Acceleration of the Universe

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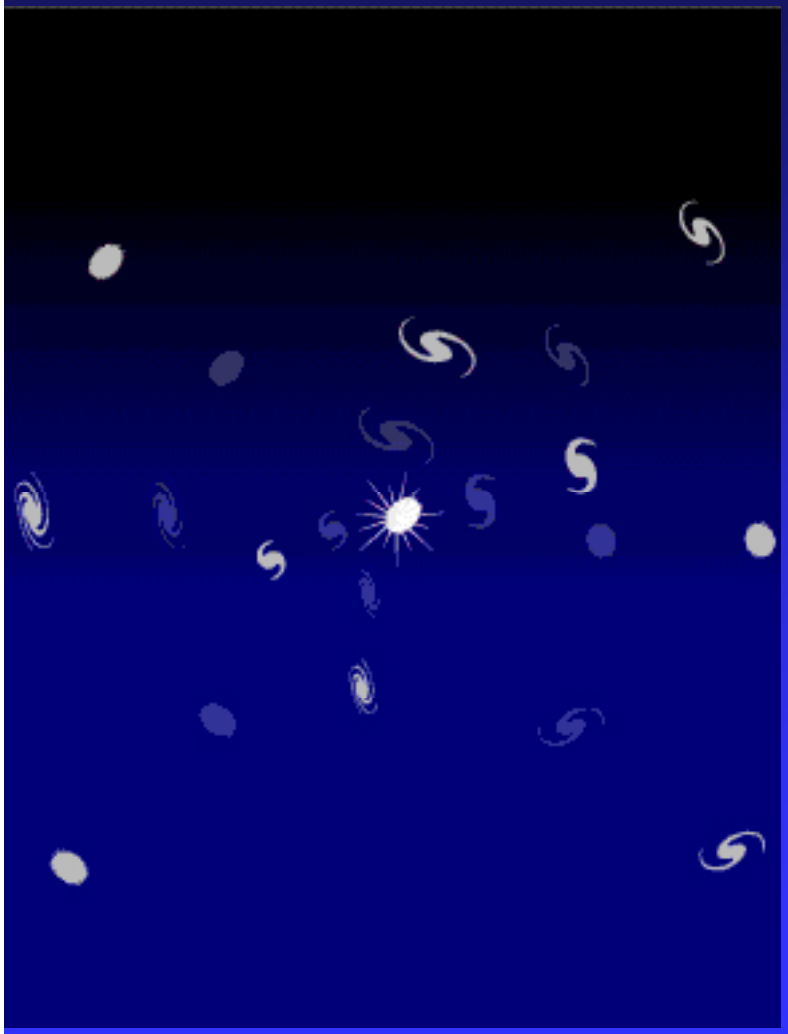
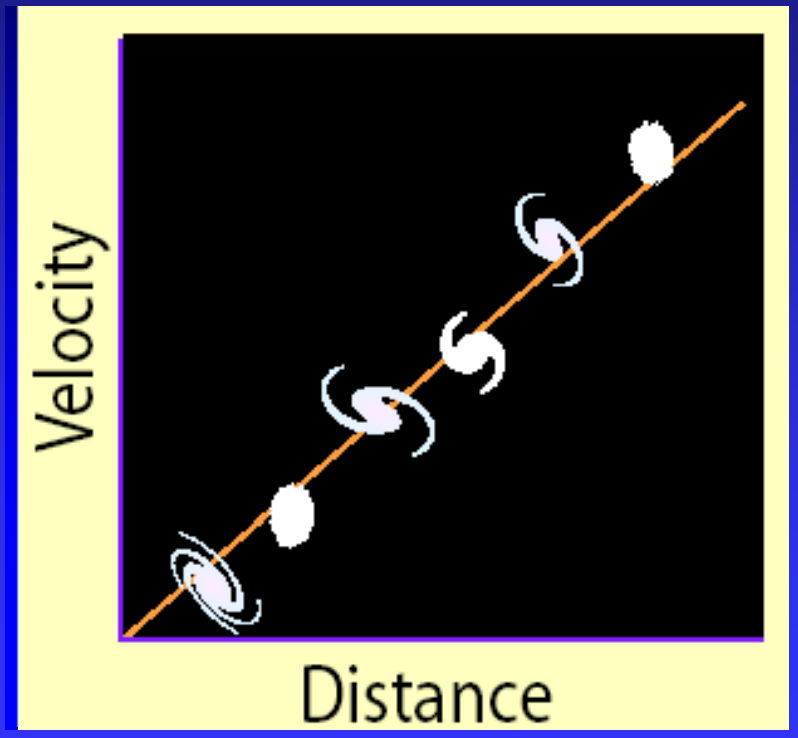
- Beginning of the Universe (Big Bang)
- Expansion of the Universe
- Present state of the Universe
- Future of the Universe
- Distances to galaxies
- Motion of galaxies

Hubble's Law: In an expanding Universe, velocity= H_0 x distance





The Expanding Universe

$v = Ha$

Hubble (1929)

- Velocities=Doppler shift=z
- Distances: Brightest "stars"

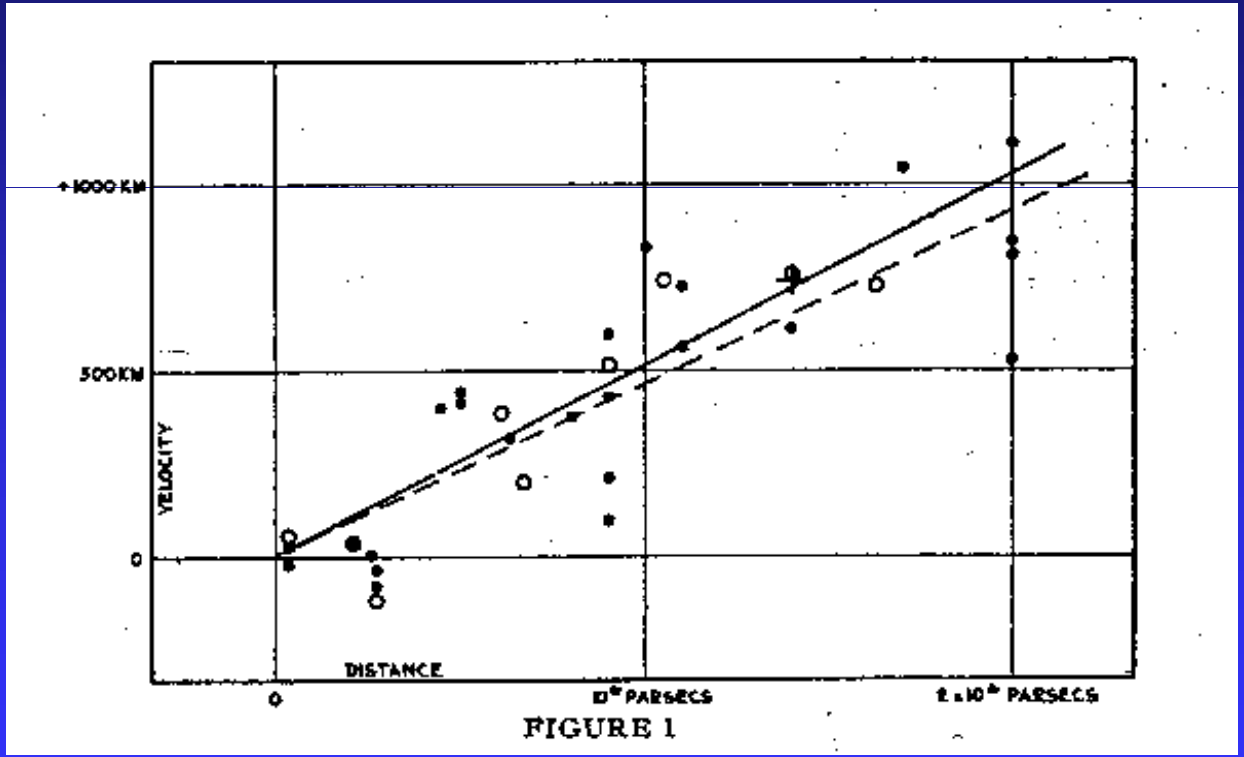
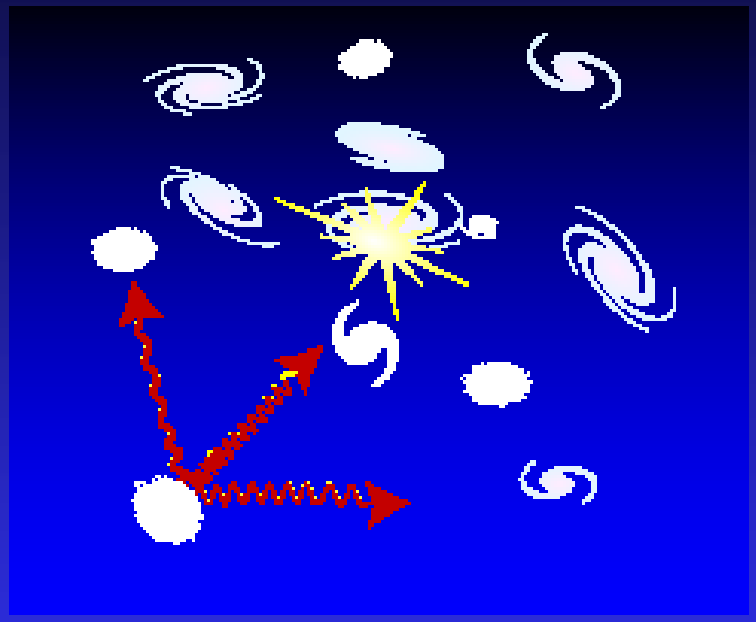


FIGURE 1

One of the original reasons for building HST was to measure H_0

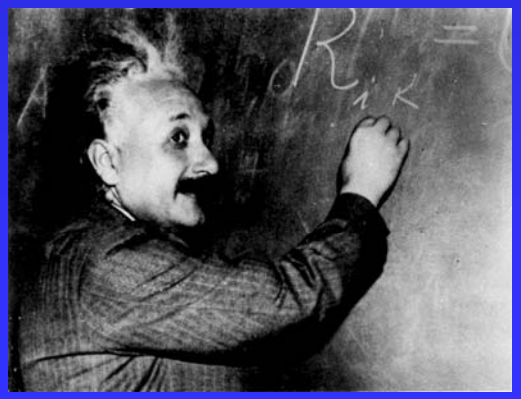
H_0 sets the scale of the Universe and its age

The Expansion Rate may be Slowing down or Speeding Up



• (Dark) Matter provides attractive gravity which should be decelerating Universe

•But Einstein thought Universe static, GR allowed for repulsive gravity, i.e., cosmological constant (Dark Energy), that could repel gravity and keep Universe static



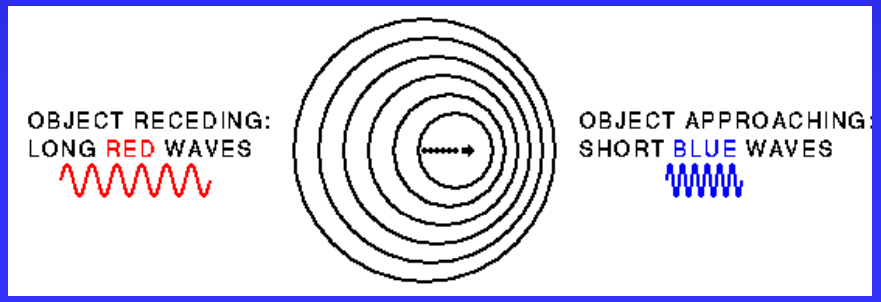
“Standard” Candles

How far away?

Bright=near dim=far

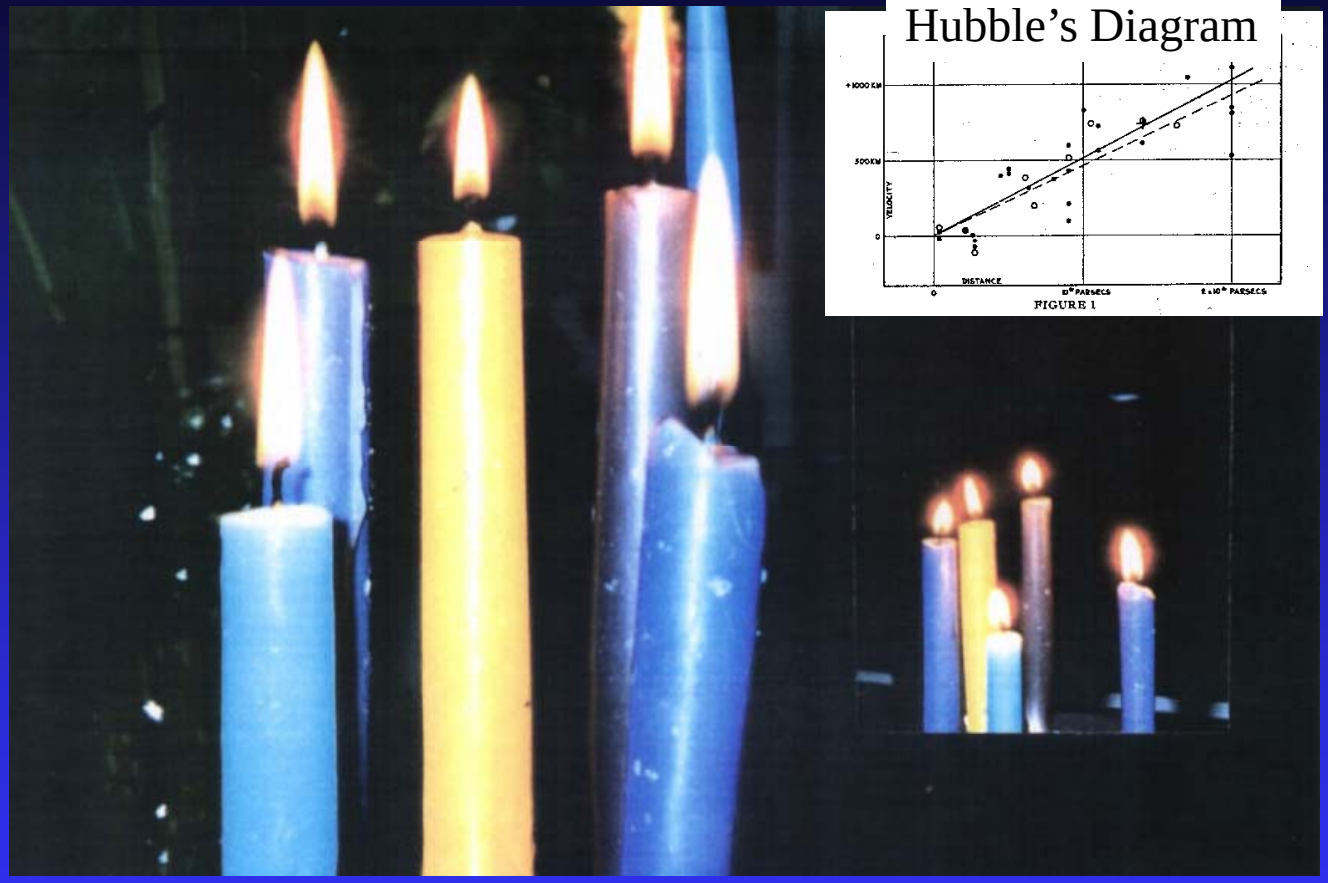
We
Need a
Standard candle
We can see
Far away,
Back in time

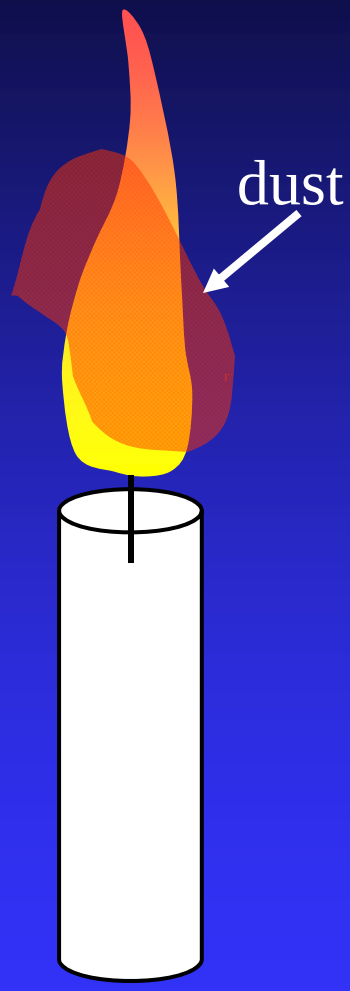
Receding how fast?



Doppler Effect

“Standard” Candles



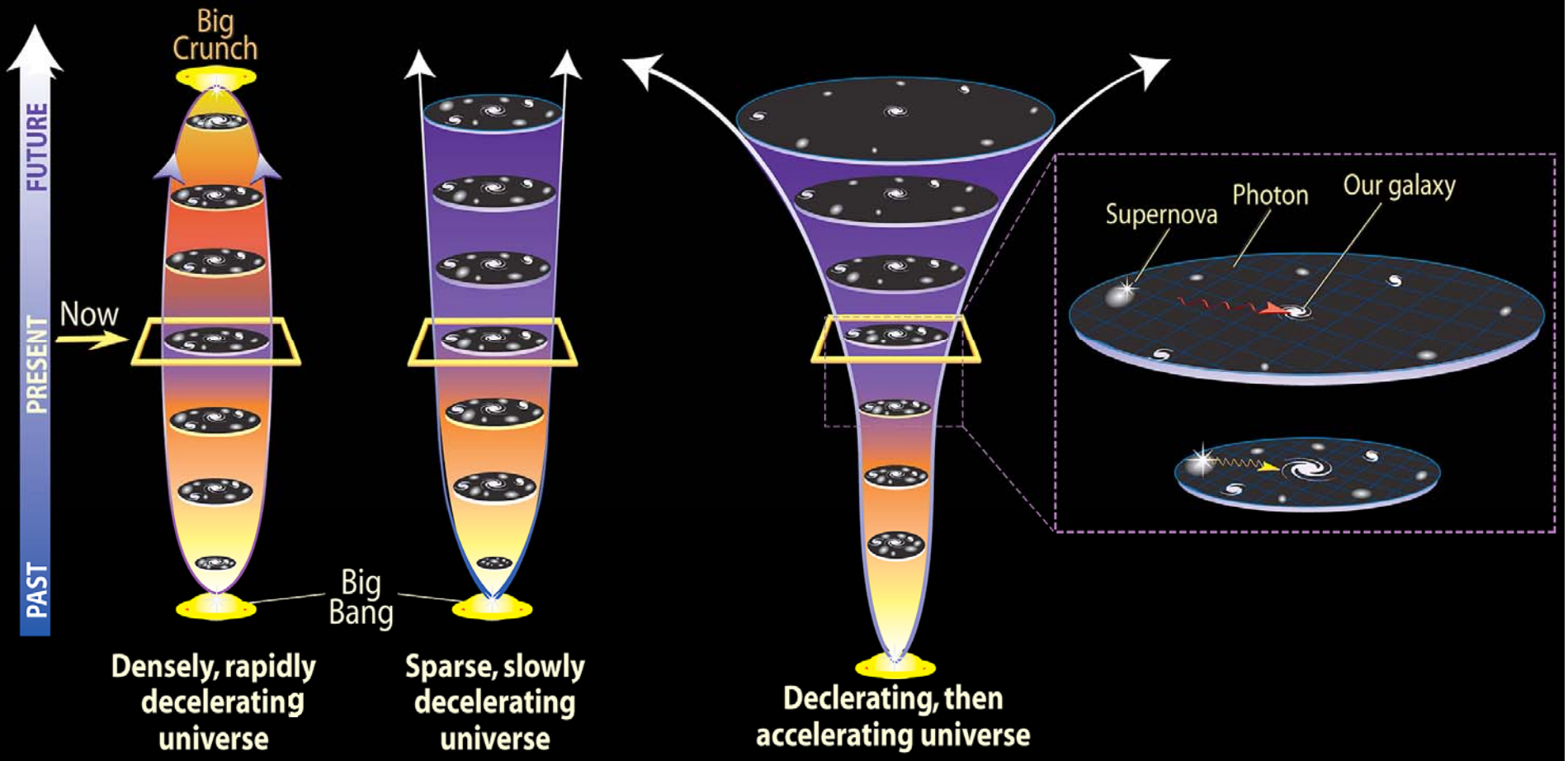


Bright=near

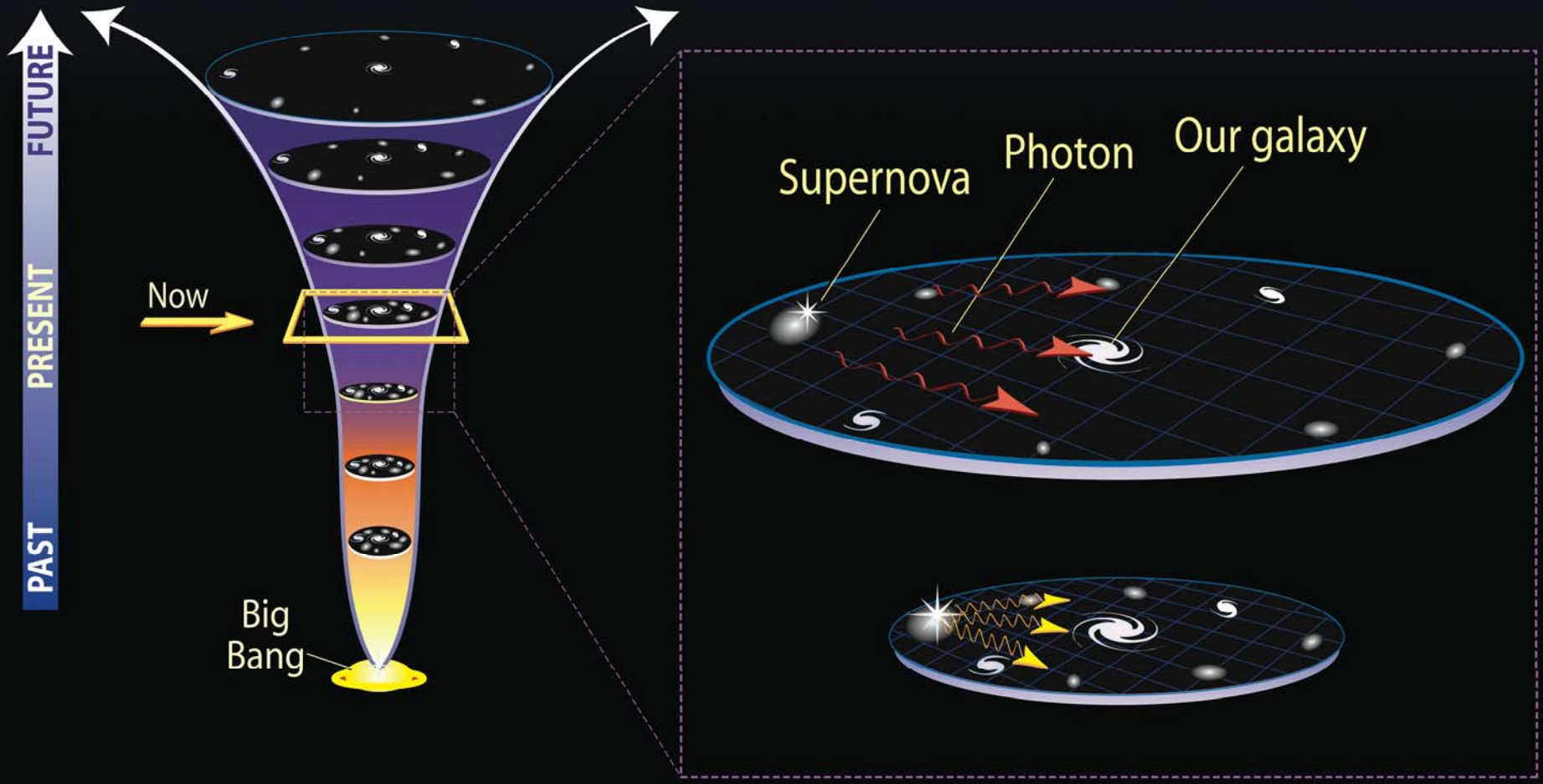
dim=far

dim & red=closer!

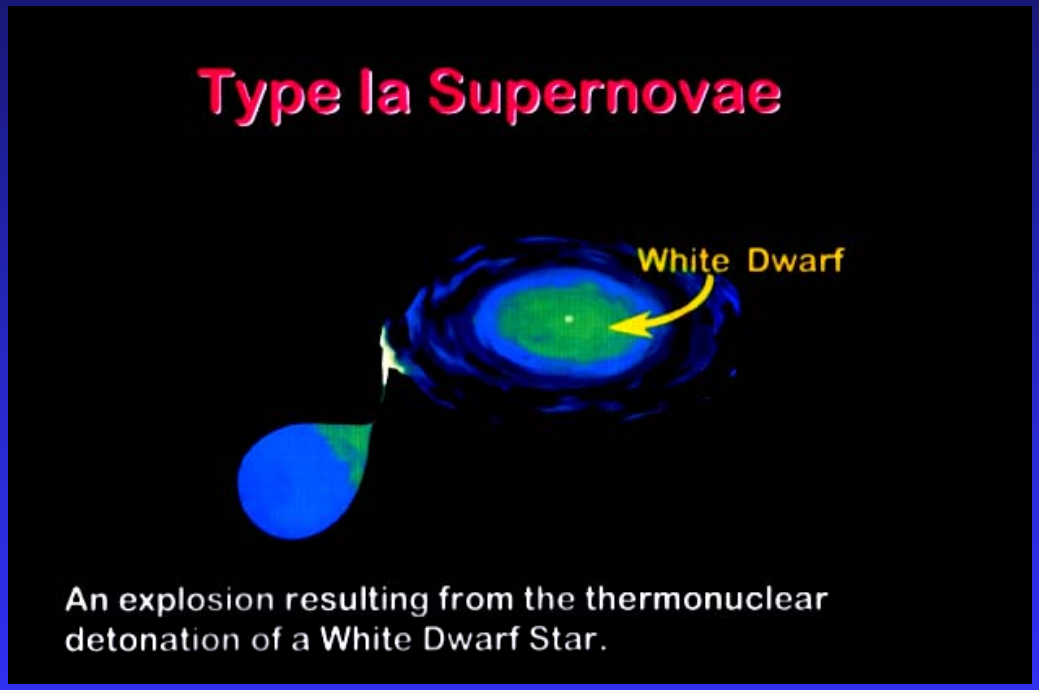
Models of the Expanding Universe



Measuring the Expansion History: Changes in scale/Changes in time



At the End of its Life, a Star is Reborn

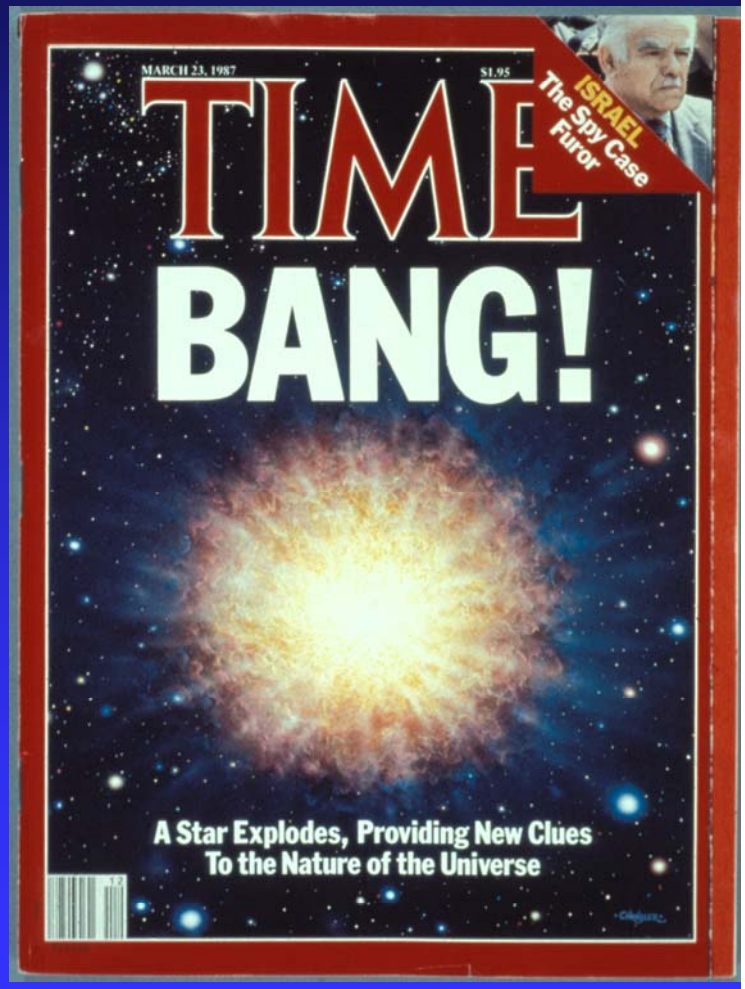



Subrahmanyan **Chandrasekhar**
1910-1995

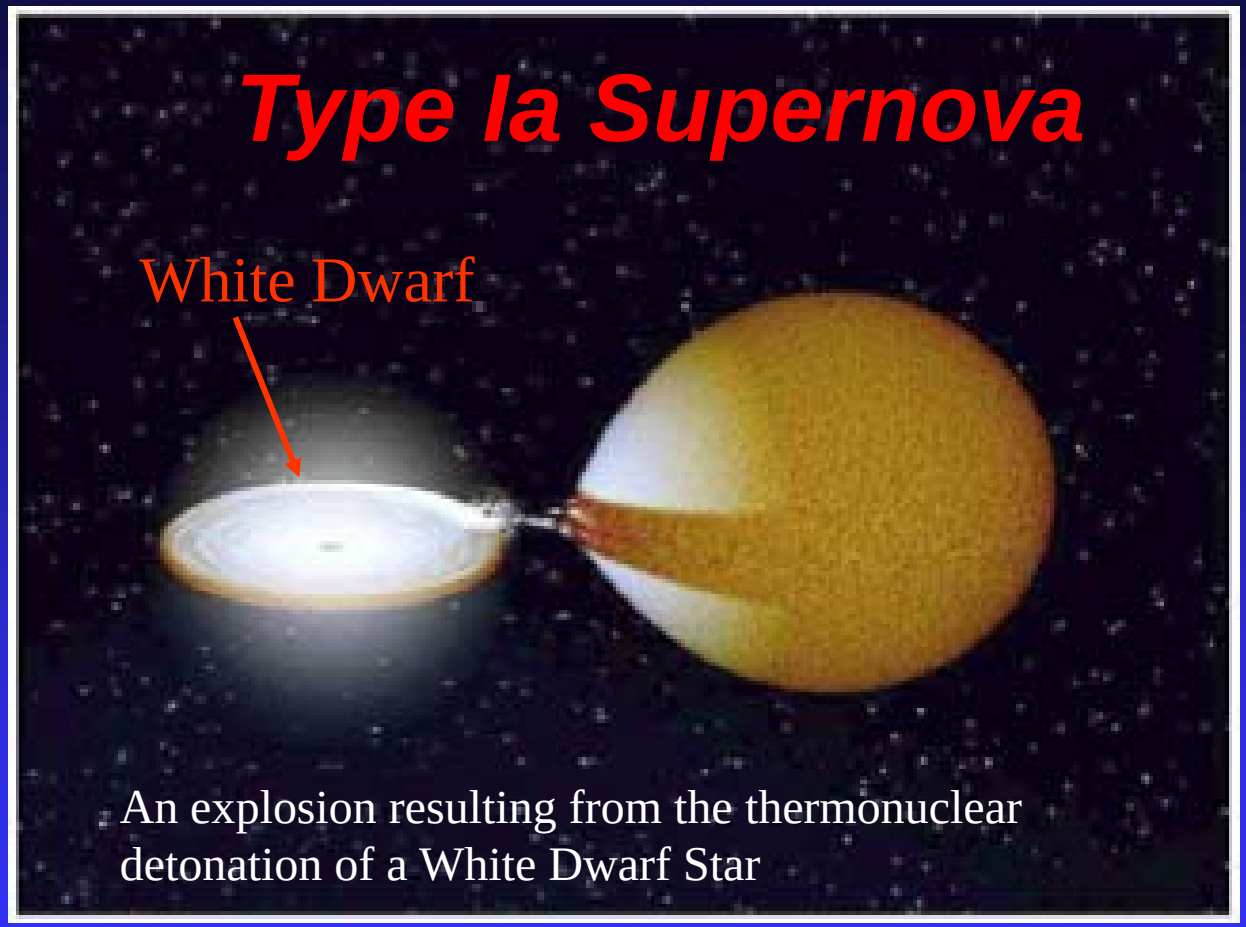
- as bright as 4 billion Suns
- can be seen halfway across the Universe

Bang! A star explodes…

1987: The galaxy next door



How (we think) Nature makes a SN Ia



- Homogeneity: 1.4 $M_{\odot}$, 10^{51} ergs
- Negligible hydrogen, lots of IME
- Mature progenitors
- Models (delayed-detonation) good fit to observations

Four months in the life of a SN Ia

Age:

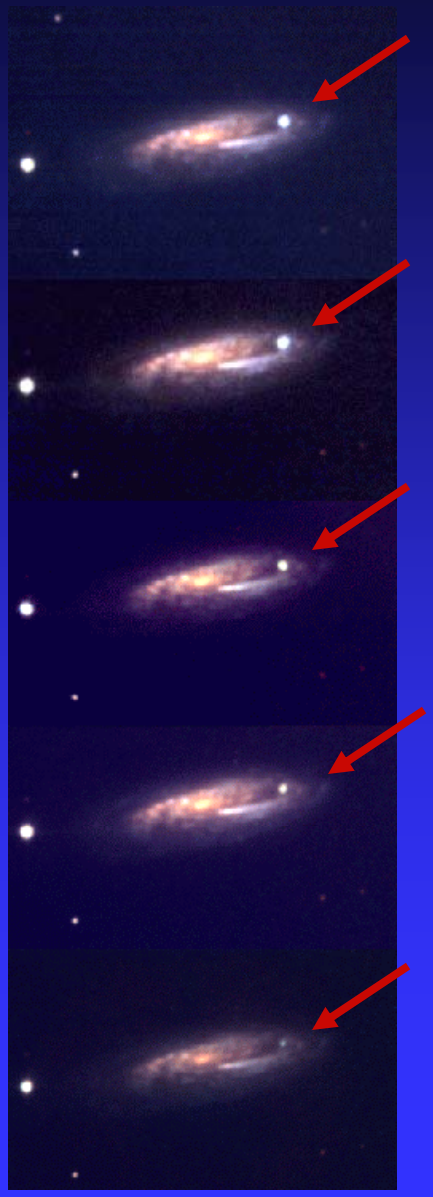
-6 days

Maximum

+26 days

+47 days

+102 days



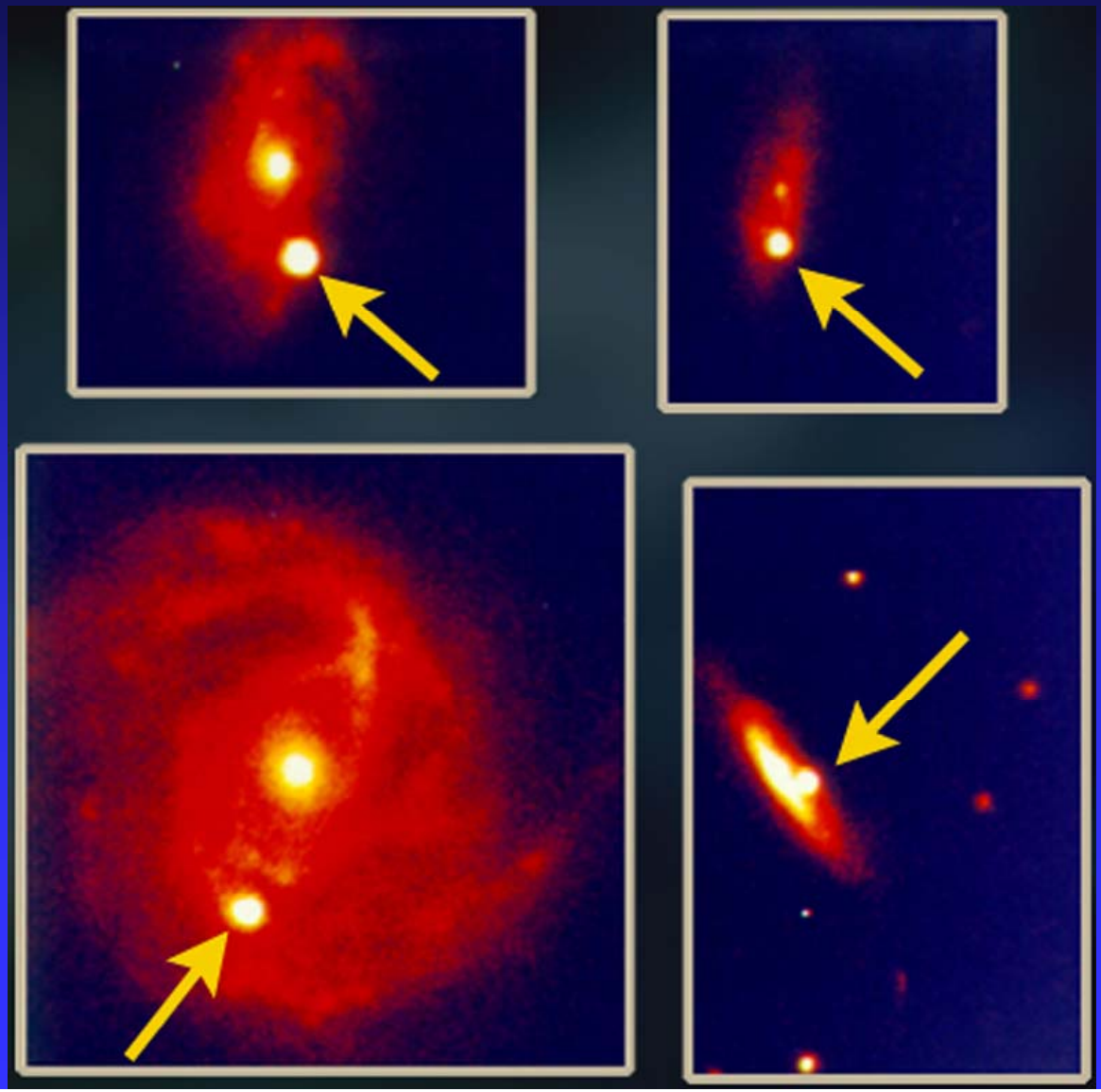
On the Rise:

Powered by radioactivity

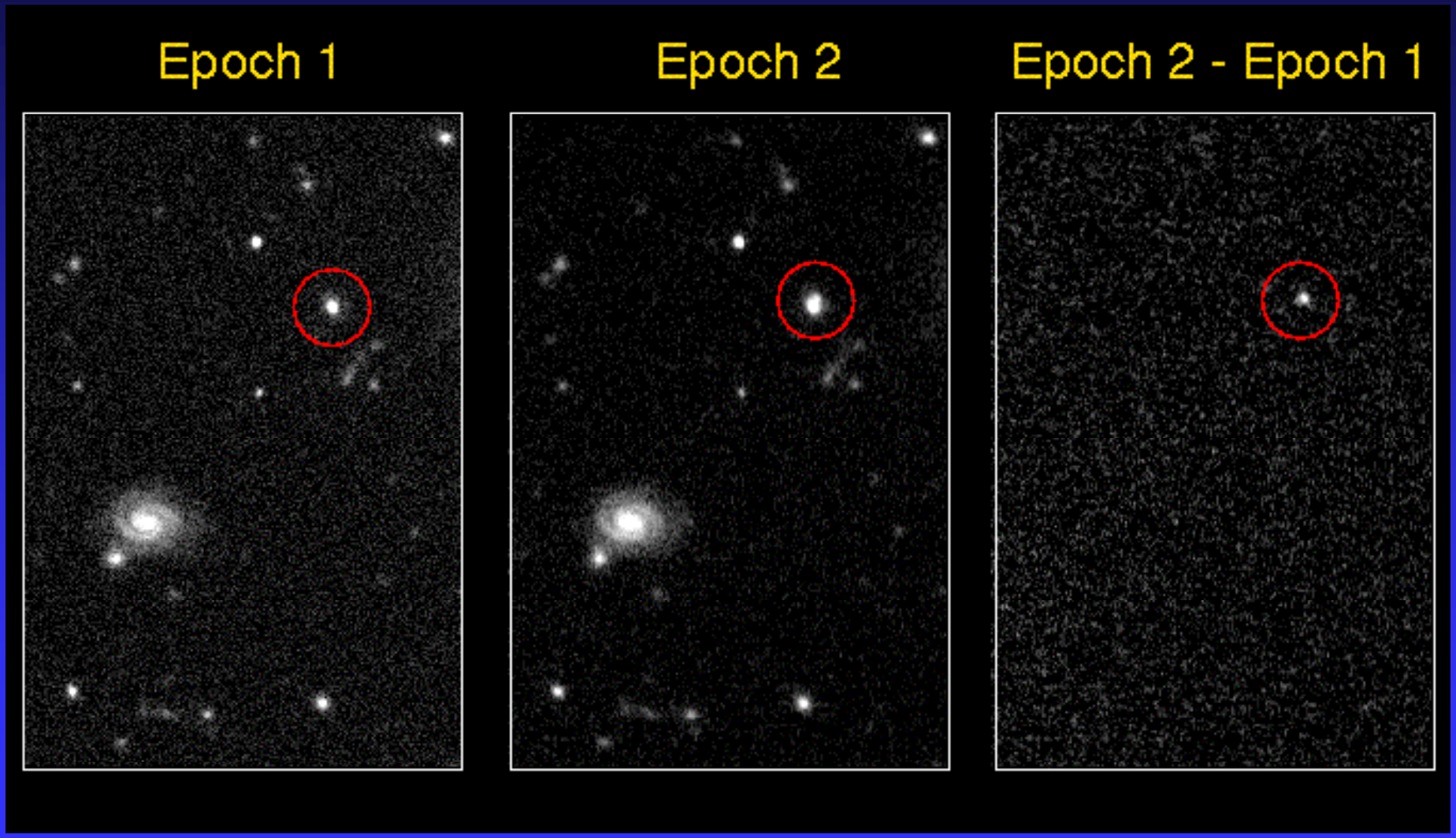
V_{ejecta}=10-20,000 km/s

Elements produced=
Fe,Co,Ni,Si,Ca

How do we Find Supernovae?



Searching by Subtraction

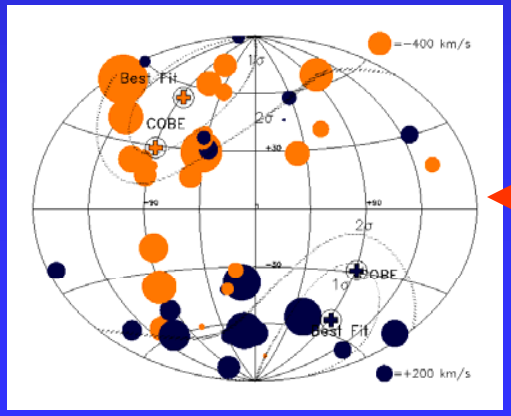


Improving the Discovery Odds

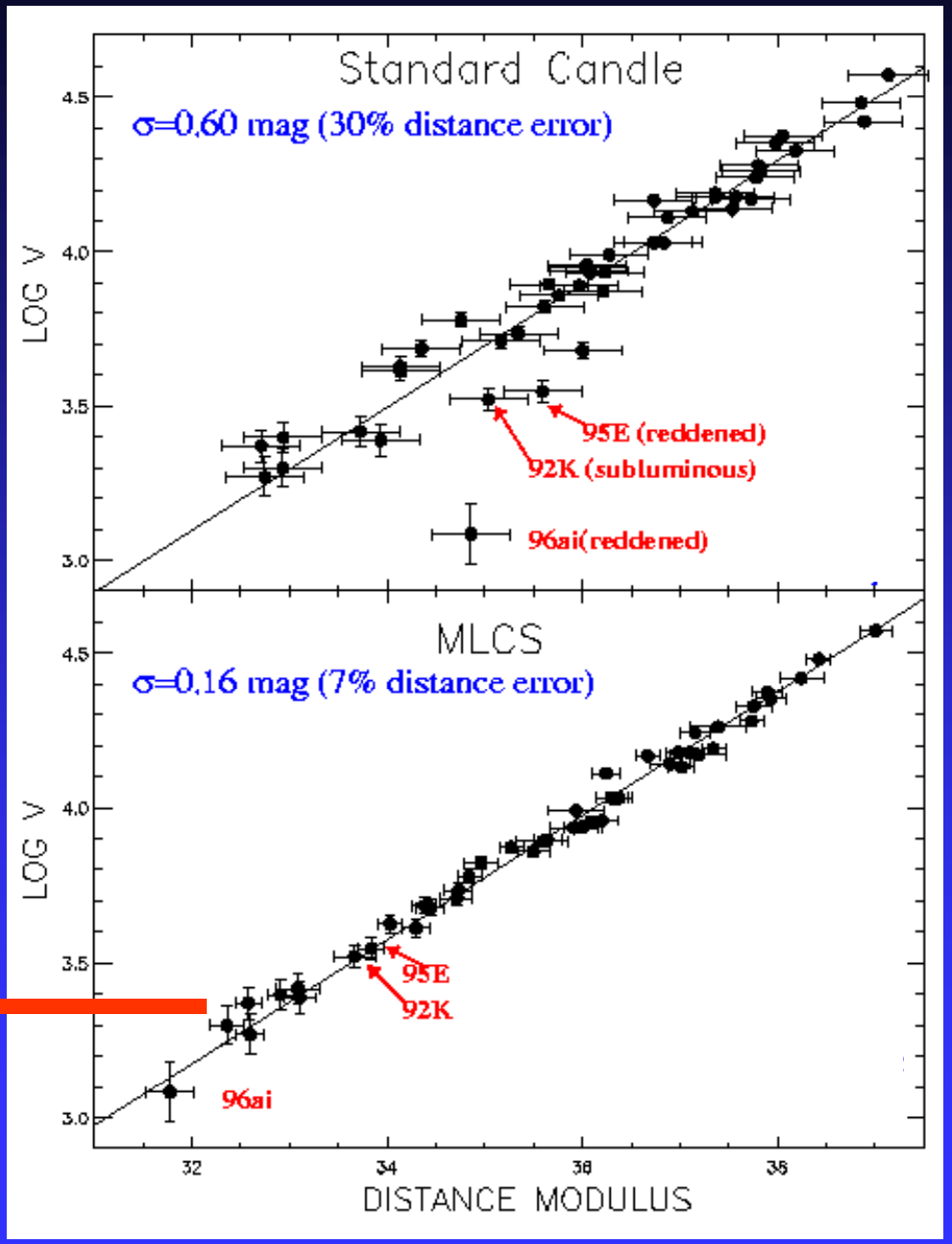
- 1 SN per galaxy per 100 years =
- 1 SN per 100 galaxies per year =
- 10 SN per 1000 galaxies per year, if monitor them frequently enough.

The Dim, the Distant and the Dusty

Improved SN Ia distances reveals motion of Local Group, and flows



Riess et al 1995,1997



What can Supernovae tell us about the *History* of Cosmic Expansion?

Disclaimer: The rest of this talk does not depend on H_0

Our Cosmological Framework Derives From…

Observations

- The Universe is Expanding
- CMB → Hot Big Bang

Theory

- General Relativity

Principles (corroborated by observations)

- Homogeneous, isotropic on large scales

Friedman Equation (Equation of Motion of the Universe)

(Dark) Matter

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_M + \frac{\Lambda}{3} - \frac{k}{R^2}$$

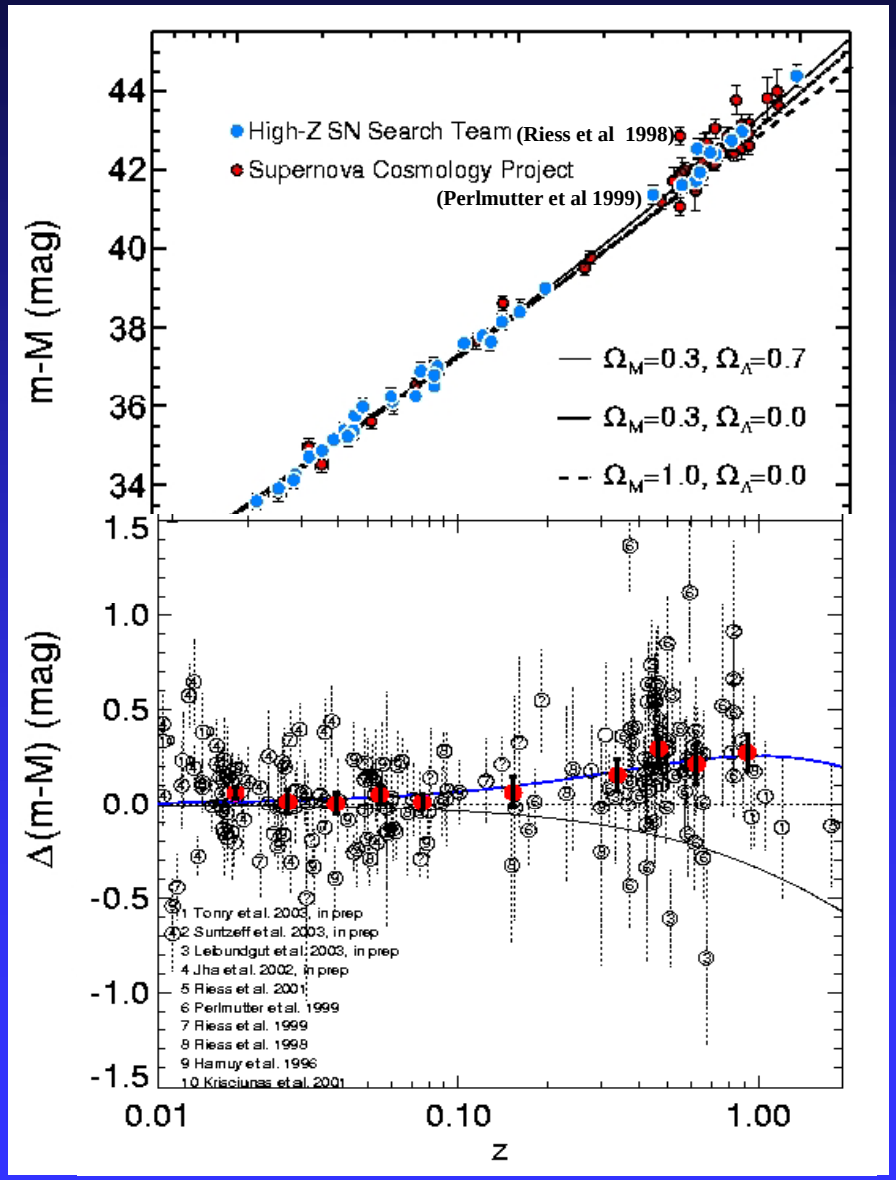
$$\Omega_M \equiv \frac{8\pi G}{3H_0^2}\rho_{M0} \qquad \Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2} \qquad \Omega_k \equiv \frac{-k}{R^2 H_0^2}$$

$$\Omega_M + \Omega_\Lambda + \Omega_k = 1 \quad k = -1, 0, +1$$

(Dark) Energy
"Einstein's 'Biggest Blunder'"

Geometry

SN Ia Hubble Diagram



After Exhaustive tests for systematics: None significant

I ~25% Fainter than Ω_M =0.3 Ω_Λ =0.0

Why is The Universe Accelerating?

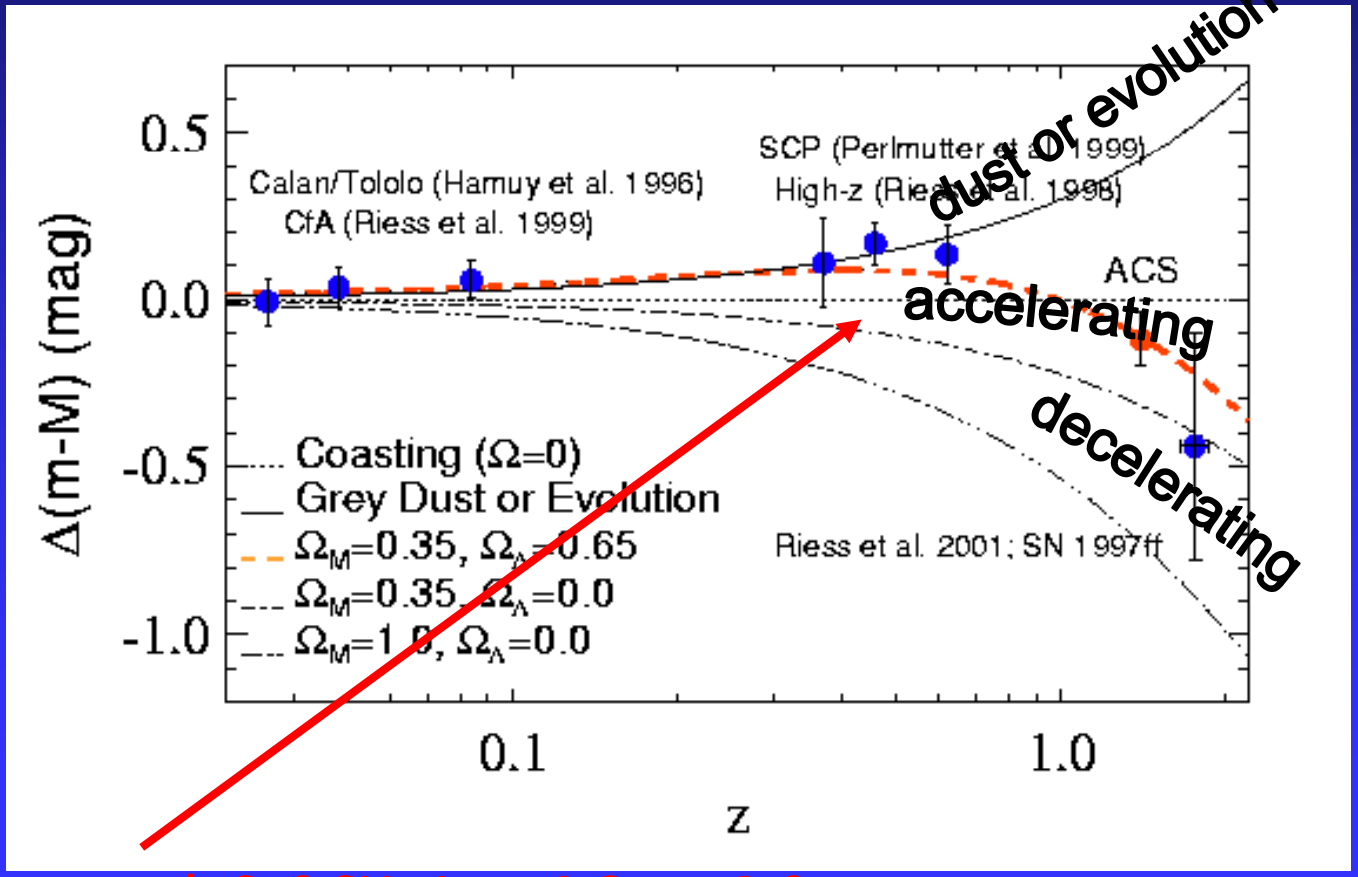
(Honestly, we don't really know)

- Vacuum energy in QM (dark energy)→right hand-side of Friedman eq
- We don't understand gravity on large scales→ left " "
- Mini-inflation episode →right hand-side of Friedman eq
- Superhorizon action, stringy effects, Chaplygin gas, etc
- Insert your idea here

Important Prerequisite ("Sanity Check"):
When was the Universe *decelerating*?

Search for cosmic deceleration

SNe Ia at $z > 1$ provide an essential test of the transition between current cosmic *acceleration* and past *deceleration*



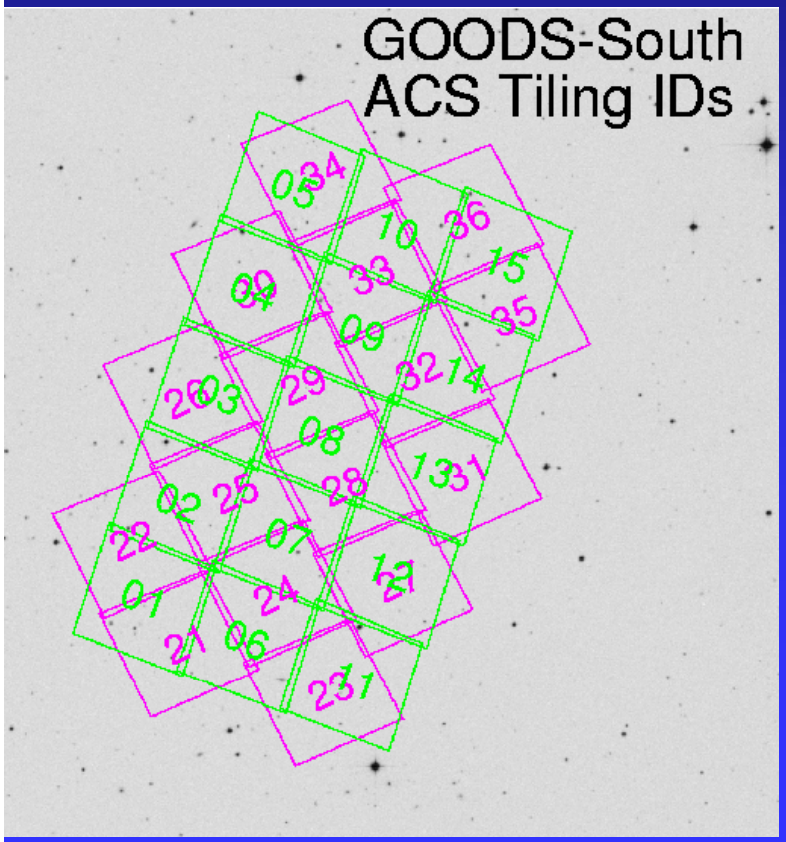
Our current goal: 6-8 SNe Ia at $1.2<z<1.8$

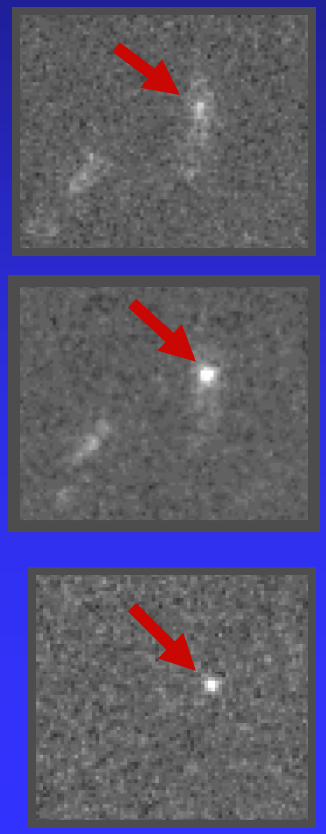
Searching for SNe Ia with ACS

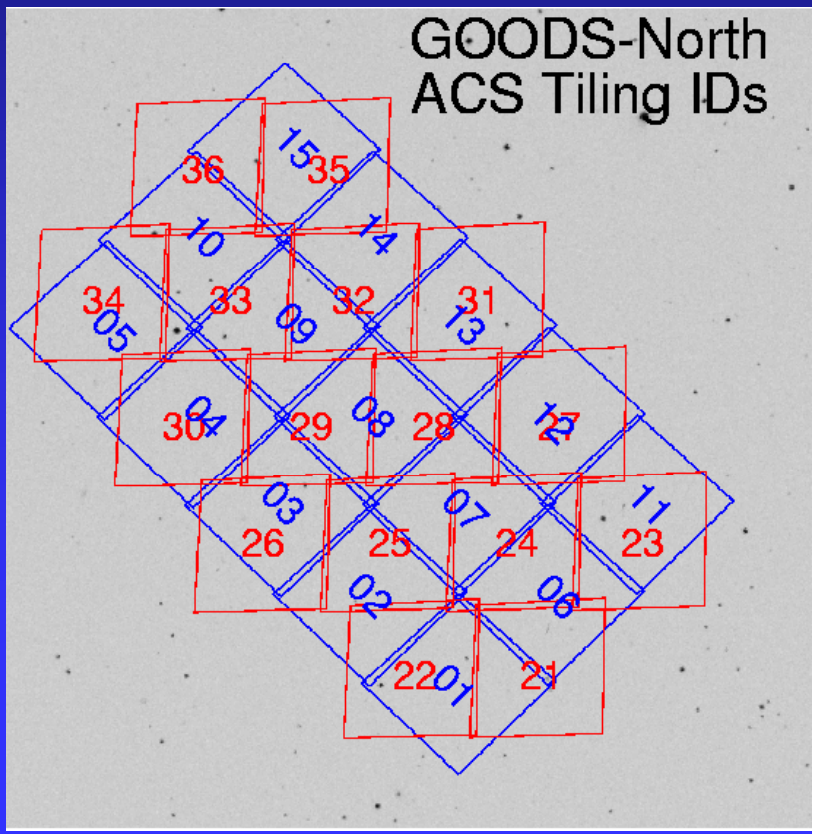
5 z-band epochs, spaced by 45 days, simultaneous v,i band, 120 tiles

CDFS

HDFN







Finding High-z Sne

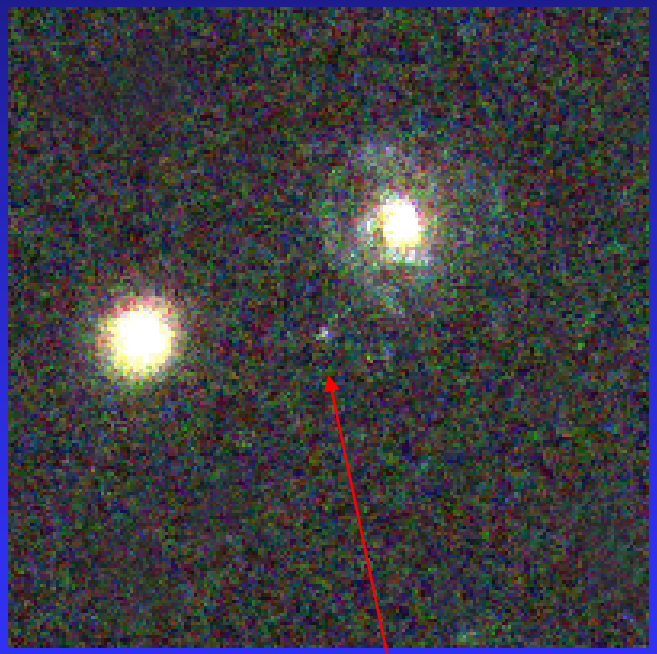
- **We found 6 of the 7 highest redshift (z>1) supernovae currently known**

Search completed:

- 43 SNe identified
- ~25 Type Ia candidates at z>1
  - *10 follow-ups by ToO program*
  - *12 spectroscopic confirmations so far*
  - *3 highest-z spectral confirmations (z>1.3)*

~1 FTE with HST "as is" will yield ~100 Sne at z>1

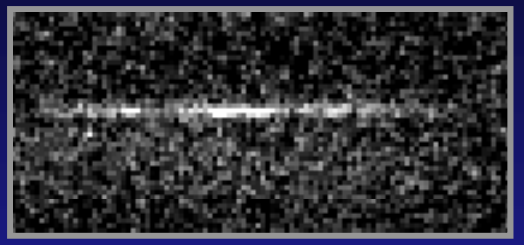
- *Probe the nature of the dark energy*
- *HST+ground=SNAP-lite NOW!*



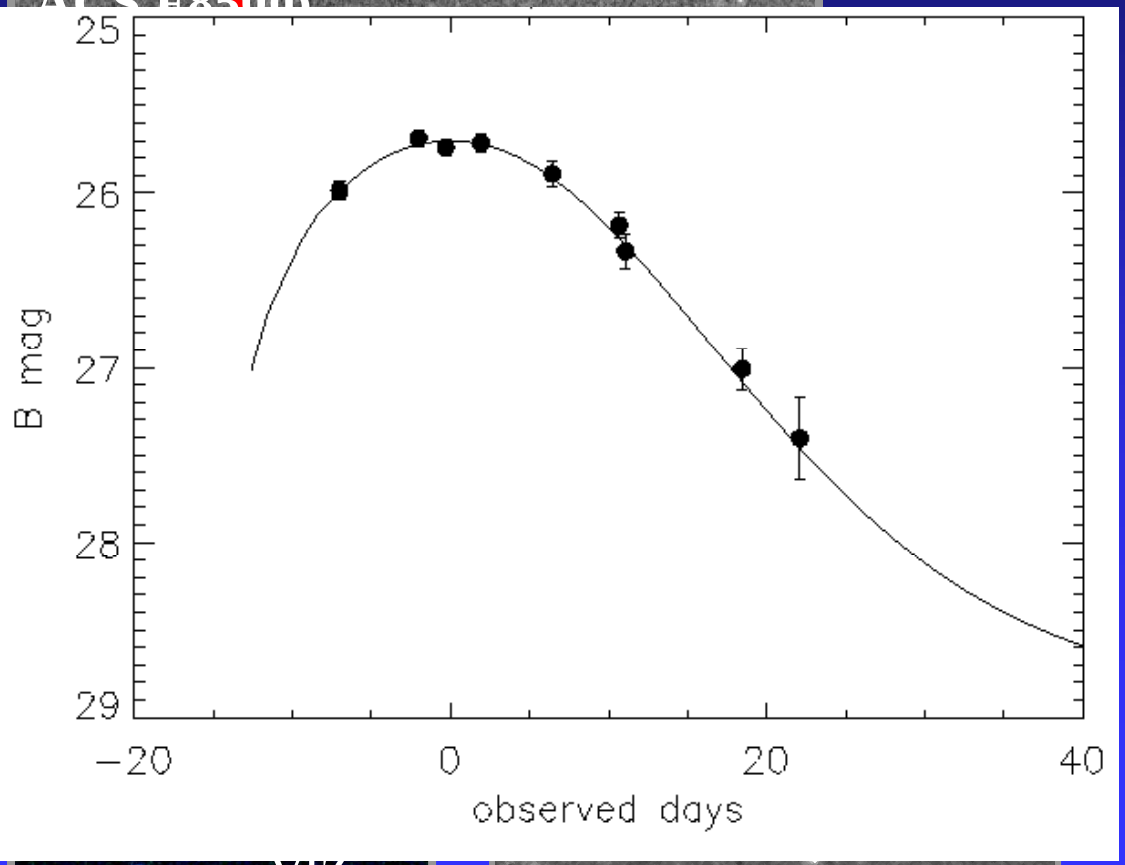
High-z SN "Artemis" from CDF-S ACS observations

Our first higher-z SN Ia, Aphrodite

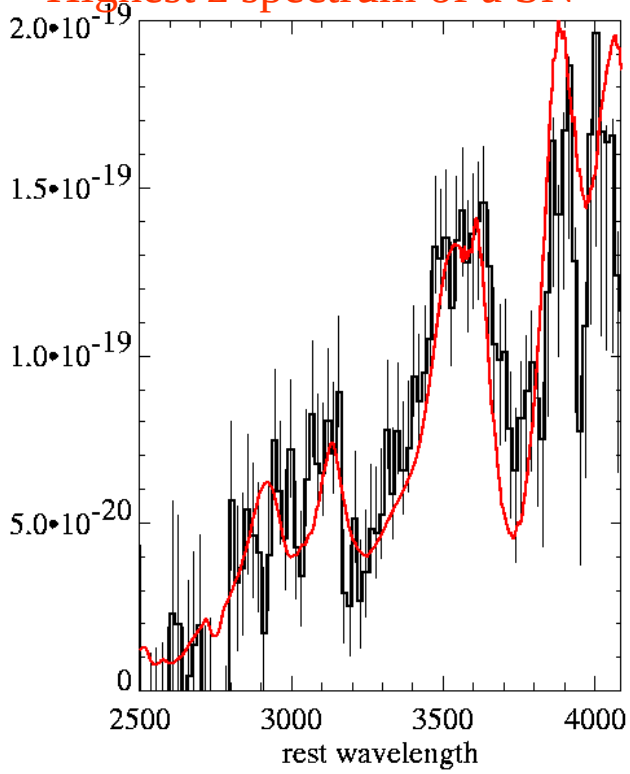
Aphrodite (z=1.3)



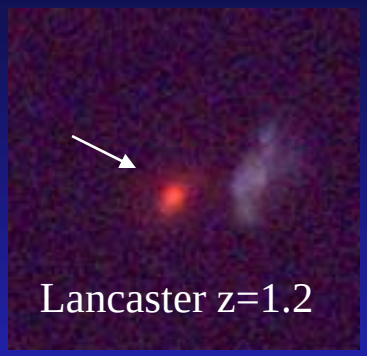
ACS grism spectrum

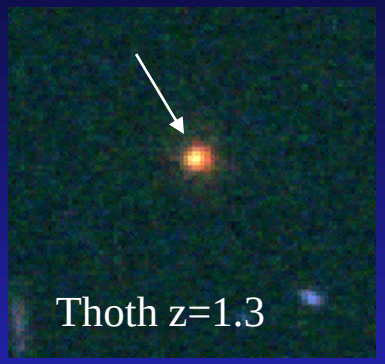


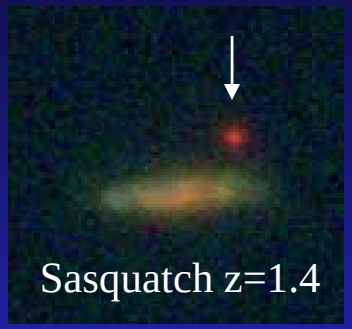
Highest z spectrum of a SN

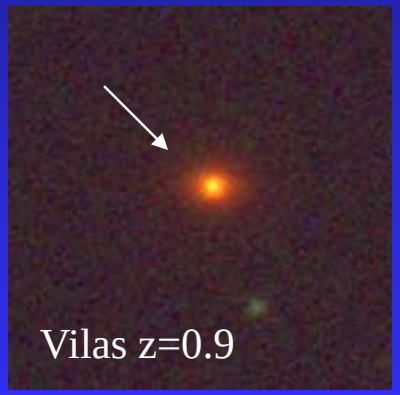


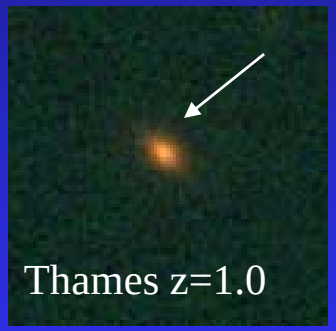
HST Found SN Ia in Early-type Hosts, 0.9<z<1.7

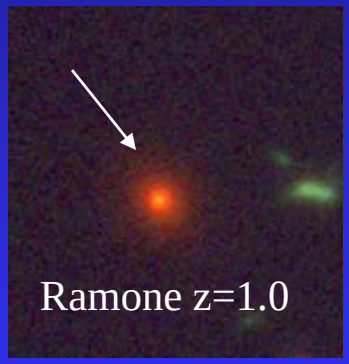


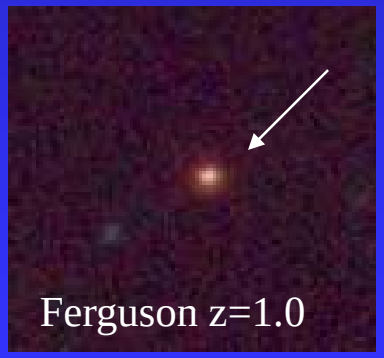


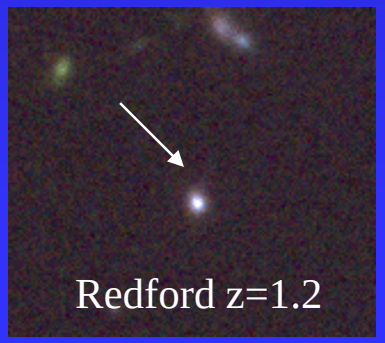




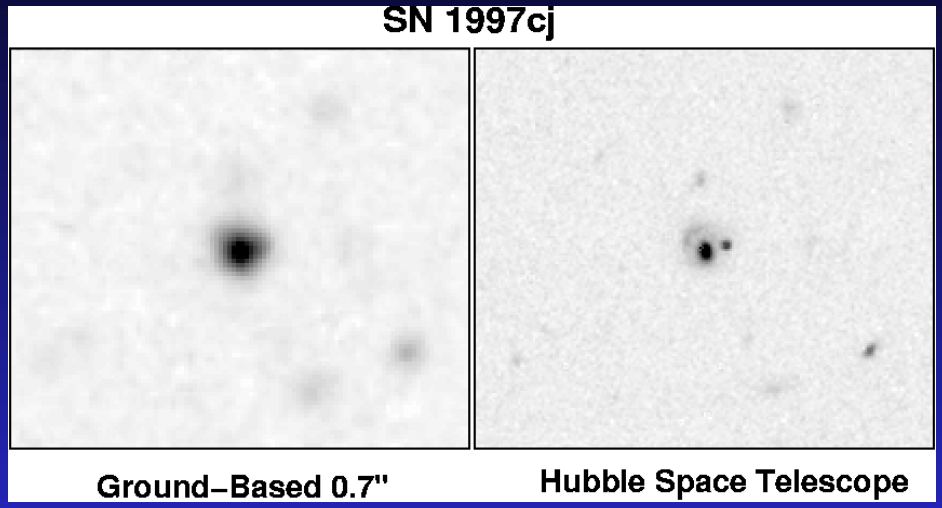




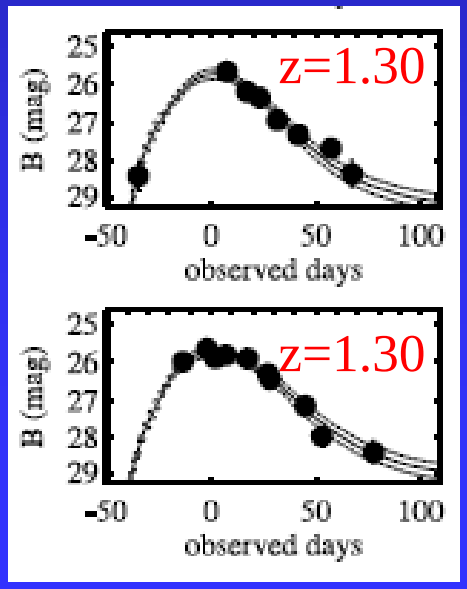




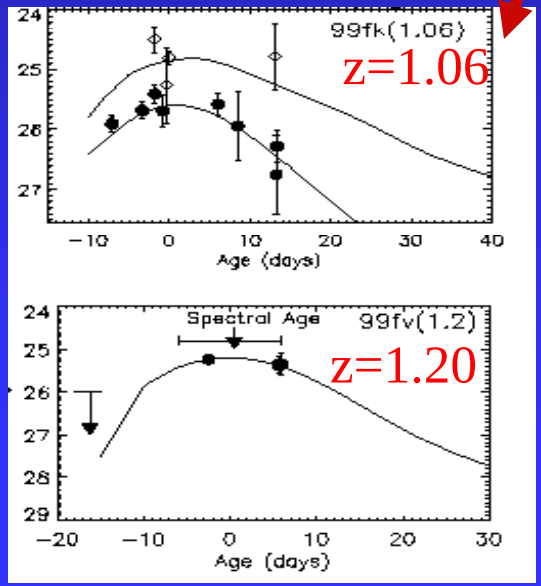
The HST Advantage



HST-ACS



Highest 2 Ground-based



Measuring Distances

$$D^2_L = (L/4\pi F)$$

$$\mu_0 = m - M = 5 \log D_L + 25$$

$$\mu\,(z; H_0; q_0; dq/dz)$$

Deceleration *vs.* Acceleration

We minimize the difference

$\mu(z_i; H_0; q_0; dq/dz) - \mu_{0,\iota}$

By optimizing q_0 and dq/dz

using χ^2 statistics.

$\mu_{,0,i}$: distance from SNe

$\mu(z_i; H_0; q_0; dq/dz)$: predicted distance

$q(z) = q0 + z\ dq/dz$

Calculate the probability density $e^{-\chi 2/2}$

$q_0 < 0$ *Recent acceleration*

$dq/dz > 0$ *Past deceleration*

Expansion Kinematics

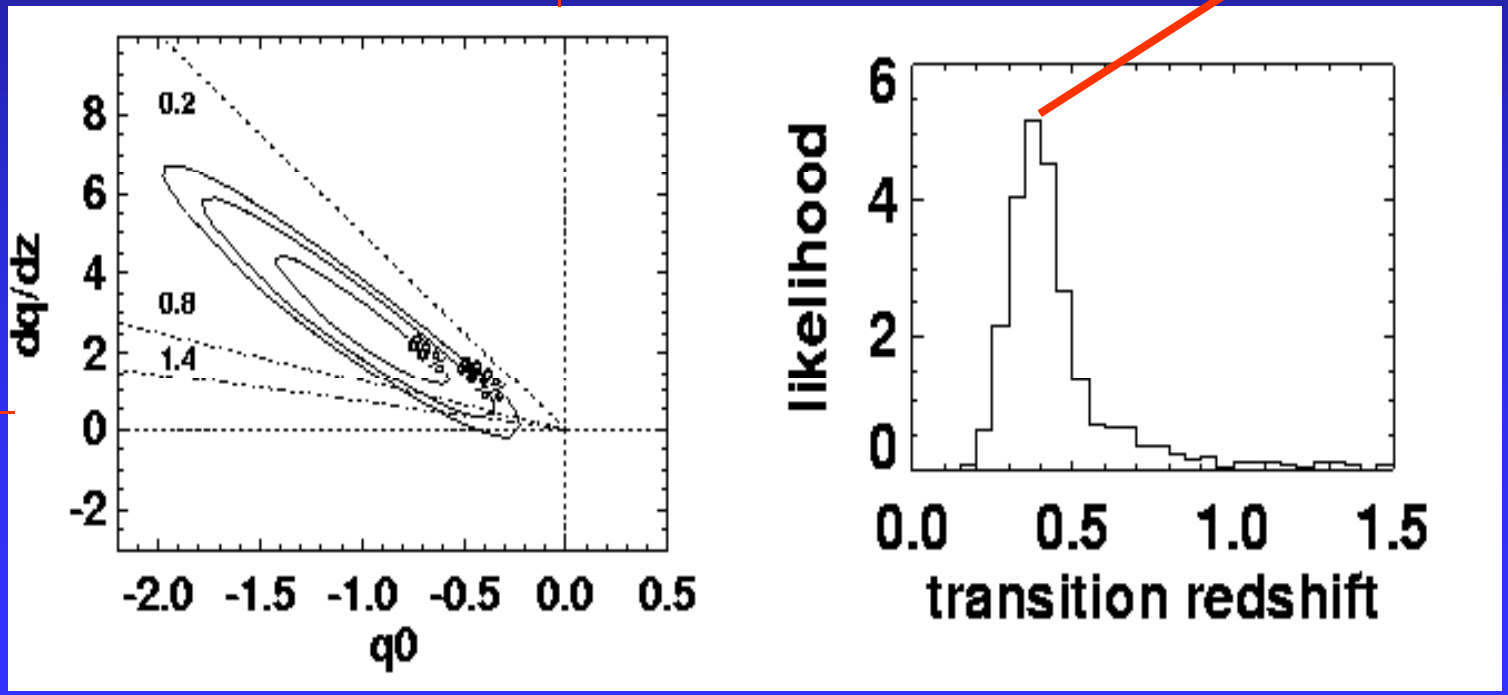
(How Long Has This Been Going On?)

$$q(z) = q0 + z\, dq/dz \qquad z_t = -q_0/(dq/dz)$$

present acceleration

past deceleration

z~0.3-0.6,
~5 GYR ago



High Redshift SN and Expansion History

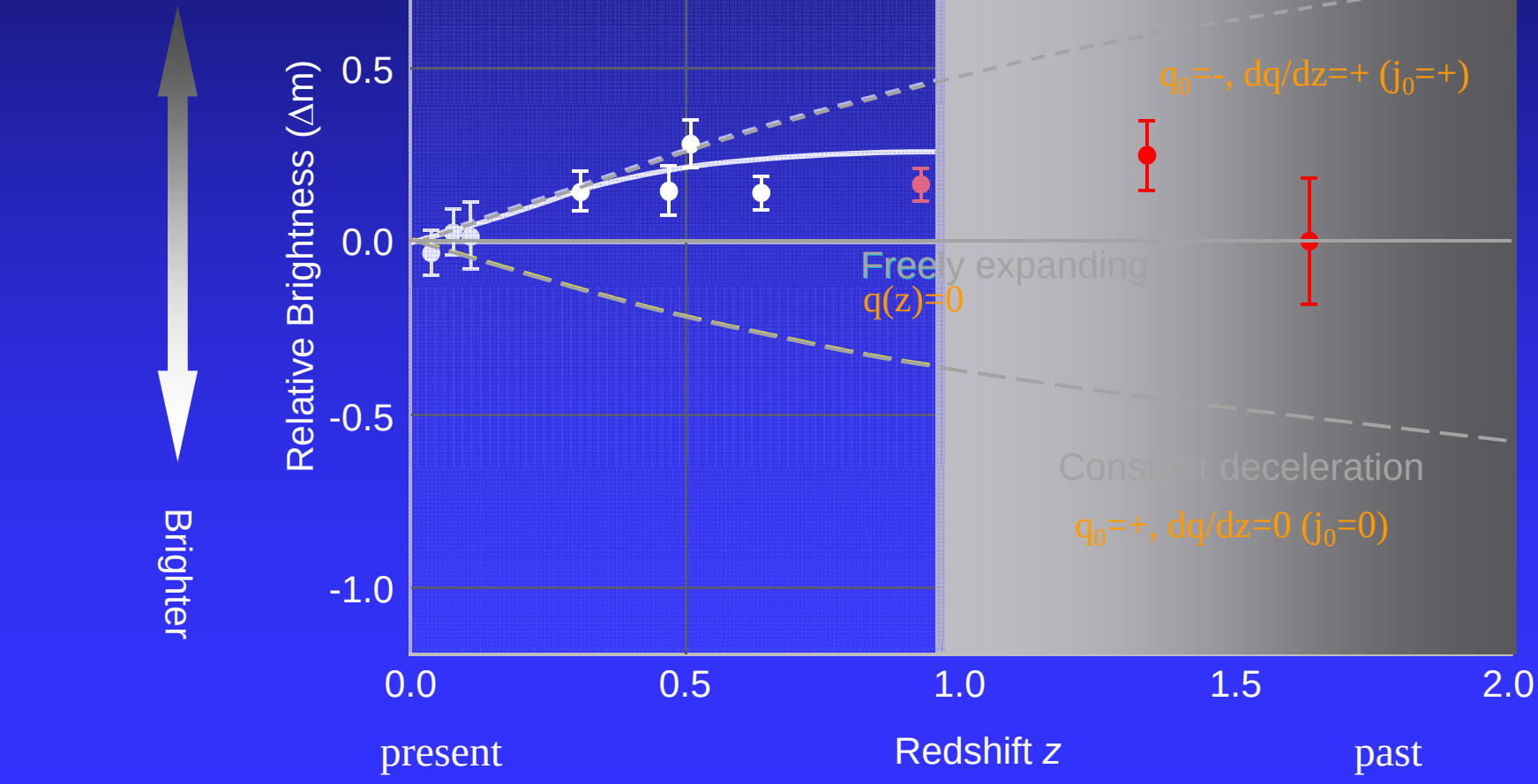
Taylor Expansion of the left handside of the Friedman Eq: a(t)=f(t,H,q,j,…)

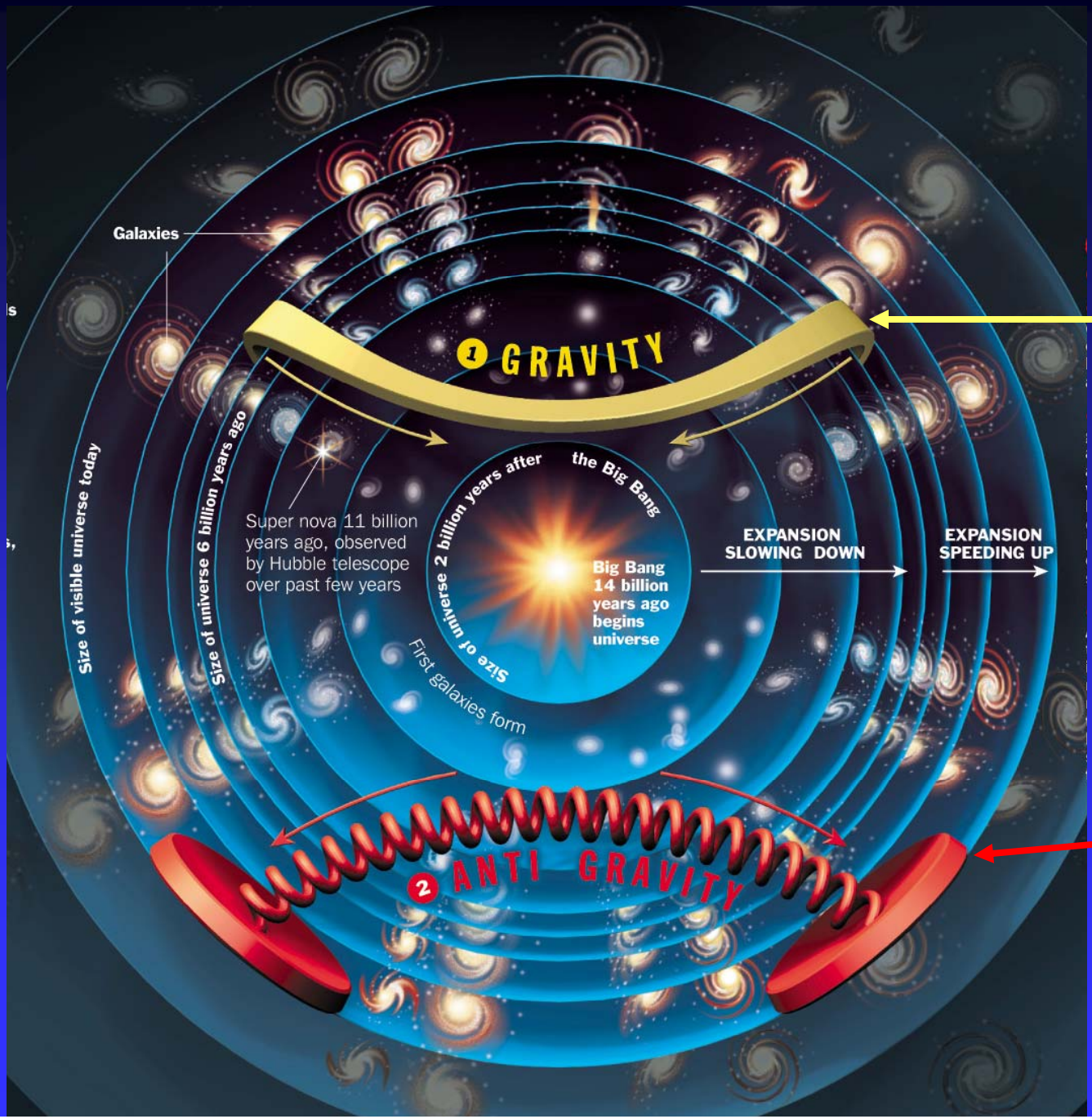
$$H(t) = +\frac{1}{a}\frac{da}{dt},$$

$$q(t) = -\frac{1}{a}\frac{d^2a}{dt^2}\left[\frac{1}{a}\frac{da}{dt}\right]^{-2},$$

$$j(t) = +\frac{1}{a}\frac{d^3a}{dt^3}\left[\frac{1}{a}\frac{da}{dt}\right]^{-3},$$

$$s(t) = +\frac{1}{a}\frac{d^4a}{dt^4}\left[\frac{1}{a}\frac{da}{dt}\right]^{-4}.$$

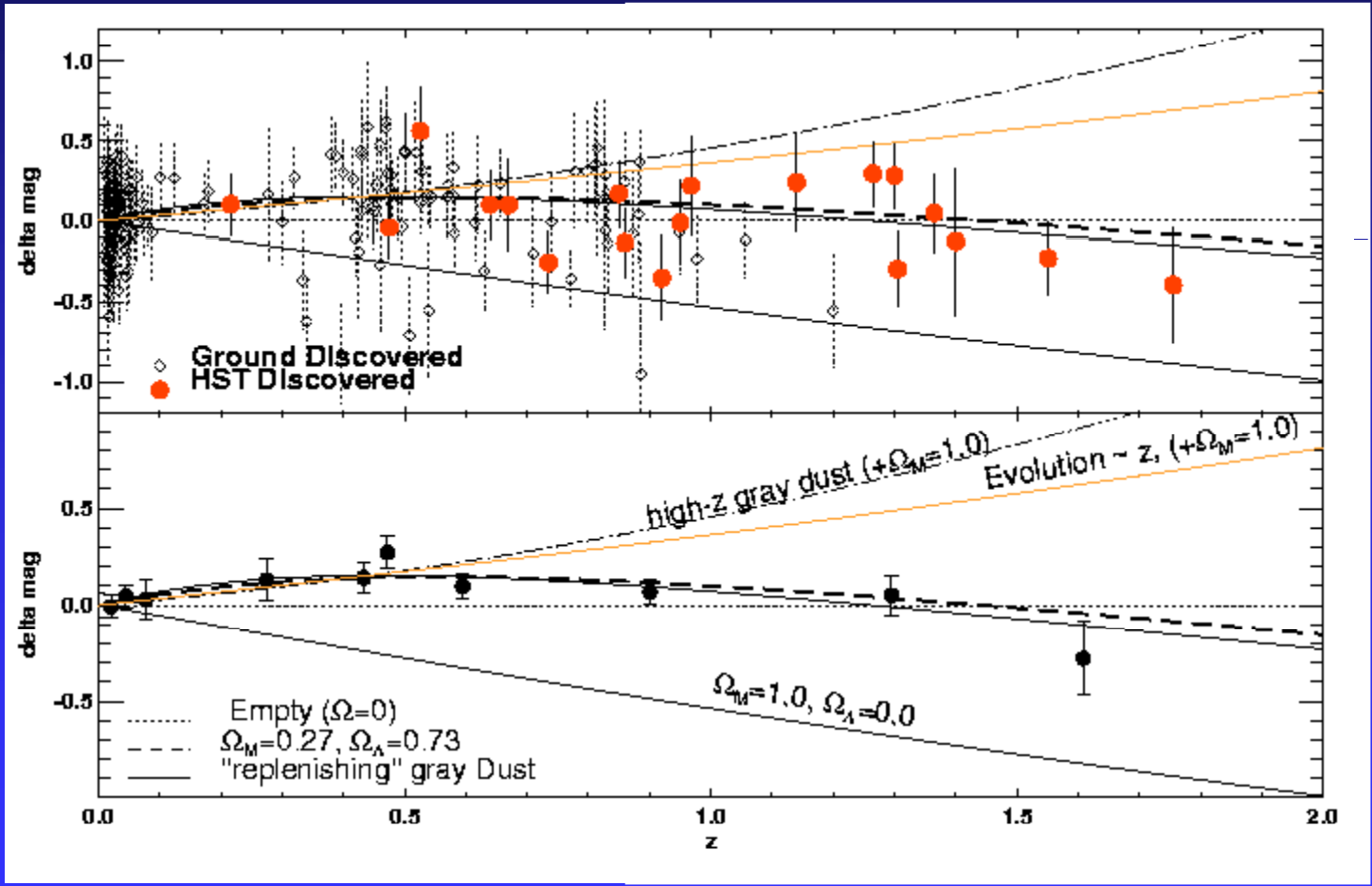




Dark Matter pulls

Dark Energy pushes

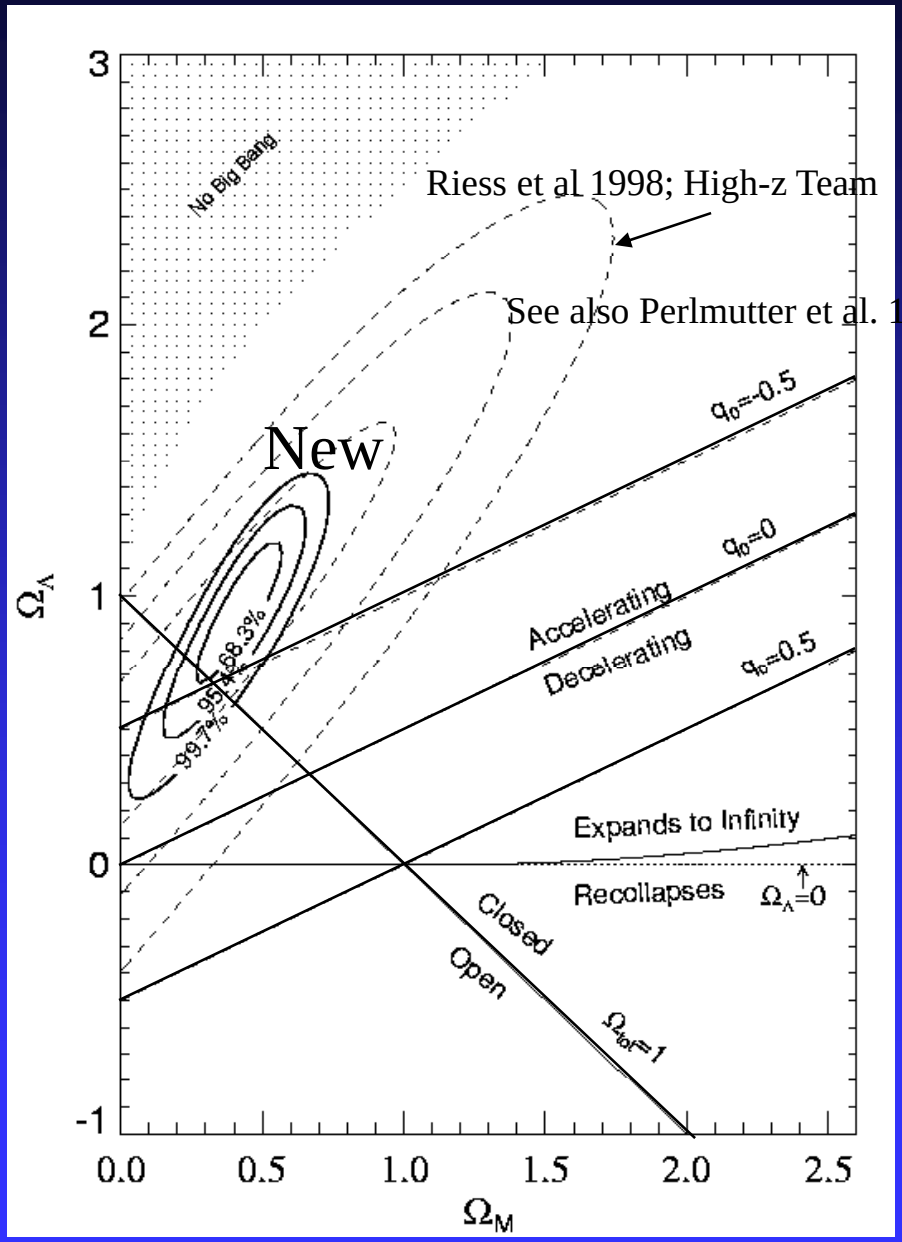
Is Cosmic Acceleration Real?



(If the Dark Energy is Lambda), Updated Constraints

factor of 7 improvement!

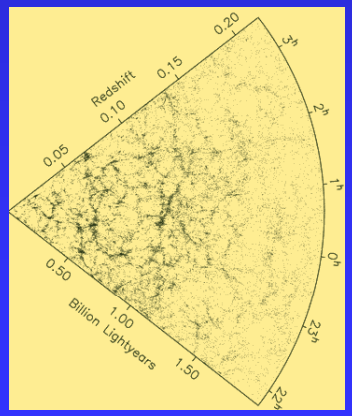
$d_L\ (\Omega_M; \Omega_\Lambda)$-$d_{L,0}$

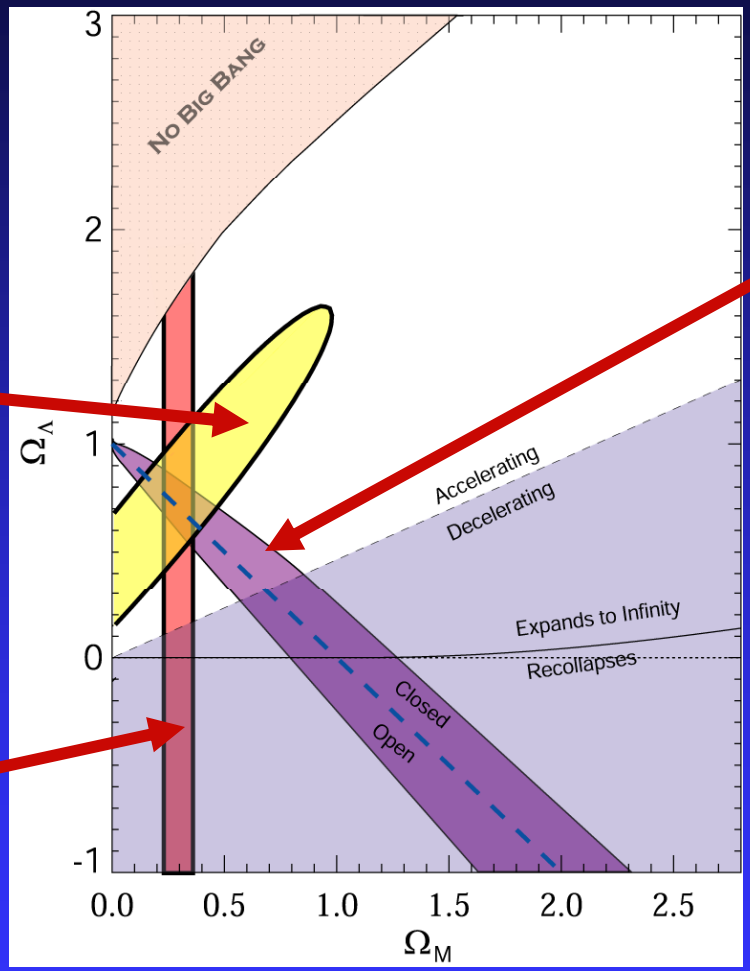


If Dark Energy is Real…

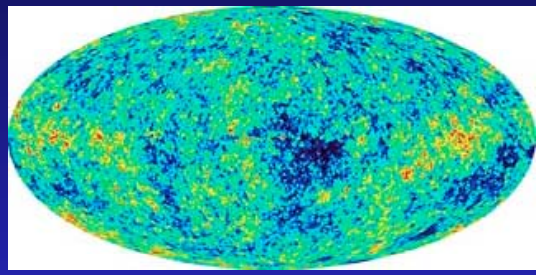
SNe Ia

LSS

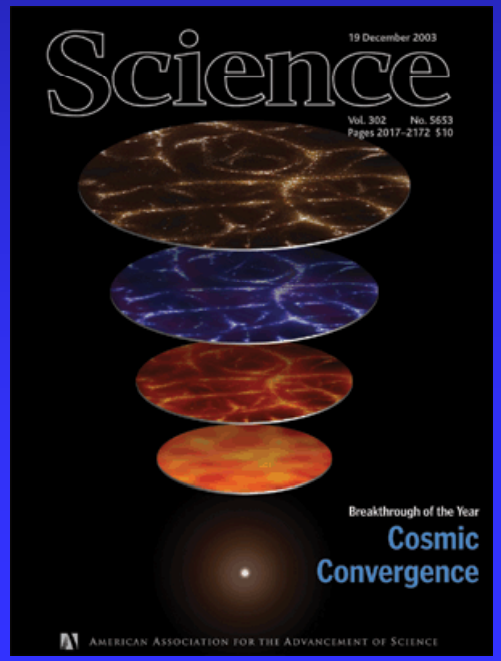




CMB(WMAP)



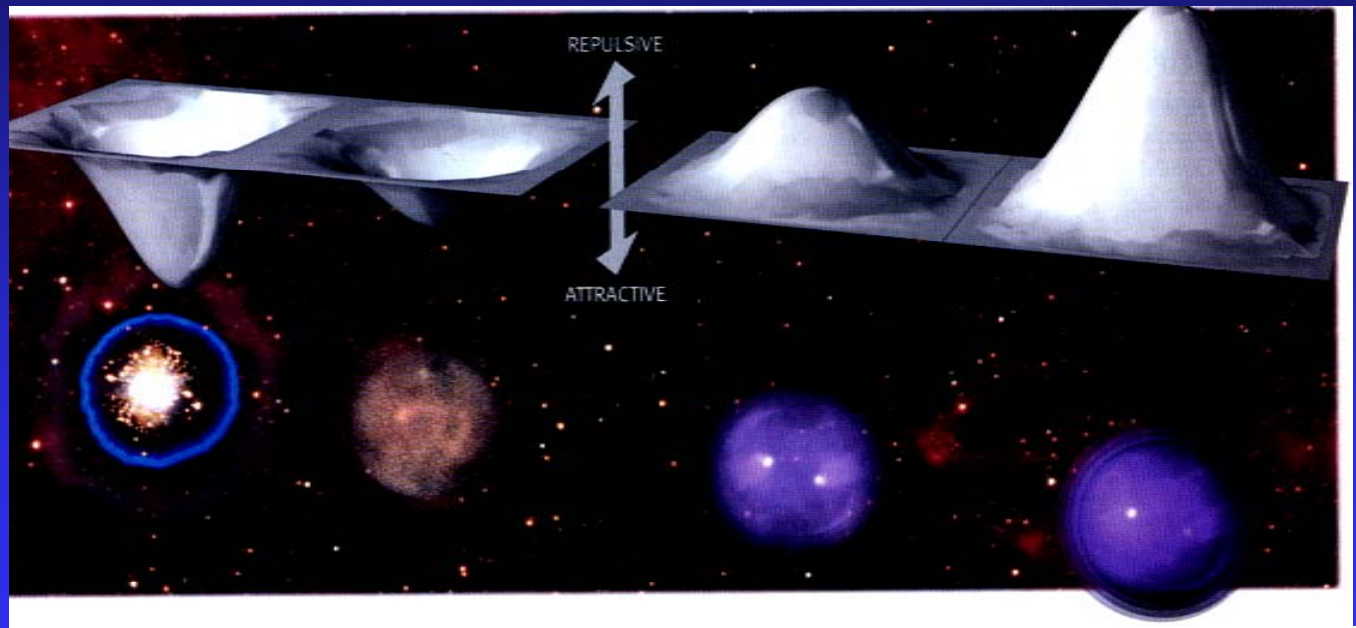
+ ISW, X-ray Clusters



What is it?

Dark Energy is repulsive Gravity
(how strong is it?)

In GR, gravitational force $\propto (\rho + 3p)$

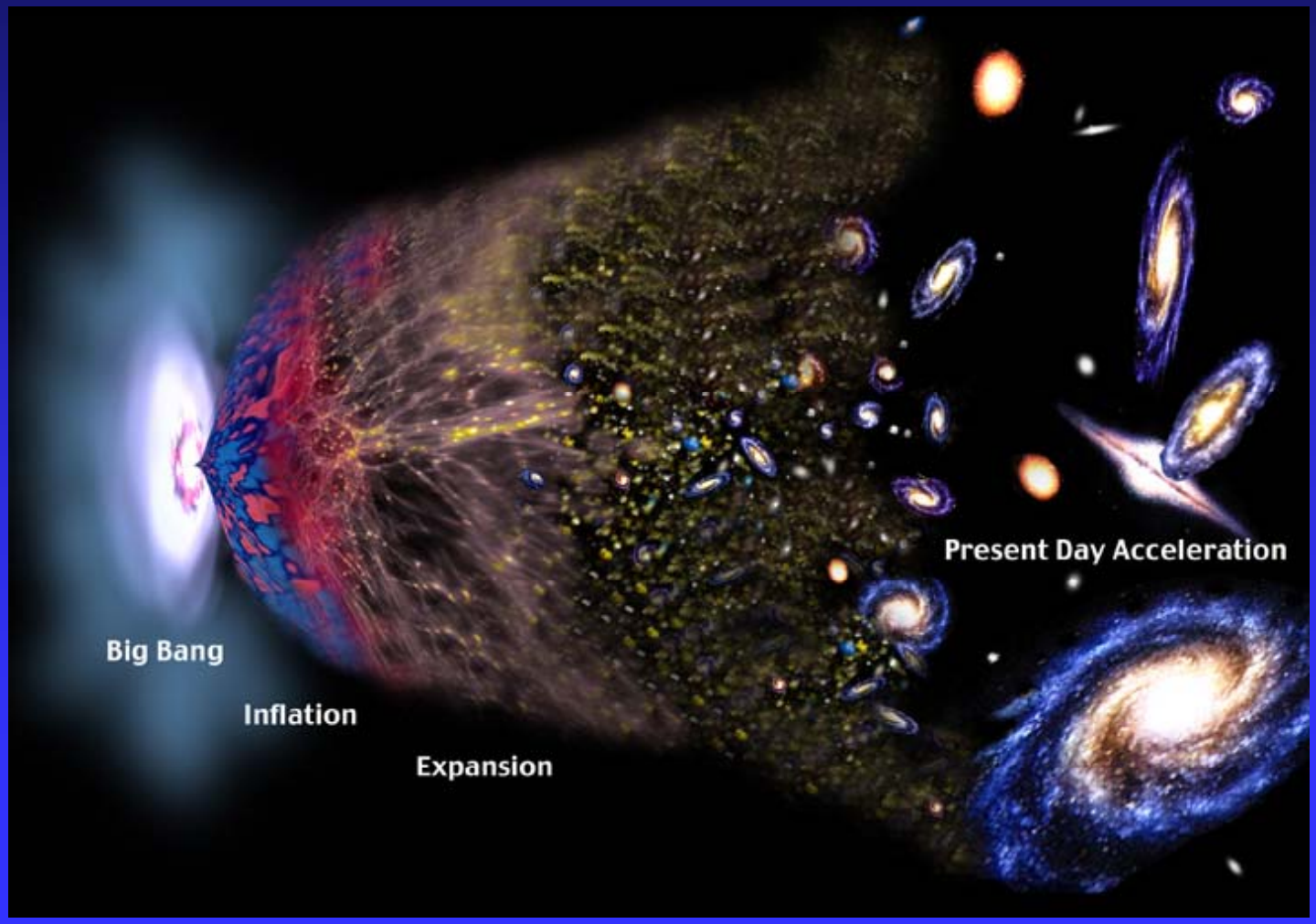


$w = p/\rho =$ +1/3 0 -1/3 <w<-1 -1

If w<-1/3 the Universe accelerates

Before Acceleration there was Deceleration

If the Universe was *always* accelerating apart, how did the galaxies, stars, and planets form?

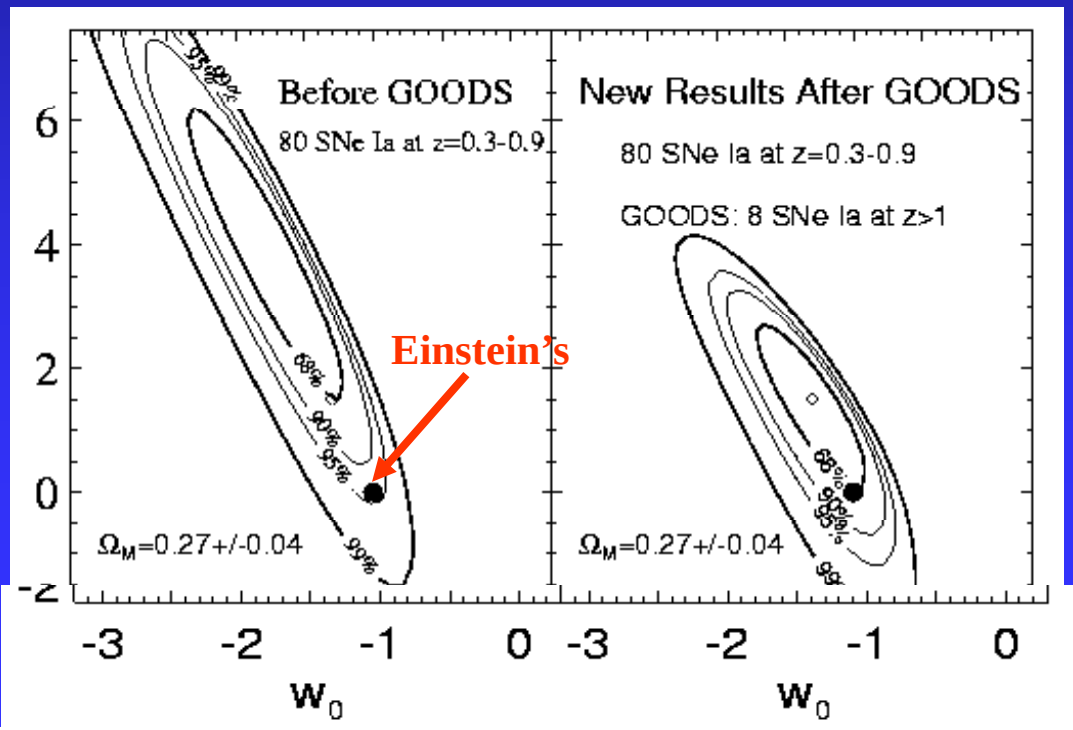


Hubble Space Telescope

Probing Dark Energy

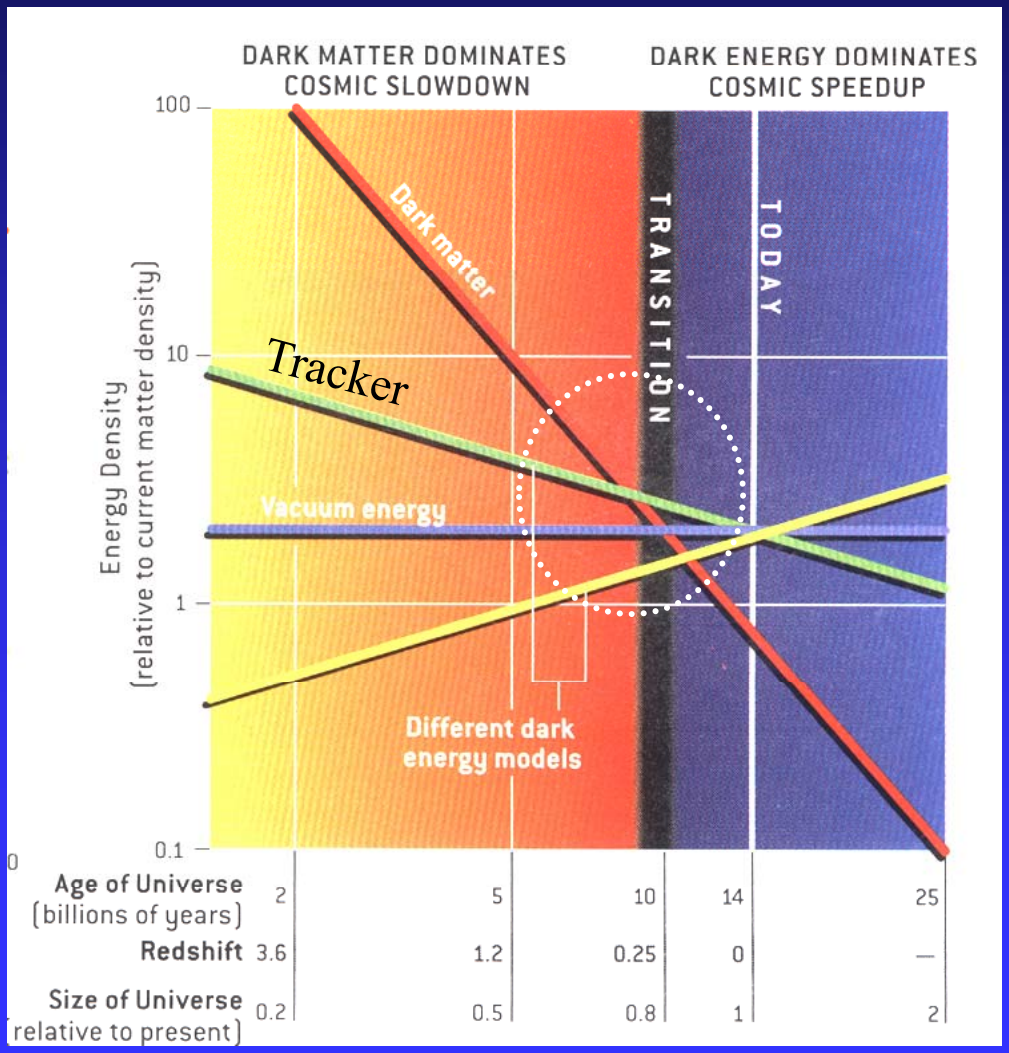
Two fundamental properties/clues of dark energy:
its strength, w_0, AND is it dynamic or static, i.e. is w'=0?

- **We have doubled our knowledge of w_0 and w' in 1 year with HST**
- **Einstein's model now looks better than ever, a way to go…**



Dark Energy: Static or Dynamic?

$\frac{dw}{dz} = ?$ (ultimately, w(z)…)



Dark Energy: Future Studies

1. Observe more SNe at z > 1 → 2007/08

2. HST/WFC3 to get Sne at z > 1.5

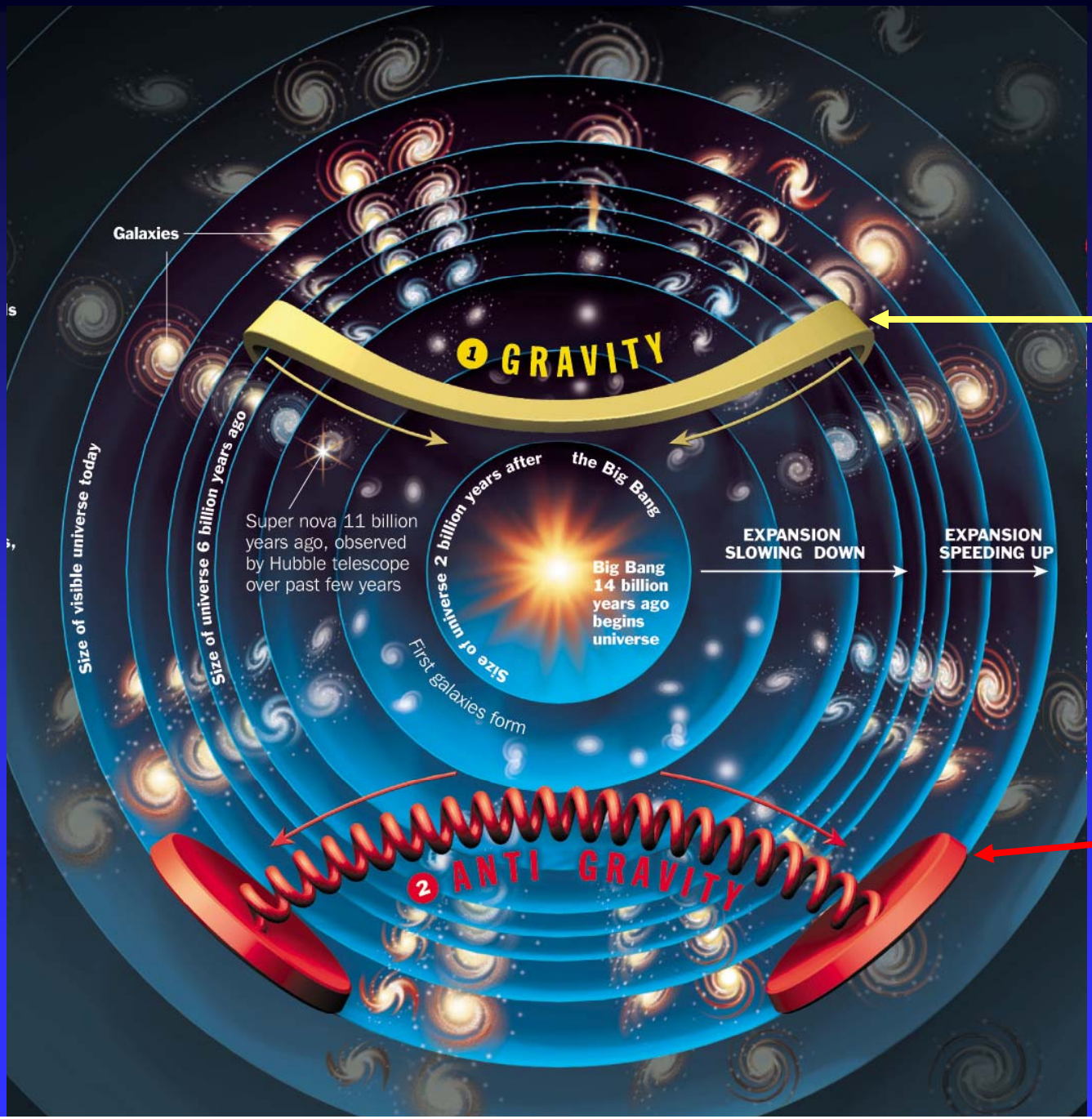
HST servicing mission →2008

3. Joint Dark Energy Mission (JDEM) and SNAP → 2014

Joint Dark Energy Mission (JDEM) ~2015???
SDT just formed…

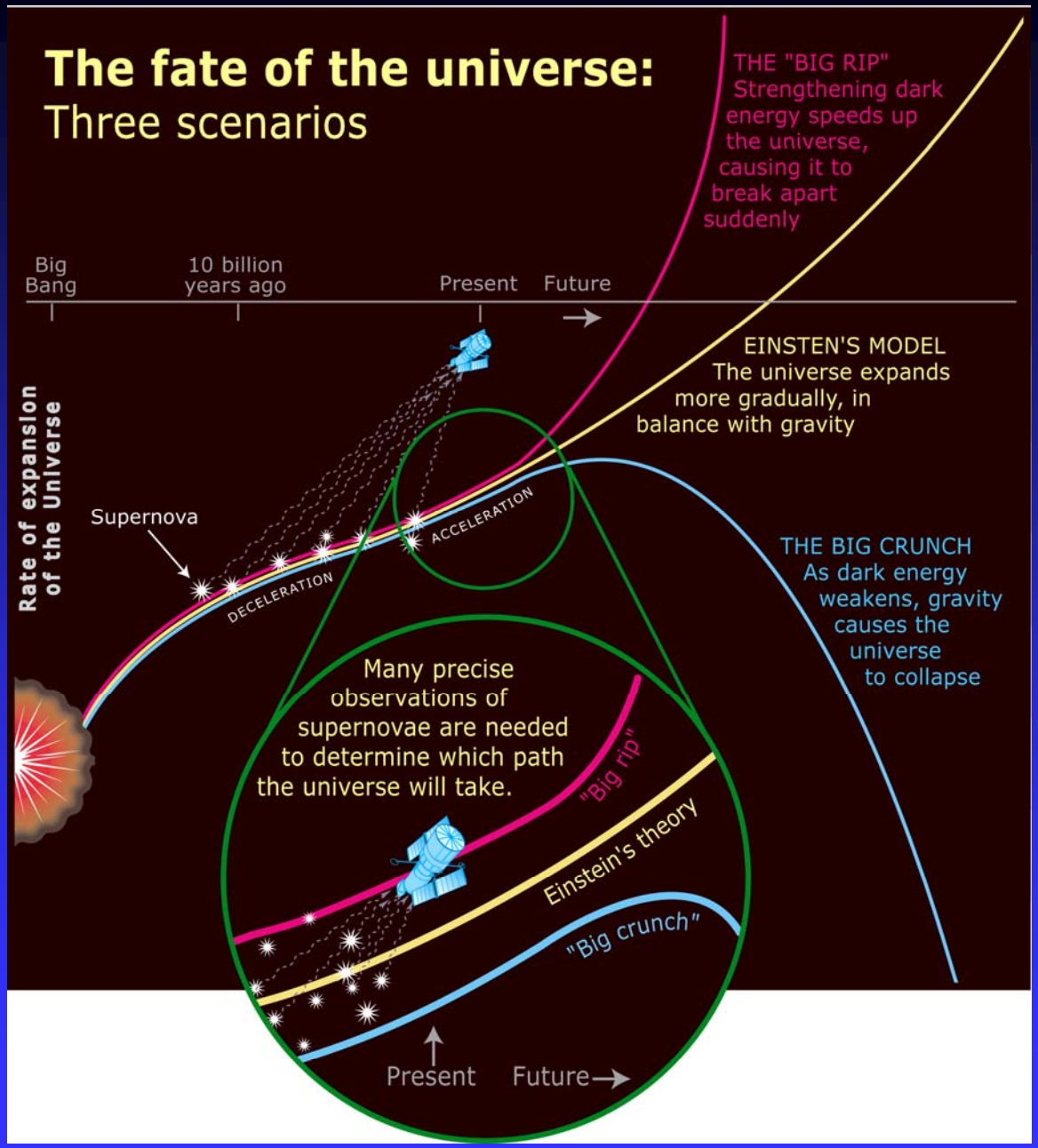
Systematics: we will need to control them to ~1%

The physics of Dark Energy will determine the fate of the Universe.



Dark Matter pulls

Dark Energy pushes


The fate of the universe:
Three scenarios
THE "BIG RIP"
Strengthening dark energy speeds up the universe, causing it to break apart suddenly
Big Bang
10 billion years ago
Present
Future
EINSTEN'S MODEL
The universe expands more gradually, in balance with gravity
Rate of expansion of the Universe
Supernova
DECELERATION
ACCELERATION
THE BIG CRUNCH
As dark energy weakens, gravity causes the universe to collapse
Many precise observations of supernovae are needed to determine which path the universe will take.
"Big rip"
Einstein's theory
"Big crunch"
Present
Future

T-minus 10 minutes to Rip…

TABLE I: The history and future of the Universe with $w = -3/2$ phantom energy.

Time	Event
$\sim 10^{-43}$ s	Planck era
$\sim 10^{-36}$ s	Inflation
First Three Minutes	Light Elements Formed
$\sim 10^{5}$ yr	Atoms Formed
~ 1 Gyr	First Galaxies Formed
~ 15 Gyr	*Today*
$t_{rip} - 1$ Gyr	Erase Galaxy Clusters
$t_{rip} - 60$ Myr	Destroy Milky Way
$t_{rip} - 3$ months	Unbind Solar System
$t_{rip} - 30$ minutes	Earth Explodes
$t_{rip} - 10^{-19}$ s	Dissociate Atoms
$t_{rip} = 35$ Gyrs	Big Rip

The End