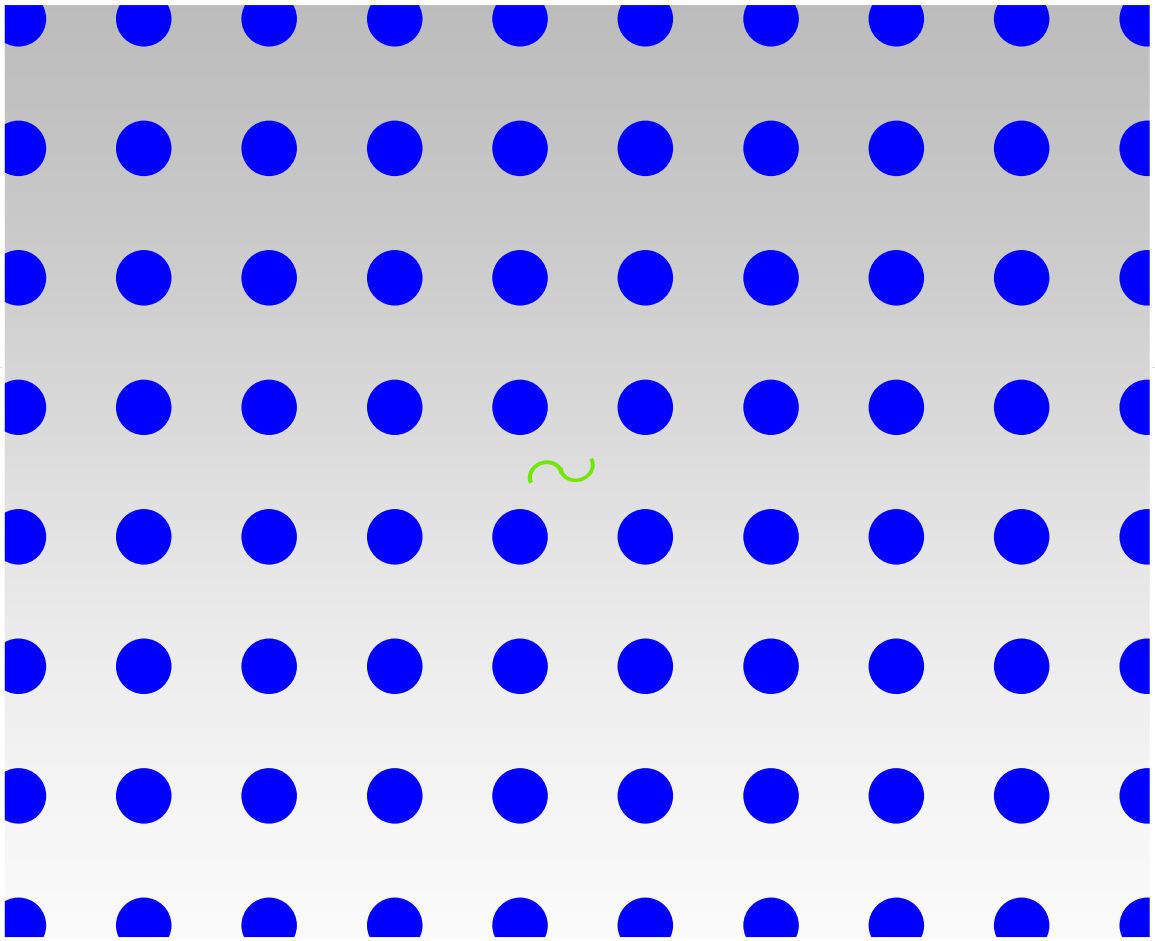
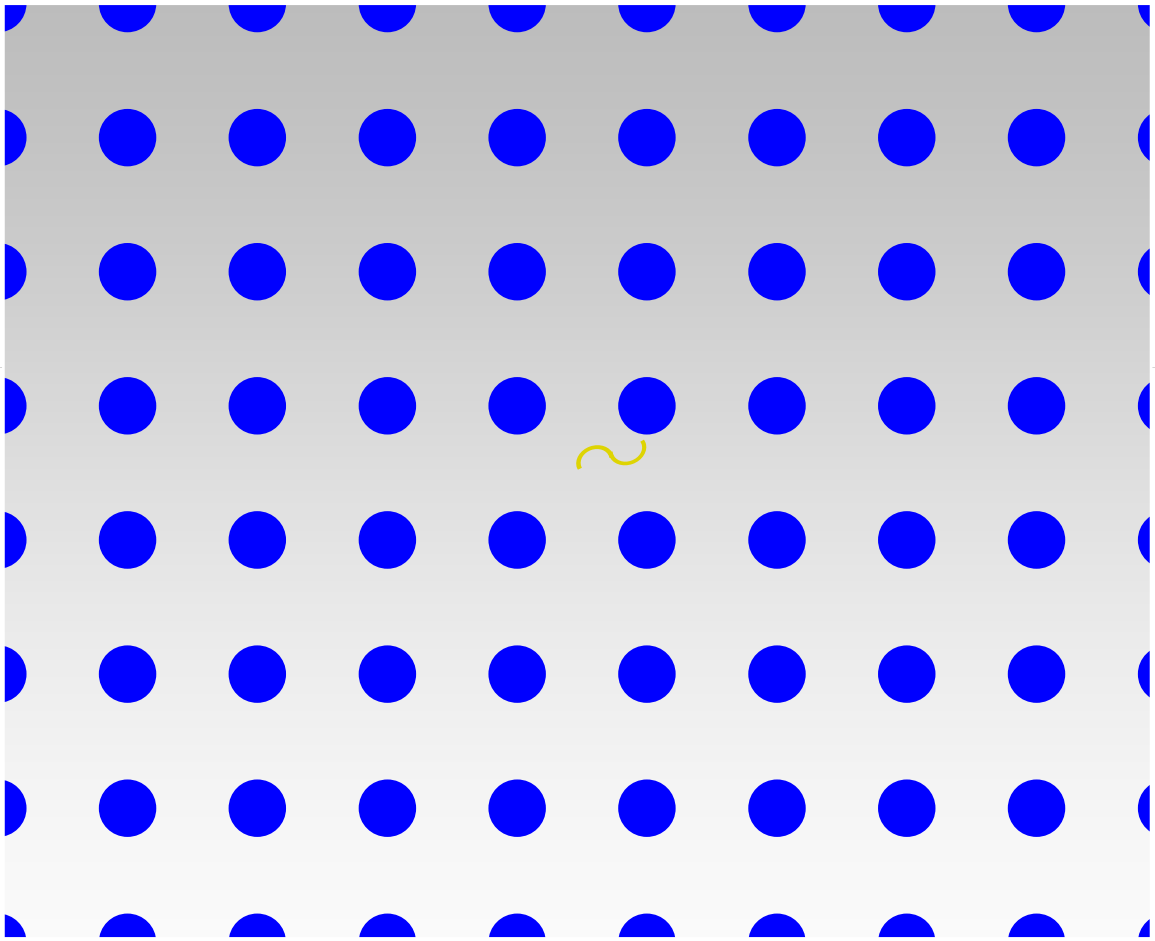
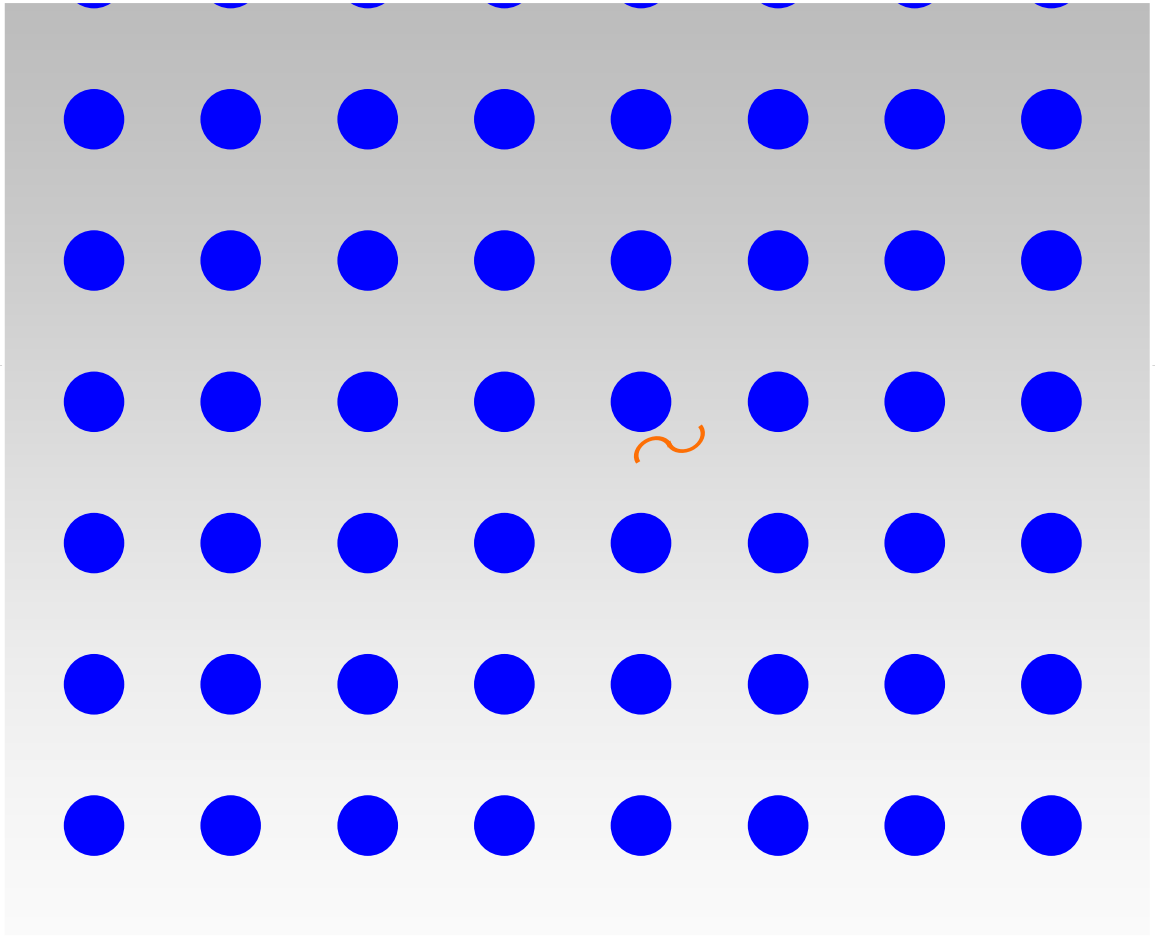
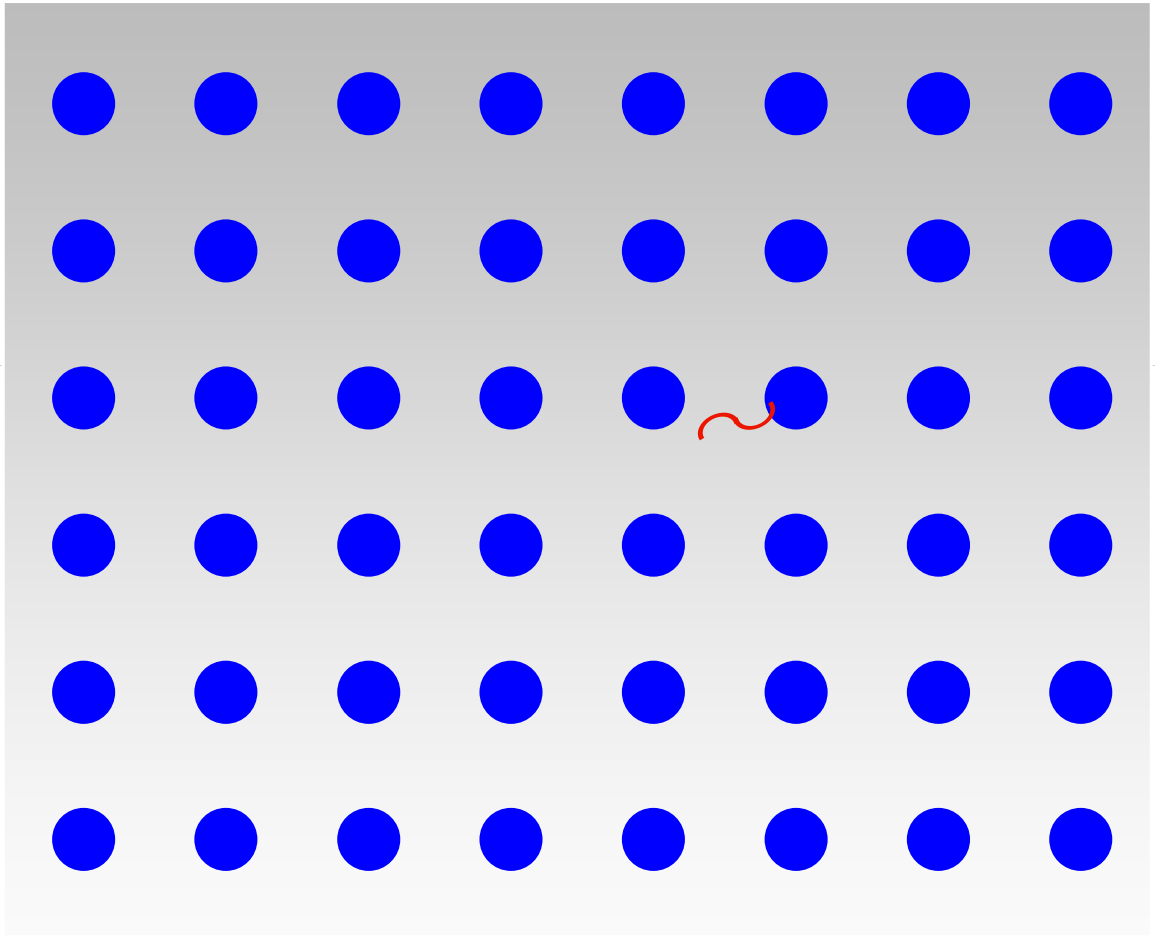
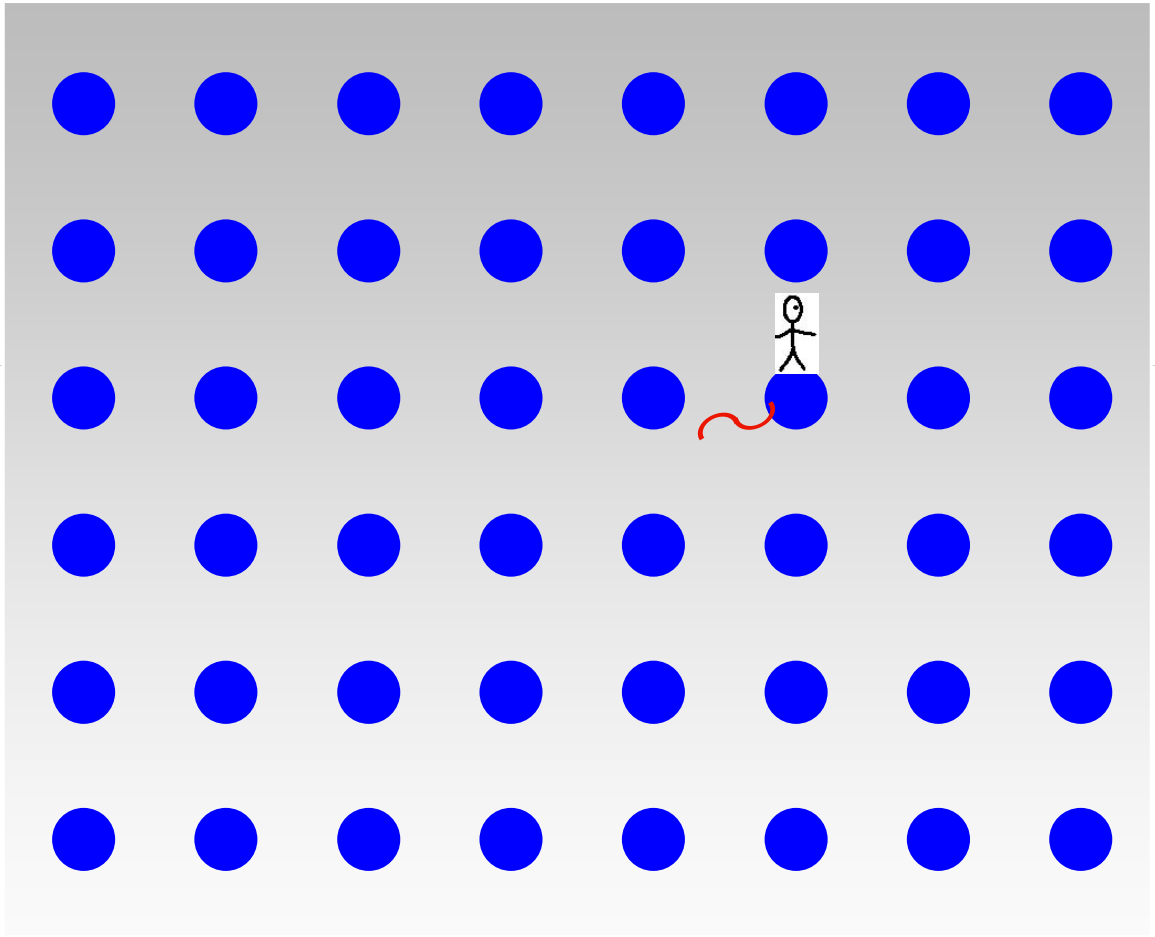


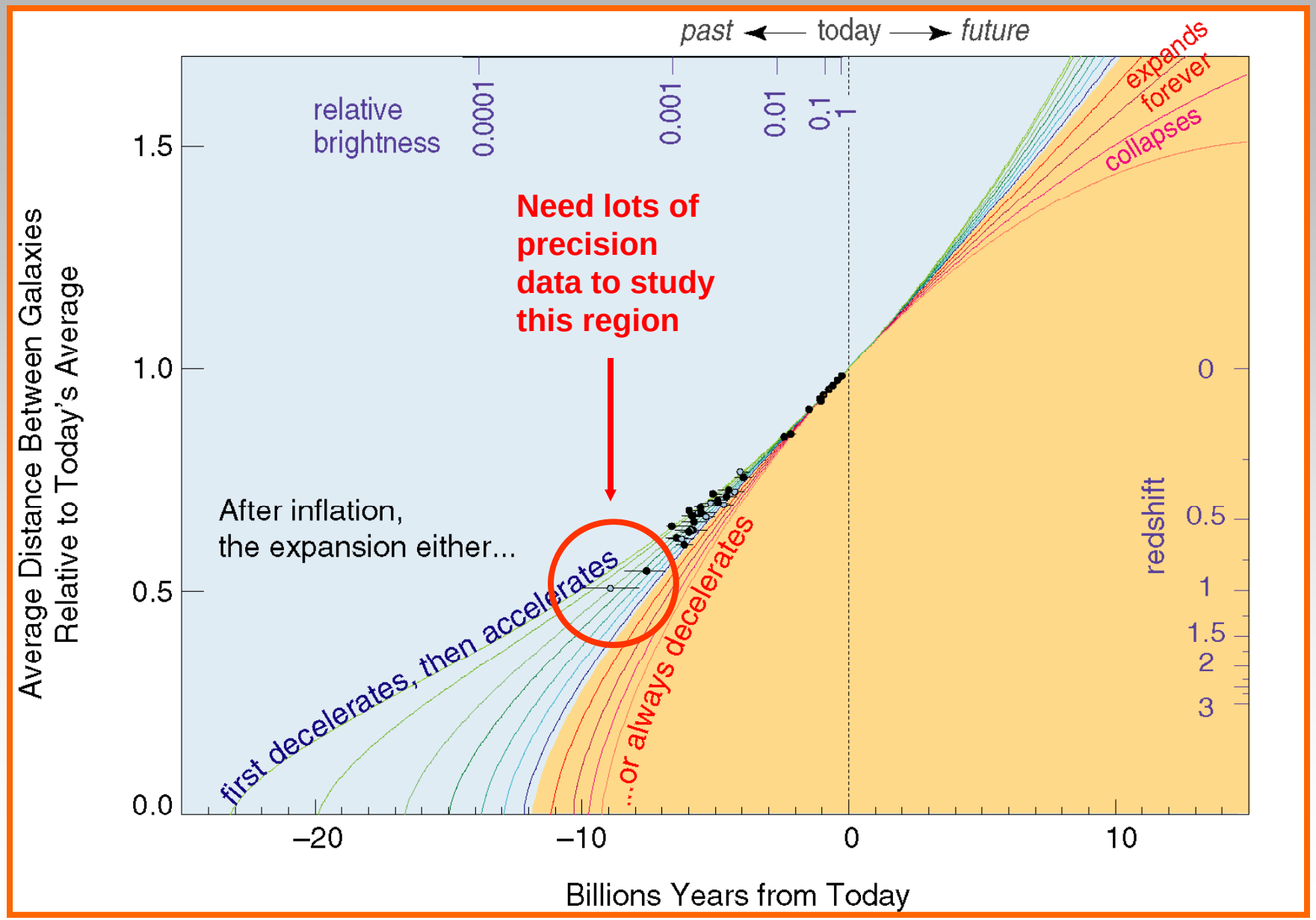




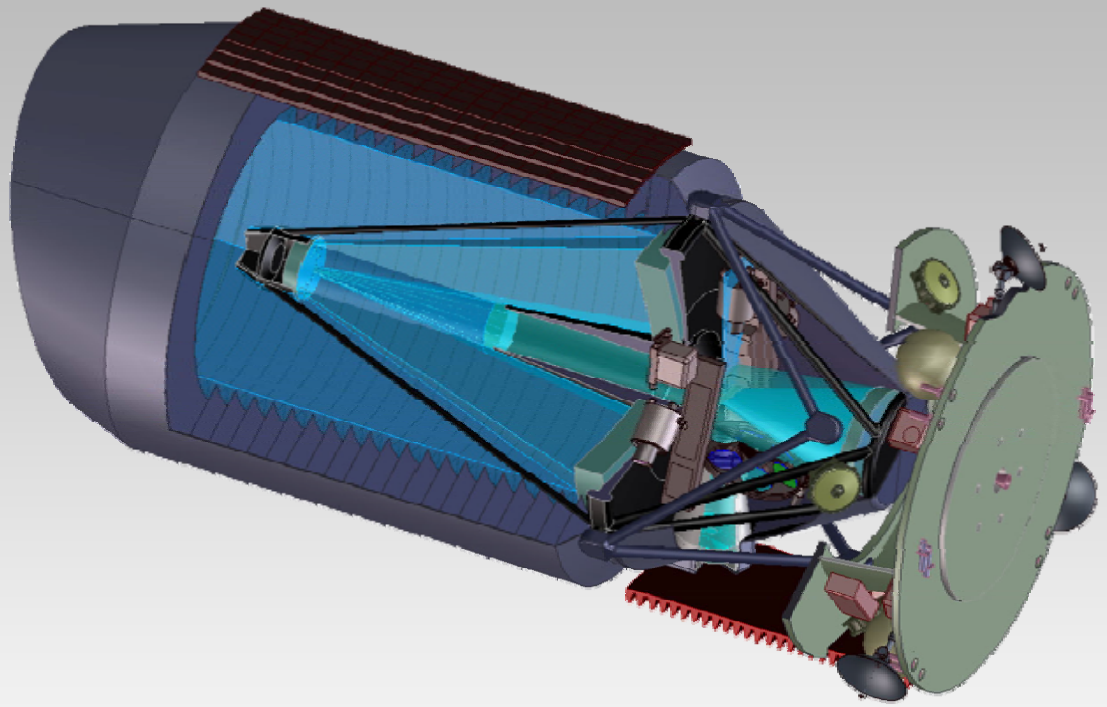


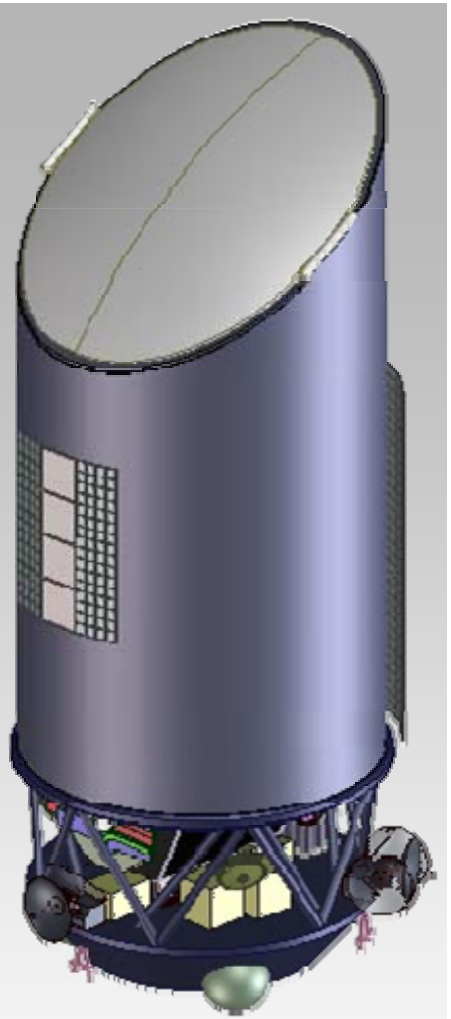


The Expansion History of the Universe



It's a SNAP! The SuperNova/Acceleration Probe



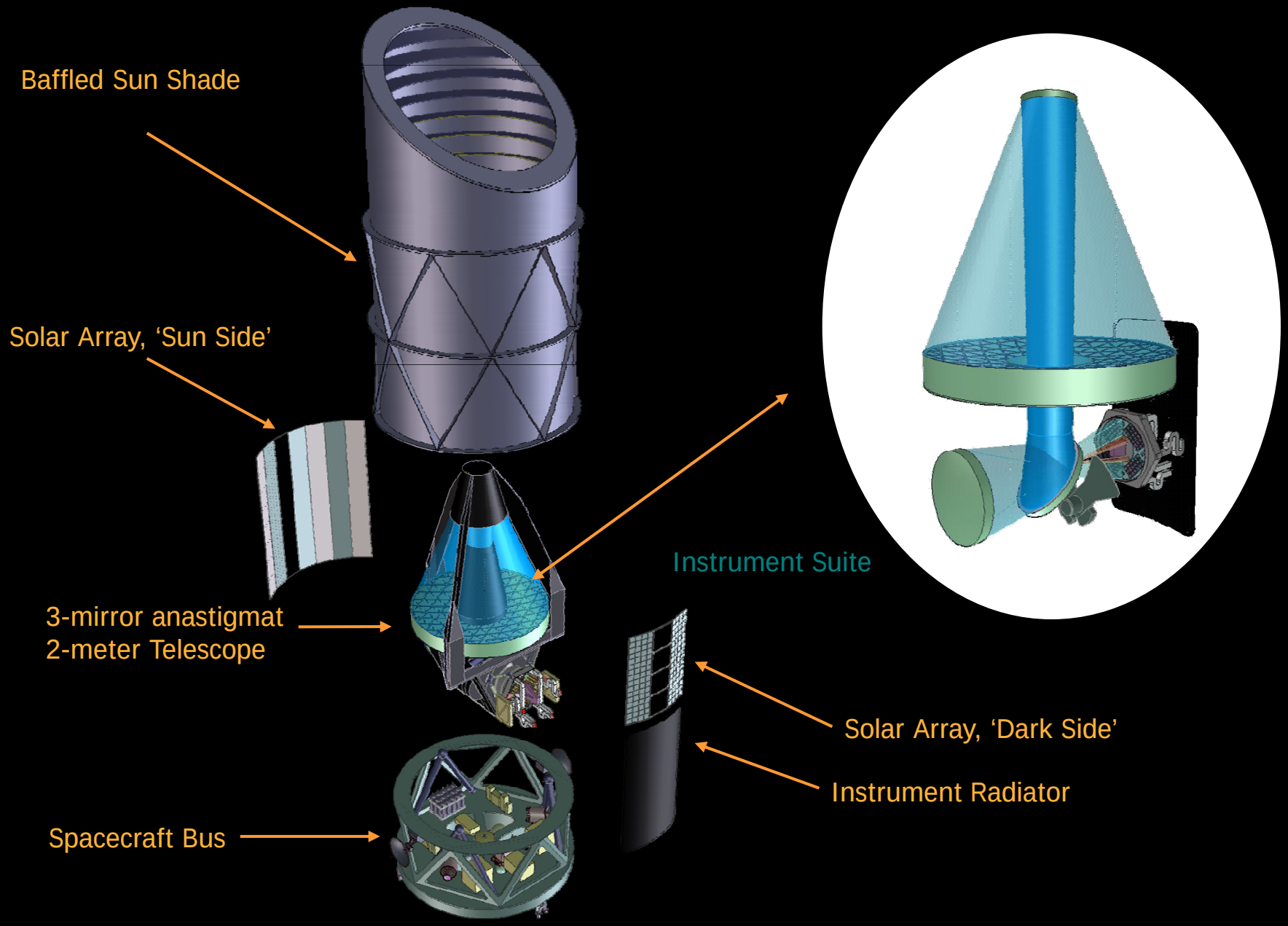


A large wide-field telescope with a state of the art camera and spectrograph to measure:

- thousands of supernovae going back 10 billion years (z=1.7), with exquisite control of systematic errors
- a high fidelity weak lensing map to study the growth of structure

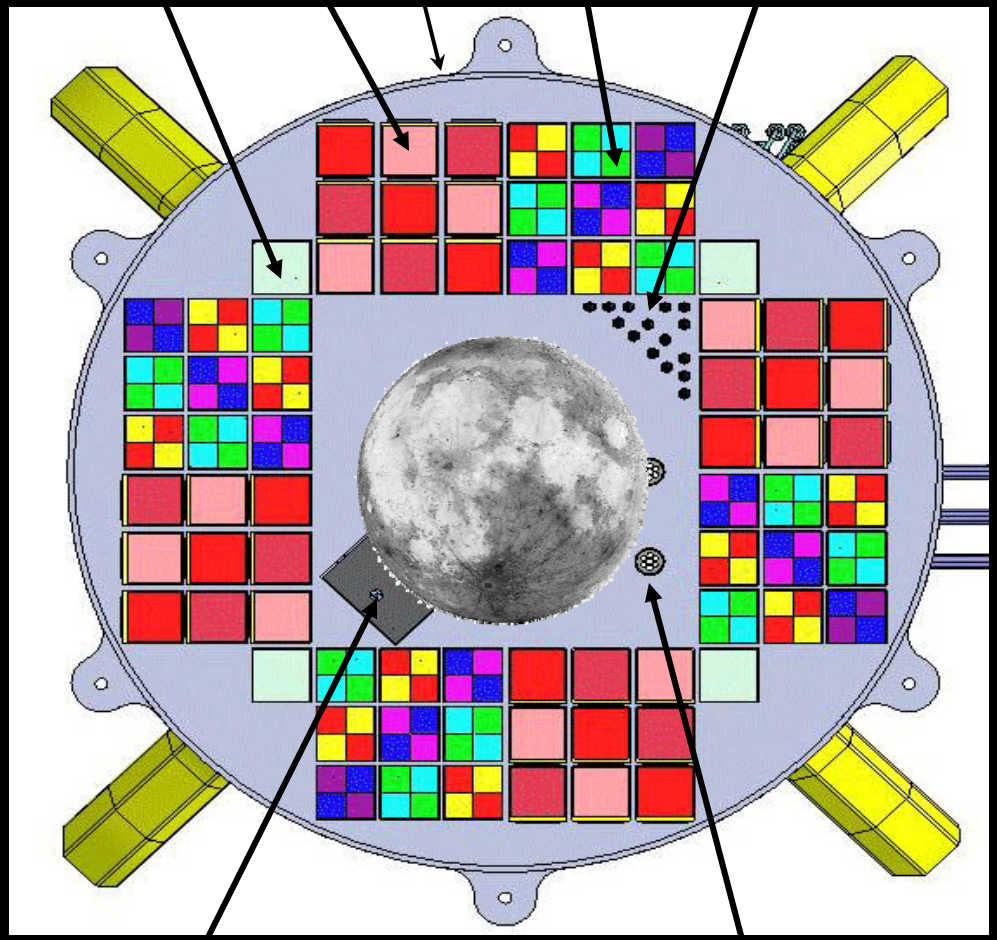
SuperNova/Acceleration Probe (SNAP) Collaboration Team

Instrument Concept

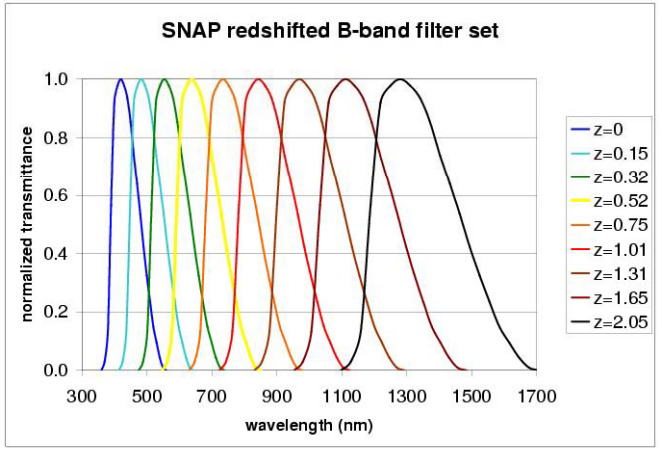


Focal plane

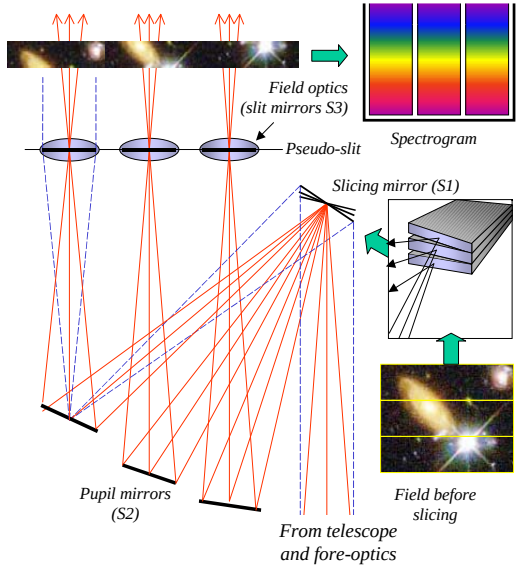
D=56.6 cm (13.0 mrad)
0.7 square degrees!



Fixed filters atop the sensors

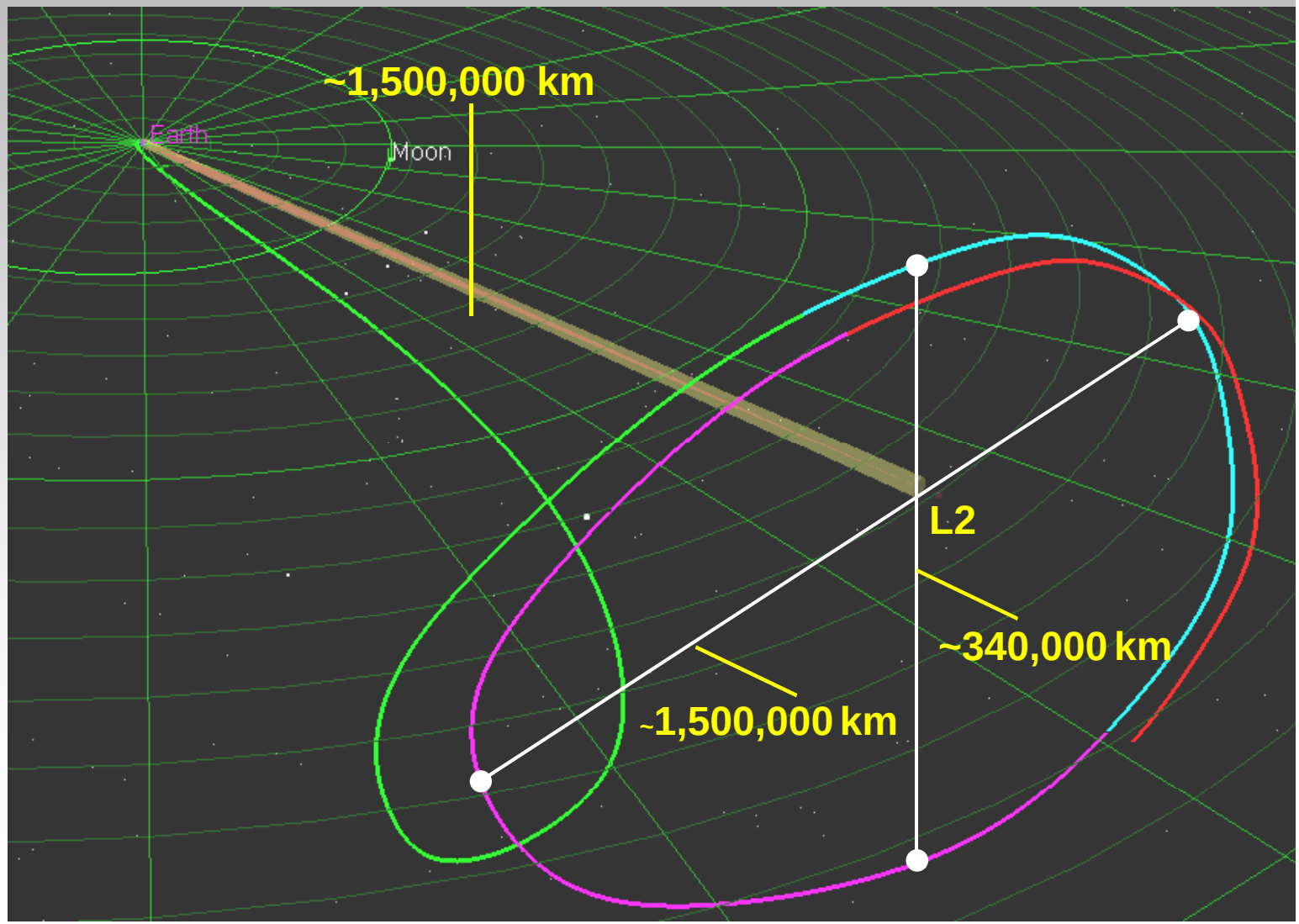


Integral Field Spectrograph



SNAP Orbit

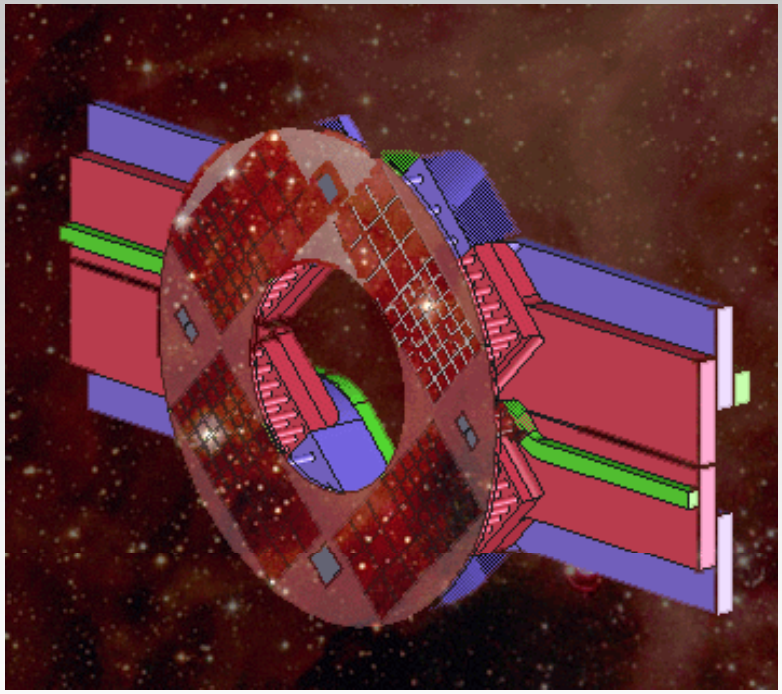
L2 Lagrange point

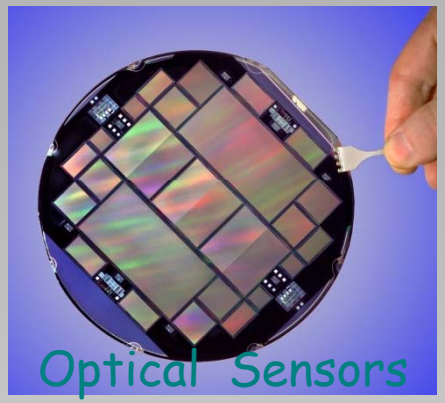


Observing

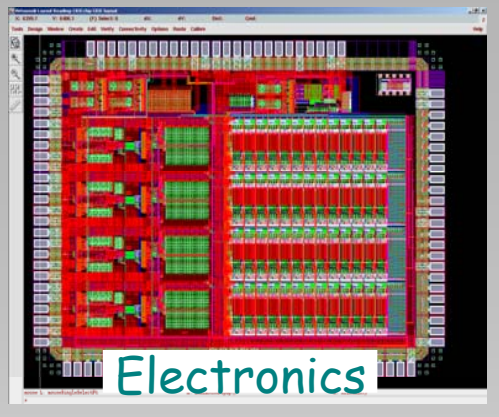
Step ‘n Stare – All Supernovae in all colors

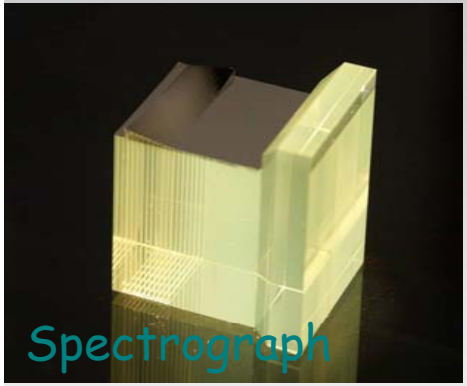
- Repetitive imaging program (SN discovery and light curve measurement)
  - Observe 15 square degrees every three days in all filters “mowing the sky”.
  - ~50% of time devoted to spectroscopy of individual SNe near maximum light.
  - Will discover and follow ~2000 selected Type Ia Supernovae with redshifts out to z=1.7
- Wide field imaging program will cover 1000 square degrees in 9 filters

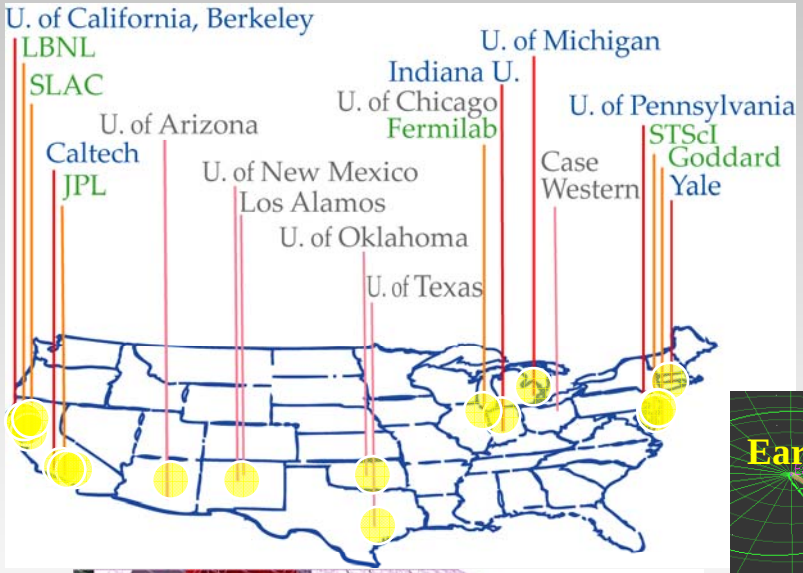



Optical Sensors

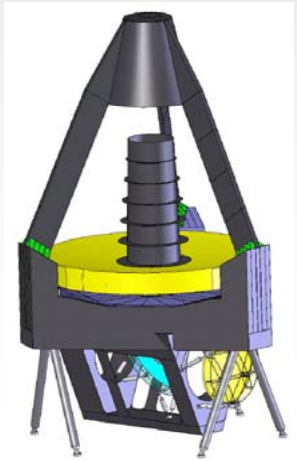

Infra-Red Sensors

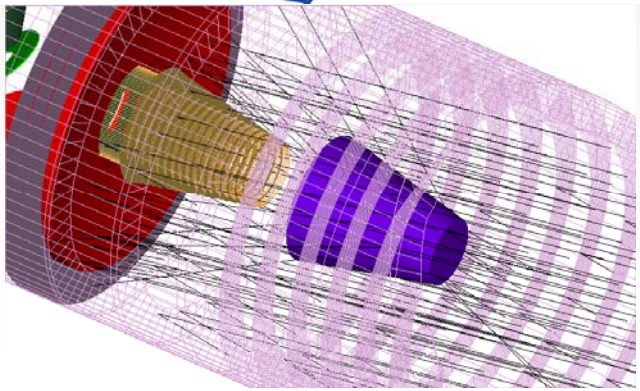

Electronics

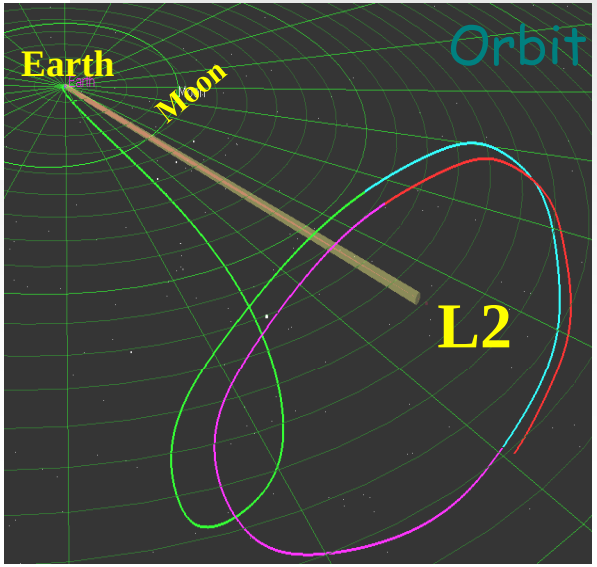

Spectrograph


U. of California, Berkeley
LBNL
SLAC
U. of Arizona
Caltech
JPL
U. of New Mexico
Los Alamos
U. of Oklahoma
U. of Texas
U. of Michigan
Indiana U.
U. of Chicago
Fermilab
U. of Pennsylvania
STScI
Goddard
Yale
Case
Western


Space Optics

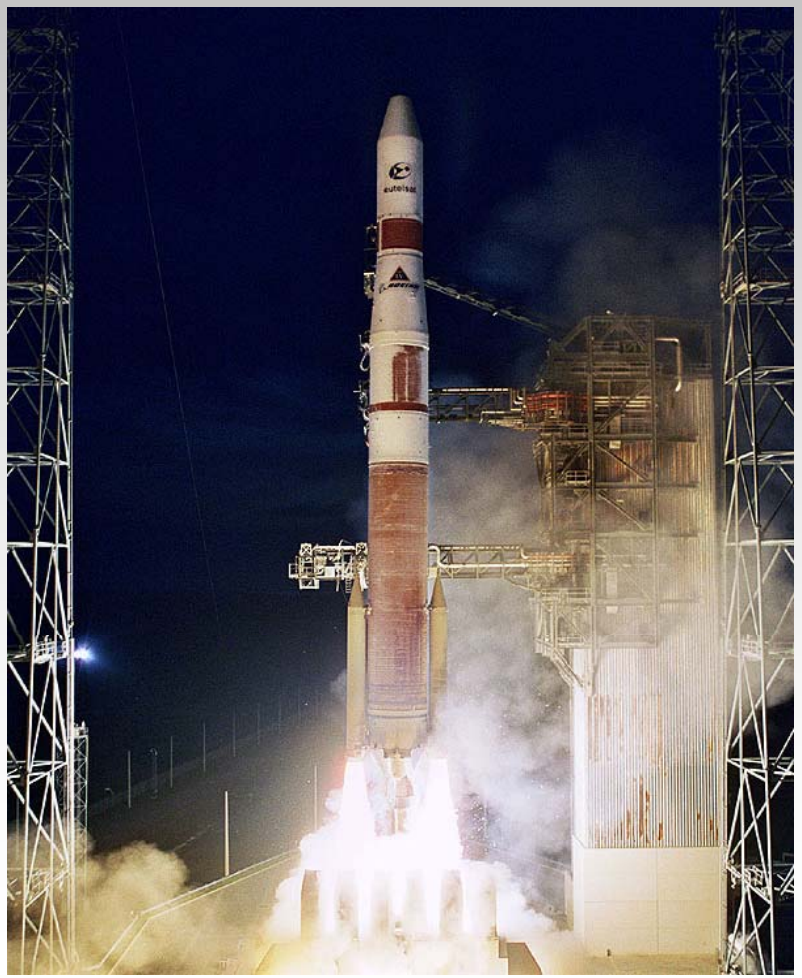


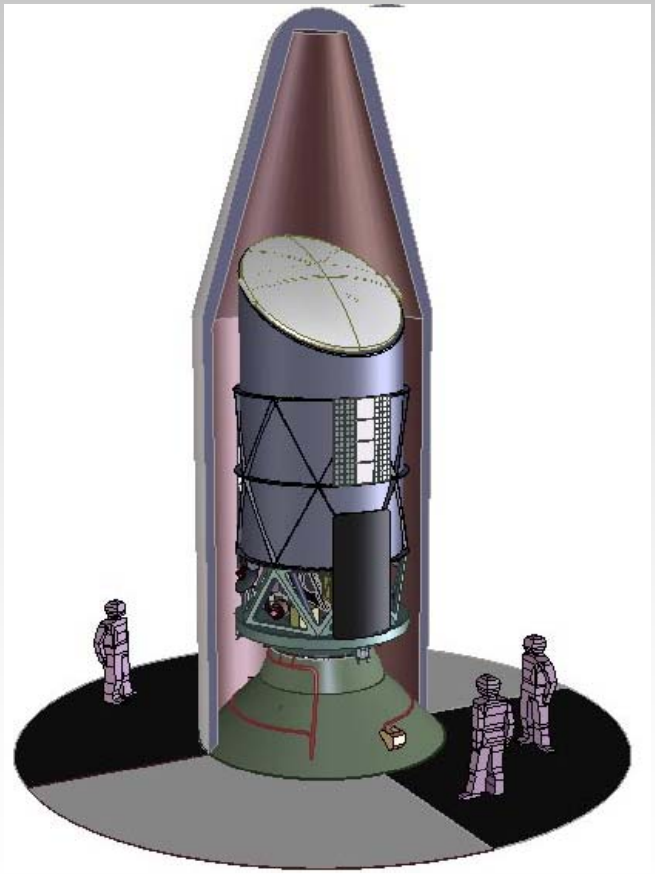



Orbit
Earth
Moon
L2

Launch in the next decade

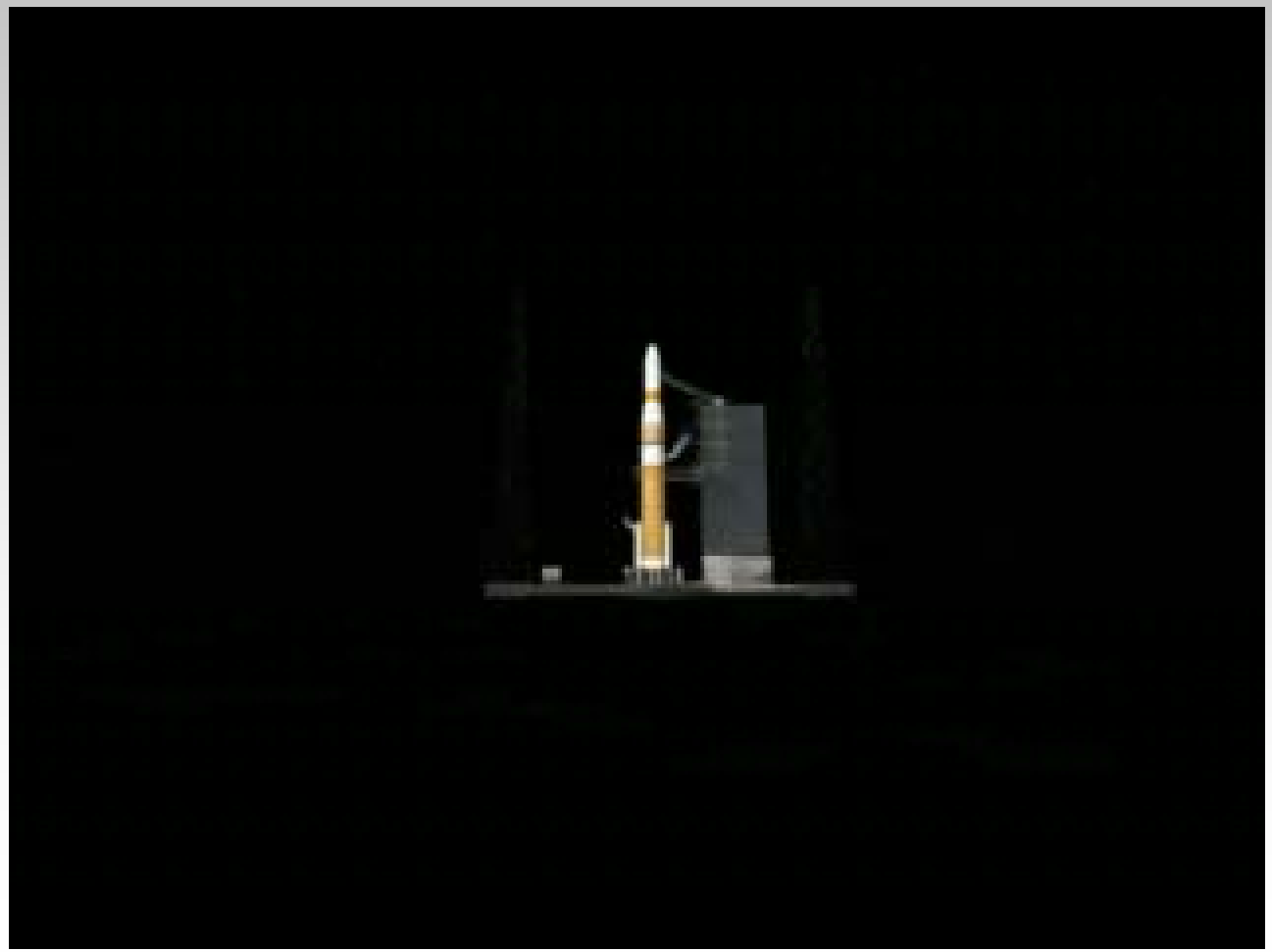
1600 kg satellite can be lifted by a Delta IV [recent first flight] to our orbit with margin.





Launch in the next decade

1600 kg satellite can be lifted by a Delta IV [recent first flight] to our orbit with margin. Can use equivalent Delta IV, Atlas, or Sea Launch.



Don't let the bright lights fool you

The DARK SIDE controls the UNIVERSE

Our Universe:

Stars:	0.5%
Dark Matter:	25%
Dark Energy:	70%

Dark Matter holds it together

Dark Energy determines its destiny

THE END

Acknowledgements

Gregory Tarle (Michigan)

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Micael Turner (Chicago)

Katherine Freese (Michigan)

Risa Wechsler (Stanford)

Clem Pryke (Chicago)

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