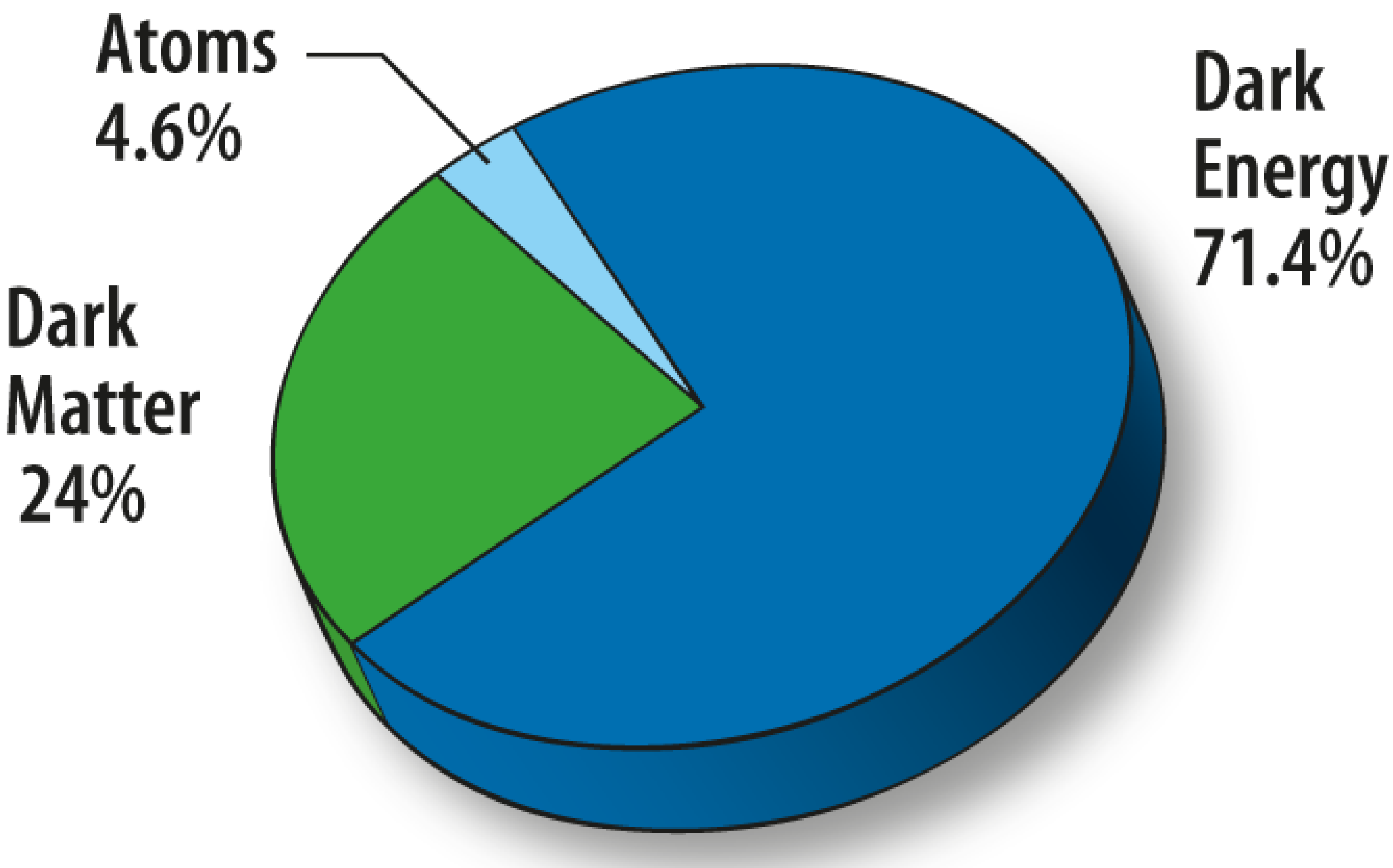
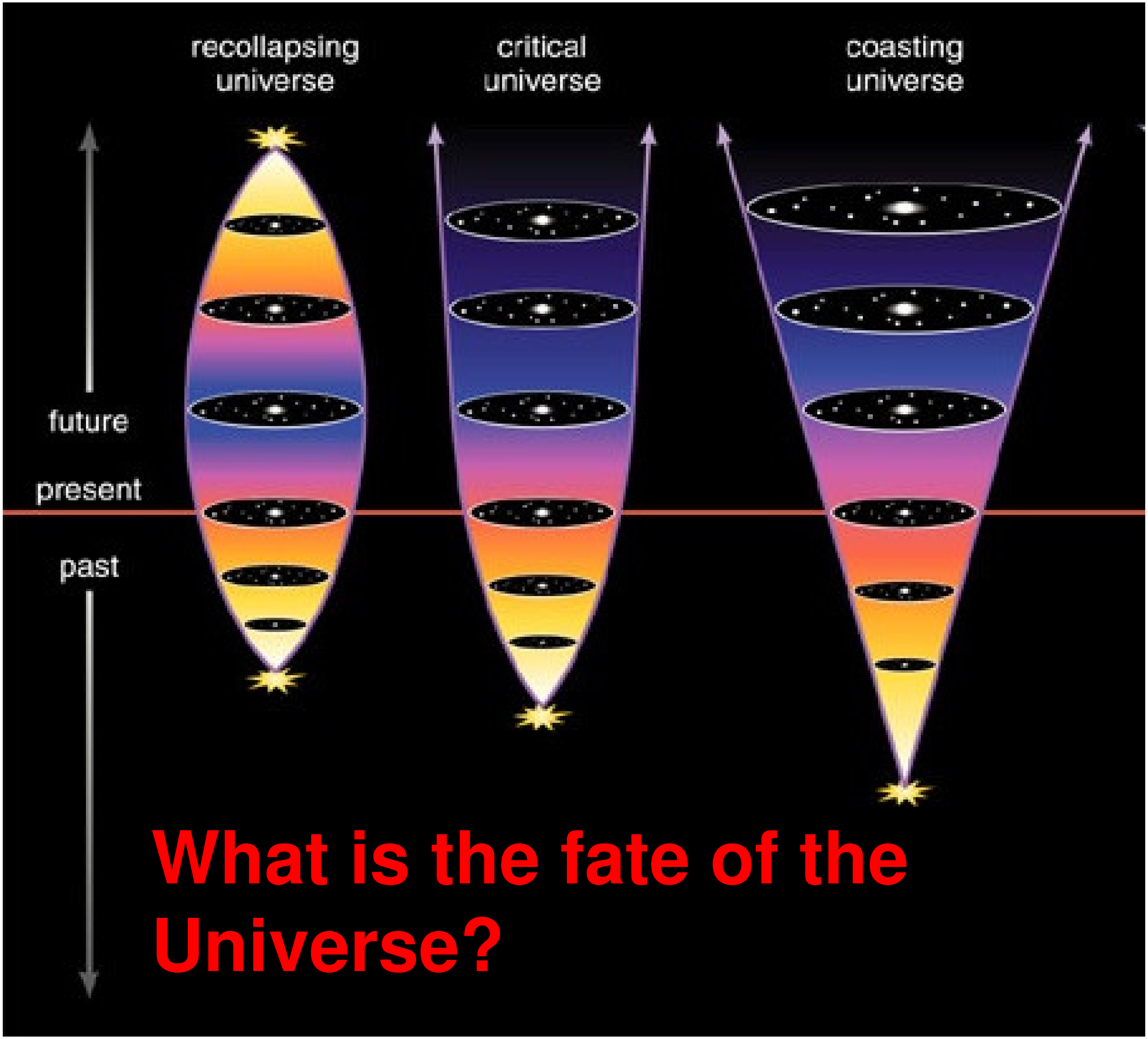
Part 3: The Dark Energy

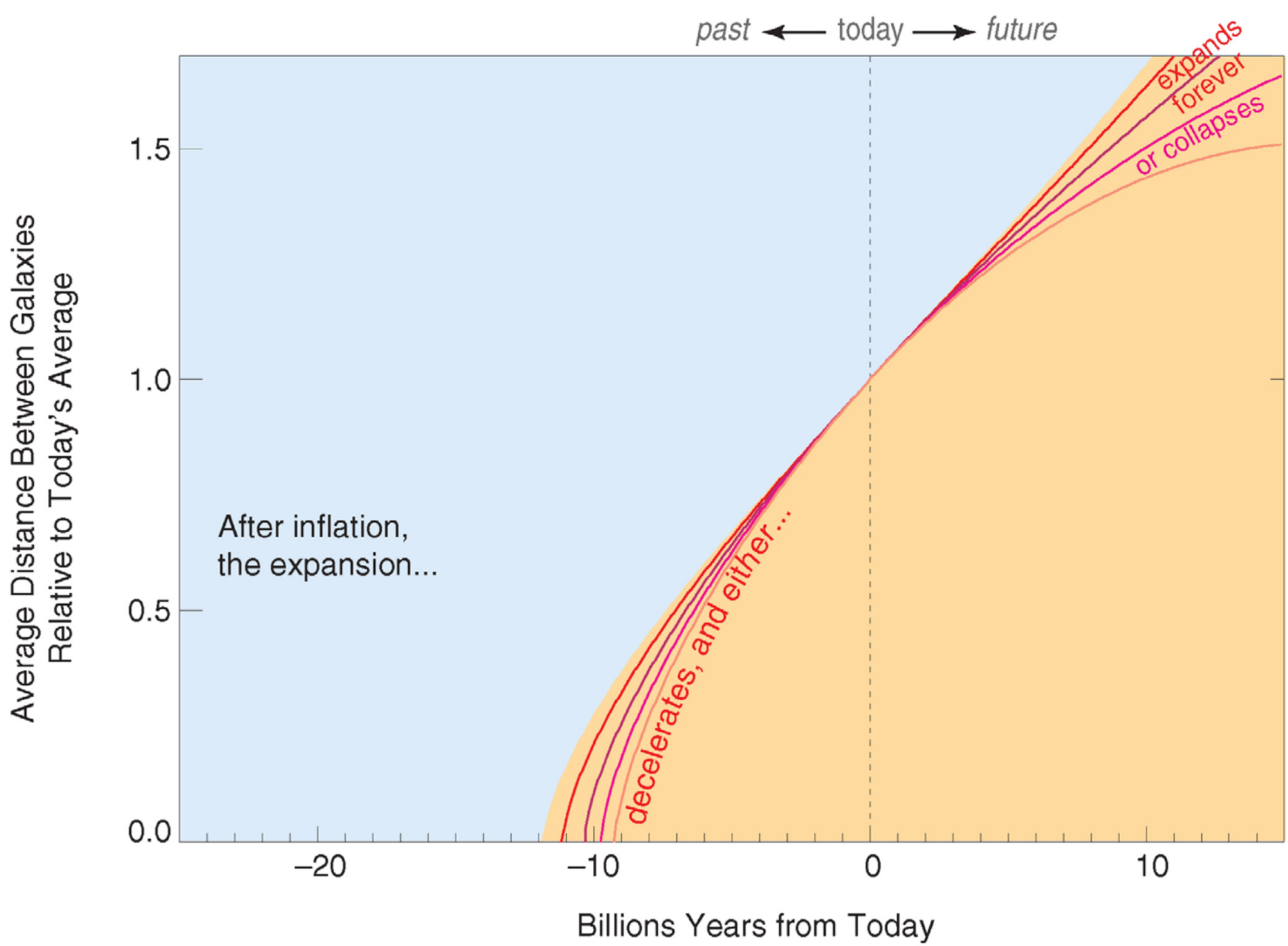


What is the fate of the Universe?



What is the fate of the Universe?

Fate of the Universe can be determined from its history



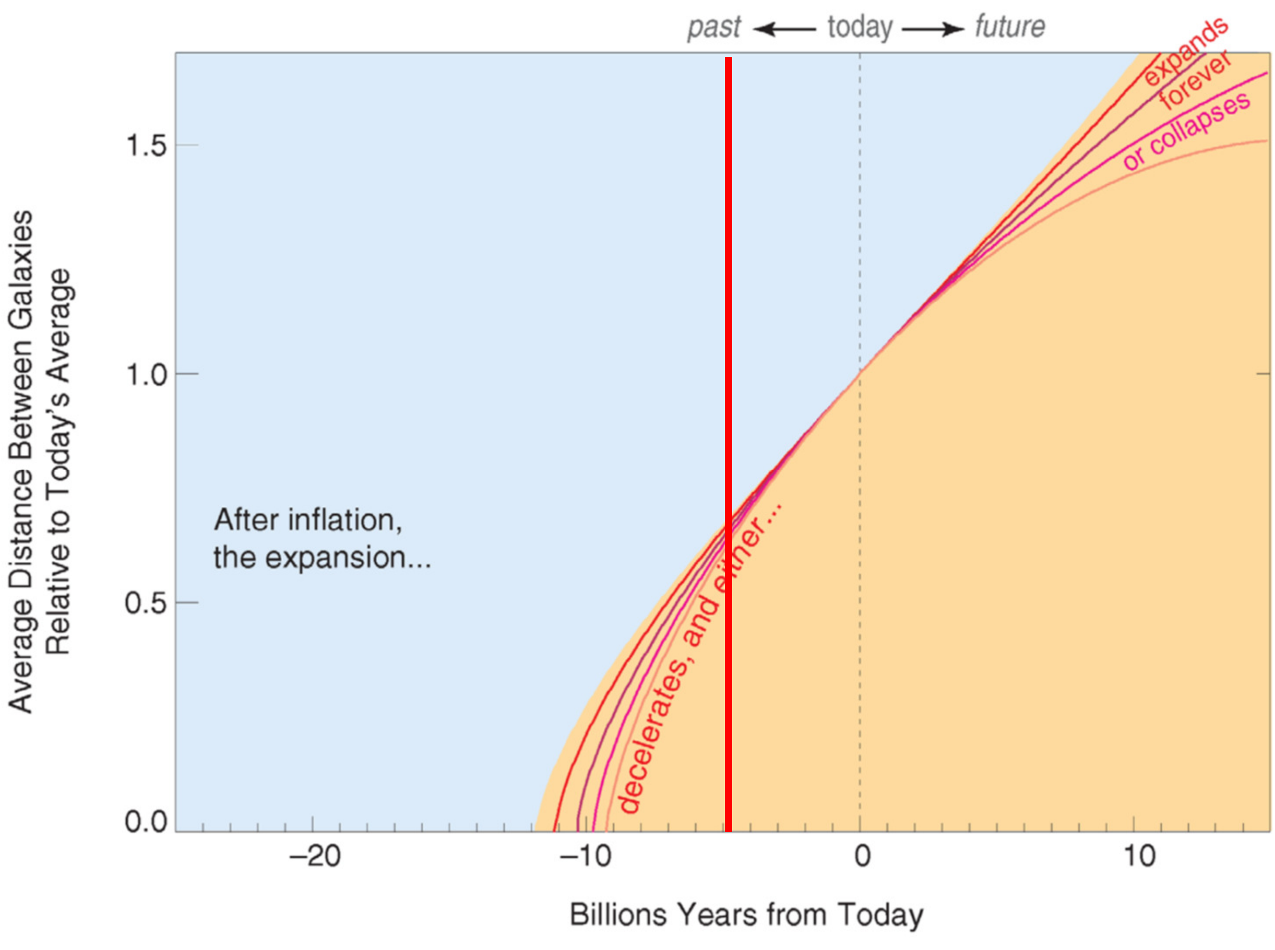
http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.html

1980s: The plan to determine the fate of the Universe

In 1980s it was expected that expansion of the Universe is slowing.

By late 1980 two groups decided the measure the **cosmic deceleration**, or how the expansion of the **Universe is slowing**.

Their method was in principle the same as the one used by Edwin Hubble to establish that Universe is expanding: to locate distant stars and to measure how they move.



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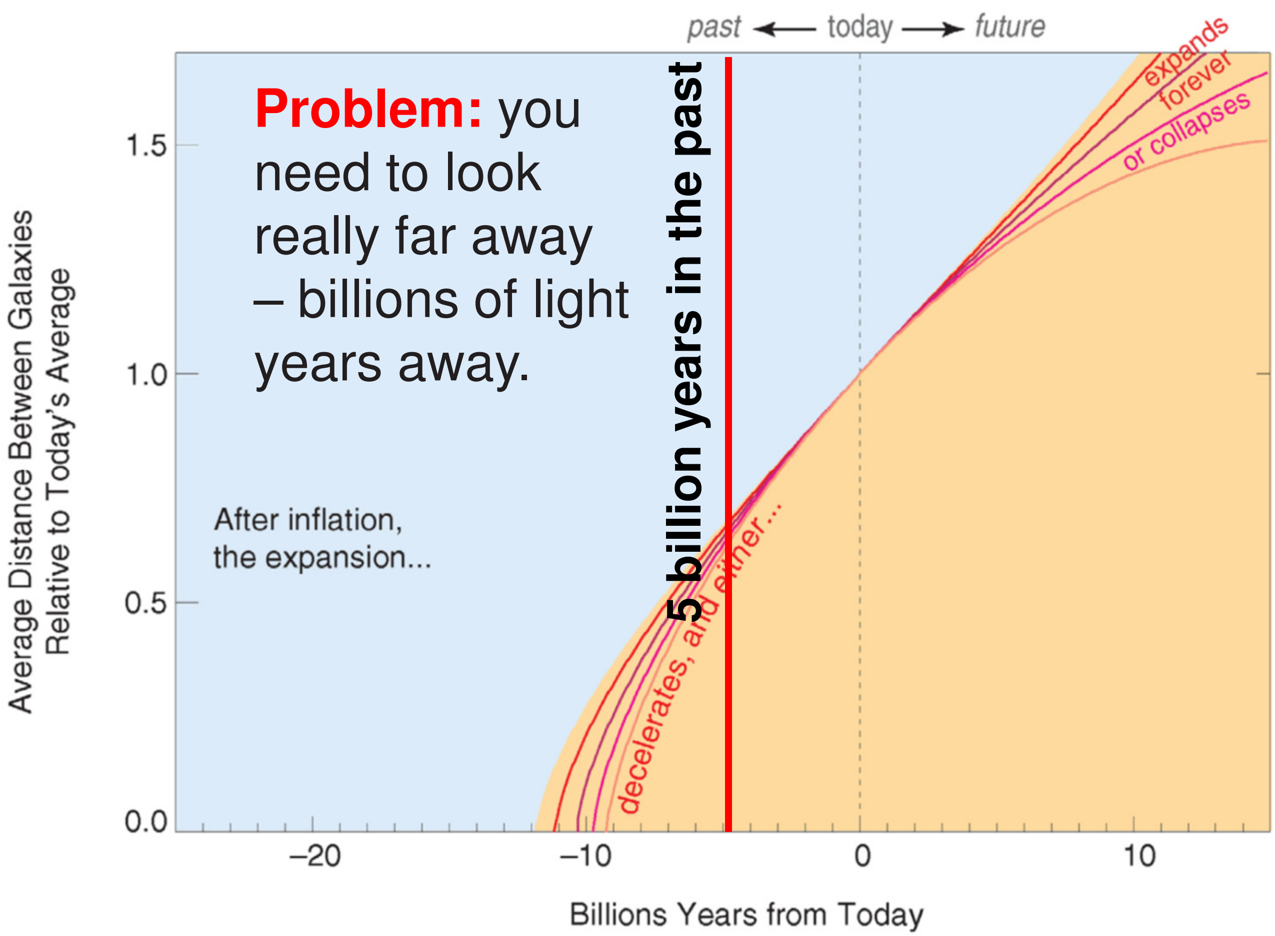


At these distance "standard candles" Edwin Hubble used – Cepheid variable stars are not visible.

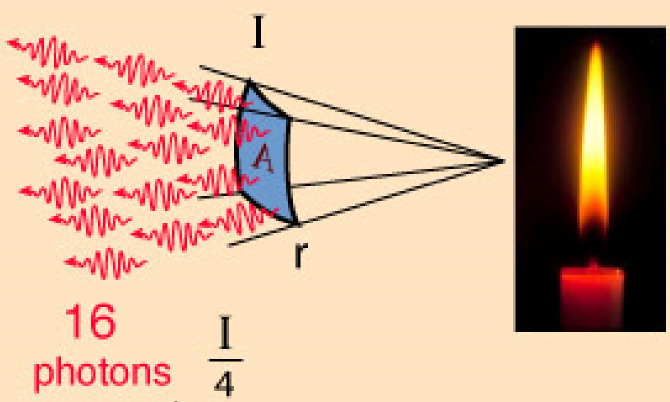
Need much brighter standard candle – we have too see it from billions of light years away!

Problem: you have to look really far back in time
Need really bright standard candles

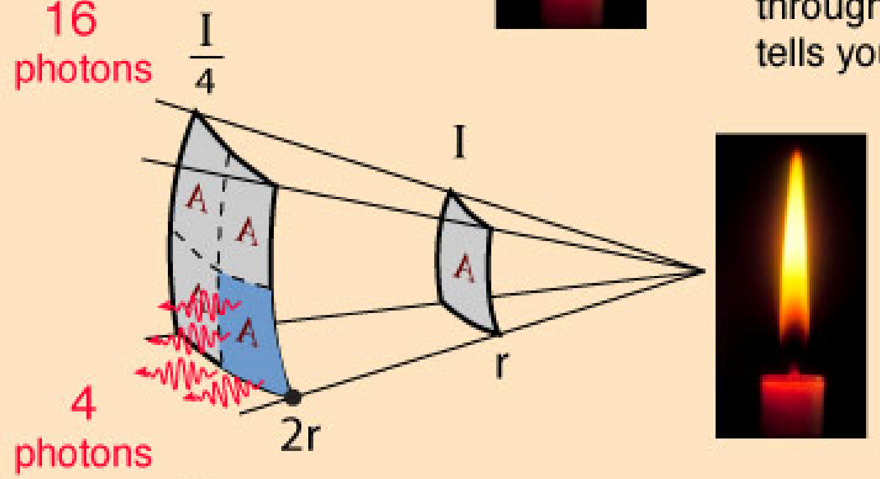
A **standard candle** is a class of astrophysical objects, such as supernovae or variable stars, which have known luminosity due to some characteristic quality possessed by the entire class of objects.

https://wigglez.swin.edu.au/site/image1.html
http://www.centauri-dreams.org/?p=11322

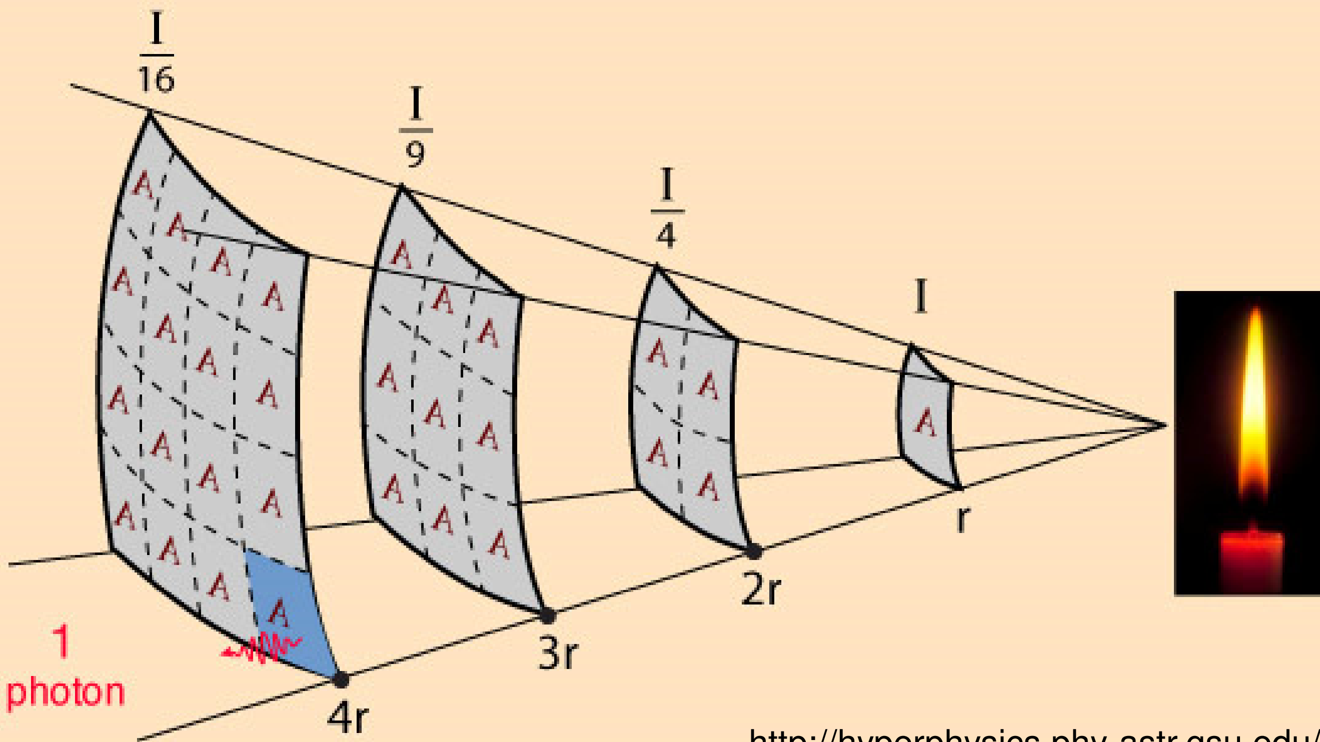
The “standard candle” approach to distance measurement.



If you know you have the same source strength of light, then counting the number of photons through a standard area detector tells you the distance to the source.

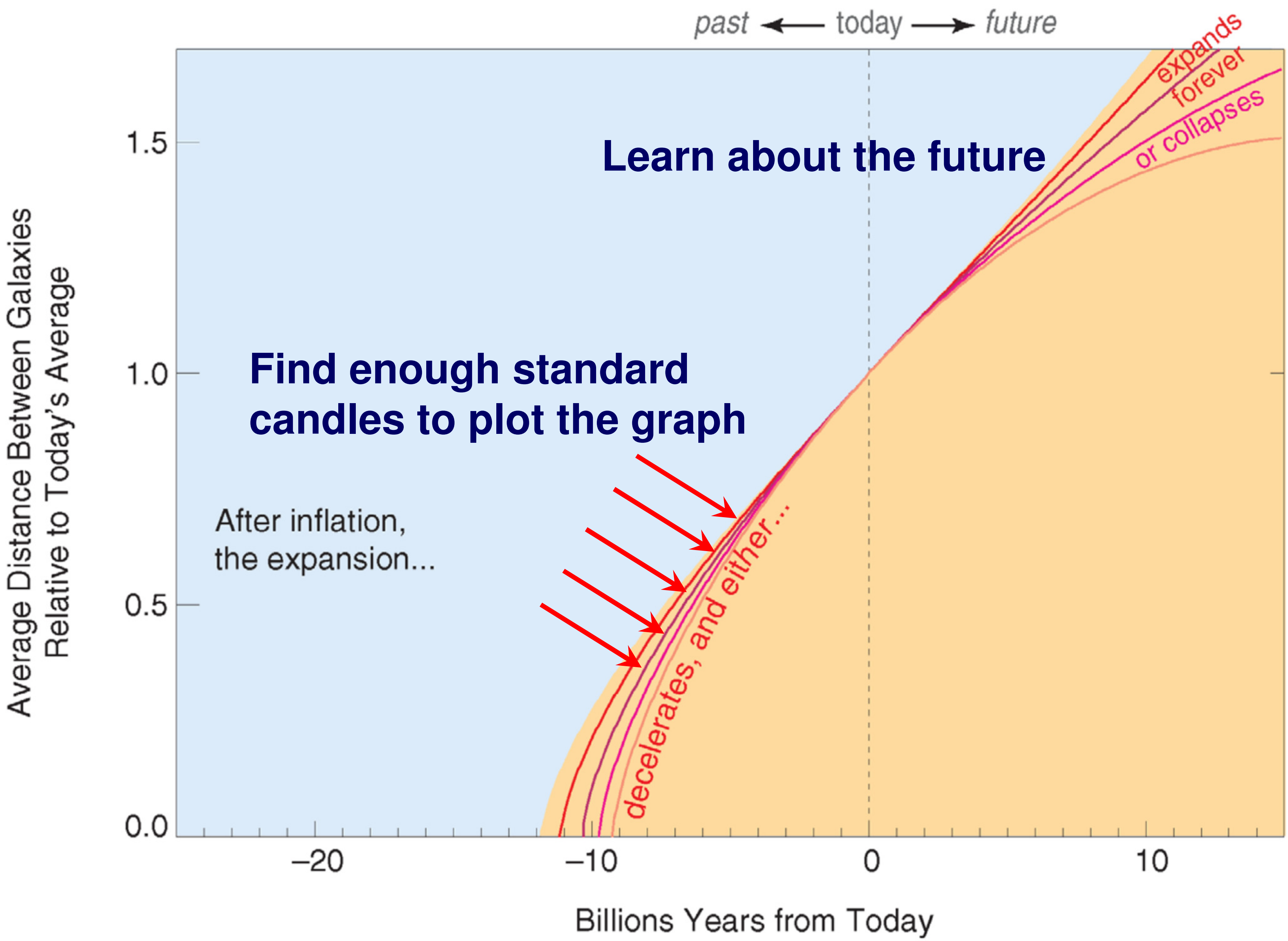


Light from a point source drops off according to the inverse square law, a strictly geometrical relationship.

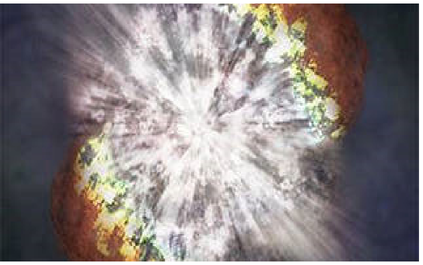


http://hyperphysics.phy-astr.gsu.edu/hbase/astro/stdcand.html

Fate of the Universe can be determined from its history



http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.html

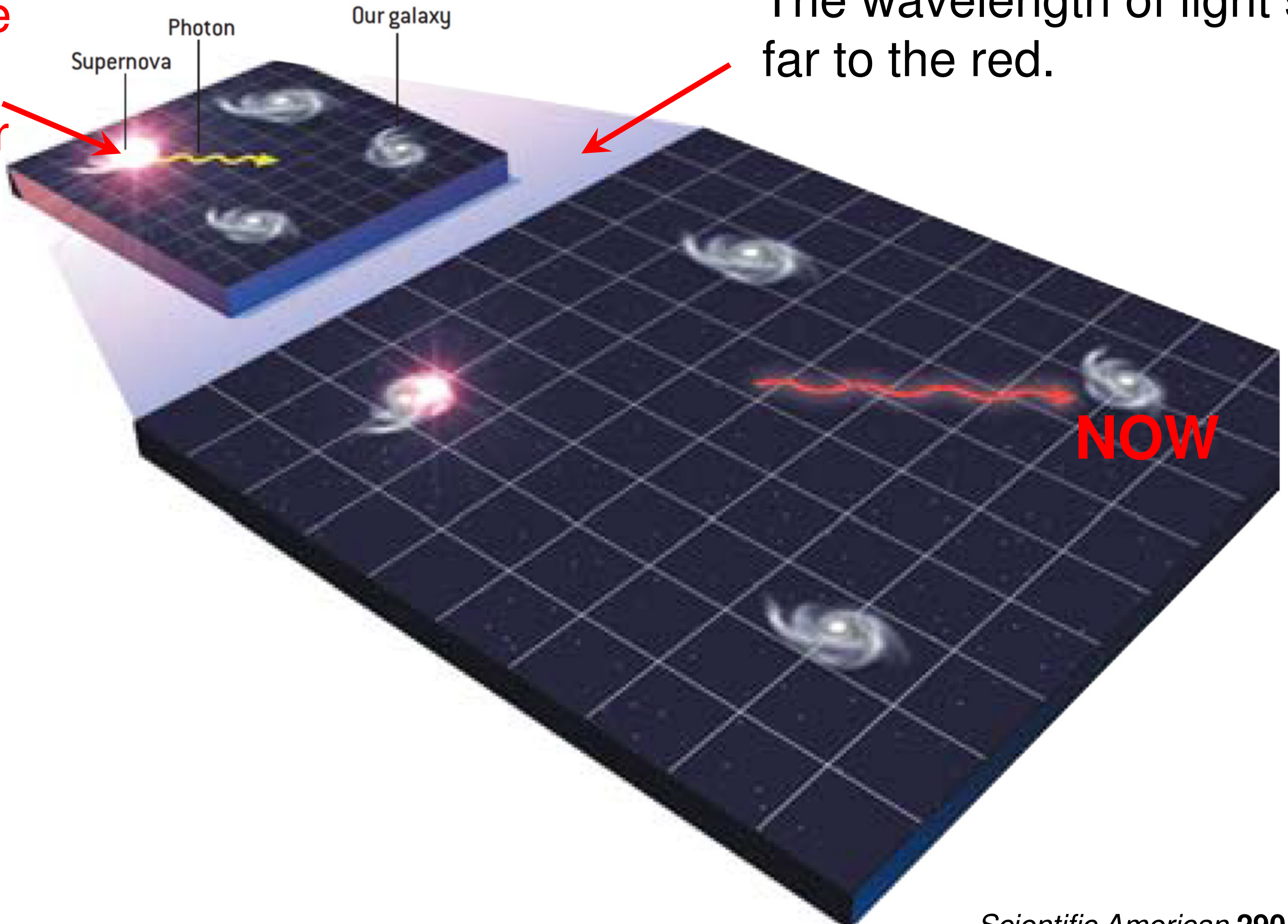


We can see supernova explosions from billions of years away! Just for a while, it shines brighter than the entire galaxy!

Credits: NASA

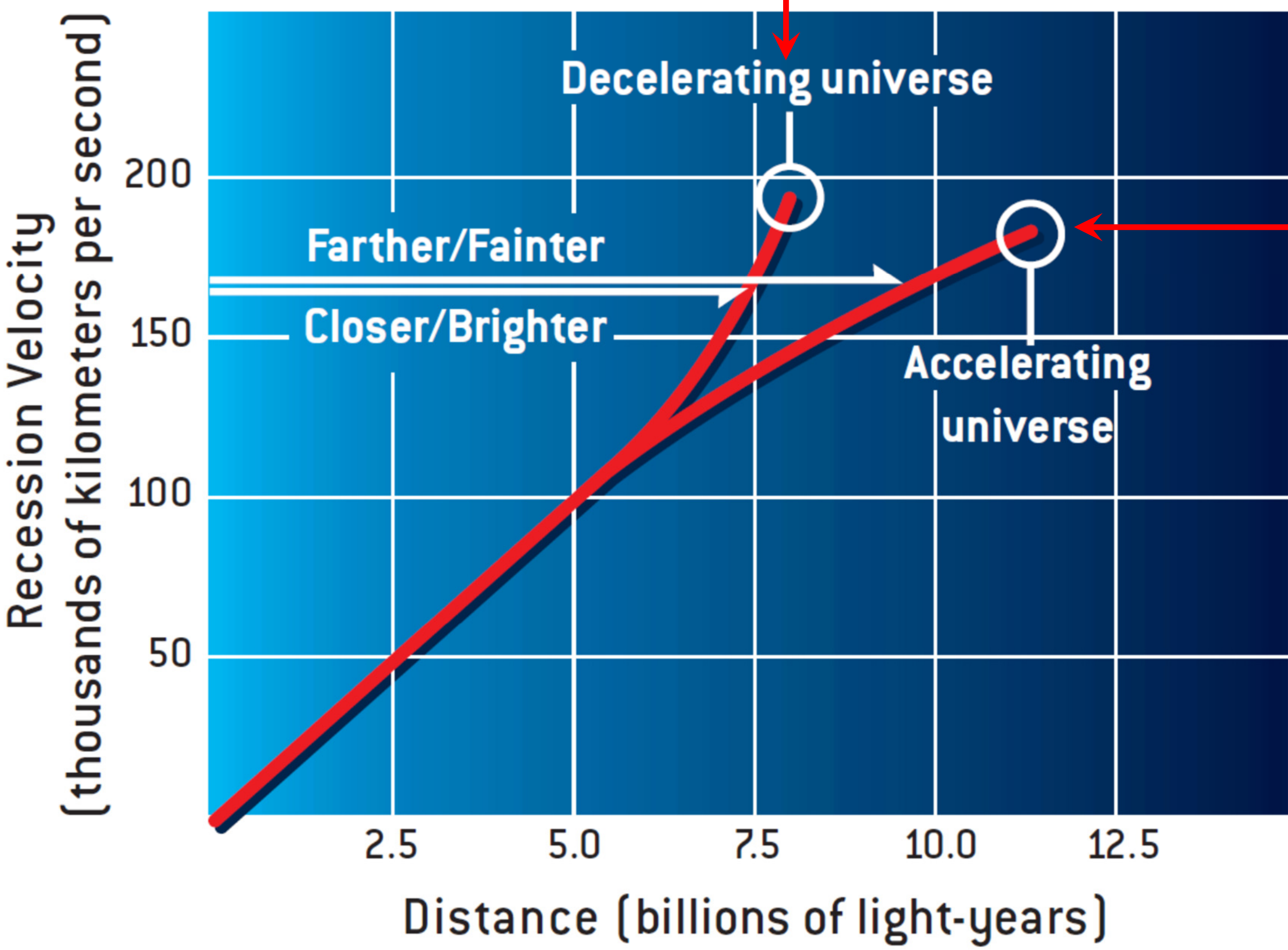
Universe expands while light from supernova travels to us. The wavelength of light shifts far to the red.

Long time ago in a galaxy far far away



Scientific American **290**, 62-67 (2004)

If the expansion of the universe were **decelerating**, the supernova would be **closer and brighter** than expected.



If the expansion were **accelerating**, the supernova would be **farther away and dimmer** than expected.

Scientific American **290**, 62-67 (2004)

Problems:

(1) Supernova explosions did not appear to be the same, so did not seem to be good standard candles.

(2) They are rare – about one per century per galaxy.

(3) They are unpredictable.

Two developments by mid 1980s

(1) Scientists realized that supernova explosions can be divided into classes.

Type Ia supernova subclass were identified which appeared to make much better standard classes than the others.

(2) New sensors, **the CCD detectors**, which are like the detectors in the back of the digital cameras that most people have today were introduced to astronomy.

New computers that were just then becoming fast enough to analyze the large amounts of data that came out of these detectors.

2009 Nobel Prize in Physics

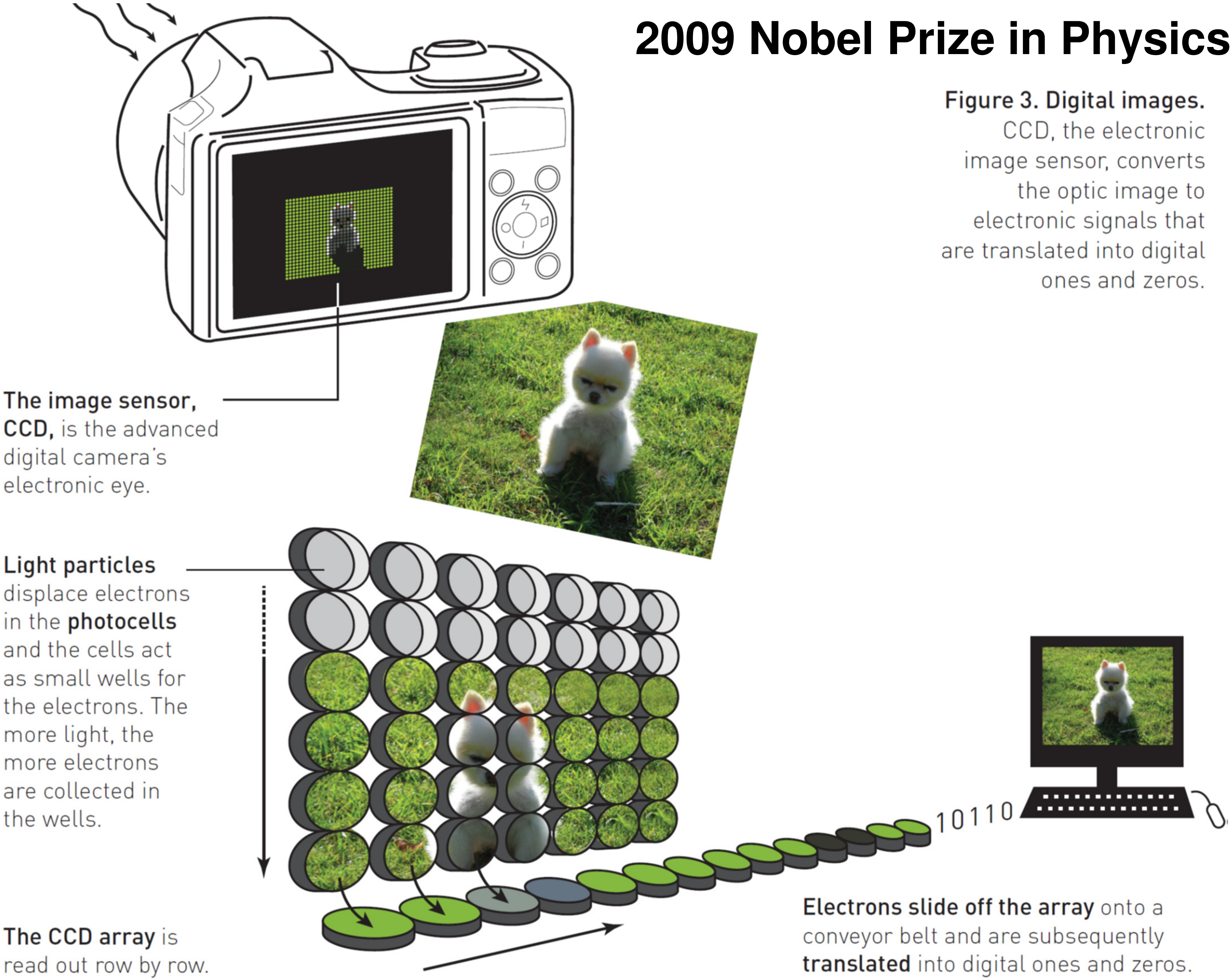
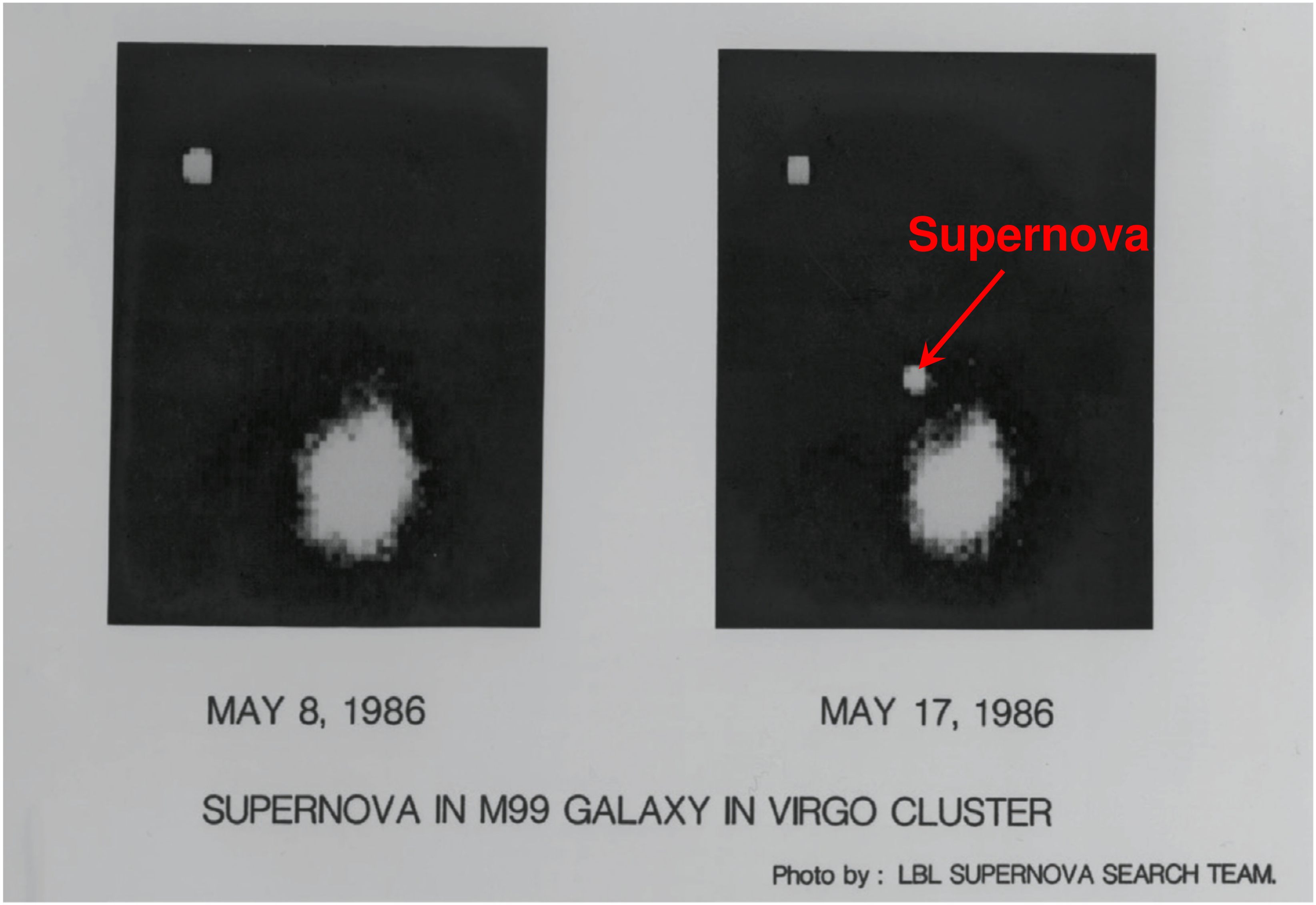


Figure 3. Digital images. CCD, the electronic image sensor, converts the optic image to electronic signals that are translated into digital ones and zeros.

http://www.nobelprize.org/nobel_prizes/physics/laureates/2009/popular-physicsprize2009.pdf

CCD and computer analysis are needed for supernova hunt



Before-and-after images of one of the supernovae discovered in 1986 by Berkeley Automated Supernova Search.

http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.pdf

CCD and computer analysis are needed for supernova hunt

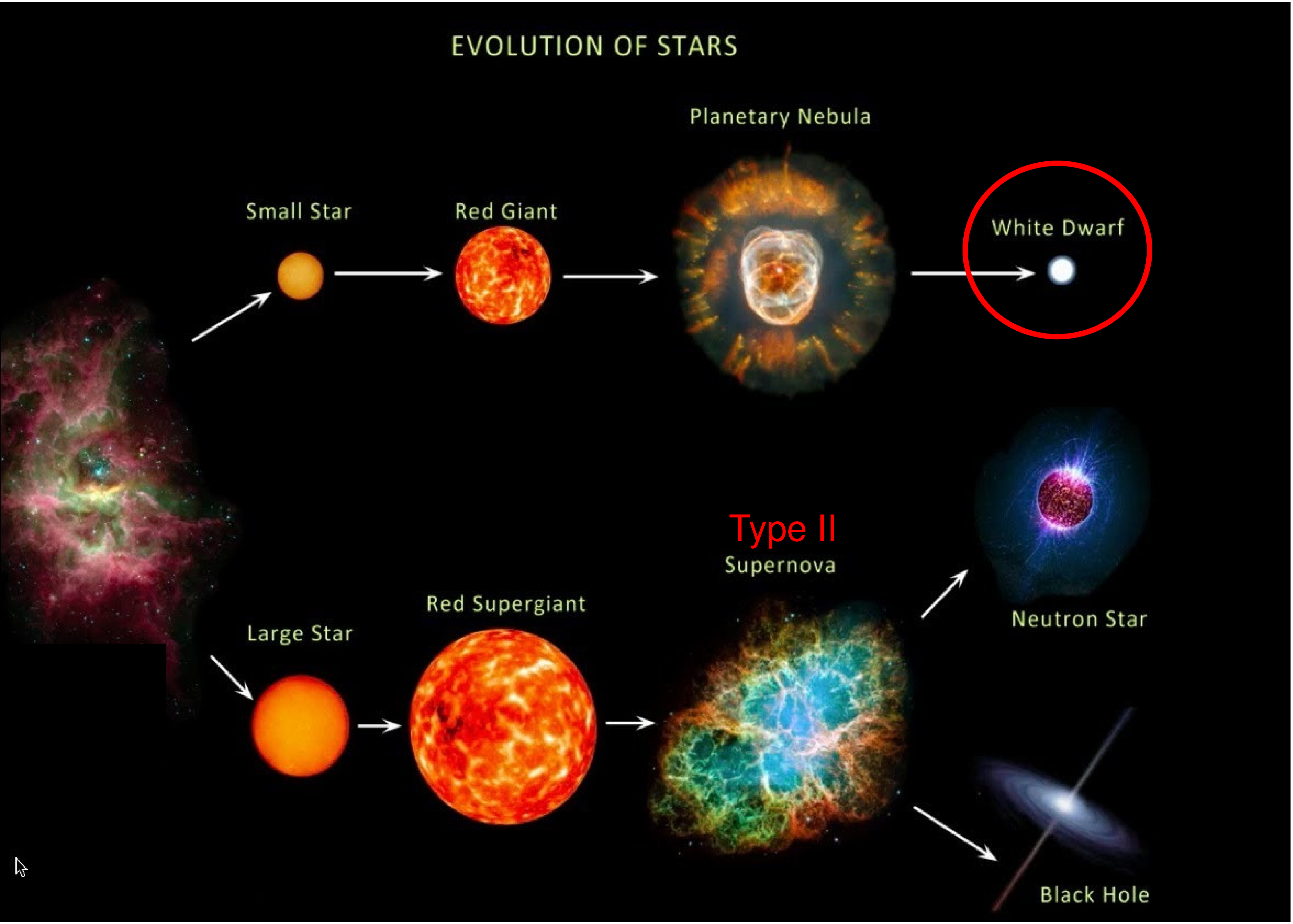
Example of digital image subtraction.

From the CCD image of a supernova and its host galaxy, we subtract an image of the galaxy before the supernova appeared (or after it disappeared), leaving an image of just the supernova.

http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.pdf

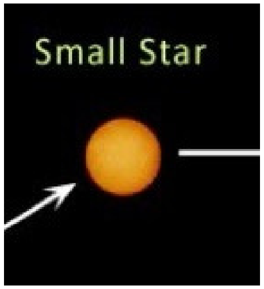
What is Type Ia supernova?

Why do we think they are all the same –
even the ones that exploded 10 billion years ago?



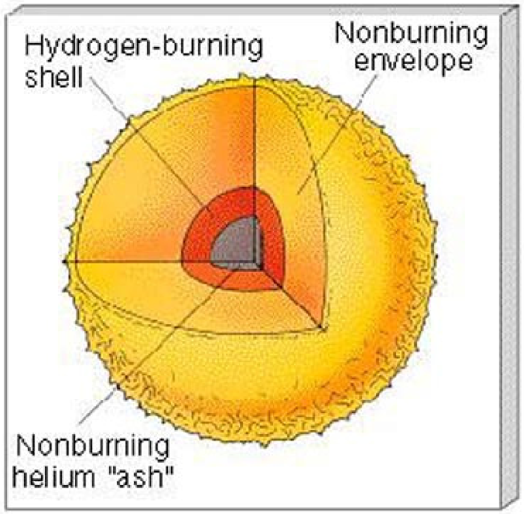
https://www.youtube.com/watch?v=CTNKk7TnkQ8

Small star to Red Giant

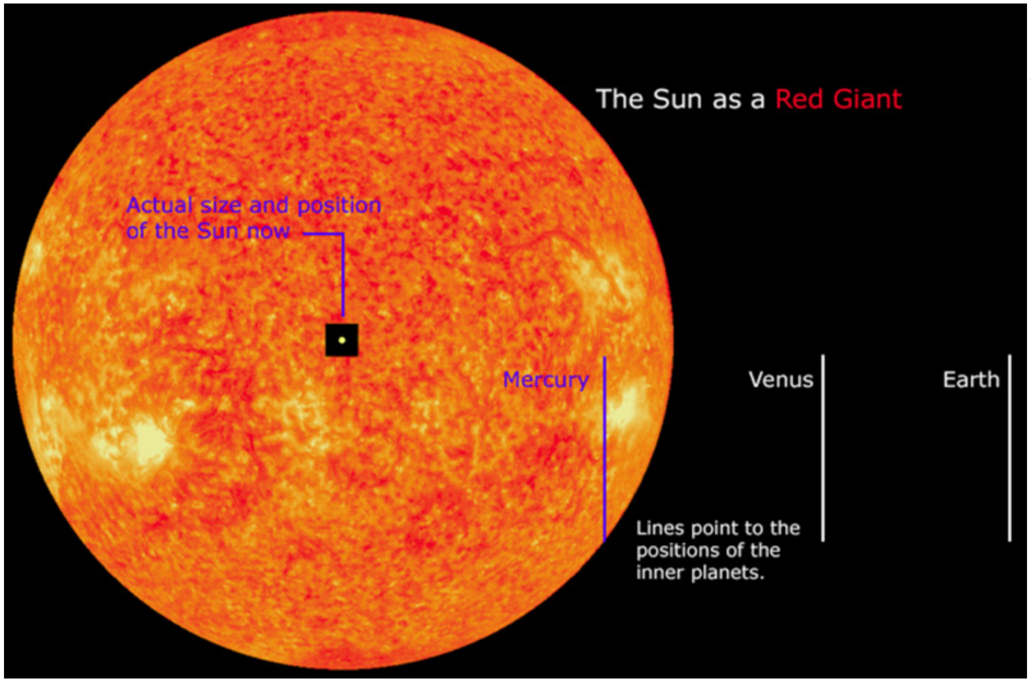


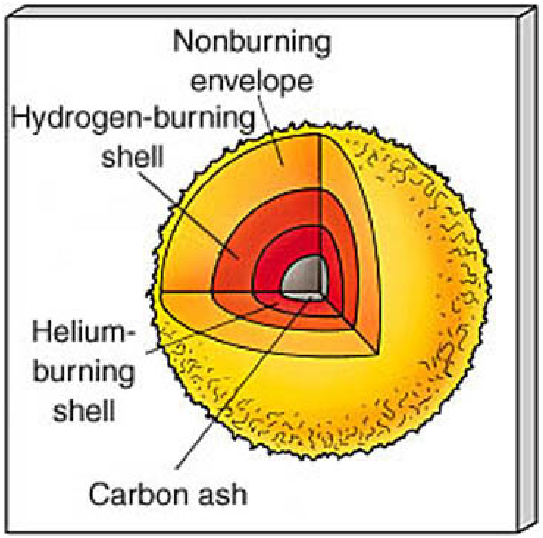
Converts H to He (fusion)

Eventually most of H in the stellar core has been converted to He
Pressure drops
Stellar core contracts



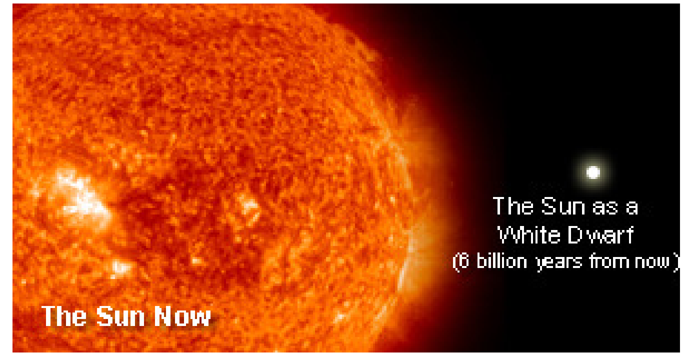
Temperature in stellar core rises
If mass is more than ½ Sun mass
He ignites, C and O are produced
Outer envelop expands – Red Giant

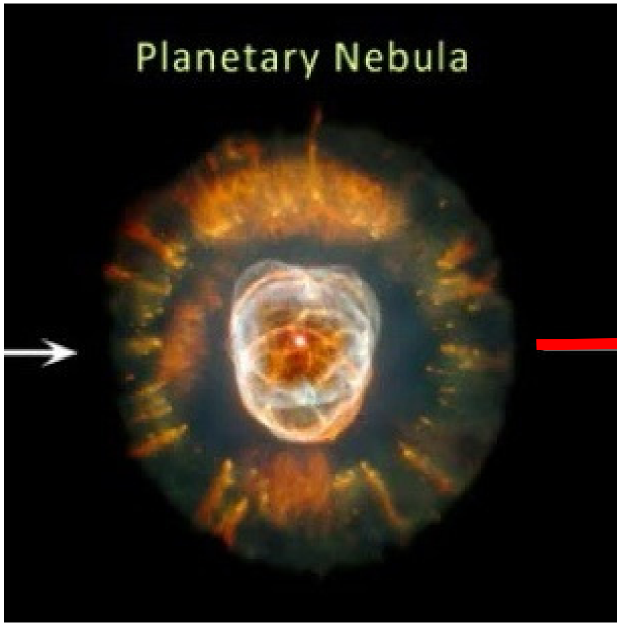




http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/starevolution.htm

Red Giant to White dwarf

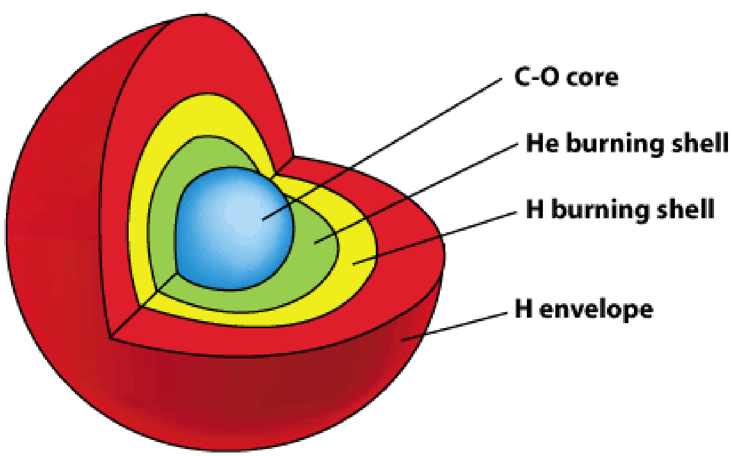




Outer stellar envelop expands further and escapes to form a planetary nebula

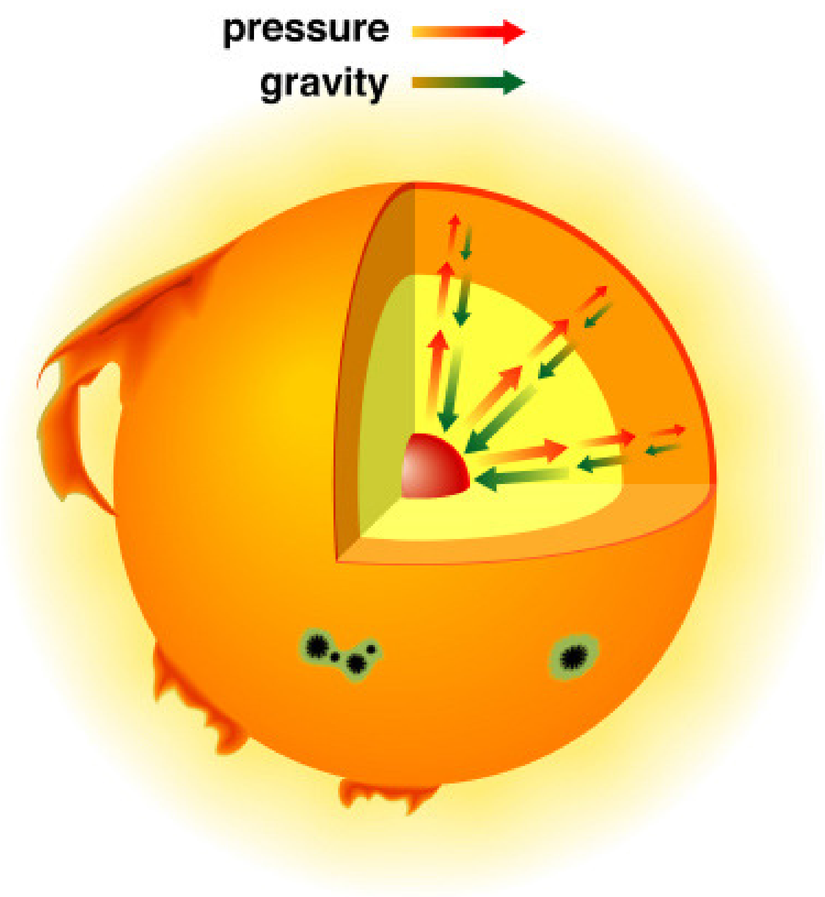
In small stars, core temperature is not high enough to start burning carbon

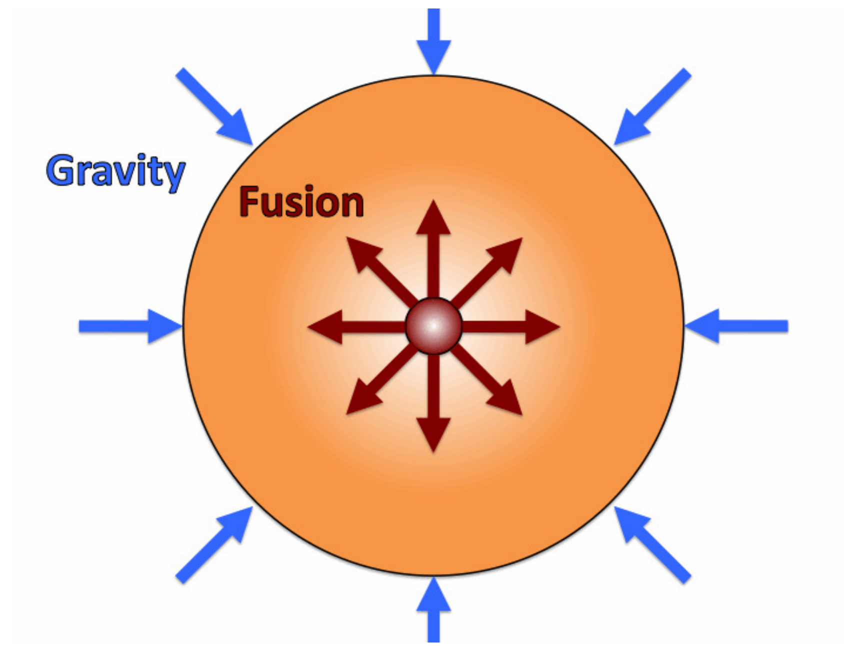
Then, when all He is used up, star has no fusion source and stars becomes to very slowly cool off -
White Dwarf (Carbon/Oxygen)



More massive white dwarfs are smaller and denser than less massive ones.

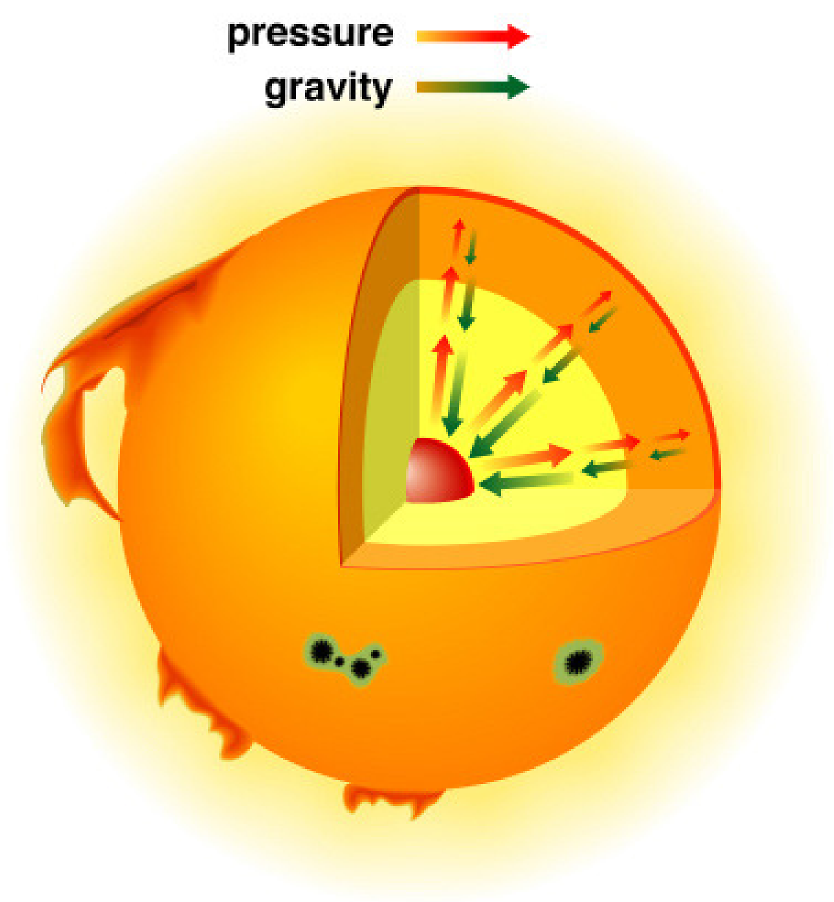
Stars: pressure vs. gravity

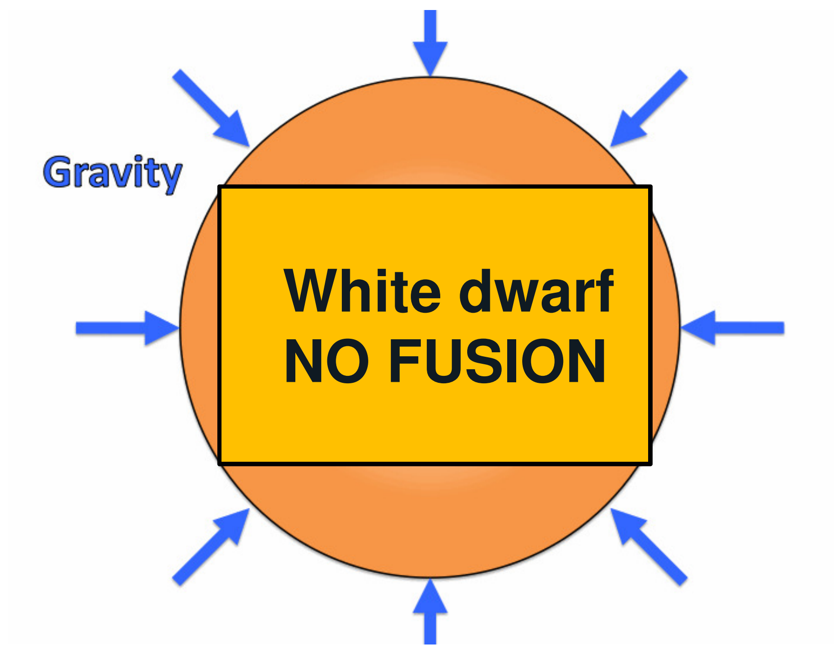




http://cse.ssl.berkeley.edu/bmendez/ay10/2002/notes/pics/bt2lf1402_a.jpg
http://large.stanford.edu/courses/2011/ph241/olson1/

Stars: pressure vs. gravity

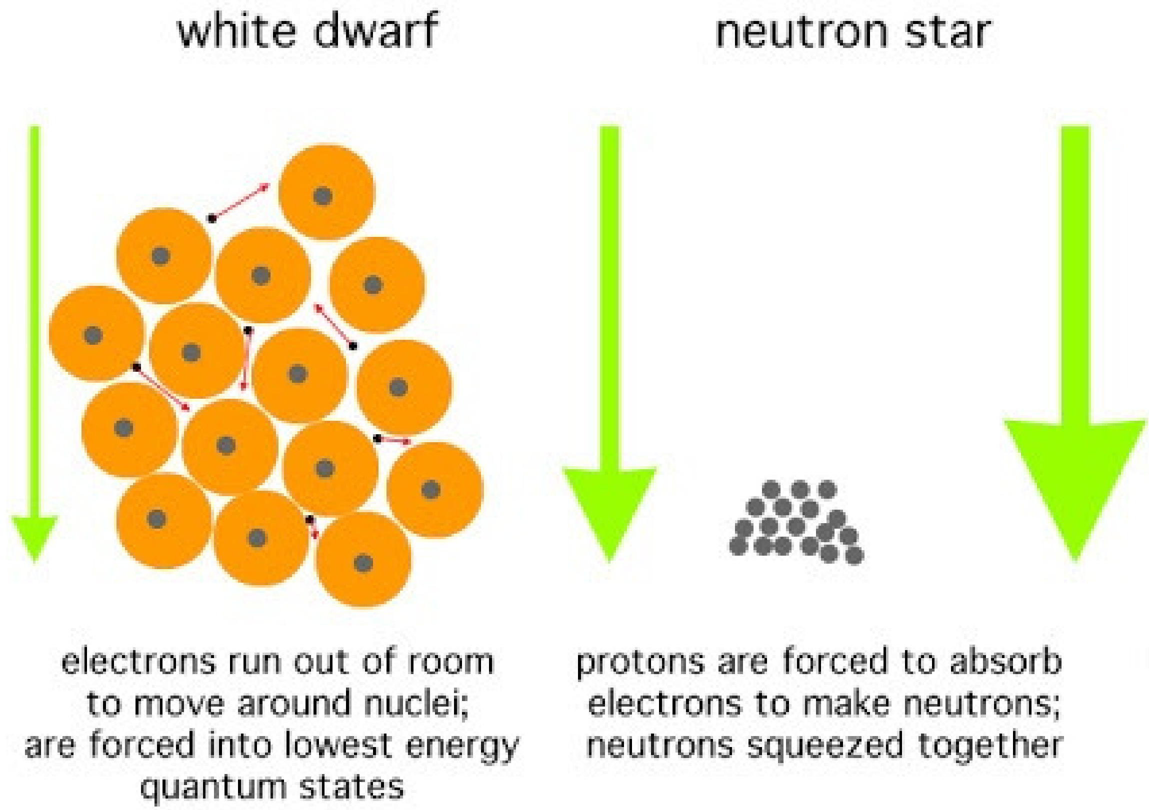




What keeps is from collapsing?

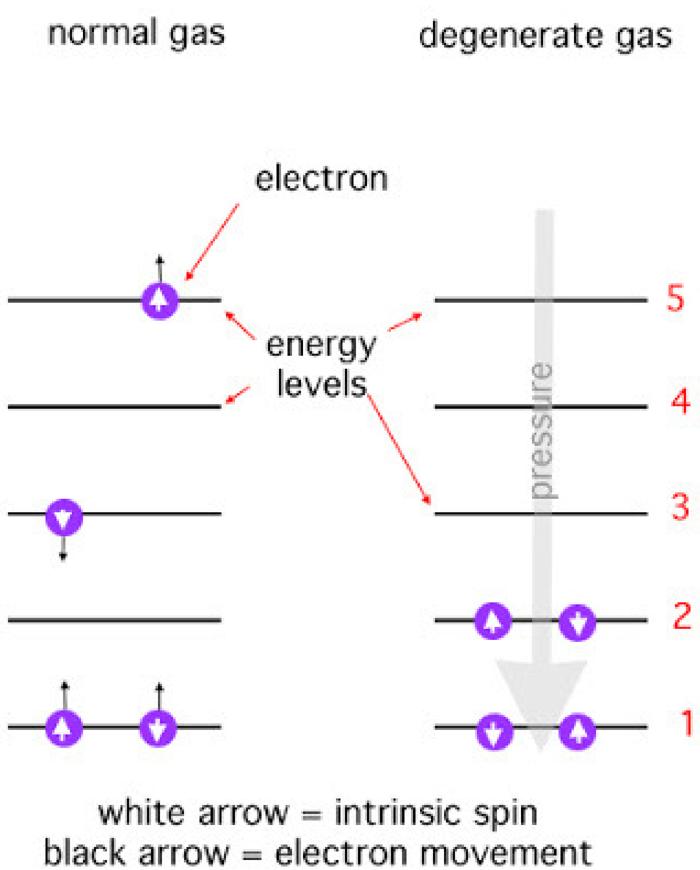
http://cse.ssl.berkeley.edu/bmendez/ay10/2002/notes/pics/bt2lf1402_a.jpg

Quantum mechanics: degeneracy pressure



http://sciexplorer.blogspot.com/2013/03/the-sun-part-4-helium-eventually-seals.html

Quantum mechanics: electron degeneracy pressure



Electrons are neutrons are fermions.

Fermions have to be in different quantum states.

In degenerate gas all quantum states are occupied by electrons.

Then, pressure arises in degenerate core since electrons can not be packed arbitrary close together.

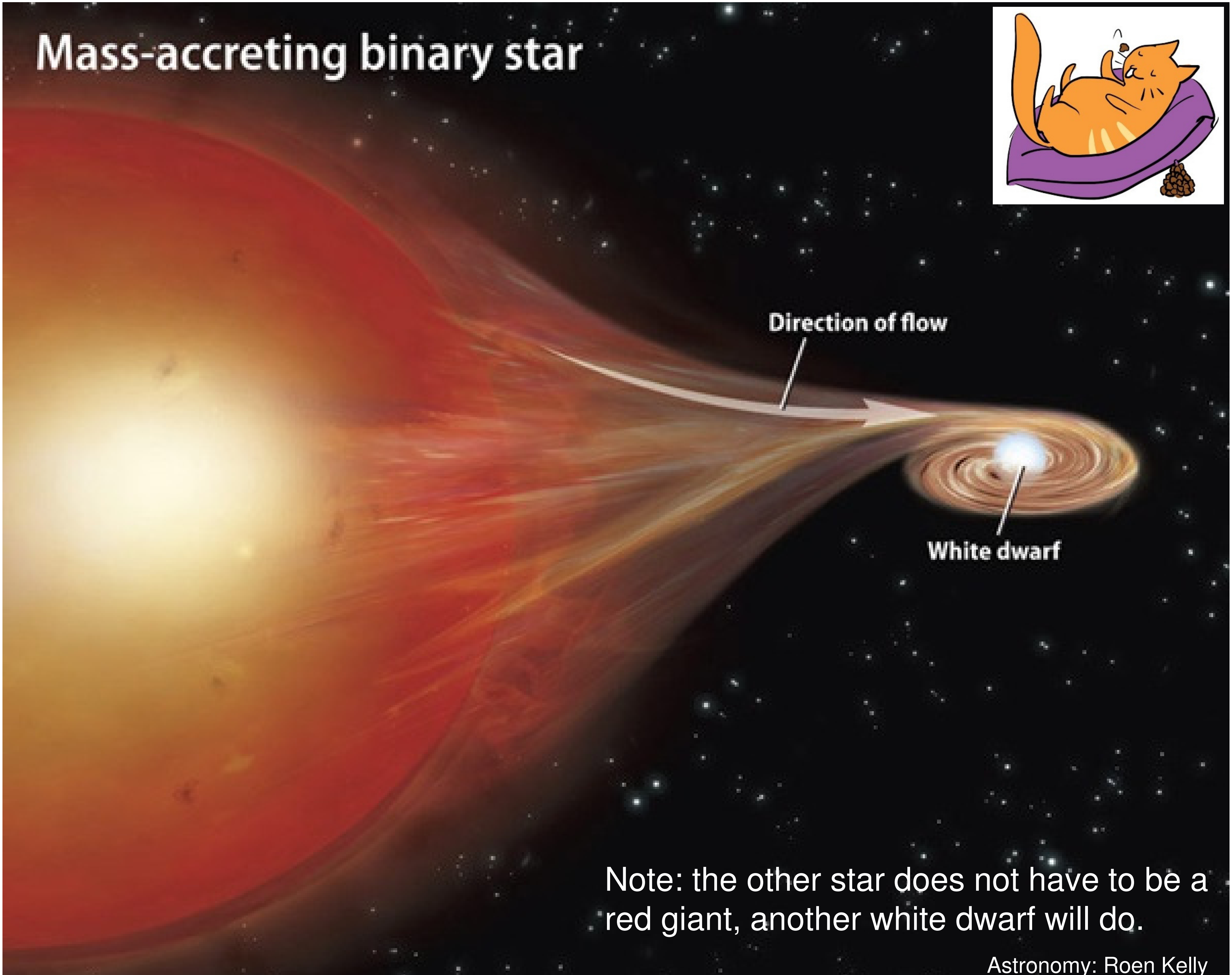
It is called degeneracy pressure.

White dwarfs are supported against gravity collapse by electron degeneracy pressure.

Here is a catch: electron degeneracy pressure can only support stars up to a certain mass against collapse!

Chandraskehar limit
1.4 solar mass

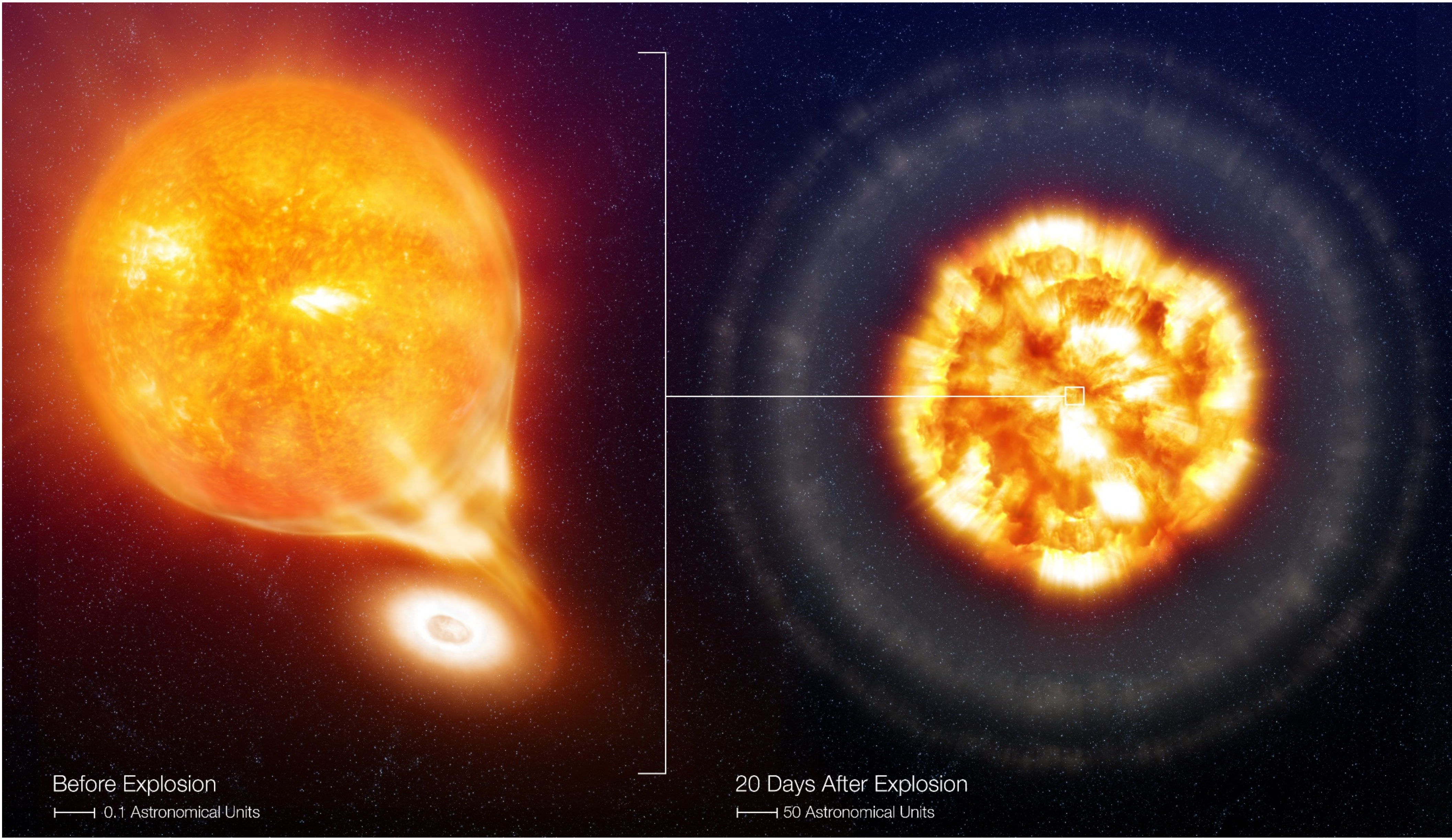
http://dingercatadventures.blogspot.com/2012/11/30-chandrasekhar-limit.html



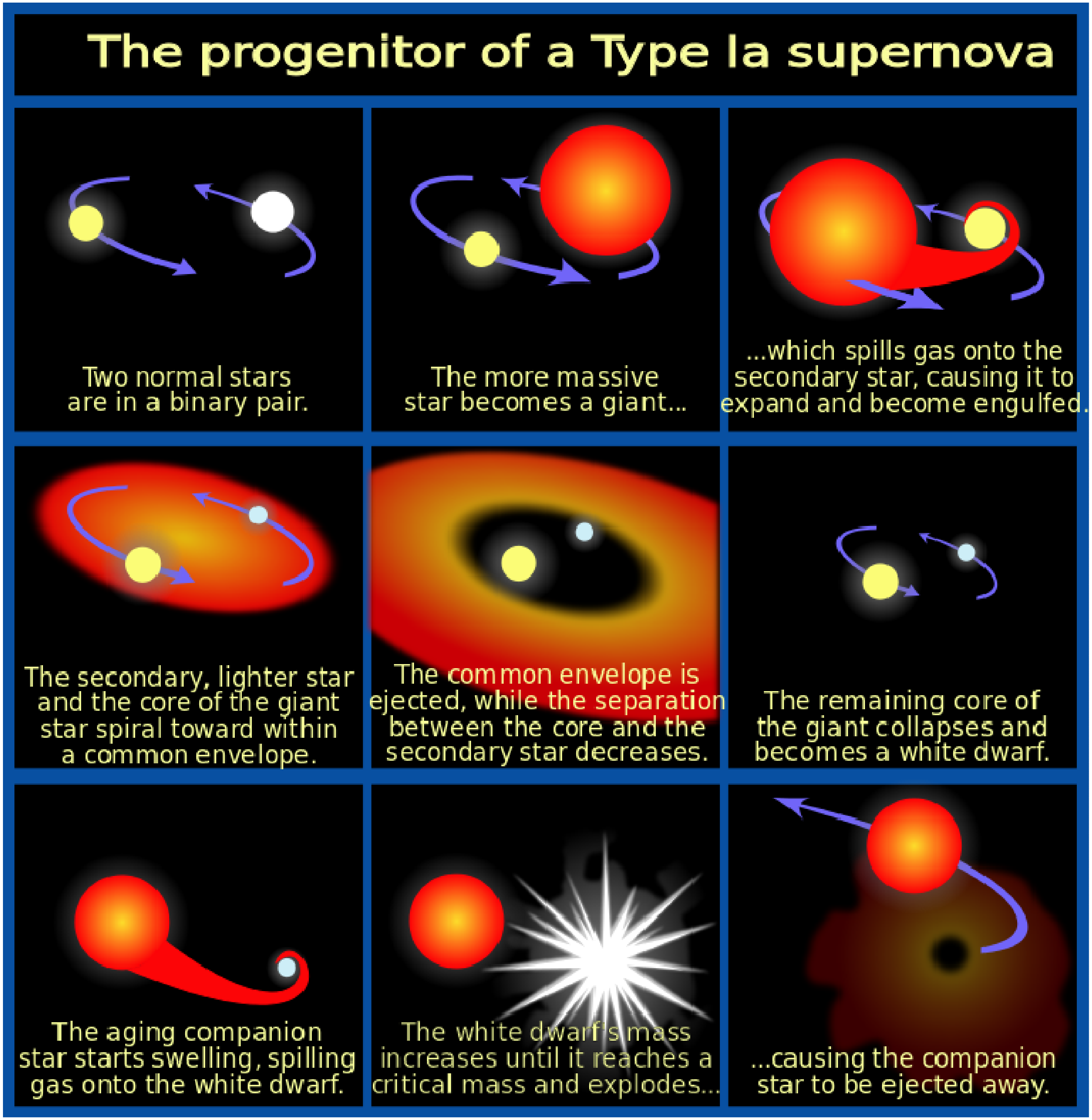
Note: the other star does not have to be a red giant, another white dwarf will do.

Astronomy: Roen Kelly

The white dwarf approaches Chandraskehar limit
… and explodes in a giant thermonuclear explosion!



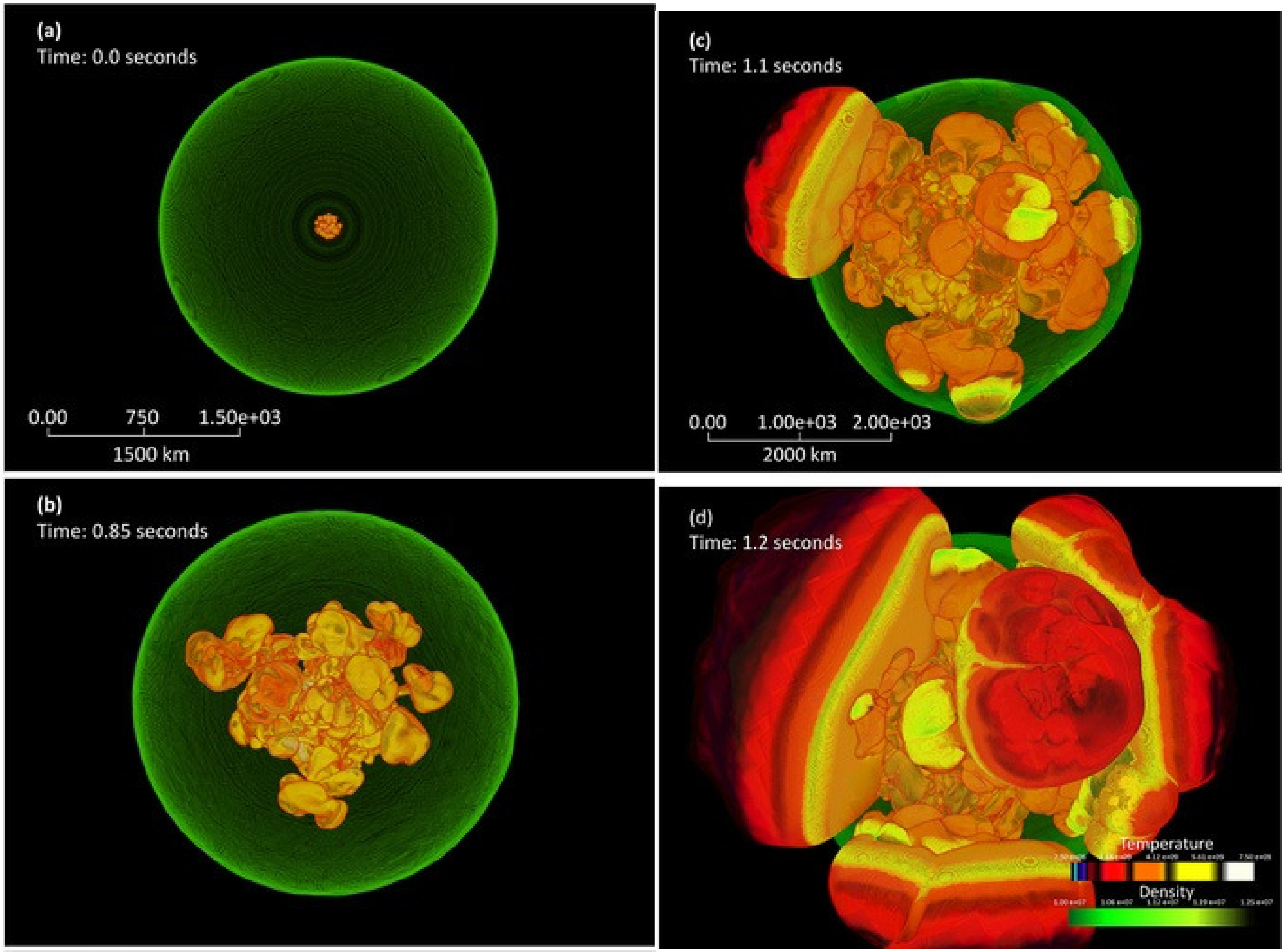
Type I supernova simulation
https://www.youtube.com/watch?v=5YZkAoR3WLE



NASA, ESA and A. Feild (STScI) http://hubblesite.org/newscenter/archive/releases/star/supernova/2004/34/image/d/

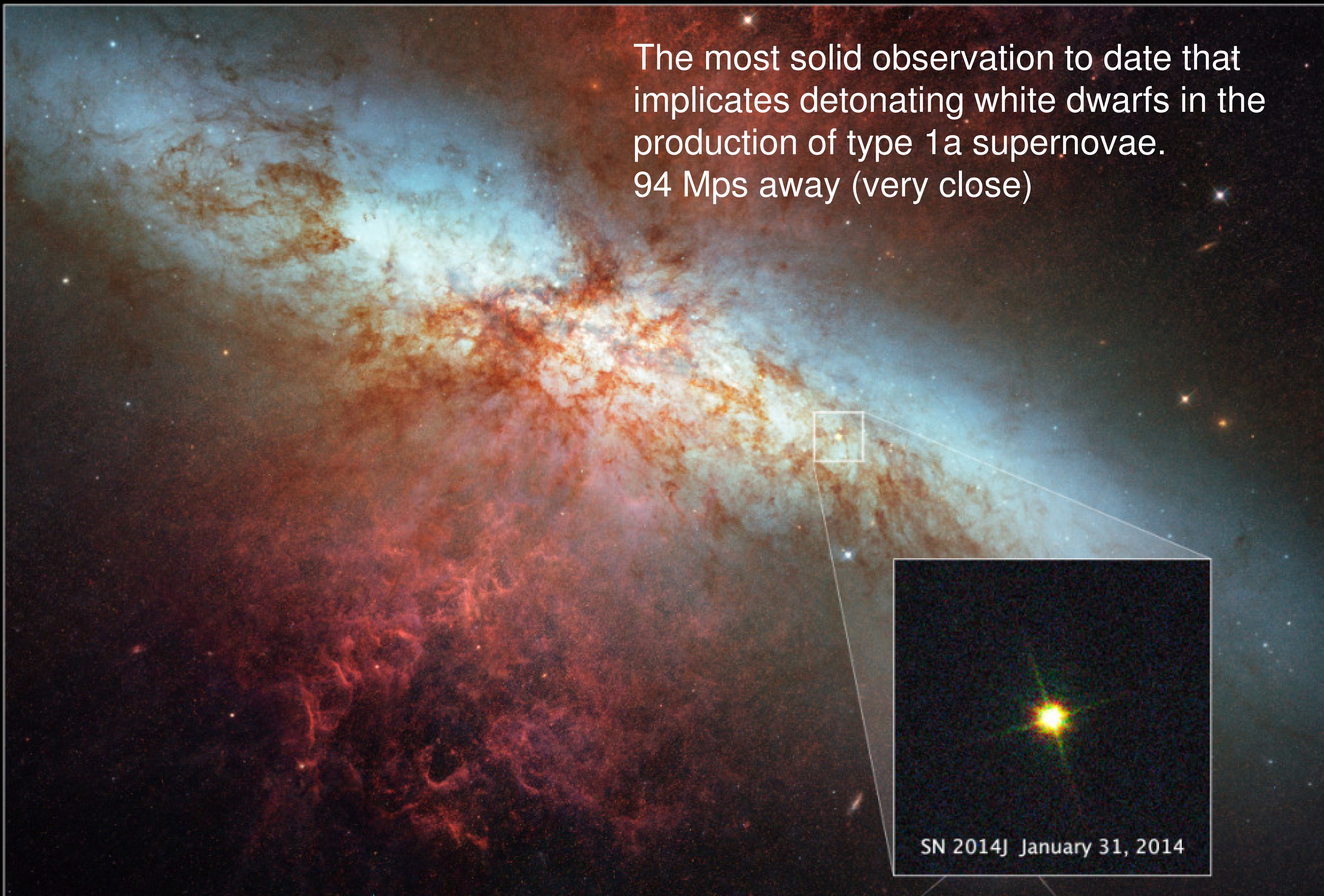
The physics of the type Ia supernova explosion are debated

Carbon ignites, thermonuclear flame rips through the white dwarf, fusing carbon into heavier elements with a sudden release of energy that tears the star apart. Can be caused by collisions with the other star.



https://en.wikipedia.org/wiki/Type_Ia_supernova#/media/File:Type_Ia_supernova_simulation_-_Argonne_National_Laboratory.jpg

Supernova 2014J in Galaxy M82 *HST* ▪ WFC3/UVIS ▪ ACS/WFC



NASA and ESA STScI-PRC14-13a

http://www.nature.com.udel.idm.oclc.org/nature/journal/v521/n7552/pdf/nature14440.pdf

Simulation of Supernova type Ia explosion

https://www.youtube.com/watch?v=gQ07sZKcUzs

Why supernova type Ia can be used as a standard candle?
Because explosion occurs when white dwarfs – which are all about the same reach the same Chandraskehar limit mass.

The details are being debated …

We now have a standard or rather “standartizable candle” and return back to discussing measuring the expansion of the Universe.

NEED TO FIND FAR AWAY SUPERNOVA OF TYPE Ia

1987: Some of the issues researches listed in the beginning of their work

Why is the supernova measurement ***not*** easy?

1. Can they be found **far enough** -- and **enough of them** -- for cosmology?
   Can they be found **early enough** to measure brightness over peak?

2. Can they be identified as Type Ia with spectra, despite how faint they will be?
   Can their brightness be compared with nearby ones, despite greatly "redshifted" spectra?

3. Are the supernovae standard enough?
   And how can one eliminate possible dust that might diminish their brightness?

4. Couldn't the supernovae evolve over five billion years?

http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.html

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Problems

with Type Ia Su

Previous survey

NB: Norgaard-Nielsen et al. searched intensively for over 2 years, and found just 1 Type Ia supernova several weeks past its peak.

Rare

1/500 years/galaxy

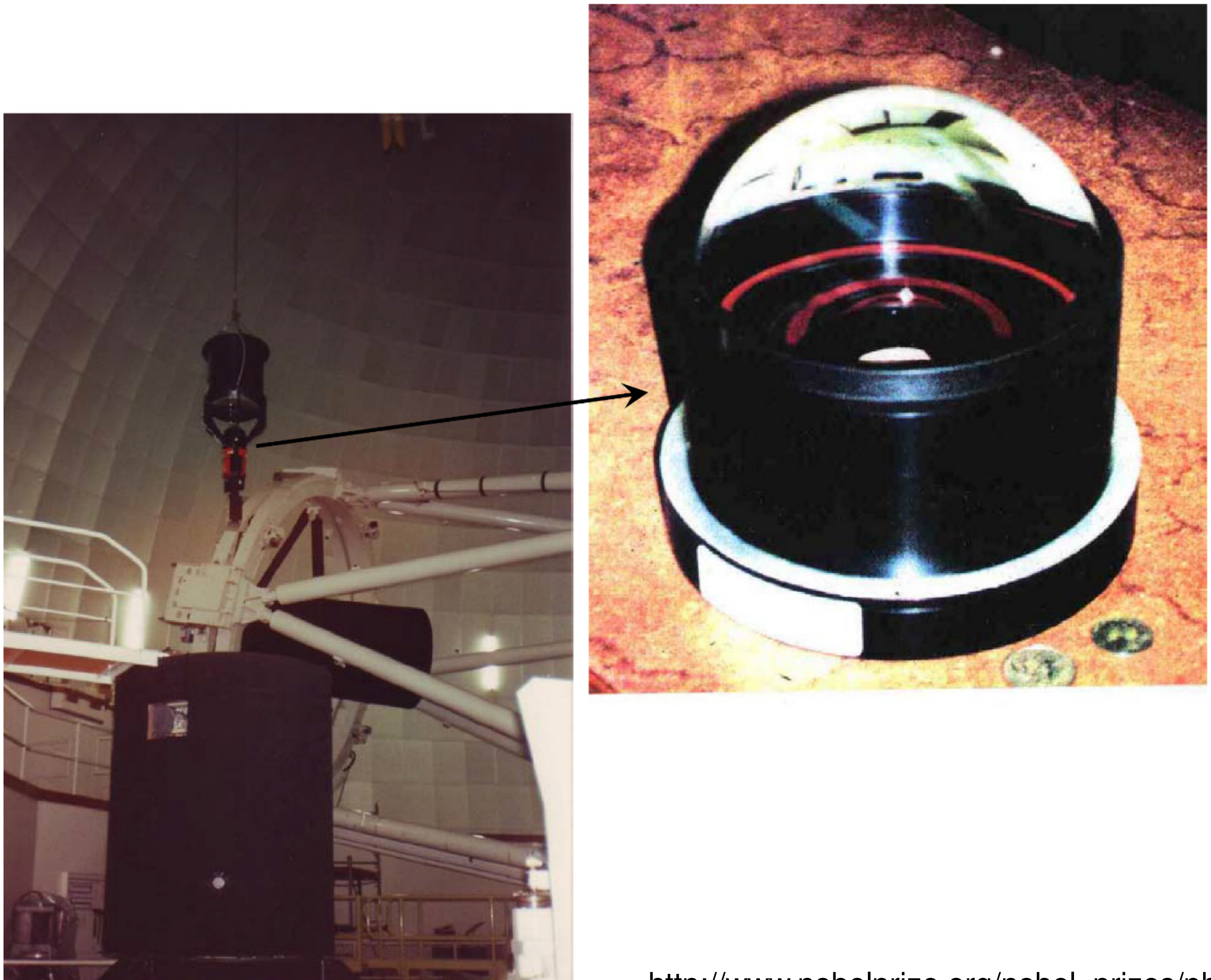
Random — can't schedu
or plan discoveries at new moon

Rapid — difficult to catch on the rise

http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.html

Pennypacker & Perlmutter 1987 proposal:

A novel F/1 wide-field CCD camera
for the Anglo-Australian 4-m telescope (AAT)



...A big enough telescope with a wide enough field to search for $z > 0.3$ Type Ia supernovae in 100s of galaxies with each image.

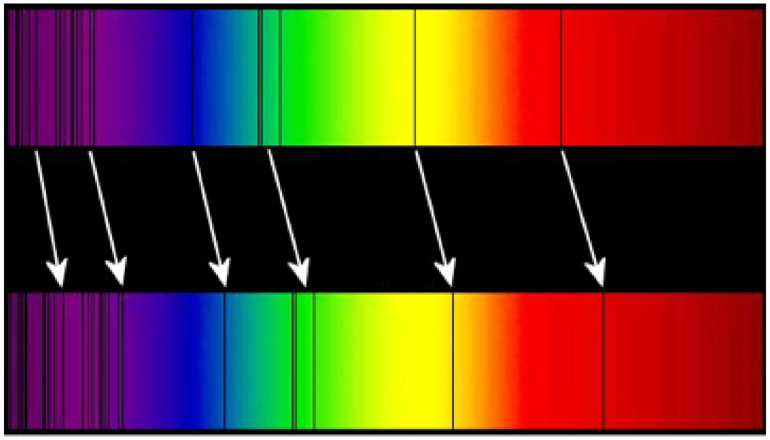
http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.html

Redshift

Redshift may be characterized by the relative difference between the observed and emitted wavelengths (or frequency) of an object.

In astronomy, it is customary to refer to this change using a **dimensionless quantity called *z*.**

$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$$



$$\lambda_{\text{emitted}} = 500\ \text{nm}$$

$$\lambda_{\text{observed}} = 1000\ \text{nm}$$

$$z = \frac{1000 - 500}{500} = 1$$

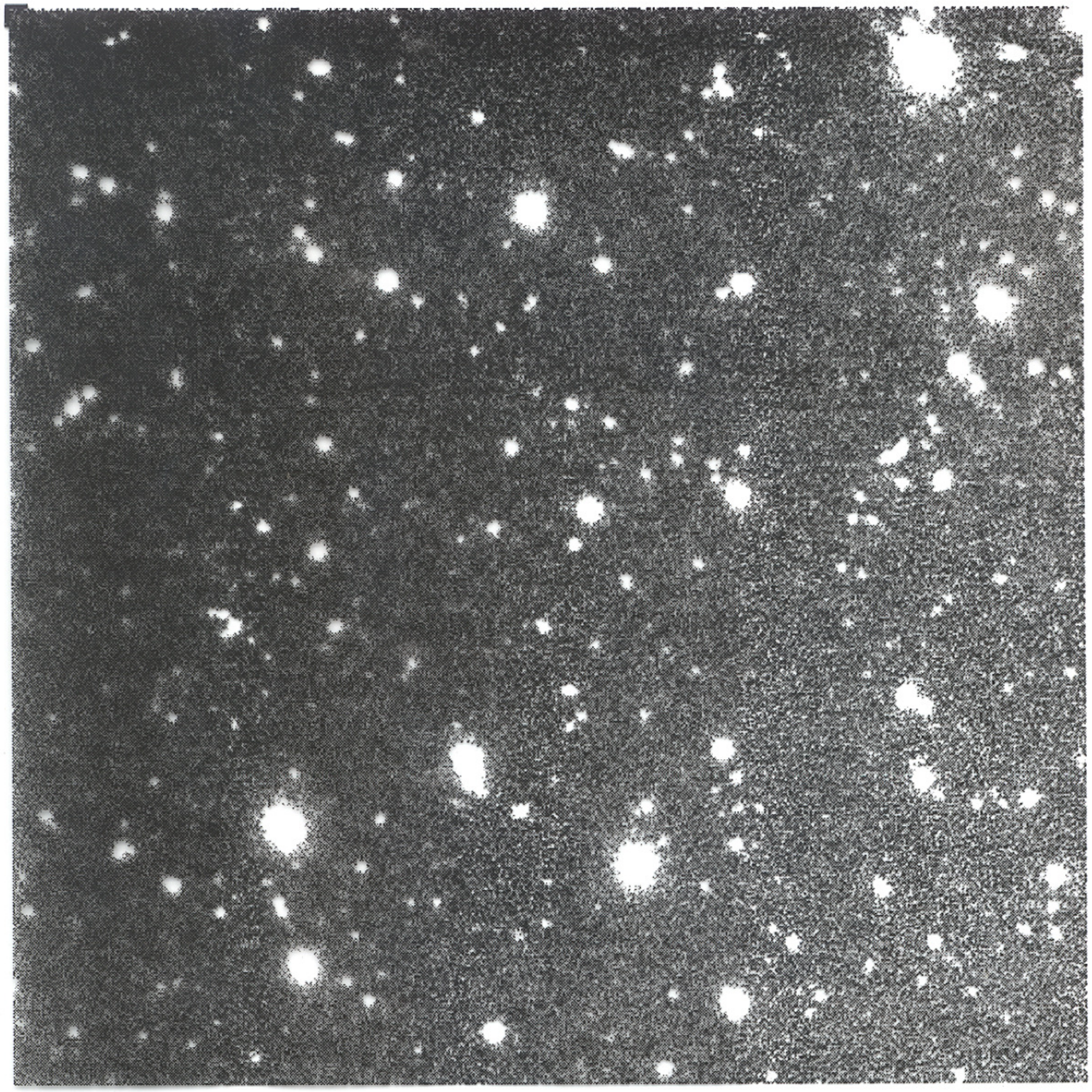
The table below gives light travel times and distances for some sample values of *z*:

z	Time the light has been traveling	Distance to the object now
0.0000715	1 million years	1 million light years
0.10	1.286 billion years	1.349 billion light years
0.25	2.916 billion years	3.260 billion light years
.5	5.019 billion years	5.936 billion light years
1	7.731 billion years	10.147 billion light years
2	10.324 billion years	15.424 billion light years
3	11.476 billion years	18.594 billion light years
4	12.094 billion years	20.745 billion light years
5	12.469 billion years	22.322 billion light years
6	12.716 billion years	23.542 billion light years
7	12.888 billion years	24.521 billion light years
8	13.014 billion years	25.329 billion light years
9	13.110 billion years	26.011 billion light years
10	13.184 billion years	26.596 billion light years

http://lcogt.net/spacebook/redshift/

f855 7 01

Pennypacker & Perlmutter 1988 wide-field CCD camera at AAT



...A big enough telescope with a wide enough field to search for z > 0.3 Type Ia supernovae in 100s of galaxies with each image.

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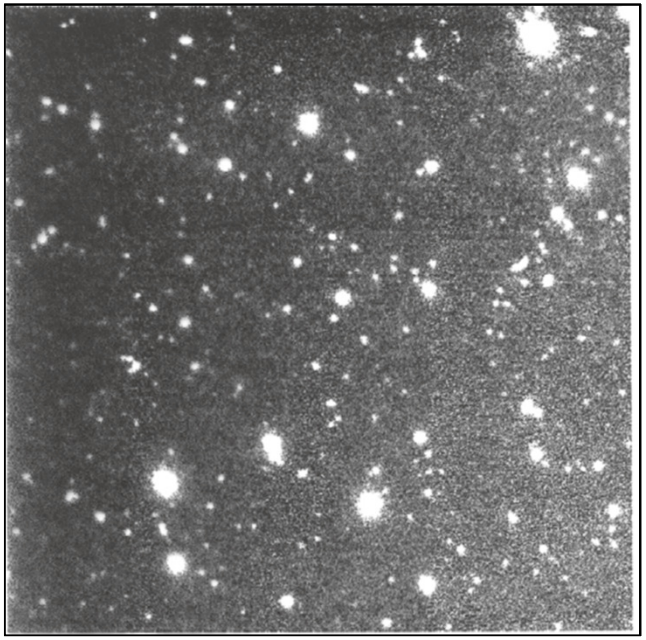
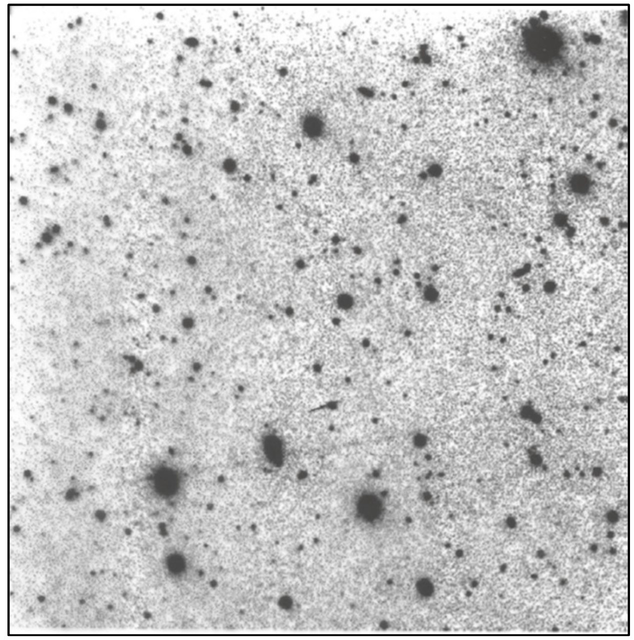
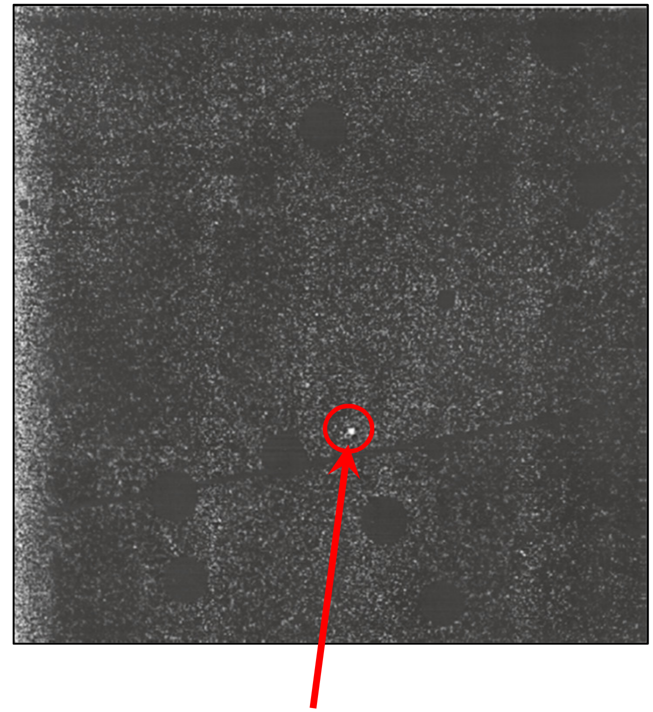
Subtract images at different times to find your supernova



An image obtained November 1989 with wide-field camera on the Anglo-Australian 4-m telescope. The small specks of light are the distant galaxies.



The same field, but observed January 1990. It is reversed in grayscale to indicate that it will be subtracted from the first.



Supernova

Computer subtraction of the images. The spot remaining is what a supernova would look like.

Hamuy et al. (*Astronomical Journal* 1993),
describing the Calan/Tololo Search for supernovae at much lower redshifts:

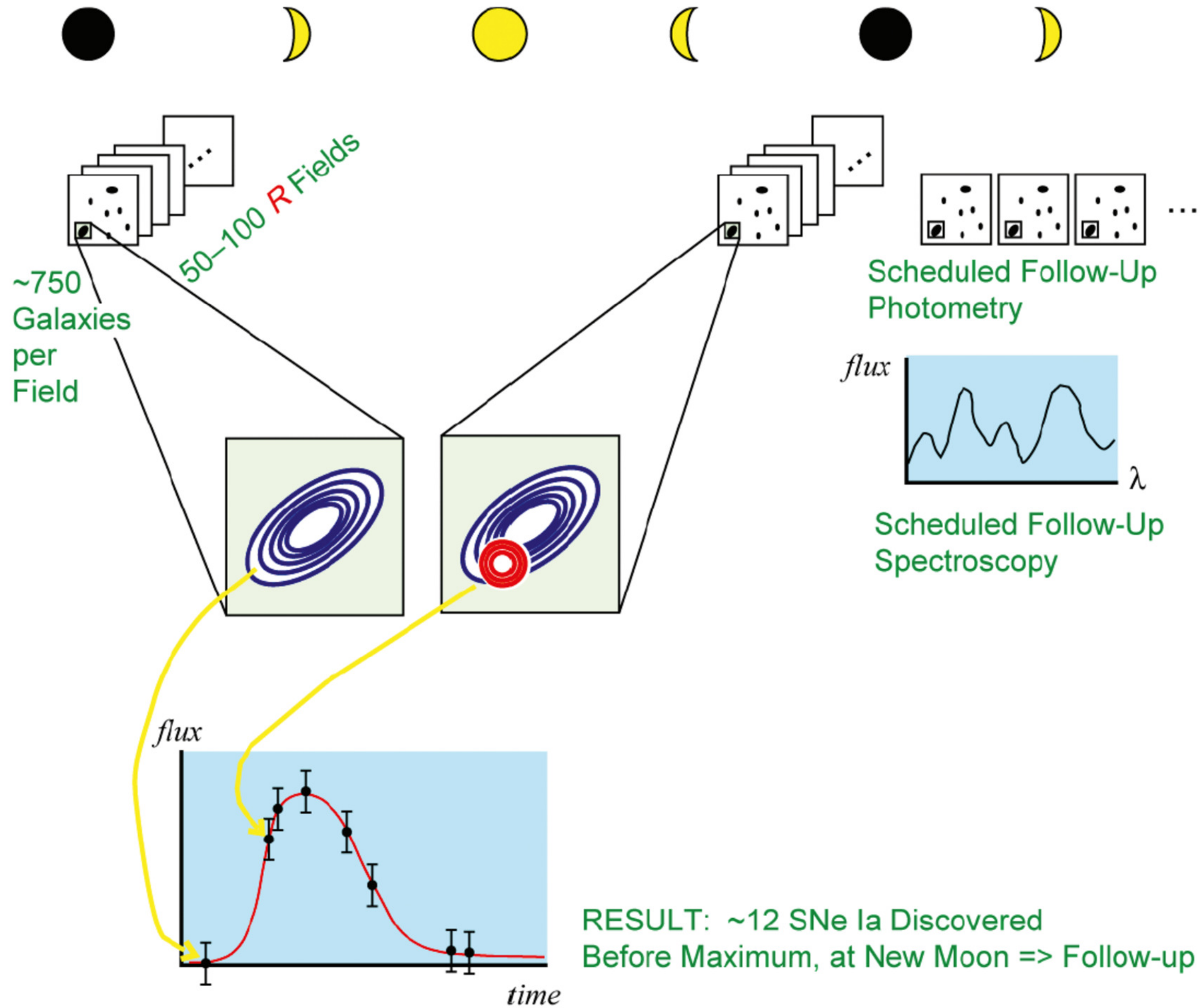
"Unfortunately, the appearance of a SN is not predictable. As a consequence of this we cannot schedule the followup observations a priori, and we generally have to rely on someone else's telescope time. This makes the execution of this project somewhat difficult."

➡ **Random** — can't schedule telescope time or plan discoveries at new moon

➡ **Rapid** — difficult to catch on the rise

http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.html

The "batch" observational strategy that made it possible to guarantee multiple new super-nova discoveries at high redshift. They would all be on a pre-specified date (in particular just before a new moon) and all while still brightening.



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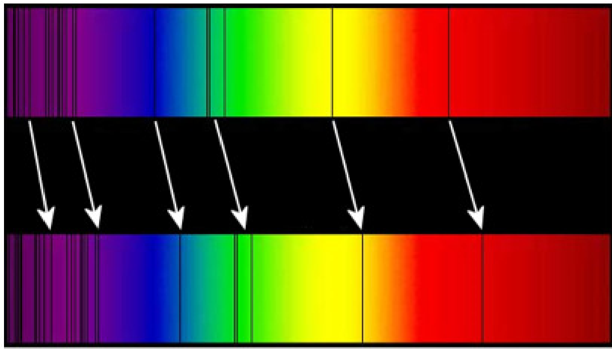
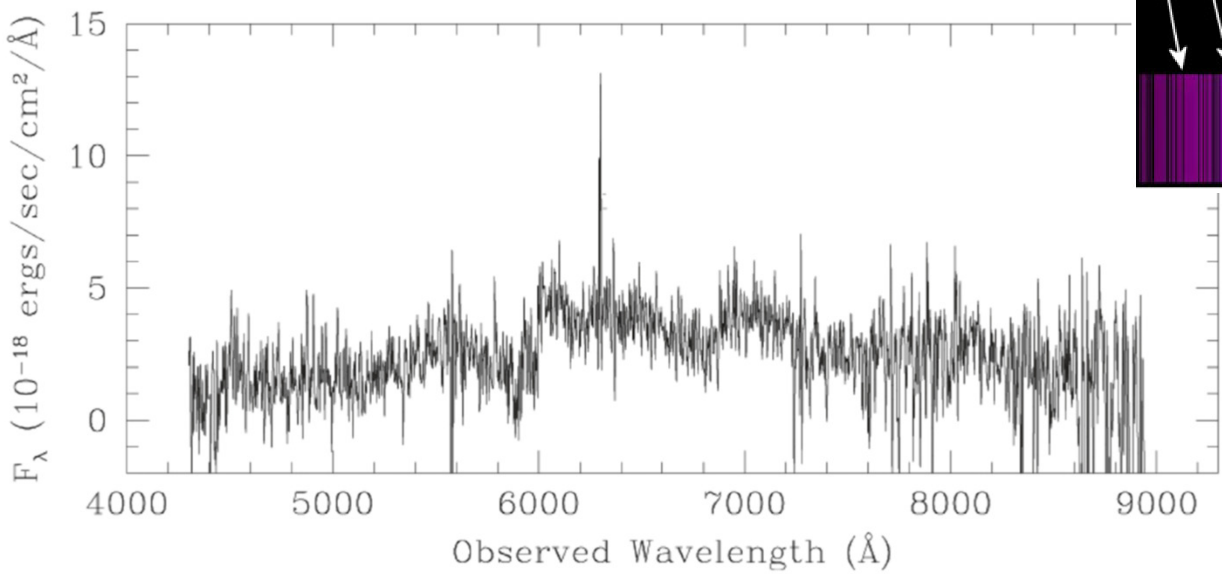
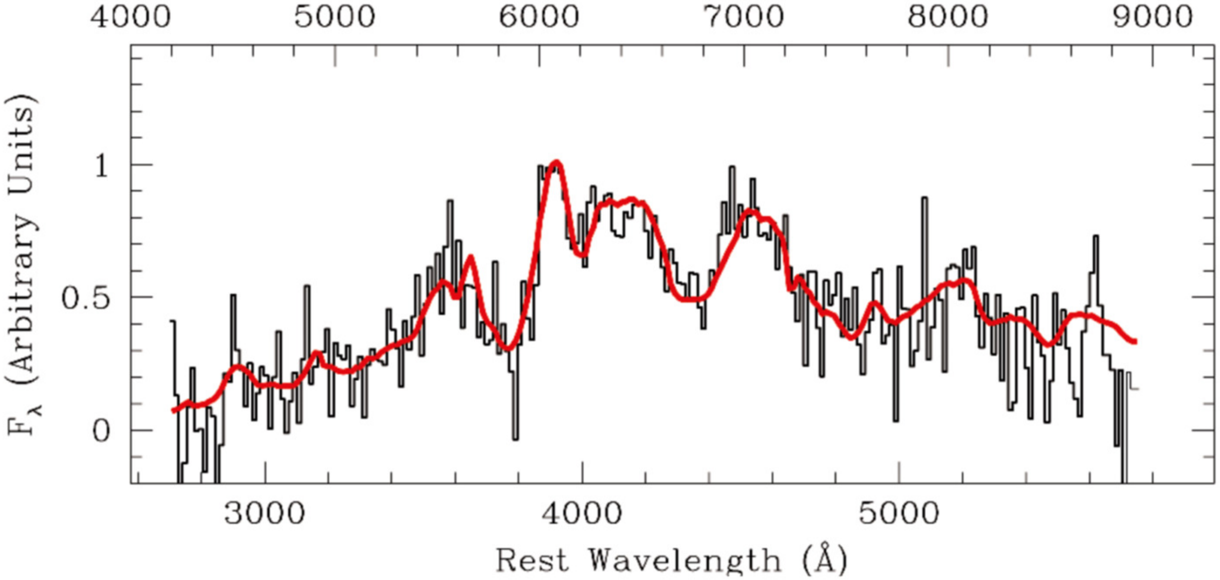
Supernova spectra look like noise … until you do not know what you are looking for!

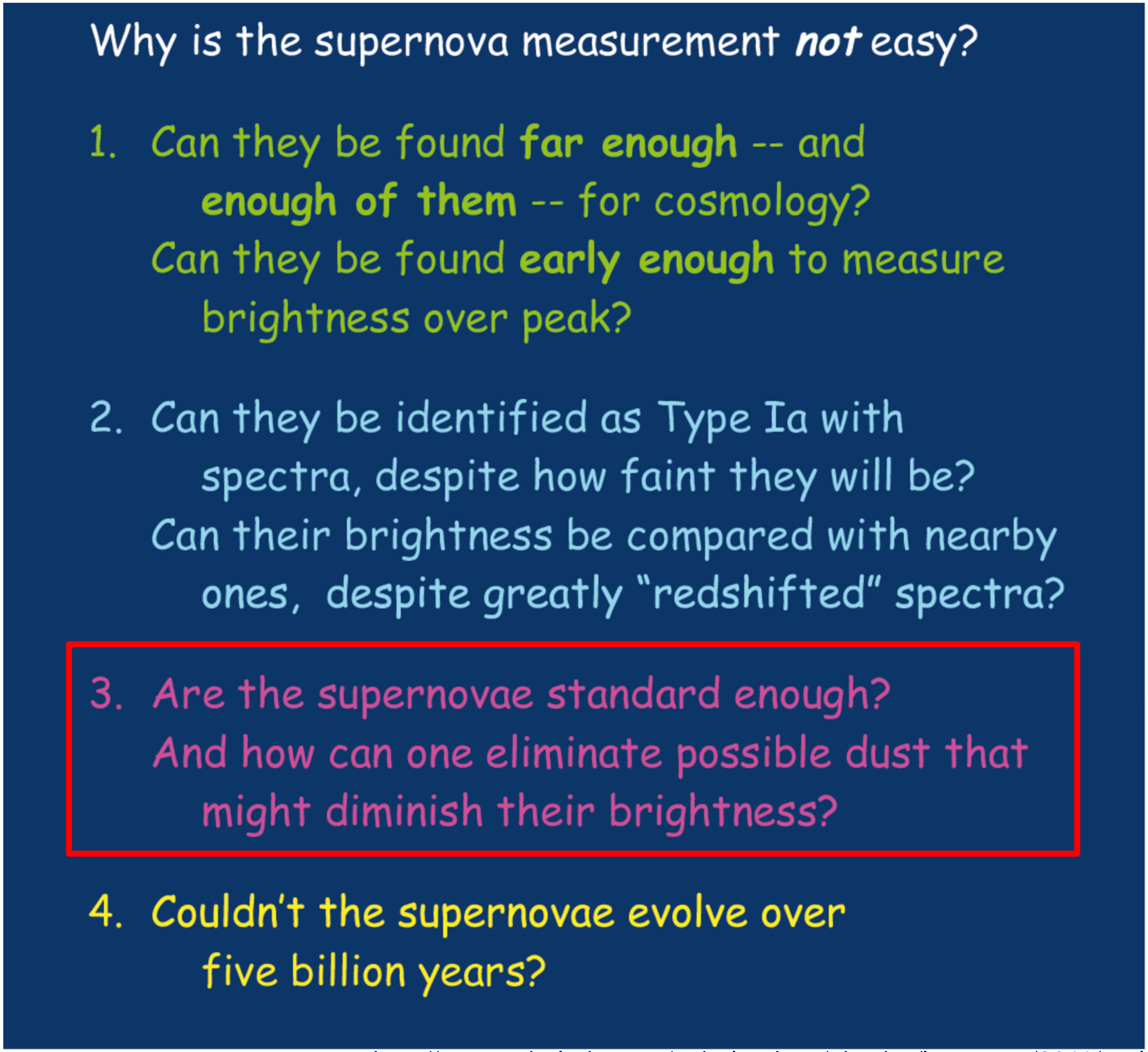






Same spectrum, after removing very narrow spectral features, and smoothing to bring out the broad supernova features. The red curve shows the excellent match with a spectrum of a low-redshift Type Ia supernova, as it would appear redshifted to z = 0.55.

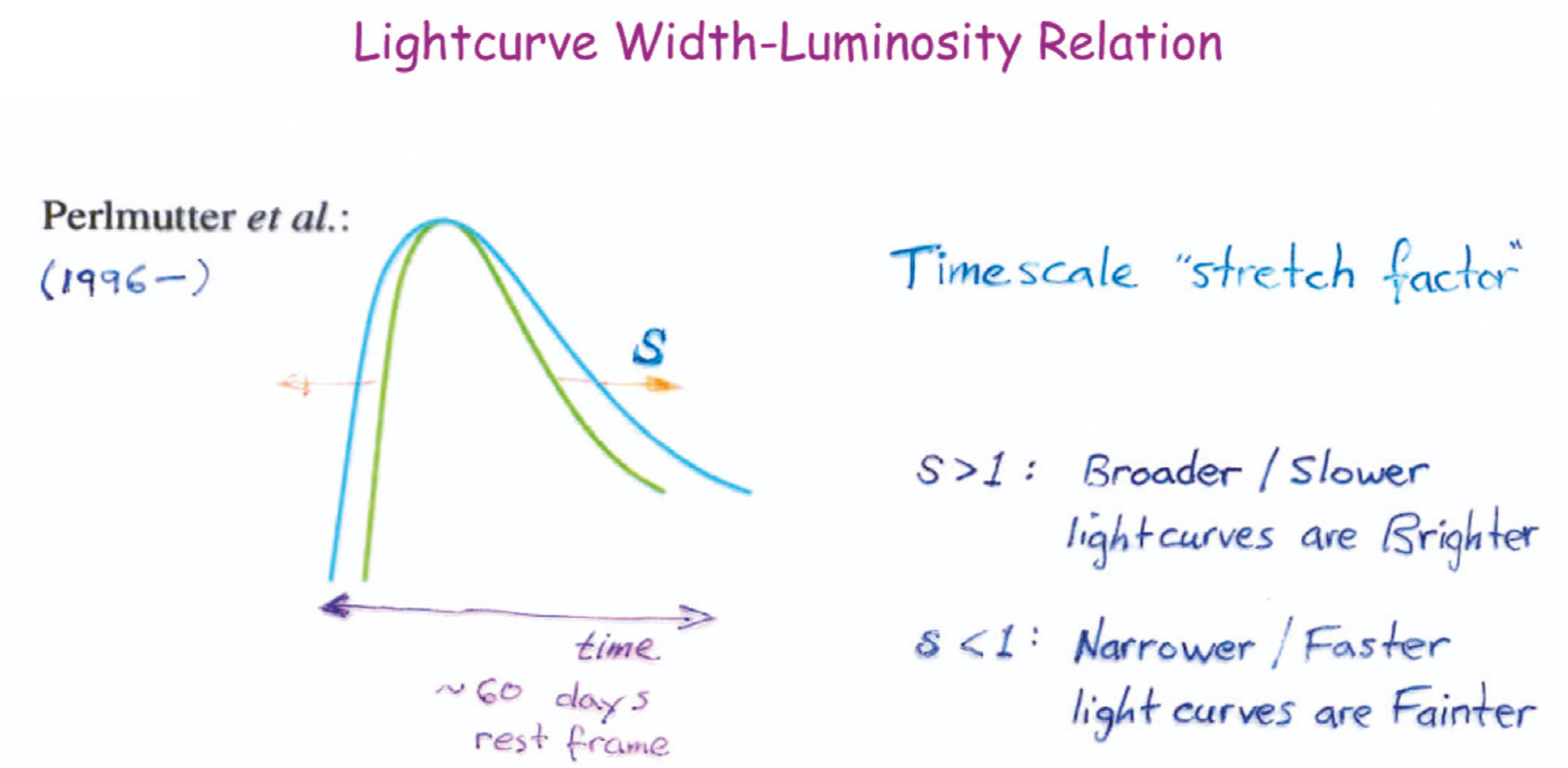
1987: Some of the issues researches listed in the beginning of their work



http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.html

How to “normalize” supernovas:

stretch or compress the time axis of the light curve by a single “stretch factor”

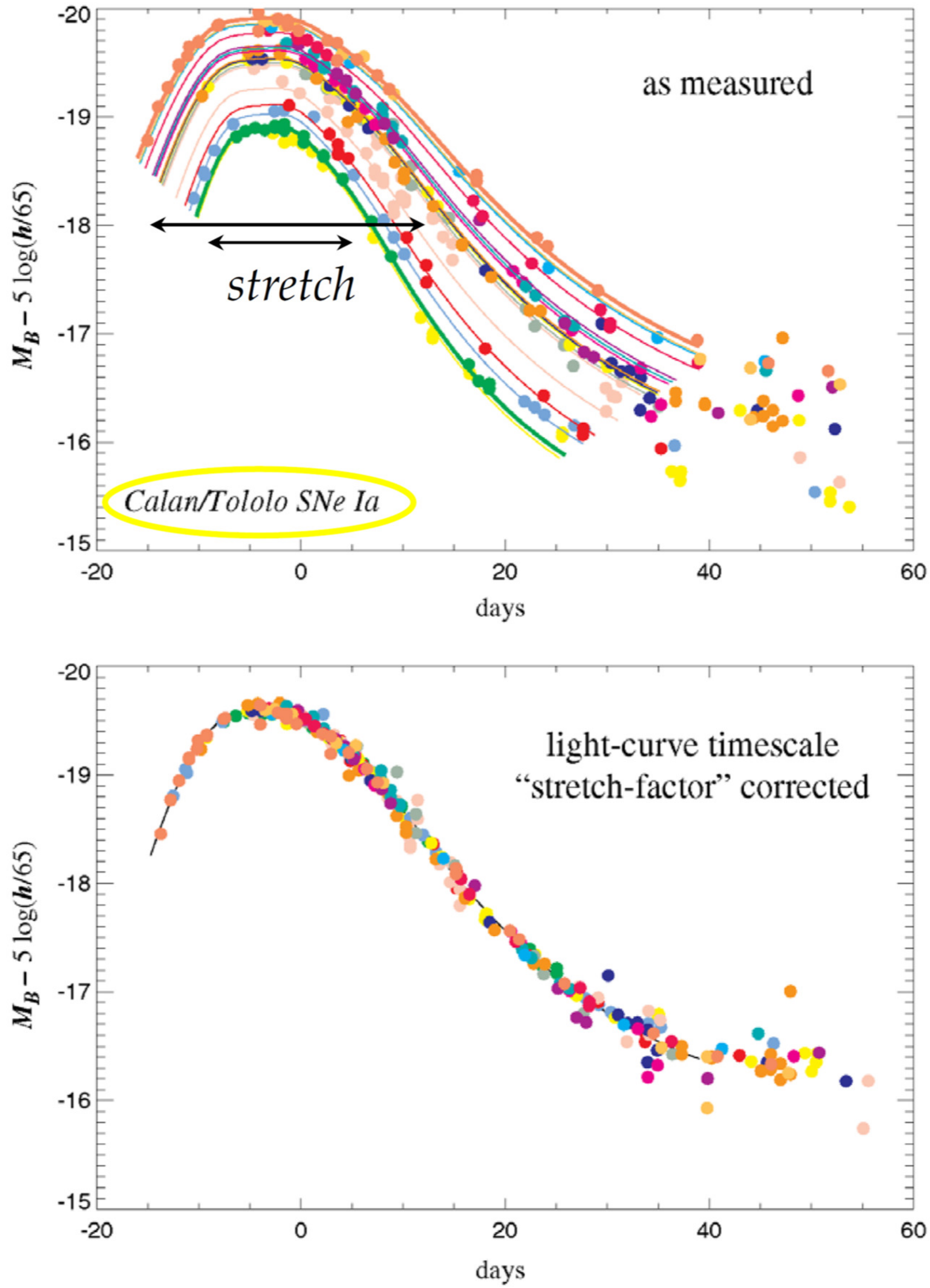


http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.html

How to “normalize” supernovas?

Some are more luminous, but …

The faster the supernova’s decline the fainter its peak magnitude.



1987: Some of the issues researches listed in the beginning of their work

Why is the supernova measurement ***not*** easy?

1. Can they be found **far enough** -- and **enough of them** -- for cosmology?
   Can they be found **early enough** to measure brightness over peak?

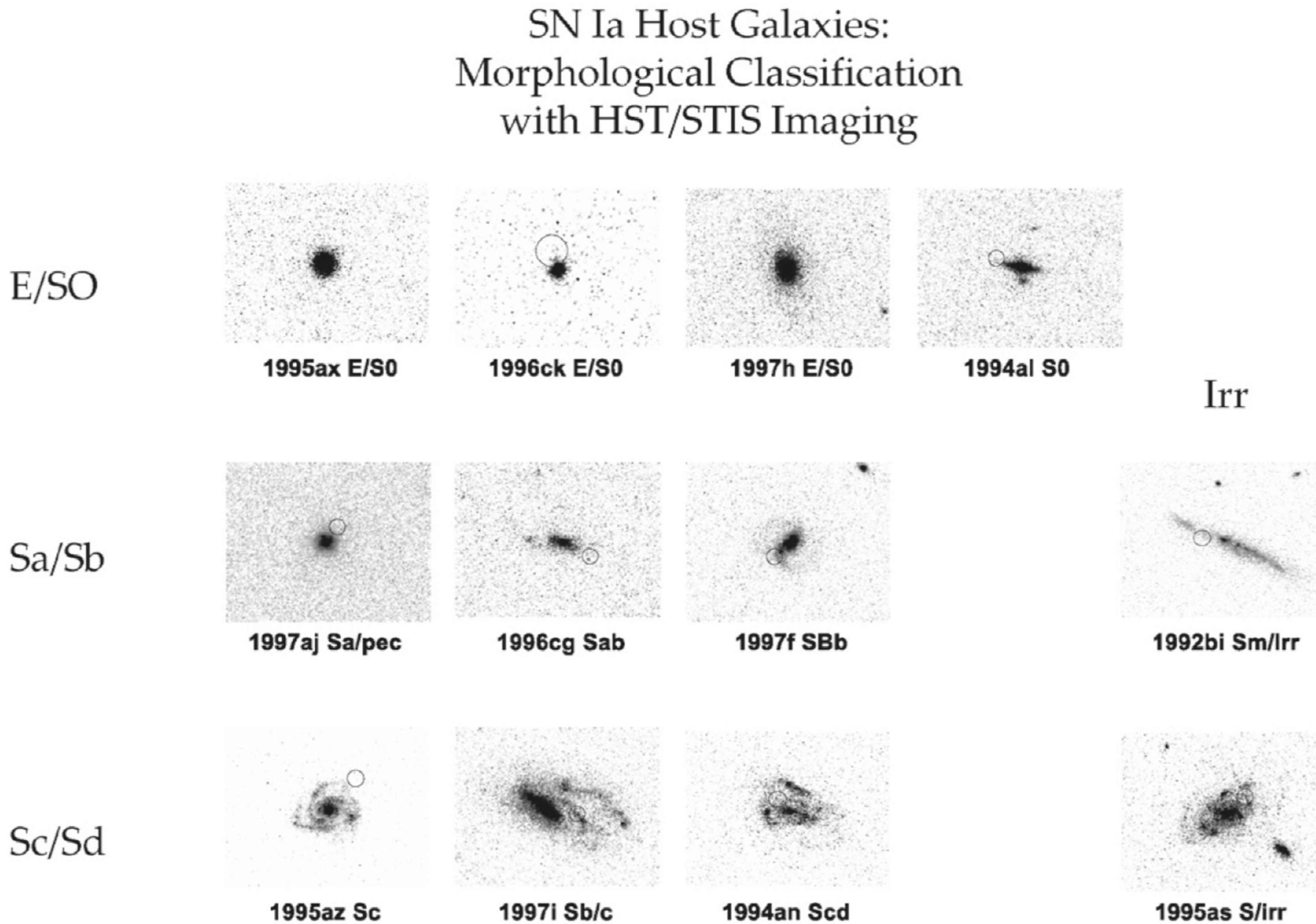
2. Can they be identified as Type Ia with spectra, despite how faint they will be?
   Can their brightness be compared with nearby ones, despite greatly "redshifted" spectra?

3. Are the supernovae standard enough?
   And how can one eliminate possible dust that might diminish their brightness?

4. Couldn't the supernovae evolve over five billion years?

http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.html

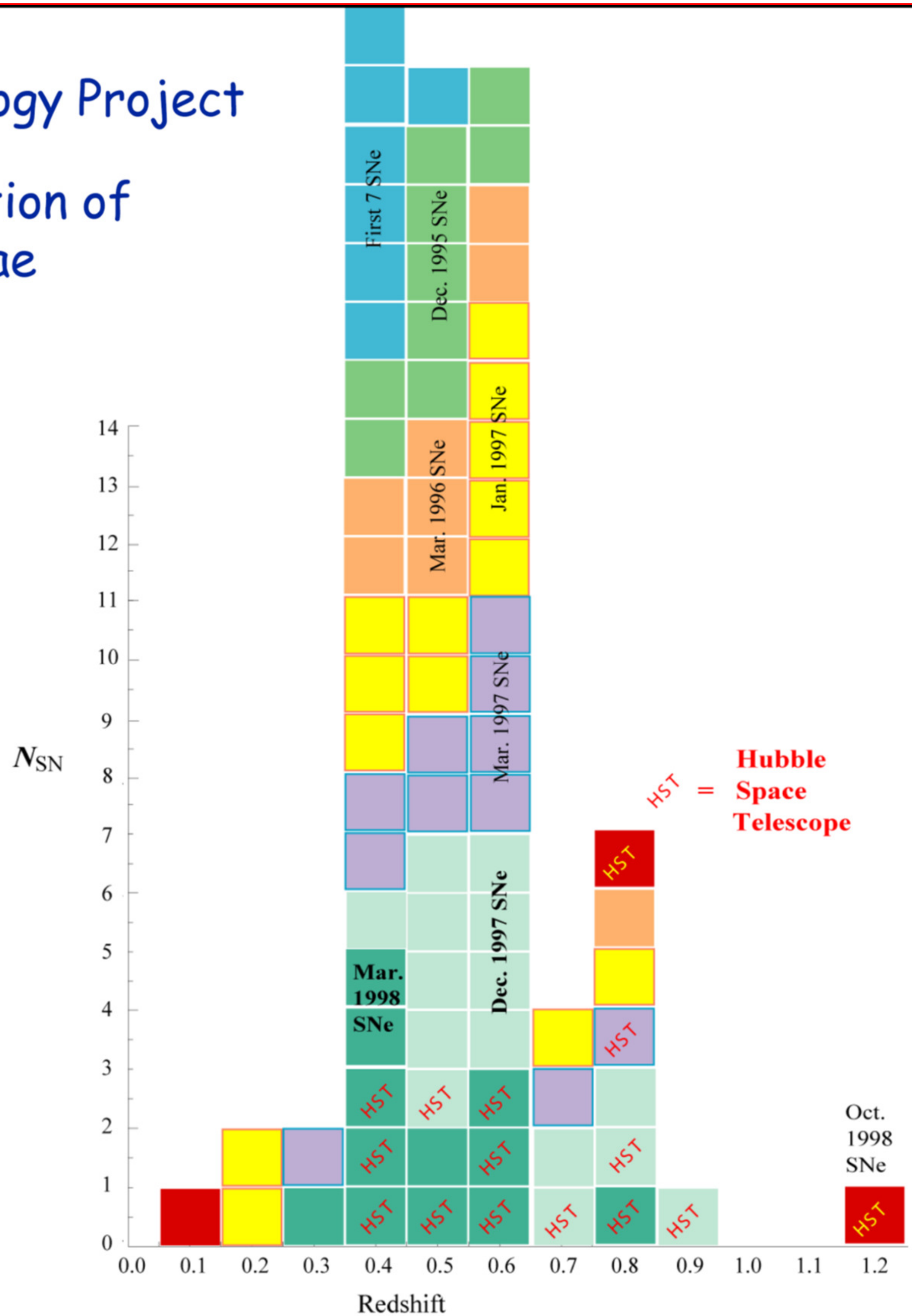
Study separately the low- and high-redshift supernovae found in elliptical galaxies and for those in spirals. These different host galaxy environments have very different histories, so if the results from these different environments than the results are not strongly distorted by the environmental histories changing the behavior of the supernovae.



http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.html

Supernova Cosmology Project

redshift distribution of
Type Ia supernovae
as of 1998



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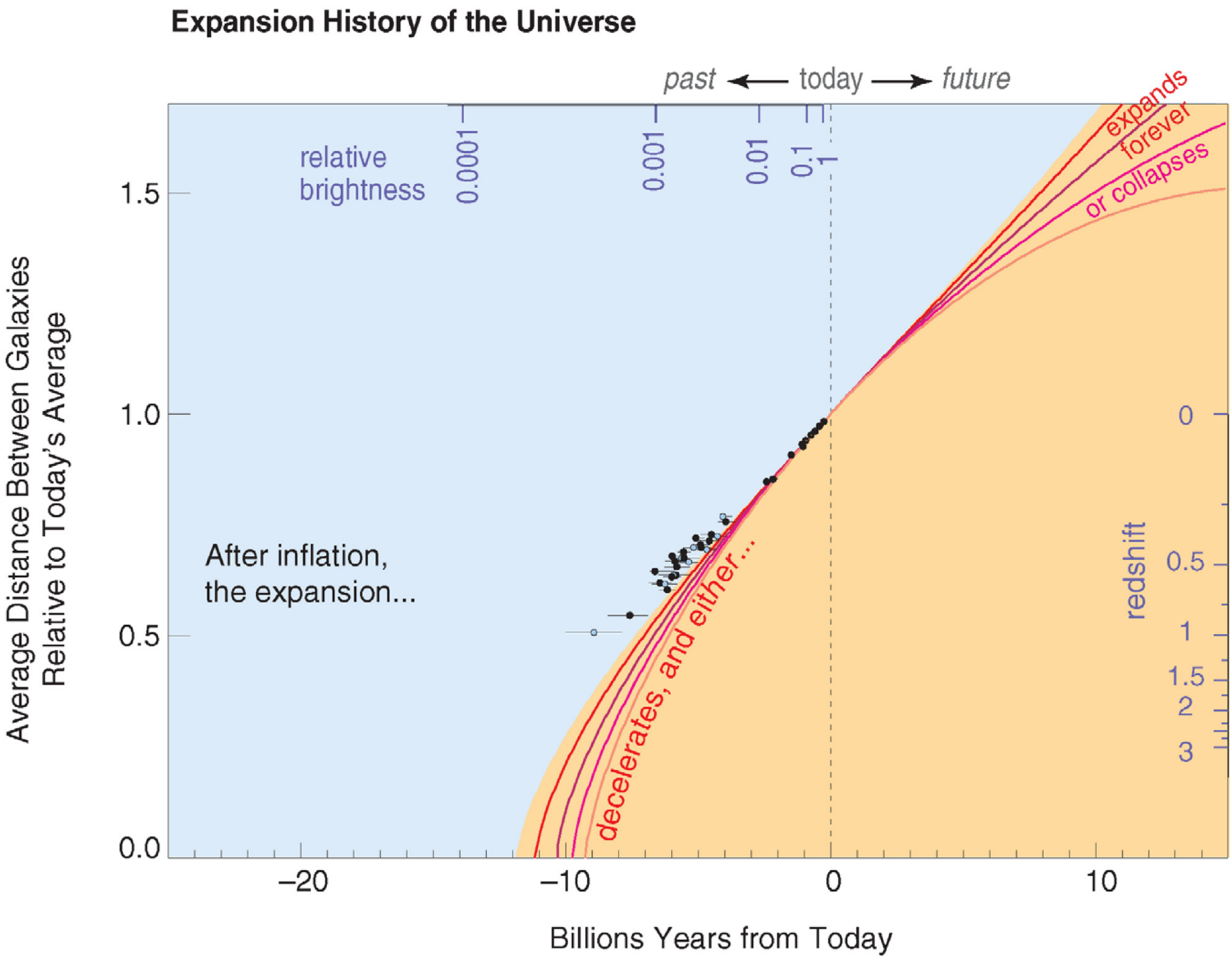

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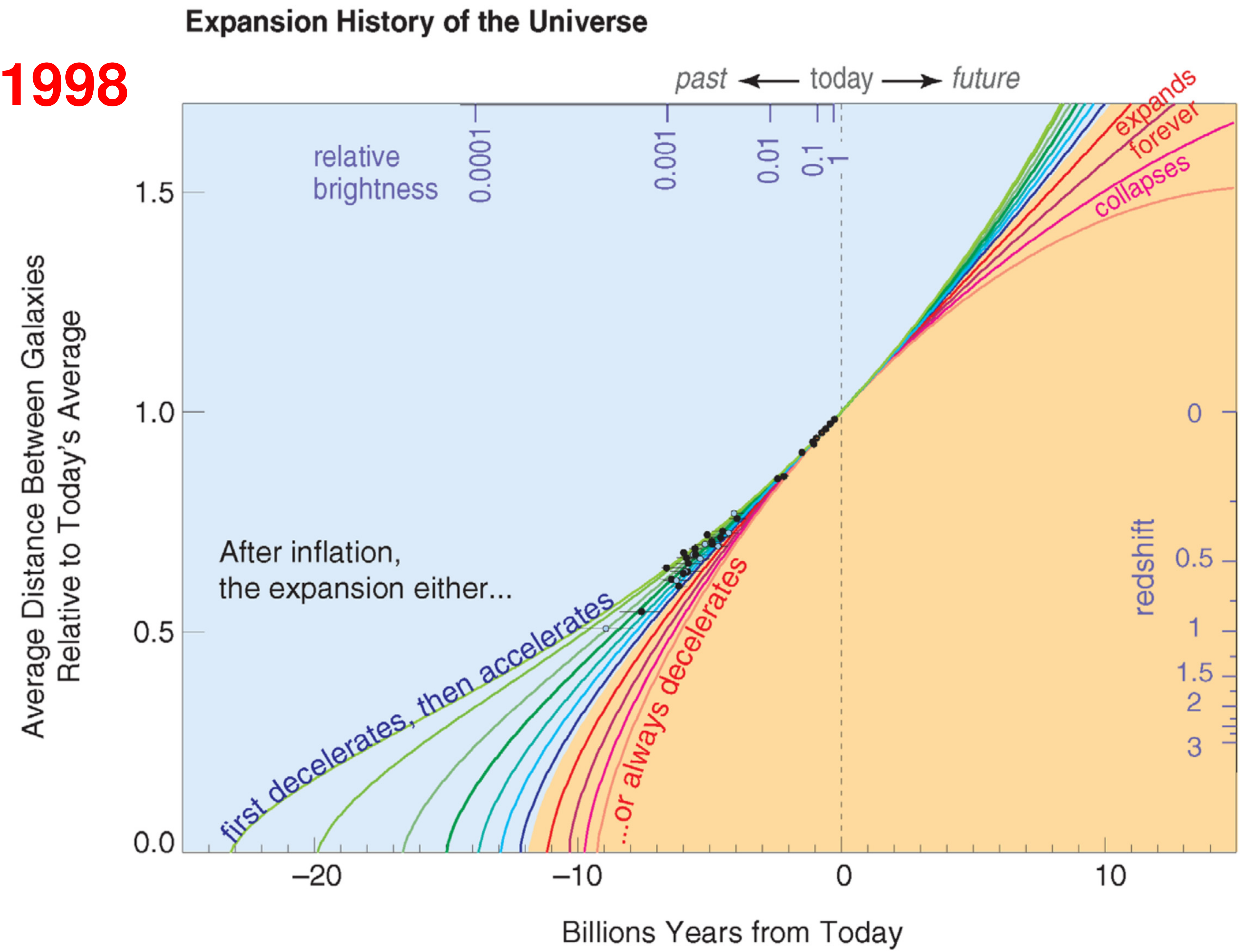
1998



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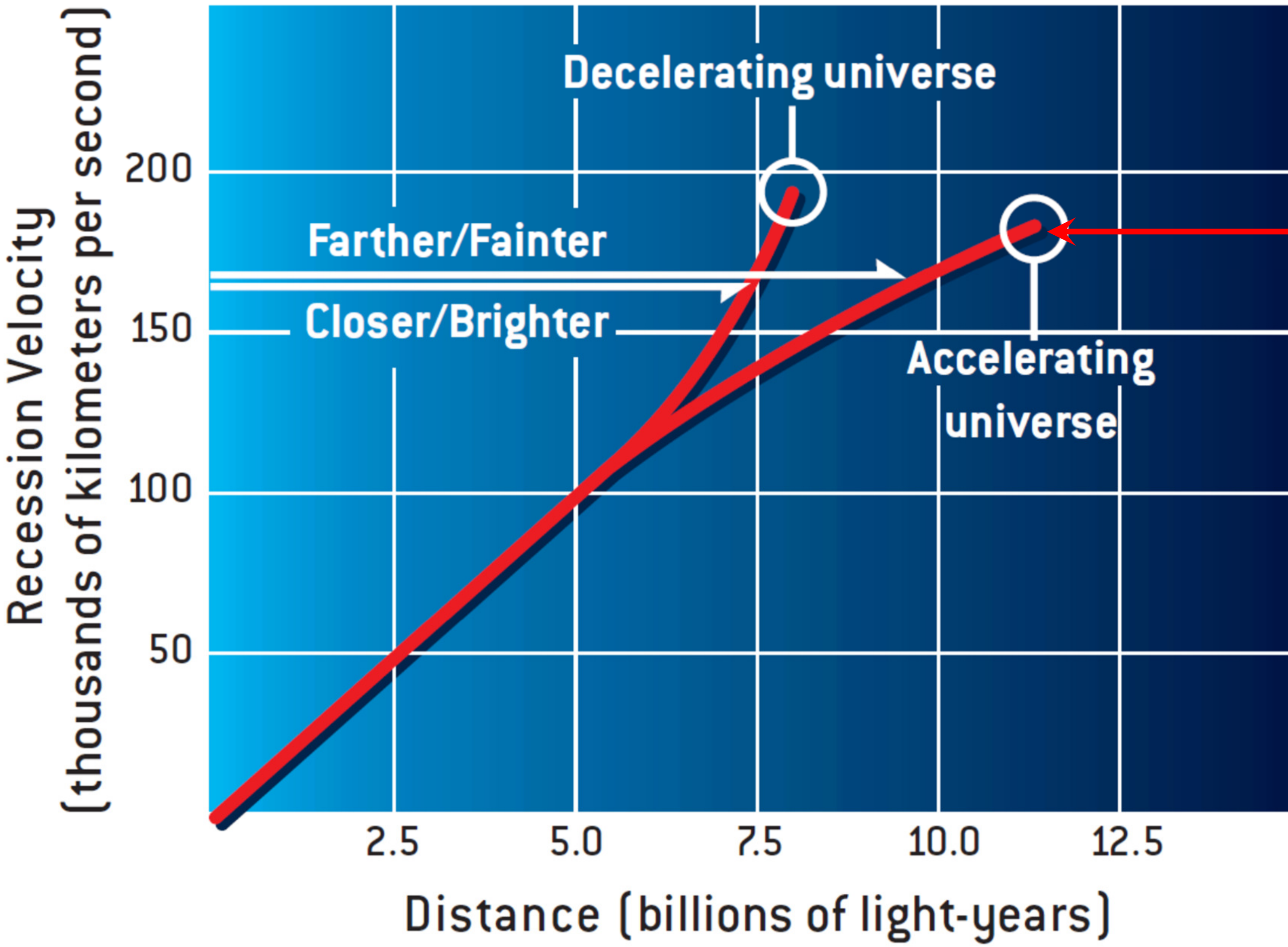
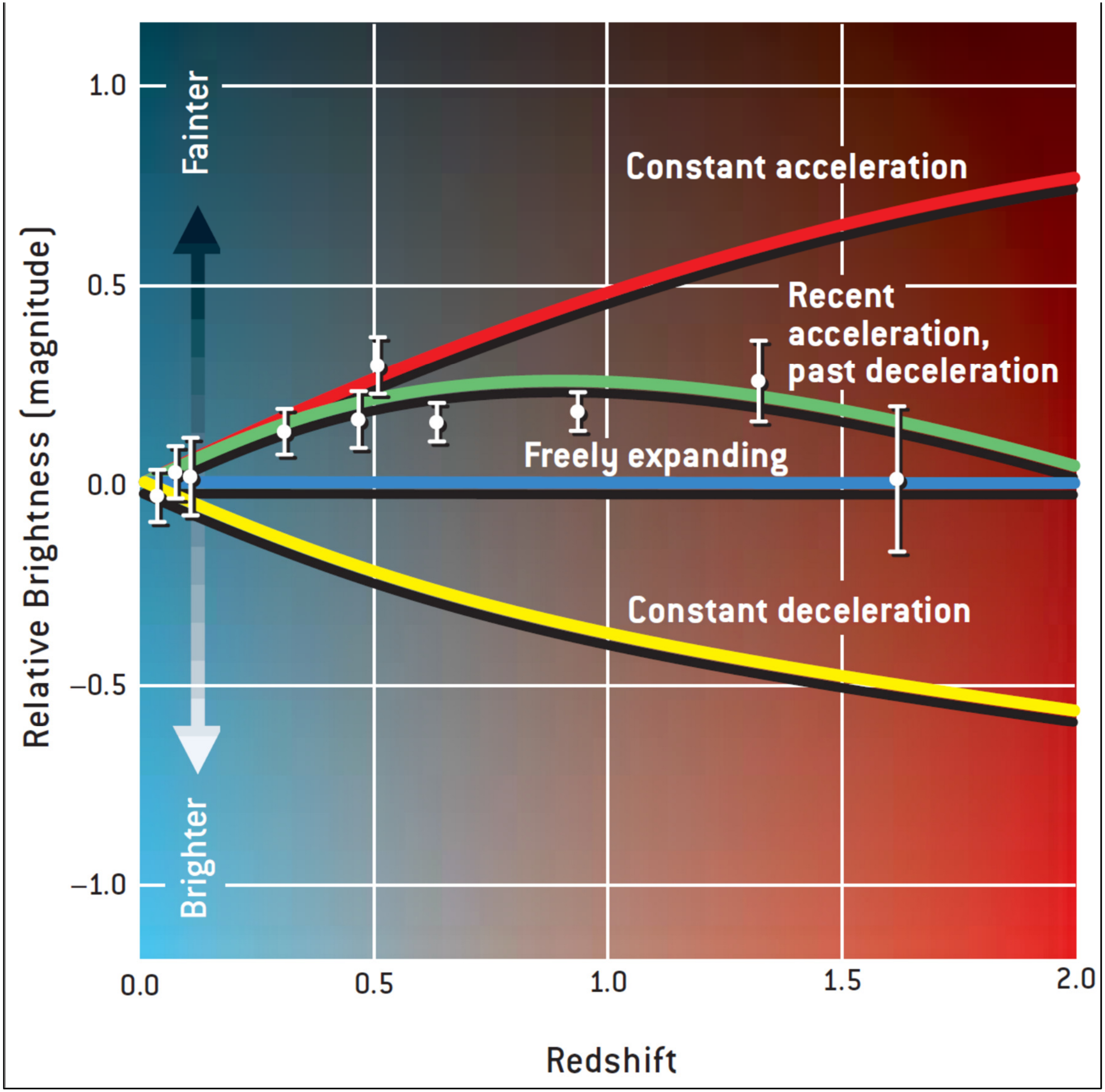


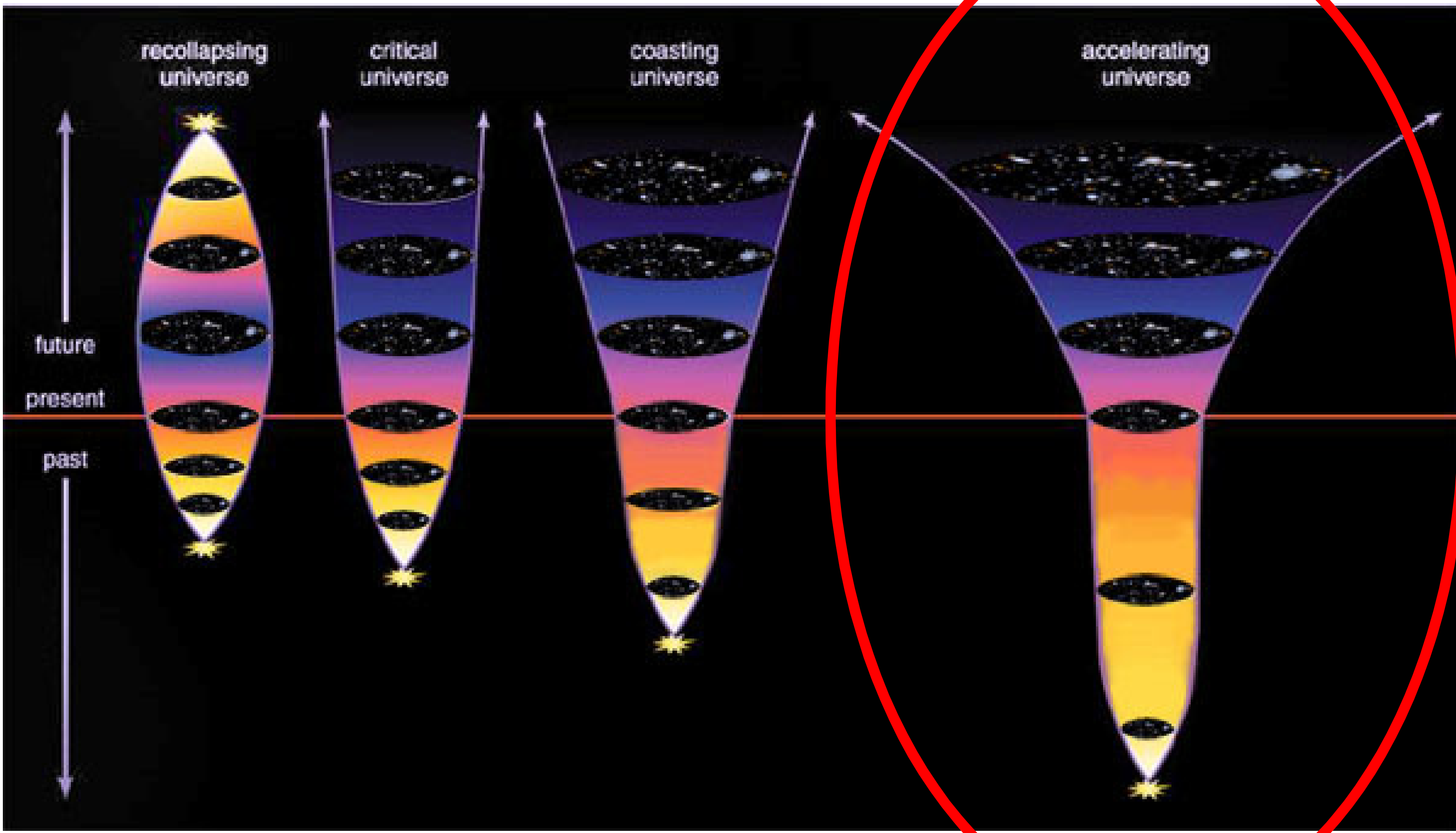
Expansion of the Universe is **accelerating**!

Scientific American **290**, 62-67 (2004)



Scientific American **290**, 62-67 (2004)

Universe is accelerating!



Completely unexpected result!

The Nobel Prize in Physics 2011

Saul Perlmutter

Brian P. Schmidt

Adam G. Riess

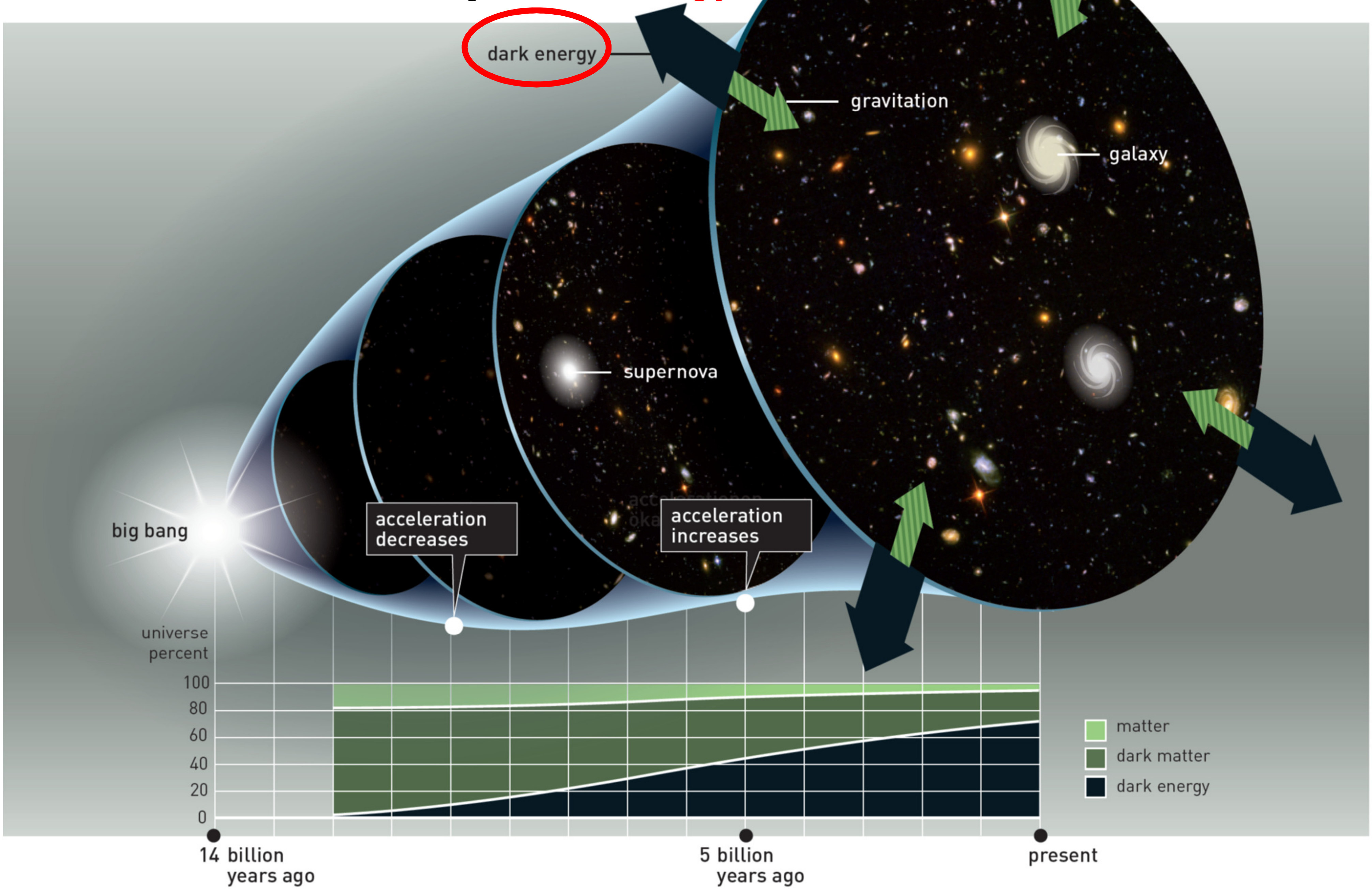
Supernova Cosmology Project

High-z Supernova Search Team

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess ***"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae".***

Something makes Universe expansion to accelerate for the past 5 billion years!

We labelled this “something” **dark energy.**



http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/popular-physicsprize2011.pdf