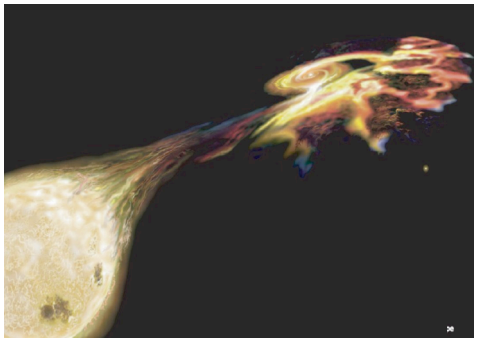
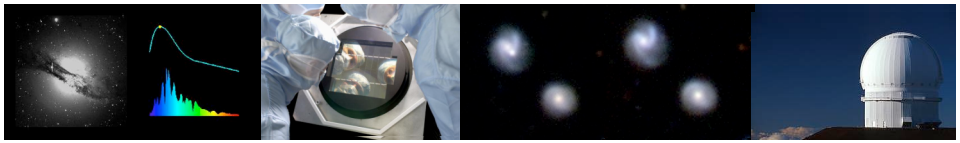
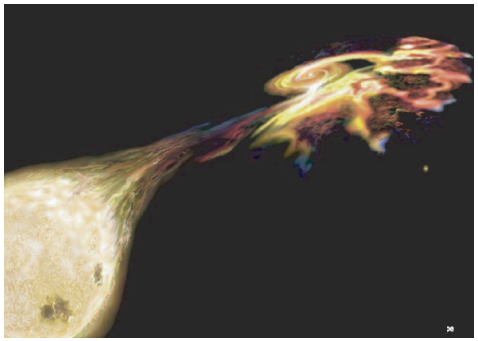


Part II

Supernova Cosmology

www.astro.uvic.ca/~pritchet/SN/A580-2008-II.pdf





- *Historical Background*
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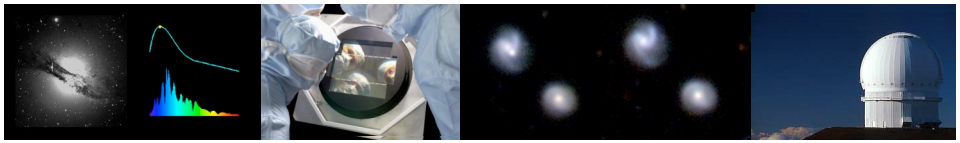
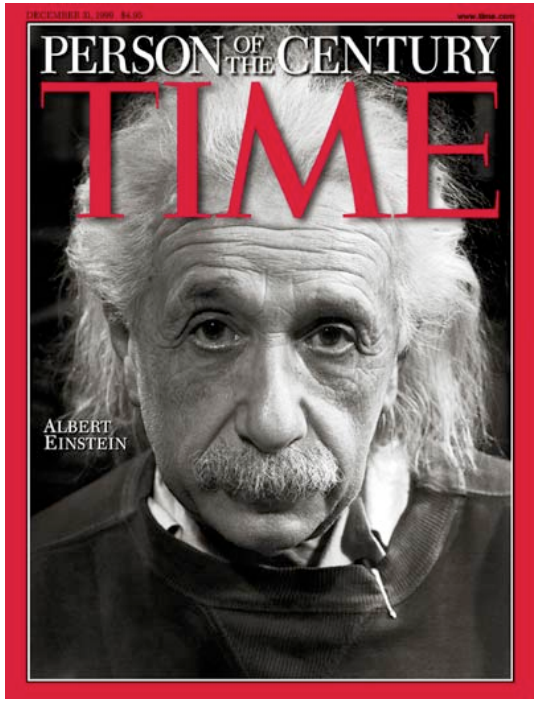


Golden Moments in Cosmology

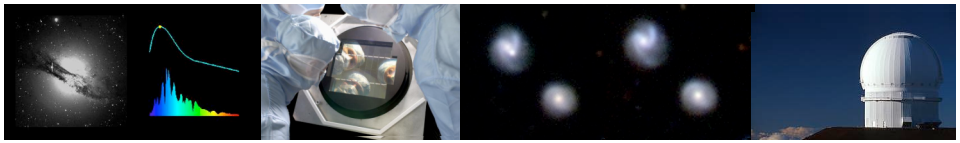


$$G^{\mu\nu} = -\frac{8\pi G}{c^4} T^{\mu\nu} - \Lambda g^{\mu\nu}$$

repulsive force,
vacuum energy,
ρ=const

"Much later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder of his life." – G. Gamow, "My World Line" (1970)

www.astro.uvic.ca/~pritchet/SN/A580-2008-II.pdf



Hubble Diagram (ℓ vs z)

(what Hubble actually did to demonstrate the expansion of the Universe)

Hubble við sjónaukann sem byggður var á Palomar-fjalli

George Darwin Lecture, delivered by Dr Edwin Hubble on* 1953 *May* 8

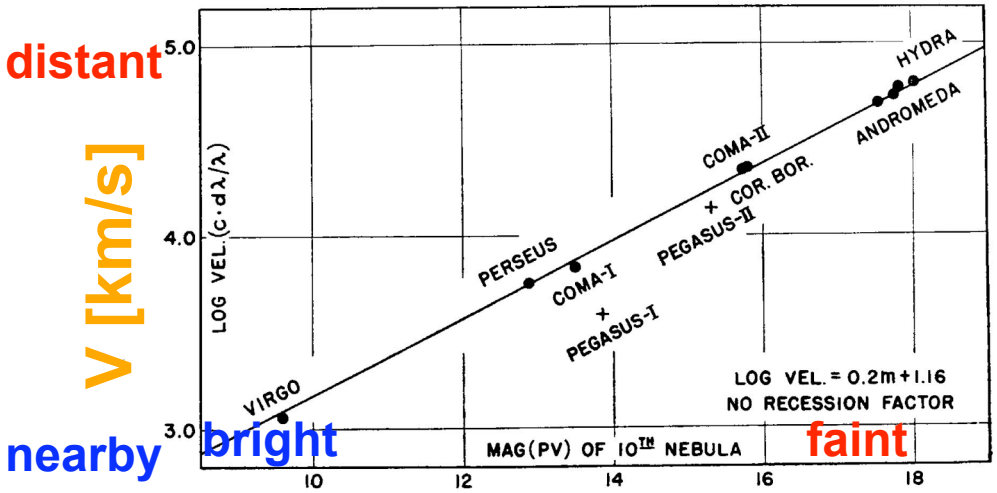


FIG. 1.—*The relation between velocity and apparent magnitude. The new data obtained with the 200-inch are represented by the last four points on the regression line. Humason's red-shifts are expressed on a scale of velocities as c . dλ/λ in km/sec. The photovisual magnitudes have been corrected for the energy effect only. They do not include the recession factor.*

Assumptions:

- Inverse square law $\ell = L/4\pi d^2$
- Euclidean space
- Standard candle

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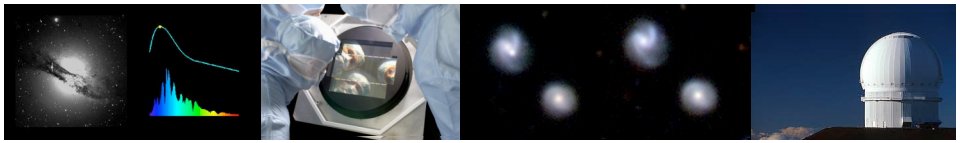
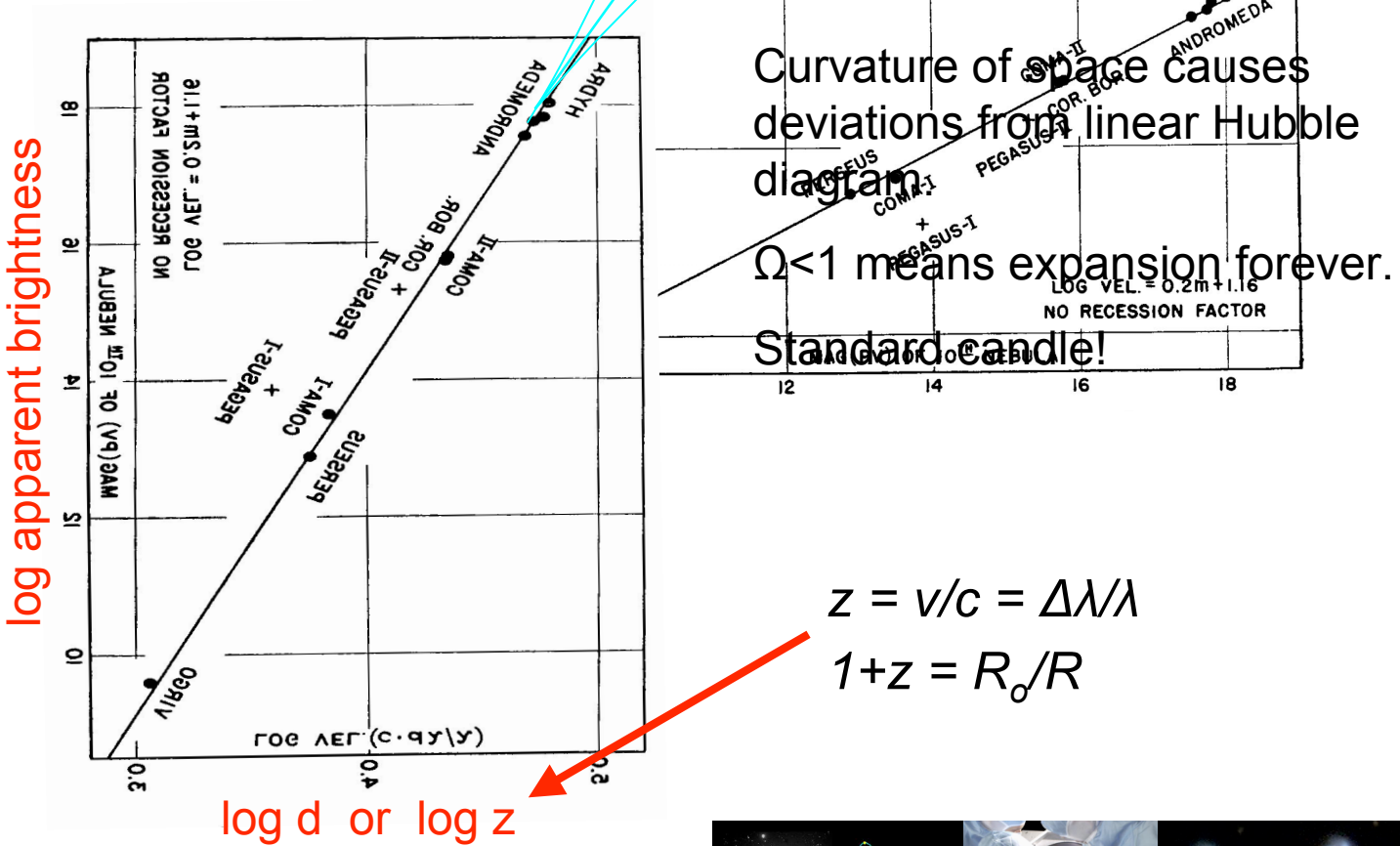


Hubble Diagram and Cosmology

Low ρ $\Omega<1$ $\Omega=1$ ***flat*** $\Omega>1$ High ρ



Curvature of space causes deviations from linear Hubble diagram.

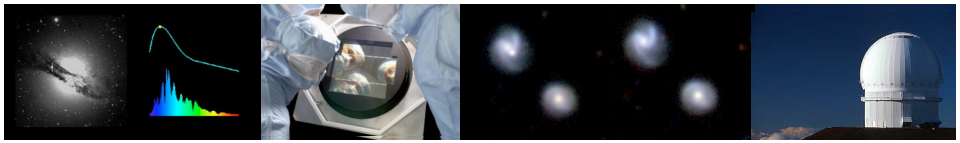
Ω<1 means expansion forever.

Standard candle!

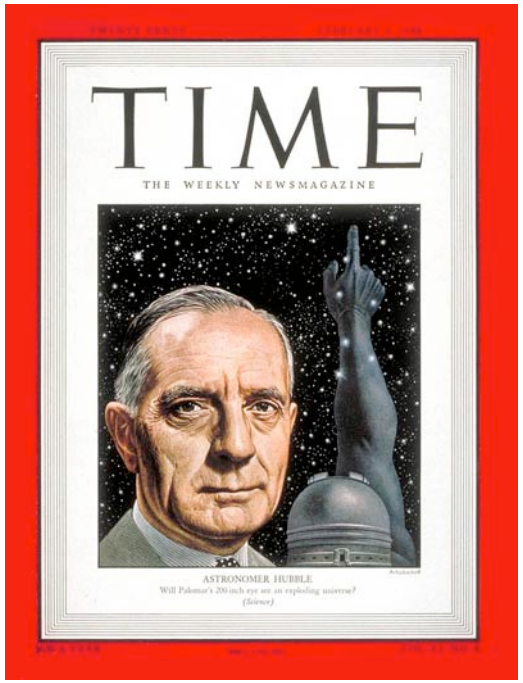
$z = v/c = \Delta\lambda/\lambda$

$1+z = R_o/R$

www.astro.uvic.ca/~pritchet/SN/A580-2008-II.pdf

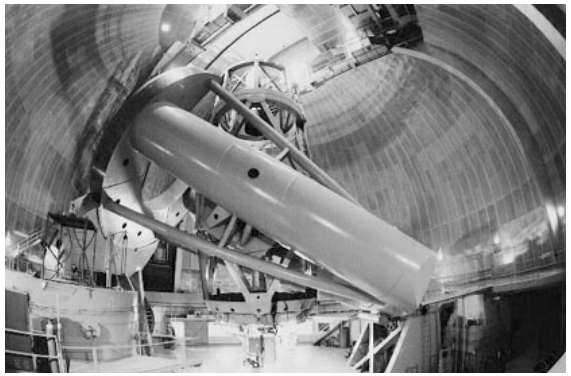


Cosmology – A Search for 2 Numbers?



H_o– rate of expansion ($v=H_o d$)

Ω_o – deceleration - matter density



THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 133 MARCH 1961 NUMBER 2

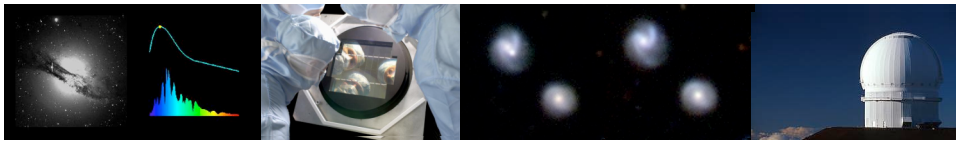
THE ABILITY OF THE 200-INCH TELESCOPE TO DISCRIMINATE BETWEEN SELECTED WORLD MODELS

ALLAN SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received October 14, 1960; revised November 5, 1960

ABSTRACT

The present paper reviews several tests which can be performed to decide between world models. Each test is discussed in terms of the capabilities of the 200-inch Hale telescope. The tests include (1) the deviation from linearity of the red-shift–magnitude relation, (2) the galaxy-count–magnitude relation, (3) the angular-diameter–red-shift relation treated for both metric and isophotal diameters, and (4) the time scale. Selected exploding models of the Friedman type and the steady-state model are considered. The object of the tests is to determine observationally the deceleration parameter q_0. Once q_0 is known, the world model follows from equations given in Section I.

www.astro.uvic.ca/~pritchet/SN/A580-2008-II.pdf



Gunn and Oke 1975

"… although the heterogeneity of the sample makes conclusions about cosmology slightly suspect."

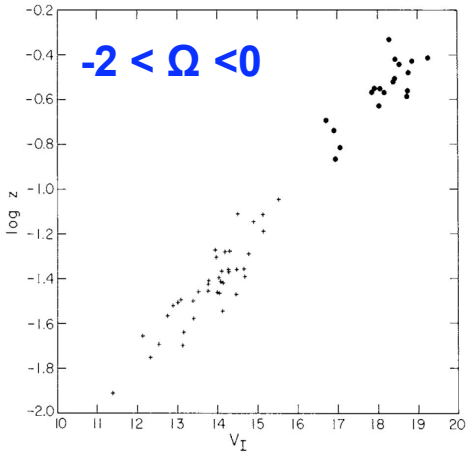
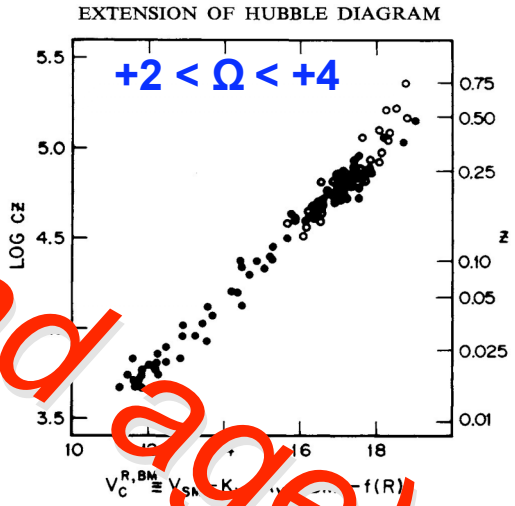


FIG. 2.—The Hubble diagram for the data used in the paper. *Solid dots*, scanner data; *crosses*, broad-band photometric data.

>400 nights of Palomar 200" time!

evolution (mass and age)



Kristian, Sandage and Westphal 1978

THE LAW OF RED-SHIFTS

George Darwin Lecture, delivered by Dr Edwin Hubble on* 1953 *May* 8

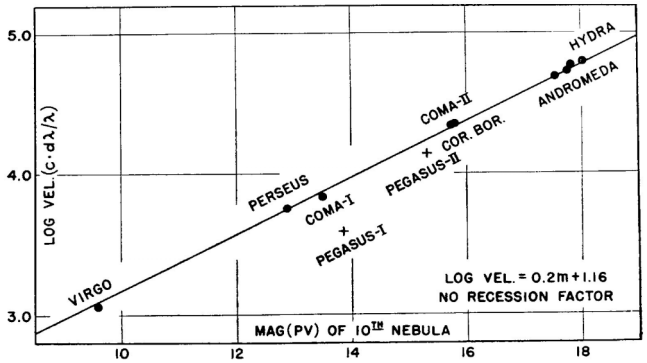


FIG. 1.—*The relation between velocity and apparent magnitude. The new data obtained with the 200-inch are represented by the last four points on the regression line. Humason's red-shifts are expressed on a scale of velocities as c . dλ/λ in km/sec. The photovisual magnitudes have been corrected for the energy effect only. They do not include the recession factor.*

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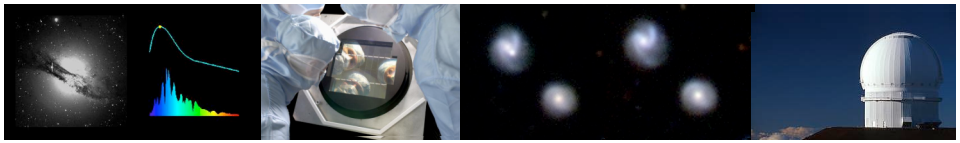
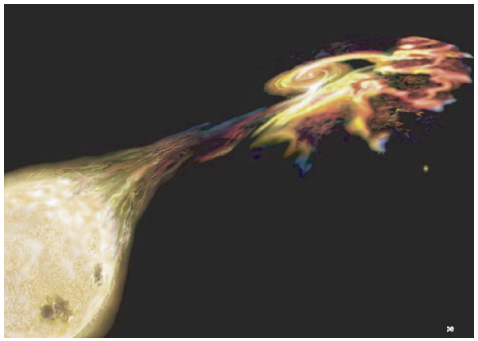
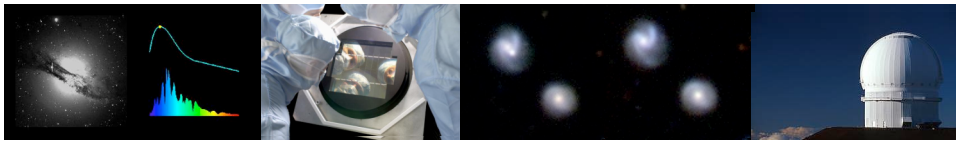


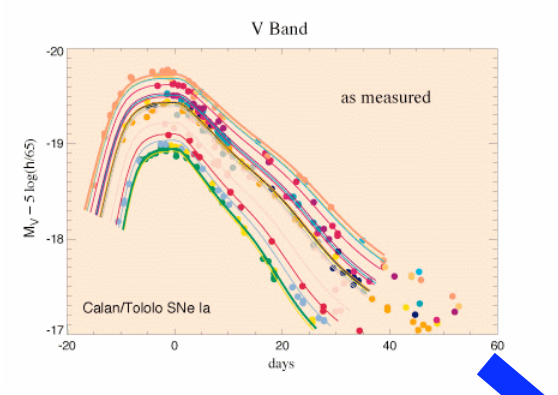


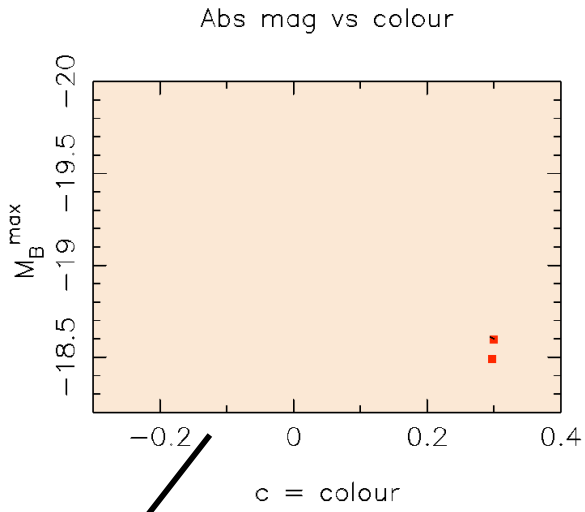
- *Historical Background*
- *Supernova Cosmology*
- **SNLS**
- **Other SN Science**
- **Conclusions/Future**

www.astro.uvic.ca/~pritchet/SN/A580-2008-II.pdf

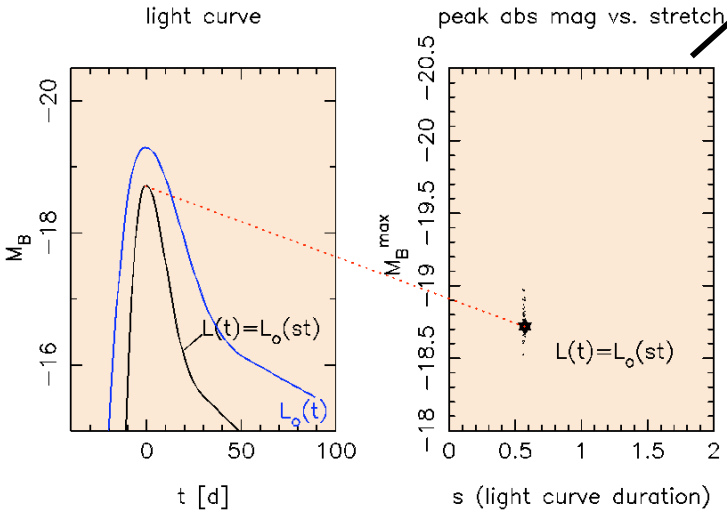


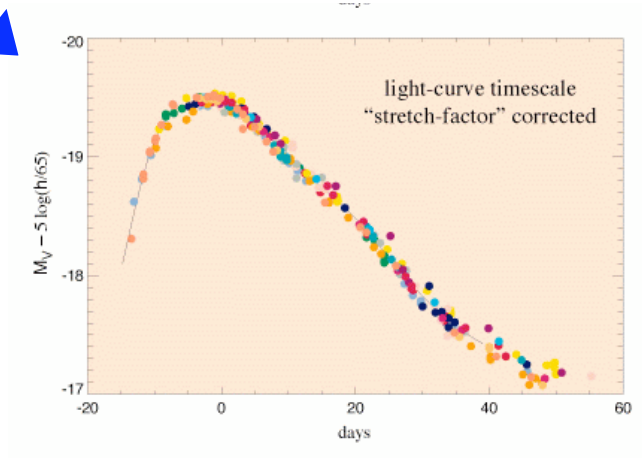
Making a standard candle





$$M_B = M_{B_O} + \alpha(s-1) - \beta c$$





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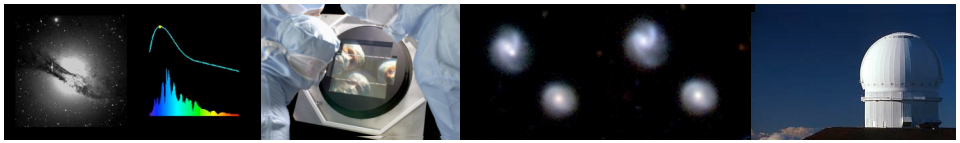
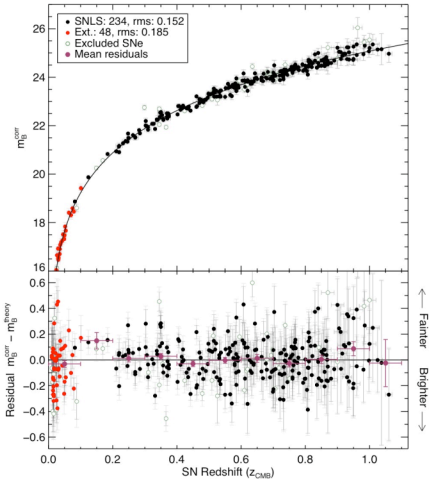
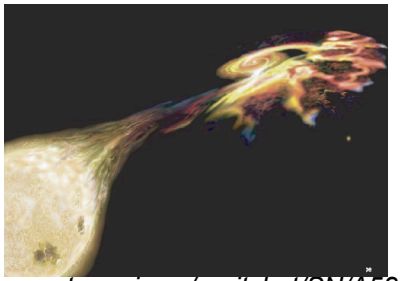


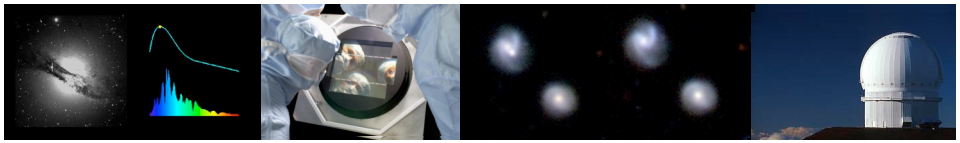
Supernovae as Cosmological Probes





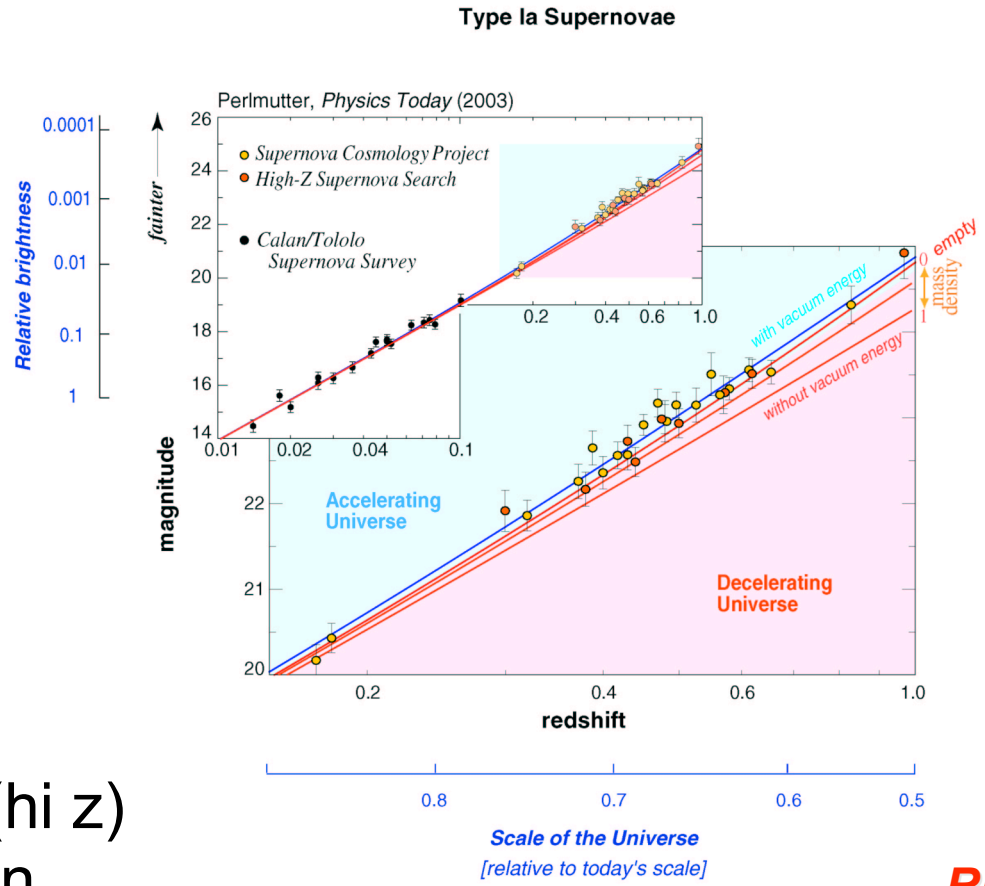
- Bright - seen to cosmological distances
- Max brightness makes an excellent standard candle - ±6% distance errors
- Standard candle has a physical basis
  - SNeIa are "well-understood" - thermonuclear disruptions of C+O white dwarfs - std physics
- *"The supernova distance-redshift relation comes from the FRW metric. DE sound speed, anisotropic stress, matter growth, etc., have no effect."* (Linder 2006)
- Systematics – possibly, but ample opportunity to study with potentially hundreds of objects

www.astro.uvic.ca/~pritchet/SN/A580-2008-II.pdf



Supernovae and Dark Energy

Cosmological constant Λ



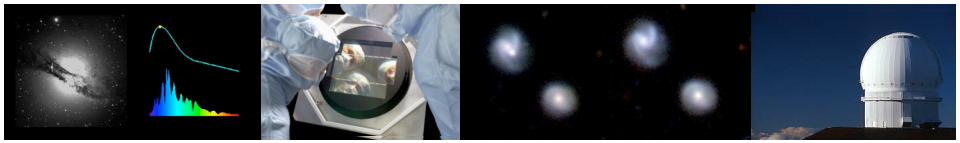
Universe is accel-erating. Λ exists!

Not:

- i/s abs (hi z)
- evolution
- selection effects

Riess et al. 1998
Perlmutter et al. 1999

www.astro.uvic.ca/~pritchet/SN/A580-2008-II.pdf



Supernovae and Dark Energy

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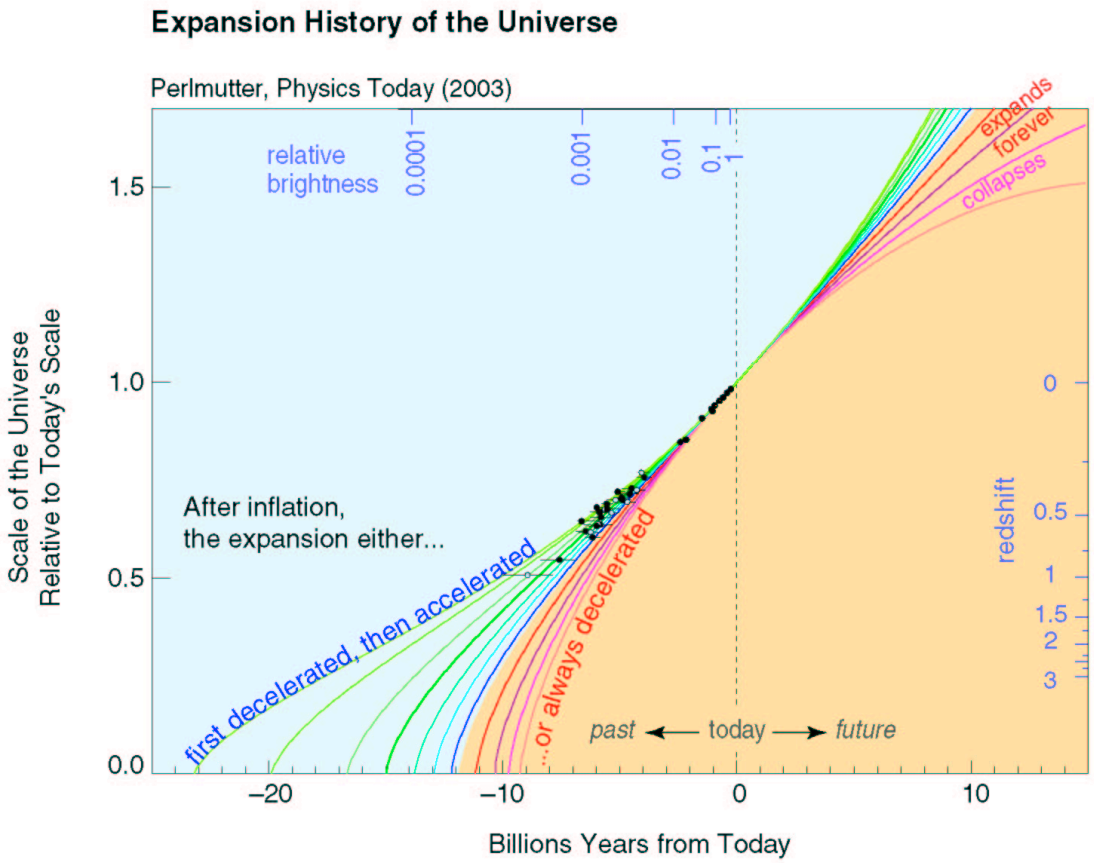
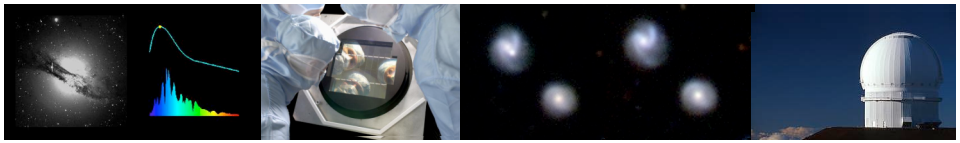
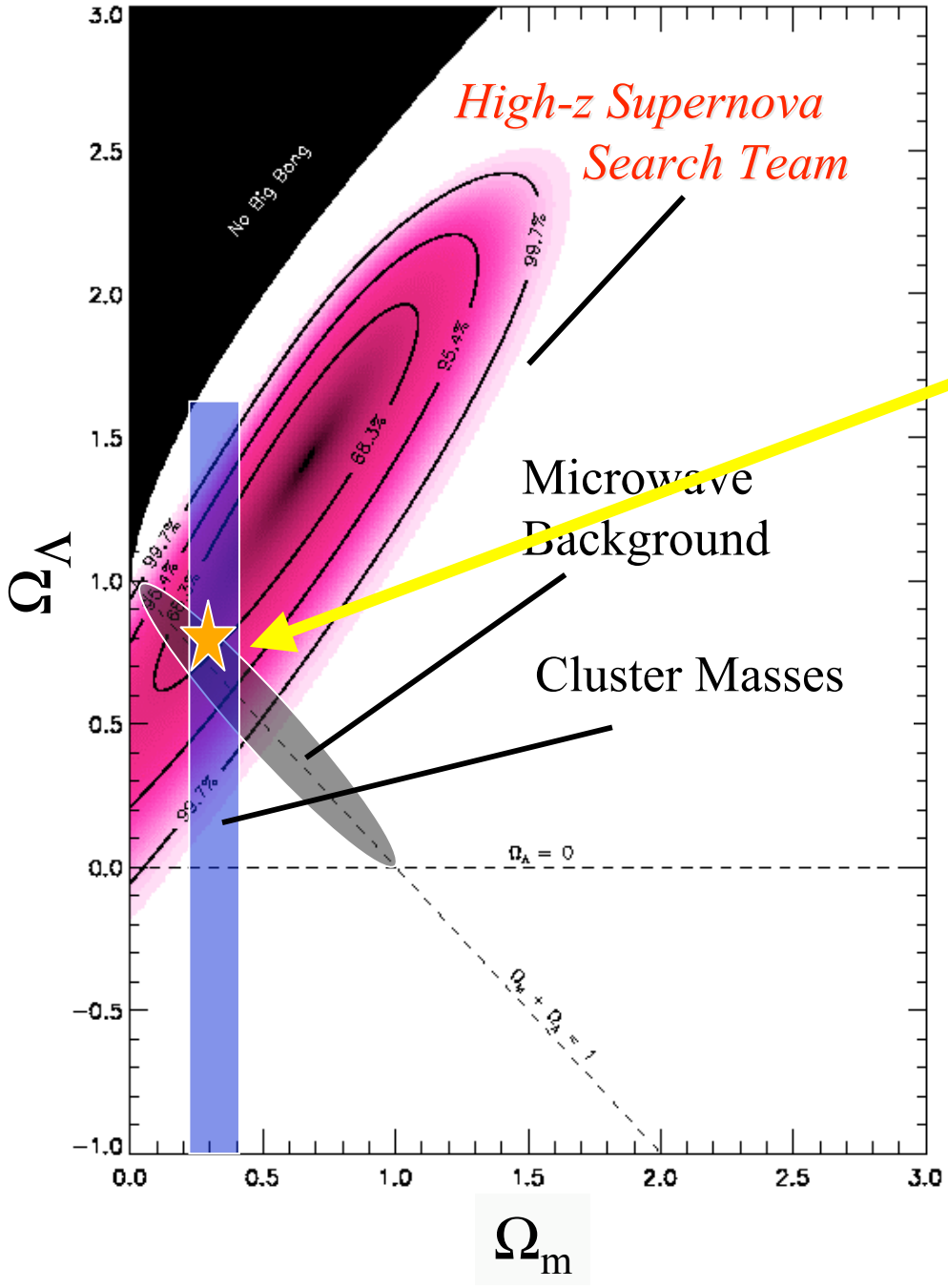


$\Omega_\Lambda = 0.7,$
$\Omega_M = 0.3$

www.astro.uvic.ca/~pritchet/SN/A580-2008-II.pdf





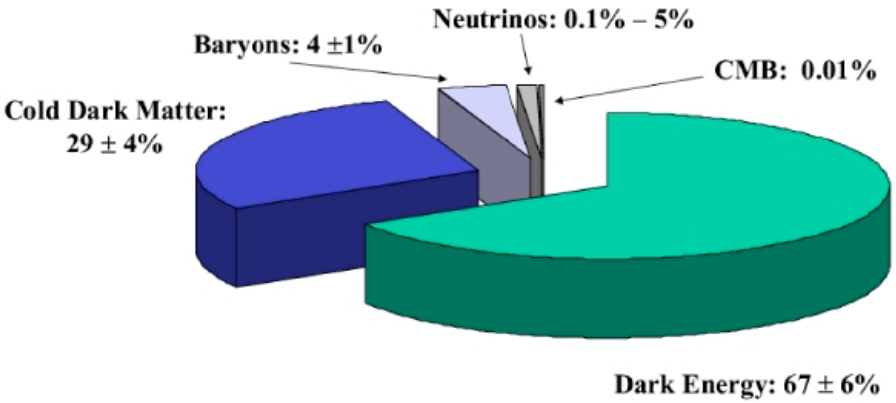
Rate of expansion is accelerating …

$\Omega_\Lambda = 0.7$, $\Omega_{mass} = 0.3$

- **vacuum energy**
- **ρ ≈ const**

Einstein was right!

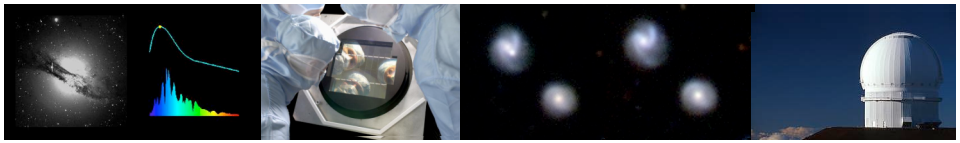
Dark Energy - a Strange Brew …



- Expansion is accelerating
- Vacuum energy, ρ ≈ const
  - Einstein was right!
- $\Omega_{tot}=\Omega_M+\Omega_{DE}=1$

- $\rho_\Lambda \approx 10^{-8}$ eV cm^{-3} $\approx 10^{-120}$ x “theoretical value”
- $\rho_\Lambda \approx \rho_M$ – why??

www.astro.uvic.ca/~pritchet/SN/A580-2008-II.pdf



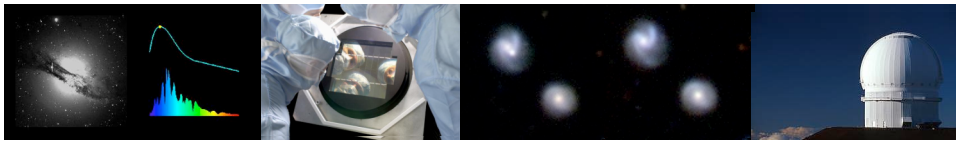
Rocky Horror Show – Tucson 2004

"Our theoretical understanding is so limited right now …" - Rocky Kolb, Tucson, Mar 2004

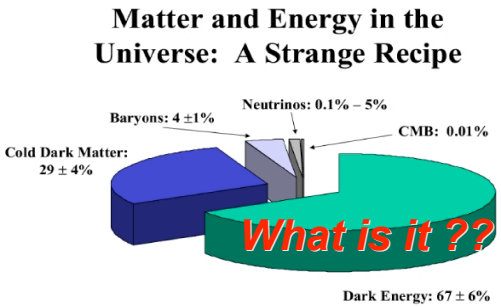
"… DE is not understood sufficiently to answer the basic questions …" - Rocky Kolb, Tucson, Mar 2004

"On a good day I can think of 3 or 4 plausible candidates for dark matter. The same cannot be said for dark energy." - Rocky Kolb, Tucson, Mar 2004

www.astro.uvic.ca/~pritchet/SN/A580-2008-II.pdf



What is the Dark Energy?

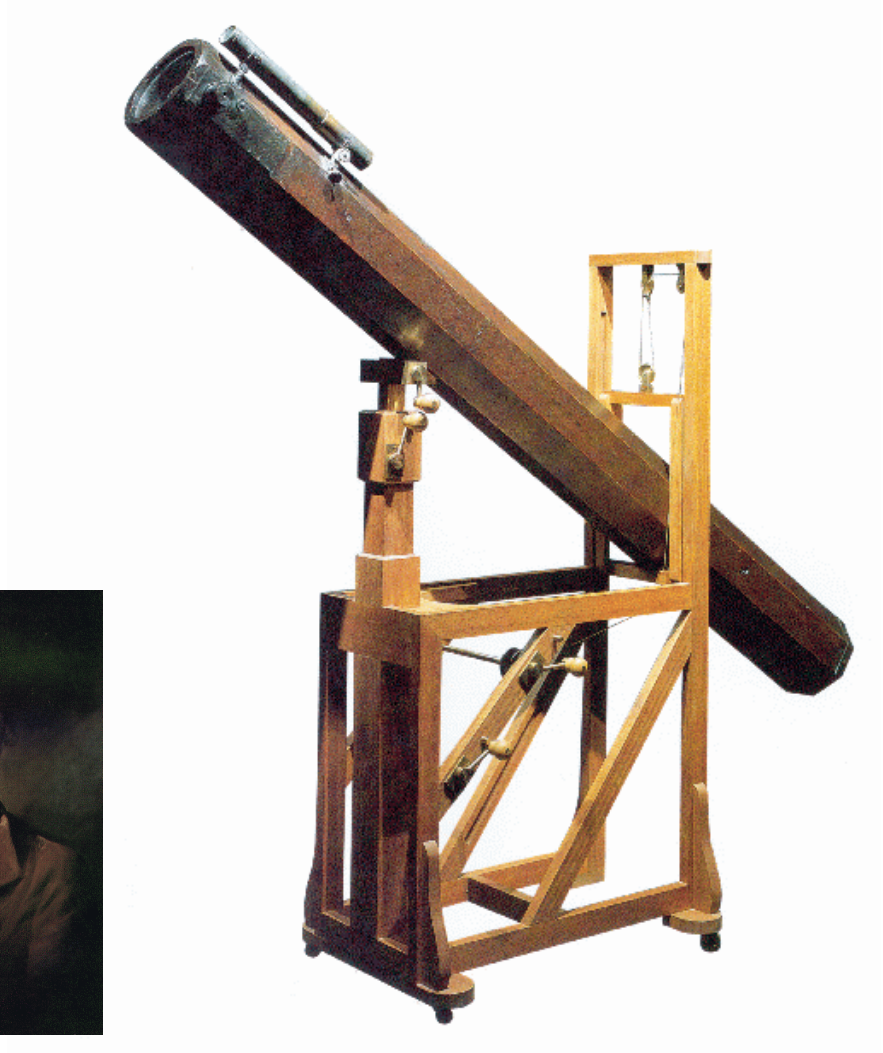


www.astro.uvic.ca/~pritchet/S

Rather than dealing directly with the cosmological constant a number of alternative routes have been proposed which skirt around this thorny issue [4, 5, 6, 7, 8]. They come in a a number of flavors. An incomplete list includes: Quintessence models [9, 10] (see also Refs. [11, 12]) which invoke an evolving canonical scalar field with a potential (effectively providing an inflaton for today) and makes use of the scaling properties [13, 14] and tracker nature [15, 16] of such scalar fields evolving in the presence of other background matter fields; scalar field models where the small mass of the quintessence field is protected by an approximate global symmetry by making the field a pseudo-Nambu-Goldstone boson [17]; Chameleon fields in which the scalar field couples to the baryon energy density and is homogeneous being allowed to vary across space from solar system to cosmological scales [18, 19]; a scalar field with a non-canonical kinetic term, known as K-essence [20, 21, 22] based on earlier work of K-inflation [23]; modified gravity arising out of both string motivated [24] or more generally General Relativity modified [25, 26, 27] actions which both have the effect of introducing large length scale corrections and modifying the late time evolution of the Universe; the feedback of non-linearities into the evolution equations which can significantly change the background evolution and lead to acceleration at late times without introducing any new matter [28]; Chaplygin gases which attempt to unify dark energy and dark matter under one umbrella by allowing for a fluid with an equation of state which evolves between the two [29, 30, 31]; tachyons [32, 33] arising in string theory [34]; the same scalar field responsible for both inflation in the early Universe and again today, known as Quintessential inflation [35]; the possibility of a network of frustrated topological defects forcing the universe into a period of accelerated expansion today [36]; Phantom Dark Energy [37] and Ghost Condensates [38, 39]; de-Sitter vacua with the flux compactifications in string theory [40]; the String Landscape arising from the multiple numbers of vacua that exist when the string moduli are made stable as non-abelian fluxes are turned on [41]; the Cyclic Universe [42]; causal sets in the context of Quantum Gravity [43]; direct anthropic arguments [44, 45, 46, 47], all of these are more or less exotic solutions to the dark energy question.

Copeland et al astro-ph/ 0603057

Discovery of Uranus 1781



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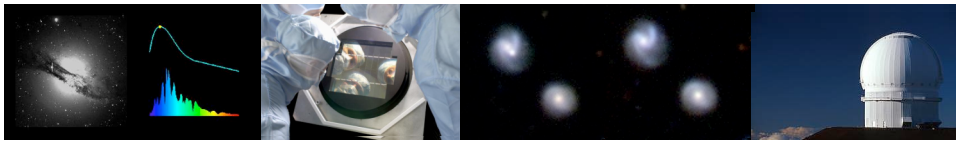
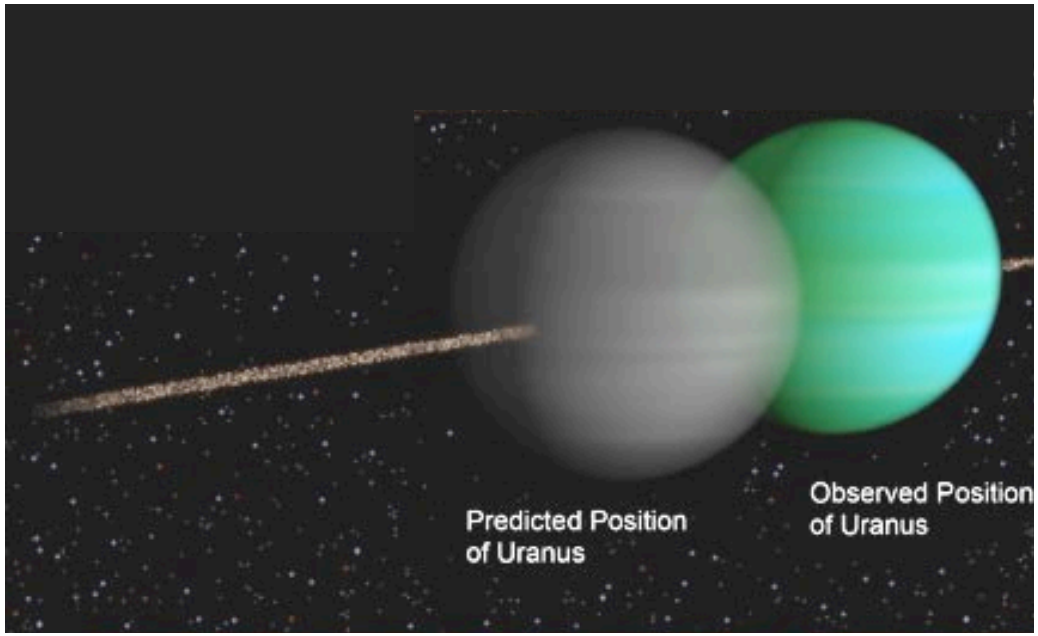
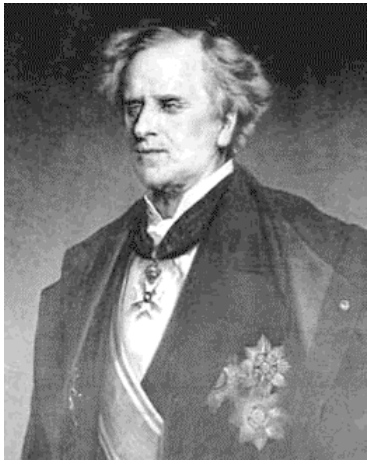


Discovery of Neptune 1846

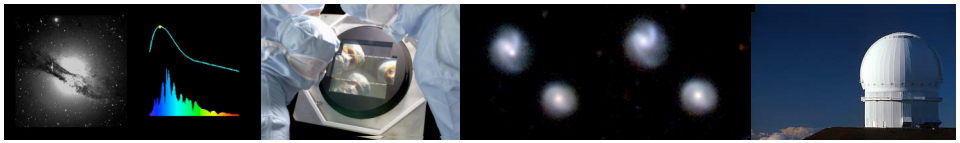
- New physical component?
- New physical law?





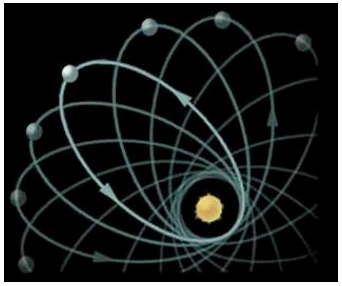
LeVerrier

www.astro.uvic.ca/~pritchet/SN/A580-2008-II.pdf



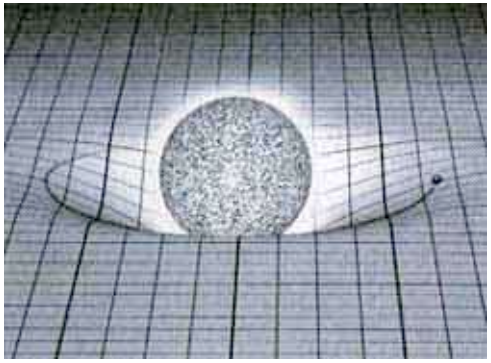
Perihelion advance of Mercury

LeVerrier1859



5600 arcsec/century, of which 43 arcsec/century is unexplained

- New physical component?
  - Vulcan? (LeVerrier!)
  - Solar oblateness (Dicke)
- New physical law?



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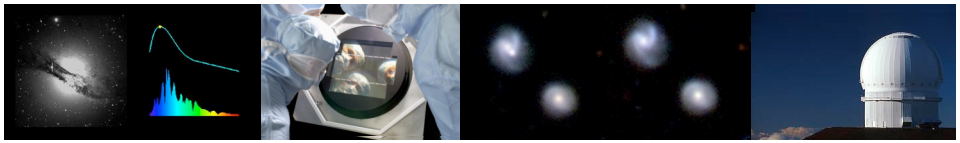
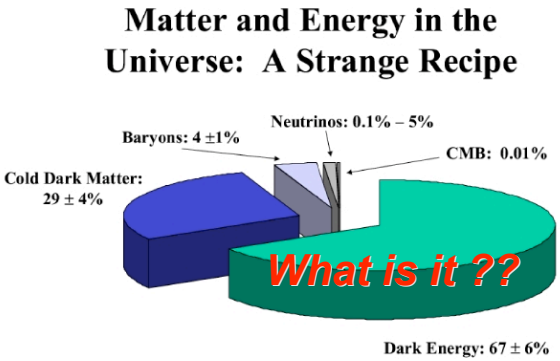


What is the DE?



- Cosmological Constant Λ
  - Pure vacuum energy
- Some other new physical component
  - e.g. scalar field models, quintessence, Chaplygin gas models
- A new physical law
  - e.g. modifications to GR

"Raffiniert is der Herrgott, aber boshaft ist er nicht." (Einstein)

(Einstein's translation: "God is slick, but he ain't mean.")

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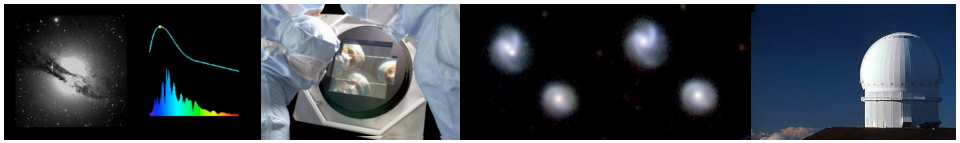
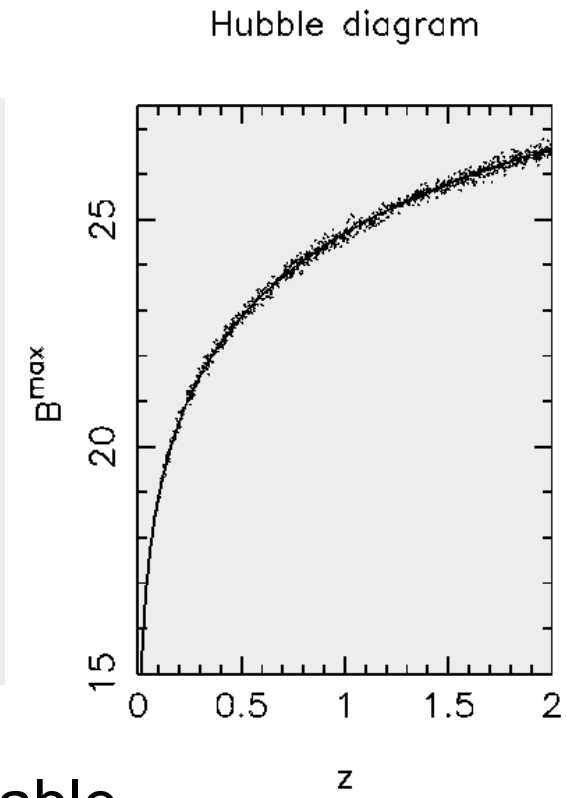


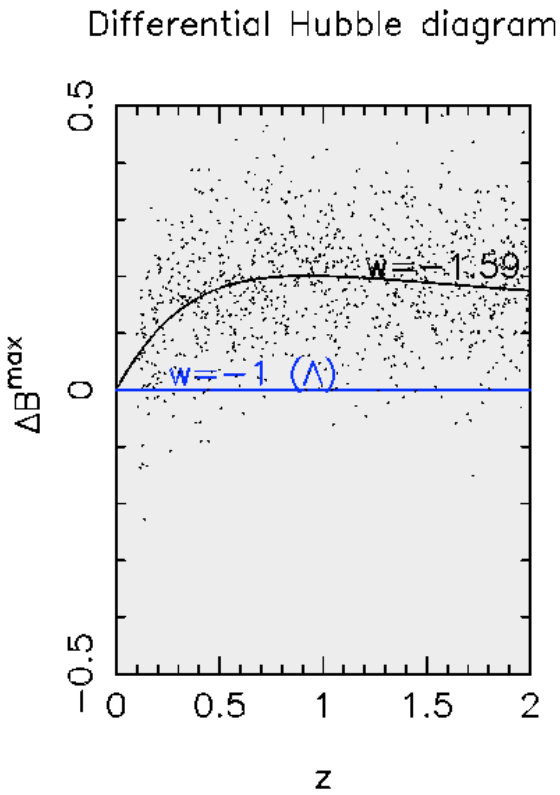
Equation of State Parameter "w"

$$P = w\rho,$$

$$\rho(a) \sim a^{-3(1+w)}$$

w = 1/3 radiation
w = 0 matter
w > -1 "quintessence"
w = -1 Λ





- w is a measurable.
- most sensitivity at z<1.
- w,dw/dz constrain DE.

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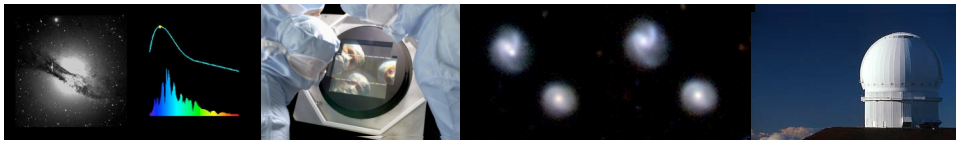

Equation of State Parameter "w"

$$P = w\rho, \quad \rho(a) \sim a^{-3(1+w)}$$

- derive w from Hubble diagram

$$\ell = \frac{L}{4\pi D_L^{\,2}} \;, \quad D_L = D_L(z, w, \Omega_m, \Omega_\Lambda, \Omega_X)$$

$$m = M + 5\log D_L - 5$$

- Most sensitivity at z < 1 (e.g. ground-based telescopes)

- w, dw/dt constrain nature of DE.

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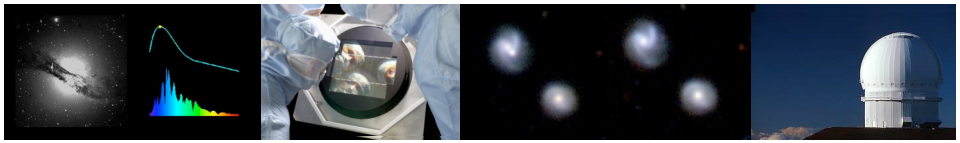
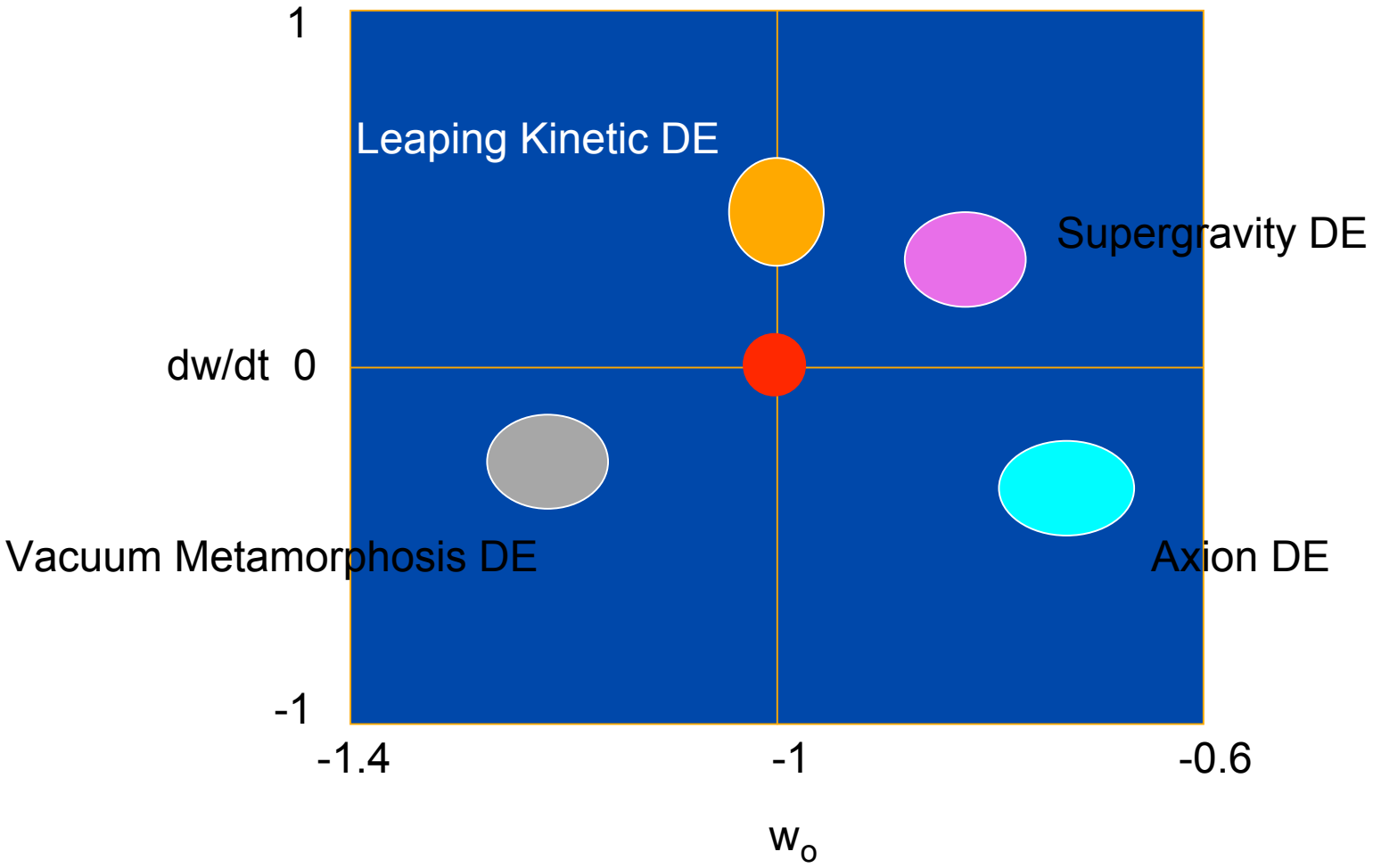


w and dw/dt



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