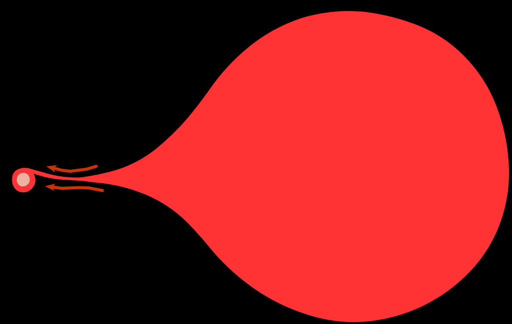
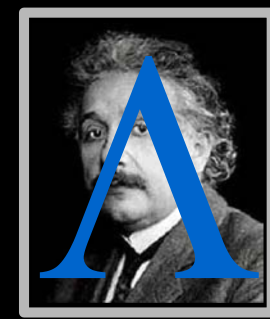
Dark Matter and Dark Energy

An Introduction to the New Cosmology





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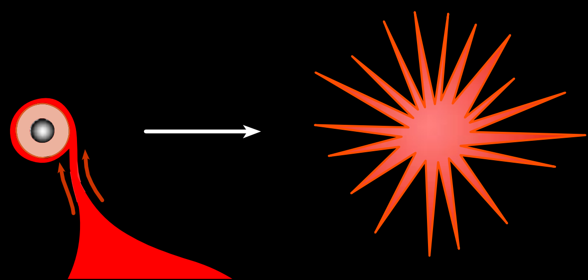
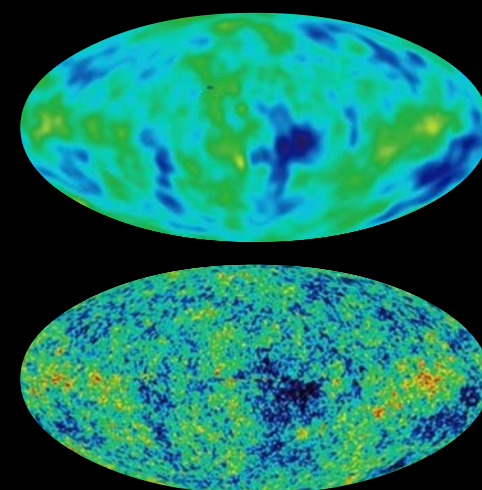




http://eagle.phys.utk.edu/guidry/seminars/darkStuff/index.html

Cosmology

Cosmology asks the big questions:

- What is the overall structure of the Universe?
- What is its past and what will be its future?
- What mathematical principles govern space and time?

The Fundamental Theoretical Idea:

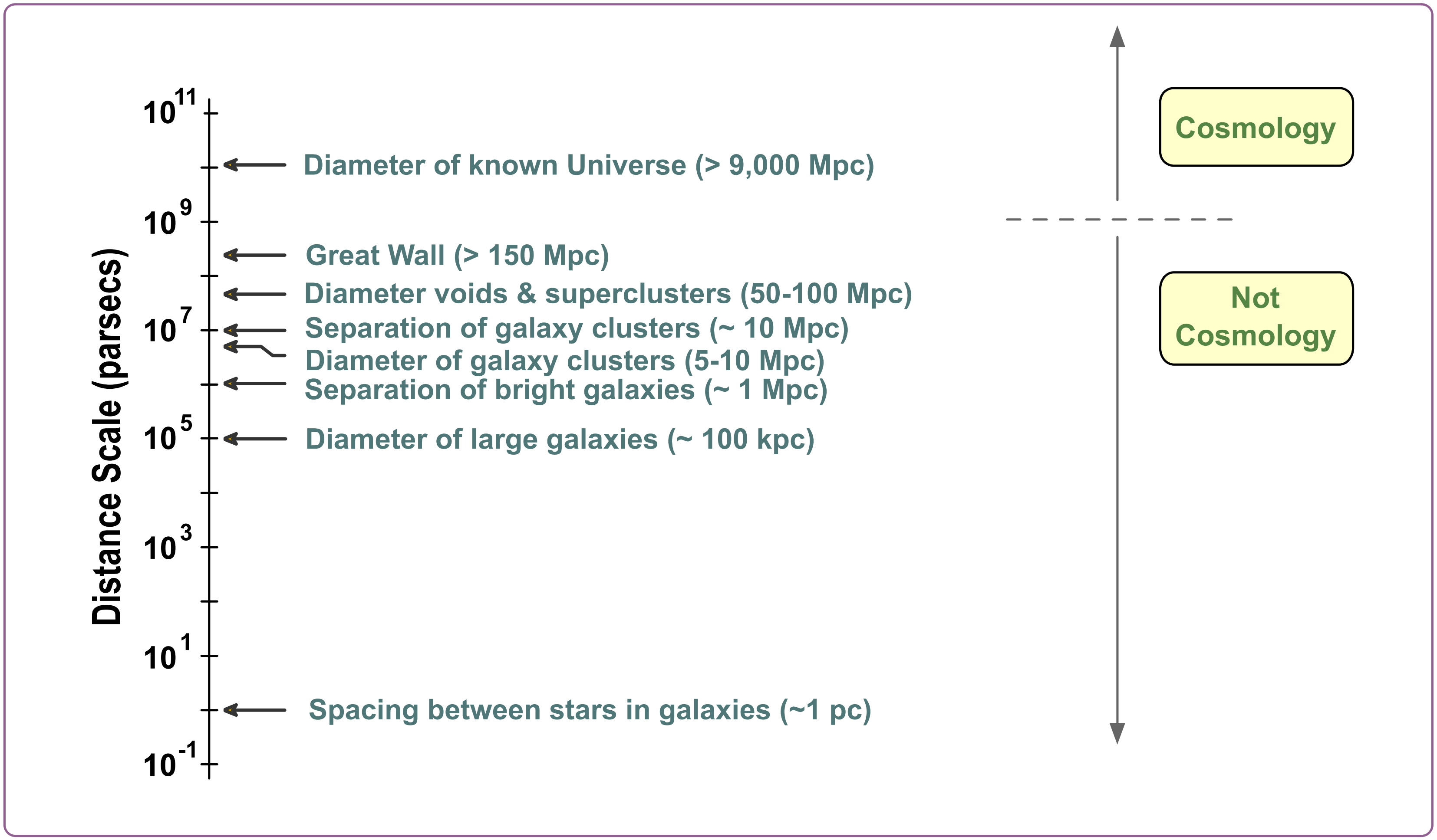
Evolution of the Universe is governed by the *General Theory of Relativity* and the *Cosmological Principle:*

> *Viewed on sufficiently large distance scales, there are no preferred directions (isotropy) or preferred places (homogeneity) in the Universe.*

The Fundamental Observation:

The Universe is expanding

Cosmological Distance Scales



1 parsec (pc) = 3.26 lightyears   1 kiloparsec (kpc) = 1000 parsecs

1 megaparsec (Mpc) = 1,000,000 parsecs

The Einstein (Friedmann) Equations

$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$ (Einstein equations)

$R^{\sigma}_{\mu\nu\lambda}$ = *Riemann curvature tensor* (covariant measure of 4D curvature in locally Minkowski space; generalizes Gaussian curvature in 2D)

$R_{\mu\nu} = g^{\lambda\sigma} R_{\lambda\mu\sigma\nu}$ (Ricci tensor)

$R = g^{\mu\nu} R_{\mu\nu}$ (Ricci scalar)

Λ = scalar (Cosmological constant)

$T_{\mu\nu} = (\varepsilon + P) u_\mu u_\nu - P g_{\mu\nu}$ (Stress-Energy tensor: general form)

The Friedmann-Robertson-Walker Metric

Mathematical statement of homogeneity and isotropy:

$$ds^2 = -dt^2 + a(t)^2\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta\, d\phi^2\right) \quad \text{(Line element)}$$

$$k = \begin{cases} +1 & \text{(positive curvature)} \\ 0 & \text{(flat)} \\ -1 & \text{(negative curvature)} \end{cases}$$

$$ds^2 = g_{\mu\nu}\, dx^\mu dx^\nu$$

The *scale factor a(t)* contains *ALL* cosmological time dependence.

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \longrightarrow g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & \frac{a^2}{1-kr^2} & 0 & 0 \\ 0 & 0 & a^2r^2 & 0 \\ 0 & 0 & 0 & a^2r^2\sin^2\theta \end{pmatrix}$$

(Minkowski metric) (FRW metric)

$$T_{\mu\nu} = T_{\mu\mu} = (P + \rho)u_\mu u_\mu - P g_{\mu\mu} \quad \text{(Stress-energy for FRW metric)}$$

The Equation of State for the Universe

Omitting the cosmological constant (its effect can be absorbed into $T_{\mu\nu}$), the Friedmann (Einstein) equations are

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \qquad \text{(evolution of } a\text{)}$$

$$\frac{\dot{\rho}}{\rho} + 3\left(1 + \frac{P}{\rho}\right)\frac{\dot{a}}{a} = 0 \qquad \text{(conserve } p^{\mu}\text{)}$$

Two equations in three unknowns

$$P = P(\rho) = P(\varepsilon) \qquad \text{(Equation of state)}$$

Since the cosmic fluid is low density, assume equation of state

$$P = w\varepsilon$$

The adiabatic sound speed c_s is given by

$$c_s^2 = \frac{dP}{d\varepsilon}c^2$$

Thus, requiring that $c_s < c$ implies that $w < 1$

The Equation of State for the Universe

Pressure — Energy density

$$P = w\varepsilon$$

w: ???

- w <1 or causality violated: if not so, the speed of sound can exceed the speed of light.

$$c_s^2 = \frac{dP}{d\varepsilon} c^2$$

- For non-relativistic matter, $w = 0$ — $P = 0$
- For relativistic matter, $w = +1/3$ — $P = \varepsilon/3$
- Accelerated expansion requires dominant component with $w < -1/3$
- Cosmological constant gives $w = -1$

$$\ddot{a} = -\frac{4\pi G}{3} a(\varepsilon + 3P)$$
$$= -\frac{4\pi G}{3} a\varepsilon(1 + 3w)$$

Definitions: Dark Matter and Dark Energy

- *Dark matter* is all matter/energy in the Universe that behaves "normally" in that it leads to attractive gravity, but is (so far) not observable by any probe except gravity.

  - Cold (massive) dark matter: $w = 0$

  - Hot (relativistic) dark matter: $w = +1/3$

  The equation of state for dark matter is like that for ordinary forms of matter, but no known elementary particles (or emergent condensates) have the observed properties of dark matter.

- *Dark energy* is any component of the cosmic fluid that has $w < -1/3$.

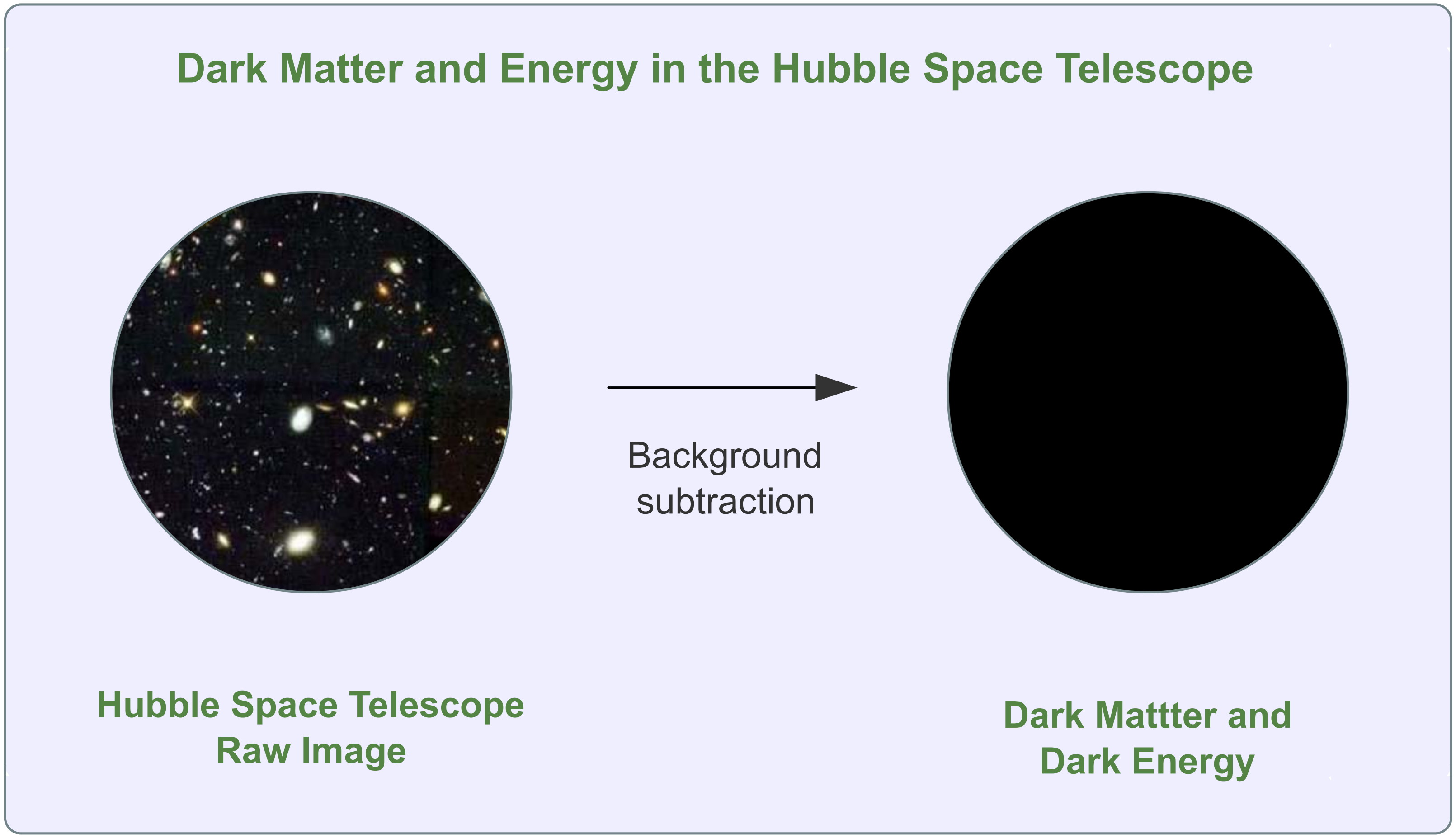
  - This implies an accelerated expansion.

  - Dark energy leads to a *repulsive gravitational force*.

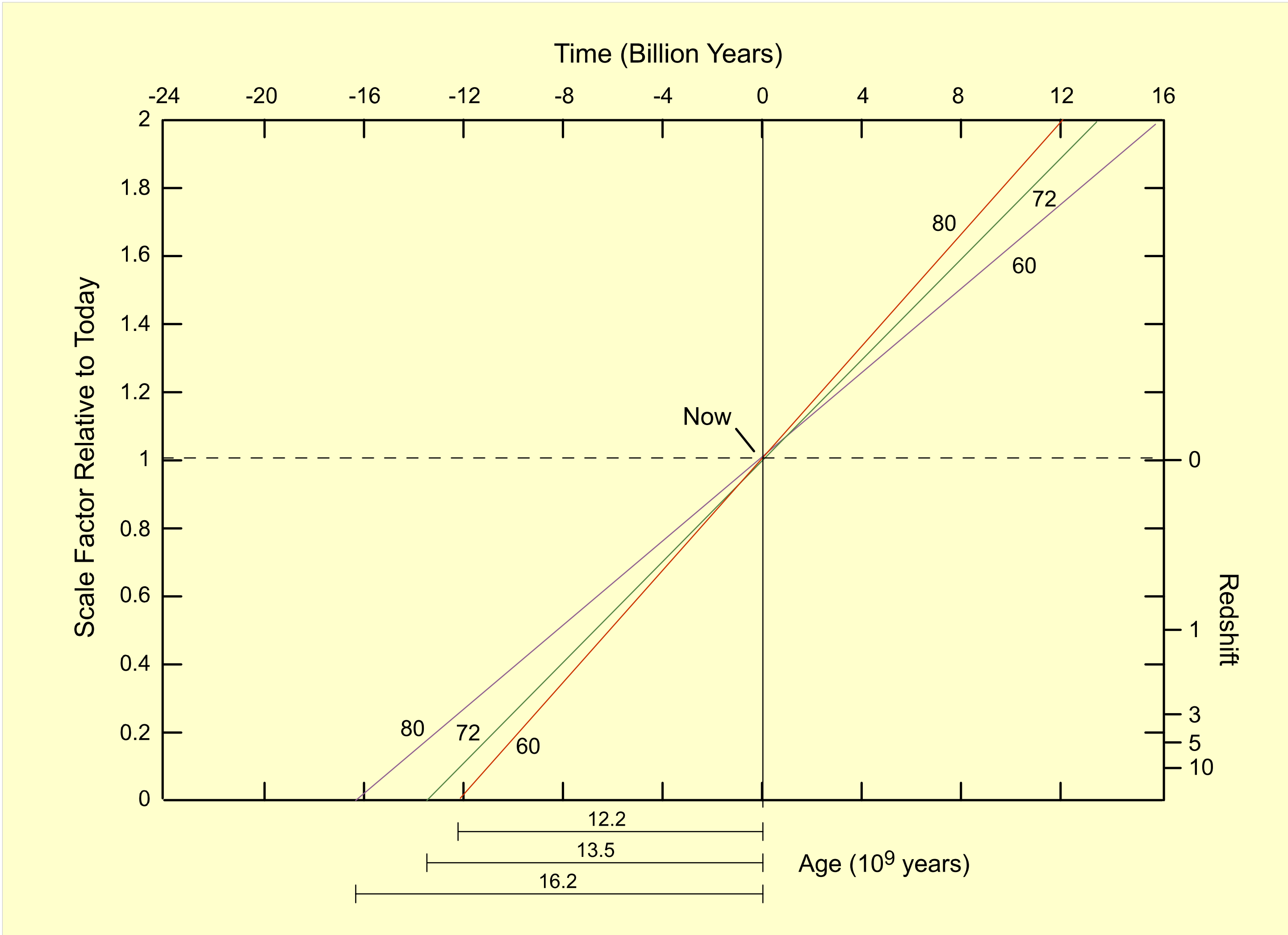
  - Dark energy behaves as a gas with *negative pressure*.

  The equation of state for dark energy is totally unlike anything ever observed in the laboratory. Obviously no known elementary particle or condensate has the properties of dark energy.

A Joke (but Actually It Isn't)

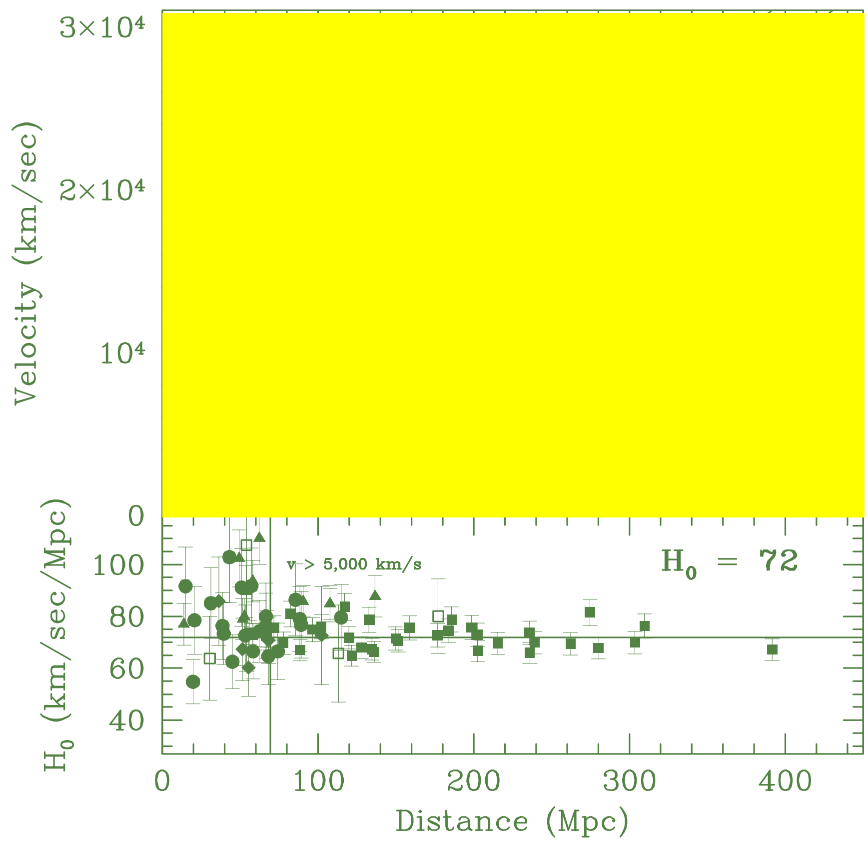


The Expanding Universe and the Hubble Law



Hubble Expander

The Expanding Universe and the Hubble Law

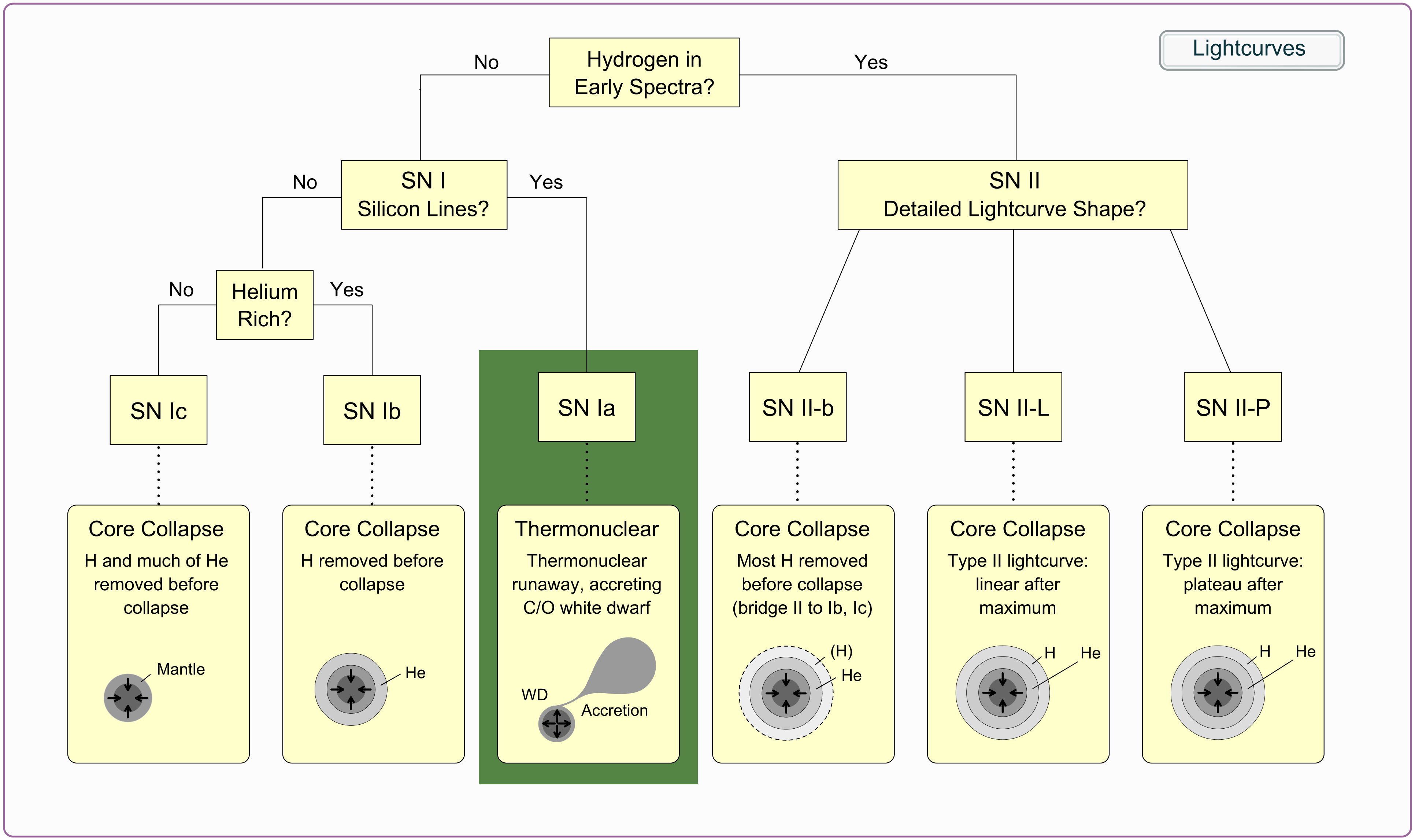


W. Freedman et al, ApJ 553, 47 (2001)

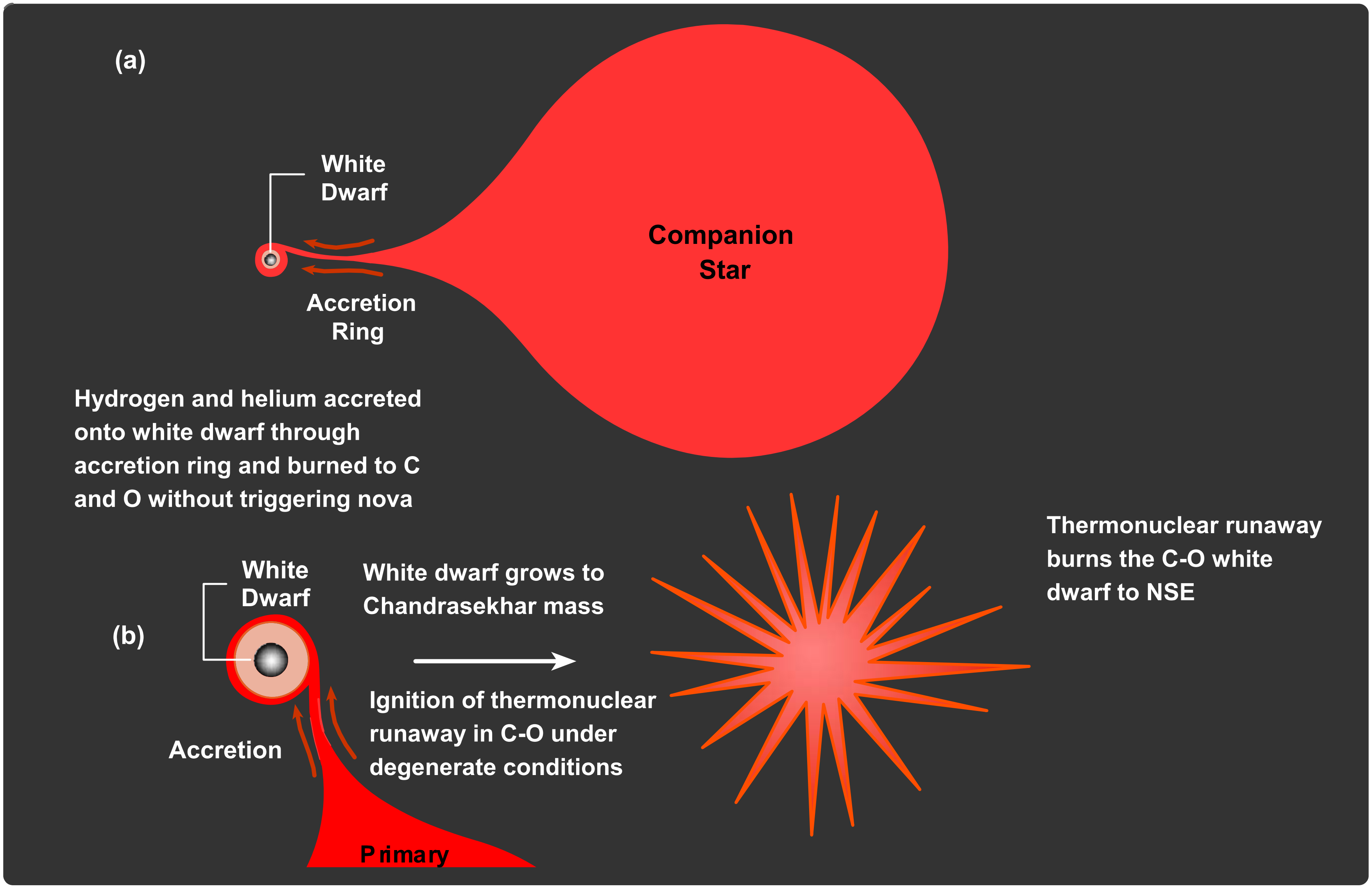
So detailed observations of more nearby galaxies (out to 30-40 Mpc) indicate that the Hubble law is obeyed fairly well.

What about for more distant galaxies? To answer that question, let's consider a seemingly completely different issue: the exploding stars that we call *supernovae.*

Classification of Supernovae



The Type Ia Supernova Mechanism



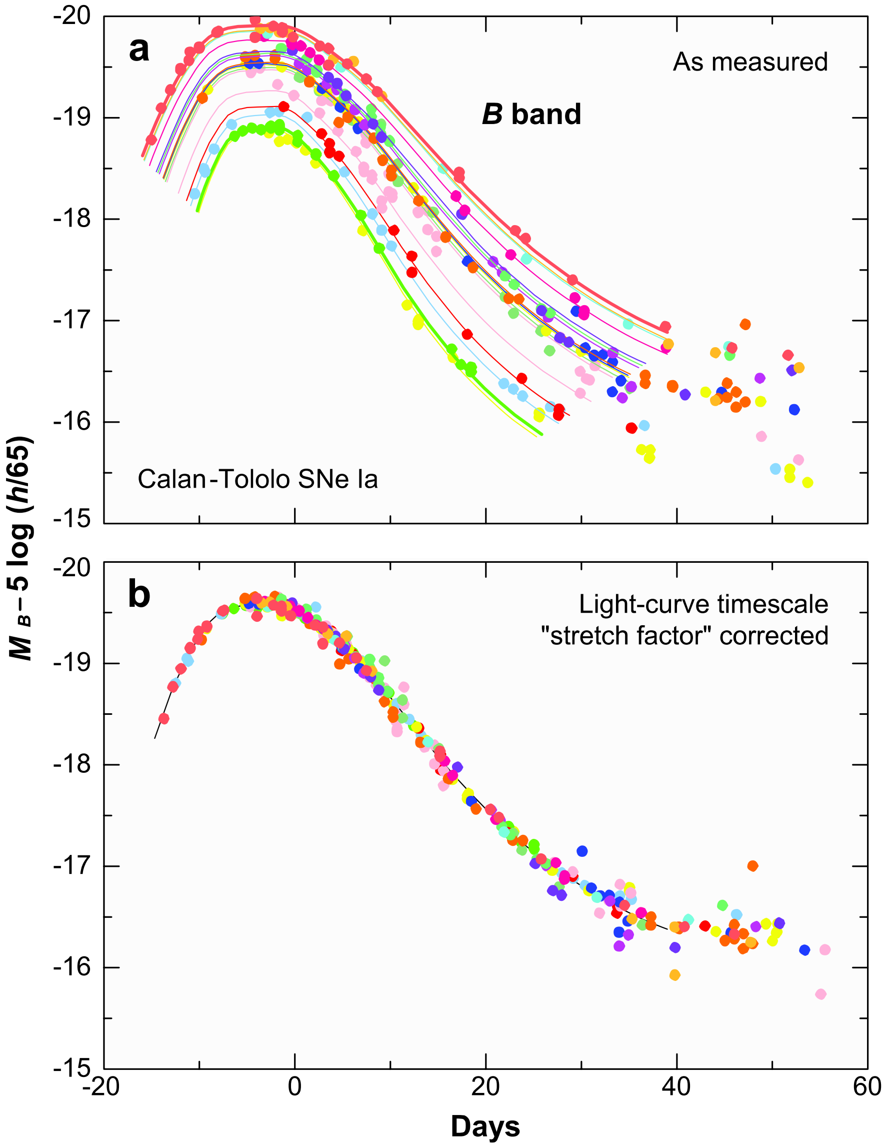
Example: Supernova 1994d

Supernova 1994D

Show Labels

Light Curve

SNIa Standardizable Candles



B-band lightcurves for low-redshift Type Ia supernovae (Calan-Tololo survey; Hamuy, et al, 1996). As measured, the intrinsic scatter is 0.3 mag in peak luminosity. After 1-parameter correction the dispersion is 0.15 mag.

From *Ann. Rev. Astronomy and Astrophysics*, 46, 385 (2008)

Simplified Friedmann Model

- Assume a flat Universe with a current value of the Hubble constant H_0 and three components of the cosmic fluid:

  - Radiation (w = 1/3). Density parameter $\Omega_r = (\varepsilon_{rad}/\varepsilon_{crit})_{today}$
  - Matter (w = 0). Density parameter $\Omega_m = (\varepsilon_{matter}/\varepsilon_{crit})_{today}$
  - Dark (vacuum) energy (w = -1). Density parameter $\Omega_\Lambda = (\varepsilon_{vacuum}/\varepsilon_{crit})_{today}$

- Then the evolution of the Universe is governed by the differential equation

$$\left(\frac{da/dt}{a}\right)^2 = H_0^2(\Omega_r/a^4 + \Omega_m/a^3 + \Omega_\Lambda)$$

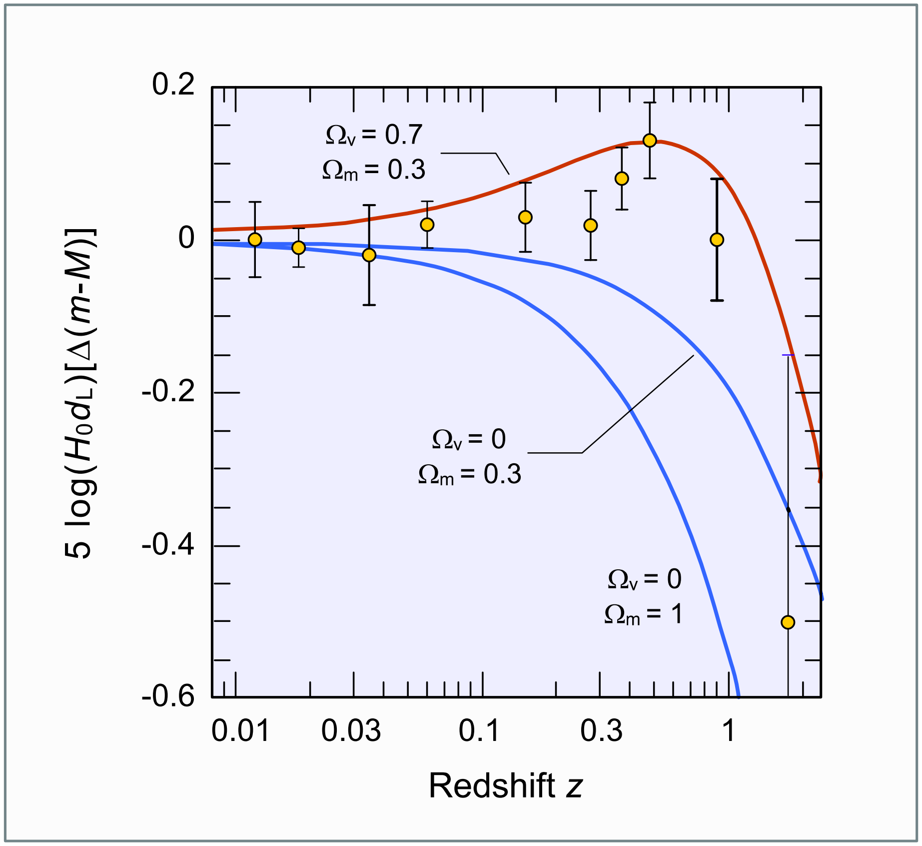
  which describes the evolution of the Universe in terms of 4 parameters: H_0, Ω_r, Ω_m, and Ω_Λ, with

$$\Omega_r + \Omega_m + \Omega_\Lambda = 1$$

- Notice the very different dependence of the contributions for different components on the scale factor a.

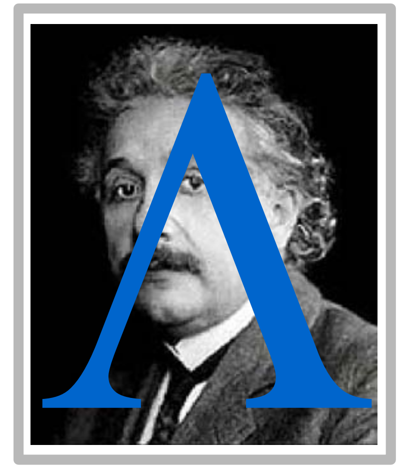
Type Ia Supernovae and Accelerated Expansion

The fundamental observation: Distant Type Ia supernovae are *fainter than they should be* if the Hubble Law were obeyed.



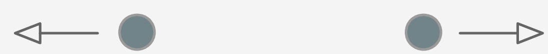
W. Freedman, et al, ApJ **553**, 47 (2001)
J. L.Tonry, et al, ApJ **594**, 1 (2003)

Friedmann Solver



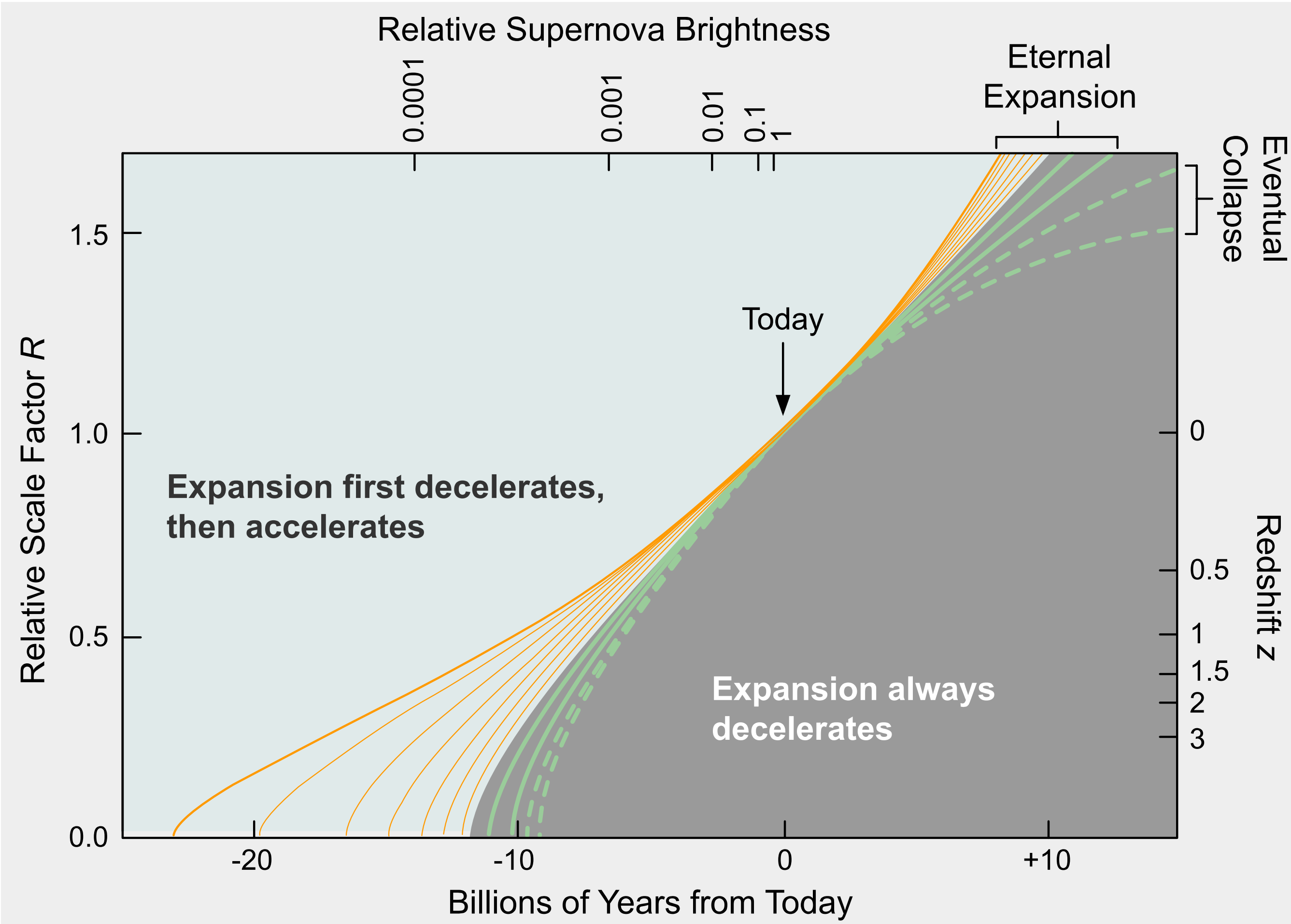
Gravity

Antigravity



(Background of dark energy)

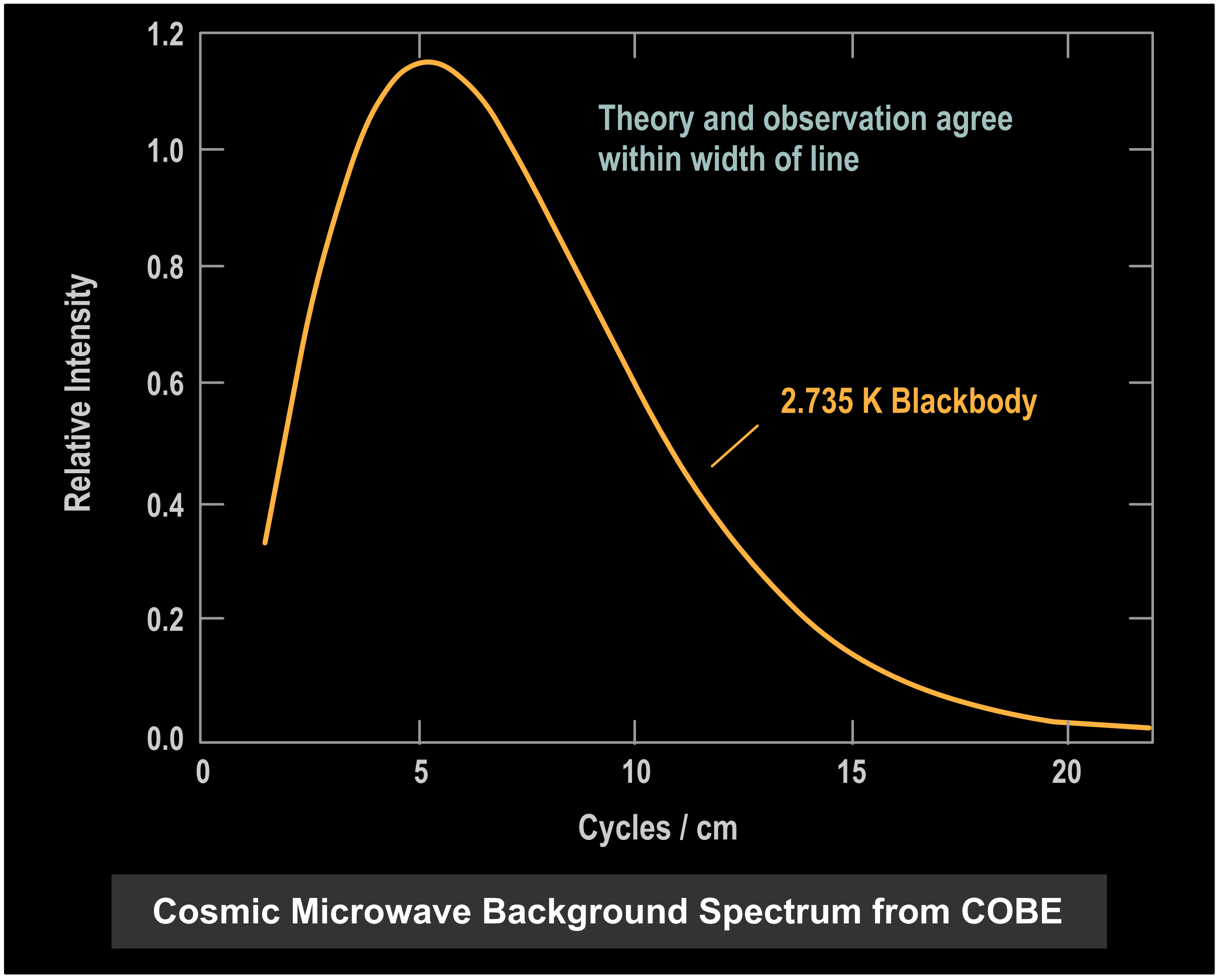
Type Ia Supernovae and Accelerated Expansion



History of Cosmic Expansion from High-Redshift Supernovae

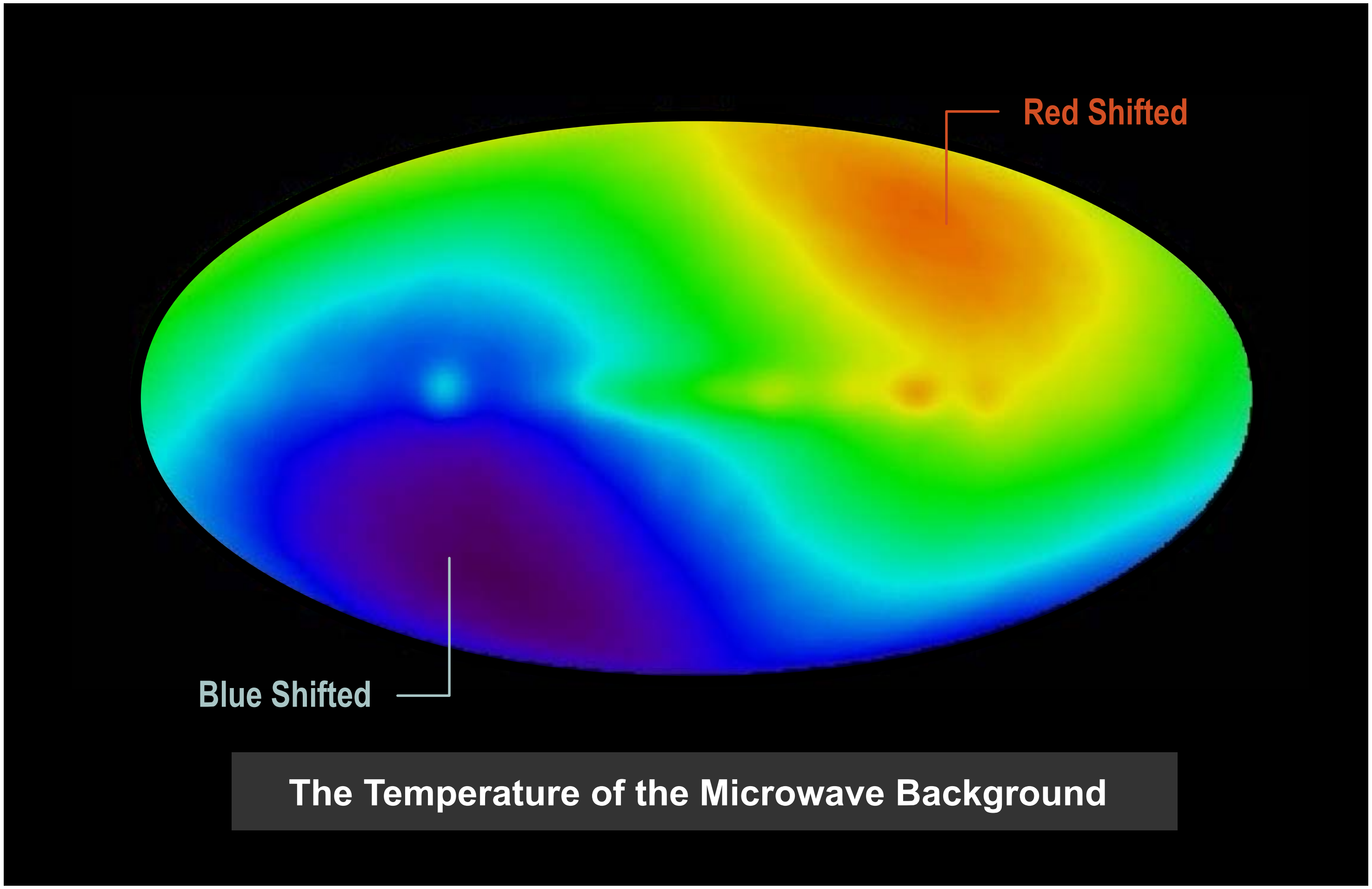
Friedmann Solver

Cosmic Microwave Background (CMB)



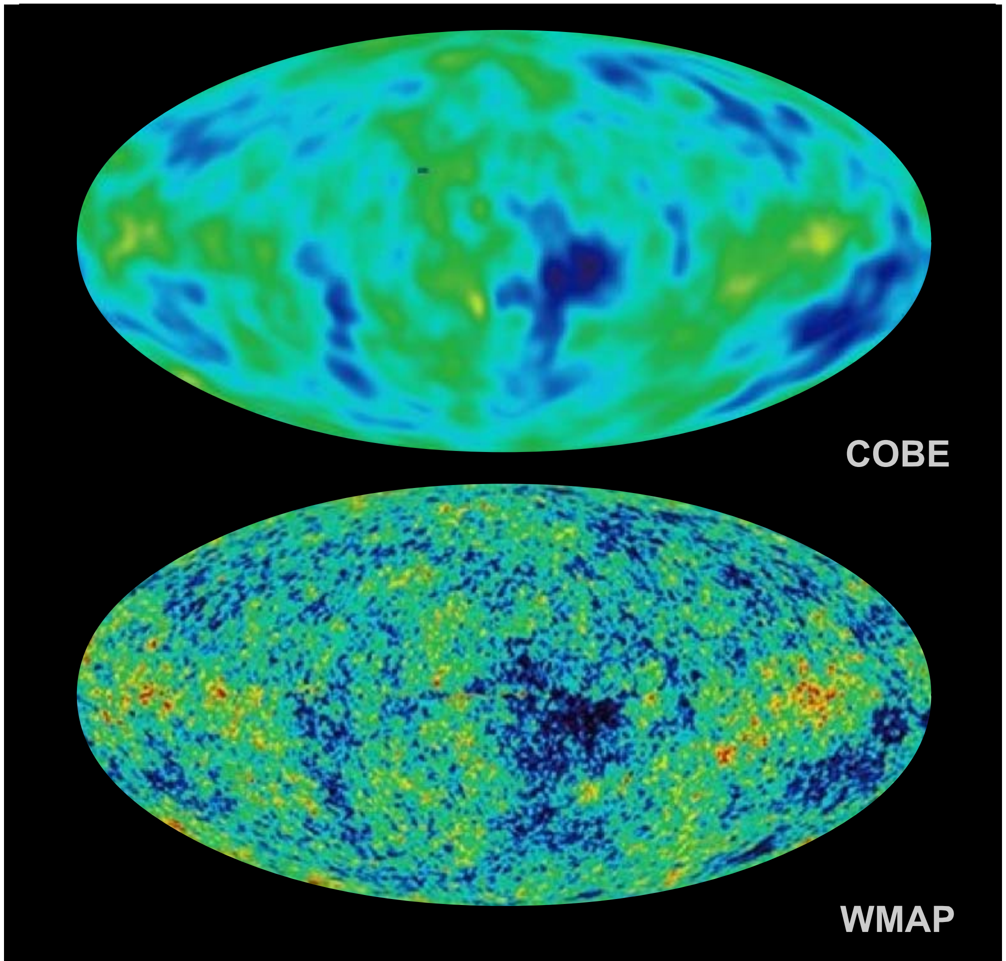
CMB Evolution

Dipole Component of the CMB



Doppler shift of the CMB because of motion of the Earth

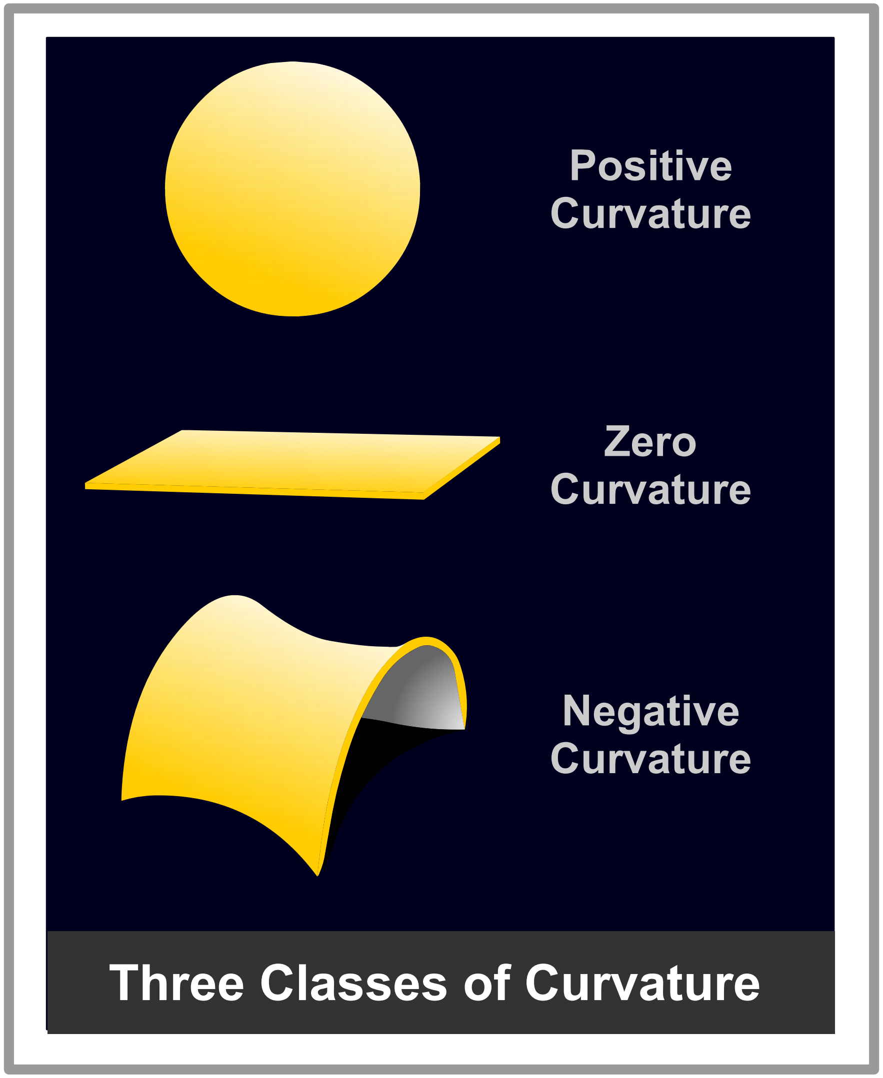
Temperature Fluctuations in the CMB



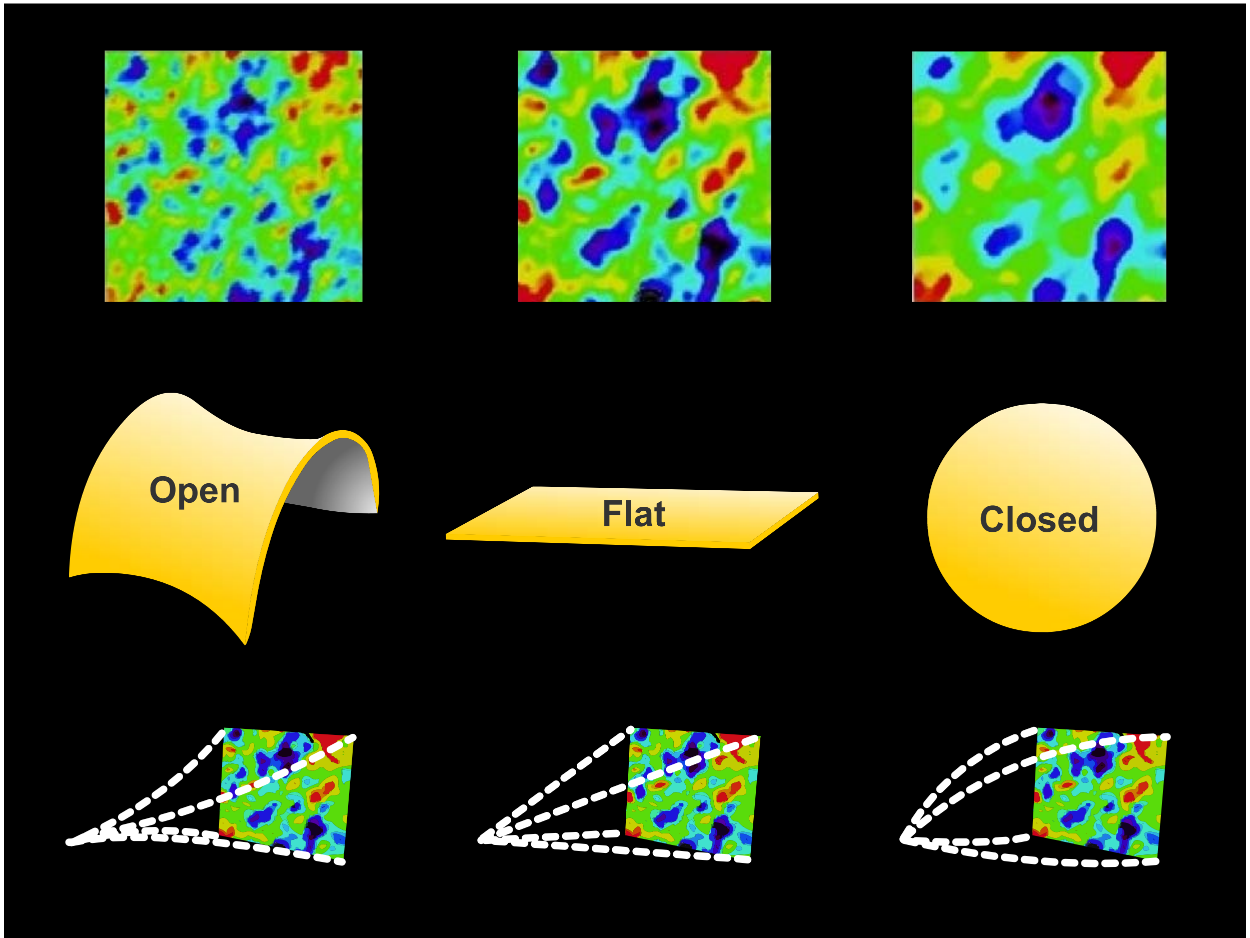
COBE and WMAP Cosmic Microwave Maps

Remarkably uniform but fluctuations at the one part in 100,000 level

The Curvature of Spacetime

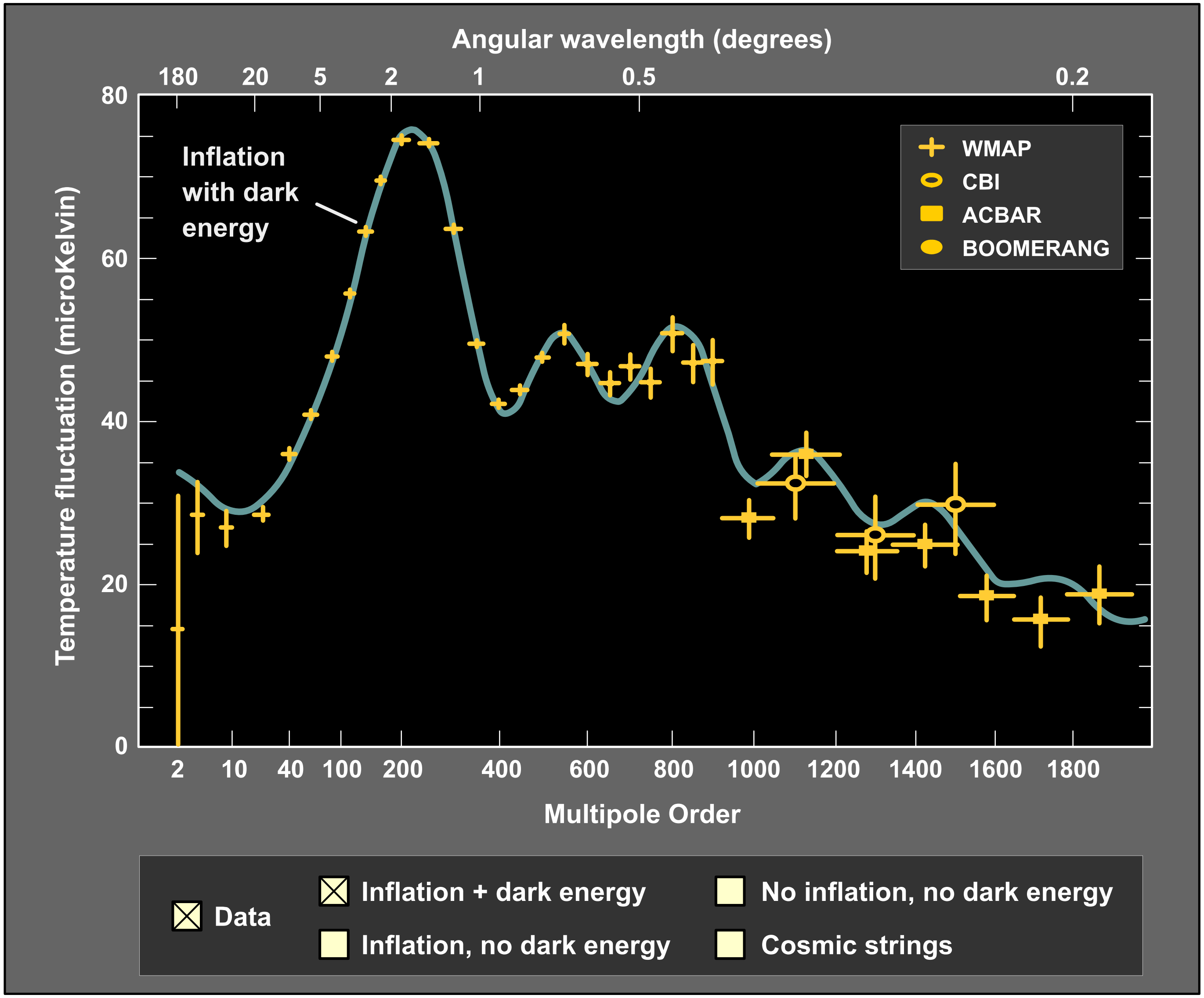


Spacetime Curvature and CMB Fluctuations



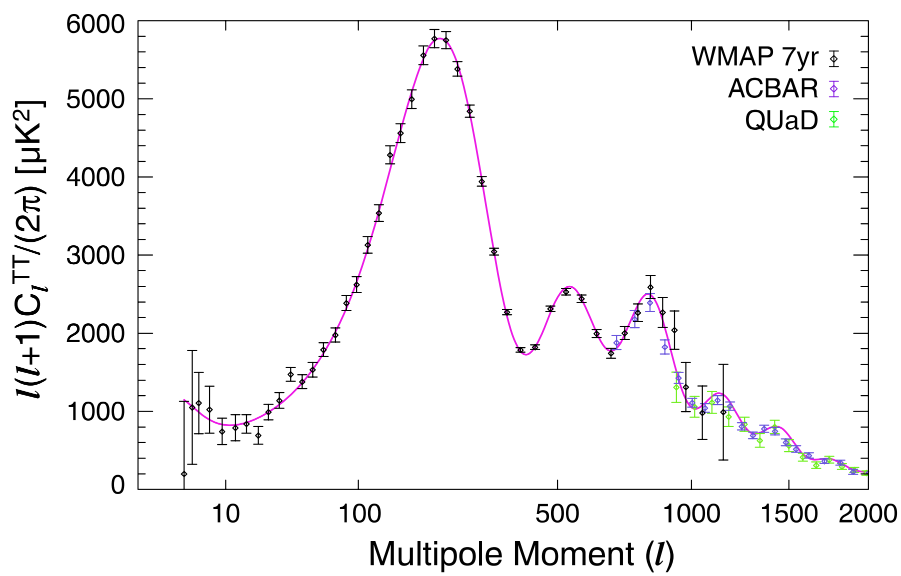
Spacetime Curvature and Microwave Fluctuations

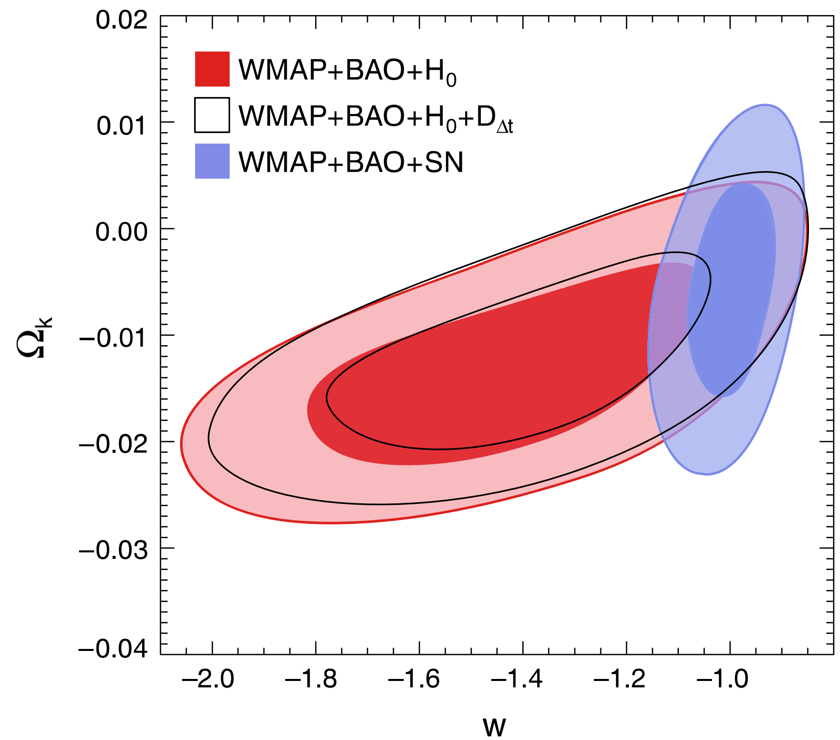
WMAP Evidence for Dark Energy and Inflation



A. H. Guth and D. I. Kalser, Science, 307, 884 (2005)

WMAP 2010 Data Analysis

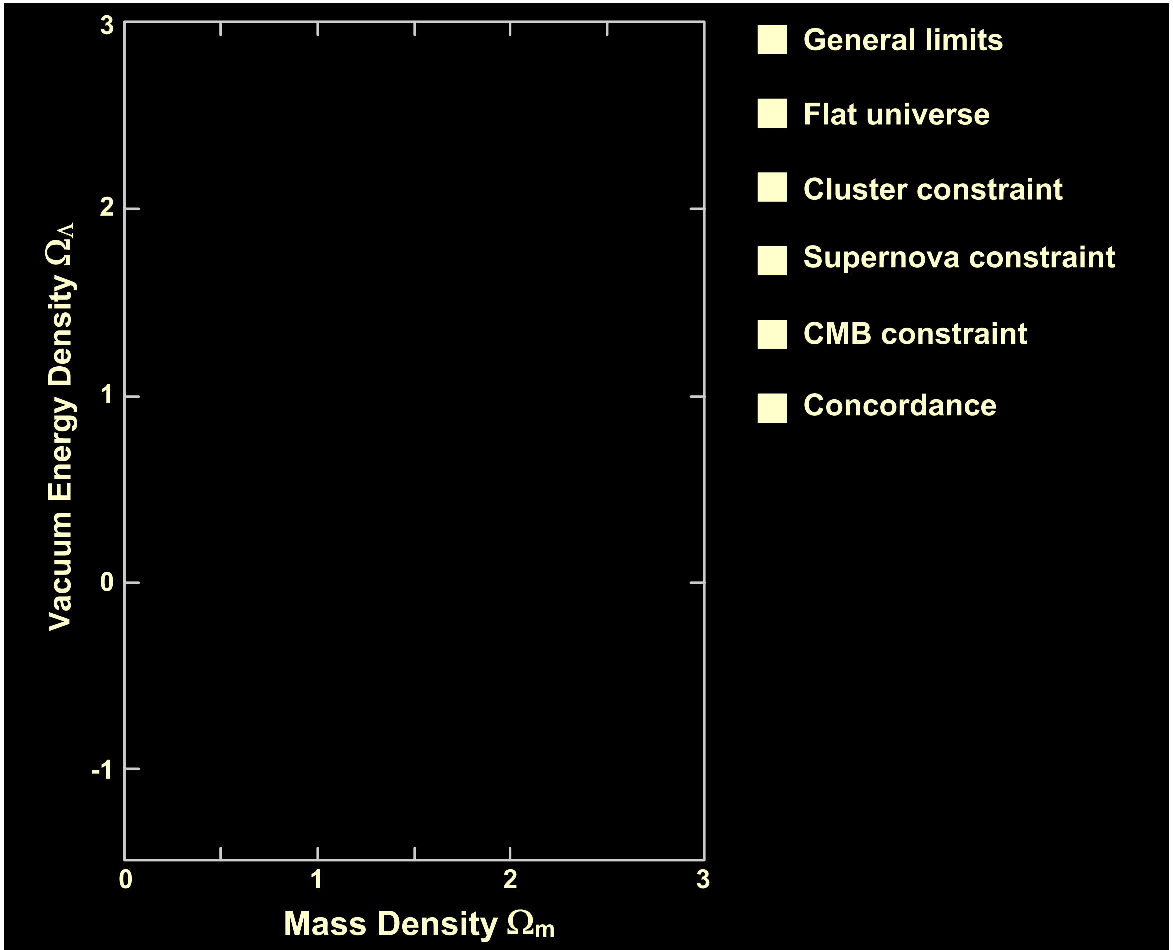




Ω_k measures the curvature density of the Universe. Inflation predicts $\Omega_k = 0$.

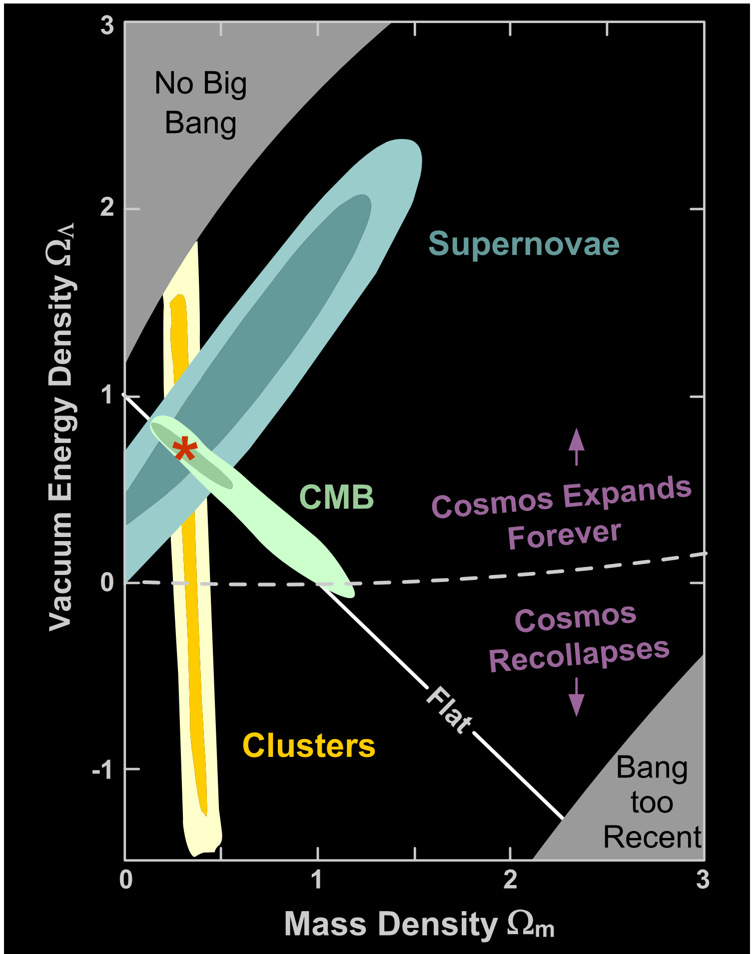
E. Komatsu et al, arXiv 1001.4538 (2010)Astro-ph. *Seven-Year Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation*

The Concordance Model



Vacuum Energy and Mass Density

The Concordance Model



Vacuum Energy and Mass Density

- The Universe is flat (Euclidean), with $\Omega = \Omega_r + \Omega_m + \Omega_\Lambda = 1$. (Inflation)
- Hubble constant $H_0 \sim 72$ km/s/Mpc.
- The energy density of the Universe now in radiation is negligible ($\Omega_r \sim 0$). Earlier it was more important.
- The energy density of the Universe now in matter is about 30% of closure density ($\Omega_m \sim 0.3$). Only a few percent of that matter is normal (baryonic) matter. The rest is dark matter.
- The energy density of the Universe presently in dark energy is about 70% of closure density ($\Omega_\Lambda \sim 0.7$).
- The Universe is flat but will expand forever because of dark energy.

Cosmic Inflation

The big bang has some "problems" (actually, some *assumed but unexplained* initial conditions). These may be cured by a modification of the classical big bang in its first tiny fraction of a second called c*osmic inflation.*

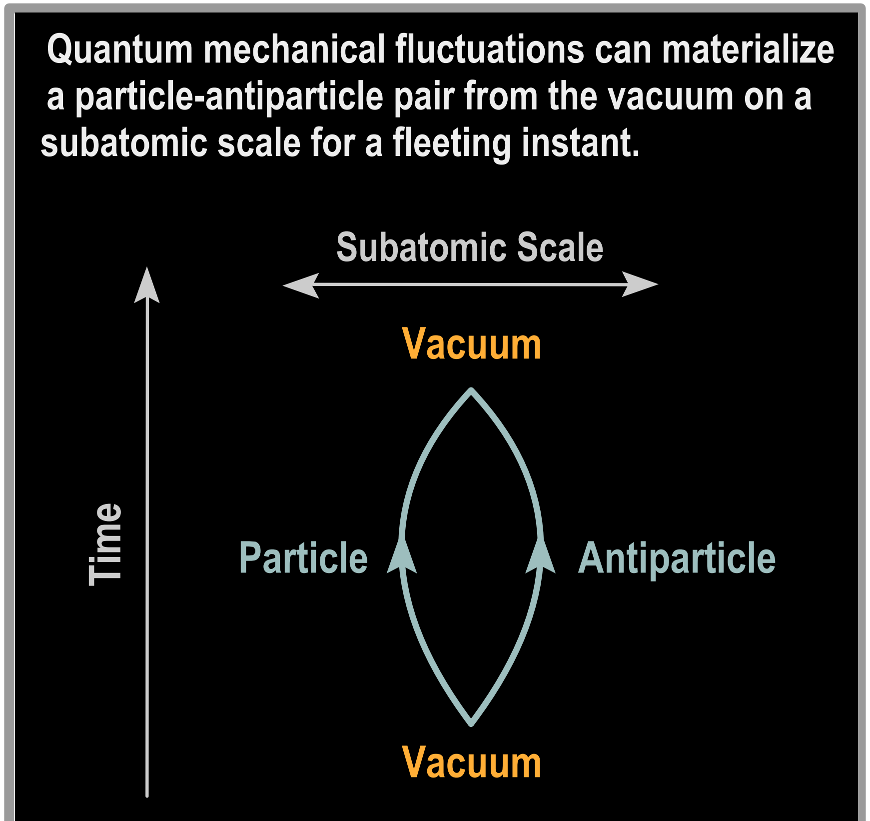
Cosmic Inflation

Inflation and the Origin of Structure

There is a fundamental cosmological problem that only inflation provides a natural explanation for: The remarkable smoothness of the CMB (one part in 100,000) implies that the very early Universe was extremely smooth. *Where then did the density perturbations that lead to stars and galaxies and physicists come from?*

Inflation and the Origin of Structure

Inflation supplies a completely outrageous answer that plausibly gives the spectrum of density perturbations required by observations:



Quantum Vacuum Fluctuations

Microscopic quantum vacuum fluctuations were stretched to astronomical scales by the exponential expansion (!!). Those inhomogeneities eventually became the gravitational seeds for the formation of large-scale structure in the Universe.

What Could Dark Matter Be?

- Large-scale structure properties require that the bulk of dark matter is cold (CDM).
- Cold dark matter could be neutron stars, white dwarfs, black holes, black coffee cups, ... (normal baryonic matter of low luminosity).
- However, the bulk of dark matter appears to be non-baryonic:
  - Observations (where possible) don't give evidence for enough such baryonic objects.
  - Successful description of big-bang nucleosynthesis of light elements limits maximum baryon density to a few percent of dark matter density.
- Known weakly-interacting leptons (neutrinos) can be at most a few percent of the mass of dark matter, and they are hot (very low mass).
- Thus, the bulk of dark matter must be weakly-interacting massive particles (*WIMPs*).
- Most plausible possibility is undiscovered massive particles carrying supersymmetric quantum numbers.

What Could Dark Energy Be?

- There is only one "simple" possibility: dark energy is zero-point energy of the quantum vacuum.
- But we probably don't know how to calculate the vacuum energy correctly.
- The naive integrals are divergent. If we cut them off at the Planck Scale:
  - The calculated vacuum energy density is about 120 orders of magnitude larger than the observed dark energy density.
  - By invoking supersymmetry, the discrepancy can be reduced to a much more respectable 60 orders of magnitude :)
- Alternatives: scalar fields left over from earlier evolution of Universe
  - Inflationary epoch???
  - Strings/branes, higher-dimensional spacetime???

Constraining Theories of Dark Energy

- Observationally, the cosmic fluid seems to have 3 components:

  - Massive particles ("matter"): $w = 0$ ($\Omega_m = 0.30$)

  - Massless particles ("radiation"): $w = +1/3$ ($\Omega_m \sim 0$)

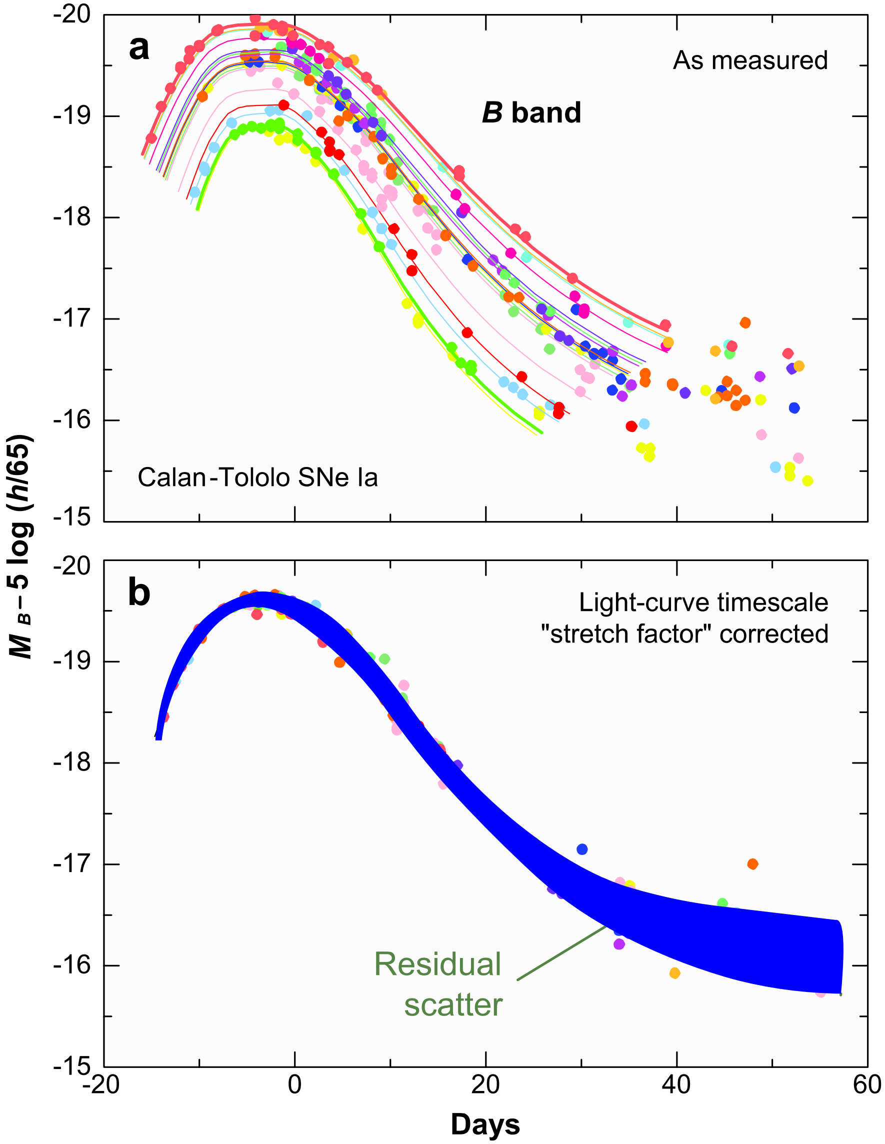
  - "Dark energy": $w < -1/3 = ?$ ($\Omega_m \sim 0.70$)

- The value of *w* for the dark energy could be constrained further if we could improve the precision of the Type Ia standardizable candle methodology:

  - Greater observational precision at deeper redshifts

  - A deeper theoretical understanding of the mechanism for Type Ia supernovae and what governs their (relatively small) differences in luminosity.

Spread in Normalized Type Ia Magnitudes



B-band lightcurves for low-redshift Type Ia supernovae (Calan-Tololo survey; Hamuy, et al, 1996). As measured, the intrinsic scatter is 0.3 mag in peak luminosity. After 1-parameter correction the dispersion is 0.15 mag.

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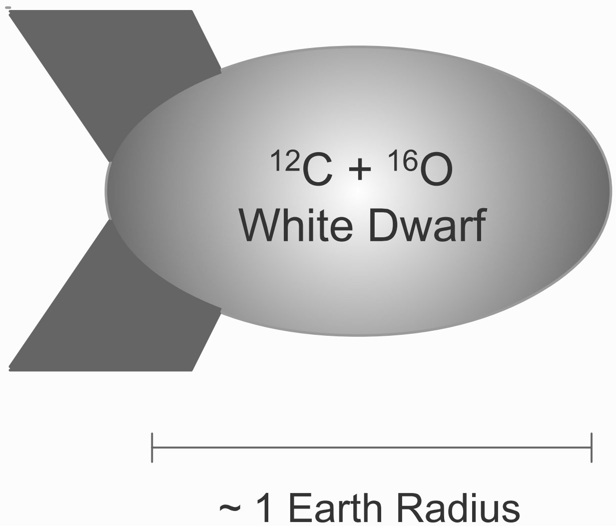
Improved Understanding of the Type Ia Mechanism

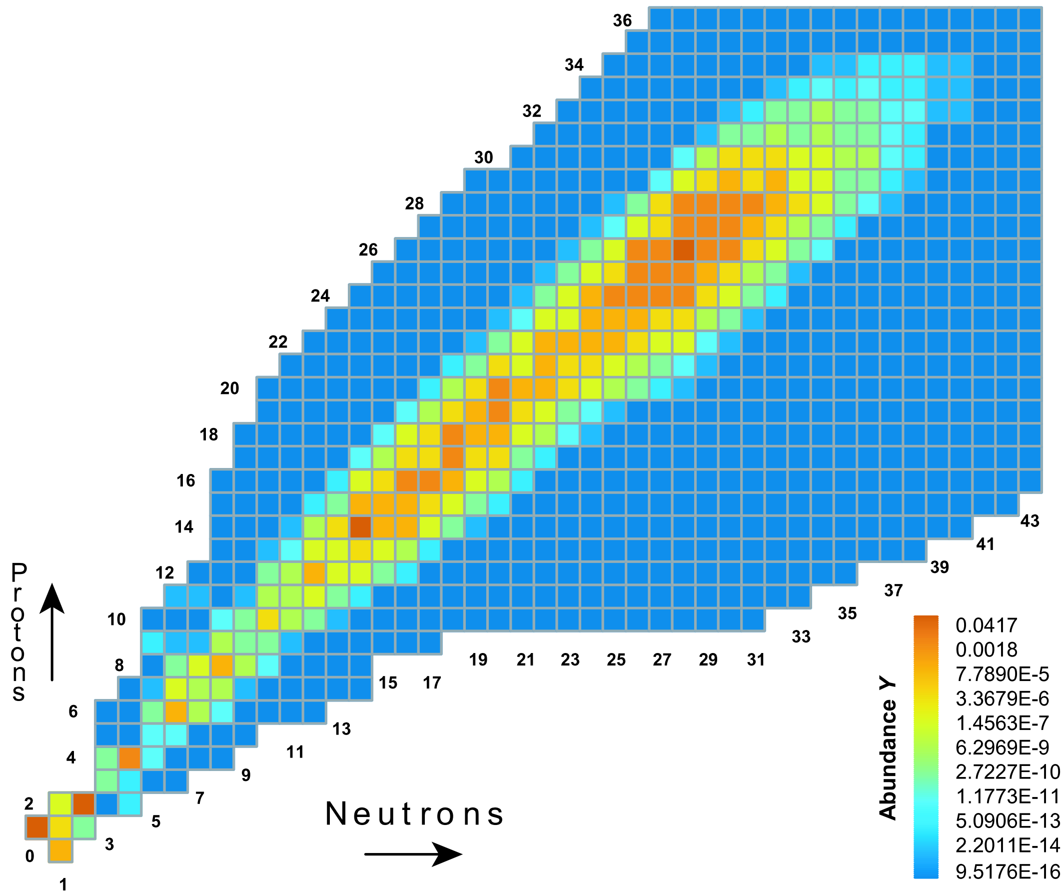
- The Type Ia precursor is a 1.5 solar mass thermonuclear bomb



$M \sim 5 \times 10^5$ Earth masses
~ 1.4 Solar masses

- Three fundamental issues for an improved understanding of mechanism
  - What triggers the bomb (merger or accretion)?
  - How does one deal computationally with the huge range of scales?
  - How does the fuel burn and what ashes does it leave behind?

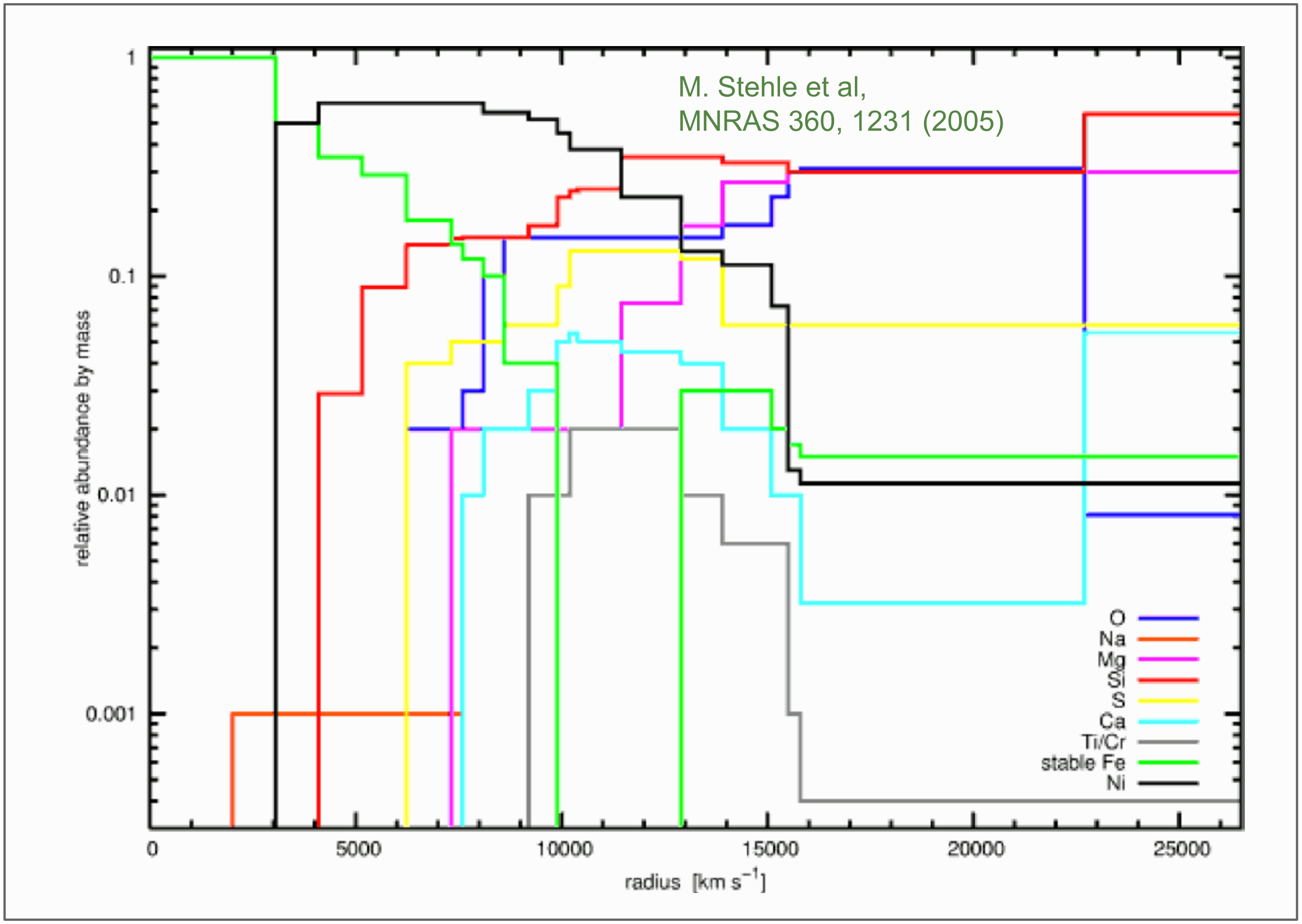
Solving Large Thermonuclear Networks



Compare Abund

Compare NZ

Abundance Tomography from SN2002bo

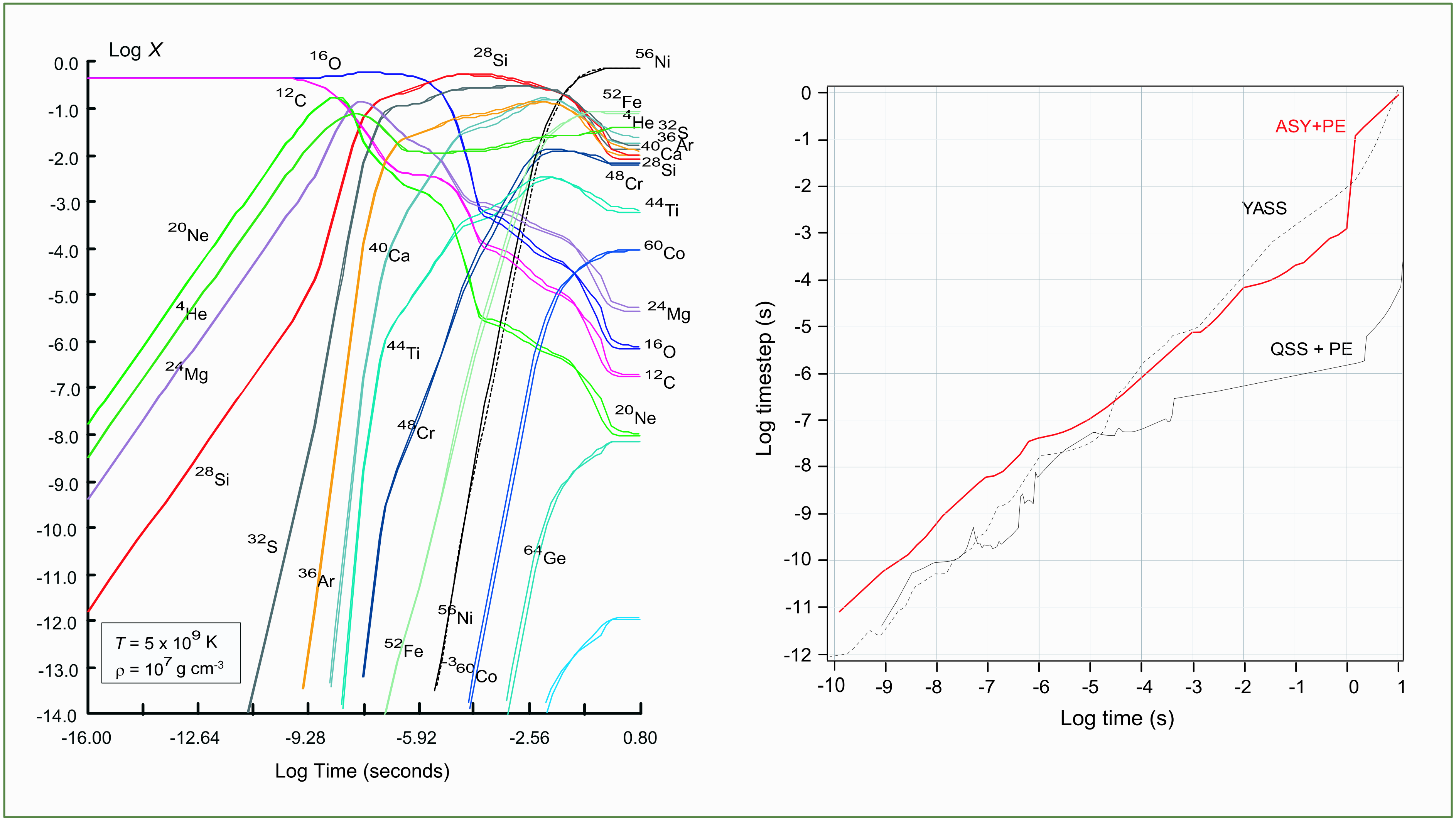


Note intermediate mass elements at high velocity

Data Require Deflagration Transitioning to Detonation

Observed light curves and elemental abundances in the expanding debris require a thermonuclear burn of the white dwarf that is partially deflagration (subsonic burn front) and partially detonation (supersonic burn front). Not easy to achieve.

Explicit Integration with Competitive Timesteps



Flame Propagation in Type Ia Supernovae

C12 6-level

C12 8-level

Pressure

Chris Smith, Suzanne Parete-Koon, Elisha Feger, Sophia He, Raph Hix, Bronson Messer, Mike Guidry

Summary

- For the first time it may be possible to couple realistic thermonuclear networks to multi-dimensional hydrodynamics in Type Ia supernova simulations.
- In addition to its intrinsic interest, an improved understanding the Type Ia mechanism has the practical implication of improving the standardizable candle properties that are critical to cosmology.
- One implication of improving the standardizable candle properties could be to precisely constrain the equation of state for the Universe.
- If the equation of state is known precisely for dark energy, this will place strong constraints on acceptable theories for the source of dark energy.

Summary

- The Universe started with a big bang about 14 billion years ago. The Universe went through a period of cosmological inflation (exponential expansion) in the first tiny fraction of a second before settling into the standard big bang evolution.
- The evolution of the Universe is determined by the solution of the Friedmann equations (Einstein equations + Cosmological Principle).
- The Friedmann evolution is, in first approximation, determined by four quantities: (1) Hubble parameter, (2) matter energy density, (3) radiation energy density, and (4) the vacuum energy density, all evaluated at the present time.
- Galaxy surveys, the CMB, and Type Ia supernovae suggest that the Universe is flat and the energy density of the Universe is ~70% dark energy, ~30% massive particles (mostly dark matter), and much less than 1% radiation.

Summary

- "Ordinary" baryonic matter (the world that we see) is at most several percent of the mass density of the Universe. The present Universe is dominated by the flatness born of inflation and dark energy and dark matter.
- The seeds for large-scale structure were quantum vacuum fluctuations stretched to astronomical scales by inflation.
- The geometry of the Universe is almost exactly flat (euclidean) because of inflation, and it appears that it will expand forever because of dark energy.