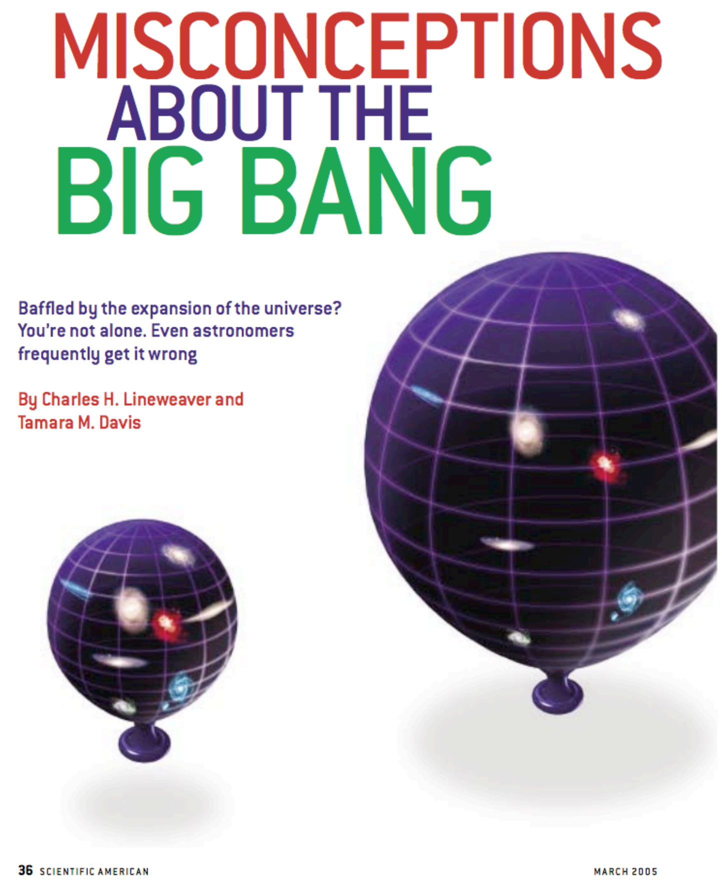
Tamara Davis, Cosmological Confusion,
Oxford RAL, 9 June 2010

Cosmological Confusion

…revealing common misconceptions about the big bang, the expansion of the universe and cosmic horizons.



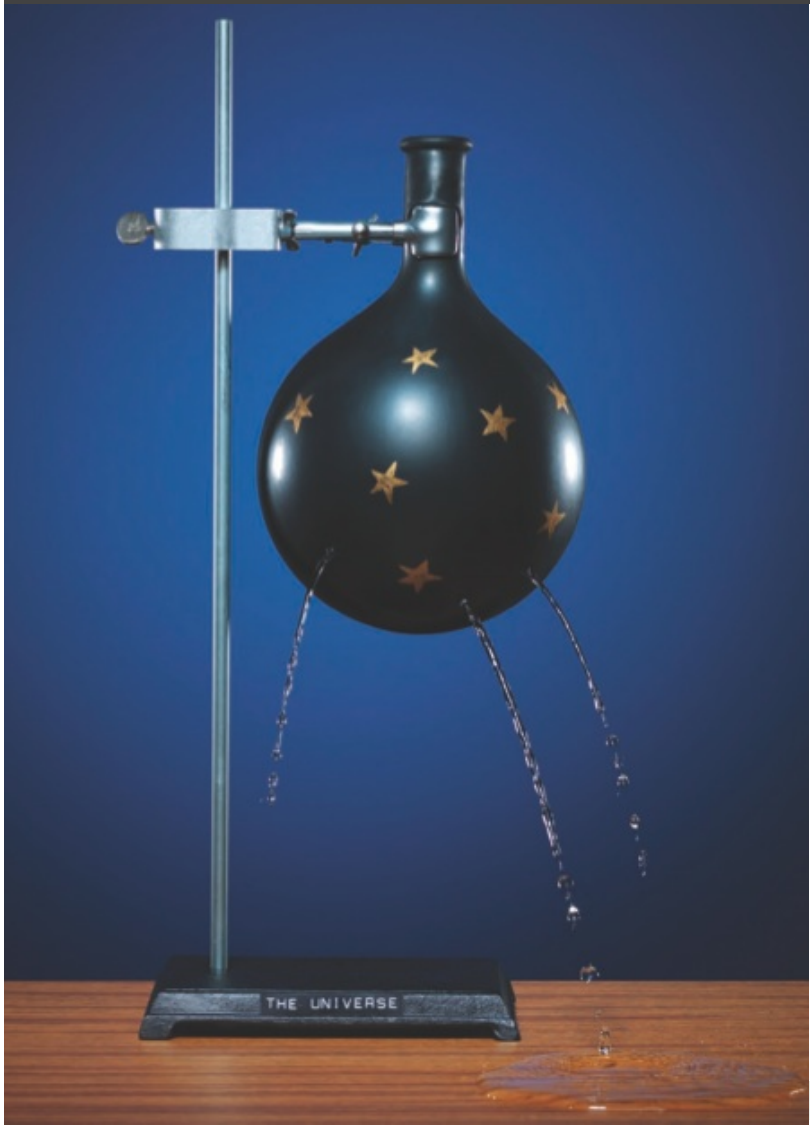
MISCONCEPTIONS ABOUT THE BIG BANG

Baffled by the expansion of the universe? You're not alone. Even astronomers frequently get it wrong

By Charles H. Lineweaver and Tamara M. Davis

36 SCIENTIFIC AMERICAN MARCH 2005

Cosmological confusion



- Dark energy – the first confusion.
- The basics – coordinates and velocities
- Horizons – limits of knowledge
- Can space expand faster than the speed of light?
- Stretching space – What is expanding space? What expands when space expands? Are galaxies dragged along by the expansion?
- Where does the energy go in the cosmological redshift?

Can the laws of physics change with time?

Observations

- The universe is expanding, v=HD

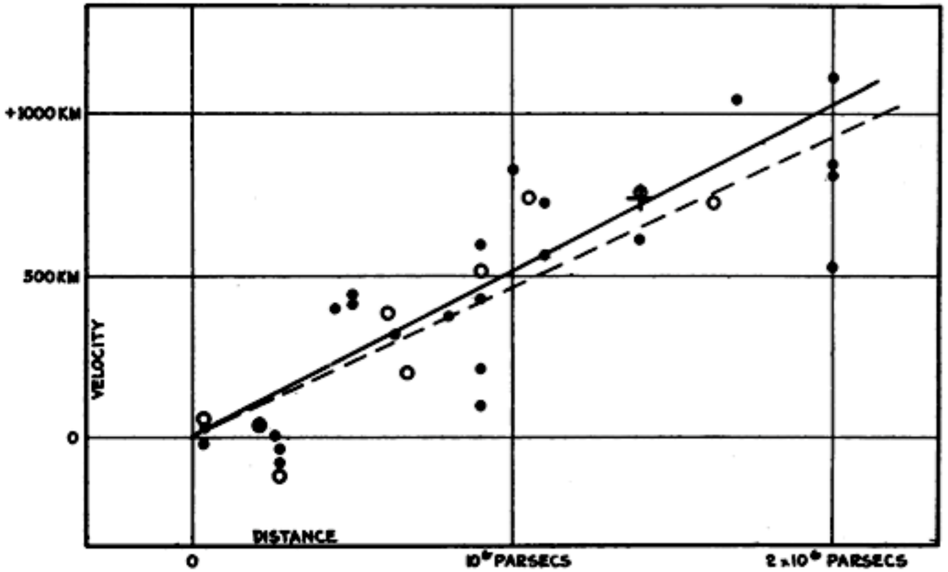
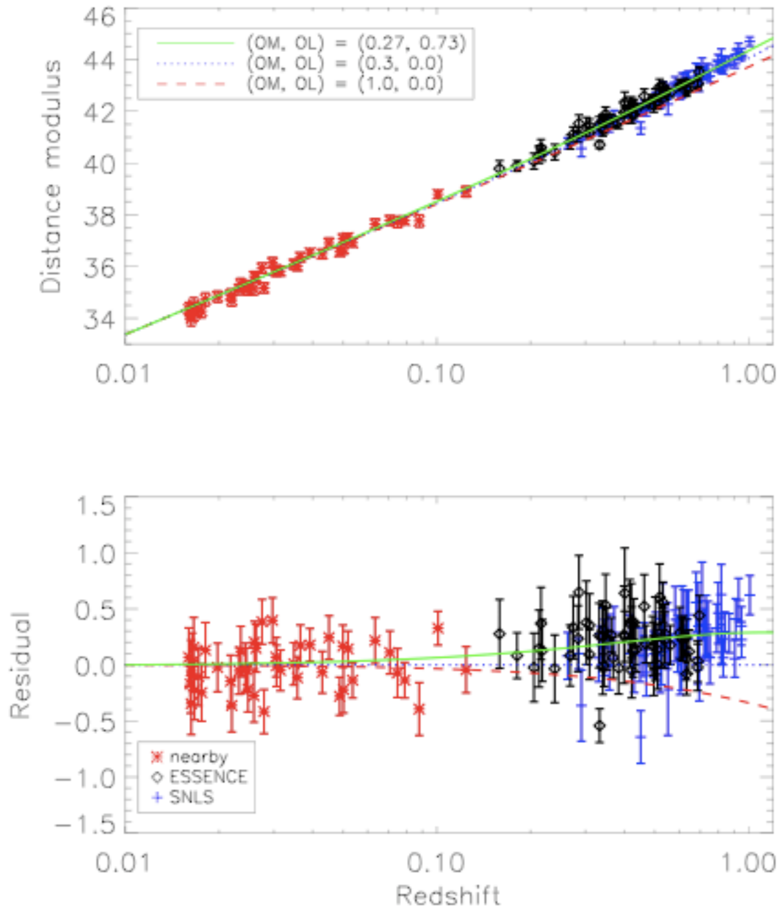


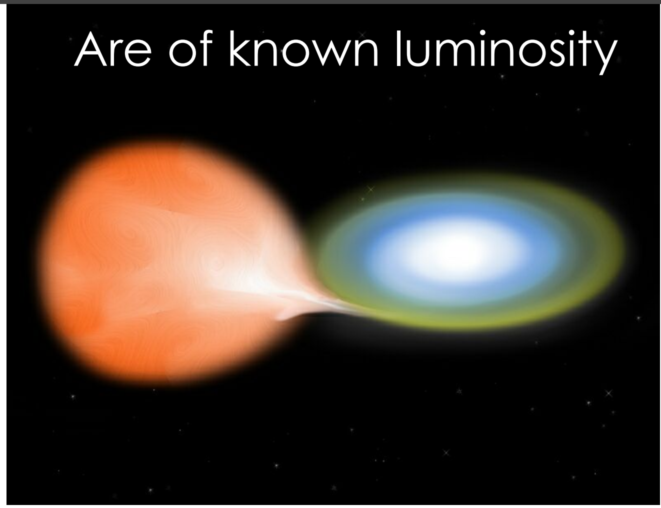
FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.



- The expansion is SPEEDING UP!!

(Contrary to everything we thought we knew about gravity!)

Type Ia supernovae

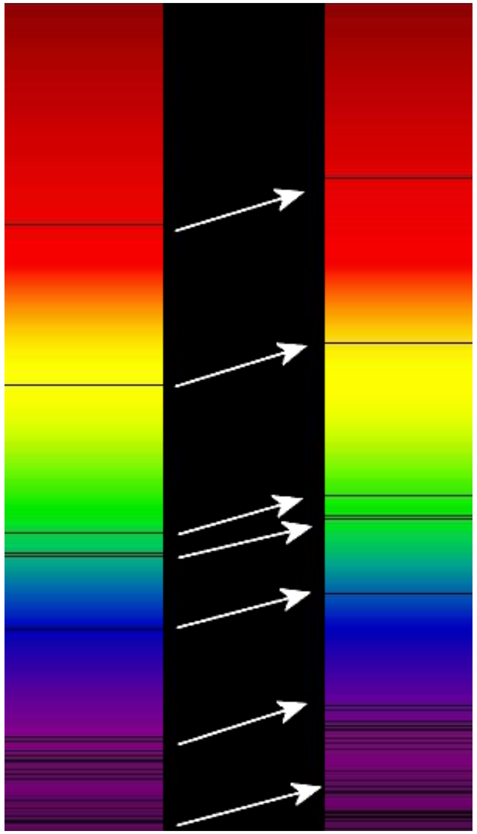


Most likely the explosion of a white dwarf
that is sucking material from a companion
triggered when mass reaches 1.4 M_{solar}

How to measure deceleration

Redshift gives velocity…

Brightness gives distance…



…which also gives time.

Velocity vs time gives de(ac)celeration

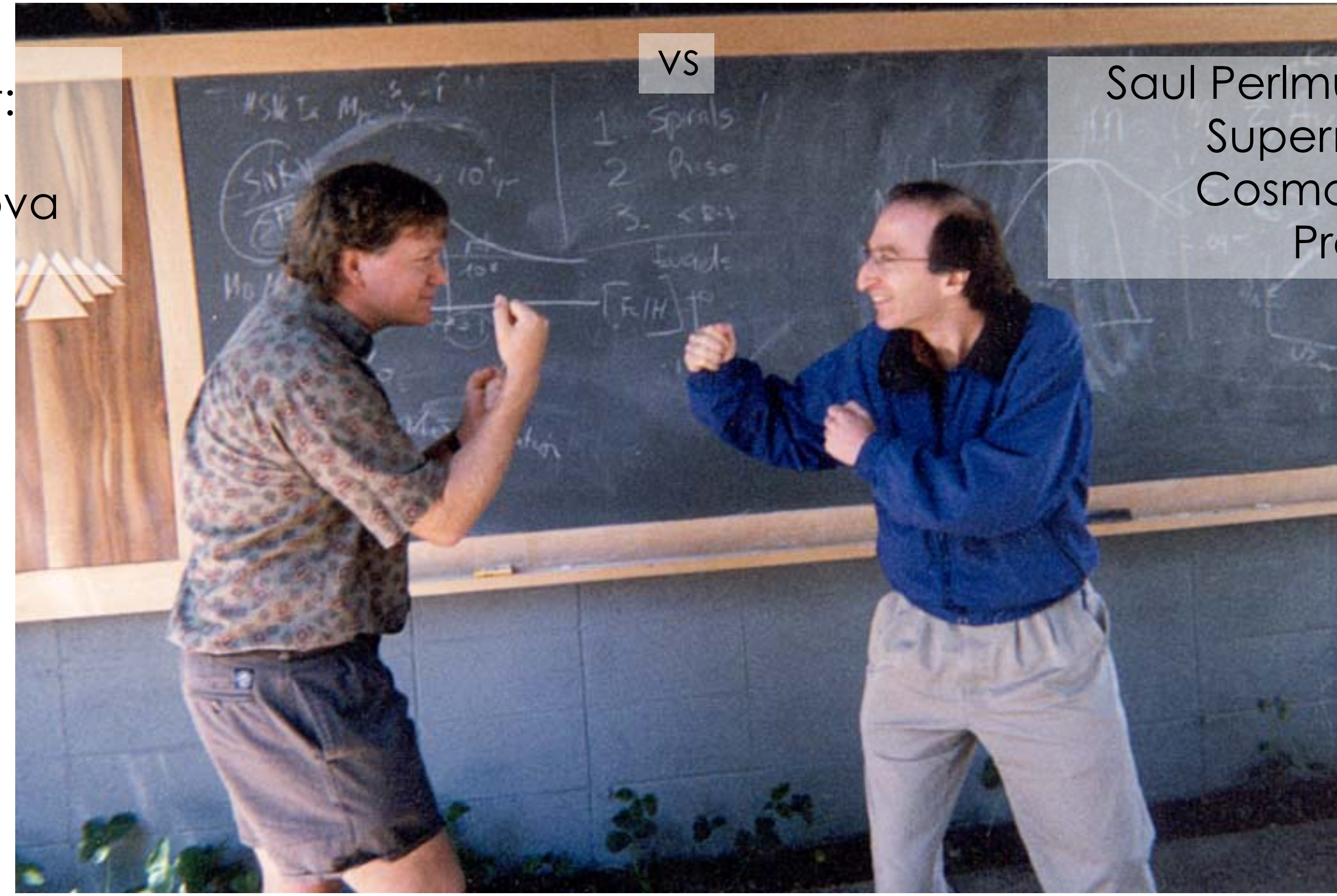
Two competing teams

- 1998/1999

Brian Schmidt:
High-z supernova team

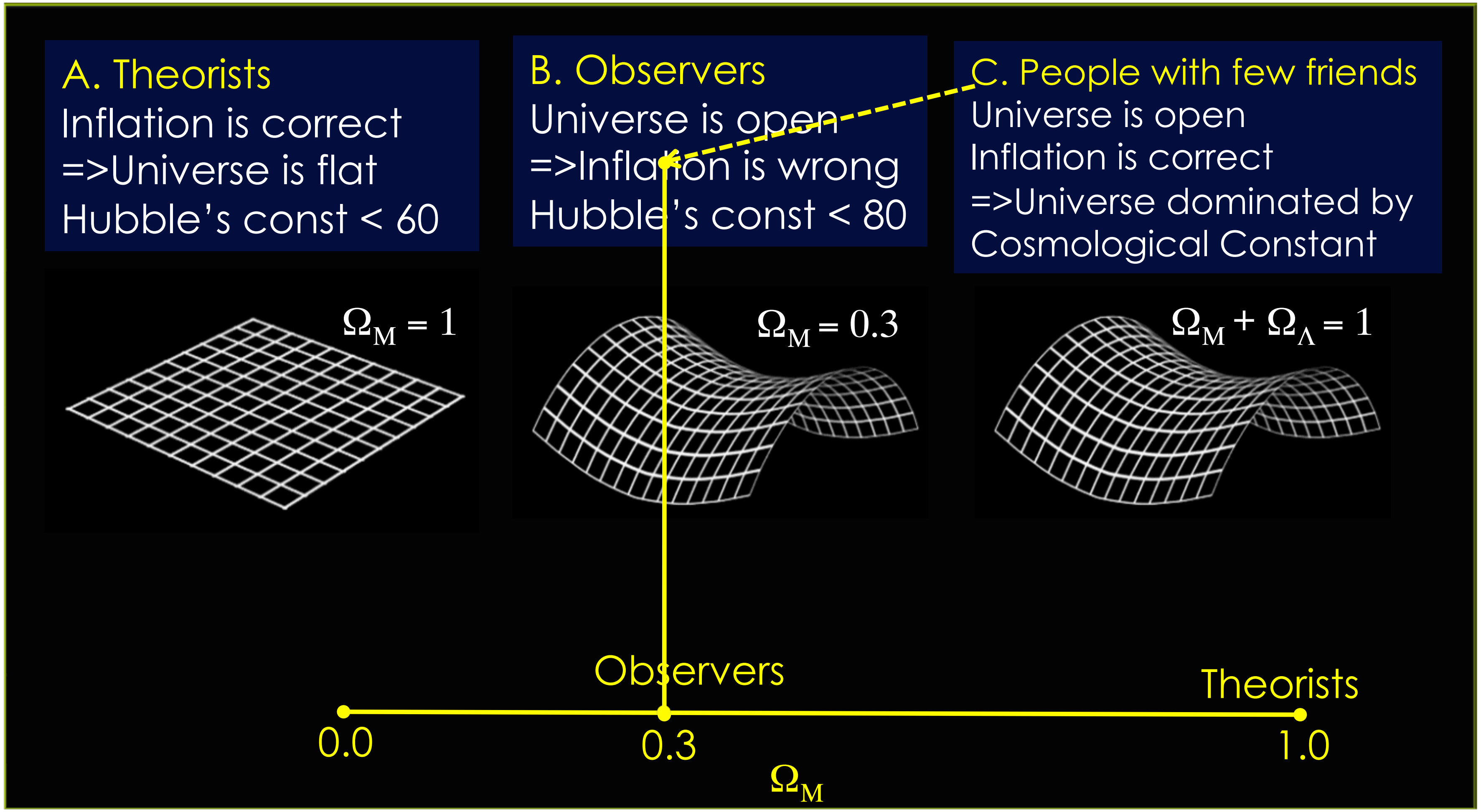
vs

Saul Perlmutter:
Supernova Cosmology Project

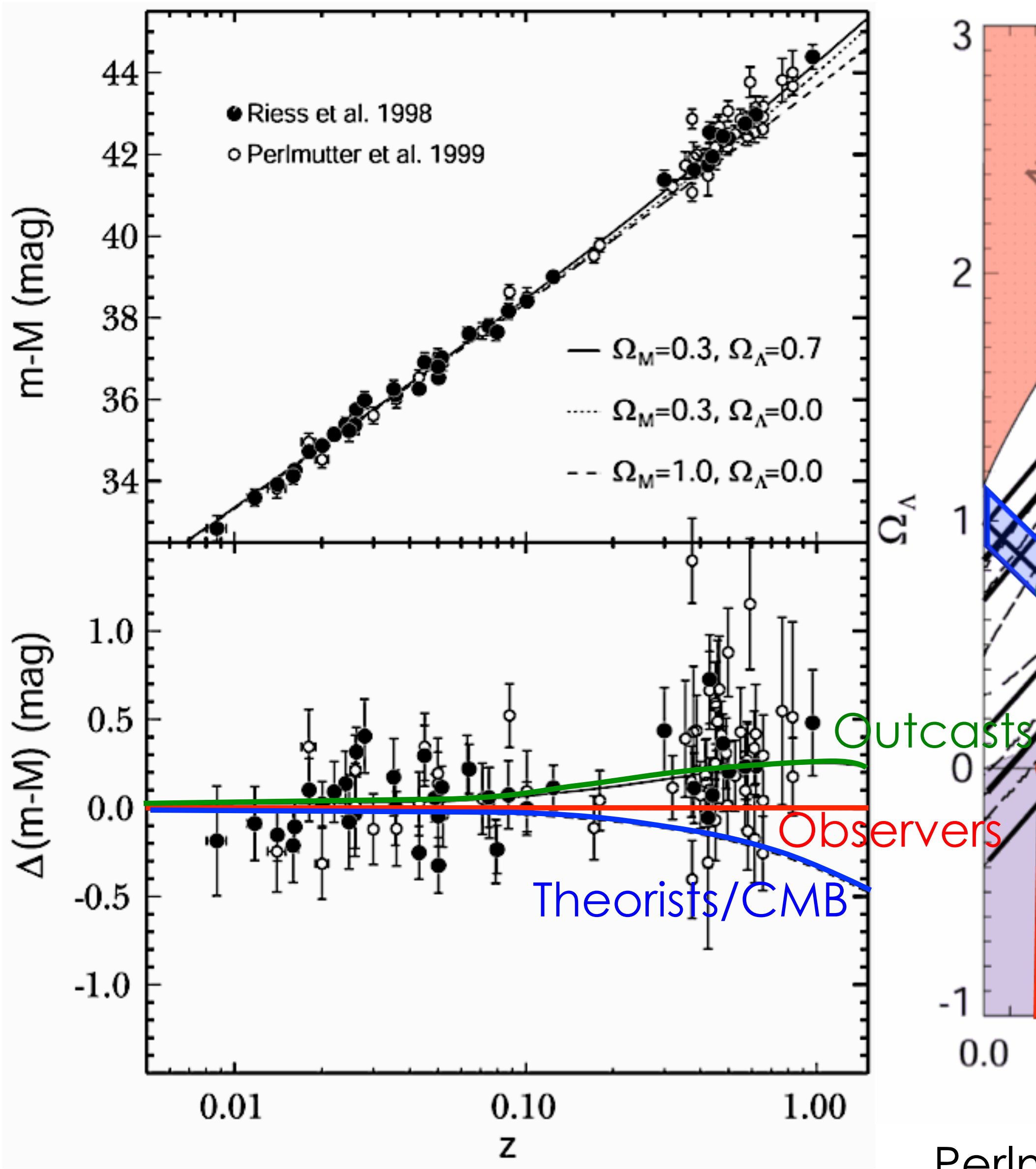


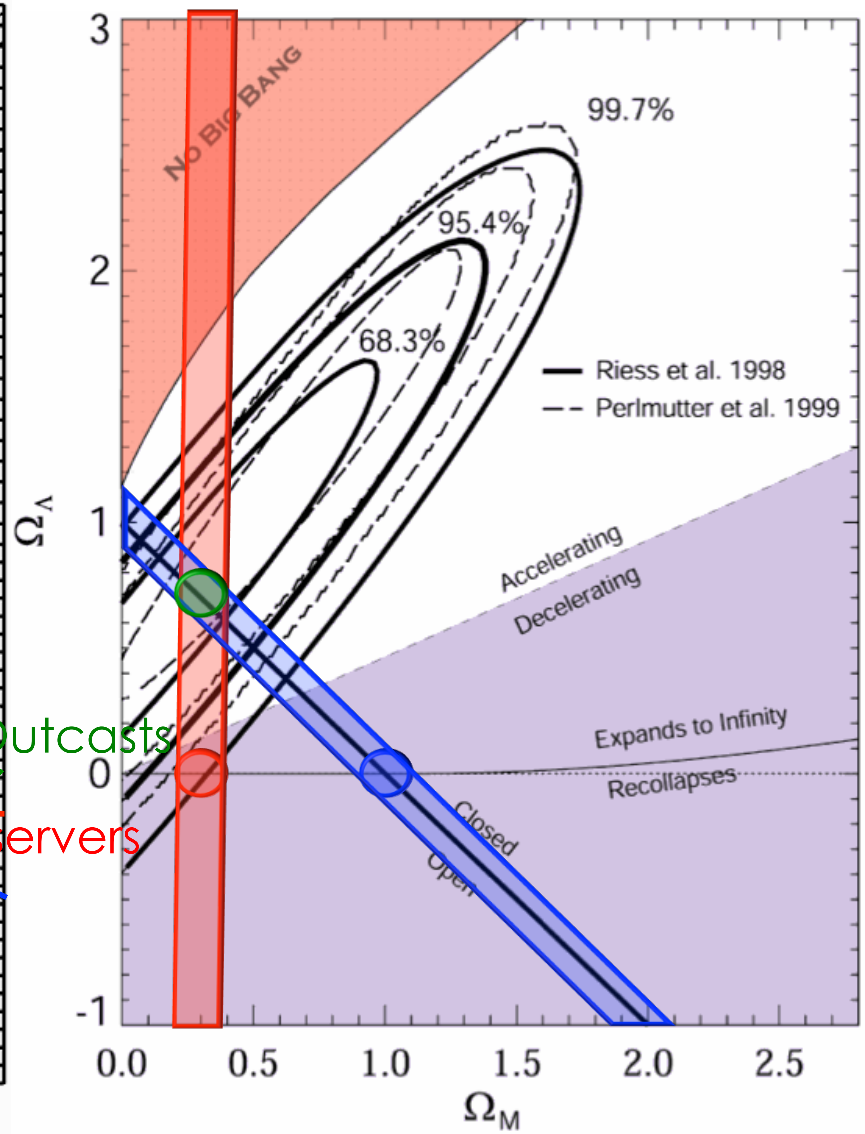
Expected results

- Three camps (as classified by Brian Schmidt)



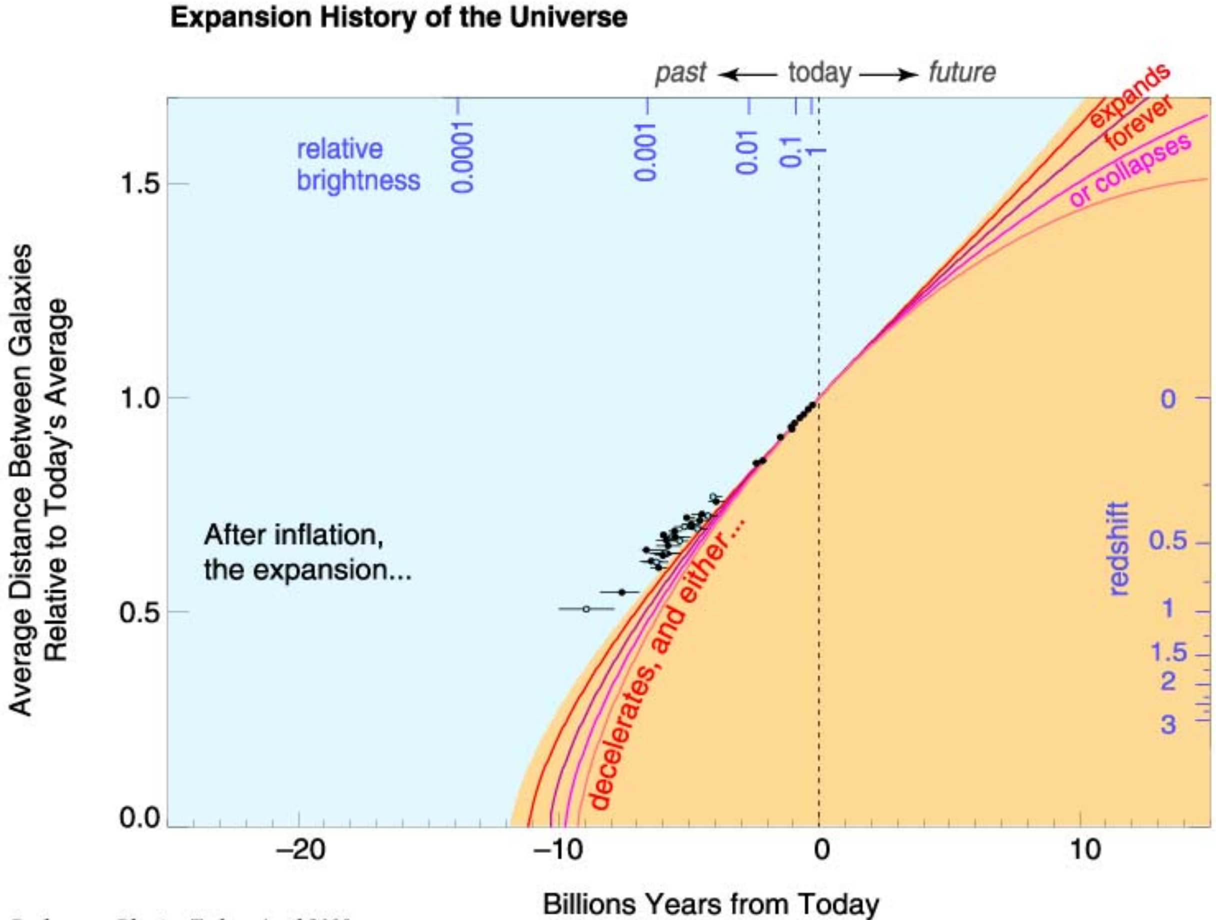
First supernova results





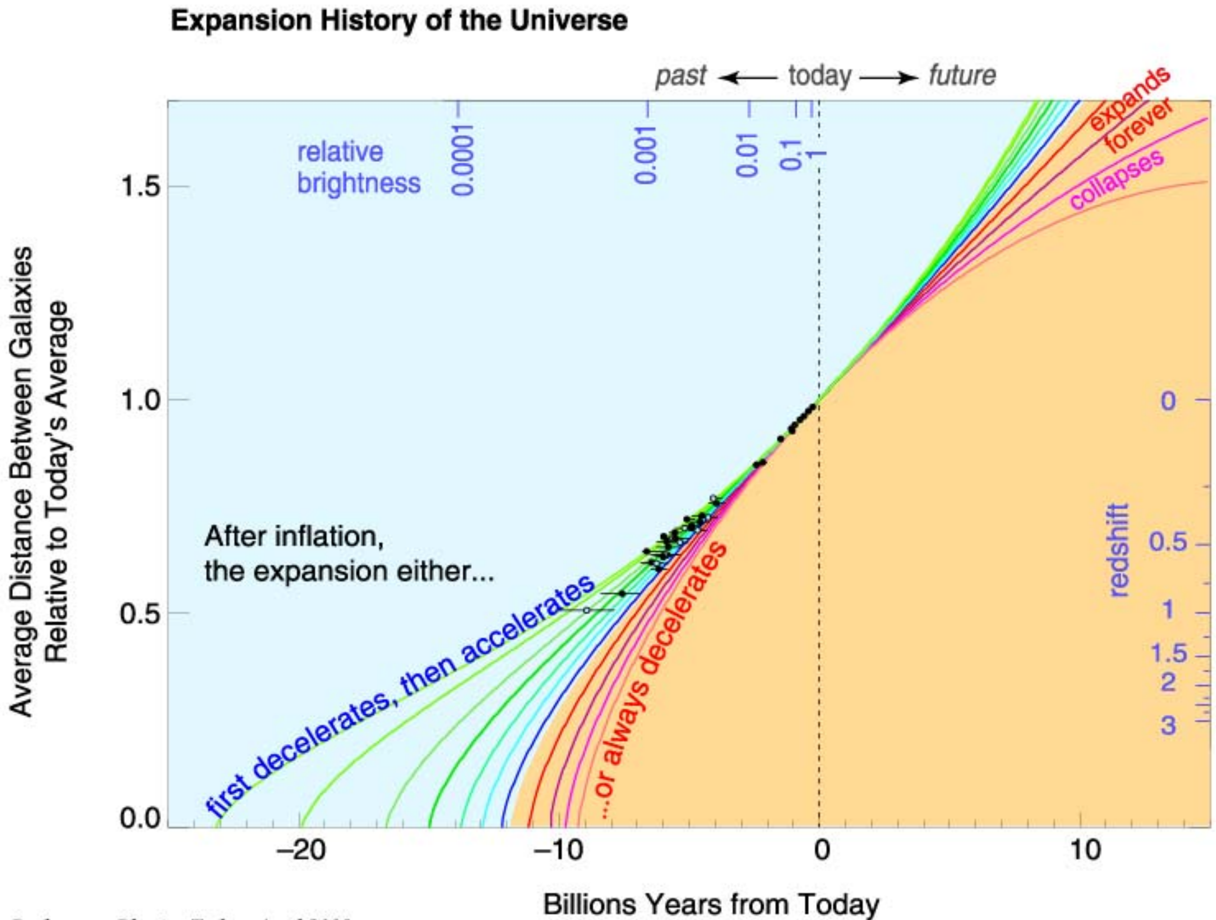
Perlmutter and Schmidt 2003

The Universe we thought we knew...



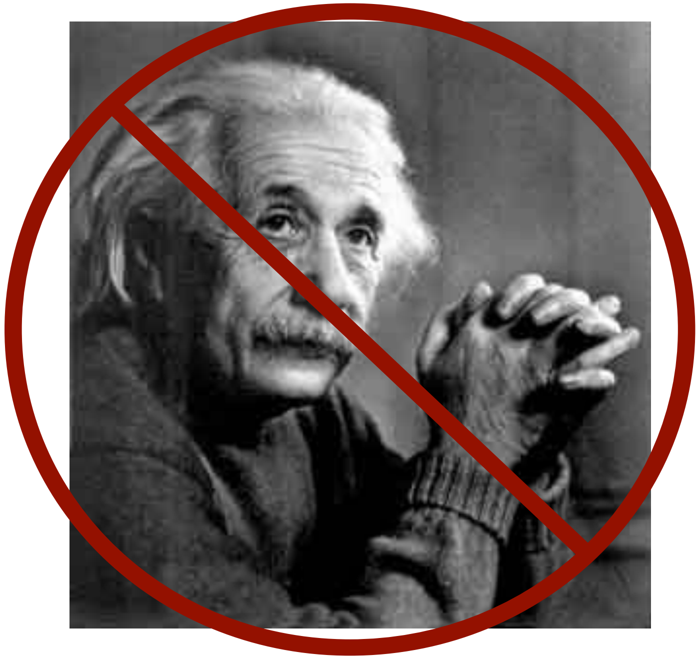
Perlmutter, Physics Today, April 2003

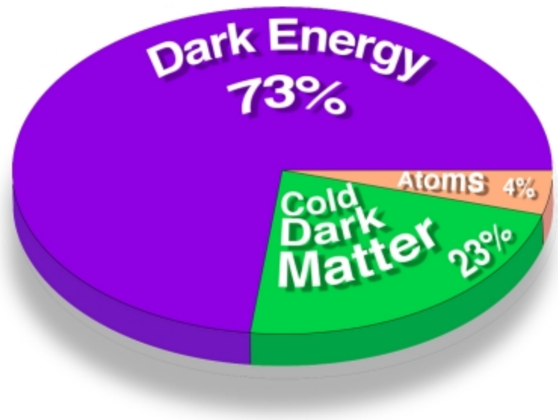
The Universe we live in...



Perlmutter, Physics Today, April 2003

Revolution in Fundamental Physics

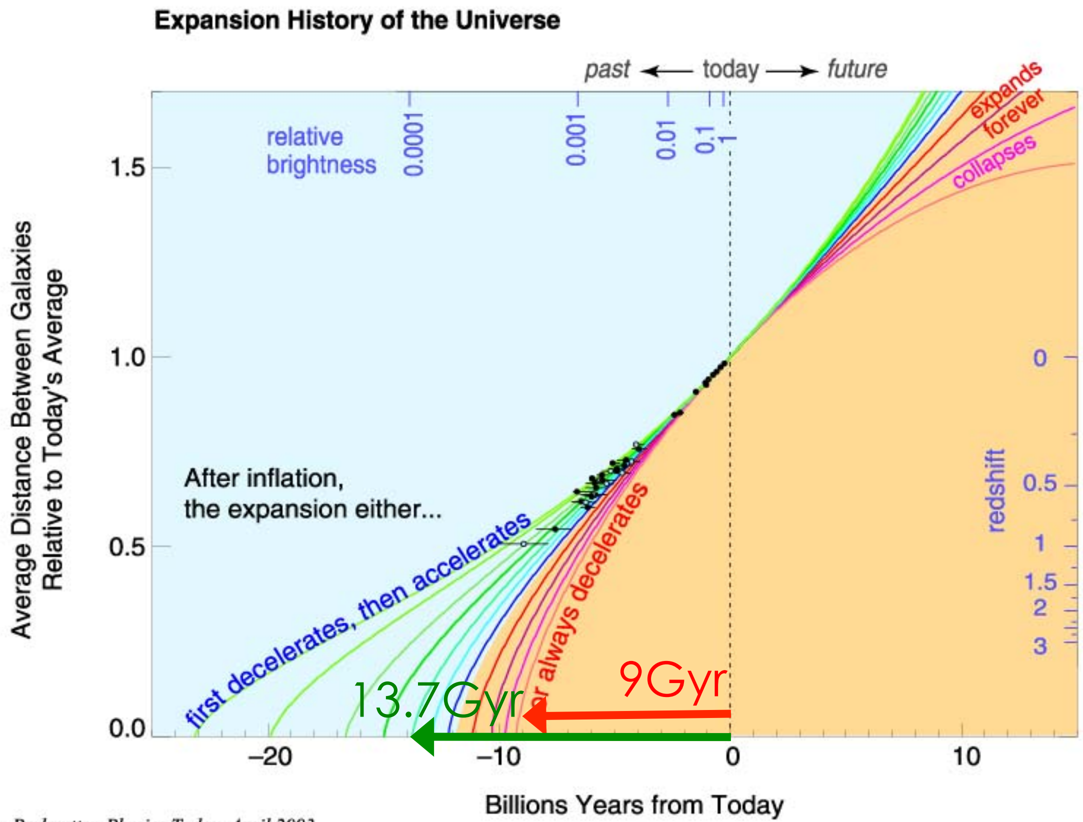




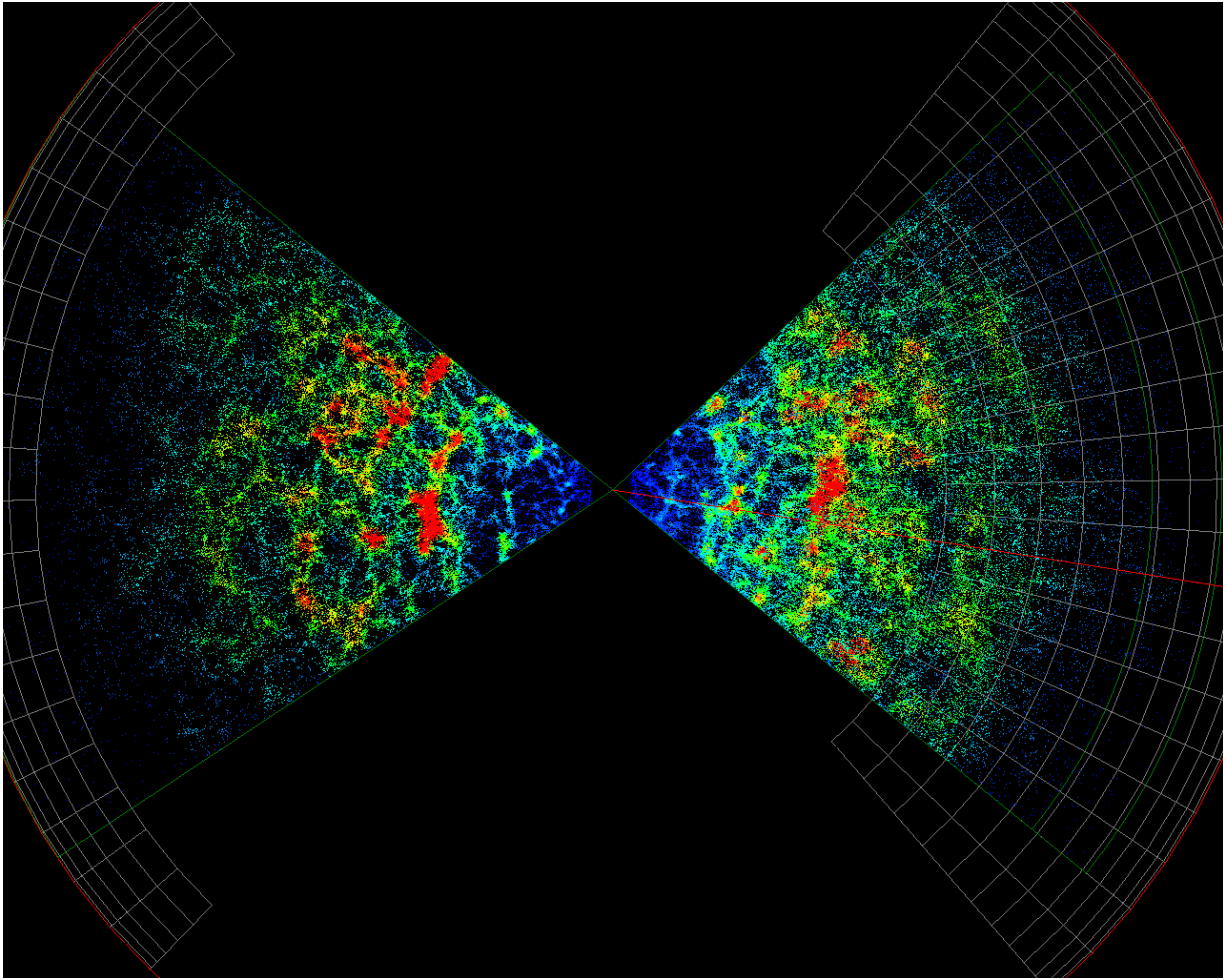
Source: Robert Kirshner
Source: NASA/WMAP Science Team

Path had already been paved

- Explained number counts of galaxies
- Explained the age of the oldest stars



Perlmutter, Physics Today, April 2003



Metric and equation of motion

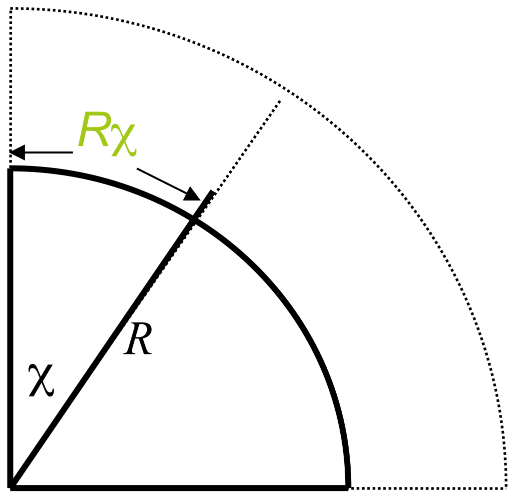
Friedmann-Robertson-Walker metric

$$ds^2 = -c^2dt^2 + R^2(t)\ [\ d\chi^2 + S_k^2(\chi)(d\theta^2+\sin^2\theta\ d\phi^2)\ ]$$

Radially: $ds^2 = -c^2dt^2 + R^2(t)d\chi^2$

Photon: $ds=0 \Rightarrow c = R\ d\chi/dt$

Time slice: $dt=0 \Rightarrow D = R\chi$



Velocity: $v= dD/dt = (dR/dt)\chi + R(d\chi/dt)$

Metric and equations of motion

- Geodesic equations

$$\frac{d^2x^\gamma}{d\tau^2} + \Gamma^\gamma_{\alpha\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau} = 0.$$

- Only non-vanishing Christoffel symbols

$$\Gamma^1_{01} = \Gamma^1_{10} = \frac{\dot{R}}{R}, \qquad \Gamma^0_{11} = \frac{R\dot{R}}{c^2}.$$

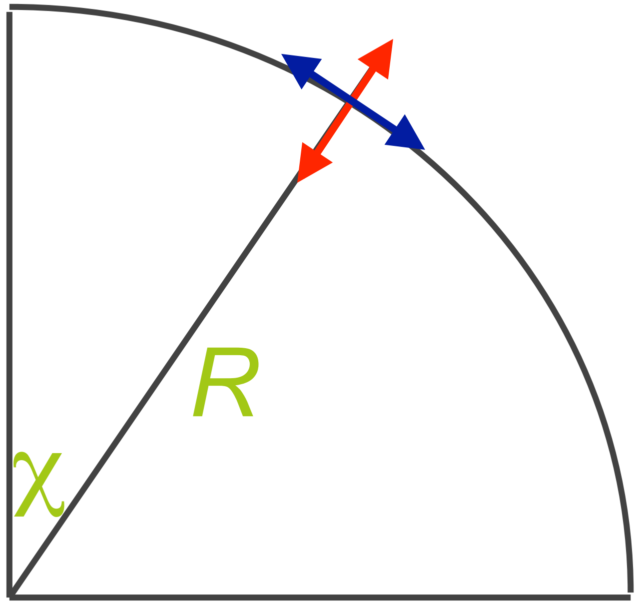
- Friedmann equations

$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \frac{\Omega_x}{a^{3(1+w)}}$$

Two types of velocity

- Velocity

$$v = \frac{dR}{dt}\chi + R\frac{d\chi}{dt}$$
$$= v_{recession} + v_{peculiar}$$



Recession velocity

$$v_{recession} = \dot{R}\chi = \frac{\dot{R}}{R}D$$
$$v_{recession} = HD$$
$$\Rightarrow H = \frac{\dot{R}}{R}$$

VIOLATES SPECIAL RELATIVITY ??

Peculiar velocity

$$v_{peculiar} = R\dot{\chi}$$

(photons)

$$c = R\dot{\chi}$$

Who trusts Monty?

The universe itself keeps on
expanding and expanding,
In all of the directions it can whizz,
As fast as it can go,
That's the speed of light you know,
Twelve million miles a minute
and that's the fastest speed there is

Monty Python, The Galaxy Song

Other metrics, other velocities

- Velocity is a coordinate dependent property
- Redshift is measurable and coordinate independent
- We choose FRW because
  - it describes an homogeneous and isotropic universe
  - time is the proper time of comoving observers
  - synchronicity can be measured by the CMB temperature
  - it makes calculations simple
- Other metrics are equally valid,
  - conformal: $ds^2 = R^2(t)\,[\,-c^2dt^2 + d\chi^2 + S_k^2(\chi)(d\theta^2+\sin^2\theta\, d\phi^2)\,]$

We need to understand the implications of our coordinate choice

Superluminal recession

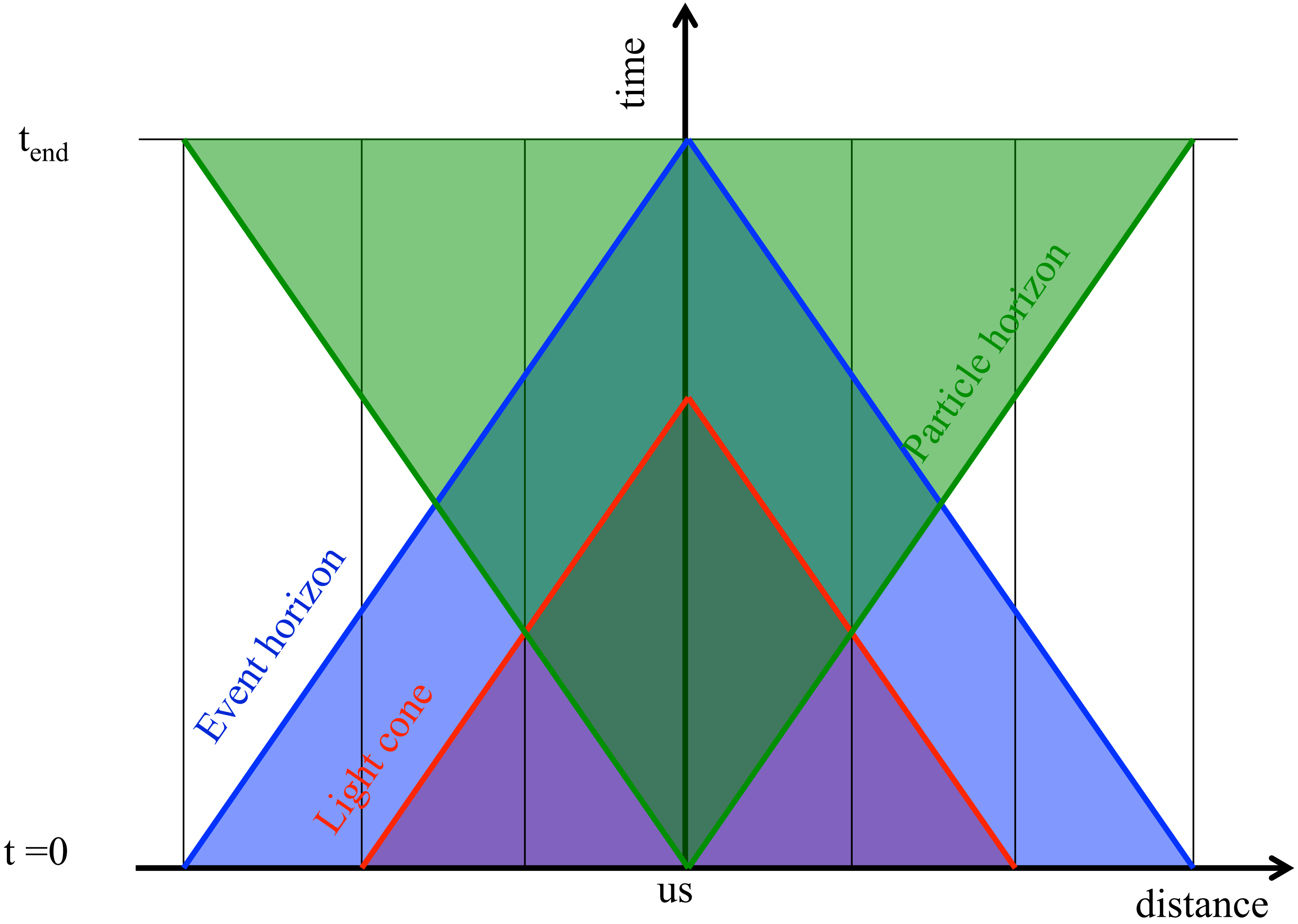
- Yes, recession velocities can exceed the speed of light.
- This DOES NOT violate special relativity
  - Nothing ever overtakes a photon
  - Photons always travel at c

Nothing recedes faster than the speed of light in any inertial frame.

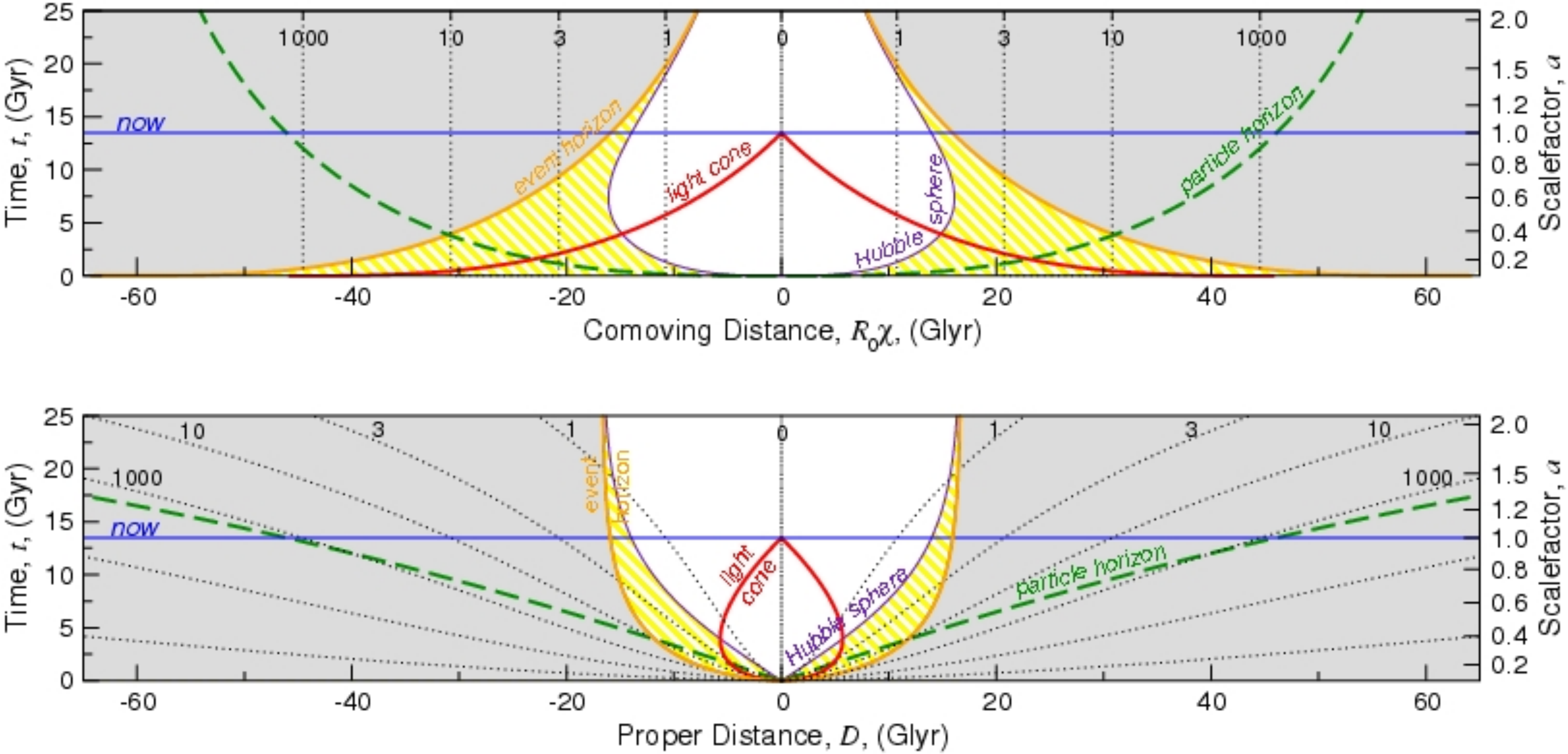
- There exist metrics that do not have superluminal recession.

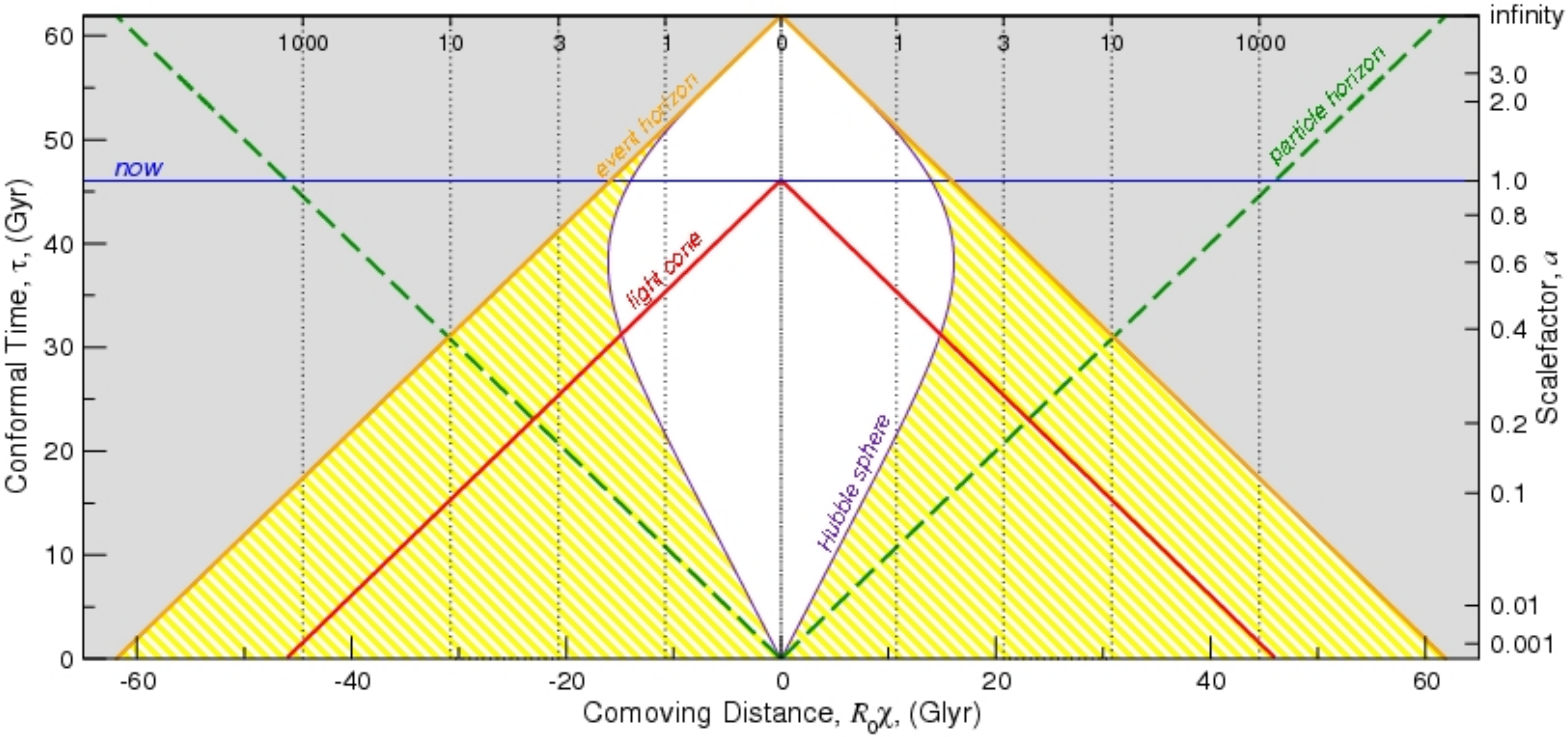
Shine a torch

- How far will the light reach?



Objects we can see at a particular time


Time, t, (Gyr)
Scalefactor, a
now
event horizon
light cone
Hubble sphere
particle horizon
Comoving Distance, $R_0\chi$, (Glyr)
Proper Distance, D, (Glyr)



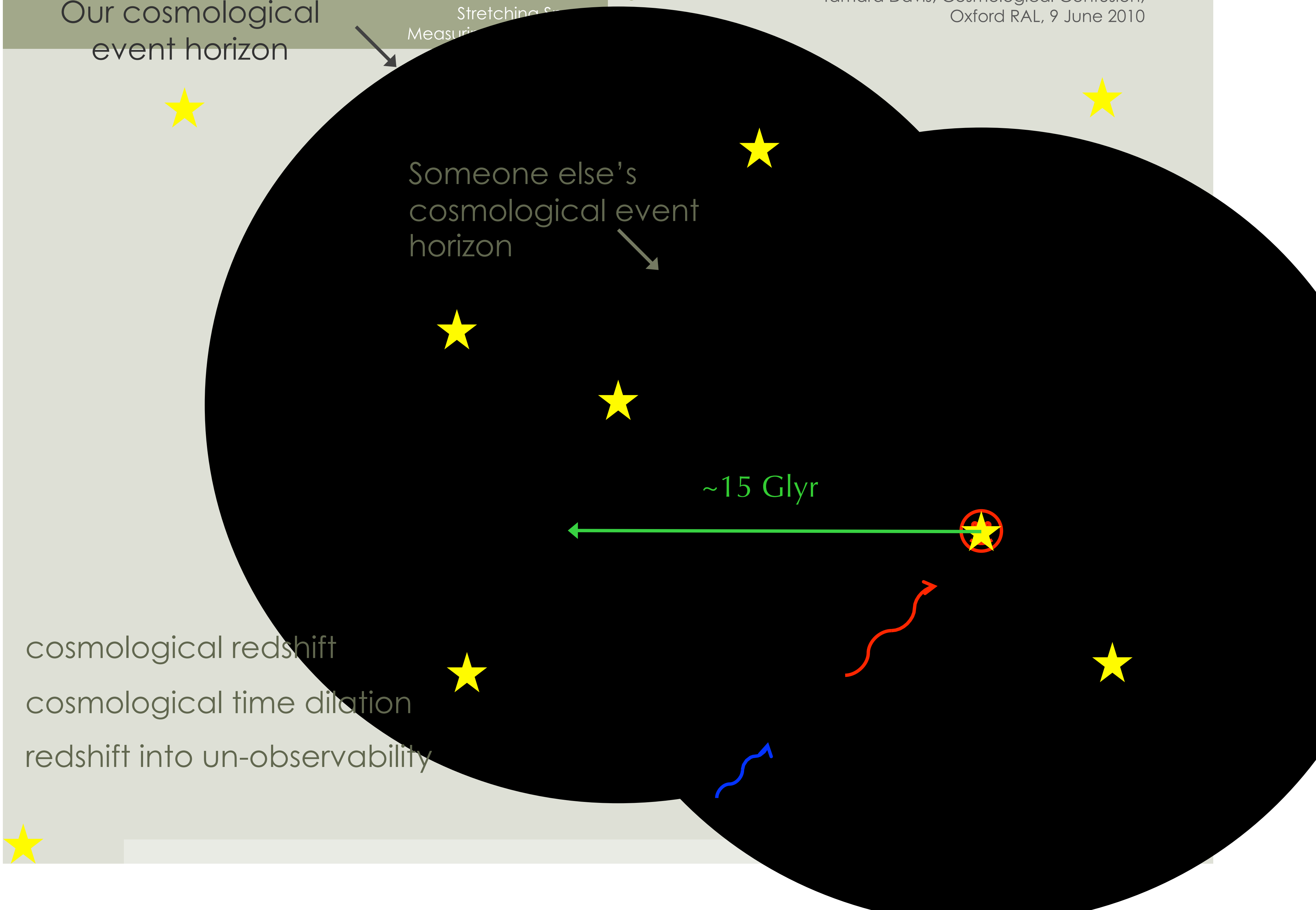
$$ds^2 = R^2(t)\,[\,-c^2dt^2 + d\chi^2 + S_k^2(\chi)(d\theta^2+\sin^2\theta\, d\phi^2)\,]$$

gravitational redshift

gravitational time dilation

redshift into un-observability

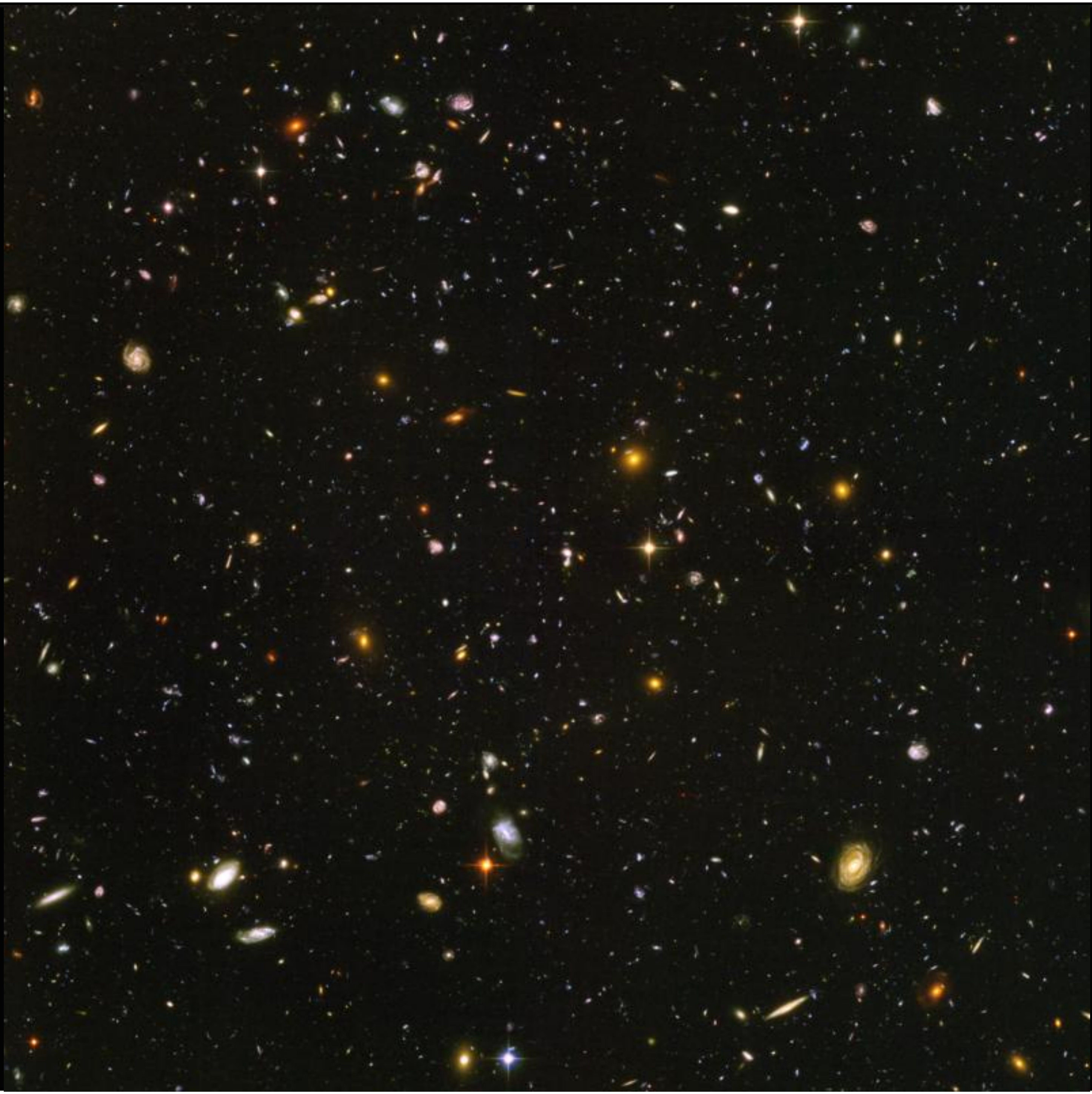
Tamara Davis, Cosmological Confusion,
Oxford RAL, 9 June 2010



cosmological redshift

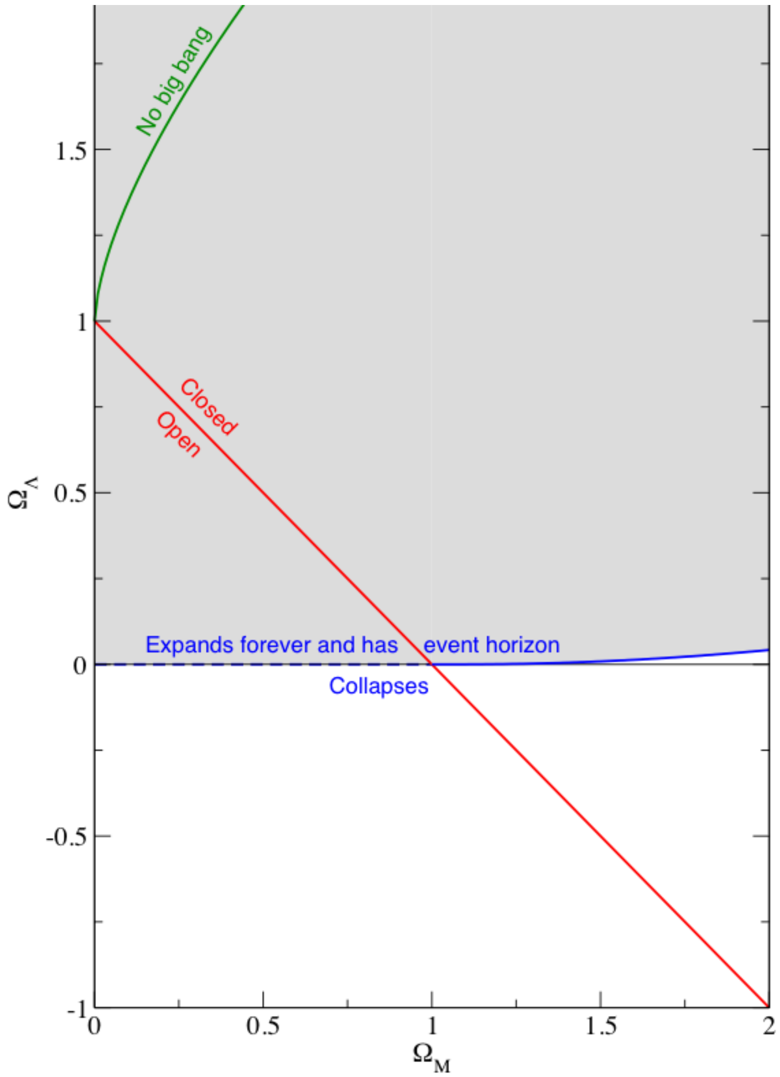
cosmological time dilation

redshift into un-observability



Do all universes have event horizons?

- No.
- Only eternally expanding and accelerating universes



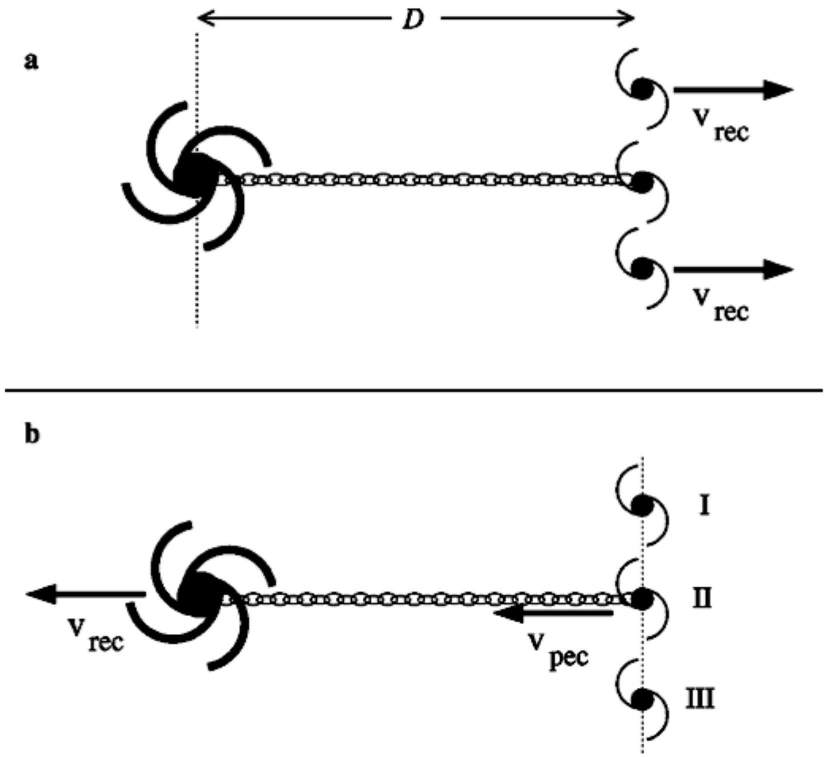
$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \frac{\Omega_x}{a^{3(1+w)}}$$

Does space stretch its contents?

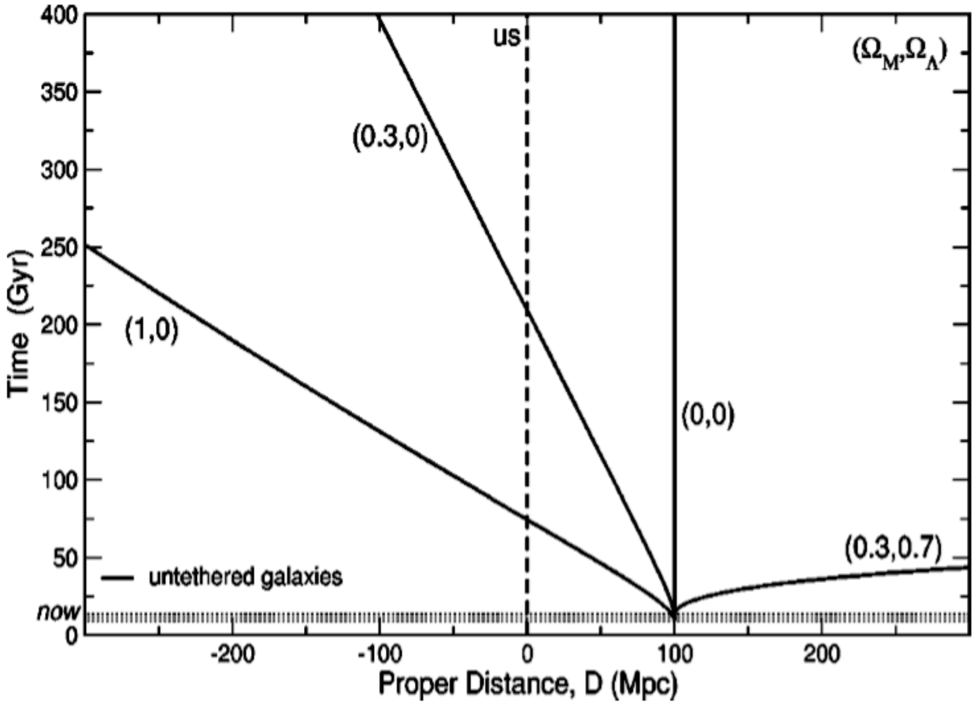
- True or false:

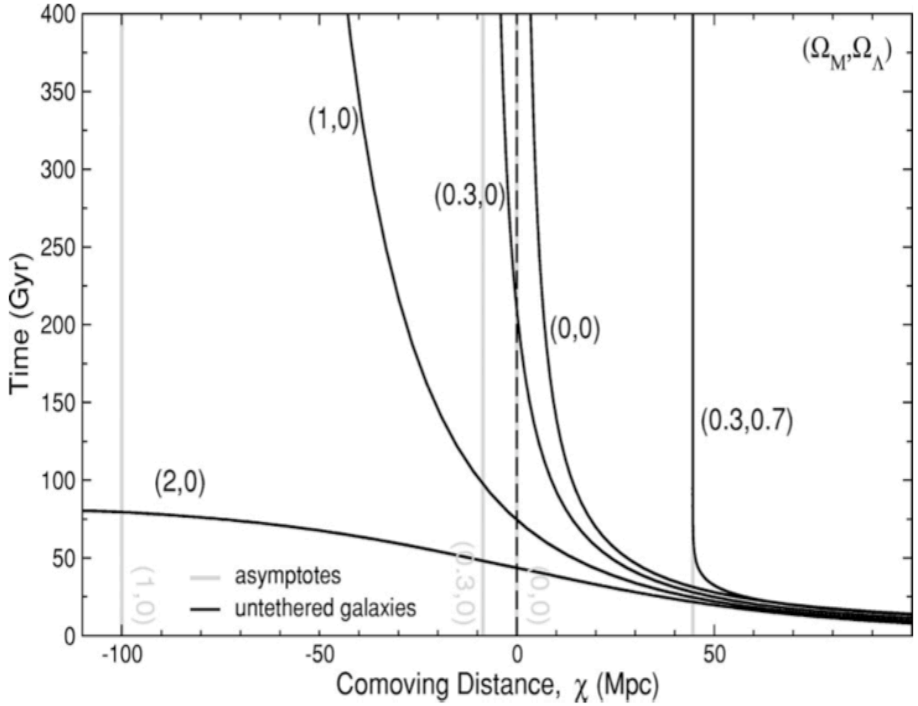
"Galaxies do not stretch with the expansion of space because gravity holds them together."

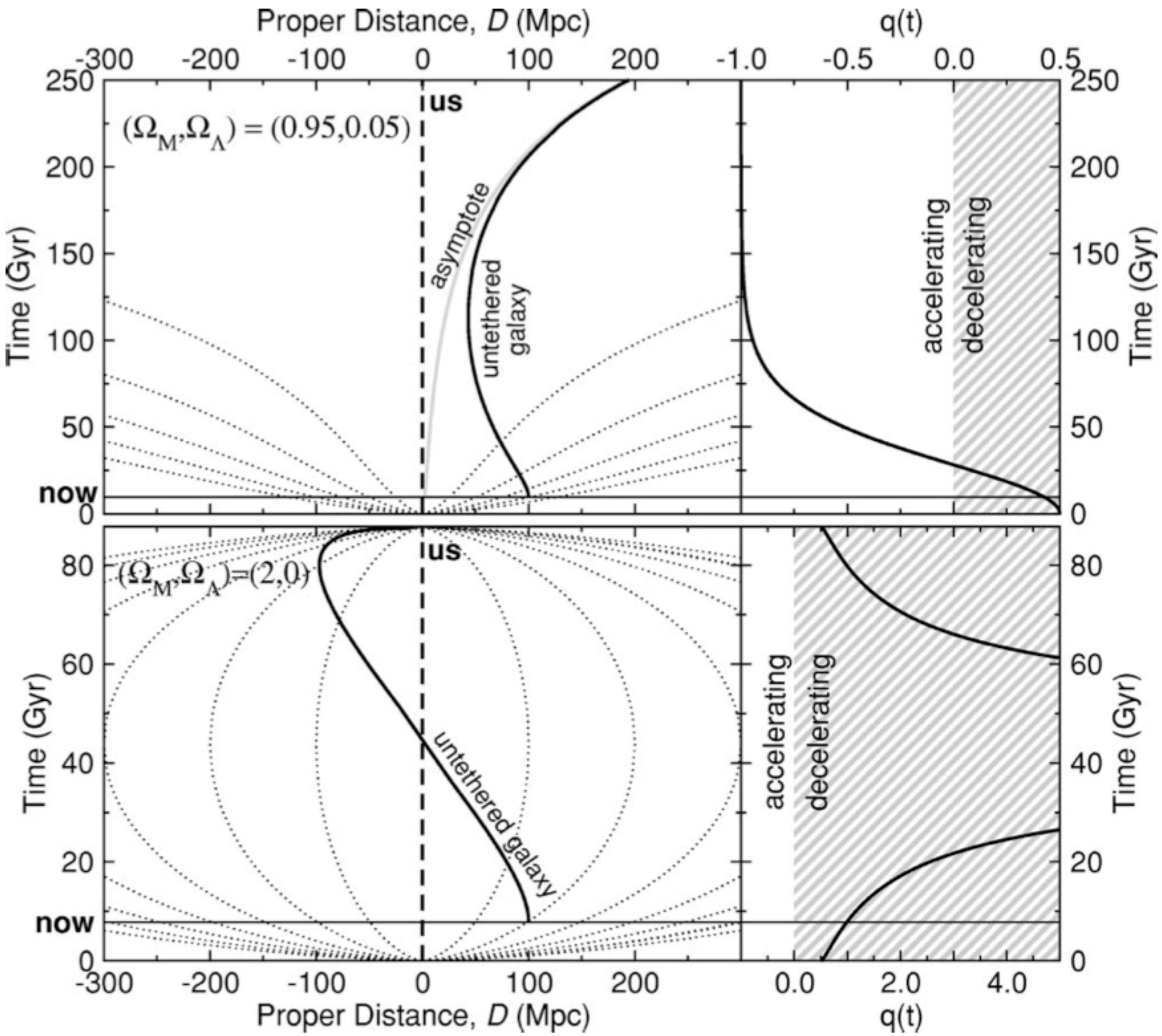
Thought experiment



- After release the untethered galaxy (neglecting the gravitational interaction of the two galaxies themselves)
  - Stays at a *constant distance*
  - Immediately gets caught by the expansion of space and *recedes with the Hubble flow*
  - Is *slowly dragged away* by the expansion of space until it rejoins the Hubble flow
  - Moves *towards us*
  - The answer depends on whether the universe is *accelerating or decelerating*


400
350
300
250
200
150
100
50
now
0
Time (Gyr)
-200
-100
0
100
200
Proper Distance, D (Mpc)
us
(Ω_M,Ω_Λ)
(0.3,0)
(1,0)
(0,0)
(0.3,0.7)
untethered galaxies


400
350
300
250
200
150
100
50
0
Time (Gyr)
-100
-50
0
50
Comoving Distance, χ (Mpc)
(Ω_M,Ω_Λ)
(1,0)
(0.3,0)
(0,0)
(0.3,0.7)
(2,0)
asymptotes
untethered galaxies



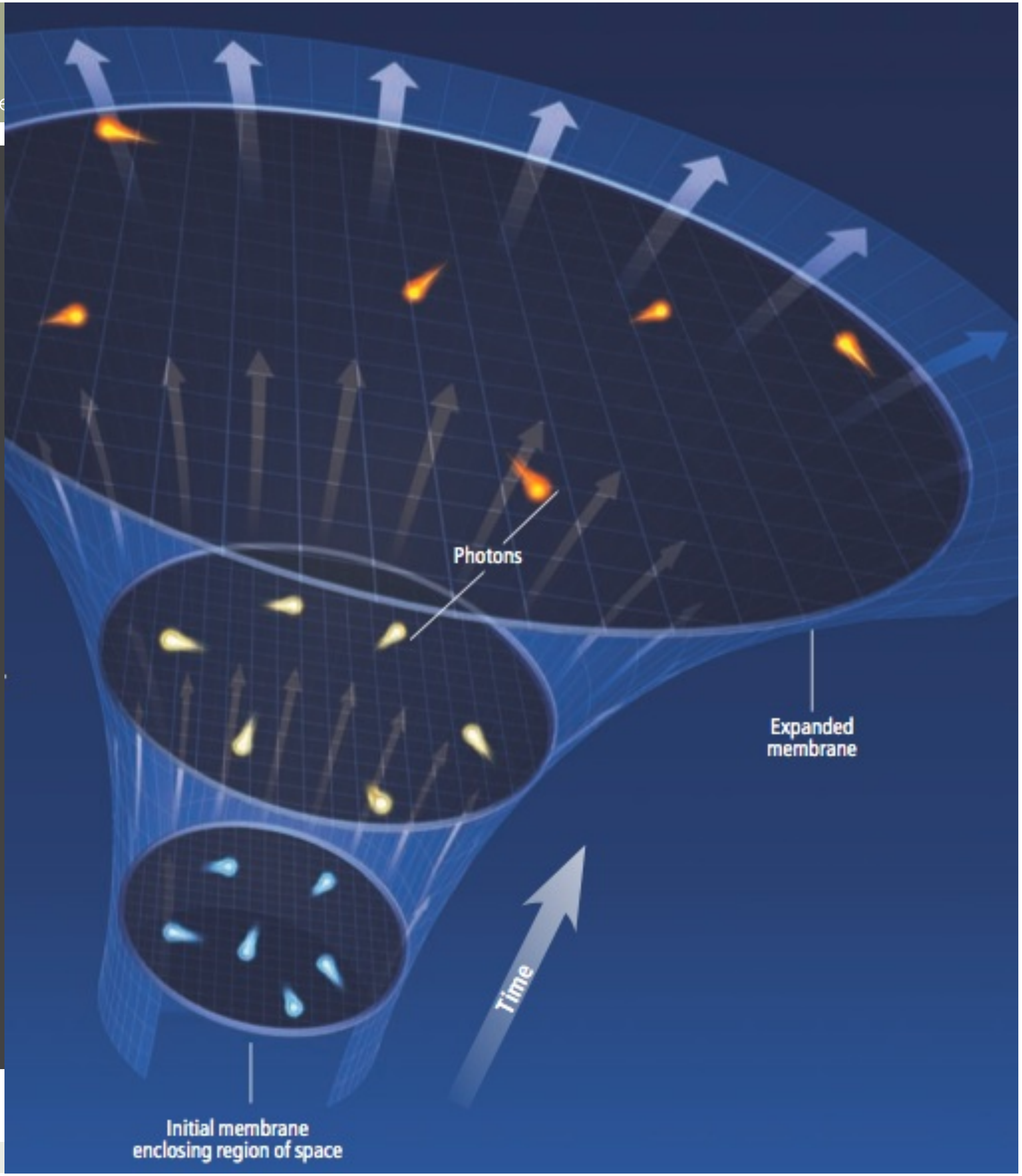
- Answer:

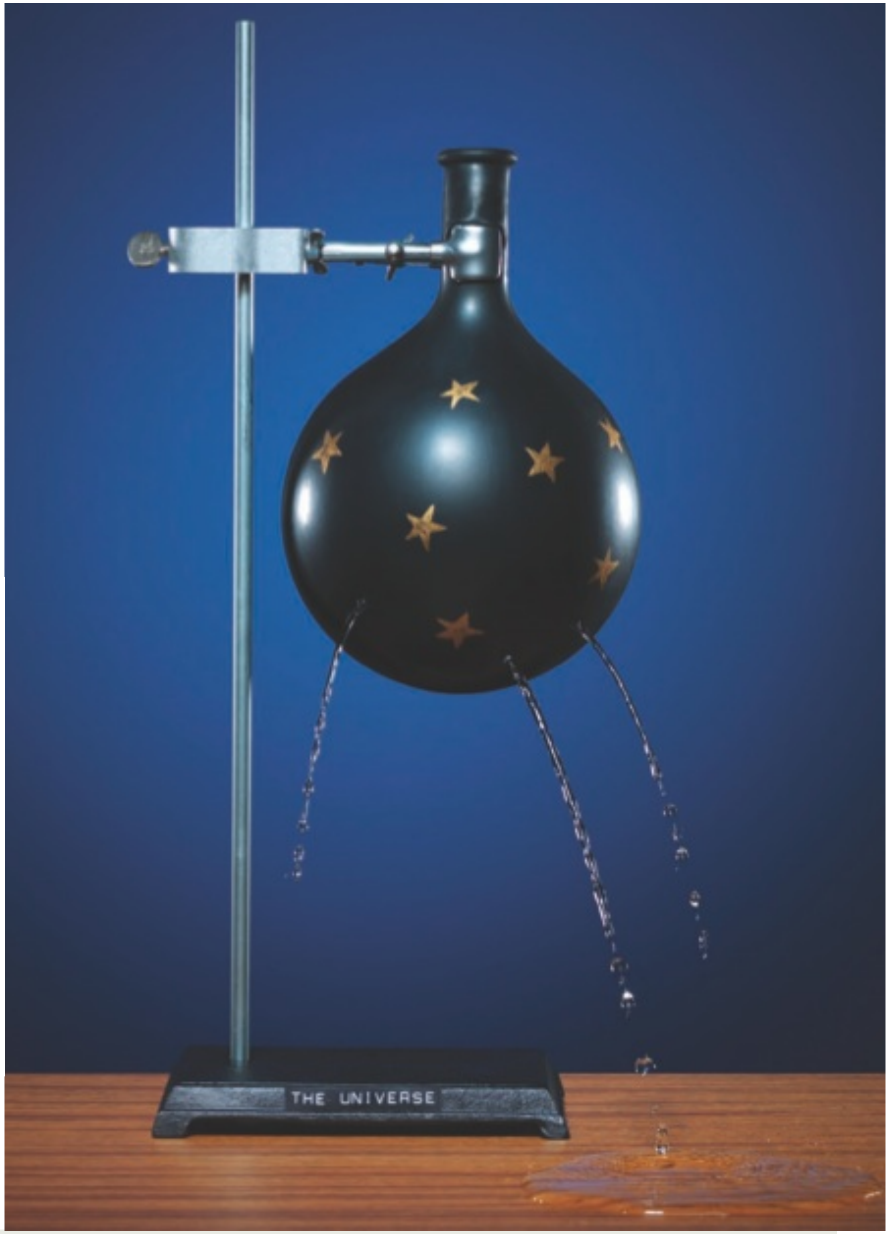
No. Objects are not stretched by the expansion of the universe.

They are stretched (or compressed) by the acceleration (or deceleration) of the universe.

Me

Where does the energy go when photons are redshiftted by the expansion of space??



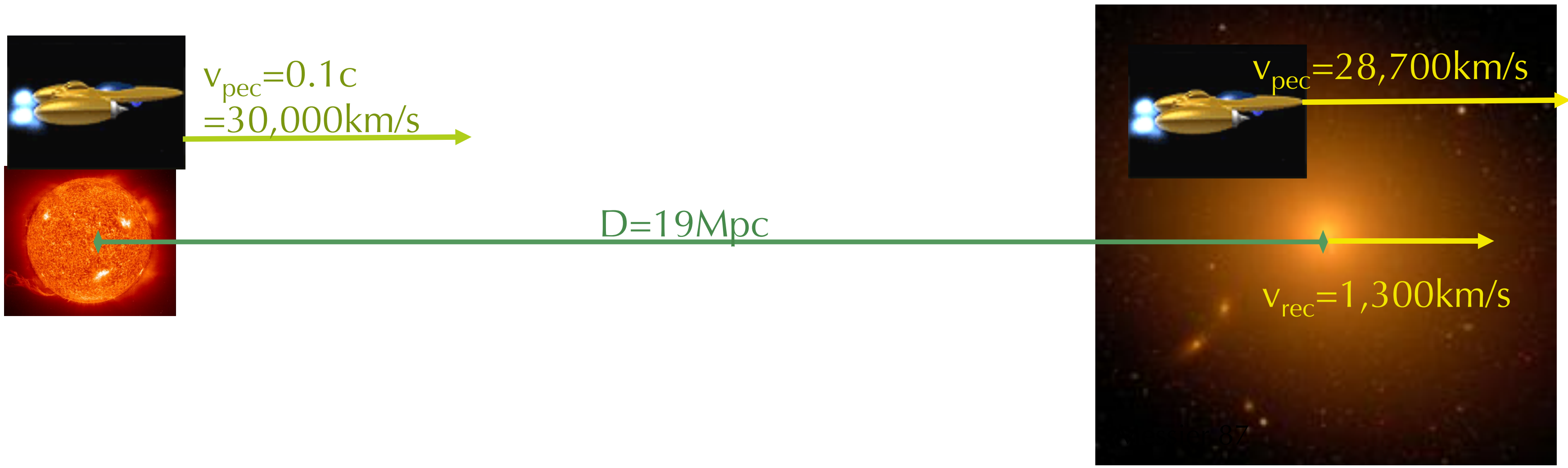


Is the Universe Leaking Energy?

Total energy must be conserved. Every student of physics learns this fundamental law. The trouble is, it does not apply to the universe as a whole By Tamara M. Davis

Peculiar velocity decay

- Peculiar velocities decrease with time: $v \propto 1/R$
- Can be understood as a simple change of reference frame



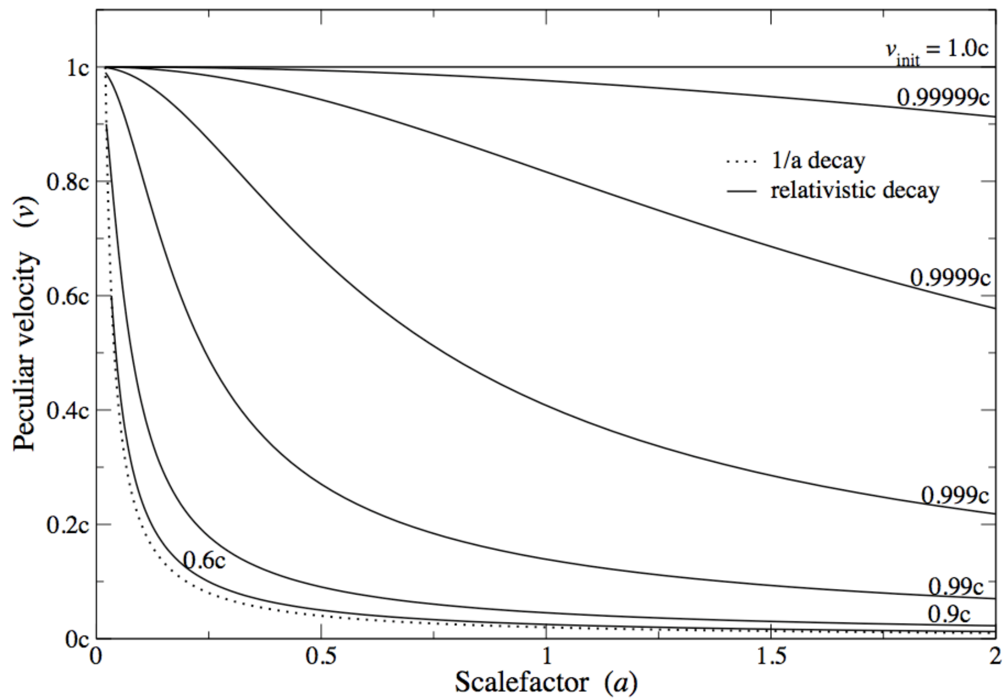
- But why does the peculiar velocity of a spaceship decay while the peculiar velocity of a photon doesn't?

Peculiar momentum decay

p ∝ 1/R for both photons and massive particles

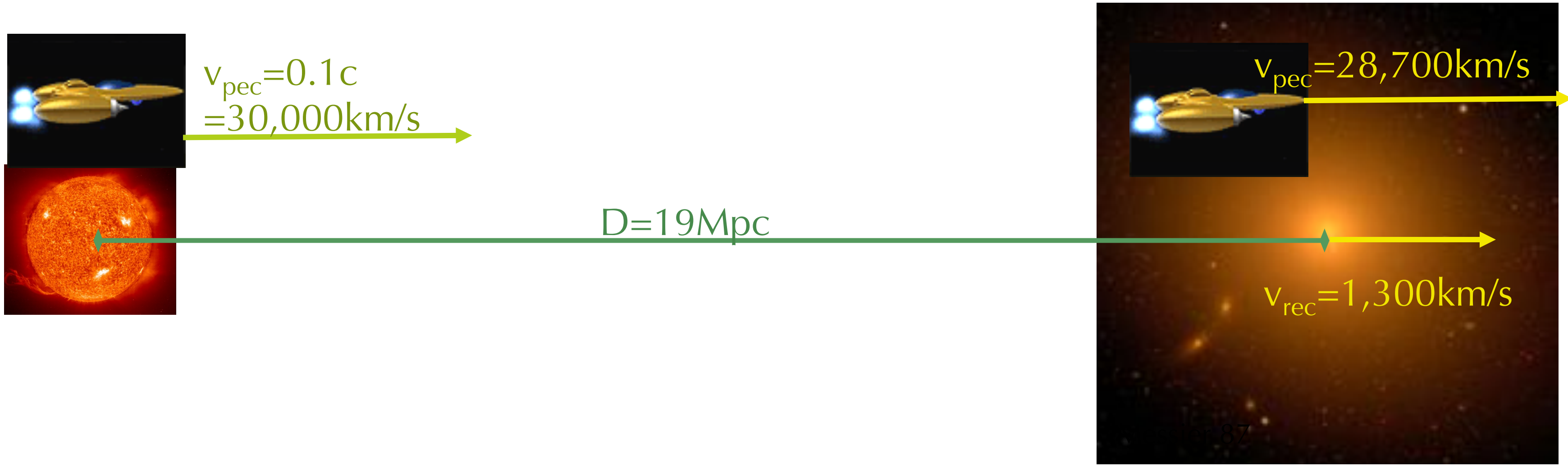
Use the relativistic formula for converting velocities between frames and matter behaves just like photons, with v ∝ 1/R the non-relativistic limit

(Derivation optional:
1. from geodesic equations
2. by integrating over infinitesimal Lorentz transformations)



Relative velocities!

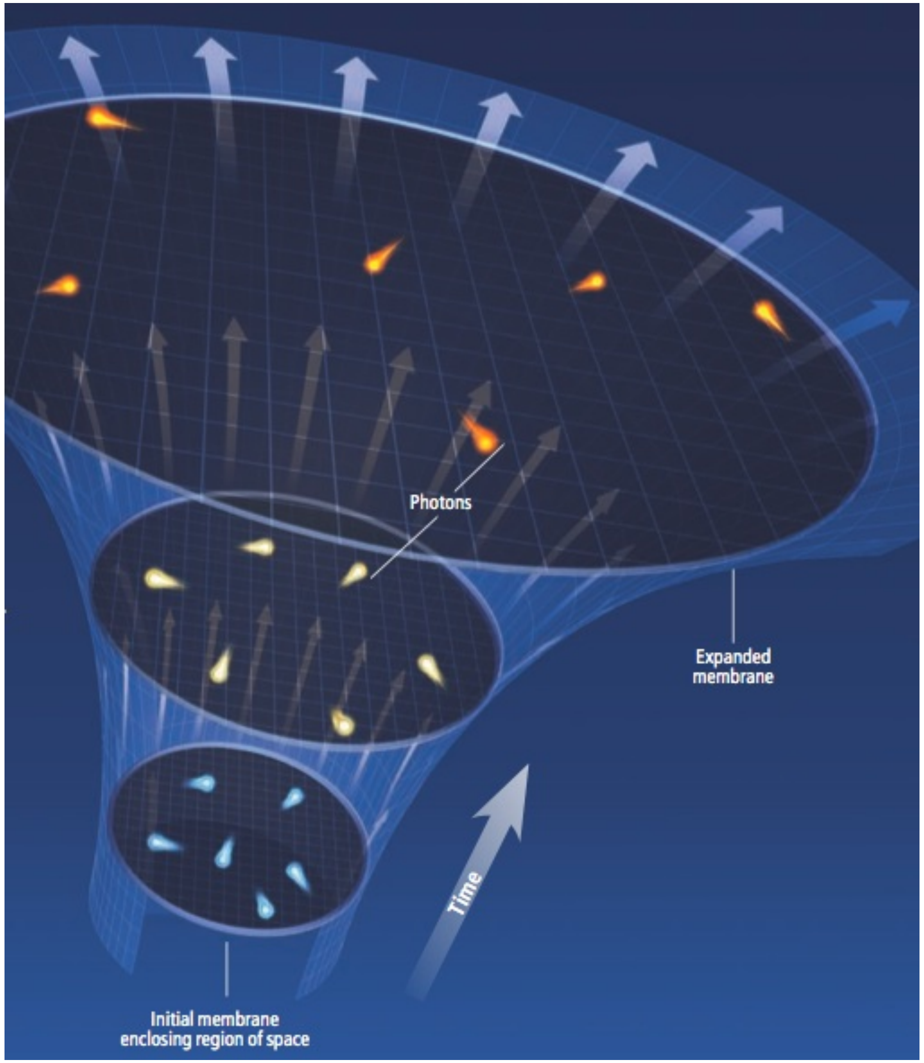
- Both photons and matter are being measured from different reference frames as they pass by galaxies that were initially receding from them



- So there is no loss of energy, just different perspectives

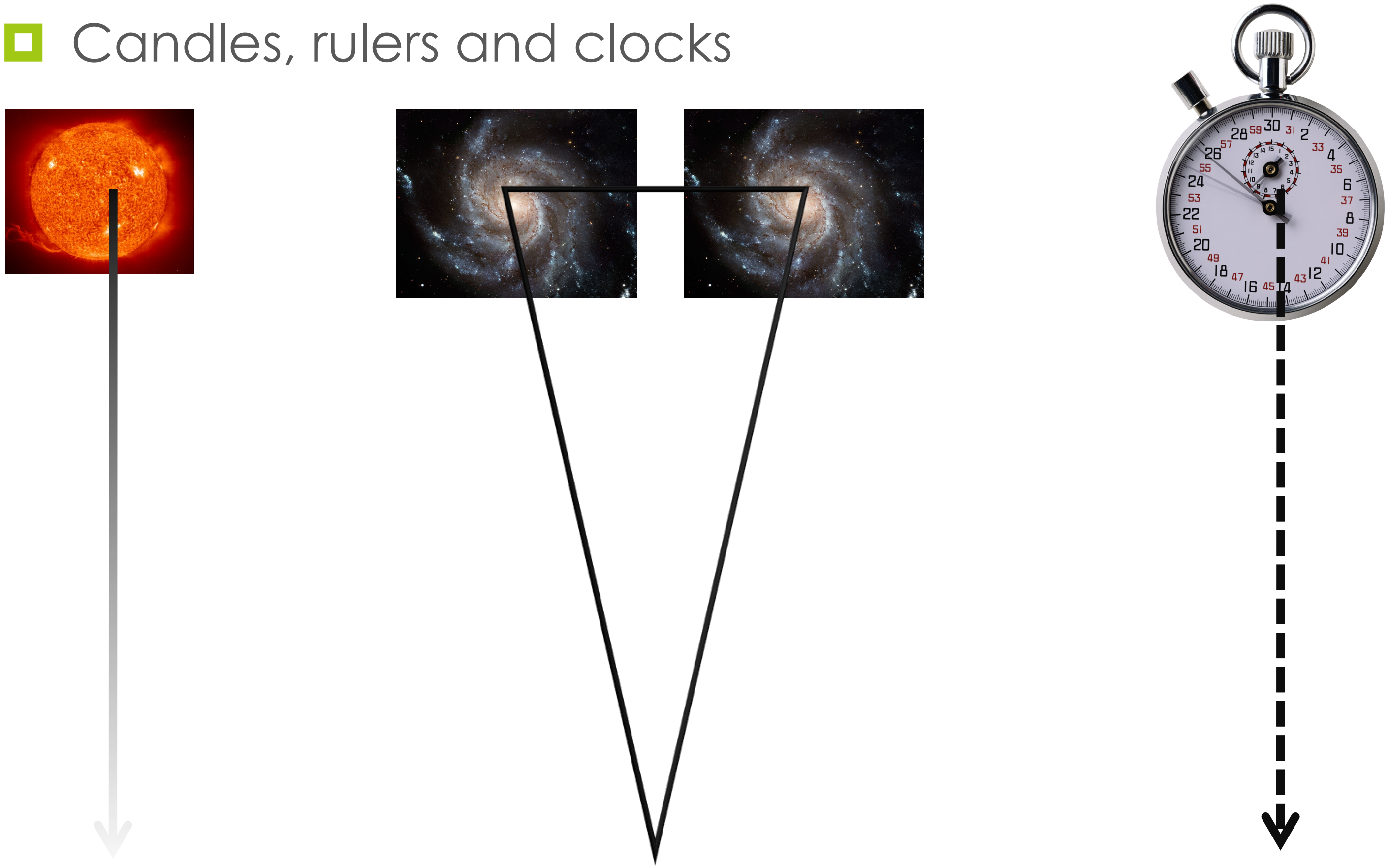
But wait!

- Add up energy in a comoving volume – not conserved.
- But if you believe Noether's theorem – conservation is on secure footing.
- Um?
- Impossible sometimes to unambiguously add up the total energy in a volume of space (can't decide which volume is the right one to choose… time is arbitrary).
- Noether's theorem doesn't apply when time-symmetry is broken. Therefore doesn't necessarily apply to the universe as a whole.



How can we prove redshifts are due to expansion?

- Candles, rulers and clocks



Stretch
Measuring ti

Measuring time dilation

- If redshifts are due to recession velocities then we expect an accompanying time dilation of (1+z)

nature Vol 454|14 August 2008

RESEARCH HIGHLIGHTS

Iceberg smash-up

J. Geophys. Res. doi:10.1029/2008JF001005 (2008)

When icebergs collide, they create seismic tremors that are detectable thousands of kilometres away and might one day be used to track the disintegration of ice shelves.

Douglas MacAyeal of the University of Chicago in Illinois and his colleagues placed four seismometers on a 50-kilometre-long iceberg (marked with an asterisk) that sits aground in the Ross Sea, off Antarctica. Over several weeks, they recorded many series of tremors, which they attribute to an adrift neighbouring iceberg (pictured centre) grating against the stationary one. Each series contained thousands of ice-quakes per hour.

The tremors share some similarities — but are distinct enough not to be confused — with recently discovered tremors that emanate from subduction zones and from the San Andreas fault.

D. MACAYEAL/MODIS/NASA

COMPARATIVE BIOLOGY

Animal models

Proc. R. Soc. B doi:10.1098/rspb.2008.0506 (2008)

The hierarchy of stages involved as blood stem cells develop into the various blood-cell types does not differ significantly across all species of mammal. But the rate at which these stem cells multiply does; it is faster the smaller a typical adult's mass.

This finding from David Dingli of the Mayo Clinic in Rochester, Minnesota, and his colleagues confirms that mammals used in experiments make accurate models of the human blood-cell-production process.

Dingli and his co-workers reached their conclusions after building a model of many aspects of blood-cell production across many species of mammal. They compared this with the limited experimental data available.

PLANETARY SCIENCE

Soft metals

Proc. Natl Acad. Sci. USA doi:10.1073/pnas.0804609105 (2008)

Metallic helium isn't as hard to make as scientists thought, according to Lars Stixrude of University College London and Raymond Jeanloz of the University of California, Berkeley. They calculate that the amount of squeezing needed to make the element conduct electricity is smaller when helium is hot than when it is cold; squeezing at close to 30 million atmospheres turns helium metallic at a 'mere' 20,000 kelvin.

This means that metallic helium should mix quite readily with metallic hydrogen in the fluid interiors of Jupiter and Saturn, where these conditions are probably reached. That squelches the idea that a layer of liquid, and therefore electrically insulating, helium, floating immiscibly on metallic hydrogen, could produce helium rain in these planets' dense atmospheres.

CLIMATOLOGY

Winter sun

Geophys. Res. Lett. doi:10.1029/2008GL034160 (2008)

The weekly weather cycles detected in some big cities have been linked to higher levels of vehicle exhaust and factory emissions on weekdays than at weekends. But researchers have now found that this effect acts over a much larger area than urban centres.

Arturo Sanchez-Lorenzo from the University of Barcelona and his colleagues examined 44 years of climate data from 13 weather stations across Spain. They discovered that winter weekends tend to be drier and sunnier than weekdays. The result held for both urban and rural areas, suggesting that the hebdomadal cycles are caused by pollution's effect on regional atmospheric circulation rather than dirty particles nucleating raindrops close to the source of smog.

The authors observed the same relationship across Western Europe, and the reverse — wetter weekends — in the eastern North Atlantic.

BUCKWINKEL/ALAMY

ASTROPHYSICS

Slow-motion supernovae

Astrophys. J. **682**, 724–736 (2008)

A survey of exploding stars shows that the farther away they are, the slower they seem to blow apart, as predicted on the basis of general relativity. The supernovae studied are known as type Ia supernovae, and are important for gauging the strength of dark energy — a mysterious force that seems to be pushing the Universe apart. These findings reassure astronomers that the far away supernovae behave like those nearby.

Stéphane Blondin at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, and his colleagues studied thirteen supernovae between 3.6 and 7.5 billion light years from Earth. The group compared several spectra from the more distant supernovae with those of nearer ones and found that the more distant explosions took longer to unfold.

ZOOLOGY

Predatory Lotharios

J. Fish Biol. **73**, 728–731 (2008)

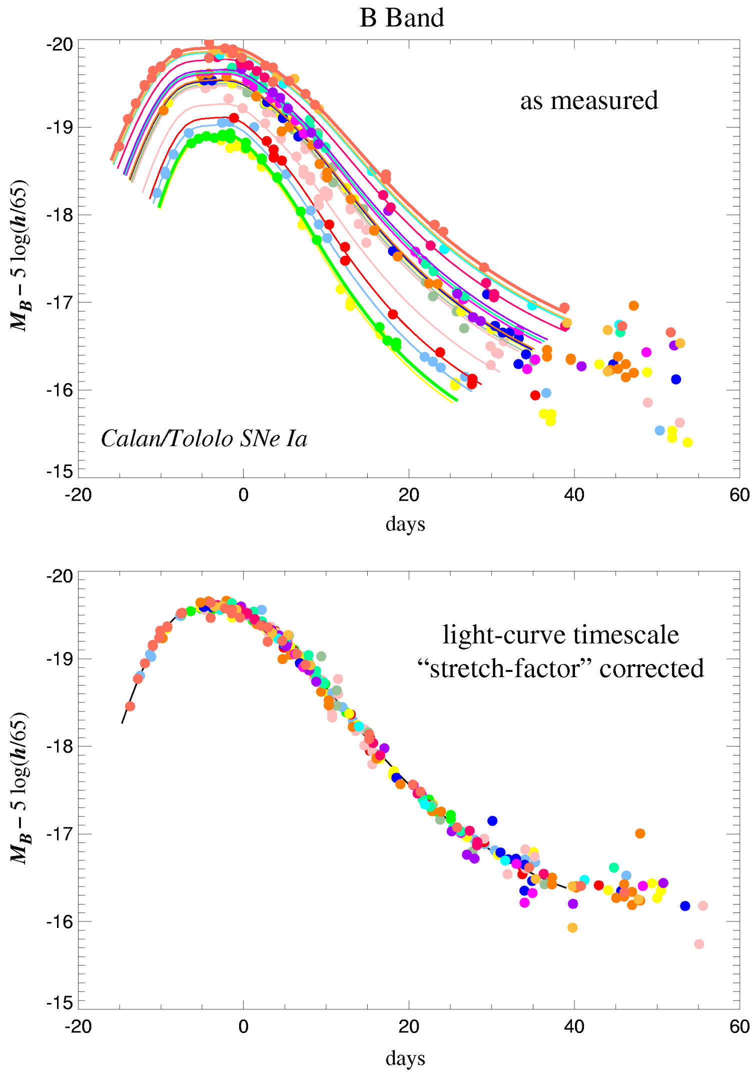
When mothers warn their daughters that boys are after only one thing, a meal probably isn't what they have in mind. However, male fish of one species have been observed enticing females of


!!! SHOCKING NEWS !!!
ASTROPHYSICICISTS CONFIRM
EXPANSION OF UNIVERSE

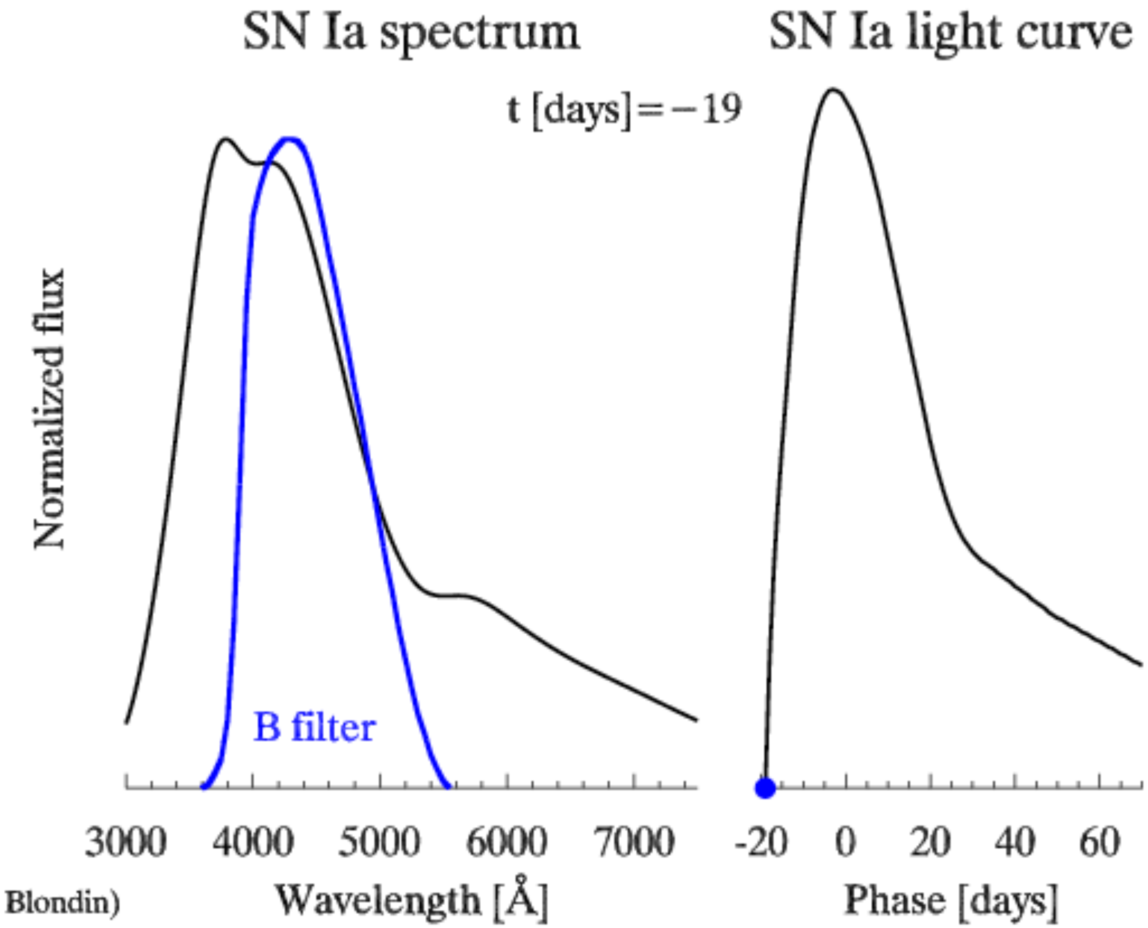
Supernovae as clocks

- Brighter = wider

- Are we only seeing bright SNe further away?



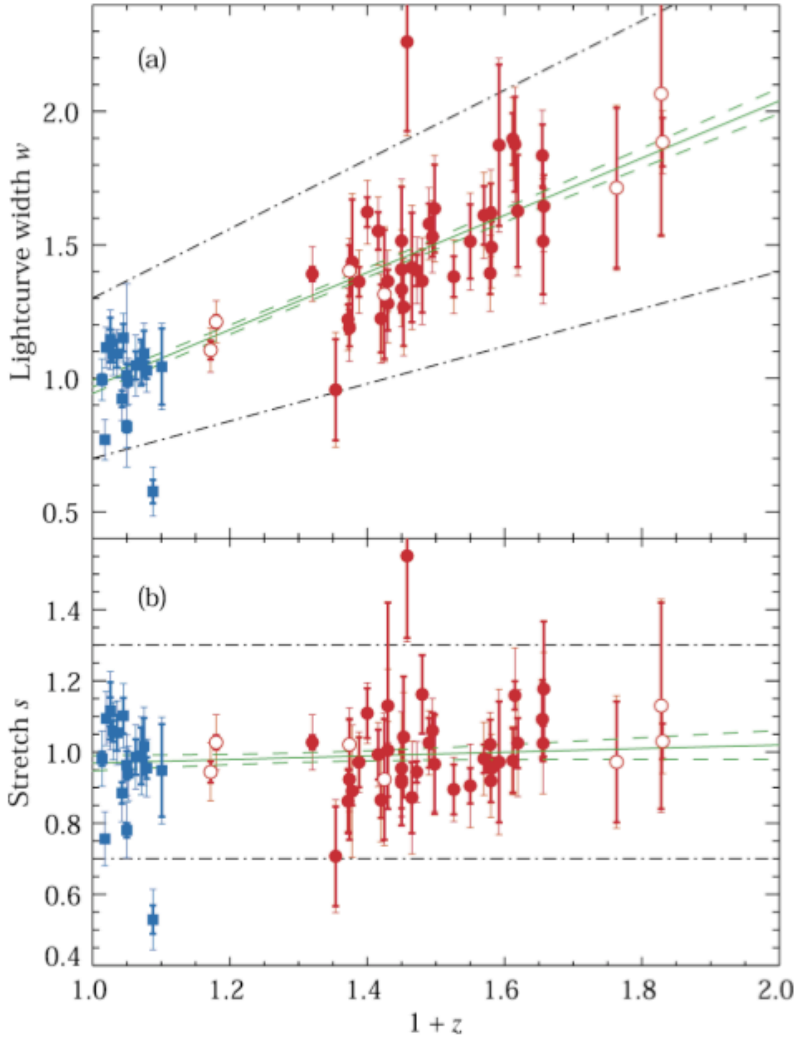
Supernovae as clocks



(S. Blondin)

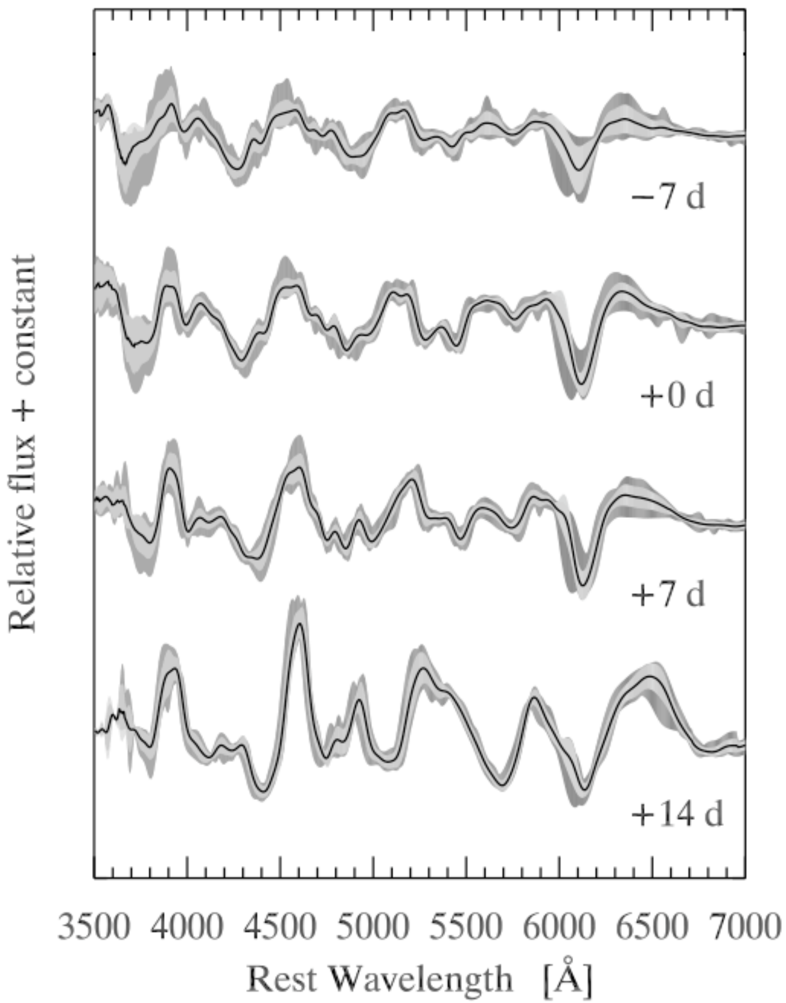
Previous measurements

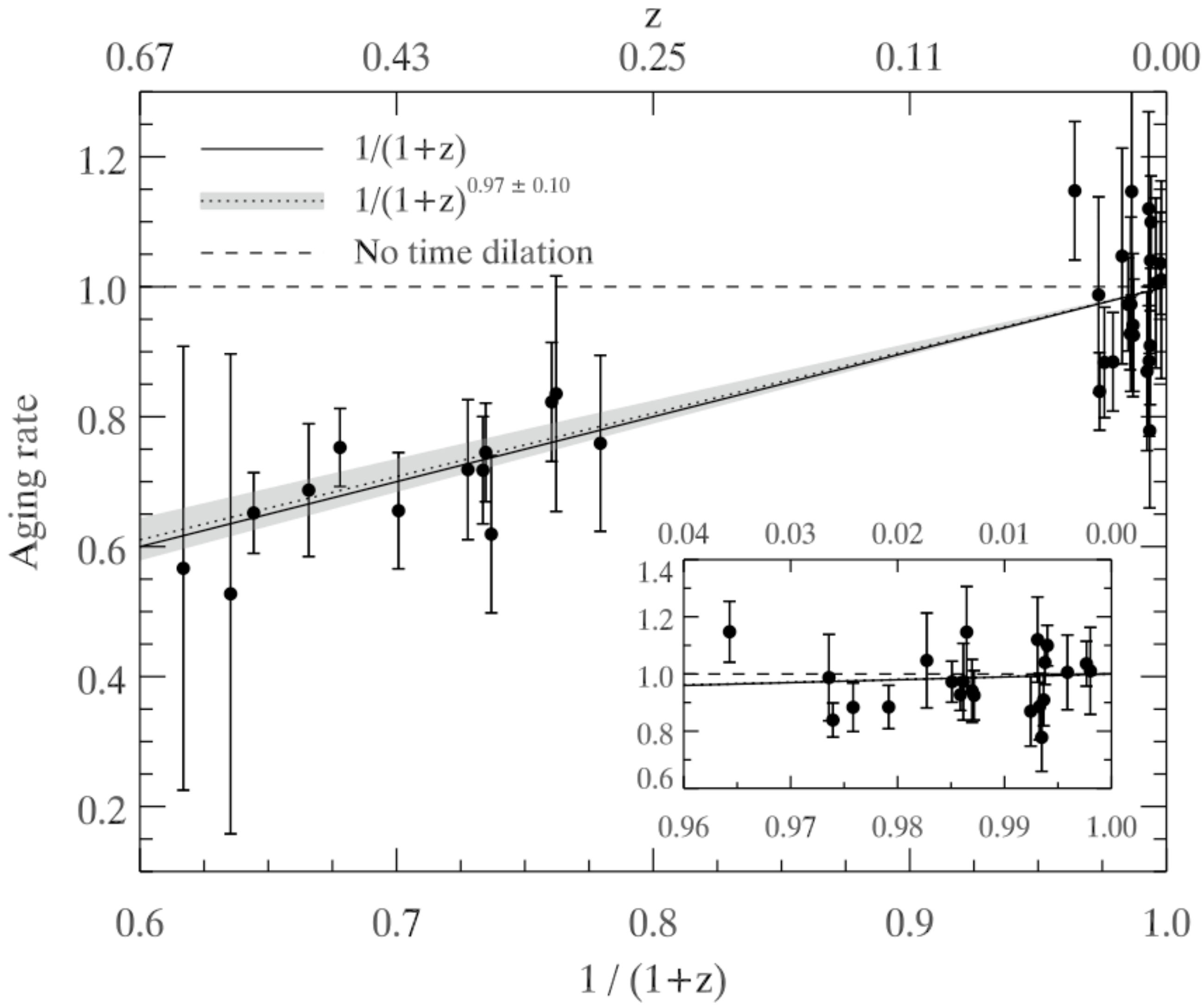
- Leibundgut 1996, Goldhaber 2001 saw this effect in SN light curves (right).
- Riess et al. 1997 and Foley et al. 2005 each used the spectra of a single supernova to measure time dilation at a single redshift
- Blondin et al. 2008 (ESSENCE) used the spectra of 13 supernovae over a range of redshifts



Dedicated SN search

- Target of opportunity on European Southern Observatory's VLT (8m optical telescope)
- Motivated by need to check high-z SNe are the same as low-z SNe
- 35 spectra of 13 SNe (each spectrum ~1hr)




z
0.67
0.43
0.25
0.11
0.00
1/(1+z)
1/(1+z)^0.97 ± 0.10
No time dilation
Aging rate
1.2
1.0
0.8
0.6
0.4
0.2
0.04
0.03
0.02
0.01
0.00
1.4
1.2
1.0
0.8
0.6
0.96
0.97
0.98
0.99
1.00
0.6
0.7
0.8
0.9
1.0
1 / (1+z)

Tools for your arsenal

- Is there an edge to space?
  - Well, there's a limit to how far we can see.
- Does the expanding universe stretch things inside it?
- What causes the expansion?
  - Nothing is necessary, not since the original inflationary push.
- What is the universe expanding into?
  - Nothing is necessary, and beyond our observable universe is unknown.
- What came before the big bang?
  - Unknown.
- What will be the fate of the universe?
  - Expand forever, see nothing but our isolated pocket of galaxies

Can't distinguish from SR

- Cosmological time dilation predicts:

$$\frac{\delta t_0}{\delta t_1} = 1 + z$$

- Special relativistic time dilation seems to have a different relationship:

$$\delta t_0 = \gamma_{SR} \delta t_1$$

$$\gamma_{SR} = \left[1 - \left(\frac{v}{c}\right)^2\right]^{-1/2} = \frac{1}{2}\left(1 + z + \frac{1}{1+z}\right)$$

- But once you take into account the extra distance light has to travel ($v dt_0/c$) you realise SR predicts the same:

$$\delta t_{0,\mathrm{tot}} = \delta t_0 (1 + v/c)$$

$$\delta t_{0,\mathrm{tot}} = \gamma_{SR} \delta t_1 (1 + v/c) = \delta t_1 \sqrt{\frac{1 + v/c}{1 - v/c}} = \delta t_1 (1 + z)$$

Metric and equations of motion

- Geodesic equations

$$\frac{d^2x^\gamma}{d\tau^2} + \Gamma^\gamma_{\alpha\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau} = 0.$$

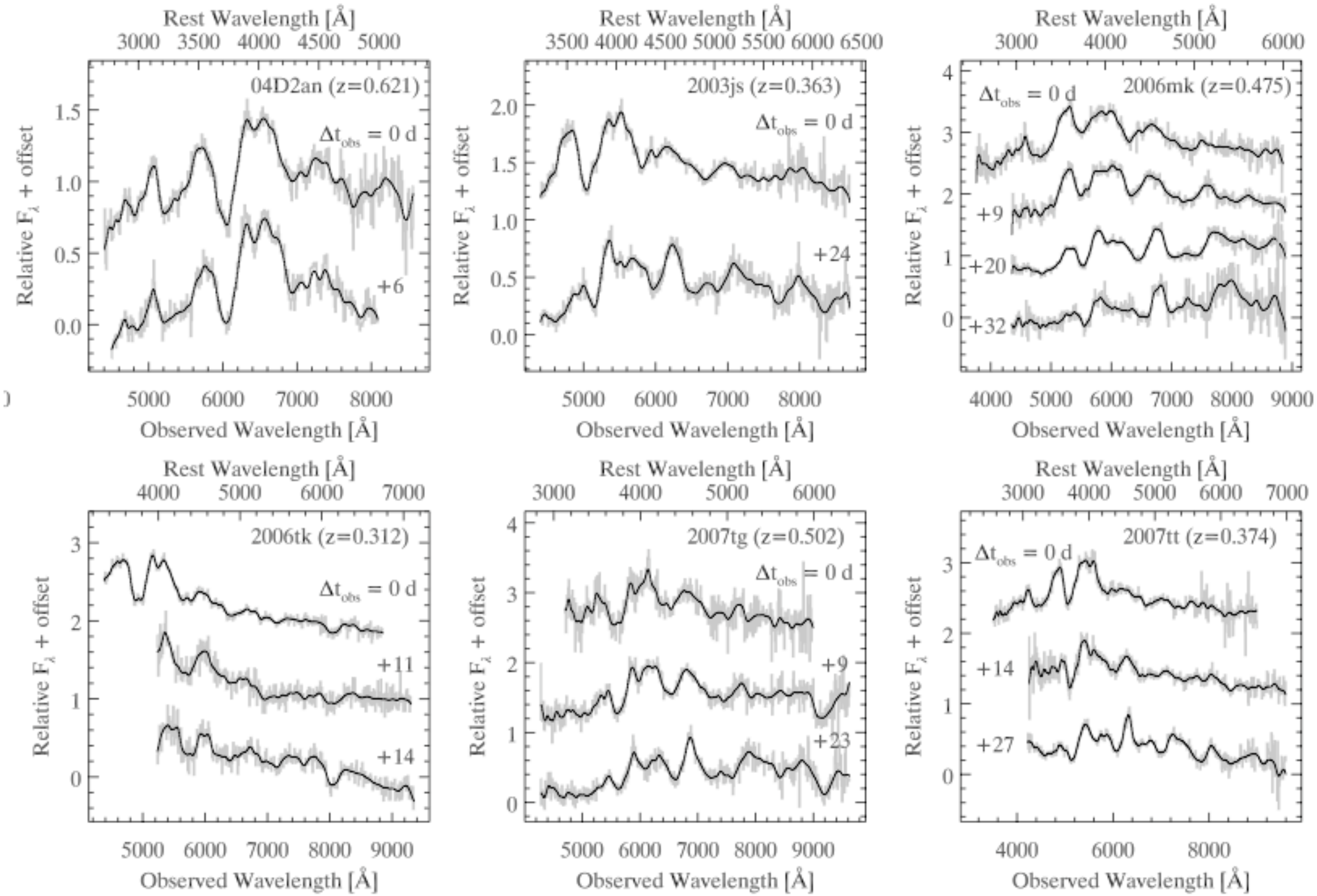
- Only non-vanishing Christoffel symbols

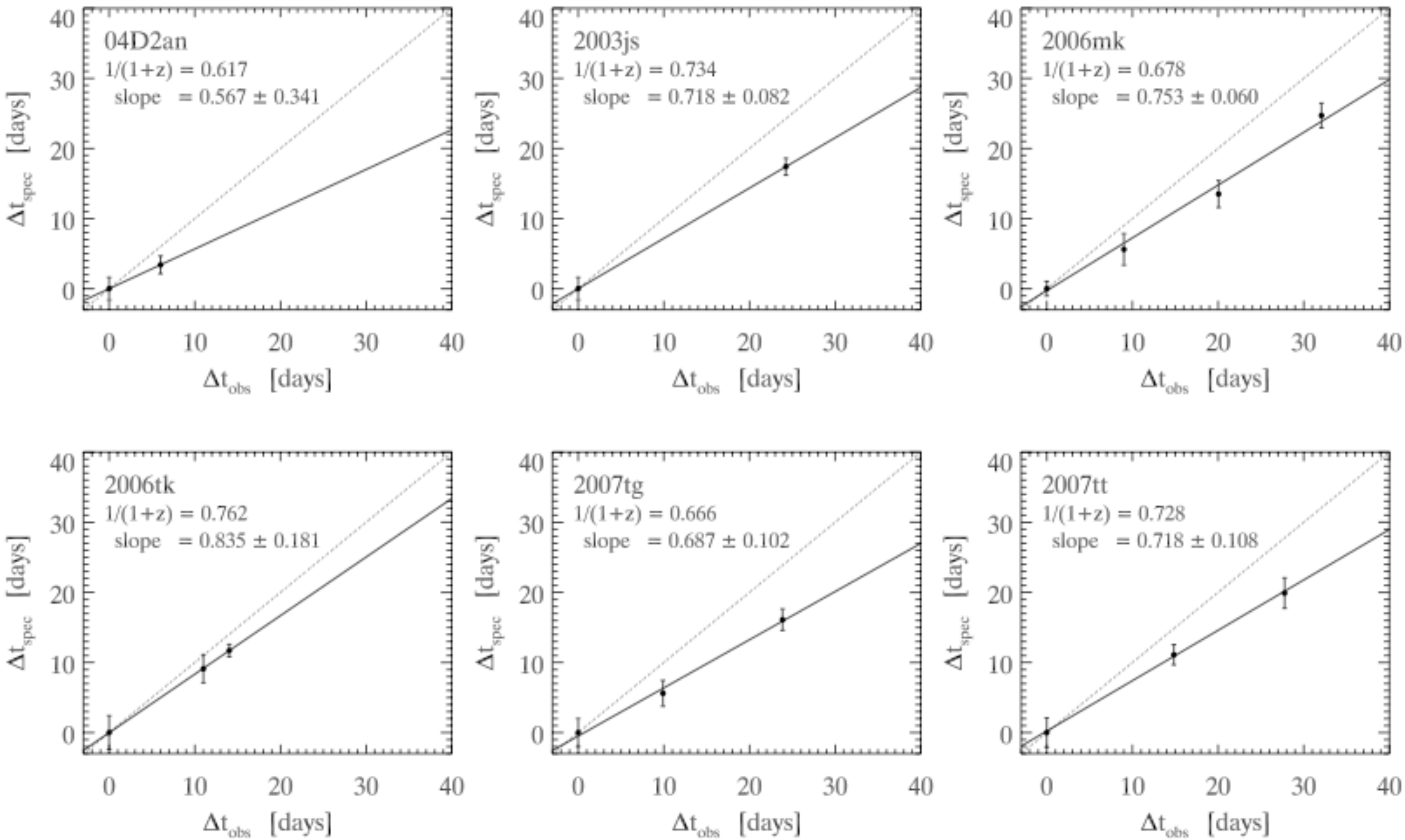
$$\Gamma^1_{01} = \Gamma^1_{10} = \frac{\dot{R}}{R}, \qquad \Gamma^0_{11} = \frac{R\dot{R}}{c^2}.$$

- Leaves two equations

$$\frac{d^2\chi}{d\tau^2} = -2\frac{\dot{R}}{R}\frac{dt}{d\tau}\frac{d\chi}{d\tau} = -2\frac{\dot{R}}{R}\frac{\dot{\chi}}{\dot{\tau}^2},$$

$$\frac{d^2t}{d\tau^2} = -\frac{R\dot{R}}{c^2}\left(\frac{d\chi}{d\tau}\right)^2 = -\frac{R\dot{R}}{c^2}\frac{\dot{\chi}^2}{\dot{\tau}^2}.$$


Rest Wavelength [Å]
Observed Wavelength [Å]
Relative F_λ + offset
04D2an (z=0.621)
Δt_{obs} = 0 d
+6
2003js (z=0.363)
Δt_{obs} = 0 d
+24
2006mk (z=0.475)
Δt_{obs} = 0 d
+9
+20
+32
2006tk (z=0.312)
Δt_{obs} = 0 d
+11
+14
2007tg (z=0.502)
Δt_{obs} = 0 d
+9
+23
2007tt (z=0.374)
Δt_{obs} = 0 d
+14
+27


04D2an
1/(1+z) = 0.617
slope = 0.567 ± 0.341
2003js
1/(1+z) = 0.734
slope = 0.718 ± 0.082
2006mk
1/(1+z) = 0.678
slope = 0.753 ± 0.060
2006tk
1/(1+z) = 0.762
slope = 0.835 ± 0.181
2007tg
1/(1+z) = 0.666
slope = 0.687 ± 0.102
2007tt
1/(1+z) = 0.728
slope = 0.718 ± 0.108
Δt_{spec} [days]
Δt_{obs} [days]