### "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.

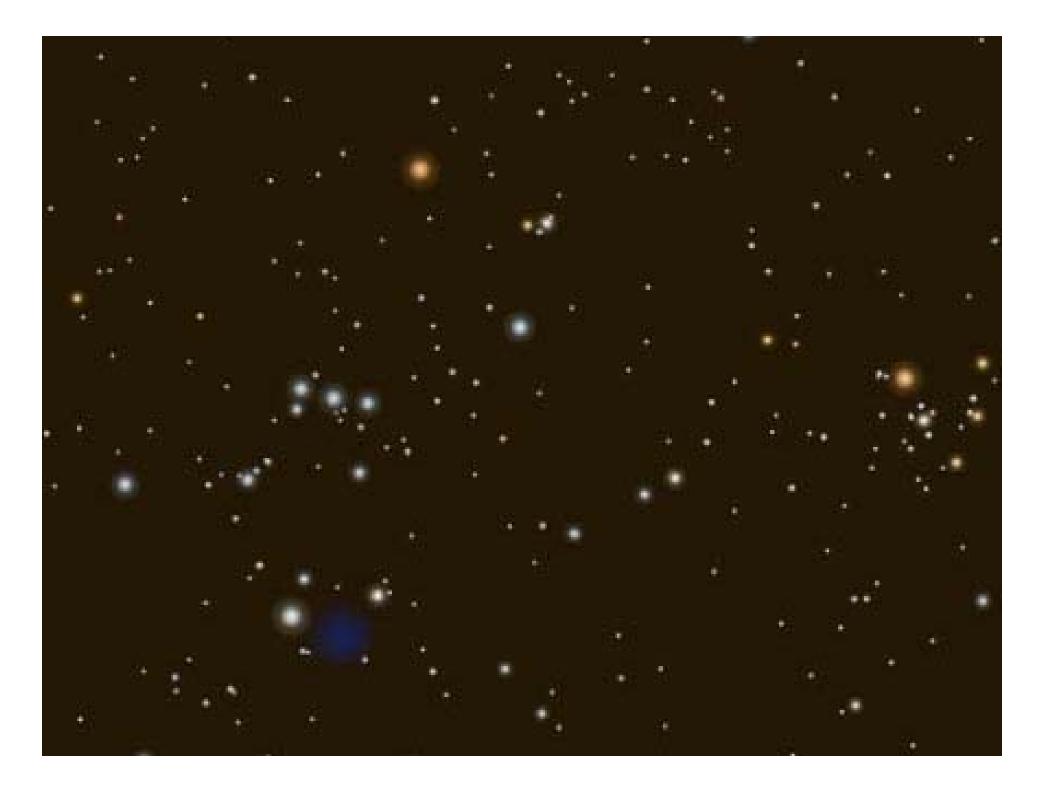
## "THE DARK SIDE OF THE UNIVERSE"

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

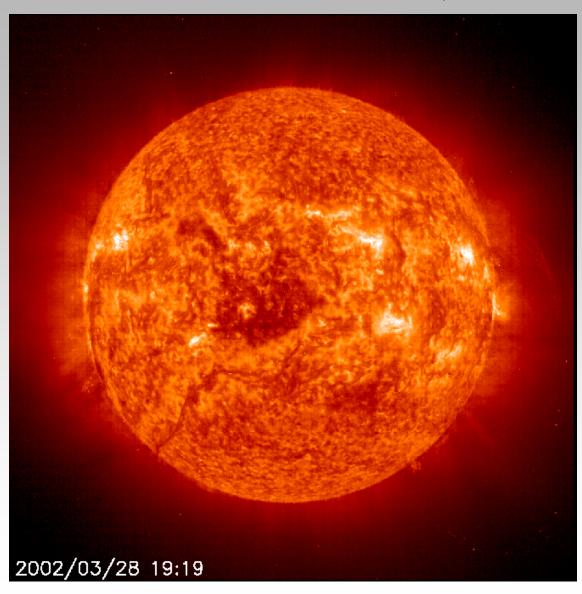
#### WHAT IS COSMOLOGY?

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



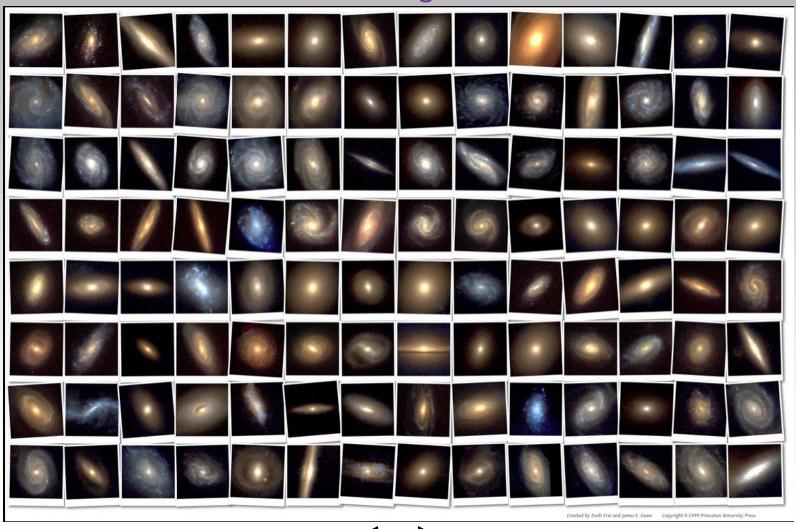
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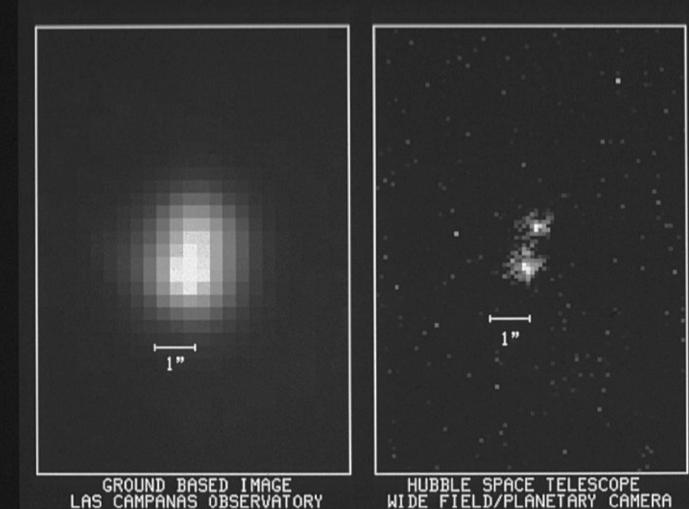


#### THERE ARE MANY GALAXIES...

#### 100 Billion galaxies



#### SEEING FROM SPACE



GROUND BASED IMAGE LAS CAMPANAS OBSERVATORY CARNEGIE INST. OF WASHINGTON



#### 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"\*

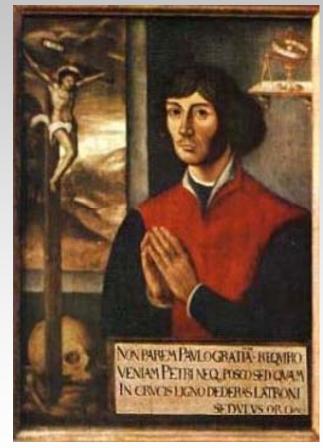
• "First of all, we must note that the universe is spherical."

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!<sub>14</sub>

#### 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.

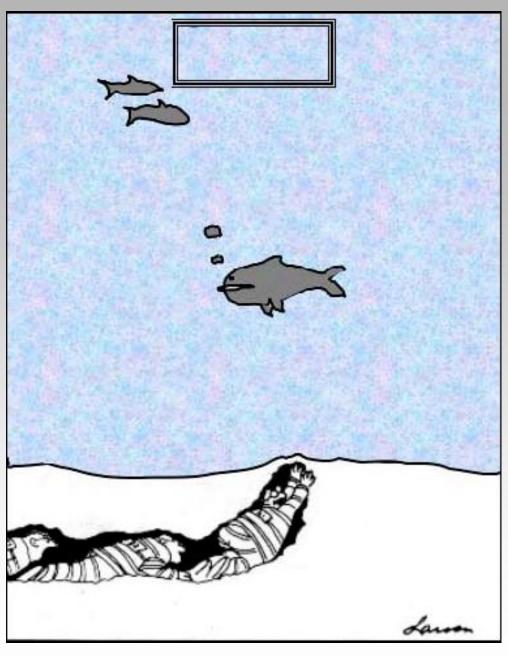


It ain't what you don't know, it's what you know that ain't so!<sub>15</sub>

#### 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!<sub>16</sub>



We're almost free, I just felt the first drops of rain 17

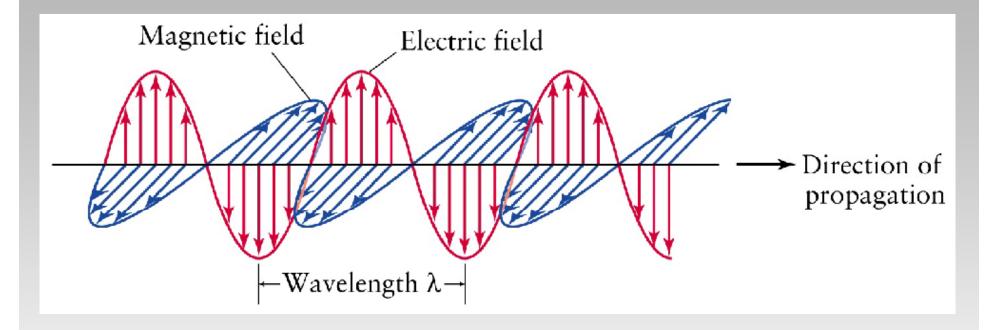
#### STAR STUFF

- 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

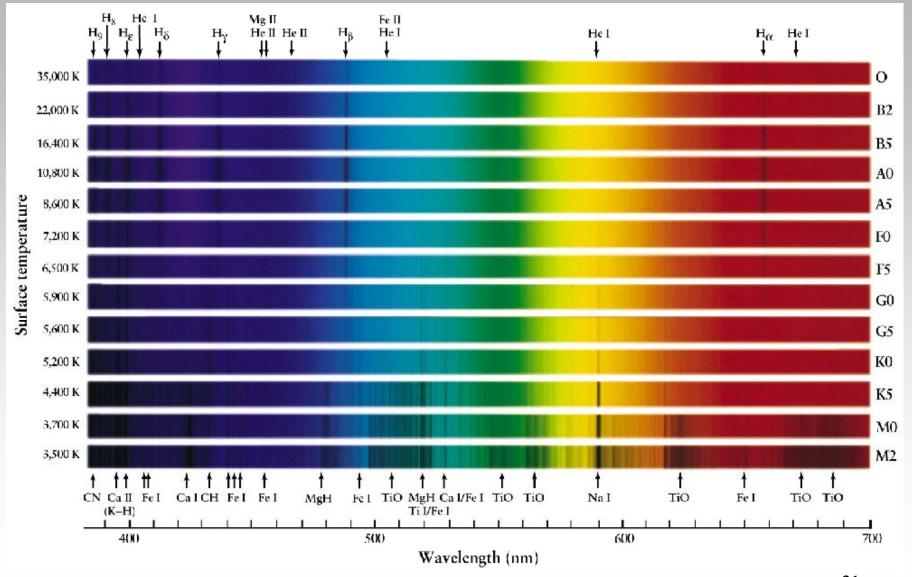


#### WHAT IS LIGHT?



- 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

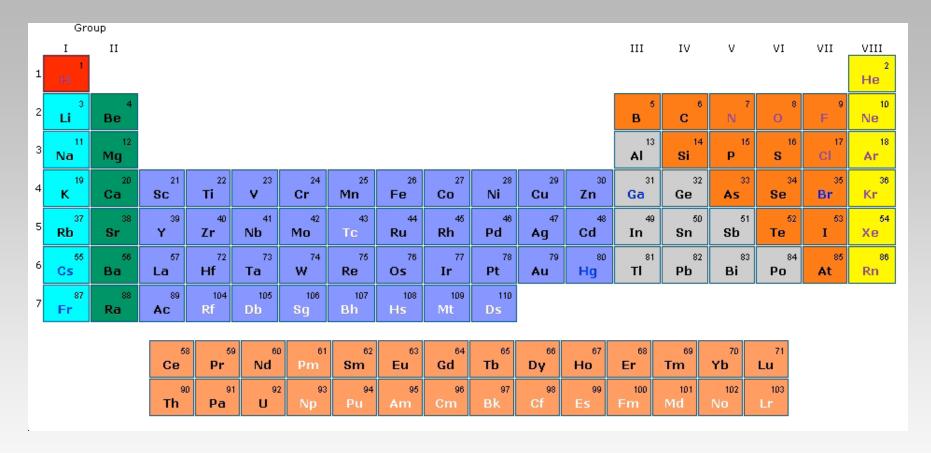
#### STELLAR SPECTRA



#### 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)

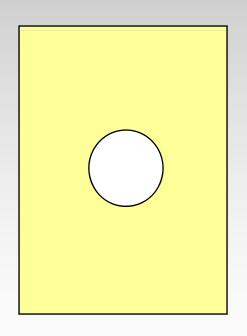
#### THE PERIODIC TABLE OF ELEMENTS



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

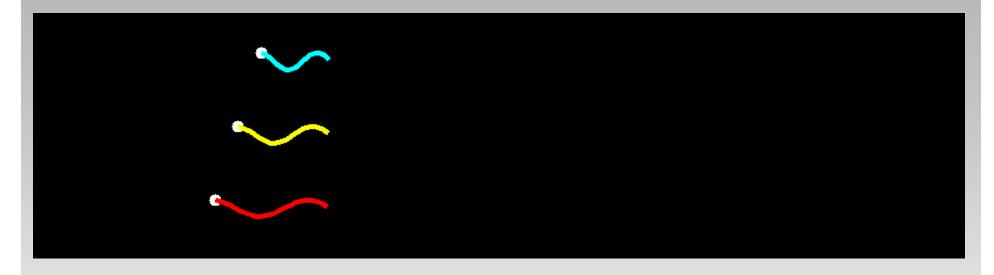
#### **EACH ELEMENT HAS A UNIQUE FINGERPRINT**

Let's see that for ourselves



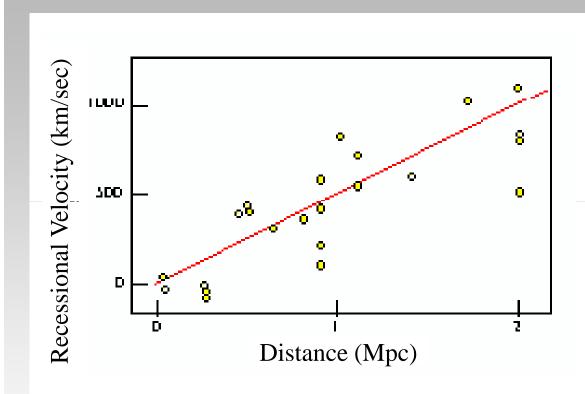
Pick up your diffraction grating sheets to view the demonstration.

#### 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.

velocity  $\propto$  distance  $v = H_0 r$ 

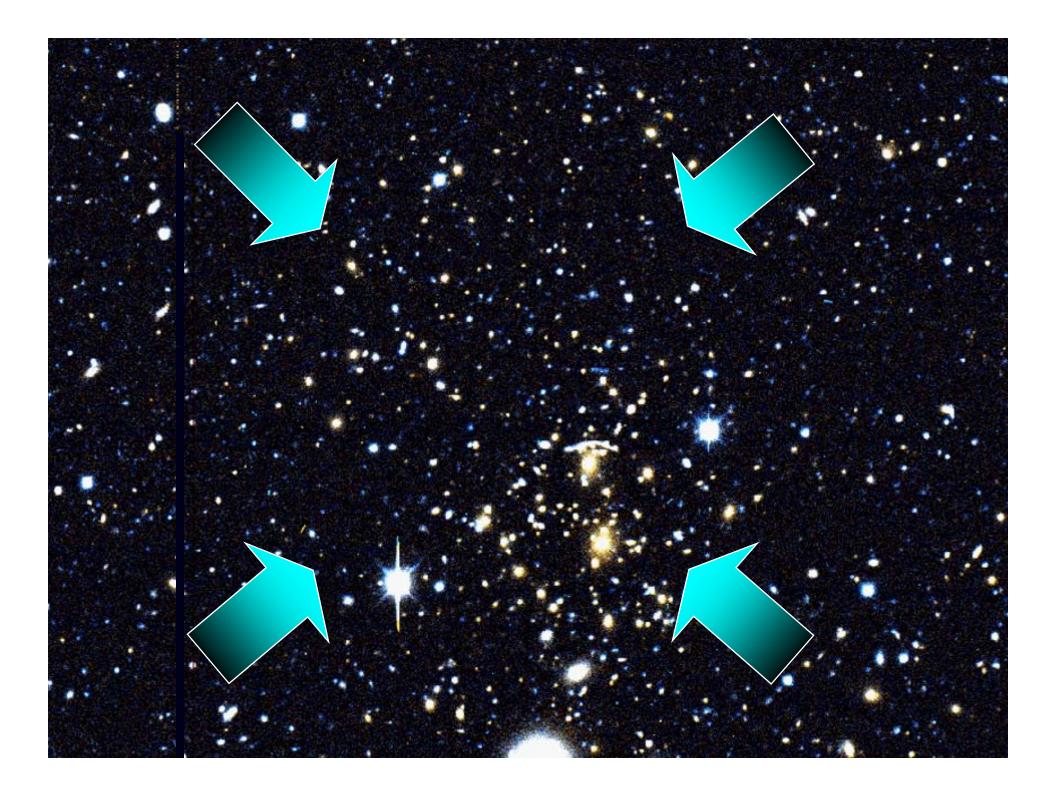
- Result: The faster they are moving, the farther away they are.
- The Universe is not static it is expanding!

#### PRE 1920s: THE STATIC UNIVERSE

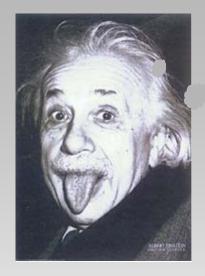


$$H^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2}$$

- 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

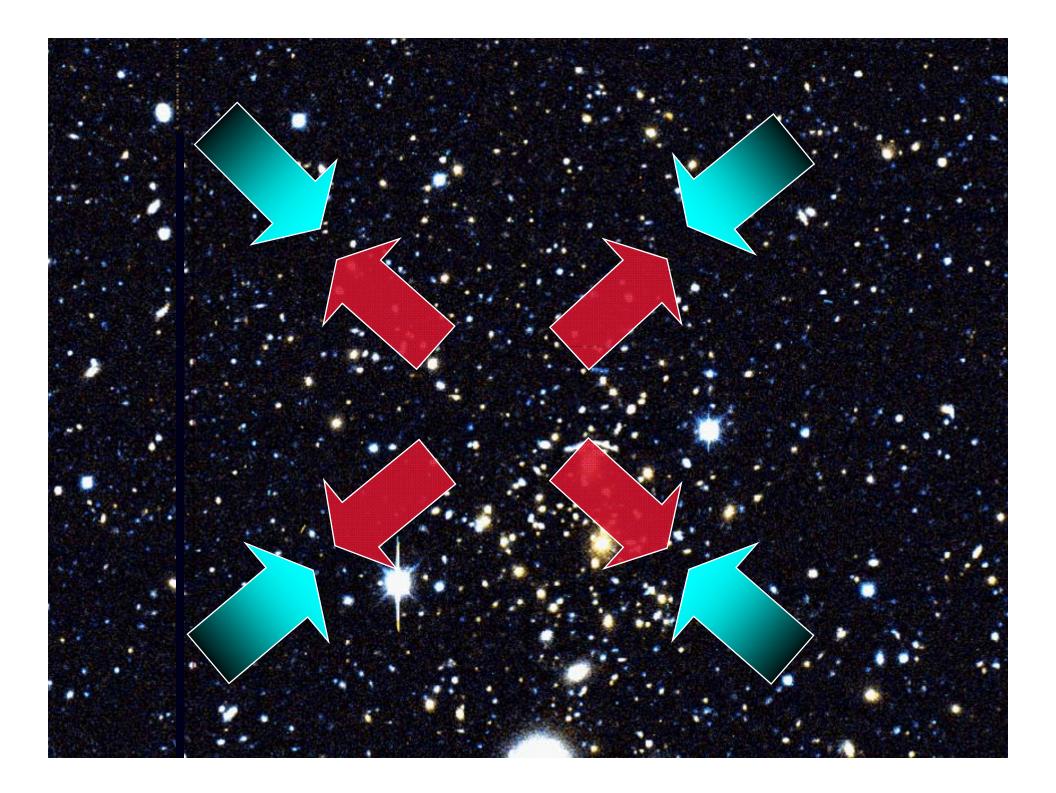


#### THE EQUATION OF THE UNIVERSE



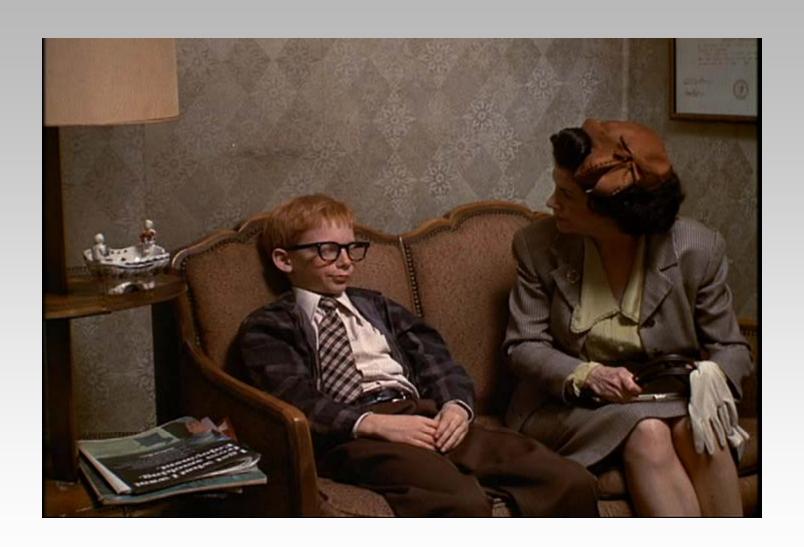
$$H^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

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



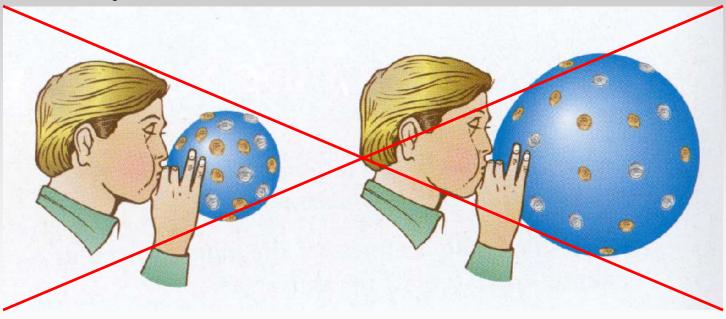
#### **EINSTEIN'S "BIGGEST BLUNDER"**

- The Universe is not static it is expanding!
- Einstein is very upset!
- Einstein declares  $\Lambda$  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

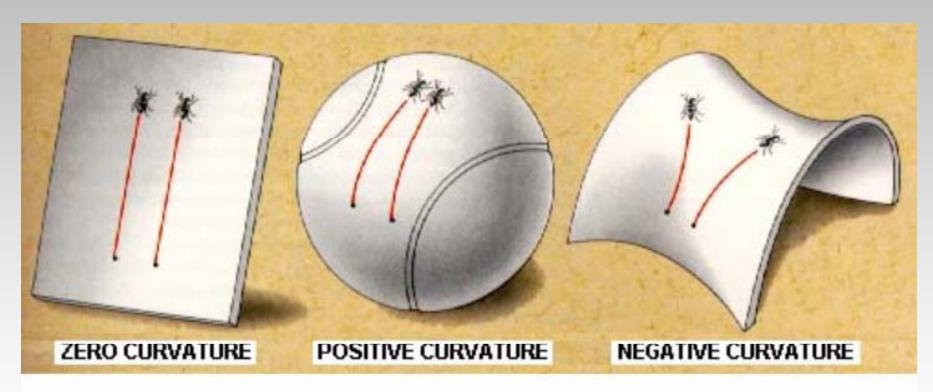
- If everything is moving away from us are we at the center?
  - No: every place is the center
- If everything is moving away from everything else some time ago in the past everything was on top of each other?
  - Yes: Winding the clock back, we reach a time of infinite density: the Big Bang!
- If the expansion rate is constant, then the age of the Universe is  $^{\sim}14$  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



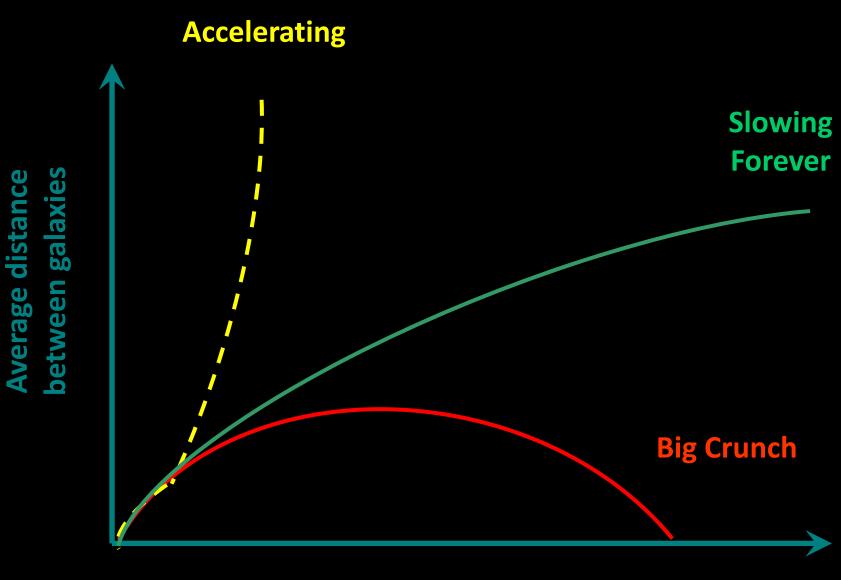
**FLAT** 

SPHERICAL HYPERBOLIC

open infinite universe ⇒ decelerates to rest

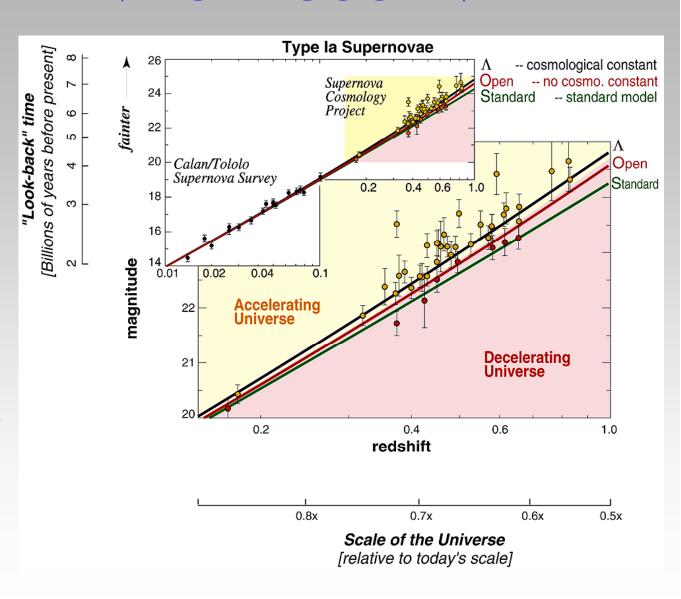
closed universe  $\Rightarrow$  eventual collapse open infinite universe  $\Rightarrow$  expands forever

# THE FATE OF THE UNIVERSE



## A STARTLING DISCOVERY

- (1998) Supernova
   Cosmology Project
   and High-Z
   Supernova team
   construct a Hubble
   diagram using Type
   la supernovae
   looking back 7 Byr
   (1/2 the age of the
   universe).
- Both found that the Universe is speeding up, not slowing down!

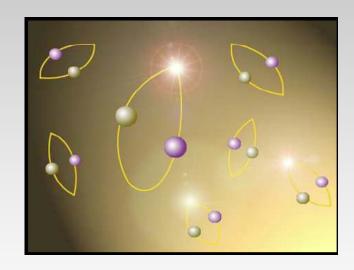


# WHY??

# 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<sup>120</sup>

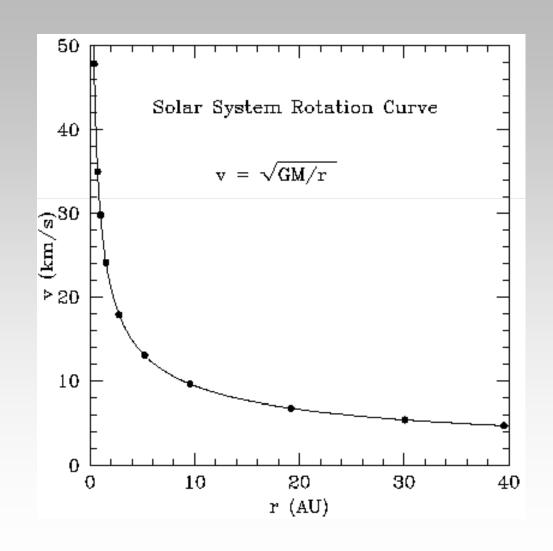
### THE MYSTERIOUS DARK MATTER

- 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 ...

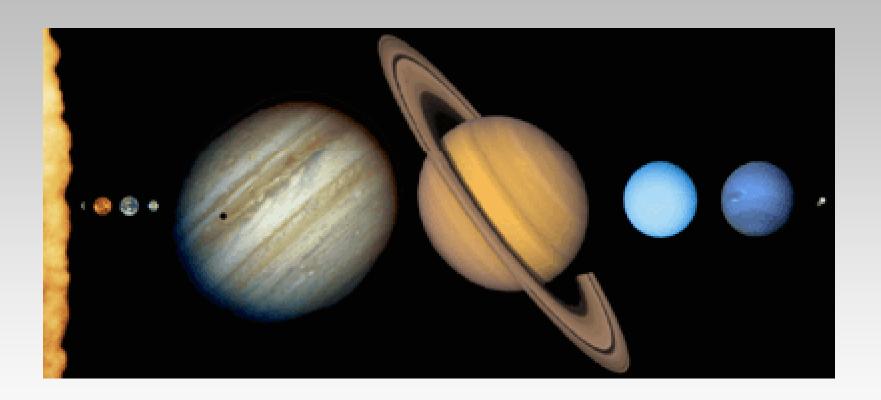
### **SOLAR SYSTEM ROTATION CURVE**

Average Speeds of the Planets

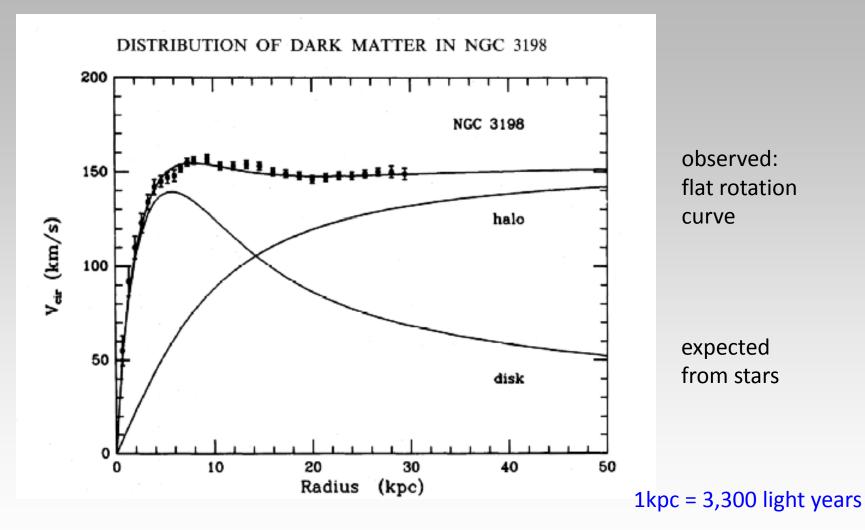
As you move out from the Sun, speeds of the planets drop.



# **SOLAR SYSTEM**

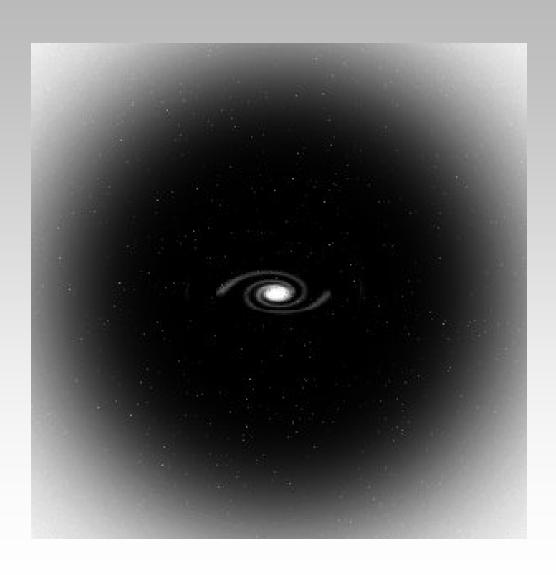


### **ROTATION CURVES OF GALAXIES**

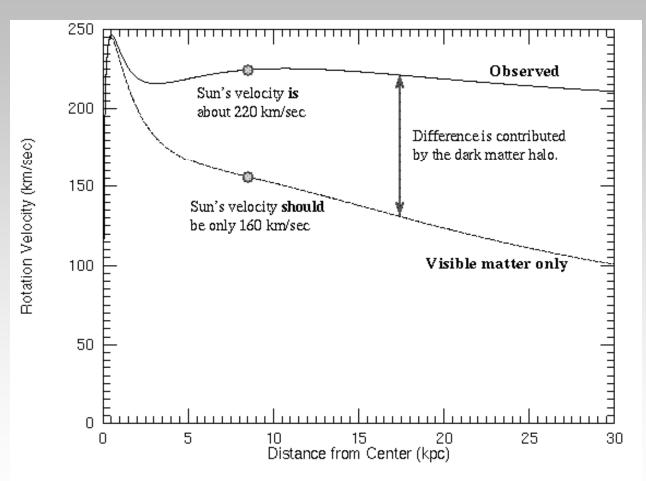


95% of the mass in galaxies is made of an unknown dark matter component

# GALAXIES HAVE DARK MATTER HALOES



# SUN'S ORBIT IS SPED UP BY DARK MATTER IN THE MILKY WAY

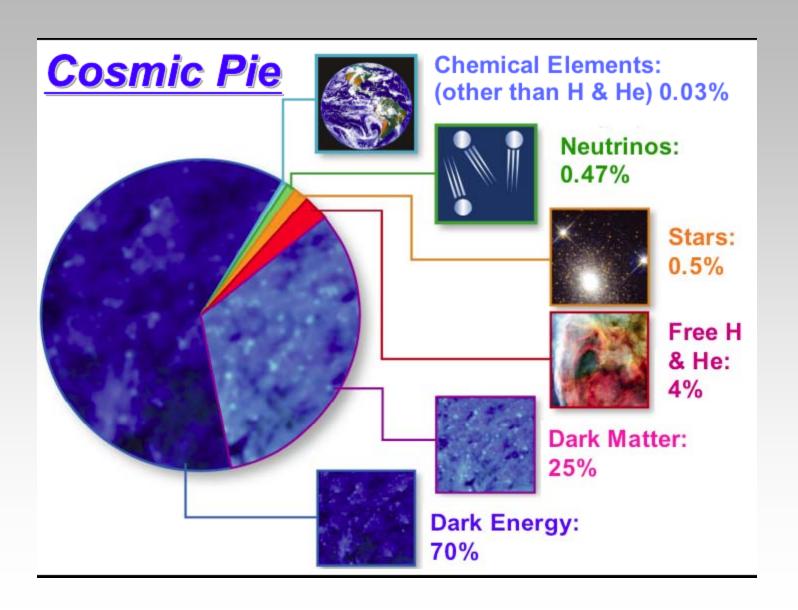


The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two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

### WHAT IS DARK MATTER?

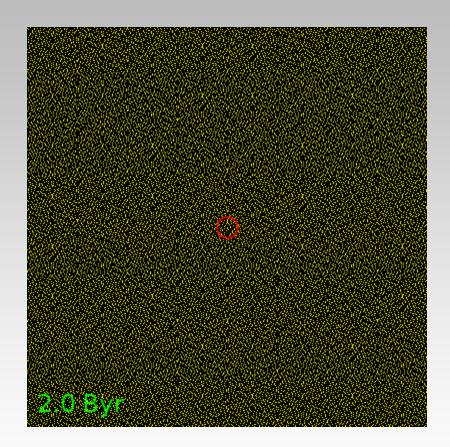
- Does not emit or absorb light in any wavelength
- Visible through gravitational effects only
- Normal stuff that does not emit light?
  - brown dwarfs or planets, white dwarfs, neutron stars, black holes, dark galaxies and clusters of galaxies?
- Exotic particles?
  - "Hot" Dark Matter: neutrinos?
  - "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



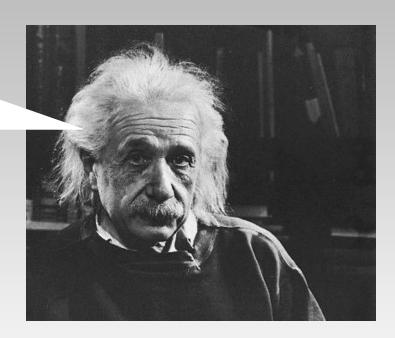
### IMPLICATIONS OF COSMIC ACCELERATION

- 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.



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





- .... for velocity through 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/ρ?
- 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!

The distant Type la.sup

## Dark Energ

National Astronomical Observatory, 2-21-1, Osawa, Mitaka, Tokyo 191-558, Japan; zong-honguhu@nac acip, fujim oto masa

expansion spenario, which w that the allowed internals for verse with a very low matter density, which ca measurements of the cosmic microwave background an isotropy and galaxy clusters (cluster baryon fraction). A sa result, this Cardassian expansion proposal does not seem to survive the magnitude redshift test for the present Type lasupernovaedata, unless the universe contains primarily banyonic matter.

Subject headings: cosmological parameters " cosmology: theory " distancescale "

1. INTRODUCTION

ery of the acceleration of the universe through observations of distant Type I a supernovae (Perlmutter et al. 1998, 1999; Riesset al. 1998, 2001; Leibundgut 2001). It is well known that all known types of matter with positive pressure gener that all known types or make a tractive forces and decelerate the expansion of the universe, conventionally, a deceleration of the universe to describe the status of the universe types on (Sanda sion (Sanda 1988). Given this, the discovery from t Ta supernovae indicates the existence a with fairly negative pressure, which is own dark energy, such as a cosmological constant (Weinberg 1989: Carroll, Press & Turner 1992: Krauss & Turner 1995 Ostriker & Steinhardt 1995) or an evolving scalar "eld (referred to by some asquintessence: Ratra & Peebles 1988; Wetterich 1988; Frieman et al. 1995; Coble. Dodelson, & Frieman 1997; Caldwell, Dave, & St 2002). While current measurements wave background anisotropies favor a with cold dark matter (de Bernardis 2001), both the deuterium abundant high redshift hydrogen clouds seen in absorption distant quasars (Burles & Tytler 1998a, 1998b) (co with the baryon fraction in galaxy clusters from X-ray data: see White et al. 1993 for the method) and the large-scale structure in the distribution of galaxies Peacock et al. 2001) have made a : It seems that all these observations explained by the hypothesisthat there cold dark matter, a dark energy con pressure in our universe (Turner 2002b). The existence of this component has also been independently indicated by

The case for detection of dark energy is not yet a

(De avet, Dvali, & Gabadadze 2002; Gu & Hwang 2002) or an altered theory of gravitation (Behnke et al. 2002). Very recently, Freeze & Lewis (2002) proposed the Cardassian

however, avoid the cosmic coincidence problem,, why the

densities of dark energy and dark matter are comparable

today (another related but distinct dill culty is the "ne-tun-

neconsidering its origin' to ne-evaluating it ultimate fixture. But perhaps the most significant change in cosmological thin king involves a new willingness to discuss what

might not ultimately evolve unless the cosmological constant were not much

because the value it seems to take is otherwise dimensional quantities are related to this

CONSTRAINTS ON CARDASSIAN EXPANSION FROM DISTANT TYPE Is SUPERNOVAE

Zong-Hong Zhu and Masa-Katsu Fujimoto National Astronomical Observatory, 2-21-1, Osawa, Mileta, Tolgo 181-6898, Japan. Izong-hong-hushao acip, Ayim oto, masa-hatsu Shao acip Recivia Osak-Aguston (2002). Paga-da and paga-da

#### A BSTRACT

The distant Type Ita supernovae data compiled by Perlmutter et al. are used to analyze the Cardassian expansion scenario, which was repently proposed by Freeze & Lewis as an alternative to a cosmological constant (or more generally a dark energy component) in explaining the currently accelerating universe. We show that the allowed intervals for n and  $z_{\rm eq}$ , the two parameters of the Cardassian model, will give rise to a universe with a very low matter density, which can hardly be reconciled with the current value derived from the measurements of the cosmic microwave background an isotropy and galaxy clusters (cluster banyon fraction). A sa result, this Cardassian expansion proposal does not seem to survive the magnitude redshift test for the present Type lasupernovaedata, unless the universe contains primarily banyonic matter. Subject headings: cosmo logical parameters , cosmology: theory , distancescale , supernovae: general

#### 1. INTRODUCTION

A major development in modern cosmology is the discov The methick-angulatorize and merry of the acceleration of the universe through observations of distant Type I a supernovae (Perlmutter et al. 1998, 1999; Riesset al. 1998, 2001; Leibundgut 2001). It is well known that all known types of matter with positive pressure gener

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Galaxy counts
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to describe the status of the universe sexpansion (Sandage , 1988). Given this, the discovery from the high-redshift Type la supernovae indicates the existence of a new component with fairly negative pressure, which is now generally called dank energy, such as a cosmological constant (Weinberg 1989: Carroll, Press & Turner 1992: Kirauss & Turner 1995 Ostriker & Steinhardt 1995) or an evolving scalar "eld the ubiquitantion mechanicy is near the (referred to by some acquintessence Flatra & Peables 1988; Salocus abonaclessegers in the Rosecest\*\* Wetterich 1988; Frieman et al. 1995; Coble, Dodelson, & Rossibly, then, ubiquitination helps to control Frieman 1997; Caldwell, Davie, & Steinhardt 1998; Gong <sup>14</sup>2002). While current measurements of the cosmic micro

wave background anisotropies favor a spatially "at universe with cold dark matter (de Bernard is et al. 2000; Lange et al. high-redshift hydrogen clouds seen in absorption against distant quasars (Burles & Tytler 1998a, 1998b) (combined with the baryon fraction in galaxy clusters from X-ray data: see White et al. 1993 for the method) and the large-scale structure in the distribution of galaxies (Bahcall 2000; Peecock et al. 2001) have made a strong case for a low is that all these observations can be concordantly had by the hypothesis that there exists, in addition to dark matter, a dark energy component with negative sure in our universe (Turner 2002b). The existence of this component has also been independently indicated by other observations such as the angular size..redshift

Physicists are learning to like with Ei relations for auround south as the langular size, itedshift constant. New thinking attempts to 16, Frey 1999, Vistwakarma 2001; Lima & Alcaniz 2002; oretarts in eleminary projection by the Constants in eleminary projection in the Constant i Chen & Ratra 2003) and FR IIb radio galaxies (Guerra, 00; Daly & Guerra 2002, Podariu et al. 2003) ets of old high-redshift galaxies (Dunlop as 1997; Albaniz & Lima 1999), and grav-g (Kochaneck 1996; Chiba & Yoshii 1999; proposed this scenario. In a previous paper, the authors

> ter commonent @3# Hers ntessence models interact

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m in an accelerating uni-

ential Section IV investi | (747) - 1 ure within the dark matte vior of the deceleration

ce coupling with cosmo of possible anomalous ac-

Futamase & Hamaina 1999; Jain et al. 2001; Deviet al. 2001;

Obverna et al. 2002: Sereno 2002).

Neither a cosmological constant nor a quintessence, the 1 present candidates for the universe acceleration mechanism. Is however, avoid the cosmic coincidence problem,, why the D densities of dark energy and dark matter are comparable o todav (an other related but distinct di culty is the "ne-tun-e ing problem; see Carroll et al. 1992 for a discussion of this noint). Although the tracking "eld model (Zlater, Wang & # Steinhardt 1999) provides a possible resolution to this prob-4. lem, a convincing dark energy model with a solid basis in  $\vdash$ particle physics is still far of. Therefore, it is desirable to a explore alternative possibilities, such as higher dimensions 11. (De avet, Dvali, & Gabadadze 2002; Gu & Hwang 2002) or e an altered theory of gravitation (Behnke et al. 2002). Very s recently. Freeze & Lewis (2002) proposed the Cardassian is expansion scenario in which the standard Friedmann-s

H2 1/4 A | B B h :

where H R≕R is the Hubble parameter as a function of cosmic time, Risthe scalefactor of the universe, and is 🌡 🗖 🖺 🥞 💣 the energy density of matter and radiation. In the usual المحمد المعالم المعا FRW equation, B %0. To be consistent with the usual FRW result, one should take A %8 G=3. It is convenient to use the redshift ze<sub>1</sub>, at which the two terms of maketa, 200 and 2 dessian model. In this parameterization of (n, z<sub>ok</sub>), it can be shown that (Freeze 8, Lewis2002) B ½ H<sub>2</sub><sup>201</sup> b z<sub>ok</sub>p<sup>201</sup> b , 1/2 b zokp<sup>201</sup> b zokp<sup>201</sup> b , 1/2 b zokp<sup>201</sup> shown that (Freeze & Lewis2002) B VH (30 b p 20) Pi<sup>-10</sup> o n VH) 6 1 b 20 Pi<sup>-10</sup> · Where o is the matter density of the universe at the present time and H o ¼ 100 h km s <sup>1</sup> Mpc <sup>1</sup> is the Hubble constant. This particular proposal is very intriguing because the expansion of the universe will be accelerated automatically later without any dark energy and the second term, which may arise as a conse-ble to explore the agreement of the Cardassian expansion model with the currently available cosmological observation data, as suggested by Freeze & Lewis (2002), who

have used the recent measurements of the angular size of

Observations cogget that car amounts has entered a paper, a very suitable in plans or accordinate appared in the monitorial foreign is a dissipative, negative qualities on the constitution to the sold apparent. Such a quantity side only in the inventor is populated by a medium accordinate on the population by a medium accordinate on the population of the population o tive pressure arises natu pour and a standard pressure and but pour defend quantum particle produce their or has all one globologies or Laguagues

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#### lution to the coincidence problem

ubi, 1 Diego Pawa, 2 and Winfried Zimdahl3 nales, Universidad de Buenos Aires, Ciudad Universitaria, Pabellen I, os Aires, Arverdina

is Ediribeio Co. Universidad Austraoma de Barcelona, ema (Barcelona), Spain tanz, P.F. M.S.78, D-78547, Konstanz, Germany pt monived 10 February 2003; published 24 April 2003!

ilar@eldand a matter uid in a spatially homogeneous and nattendominated era to an accelerated expansion place and ir present Universe. For this purpose we study the evolution nis. We demonstrate that a stationary attractor solution is Universe. We extend this study to account for dissipation Finally, type Ia supernovae and primordial nucleosynthesis

PACS numbers!: 98.80.7k; 04.20.7b; 95.35.1 d; 98.80.Es

obtained as the result of a dynamical evolution. In the present paper we clarify this point and establish an exactly solvable model for a smooth transition from a matter dominated phase to a subsequent period of accelerated expansion This model implies the evolution of the density ratio towards. a Onite stable, asymptotic value. Thus it may represent a solution to the coincidence problem.

As shown in another previous paper, a very suitable ingredient of quintessence models is a dissipative, negative, scalar pressure of the matter commonent. Such a quantity may simultaneously help to drive acceleration and solve the coincidence problem G2# A negative pressure arises natu rally from bulk viscous dissipation, quantum particle production or self-interaction in the matter commonent GG# Here we combine the advantages of quintessence models interacting with matter -QIM! with those relying on a dissipative

Robertson-Walker (FRW) equation is modified as follows: PRW D (3.) COM 4 CHO)

All action Coldes dark energy

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Chen & Ratra 2003) and FR IIb ra

Dalv. & Wan 2000; Dalv & Guerra 200

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et al. 1995: Krauss 1997: Albaniz & L itational lensing (Klochaneck 1996; d

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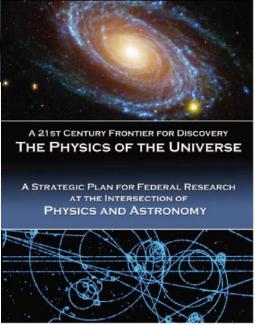
### **National Academy of Sciences**

### **Department of Energy**





### **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 la 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."

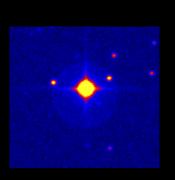
# A PRACTICAL POINT:

Light takes time to travel.

### How long does light take to reach us from...

The Sun

Nearest Star



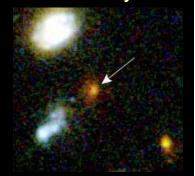
Nearest Galaxy



Nearest Galaxy Cluster



Supernova in Distant Galaxy



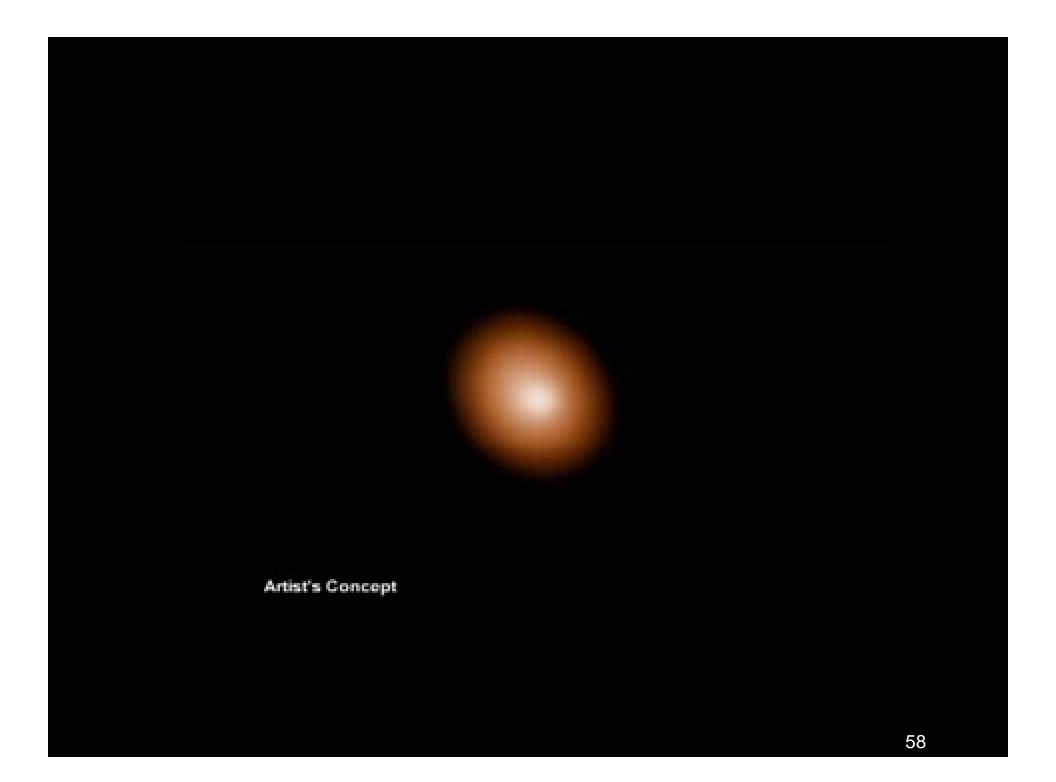
8 minutes

4 years





10 billion years



# Type Ia SNe as Standard Candles



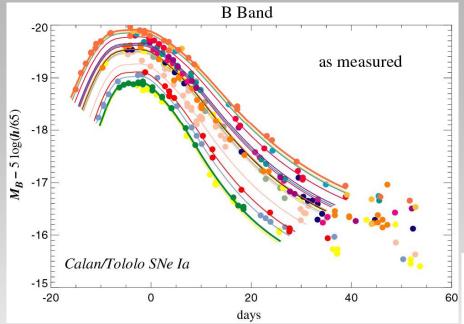




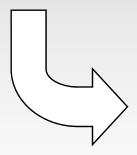


apparent magnitude = distance = time

# "STANDARD-IZABLE" CANDLES

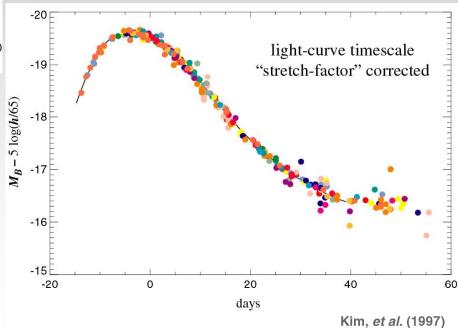


Peakmagnitude dispersion of 0.25 – 0.3 magnitudes



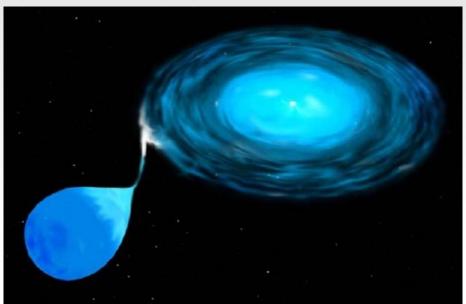
~00.165 magnitude dispersion

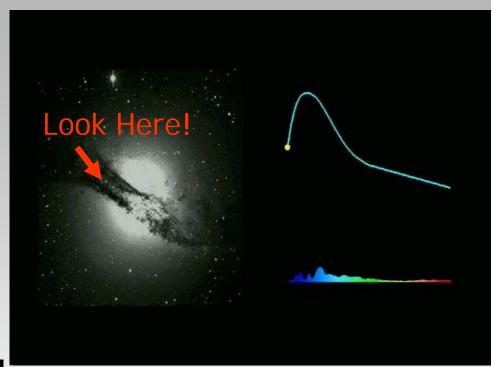
- Nearby supernovae used to study SNe light curve (z<0.1)</li>
- Brightness not quite standard
- Intrinsically brighter SNe last longer
- Correction factor needed



# 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

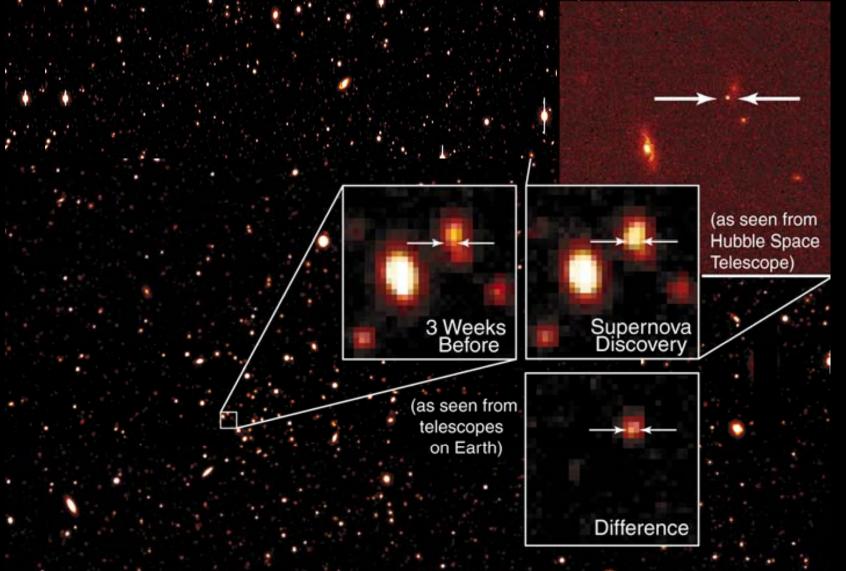




# What makes the supernova measurement special?

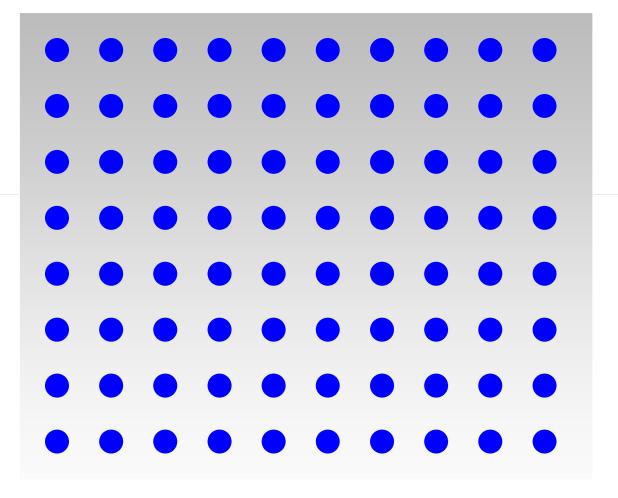
Can measure both intensity and spectra as the supernova brightens and fades over many days.

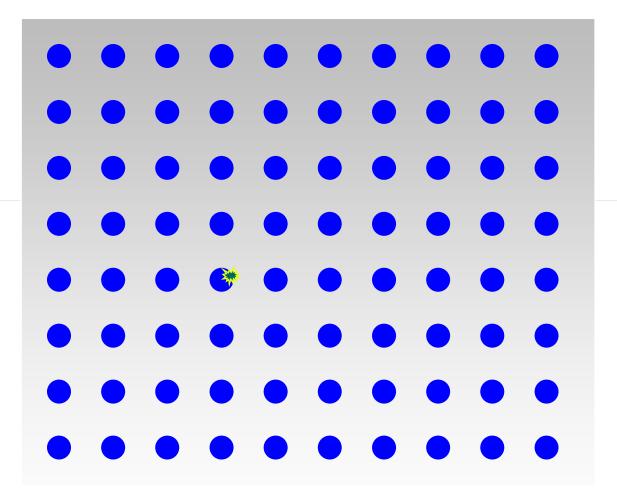
# DISCOVERING SUPERNOVAE

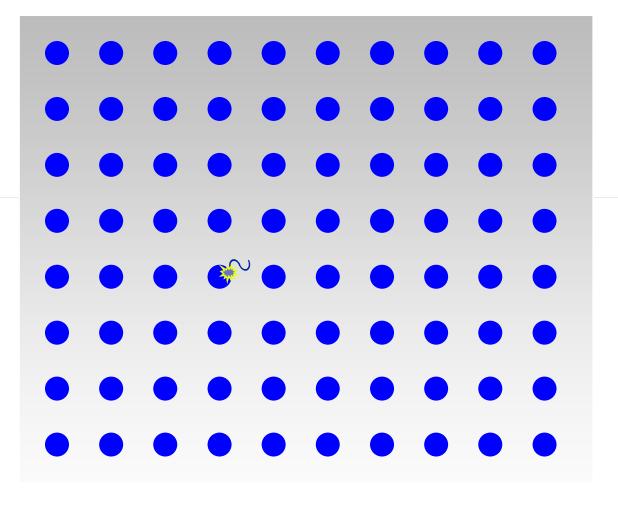


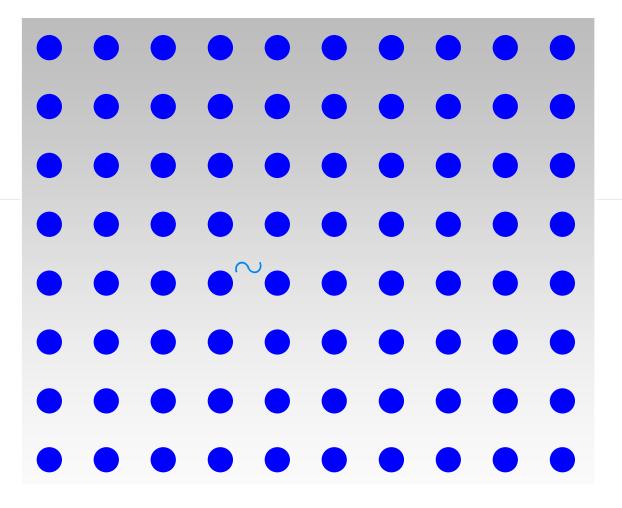
### ONE AMAZING TRICK:

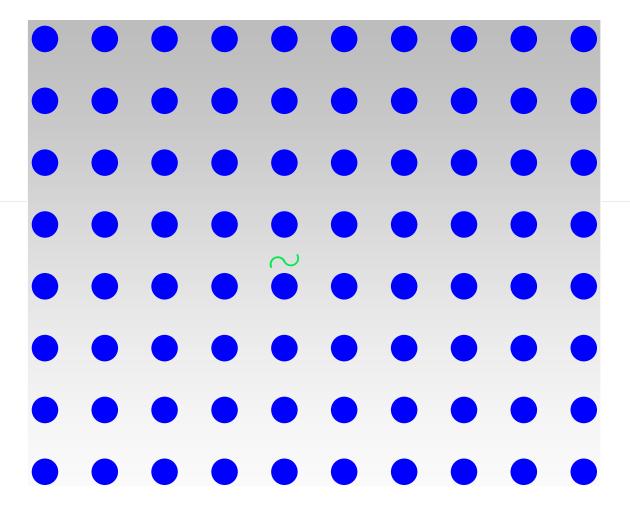
A supernova's "redshift" tells us how much the universe has stretched since the supernova exploded.

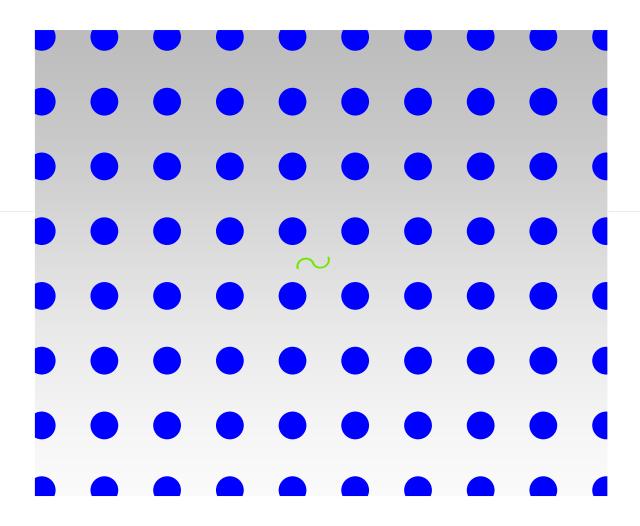


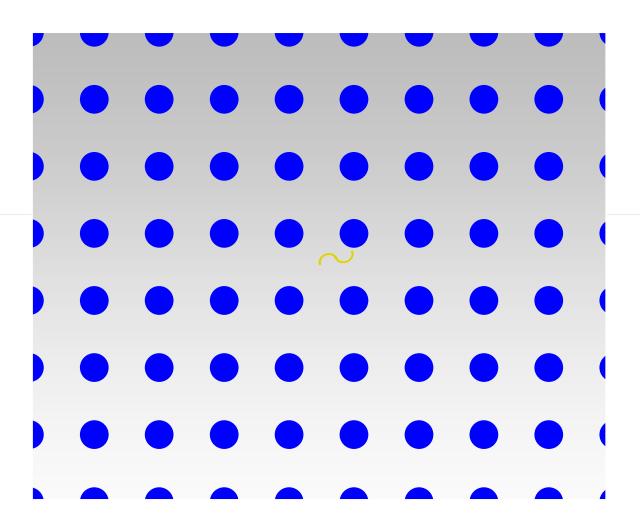


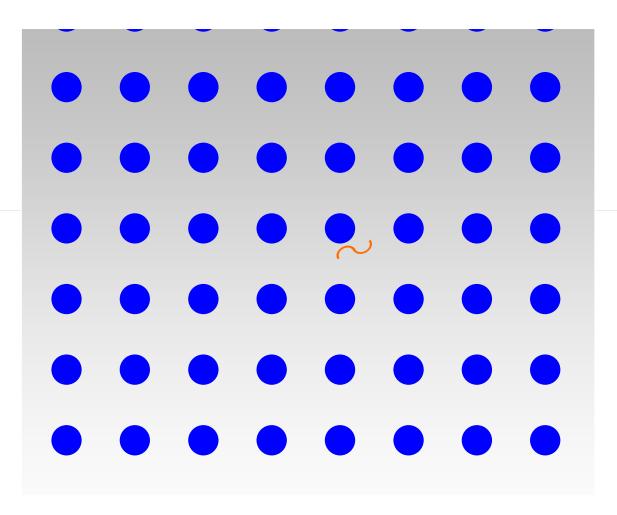


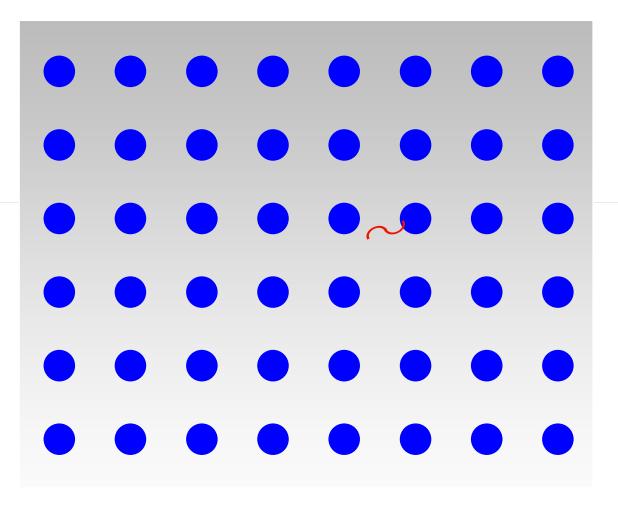


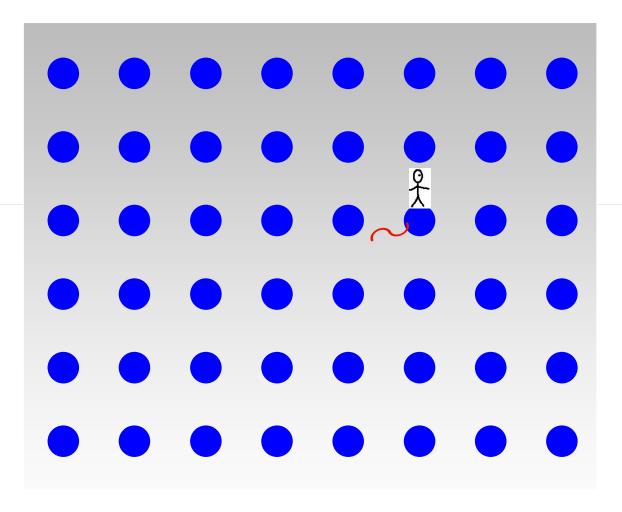




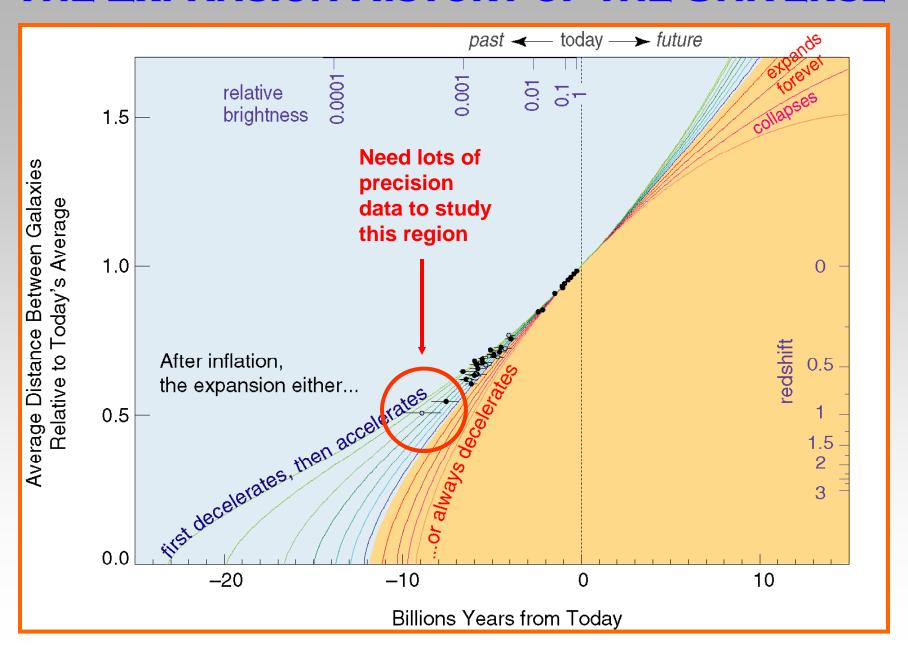




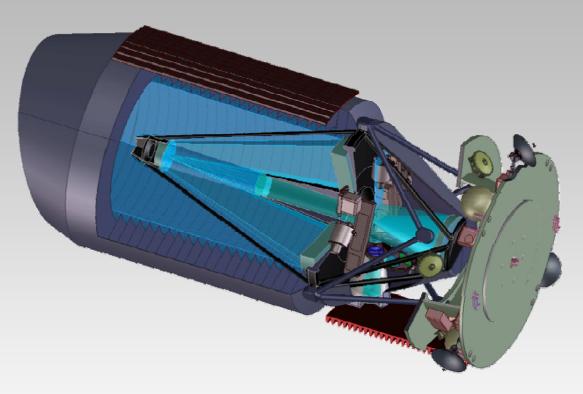




#### THE EXPANSION HISTORY OF THE UNIVERSE



### It's a SNAP! THE SUPERNOVA/ACCELERATION PROBE





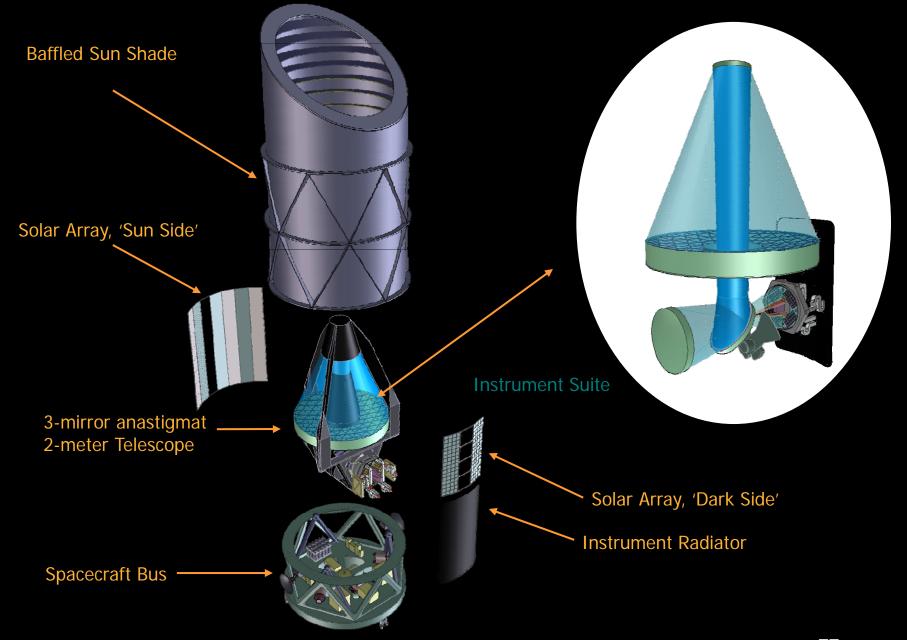
A large wide-field telescope with a state of the art camera and spectrograph to measure:

- 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



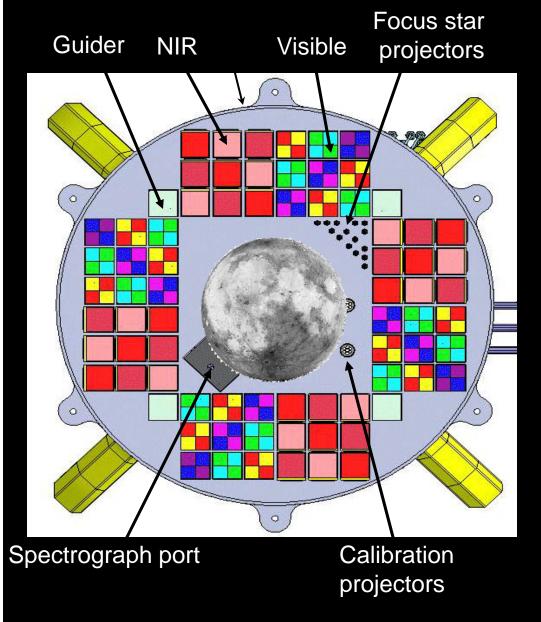
## SuperNova/Acceleration Probe (SNAP) Collaboration Team

#### **INSTRUMENT CONCEPT**

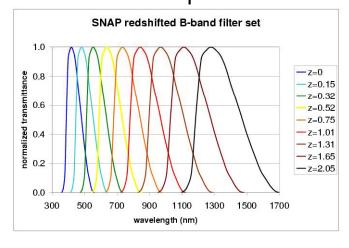


#### D=56.6 cm (13.0 mrad) FOCAL PLANE

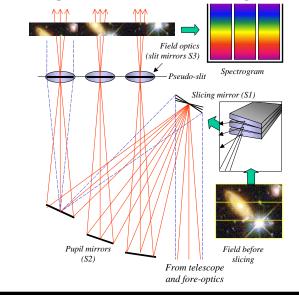
0.7 square degrees!



#### Fixed filters atop the sensors

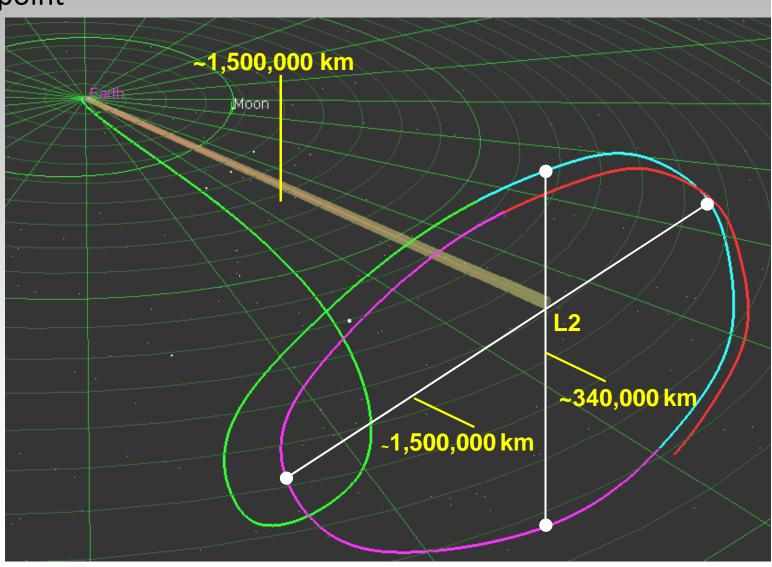


#### Integral Field Spectrograph



#### **SNAP ORBIT**

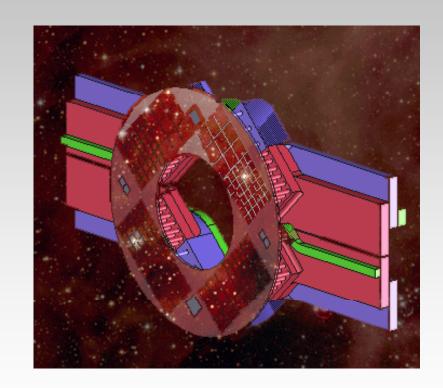
#### L2 Lagrange point

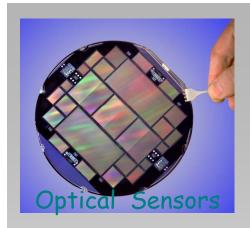


#### **OBSERVING**

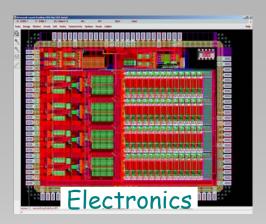
#### Step 'n Stare - All Supernovae in all colors

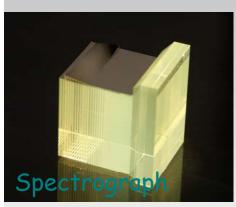
- Repetitive imaging program (SN discovery and light curve measurement)
  - Observe 15 square degrees every three days in all filters "mowing the sky".
  - ~50% of time devoted to spectroscopy of individual SNe near maximum light.
  - Will discover and follow ~2000 selected Type Ia Supernovae with redshifts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

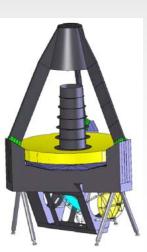


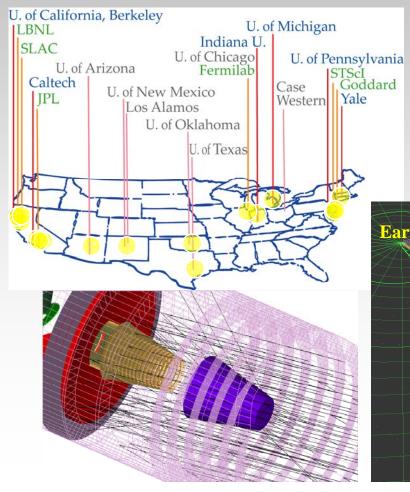


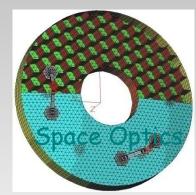


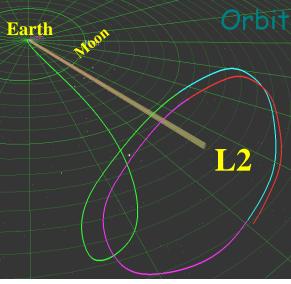












#### LAUNCH IN THE NEXT DECADE

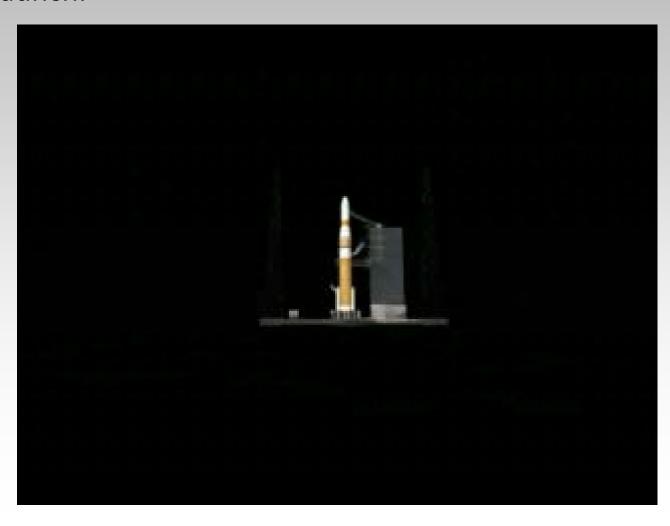
1600 kg satellite can be lifted by a Delta IV [recent first flight] to our orbit with margin.





#### 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)

Rocky Kolb (Chicago)

Micael Turner (Chicago)

Katherine Freese (Michigan)

Risa Wechsler (Stanford)

Clem Pryke (Chicago)

Saul Perlmutter (LBL)



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