Hot Science Cool Talks

UT Environmental Science Institute

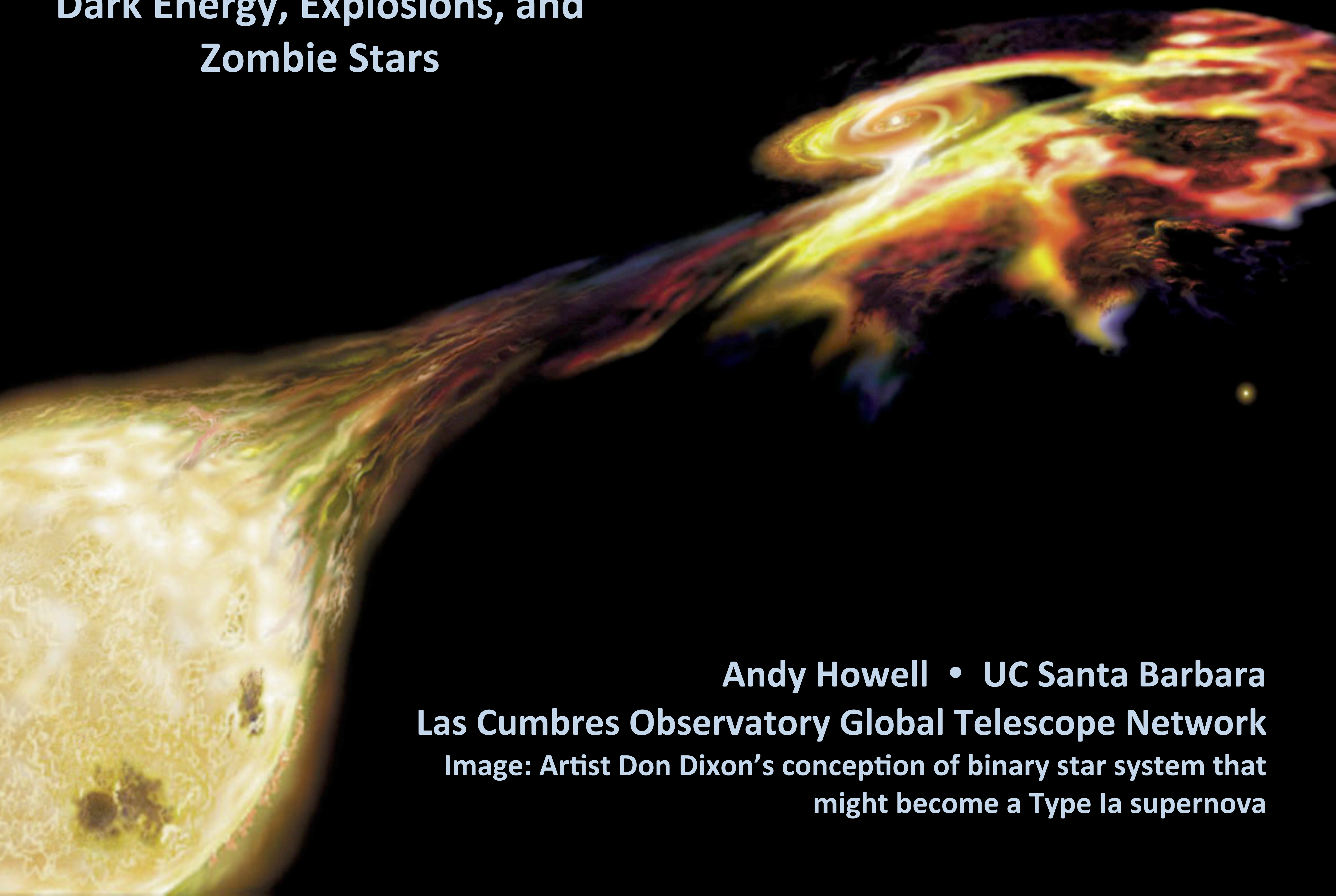
76

Dark Energy, Explosions, and Zombie Stars

Dr. Andrew Howell

January 13, 2012

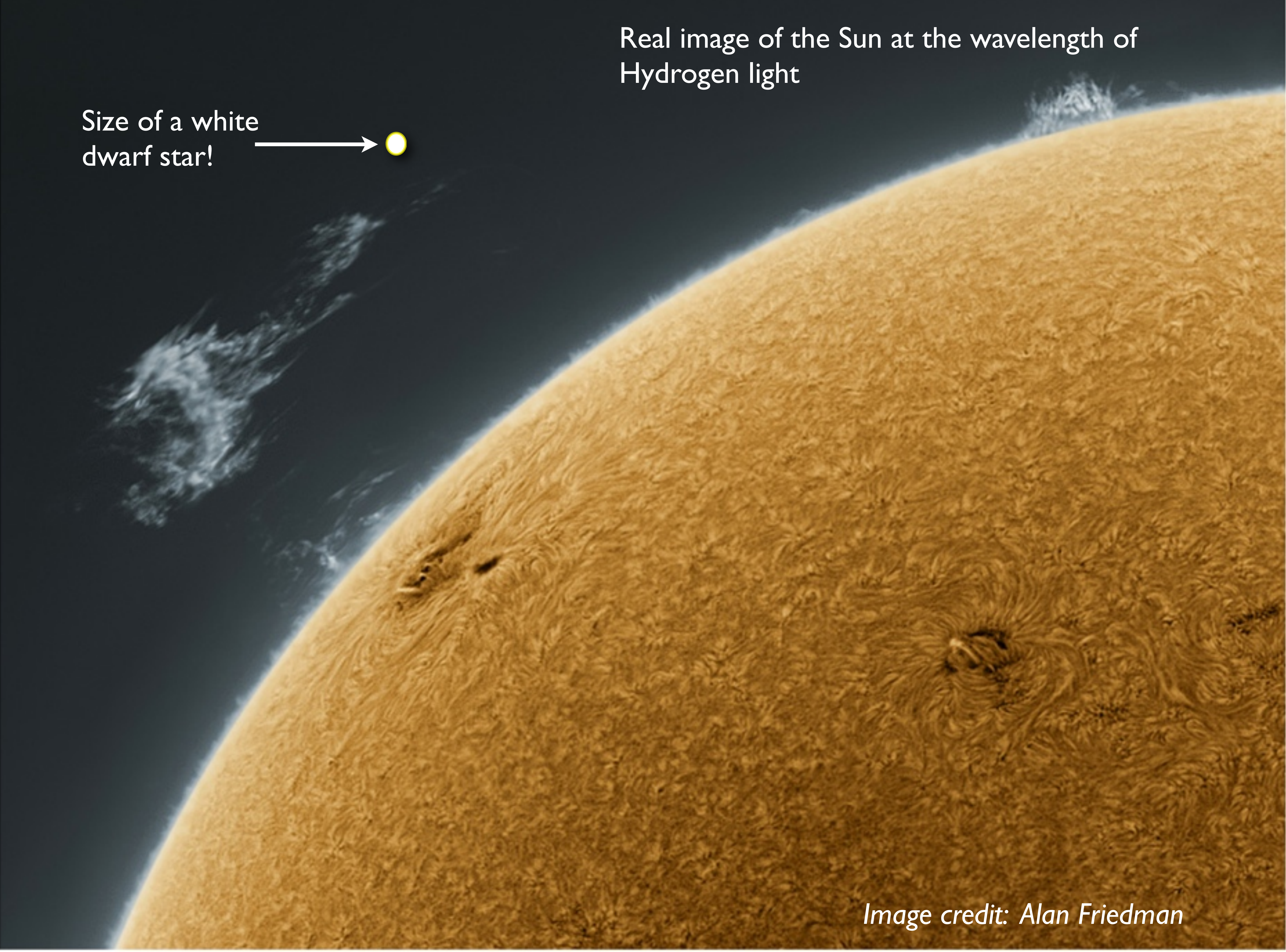
Dark Energy, Explosions, and Zombie Stars

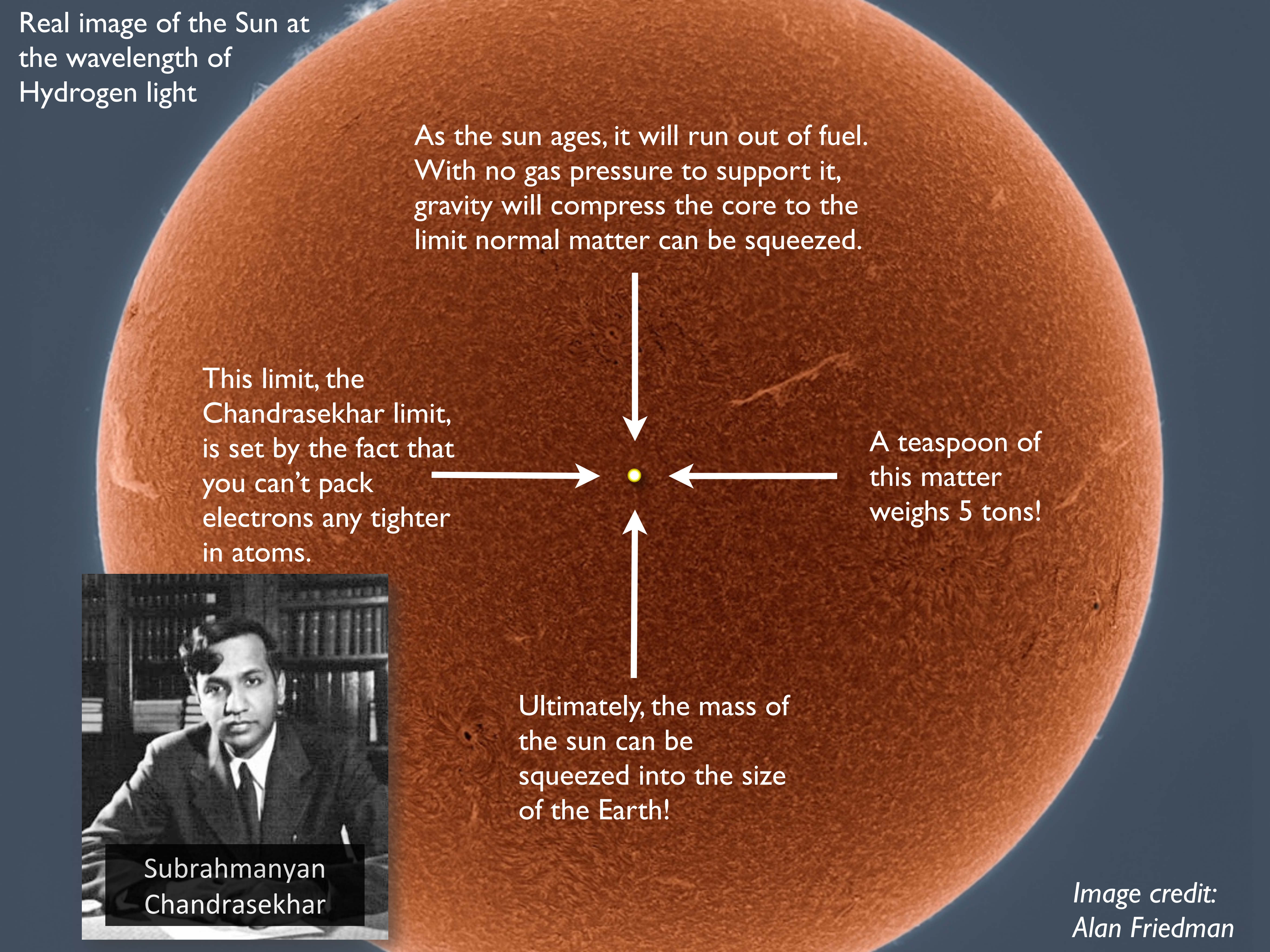


Andy Howell • UC Santa Barbara
Las Cumbres Observatory Global Telescope Network

Image: Artist Don Dixon's conception of binary star system that might become a Type Ia supernova


ROCHE
LOBE TROTTERS


Real image of the Sun at the wavelength of Hydrogen light
Size of a white dwarf star!
Image credit: Alan Friedman


Real image of the Sun at the wavelength of Hydrogen light
As the sun ages, it will run out of fuel. With no gas pressure to support it, gravity will compress the core to the limit normal matter can be squeezed.
This limit, the Chandrasekhar limit, is set by the fact that you can't pack electrons any tighter in atoms.
A teaspoon of this matter weighs 5 tons!
Ultimately, the mass of the sun can be squeezed into the size of the Earth!
Image credit: Alan Friedman
Subrahmanyan Chandrasekhar

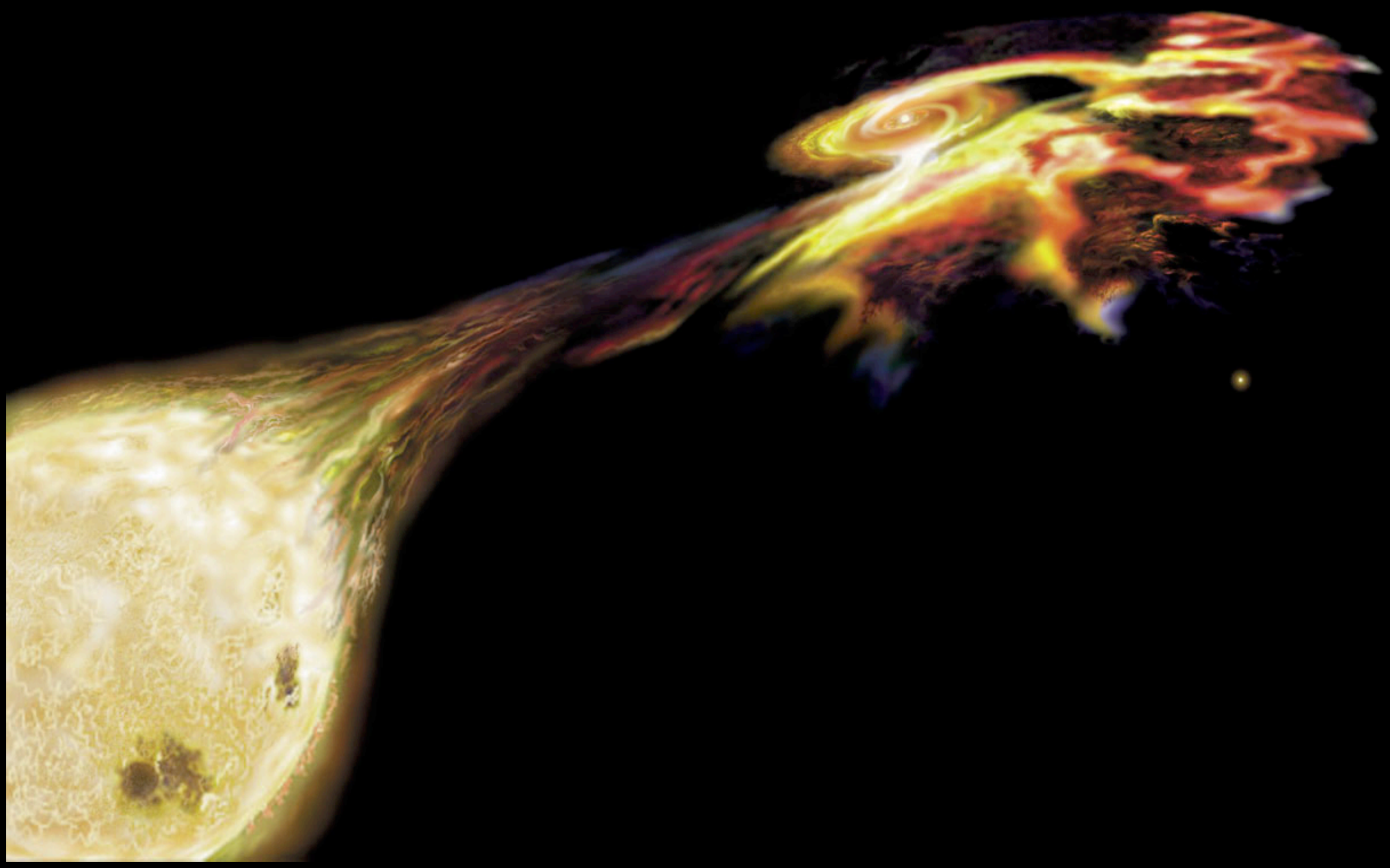
The remaining outer layers of the star are ejected into space. This is the fate of our Sun (in 5 billion years). The core is now a white dwarf star.

A solid star! A crystalline structure of carbon and oxygen. It is essentially a diamond the size of the Earth in space!

A white dwarf is a dead star, it doesn't generate energy. If left alone, it will cool off and freeze solid.

But what happens if you don't leave it alone?

It can come back from the dead...
a zombie star!



By stealing matter from a living star, the white dwarf can start nuclear fusion (“burning”) on the surface again, and increasing in mass.

But if it gets too close to the limit, it explodes!


NATIONAL
GEOGRAPHIC
CHANNEL

What is a Type Ia Supernova?

Not this, but is by best attempt at making one on Earth

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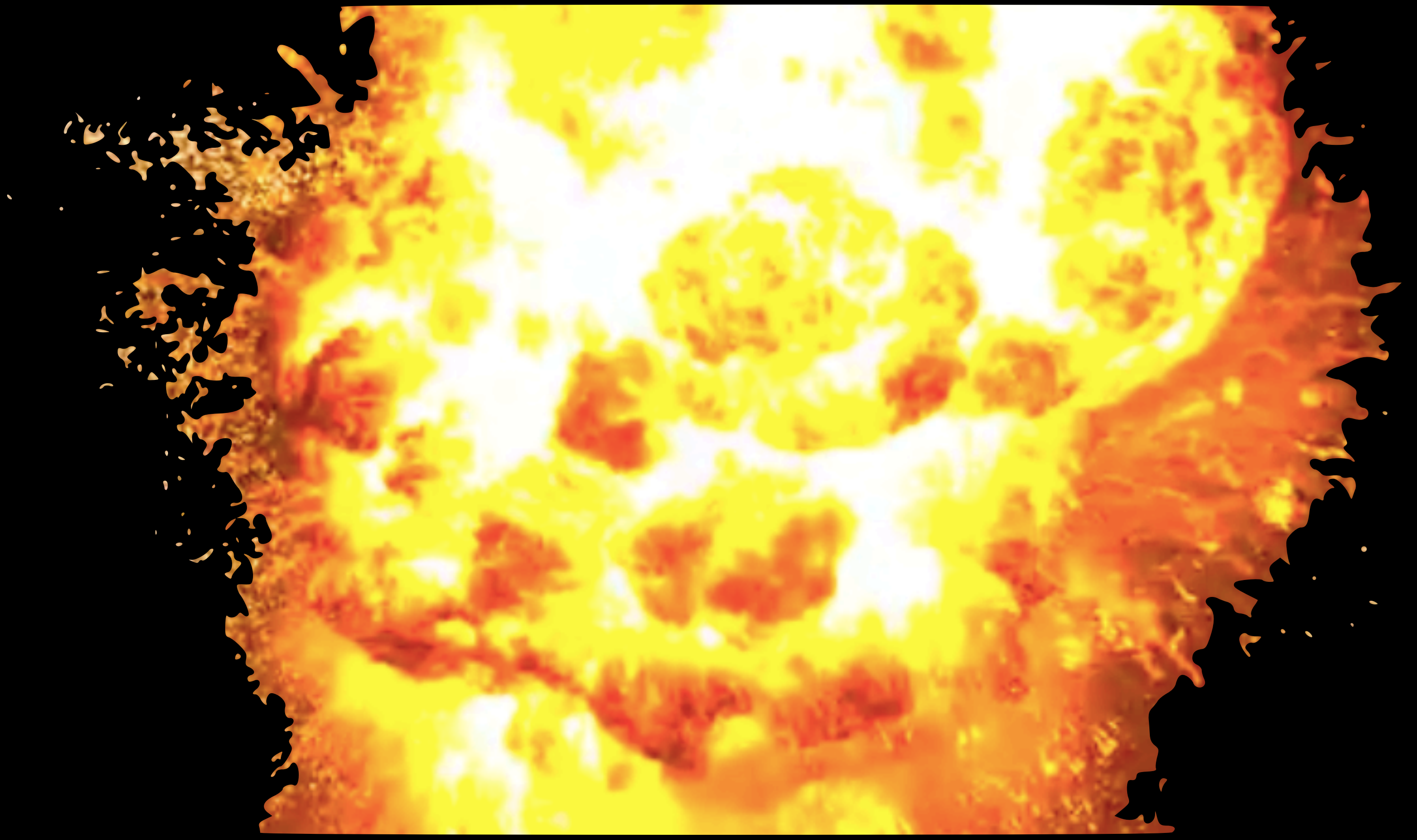


Acetylene+Oxygen explosion from *Known Universe*

Terrestrial explosion

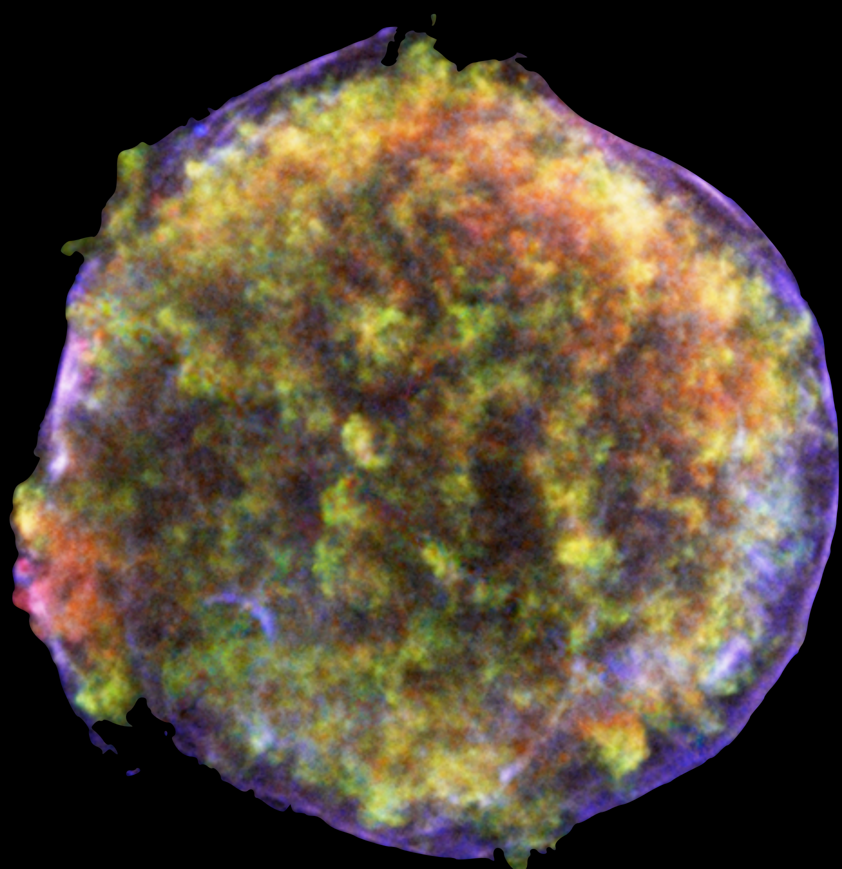
Burning: Chemical

Fuel: 4 kg $C_2H_2+O_2$

t_{exp} = ~1 s

E = 10^5 J

SN Ia model by F. Ropke



Tycho's SN (1572) today

SN Ia

Burning: Fusion

Fuel: 1.4 $M_\odot$ (3×10^{30} kg)

C+O white dwarf

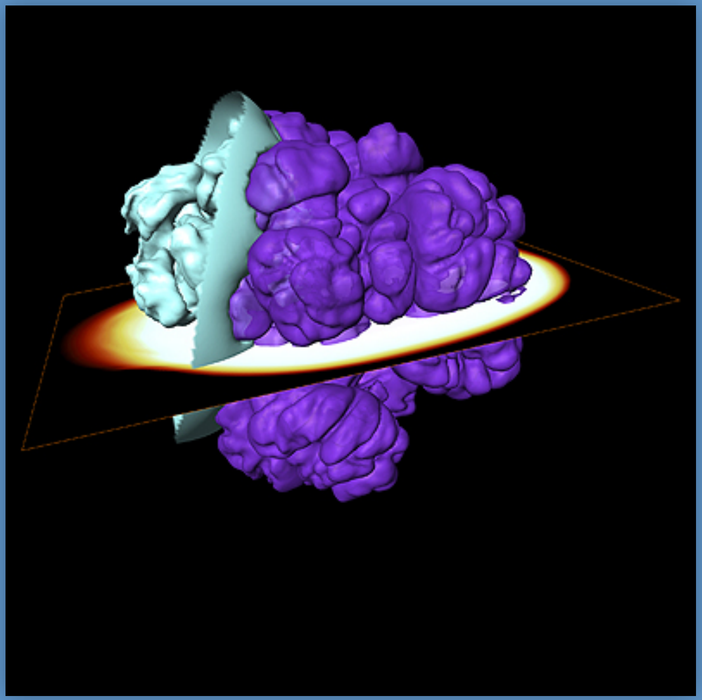
t_{exp} = ~1 s

t_{LC} = ~ months

E = 10^{44} J

SN Ia power source

Explosion



Fusion. In a few seconds, a white dwarf star the size of the Earth has an explosion rip through it, fusing carbon and oxygen into iron and nickel.

Alchemy! This is how most of the iron in your blood was created!

Radioactive decay

But we never see the explosion, we see the fallout: radioactive decay

^{56}Ni → ^{56}Co → ^{56}Fe Takes ~ 3 weeks

Converted to nickels,

1SN = $6 nonillion ($\$6 \times 10^{30}$)

#	name	SI prefix
10^9	billion	giga-
10^{12}	trillion	tera-
10^{15}	quadrillion	peta-
10^{18}	quintillion	exa-
10^{21}	sextillion	zetta-
10^{24}	septillion	yotta-
10^{27}	octillion	hella?
10^{30}	nonillion	

boingboing TECH GADGETS SCIENCE BIZ ENT ART/DESIGN CULTURE ACTIC

Petition to make "Hella" the prefix for 1,000,000,000,000,000,000,000,000,000

Cory Doctorow at 10:32 PM March 1, 2010

Carl sez, "A petition to make Hella- the official SI prefix for 10^27, for measuring things bigger than Yotta- (the prefix for (US) billion trillion). For instance: 'the sun (mass of 2.2 hellatons) would release energy at 0.3 hellawatts.' It would also come in handy for eventually measuring Internet traffic and US national debt."

10^{27}

The Official Petition to Establish "Hella-" as the SI Prefix for 10^27

List of SI prefixes

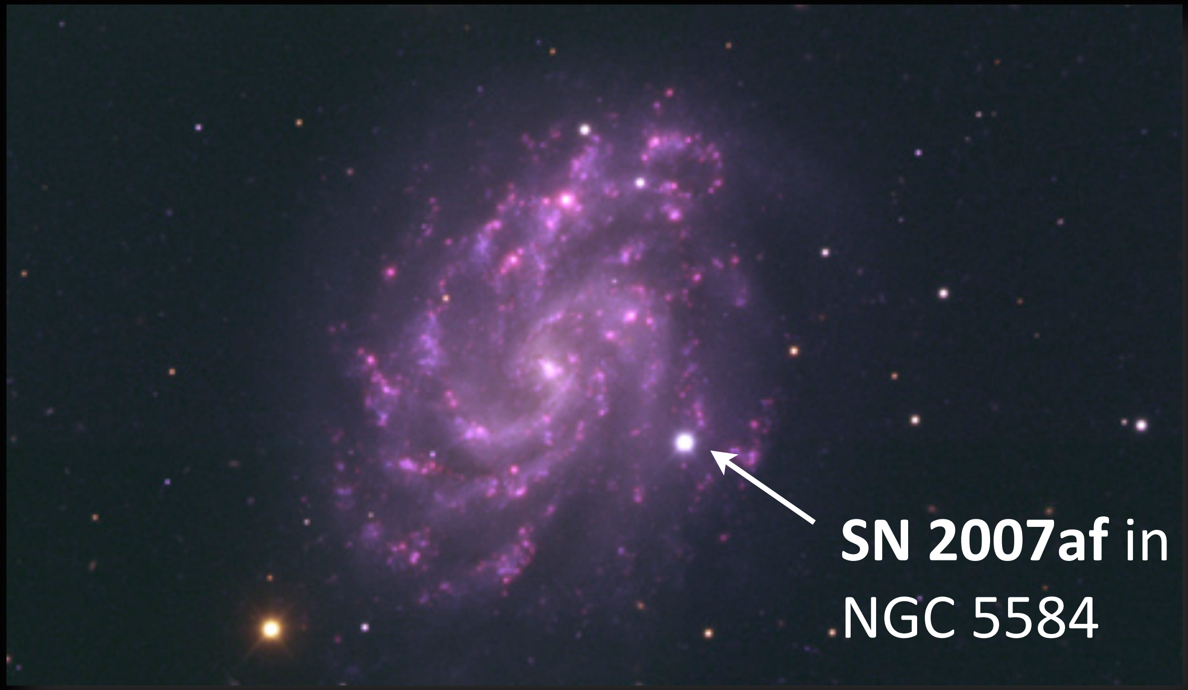
1 SN = 6000 helladollars.

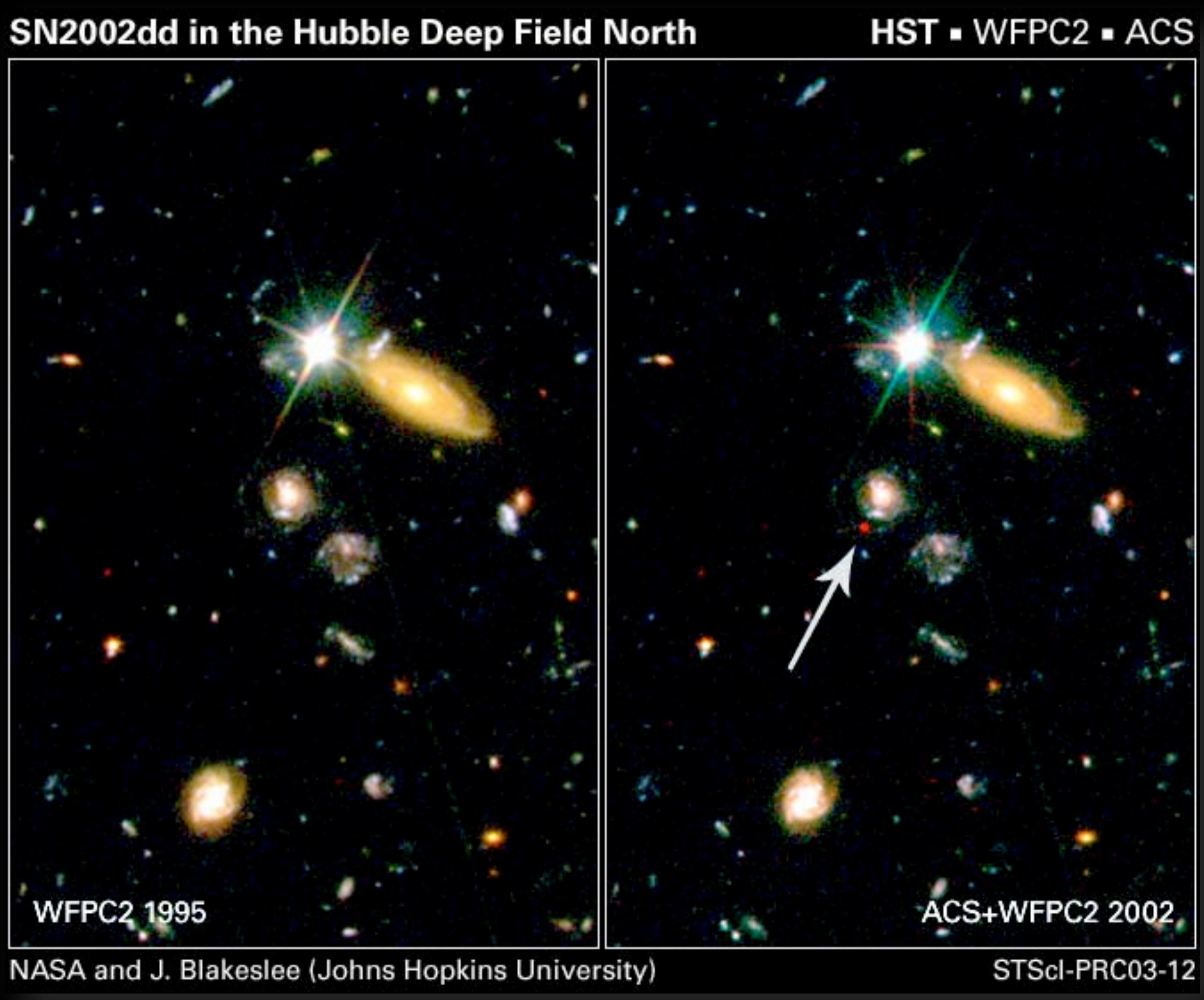
There have only been 2 SNe Ia seen by humans in our galaxy as far as we know.

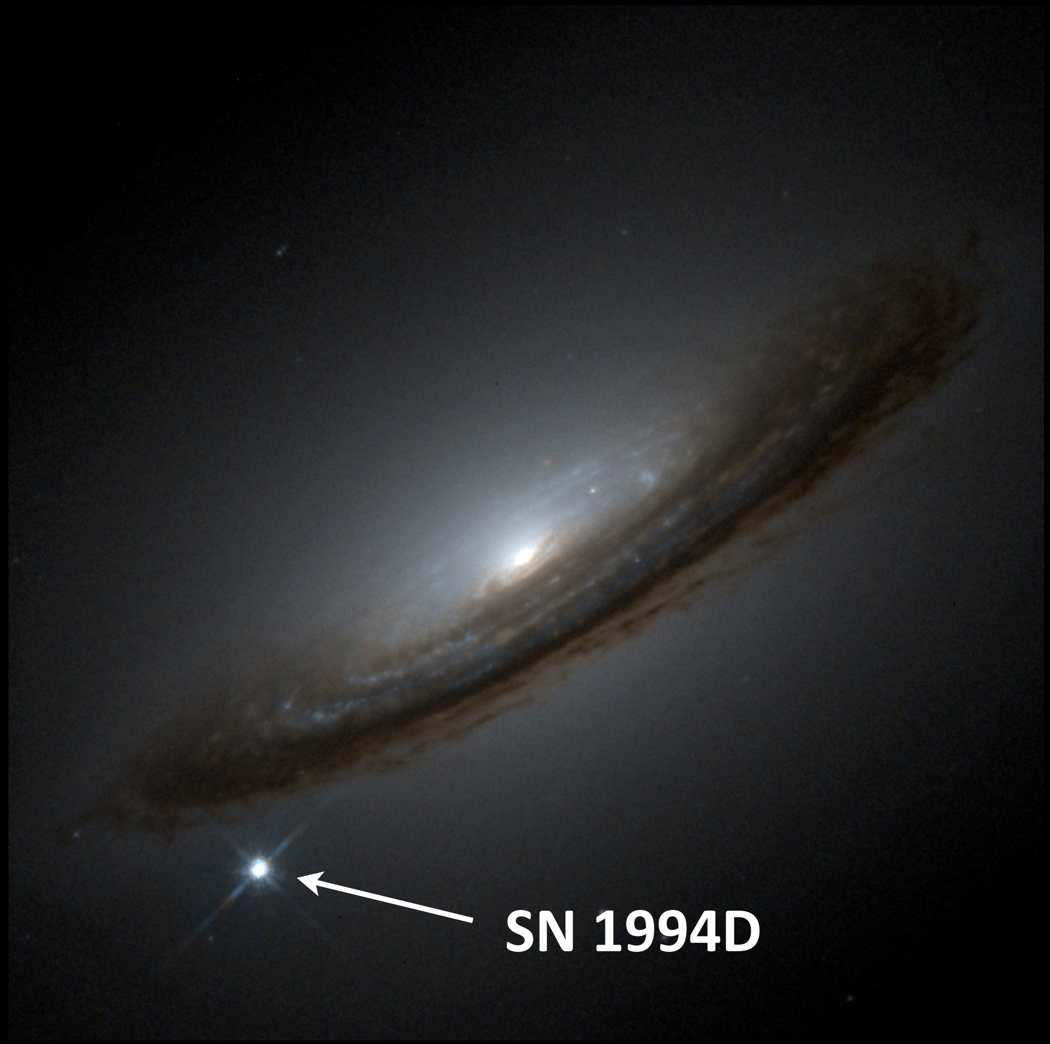
Almost all our knowledge comes from SNe Ia in distant galaxies.

They are so far away they are just point sources of light: we can't resolve details.

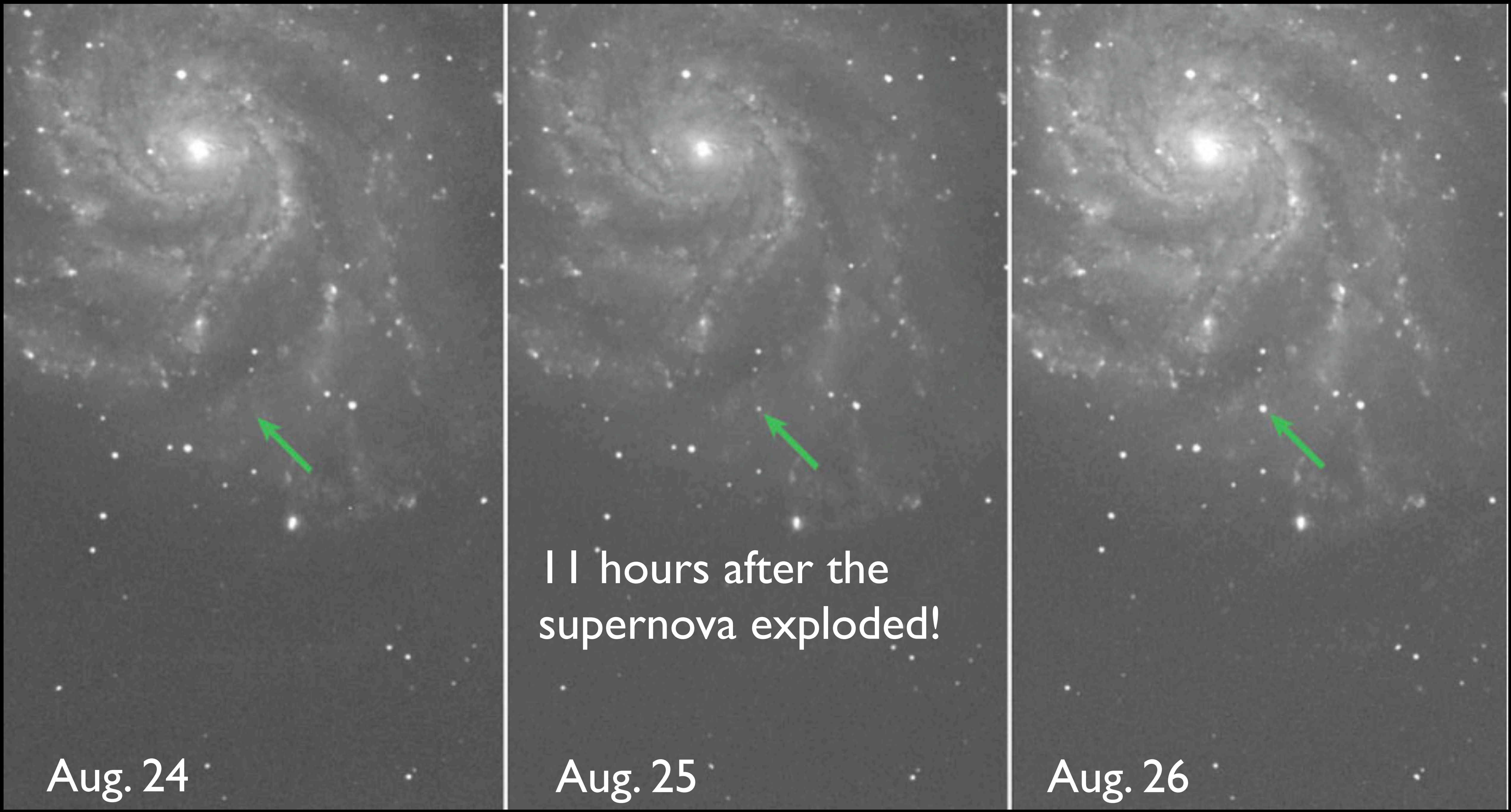
And they are so far away that we can't see the star that blew up -- it is too dim.







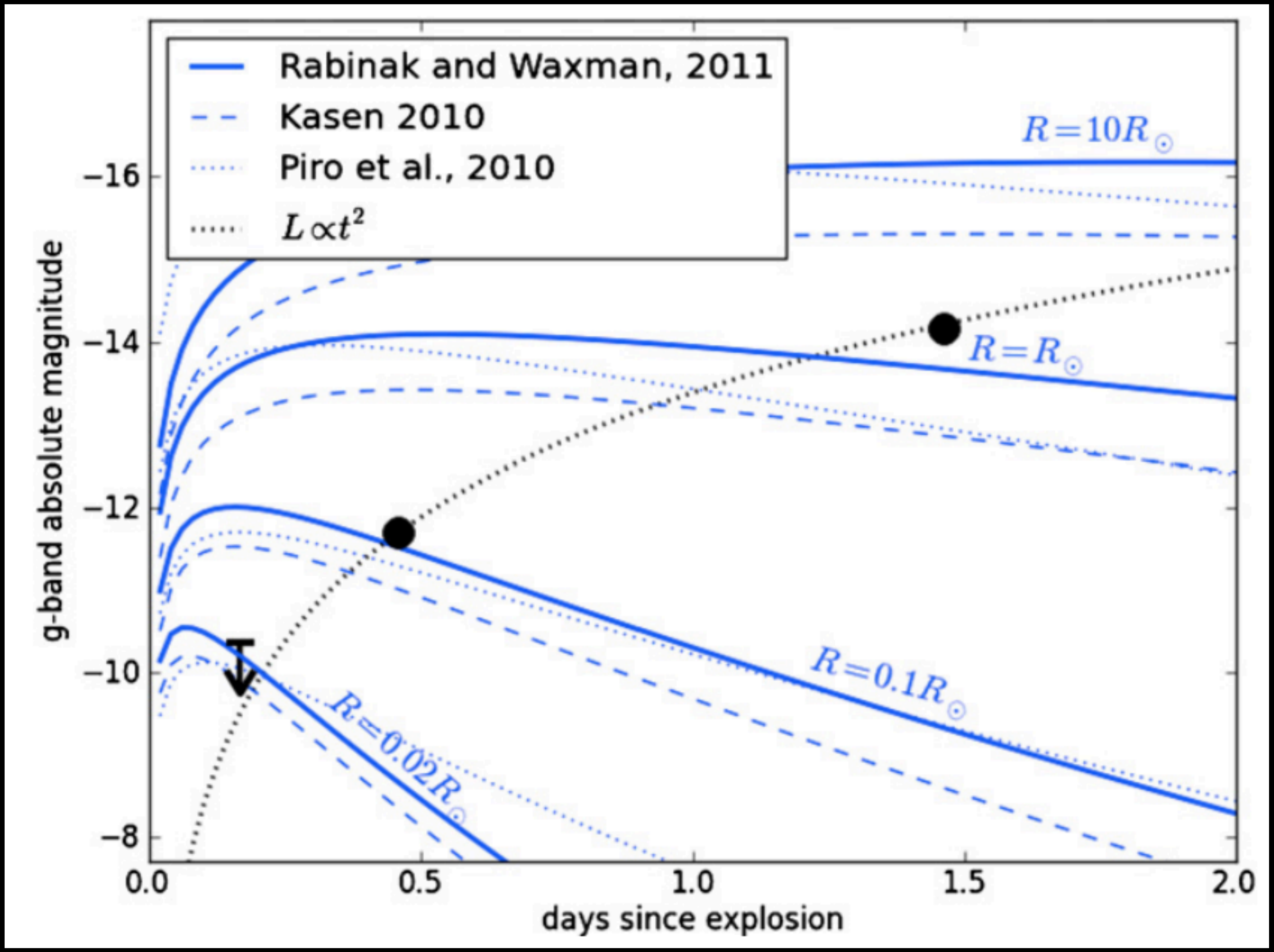
SN 2011fe
Aka PTF 11kly



Credit: P. Nugent (LBL), PTF

Aug. 25: Earliest a SN Ia has ever been caught. From that, we could work backwards to determine the size of the star that exploded. It had to be a white dwarf! First proof!

SN 2011fe
Aka PTF 11kly



Bloom et al. 2012

We tracked down someone who had observed the galaxy just 2.5 hours after the explosion and it was so dim they didn't see it!

From that, we could work backwards to determine the size of the star that exploded. It had to be a white dwarf! First proof!

SN 2011fe
Aka PTF 11kly

Closest Type Ia supernova in 25 years.

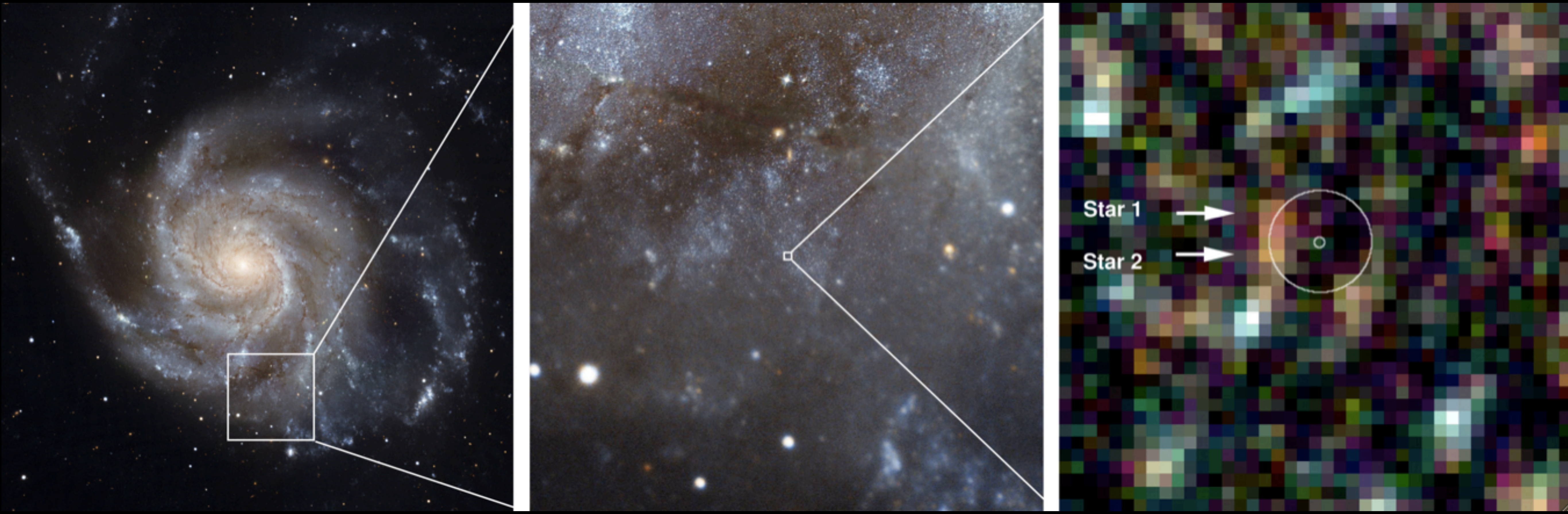
21 million lightyears away in the Pinwheel Galaxy (M101)

Image credit: BJ Fulton (LCOGT) / PTF.

SN 2011fe
Aka PTF 11kly

Image credit: BJ Fulton (LCOGT) / PTF, STScI

SN 2011fe
Aka PTF 11kly

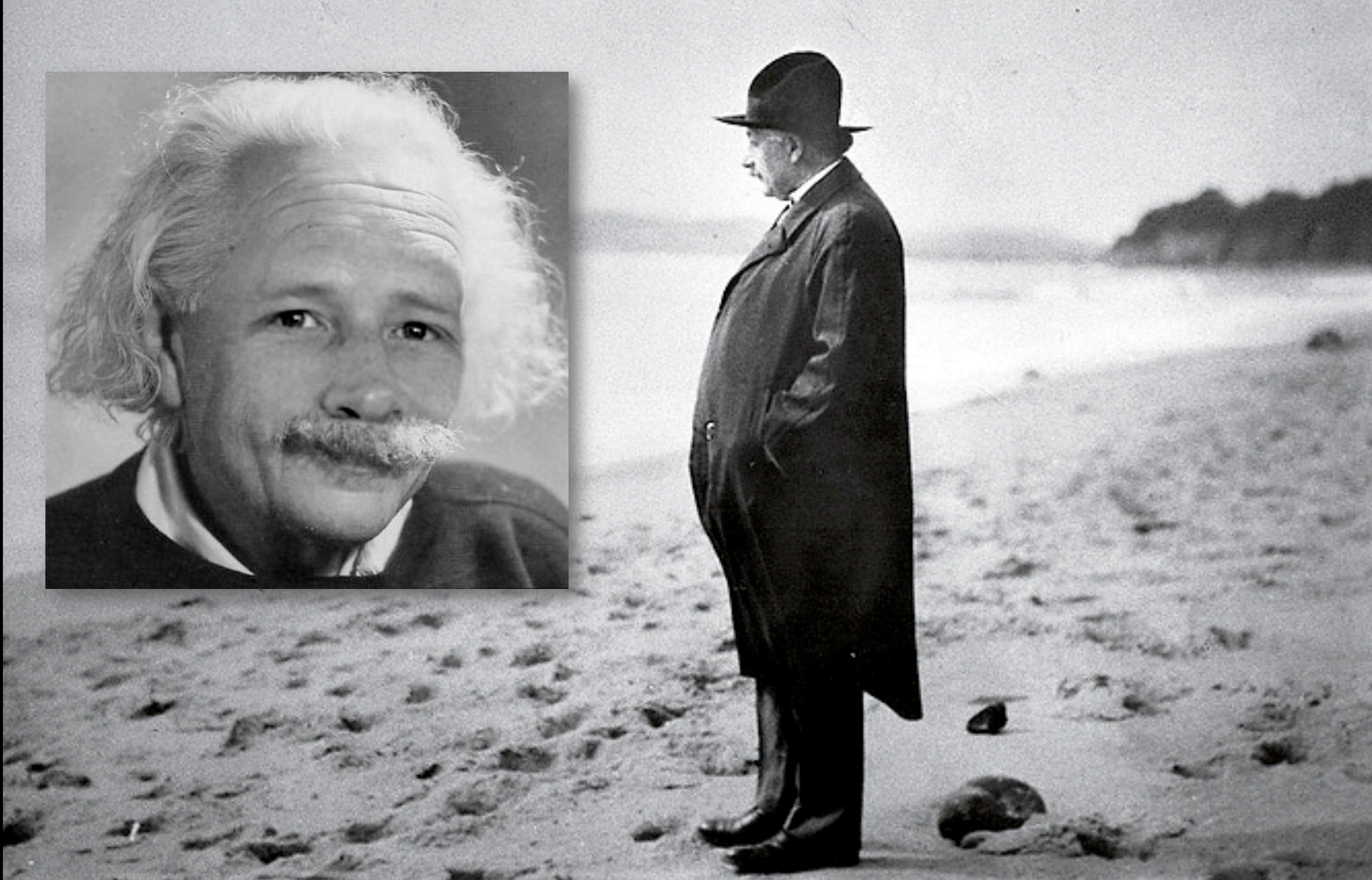


From this pre-explosion Hubble image we don't see a star at the position of the supernova. So the second star was not a red giant!

Image credit: W. Li (UC Berkeley), STScI

Cosmology

Einstein in Santa Barbara!



Albert Einstein

Einstein in 1905

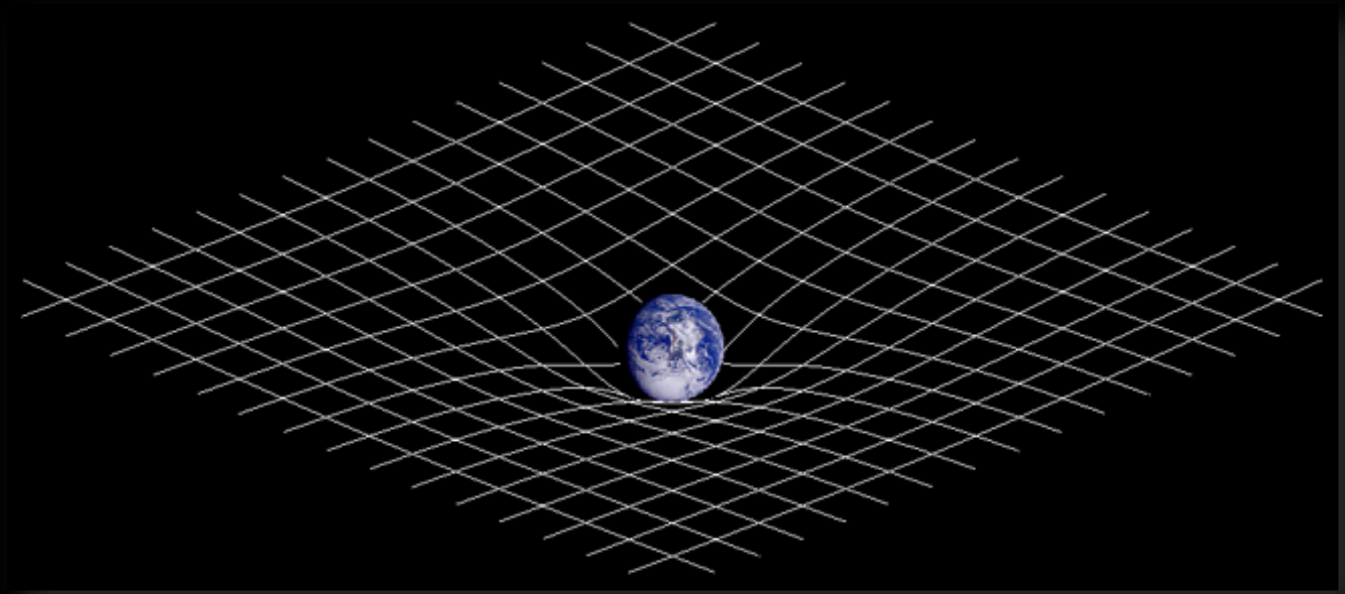
Theory of Relativity:

Einstein field equations –

$$G_{ab} = \kappa T_{ab}$$

Einstein tensor: curvature of spacetime

Stress-energy tensor: source of gravity field



Spacetime tells mass how to move, mass tells spacetime how to curve.

Great-grandparents cosmolgy

Early 1920s: The whole universe was thought to consist of our galaxy, the Milky Way.

Andromeda:
Thought to be a "spiral nebula" – a gas cloud in our Milky Way

Static universe: Neither expanding or contracting.

Maintaining a static universe

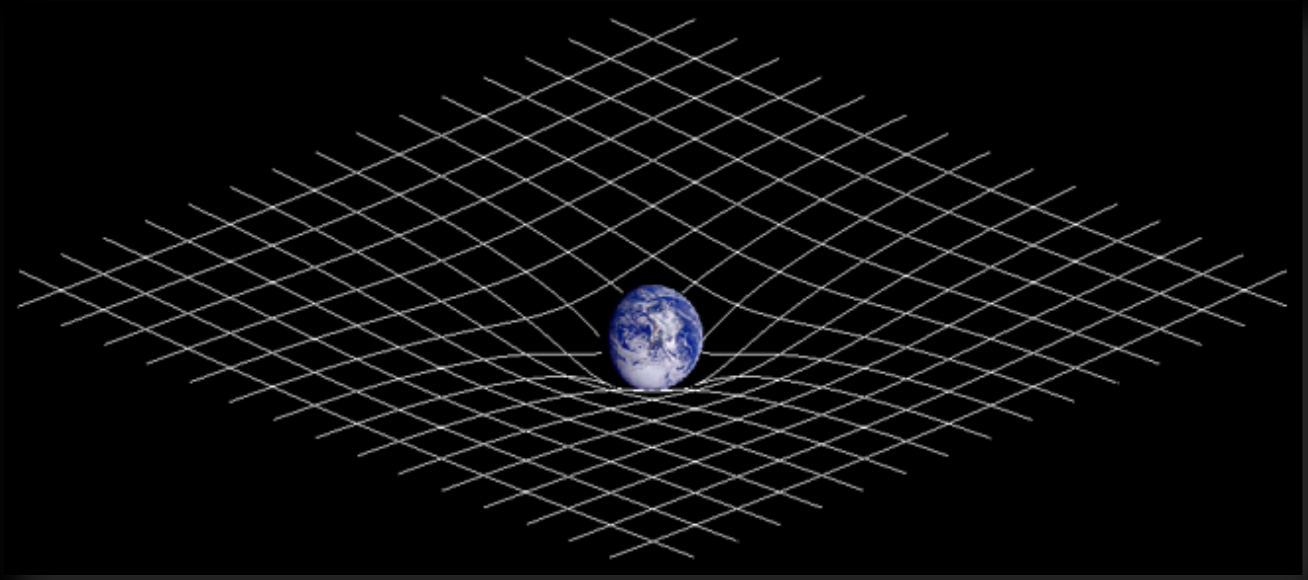
Einstein in 1922

Modified Field Equations –

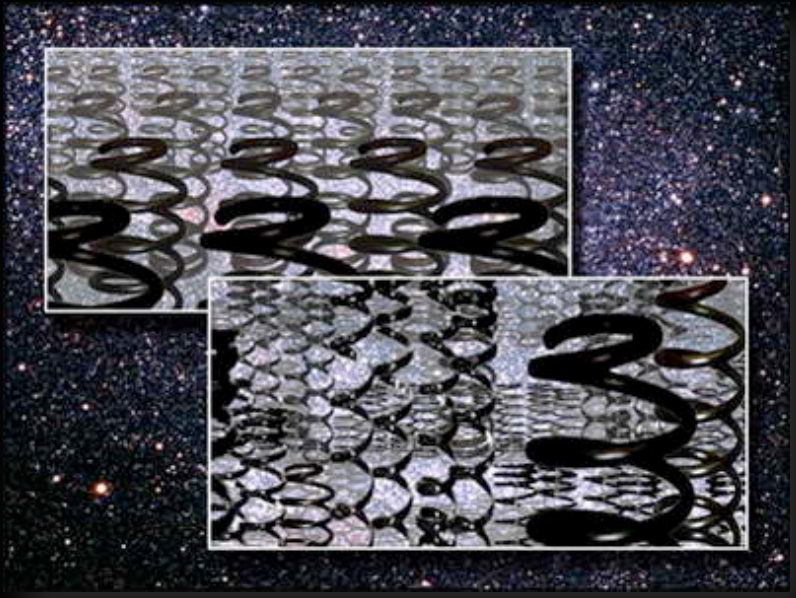
$$G_{ab} + \Lambda g_{ab} = \kappa T_{ab}$$

Cosmological constant: energy of vacuum

Spacetime metric: measure of lengths in spacetime

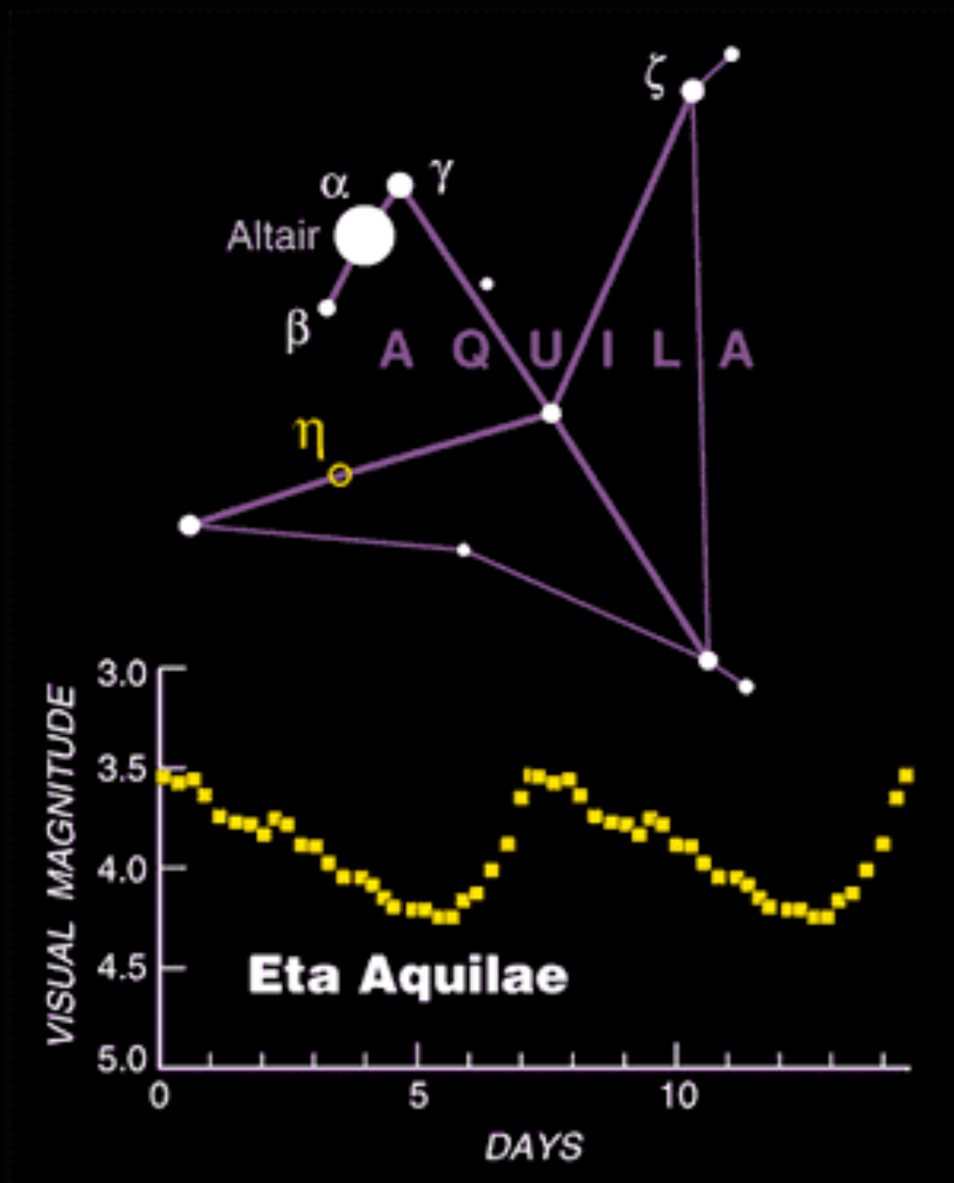


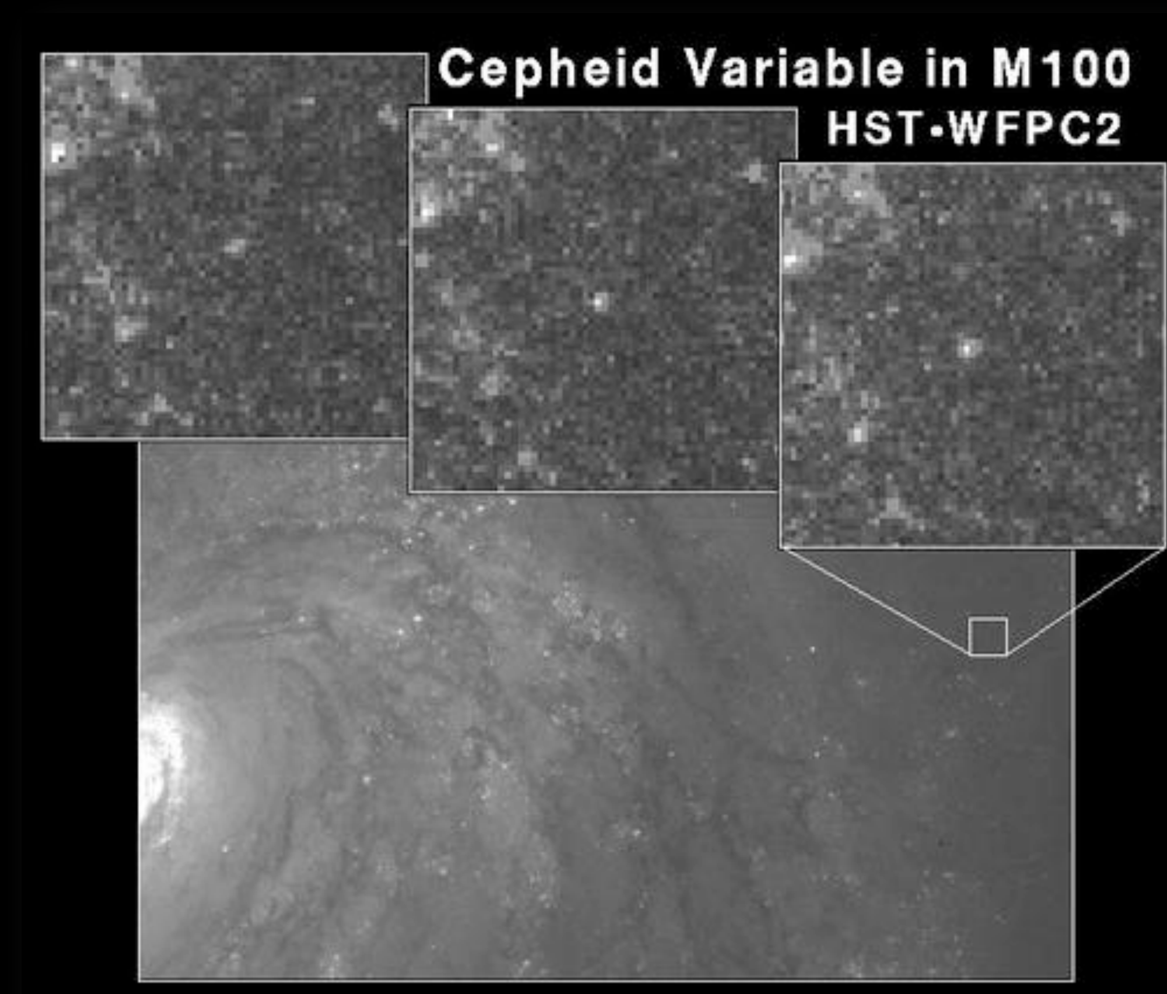
Spacetime has energy that prevents collapse

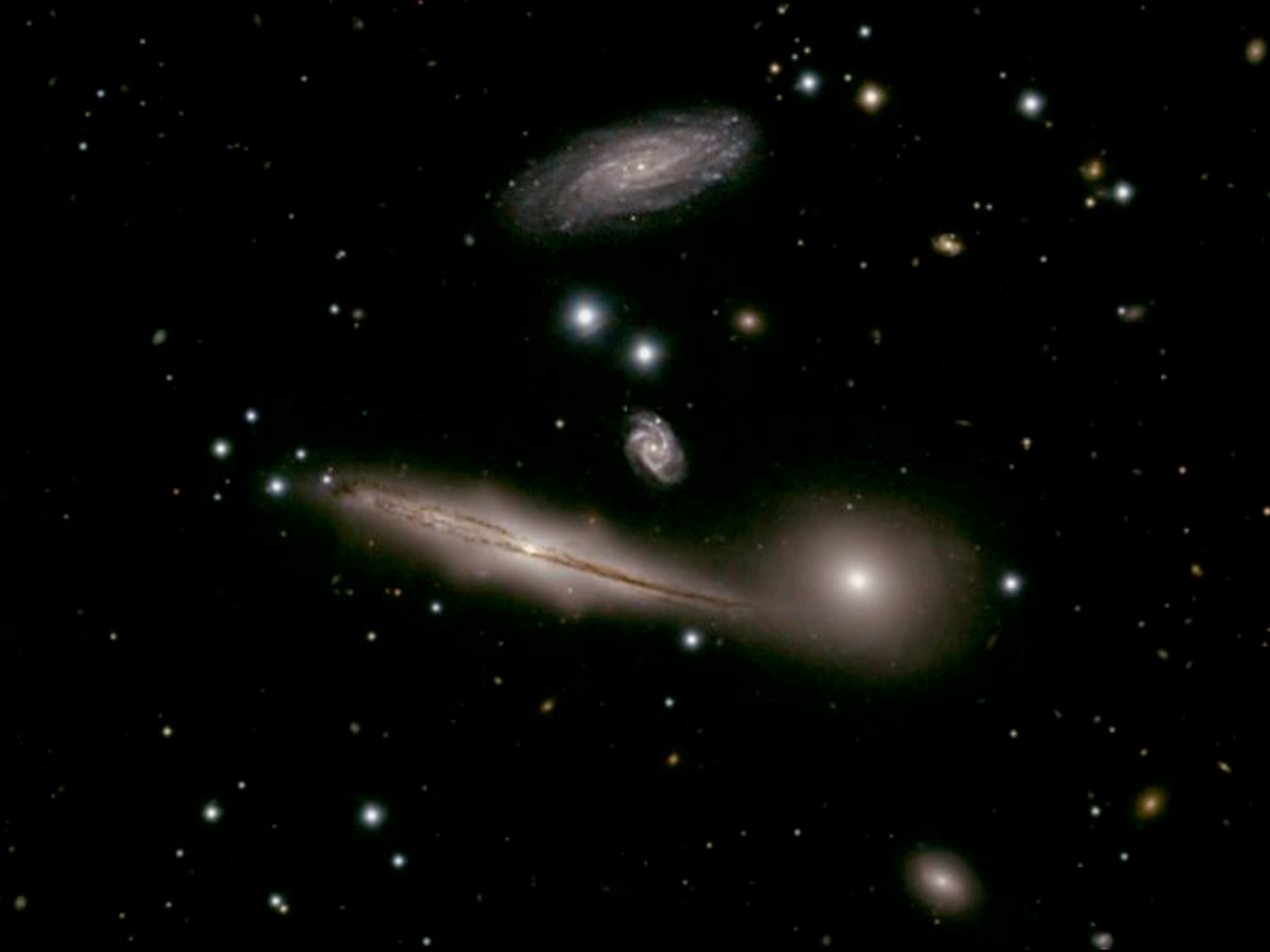


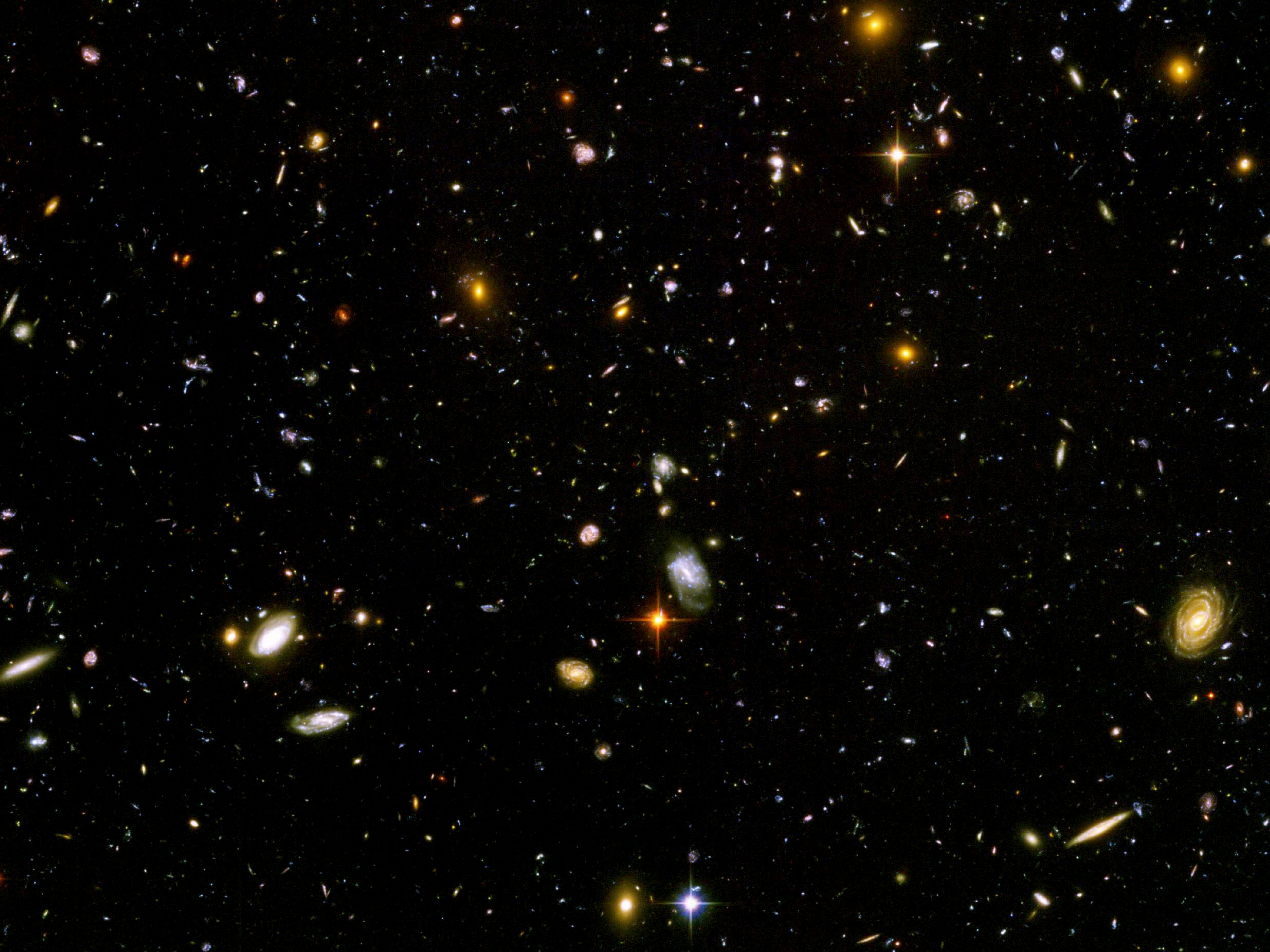
Henrietta Swan Leavitt (1868-1921) discovered that certain pulsating stars (Cepheid Variable stars) take longer to pulsate the brighter they are.

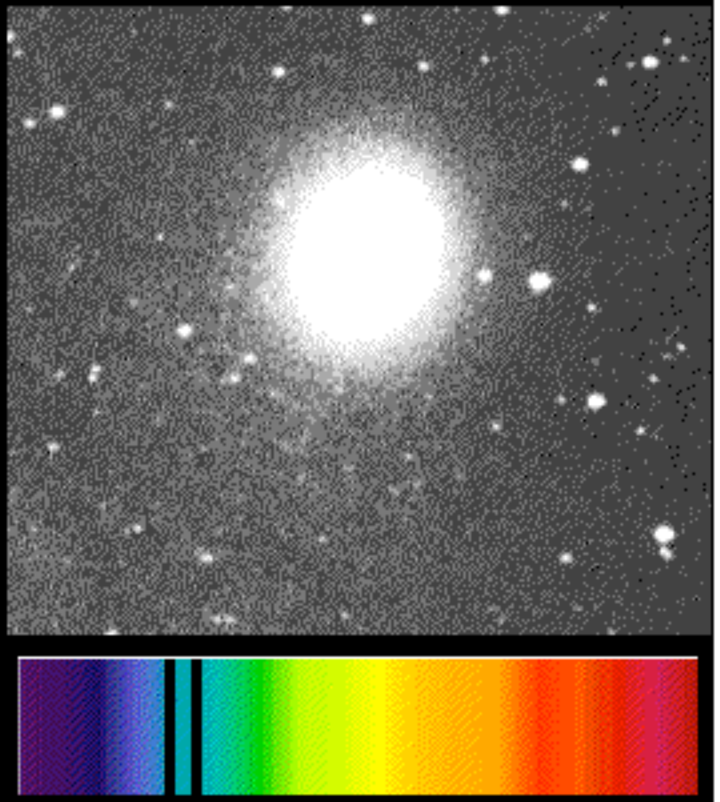
Edwin Hubble: In Mid 1920s used Cepheid Variable stars to determine distances to "Spiral nebulae" – proved they were distant galaxies like the Milky Way

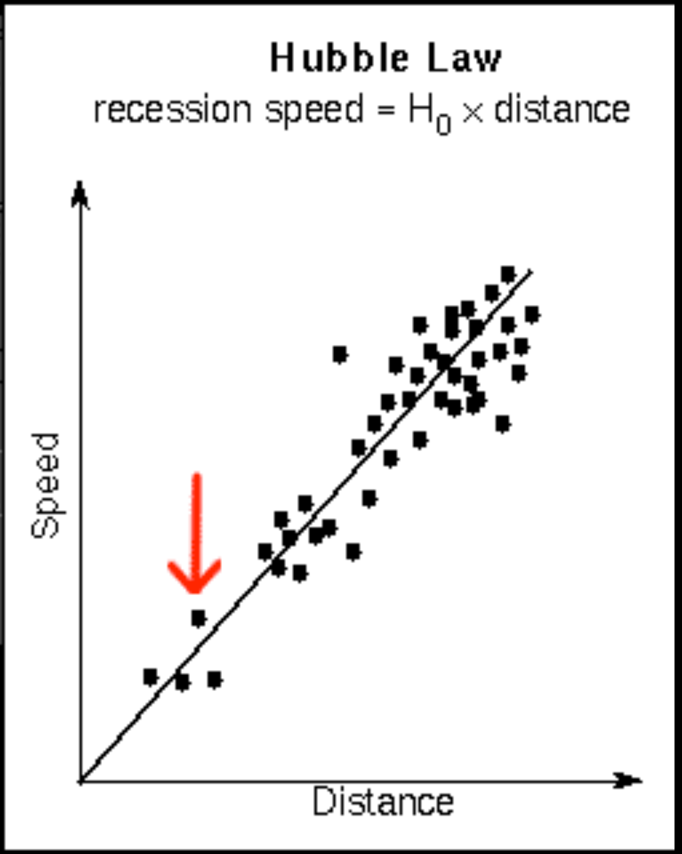






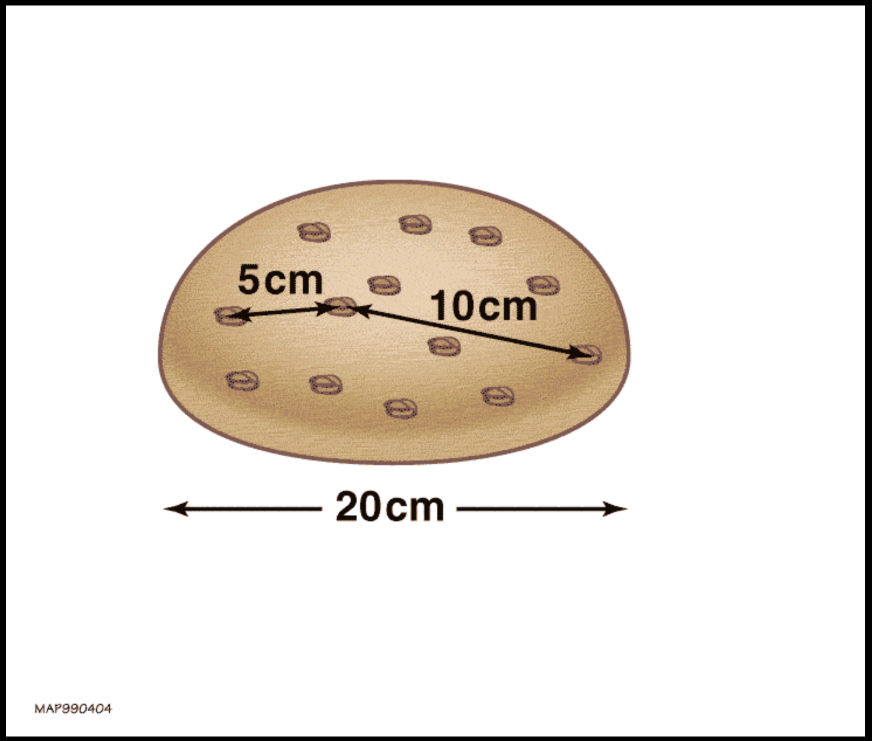






Hubble's Law: More distant galaxies had a higher redshift – they appeared to be moving away from us!

The universe is expanding.



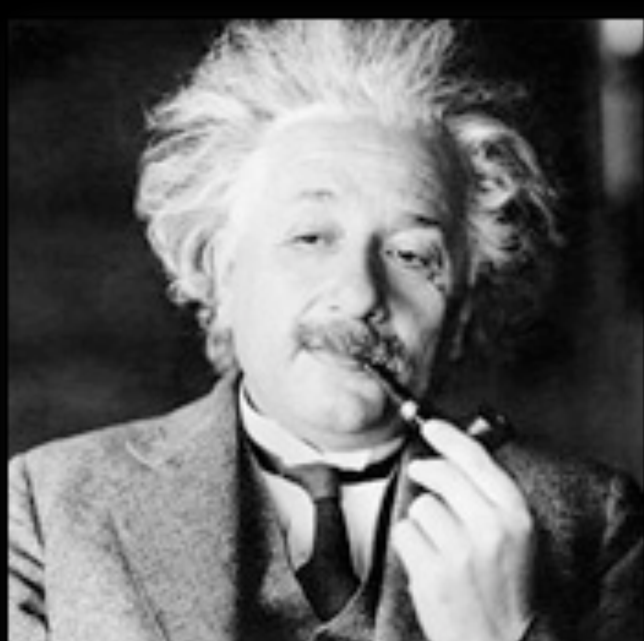
Like a rising loaf of raisin bread.

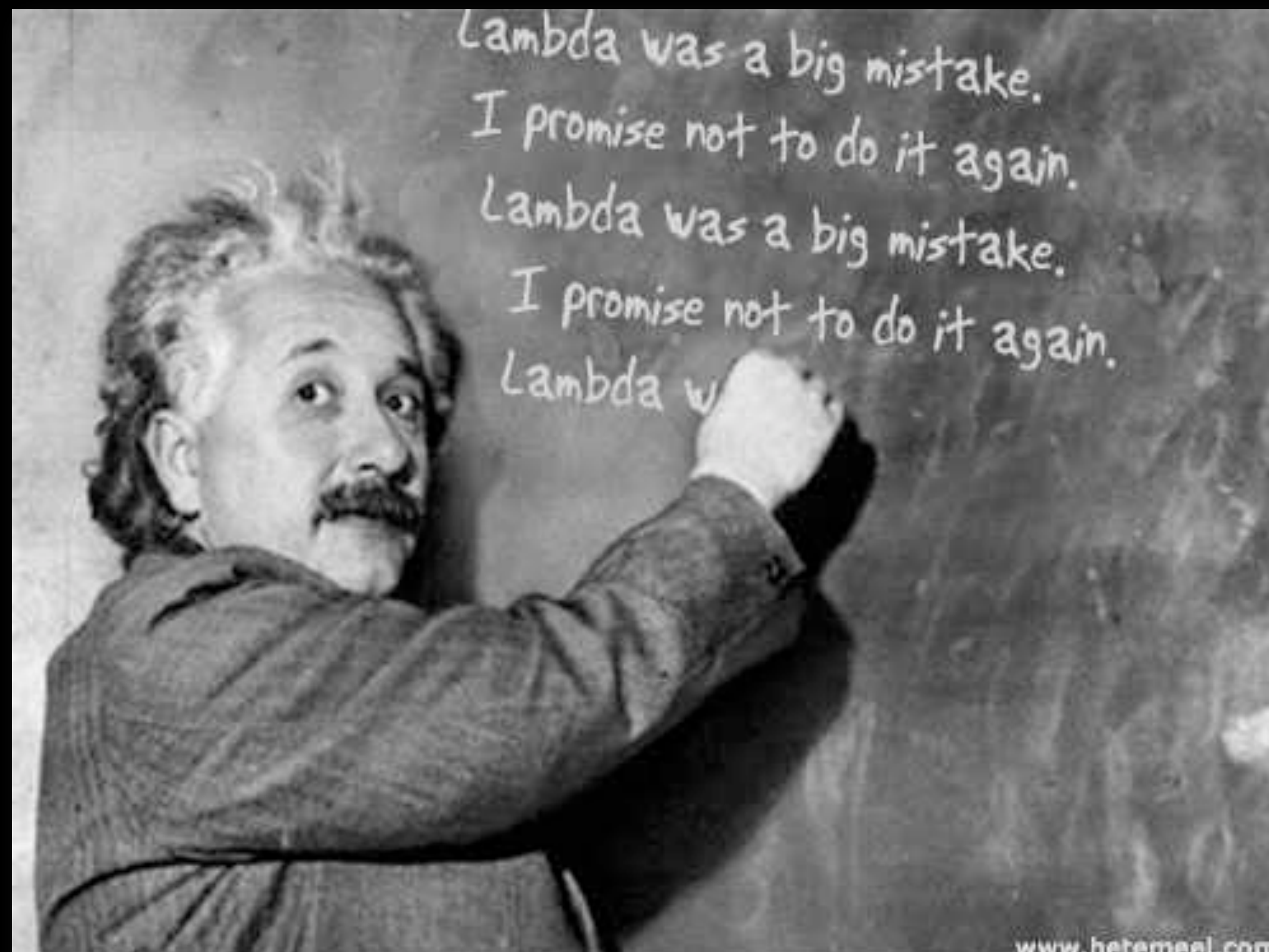
The distance from each raisin (galaxy) to all other raisins is increasing.

The Universe is not static!

Don't need the cosmological constant, Lambda: $G_{ab} + \cancel{\Lambda g}_{ab} = \kappa T_{ab}$
Expansion prevents the universe from collapsing.

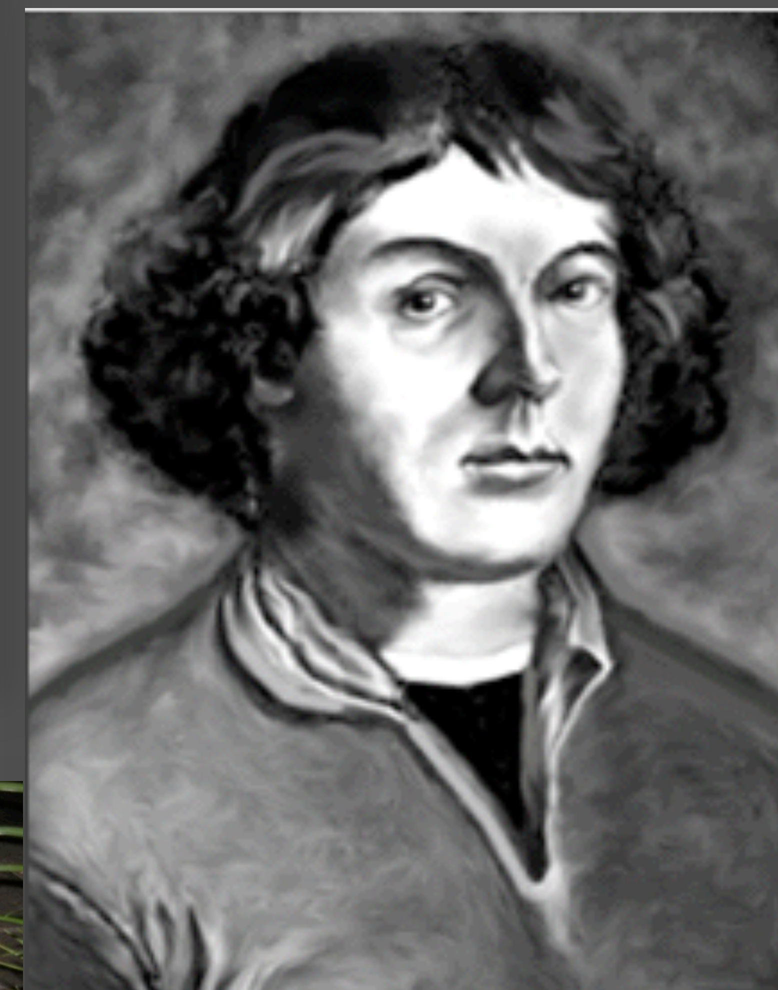
Einstein supposedly called the cosmological constant his "biggest blunder."





Aristotle

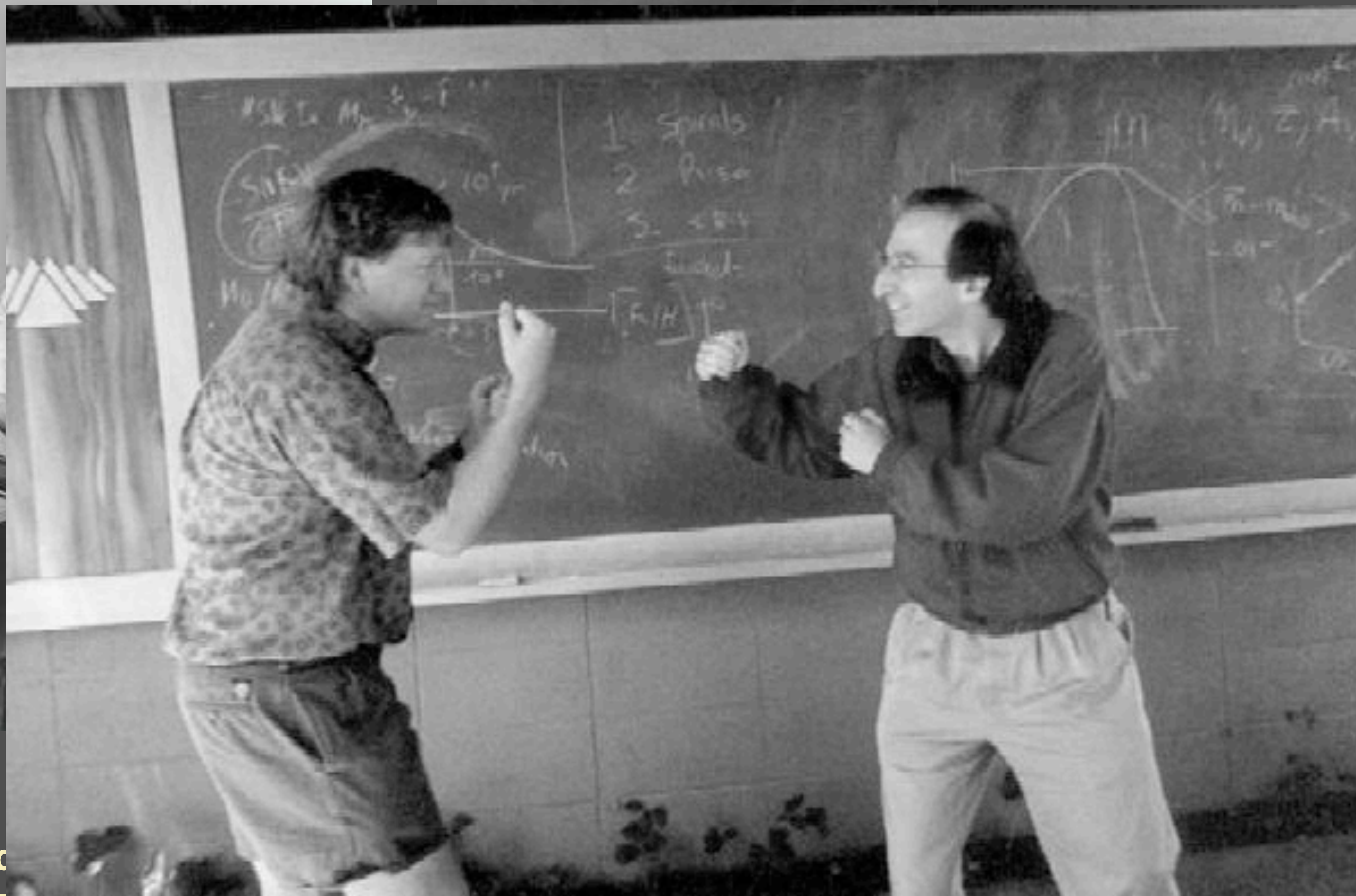
The heavens are perfect and unchanging (and made of aether)



Copernicus

The earth is not the center of the universe


Discovers the rest of the universe, it is expanding!
There is no luminiferous aether. Nobel Prize.
Edwin Hubble
Yes.
W.W. Campbell
Albert Michelson
Milton Humason
Janitor concurs!
Albert Einstein
Walter Adams
Charles St. John
Yes.
Relativity, etc
Nobel Prize
Dang it, I should have figured that out! Guess I don't need the cosmological constant
Wait, solutions unstable, need cosmological constant
Discoveres White Dwarf Stars



idt

They're c

there is Dark Matter, and
you're all spherical
bastards!

white dwarfs to probe the
expansion.

Good idea, I will beat you.

It's on!

2011 Nobel Prize in Physics

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

Saul Perlmutter

Brian Schmidt

Adam Riess

2011 Nobel Prize in Physics

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

Some of the High-z team

Some of the Supernova Cosmology Project

Since light takes a while to get here, the farther away you look, the farther back in time you are looking.

Type Ia supernovae are standard candles. You can use them to determine distances in the universe.

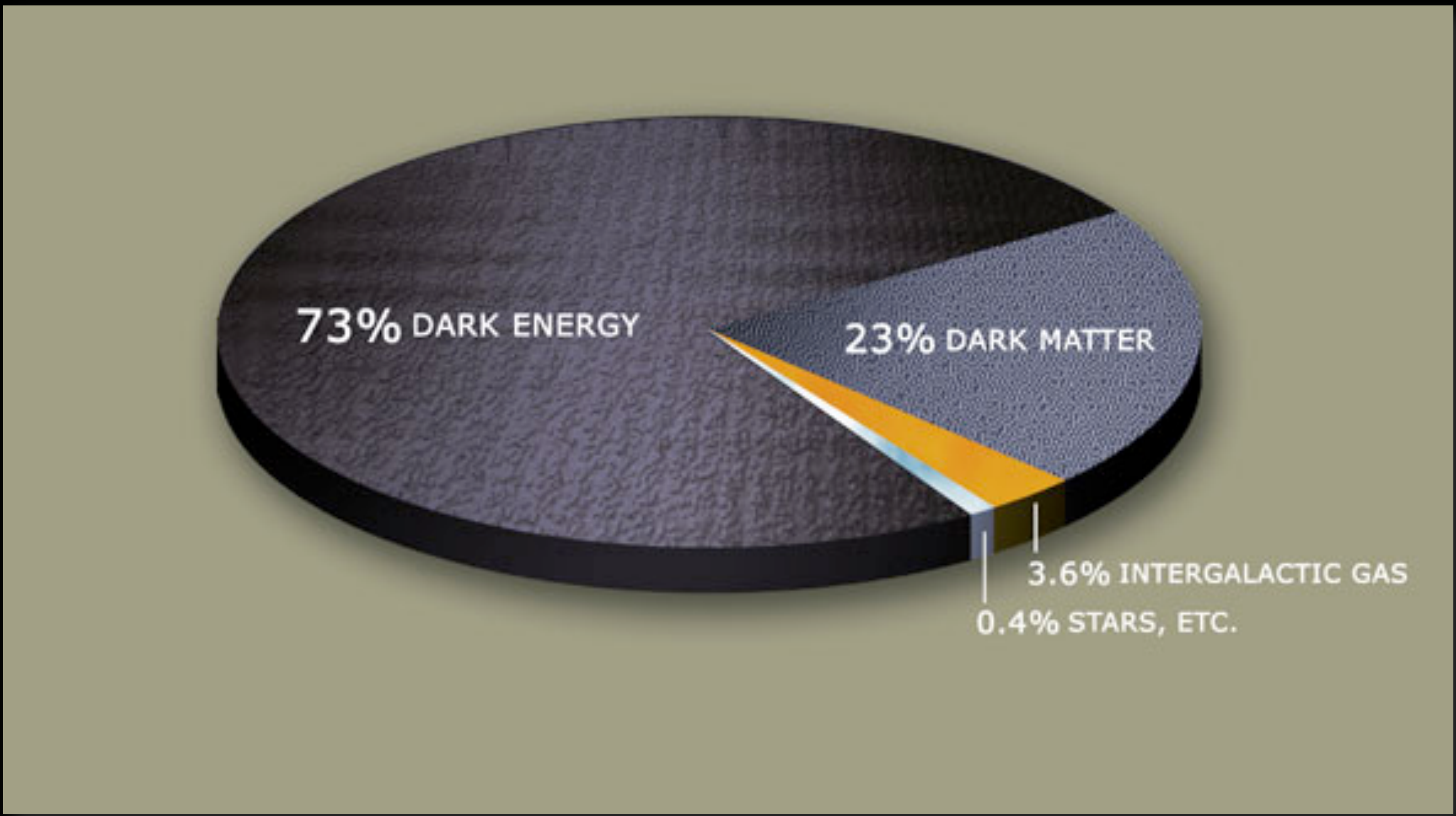
Cosmic web: artist's impression – National Geographic

SN 2007af in NGC 5584

You can use distant supernovae to make a map of the history of the expansion of the universe.

The composition of the universe

There must be some energy accelerating the universe.
Since we don't know what it is, we call it Dark Energy.



Different kinds of Dark Energy will make the universe expand at different rates over time.

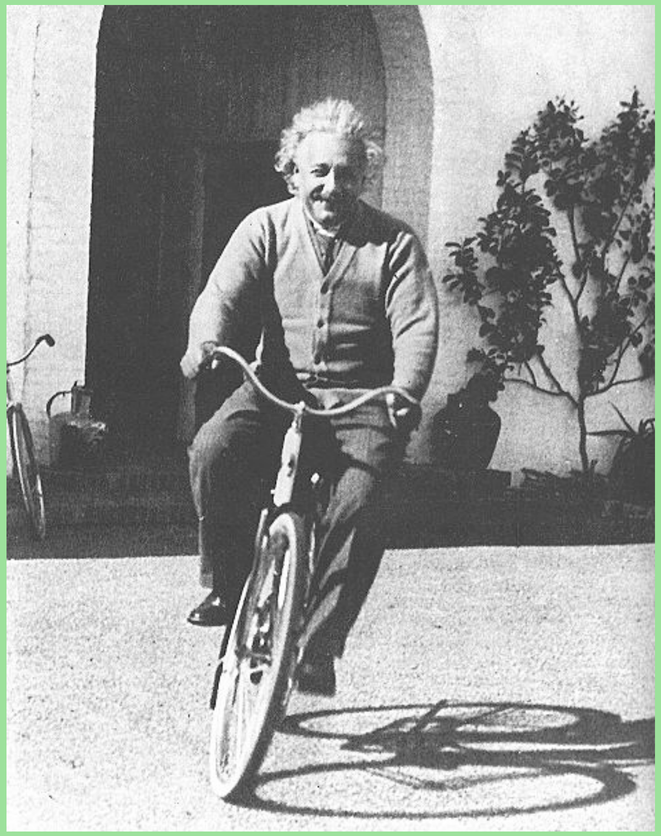
As the universe expands, does the Dark Energy....

Increase

Big rip: In billions of years, Dark Energy will rip apart galaxies, stars, and even subatomic particles.

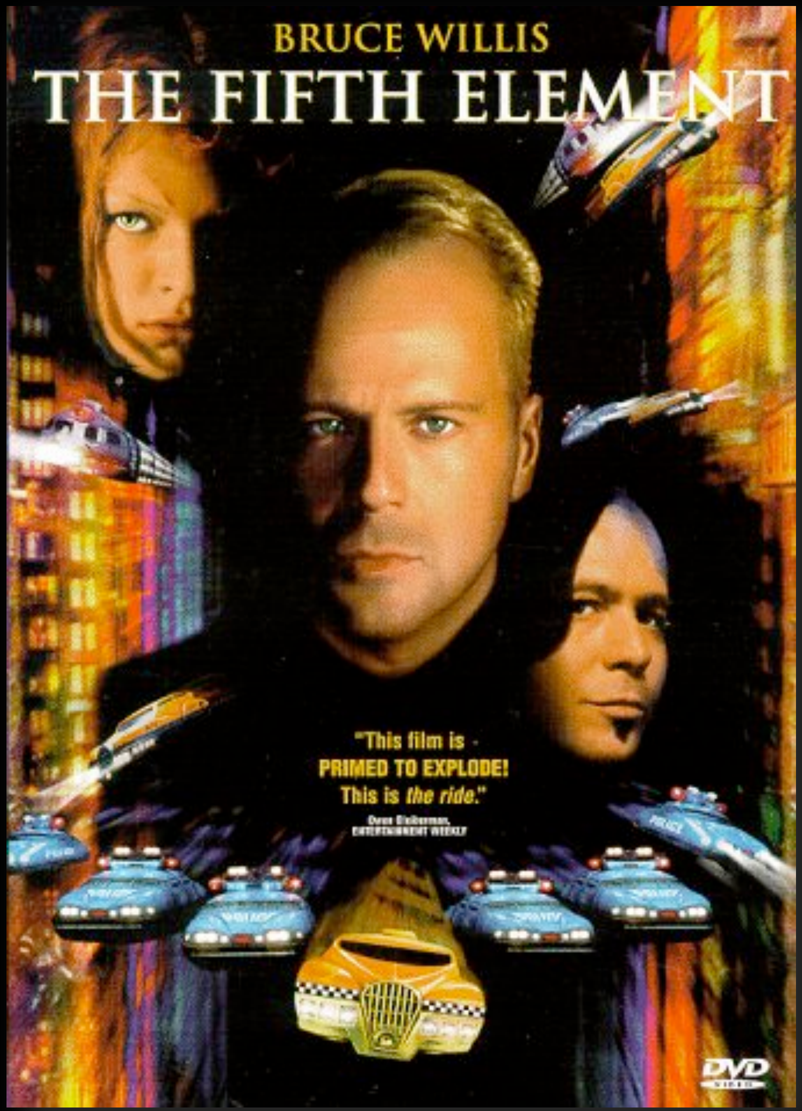
Remain constant

Cosmological constant, Λ: property of vacuum of space. Energy does not dilute as Universe expands

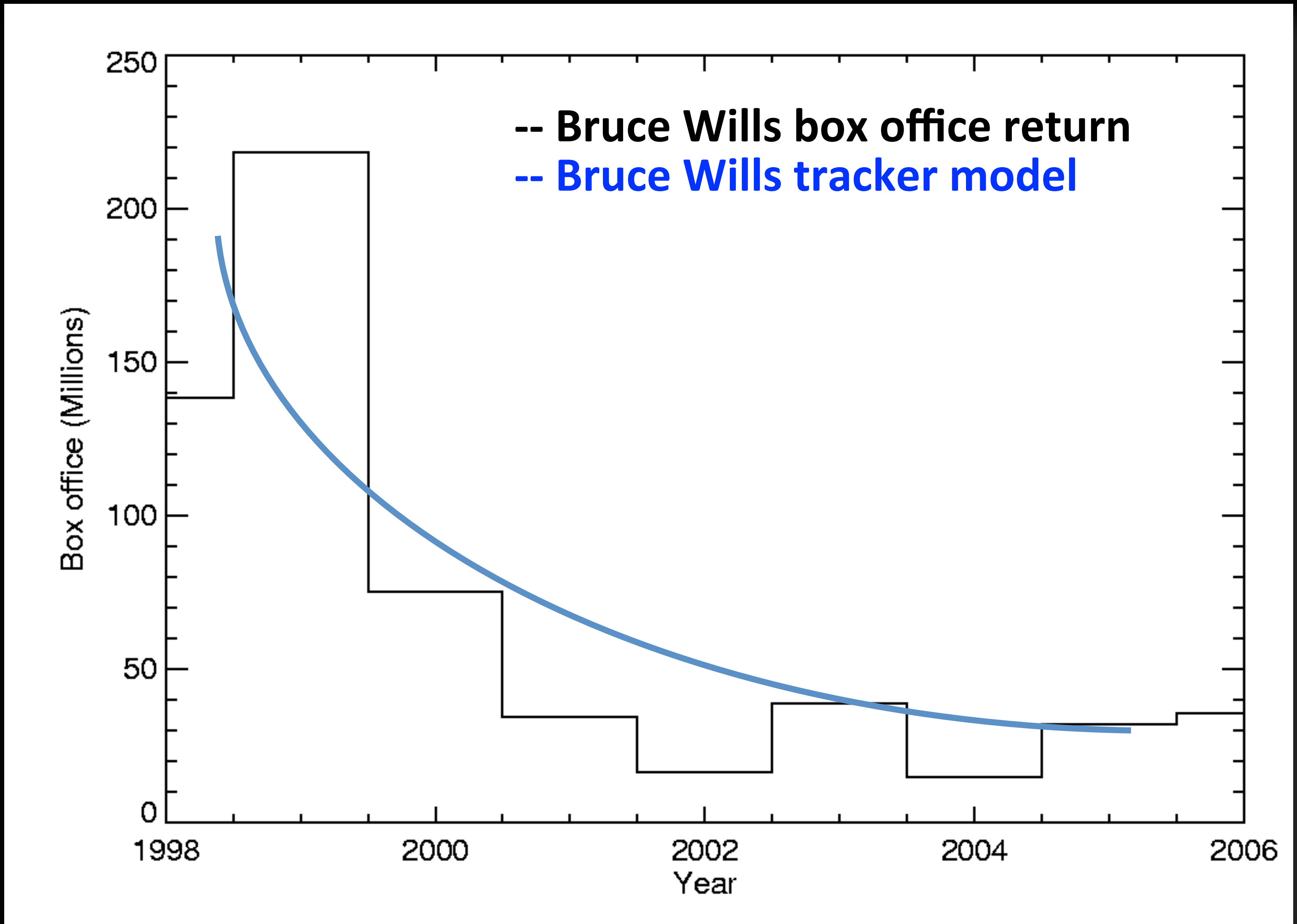


Decrease

Quintessence: An energy field that fills space – Plato had 4 terrestrial elements: fire, earth, air, and water. Aristotle added aether, the substance of the heavens. From *quinta essentia*, "fifth element"

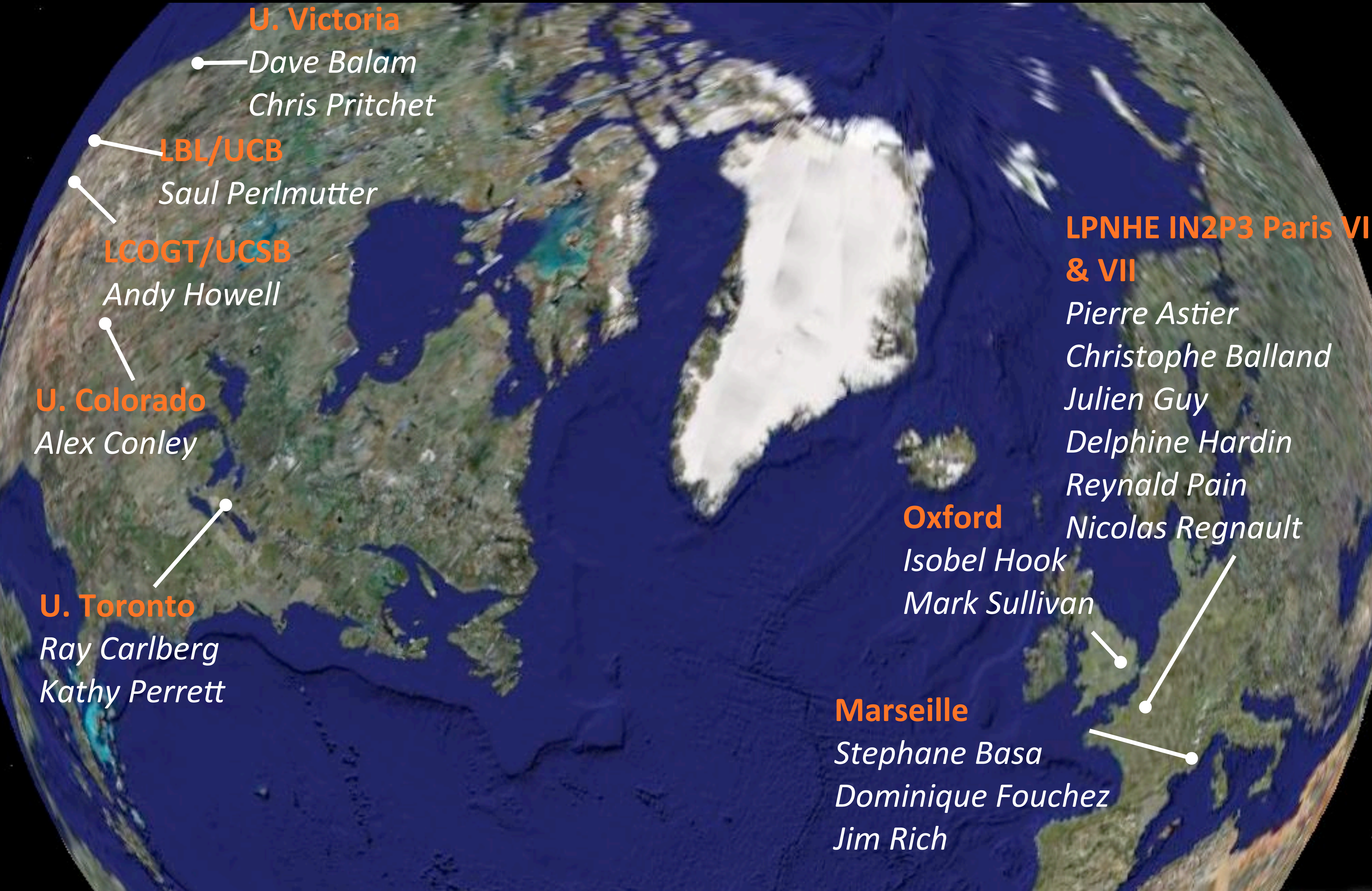


Quintessence – a Bruce Willis-like substance whose power decreases with time.

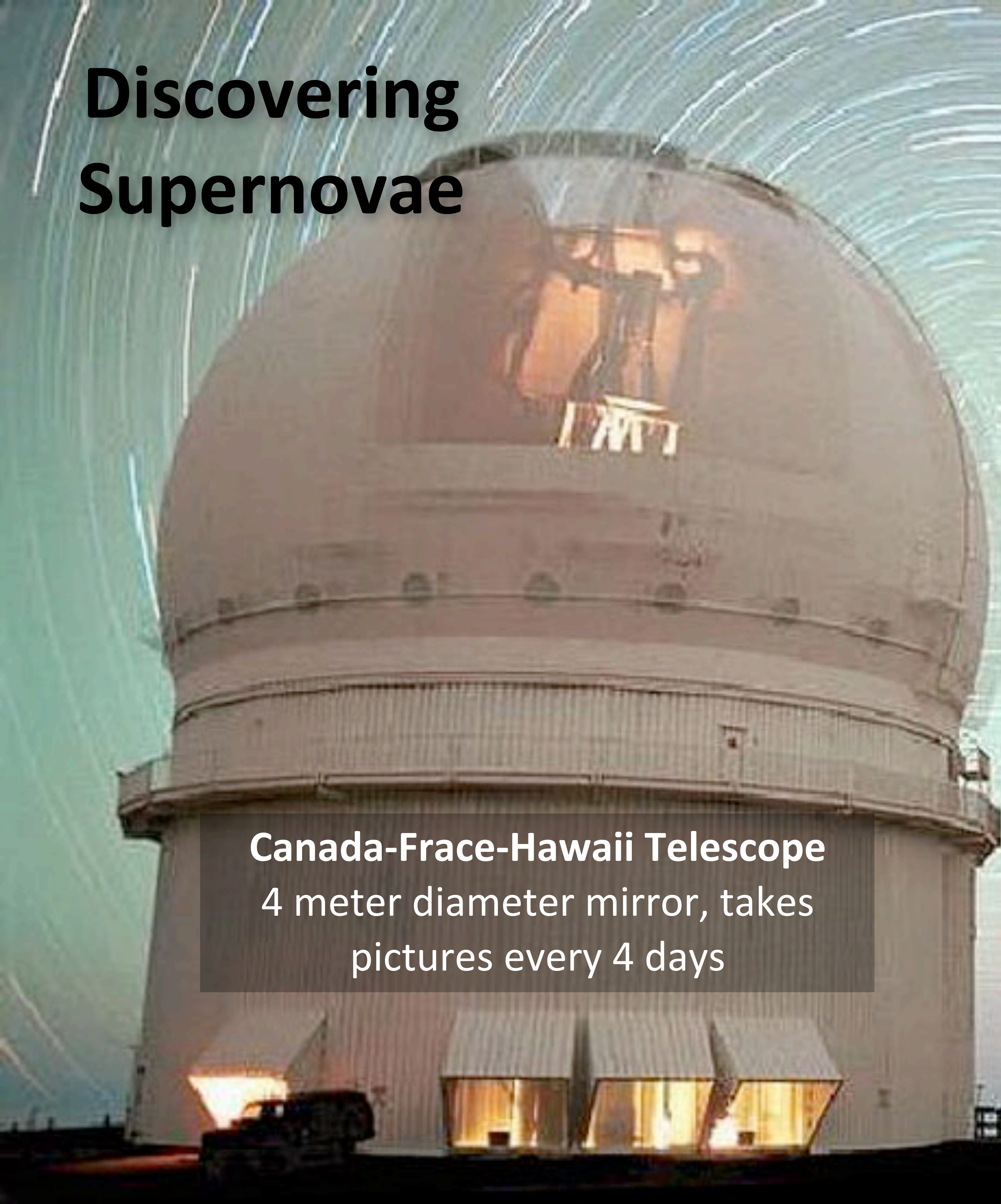


SNLS: Supernova Legacy Survey

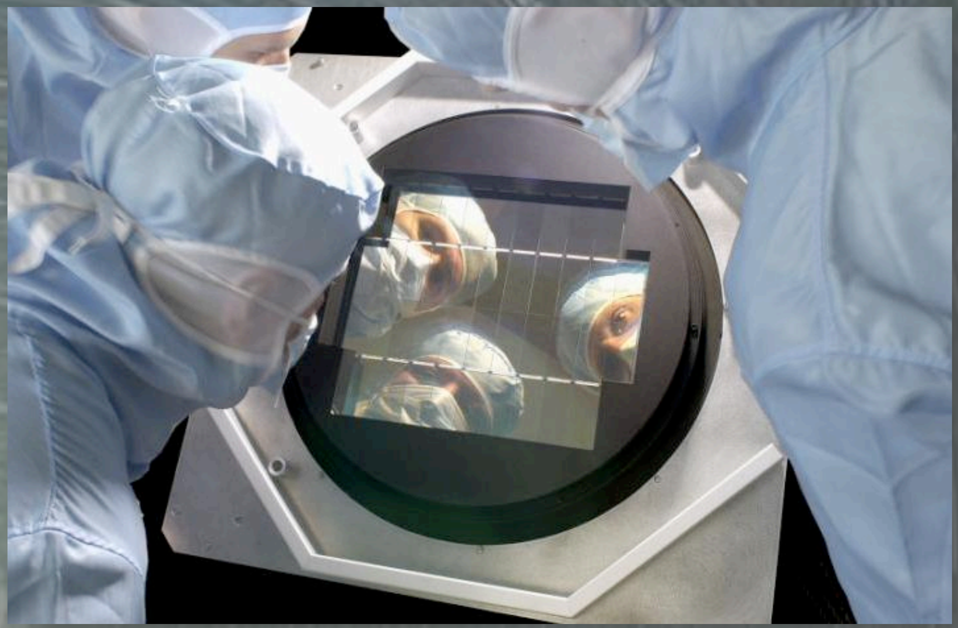
Core Members



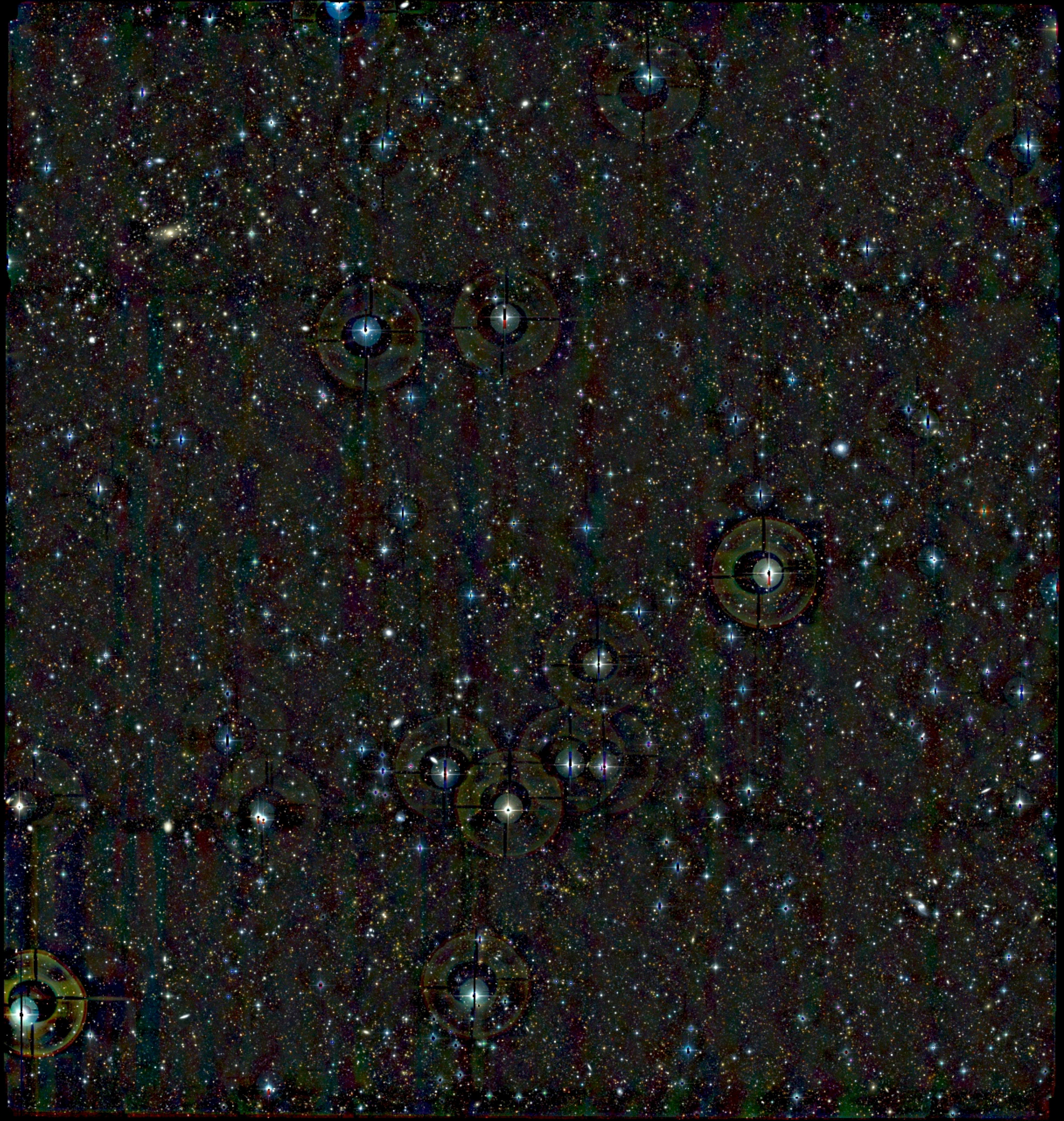
Discovering Supernovae

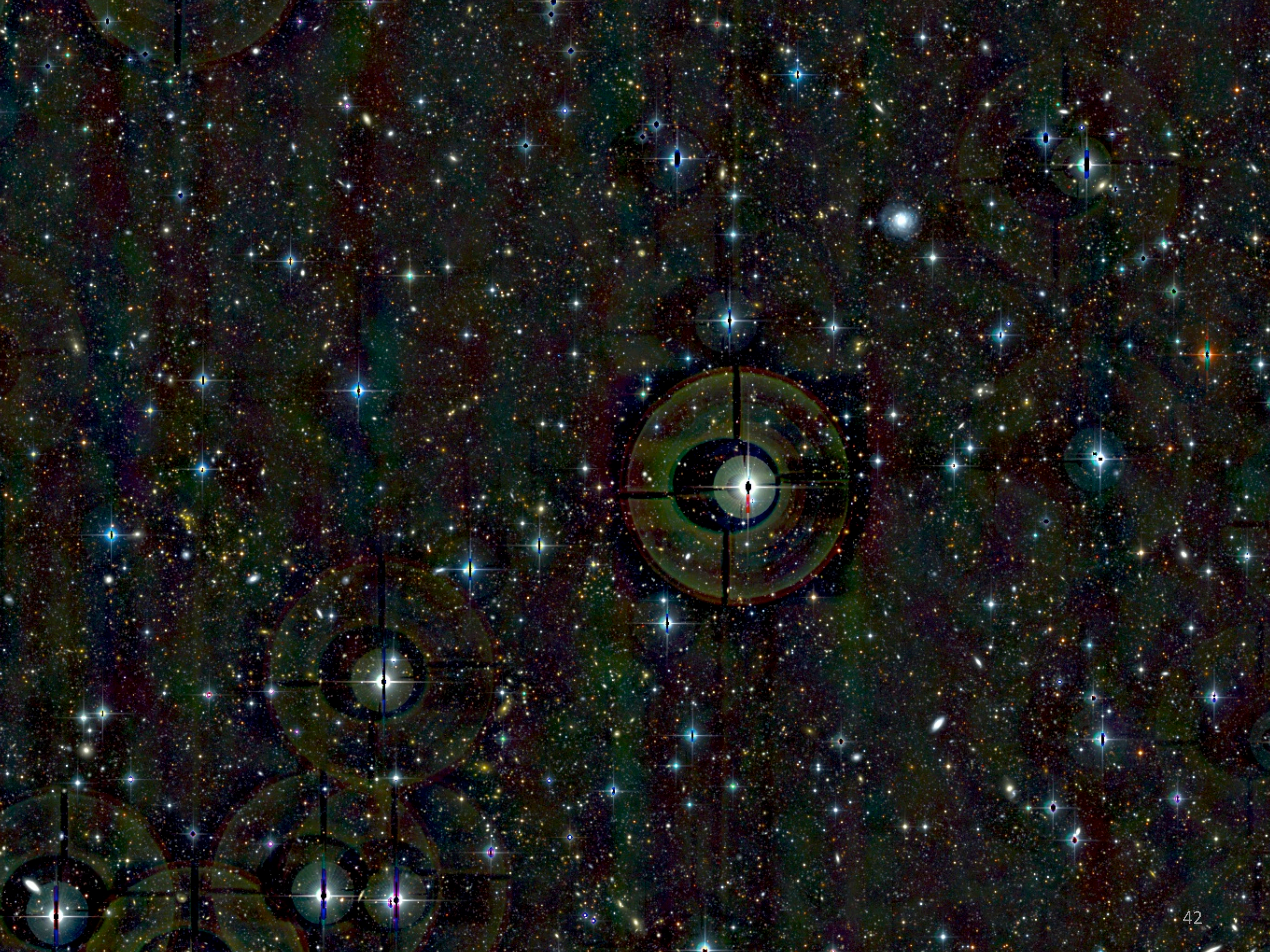


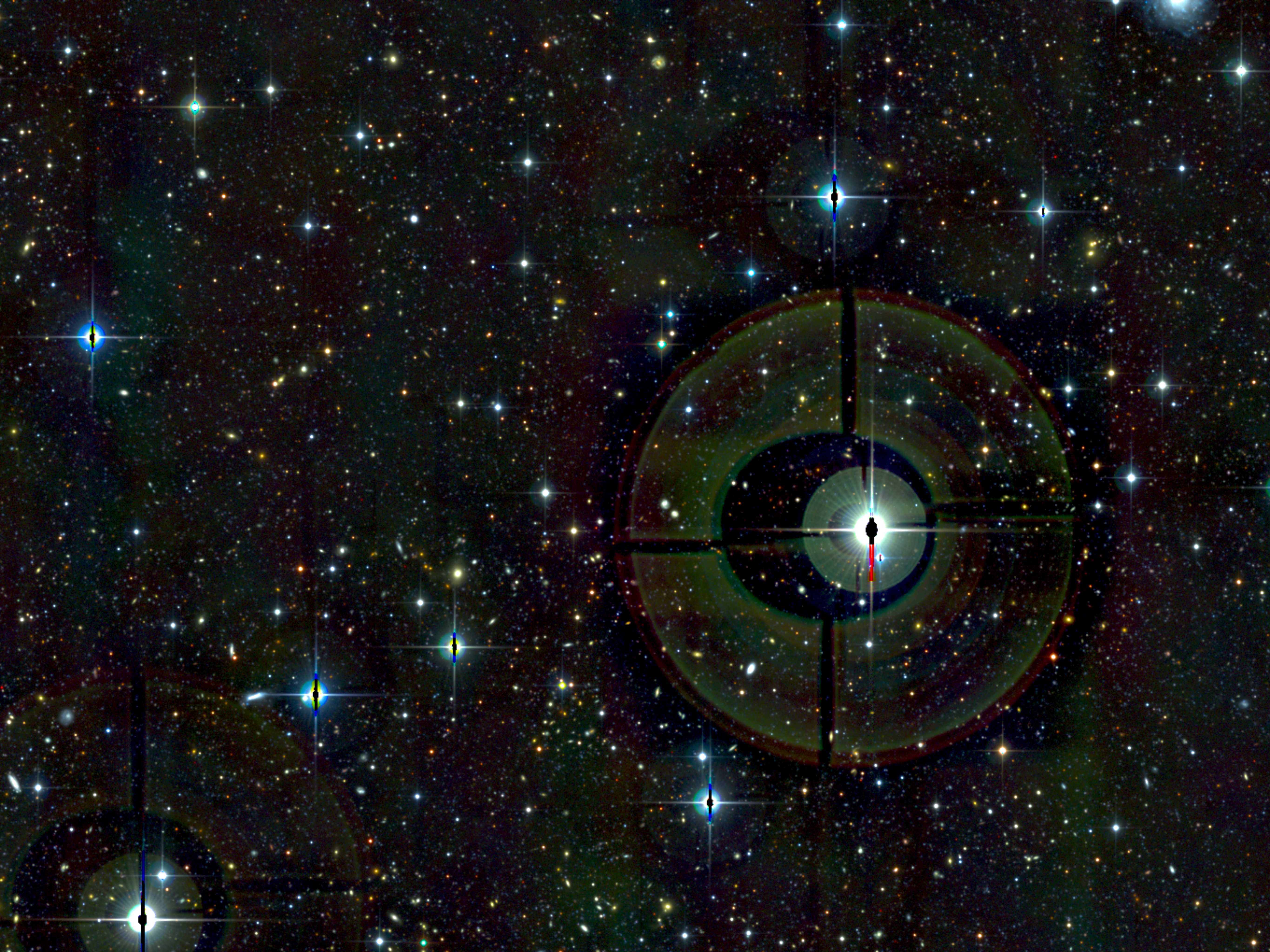
Canada-Frace-Hawaii Telescope
4 meter diameter mirror, takes pictures every 4 days

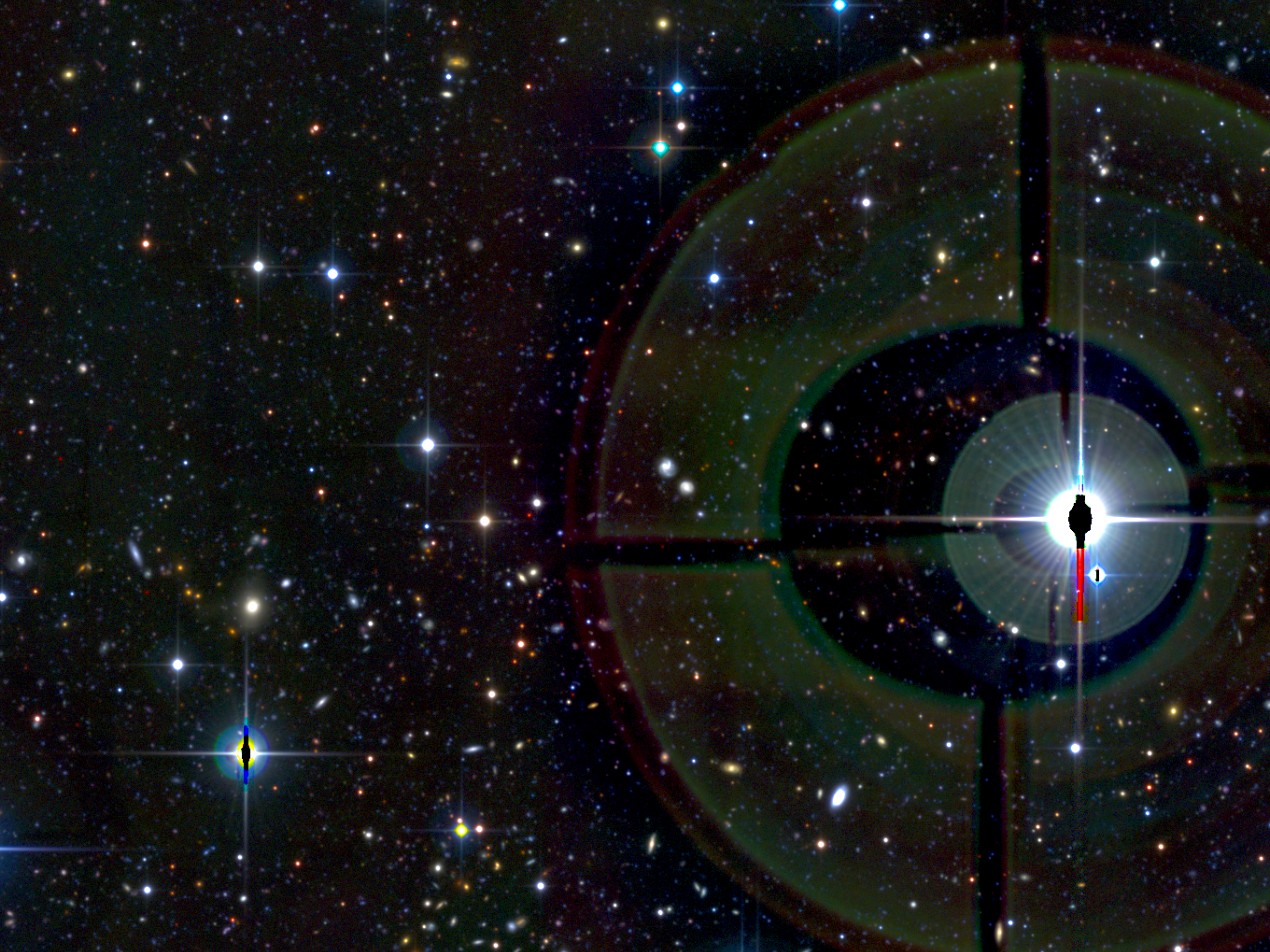


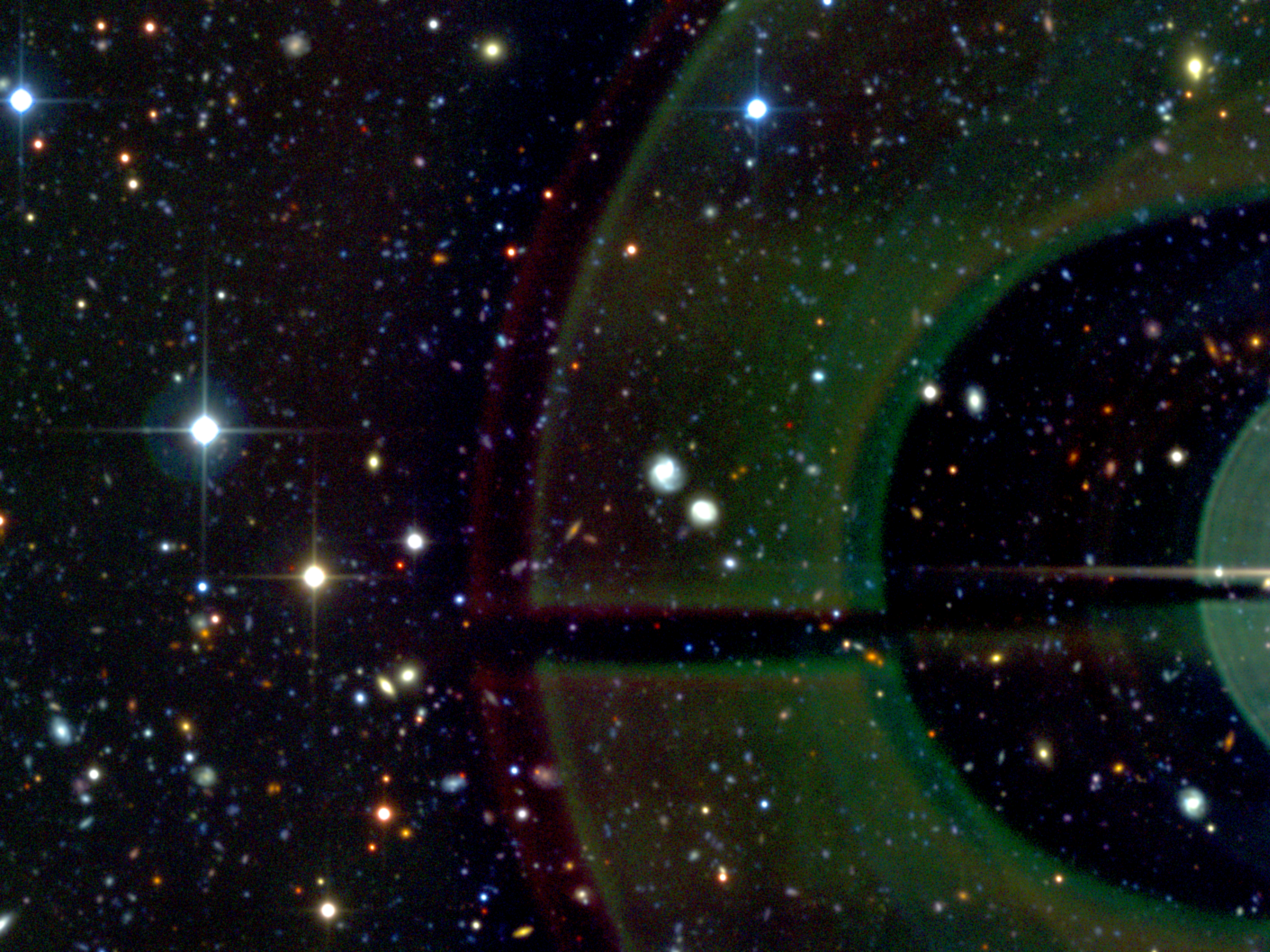
Megacam: When built, the world's largest digital camera: 340 megapixels

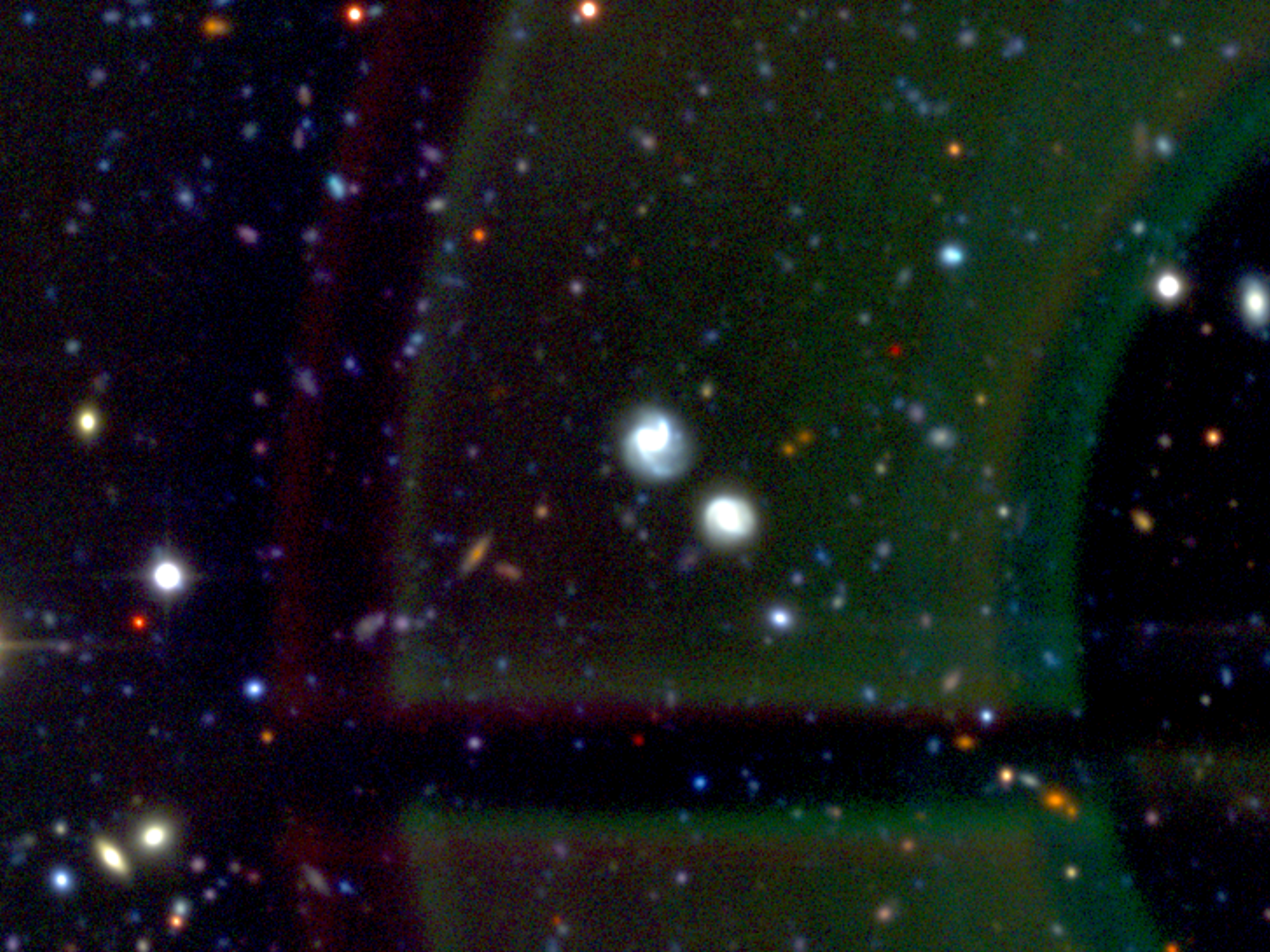


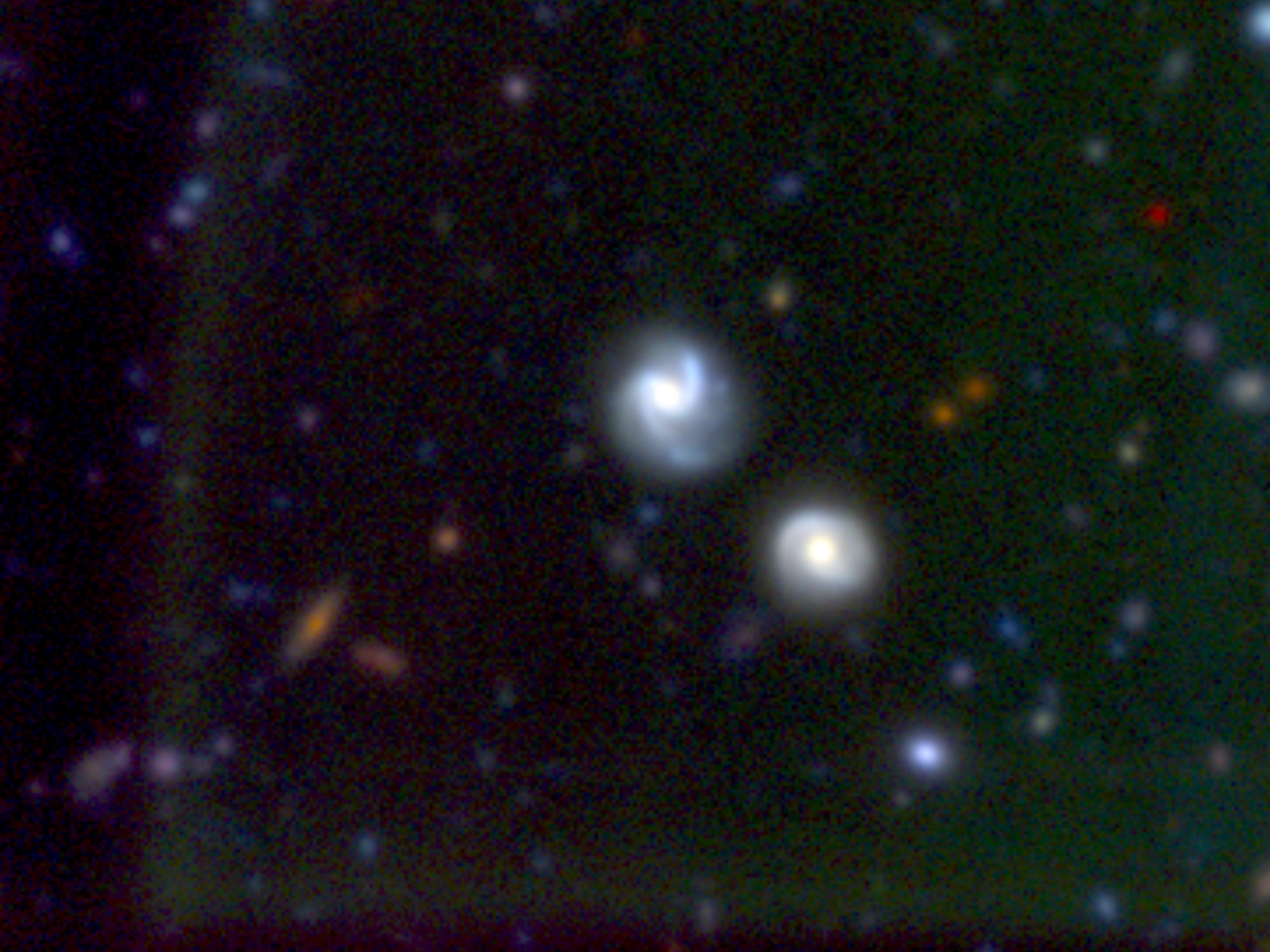




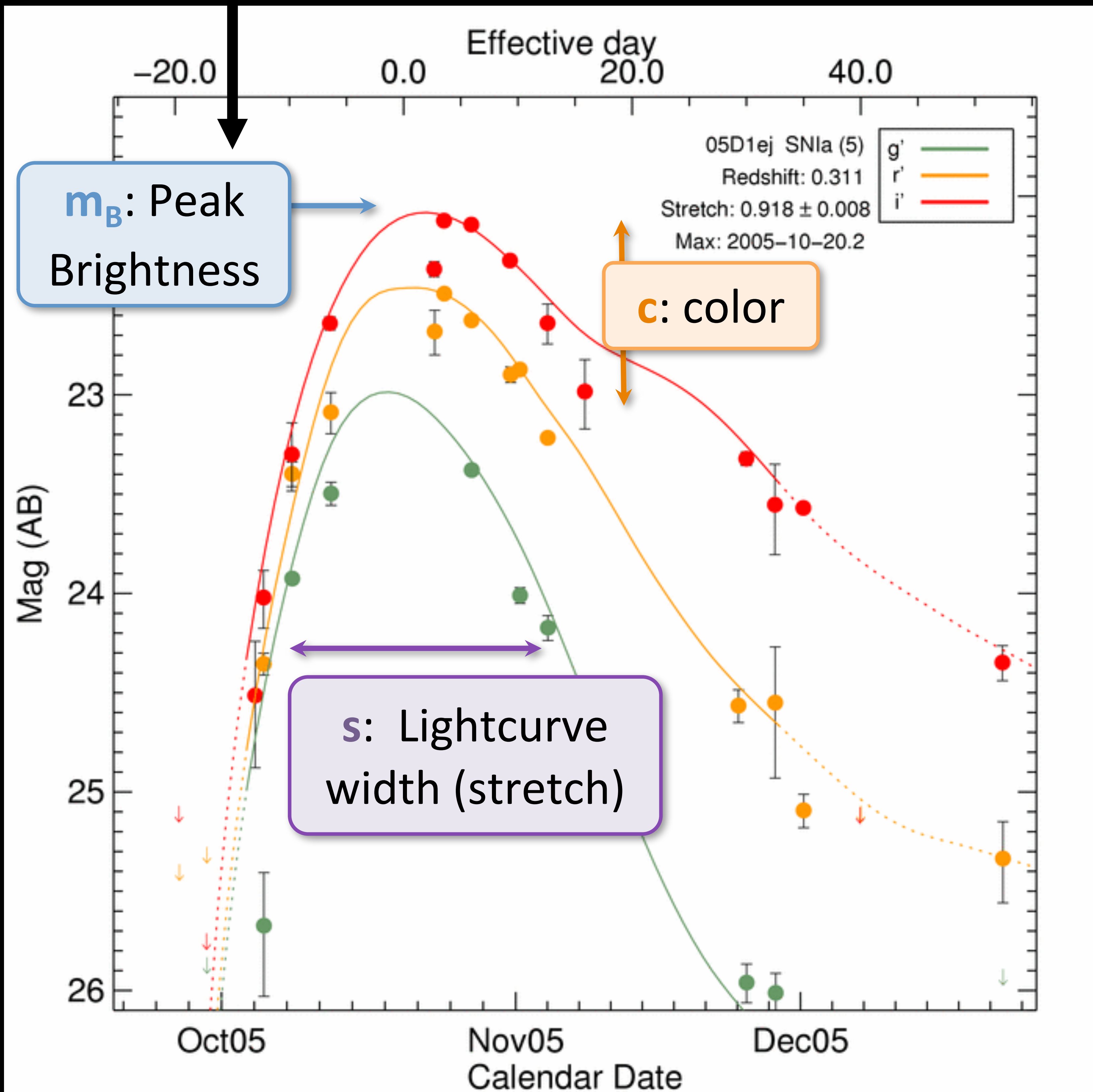








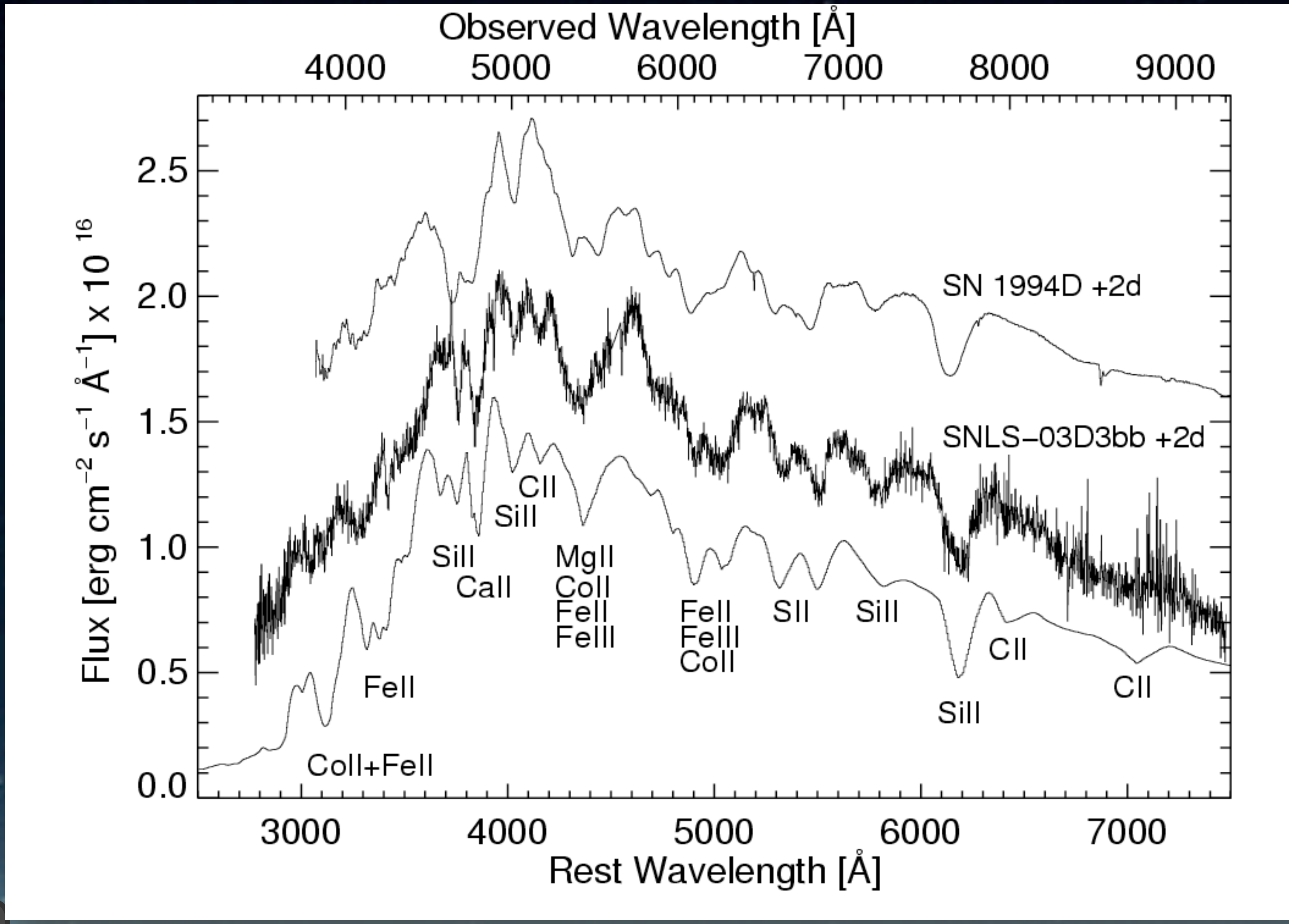
Typical SNLS SN Ia



What we need to measure

VLT

120h / yr: France, UK



Keck

8 nights per year
Caltech: Ellis
LBL: Perlmutter

Gemini

120 hr / yr: Canada, US, UK

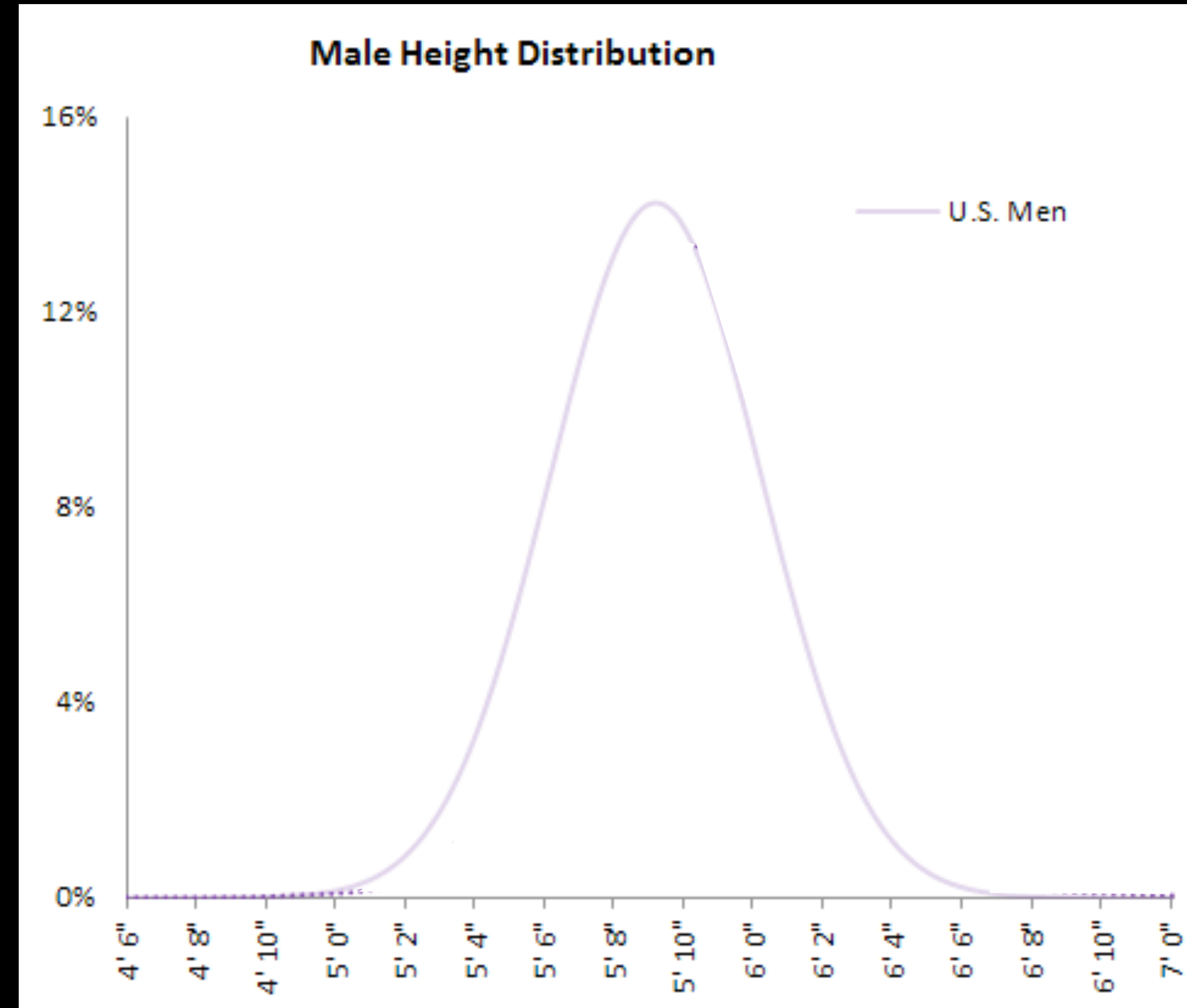
Spectra: Few % of time on world's Largest telescopes for 5 years

- SN Identification
- Redshifts

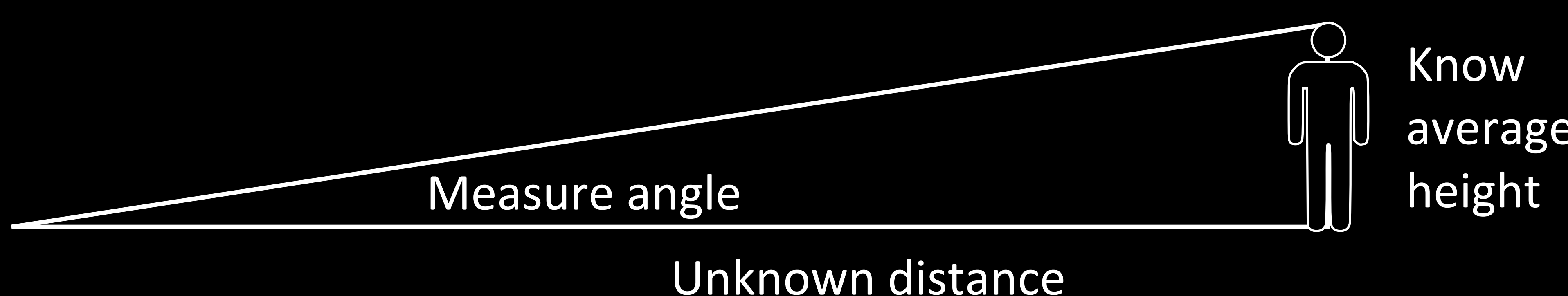
People’s heights are as good a standard ruler as SNe Ia are standard candles...

If someone is standing far away and you measure their apparent height and you know an average human's height, you can get a good estimate of how far away they are.

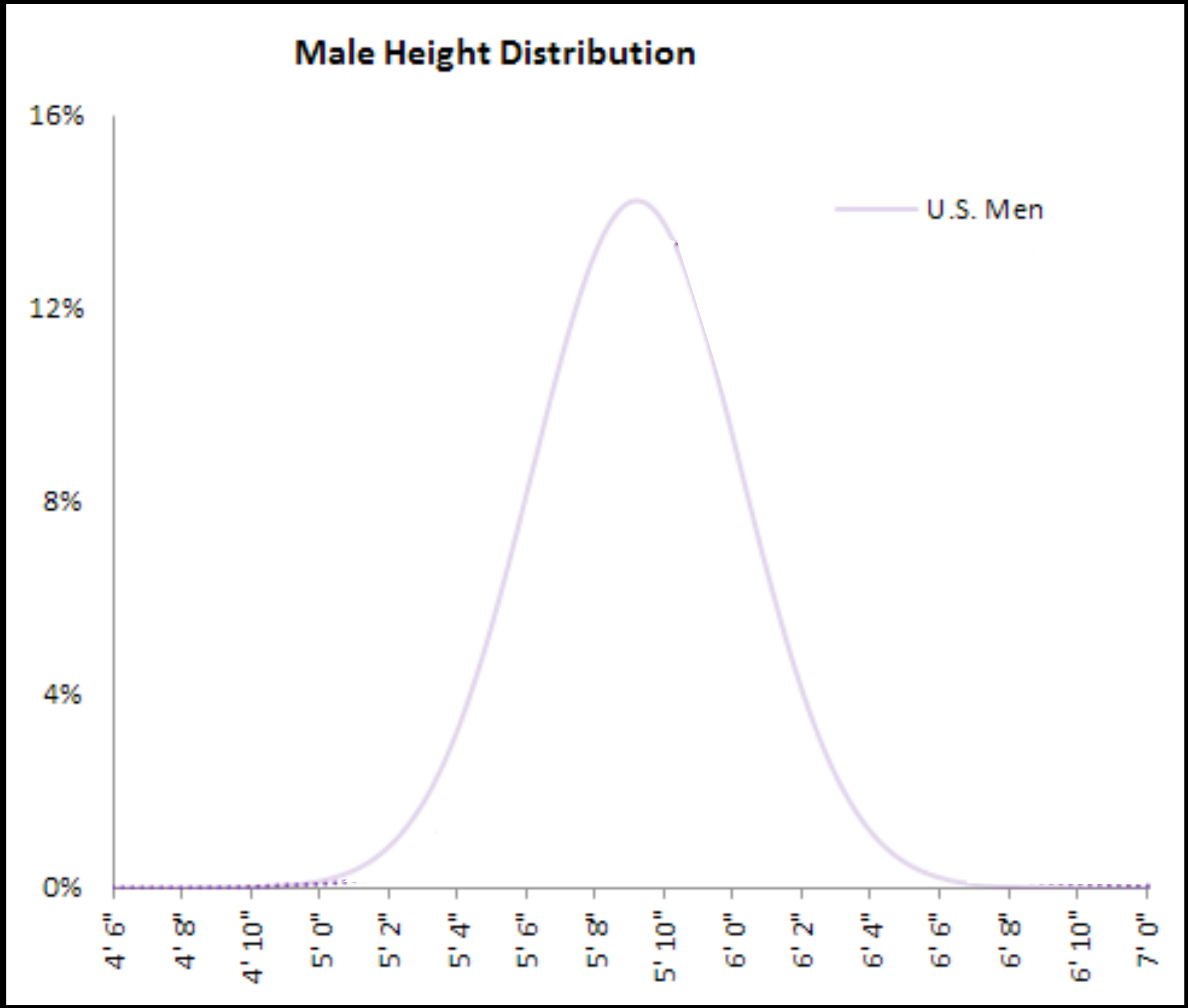
The better you know the average height, and the variables affecting it, the better you can determine the distance.



Average American male is 69" ± 3" tall (5'9"). So guessing the average is good to ~4%. (SN distances after corrections are good to ~4%.)



But that assumes you know they are an adult, male, and American. Even if they aren't, you can correct for that.



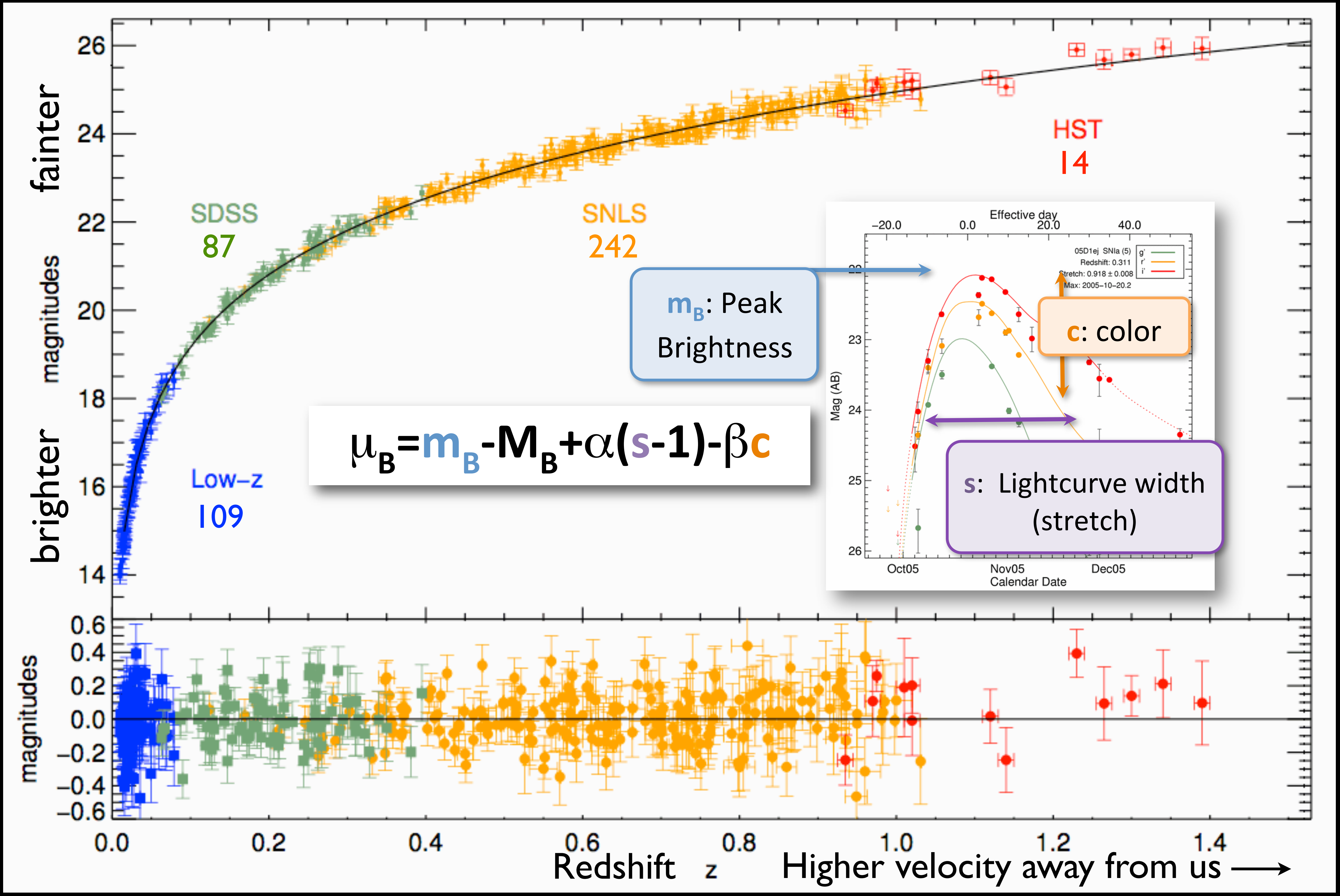
Lightcurve width is like age... people get taller as they age (up to a point), SN lightcurves get wider as they get brighter

Color is like nationality (kind of)... different groups have different height (luminosity) distributions:

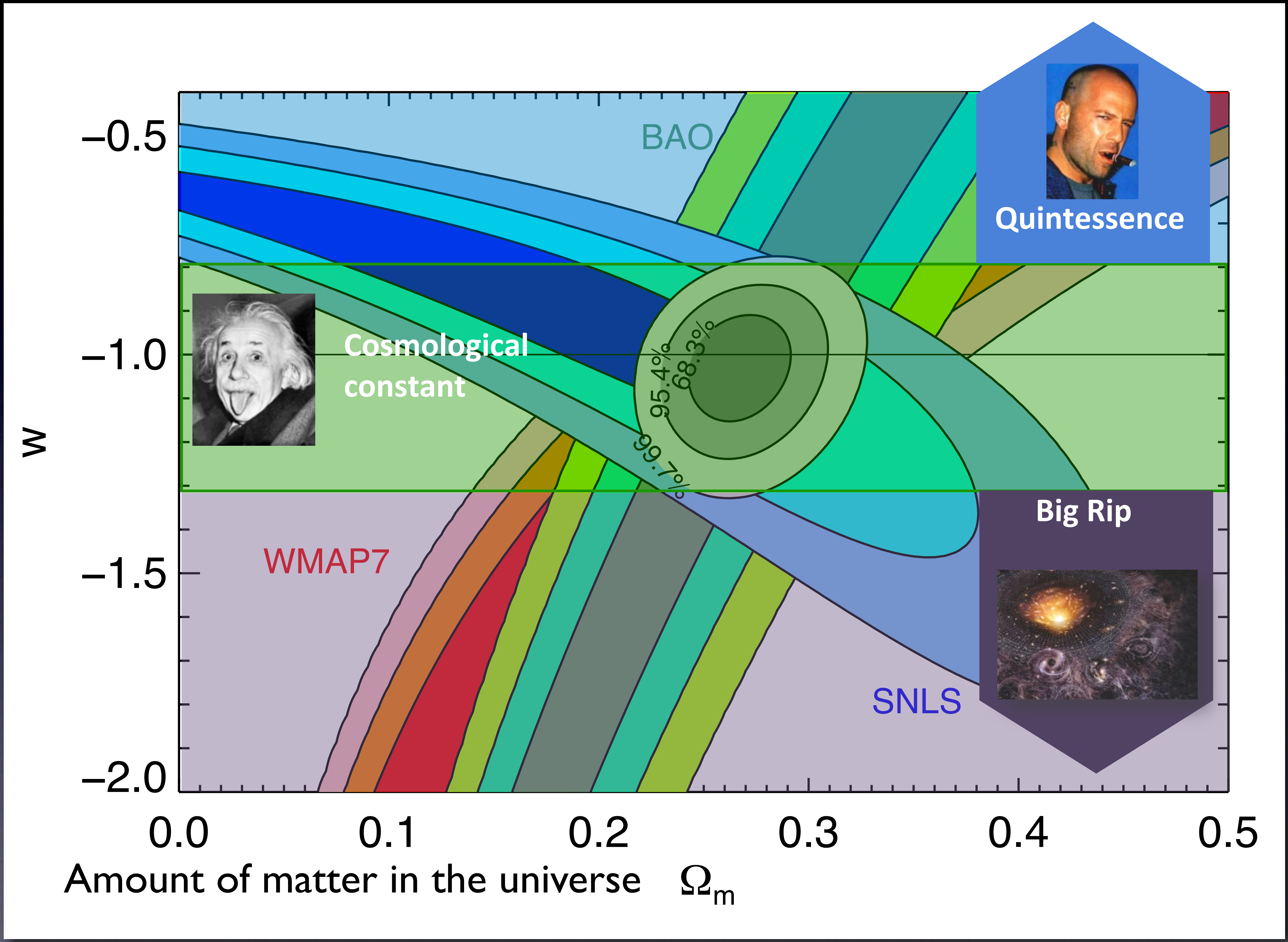
Average Indonesian: 5'4"

Average Swede: 6'

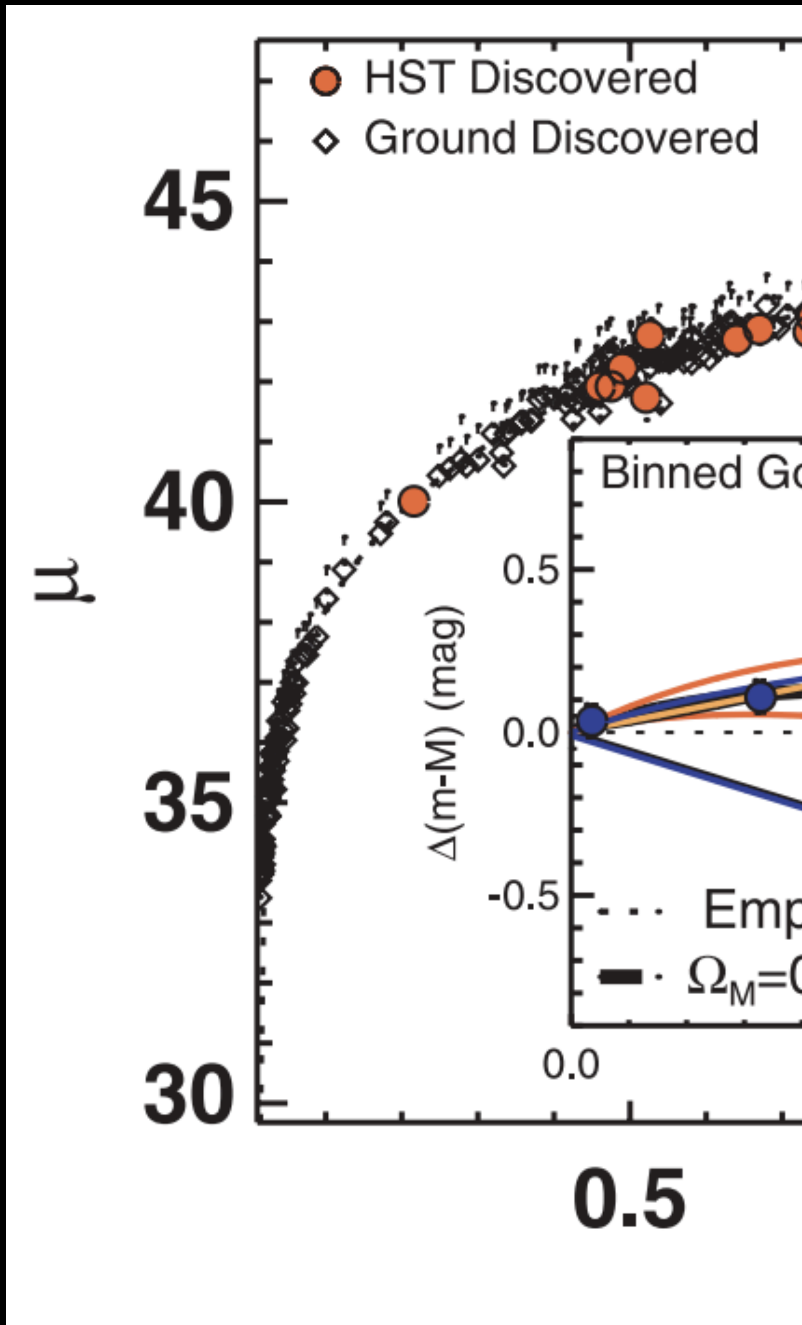
Now skipping 100,000 hours of work...



The SNLS map of the history of the expansion of the universe!



BAO
WMAP7
SNLS
Quintessence
Cosmological constant
Big Rip
95.4%
68.3%
99.7%
−0.5
−1.0
−1.5
−2.0
w
0.0
0.1
0.2
0.3
0.4
0.5
Amount of matter in the universe Ω_m



THE NEW YORK TIMES NAT

A 'Cosmic Jerk' That Reversed the Universe

By DENNIS OVERBYE

CLEVELAND, Oct. 10 — Astronomers said on Friday that they had determined the time in cosmic history when a mysterious force, "dark energy," began to wrench the universe apart.

Five billion years ago, said Dr. Adam Riess, an astronomer at the Space Telescope Science Institute in Baltimore, the universe experienced a "cosmic jerk." Before then, Dr. Riess said, the combined gravity of the galaxies and everything else in the cosmos was resisting the expansion, slowing it down. Since the jerk, though, the universe has been speeding up.

The results were based on observations by a multinational team of astronomers who used the Hubble Space Telescope to search exploding stars known as Type 1a supernovas, reaching back in time three-quarters of the way to the Big Bang, in which the universe was born. The results should help quell remaining doubts that the expansion of the universe is really accelerating, a strange-sounding notion that has become a pillar of a new and widely accepted model of the universe as being full of mysterious dark matter and even more mysterious dark energy.

Marty Katz for The New York Times

Dr. Adam Riess, who reported yesterday on the speeding and expanding universe, at the Space Telescope Science Institute in Baltimore.

The goal was to measure how much the universe was being slowed by the collective gravity of the cosmos and determine whether the universe would go on forever or recol-

collaborators found Hubble observations of a supernova 10 billion years in the past. It proved to be anomalously bright, lending credence to the

The universe only star
past 5 billion years or
close enough together that matter dominated.

We see this change in acceleration in the supernova data.
A change in acceleration is called a "jerk."

The Future

Dark Energy is already dominating the expansion of the universe.

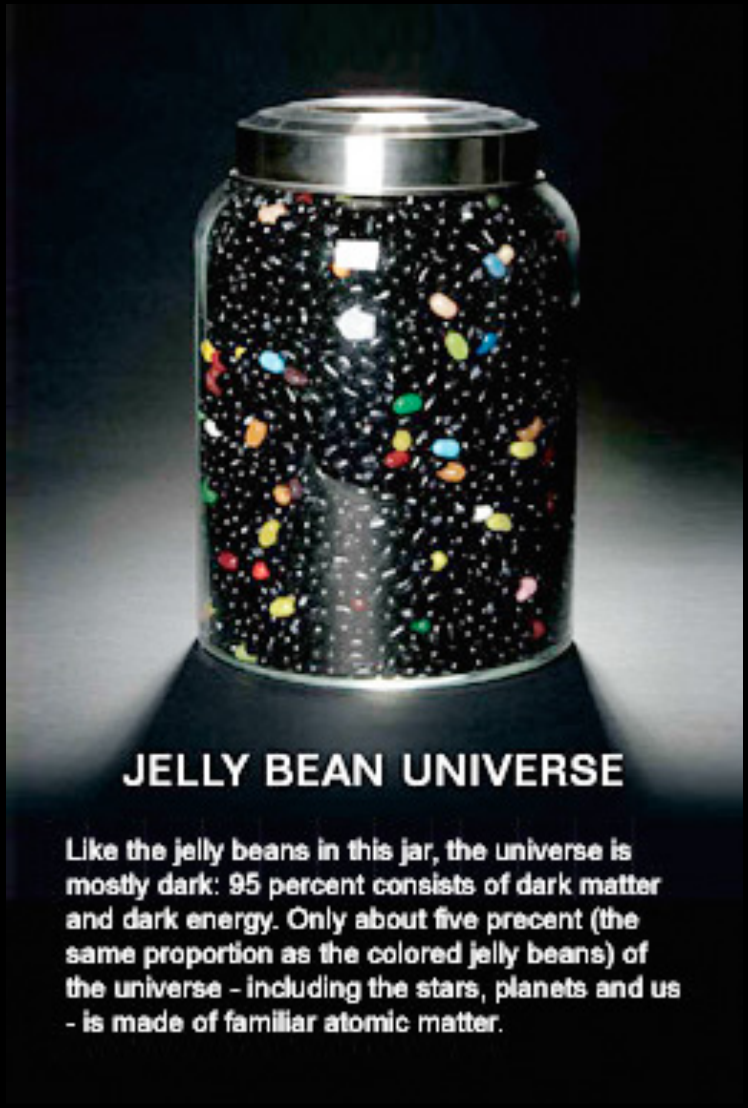
In the far future (say 100 billion years), almost all galaxies will have expanded past the cosmic horizon -- the limit we can see. The only ones we'll be able to see are the ones gravitationally bound to ours -- the ones in our local group of galaxies.

So far future astronomers won't be able to know the true nature of the universe.

Conclusions

After 70 years of mystery, we are finally making progress determining the kinds of stars that blow up as thermonuclear (Type Ia) supernovae.

We are the oddballs in the universe – we don't know what 95% of the universe is.



The universe is not just expanding, it is accelerating in its expansion. There seems to be some kind of antigravity force that works over long distances.

Spacetime seems to be filled with a strange energy whose density stays constant as the universe expands -- it will ultimately dominate the universe.

Extra slides

Extremes

The tallest and shortest man in the world.
These guys are 6σ+

Though most SNe Ia are "average" you can learn a lot from the outliers.

For core-collapse supernovae (i.e. collapse of a massive star), new surveys have found supernovae 100x brighter and 100x dimmer than previously thought possible (e.g. Lars Bildsten's colloquium).

What about SNe Ia?

Chandrasekhar Limit

Subrahmanyan Chandrasekhar

Theoretically a white dwarf should not exceed 1.4 solar masses – the Chandrasekhar limit.

Limit of electron degeneracy pressure (Pauli exclusion principle) – can't pack electrons any tighter.

SNe Ia explode as carbon ignites just before the limit – standard bombs

Broken?

Howell et al. 2006, Nature, 443, 308

BBC's Sky at Night, January 2007

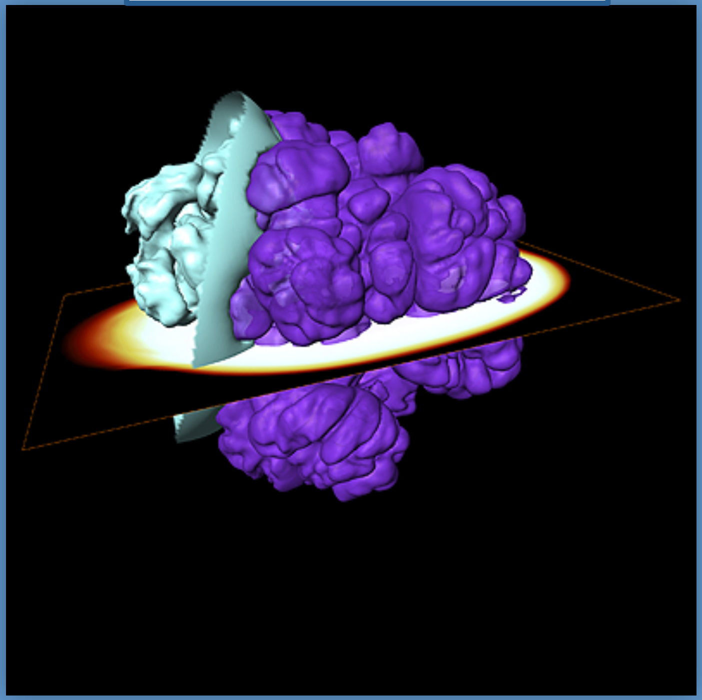
SN Ia power source

Radioactive decay

SNLS-03D3bb was >2x as bright as a normal SN Ia, so it had >2x as much nickel, about 1.3 times the mass of the sun.

When you add in other elements, the white dwarf that exploded had to be about twice the mass of the sun, well above the Chandrasekhar limit.

Explosion



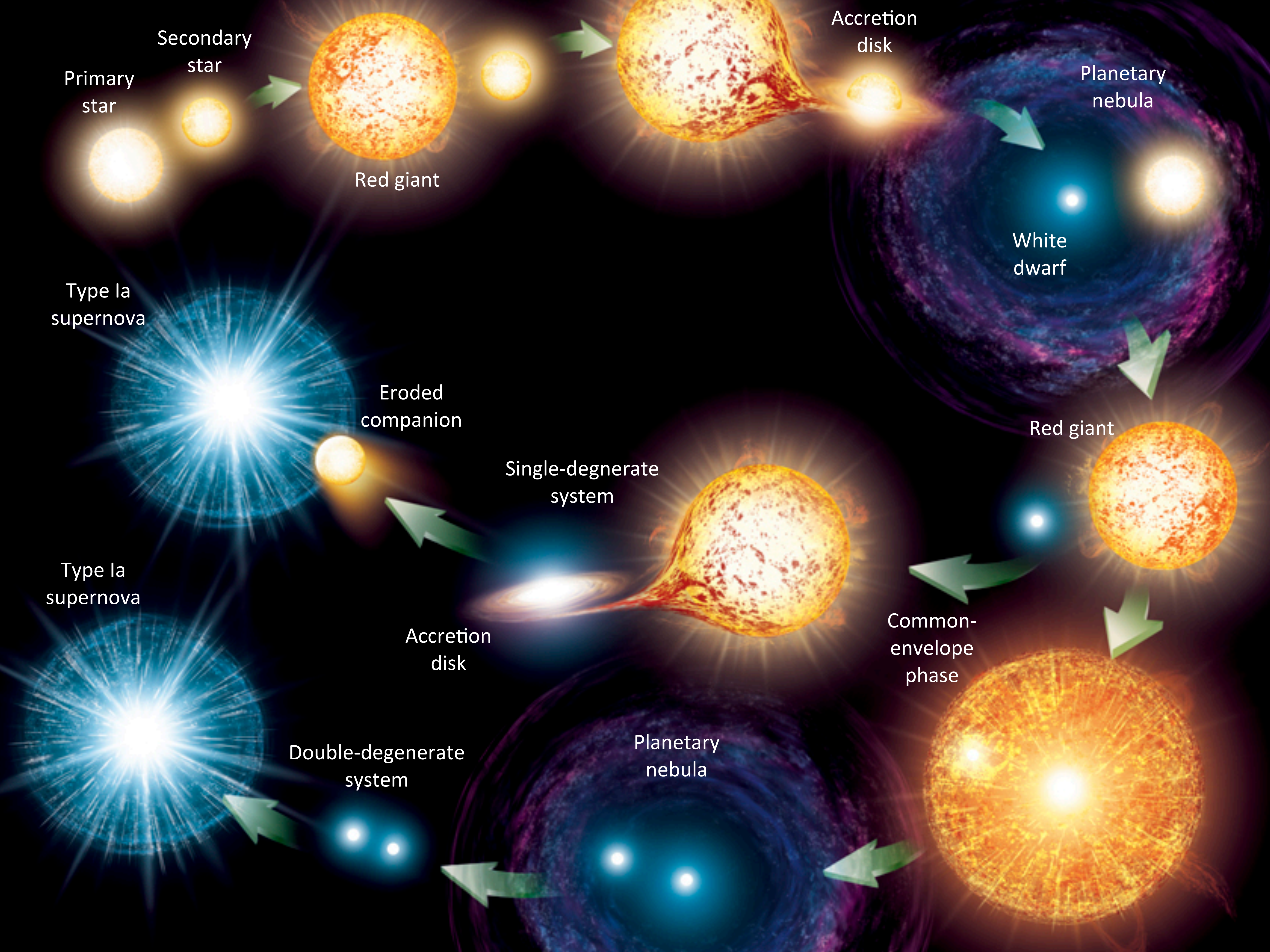
With all that nuclear energy, it should have been one of the fastest expanding explosions ever seen.

Instead, it was one of the slowest!

→ Extra binding energy from larger white dwarf star slowed it down.

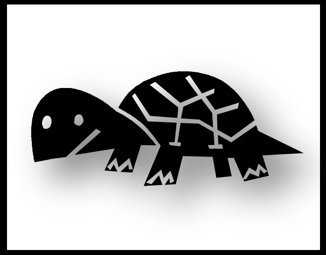
Possible Explanation

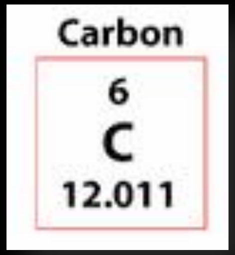
Merger of two white dwarf stars.


Primary star
Secondary star
Red giant
Accretion disk
Planetary nebula
White dwarf
Red giant
Common-envelope phase
Single-degnerate system
Eroded companion
Accretion disk
Type Ia supernova
Type Ia supernova
Planetary nebula
Double-degenerate system

New evidence for super-Chandra

New class of Type Ia supernovae





	Super-Chandra	Low speed explosion	Carbon	Young pop.
SNLS-03D3bb	☑	☑	☑	☑
SN 2006gz	☑?	☒	☑	☑
SN 2007if	☑	☑	☑	☑
SN 2009dc	☑	☑	☑	☑?

SN 2007if: M_{Ni}= 1.6 $M_\odot$

SN 2009dc: M_{Ni}= 1.8 $M_\odot$

+2 more!

LCOGT.net

Current sites

Future sites

Possible future sites

All sites will have 2-3 1m telescopes and 3-4 0.4m telescopes.

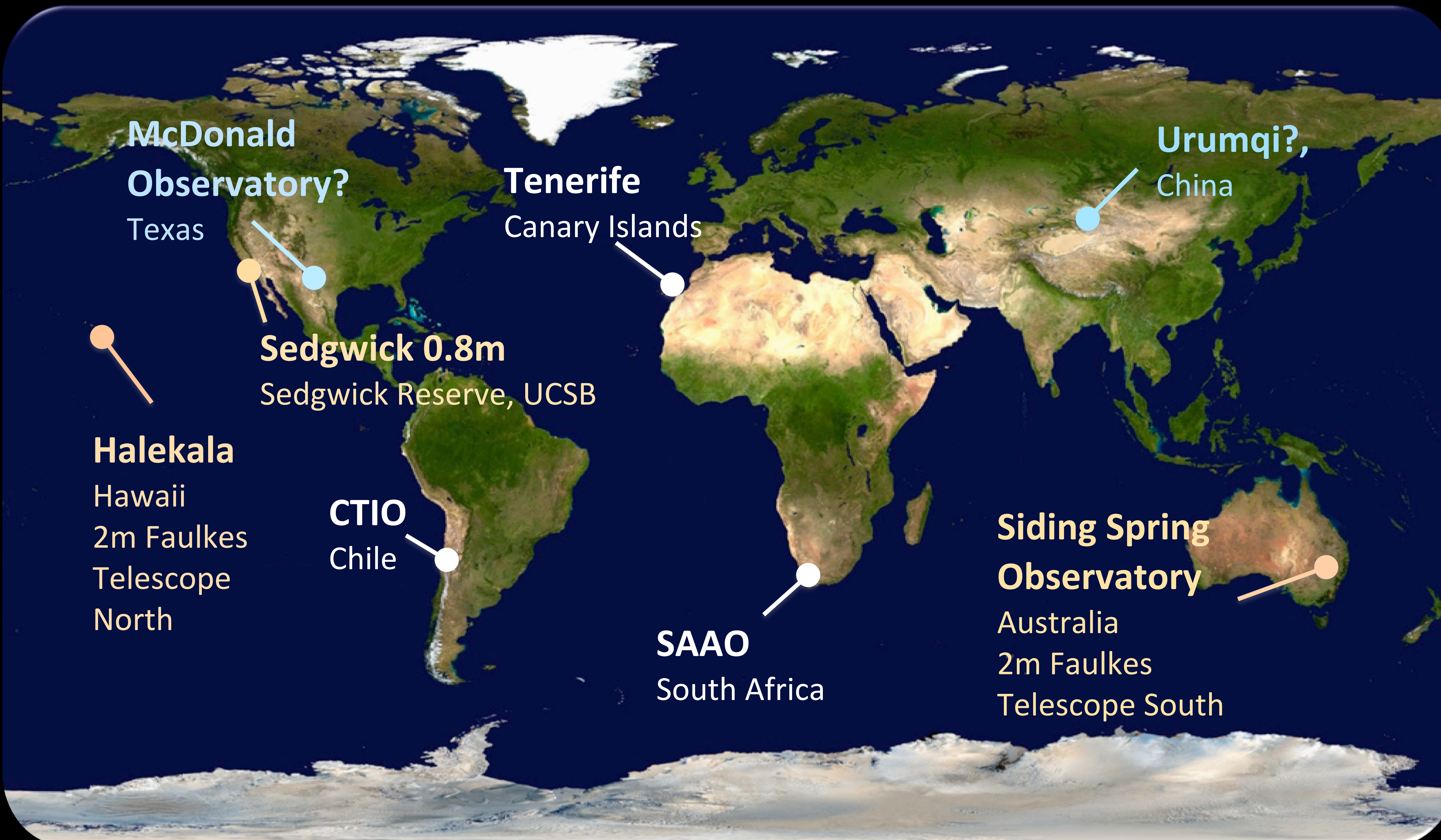
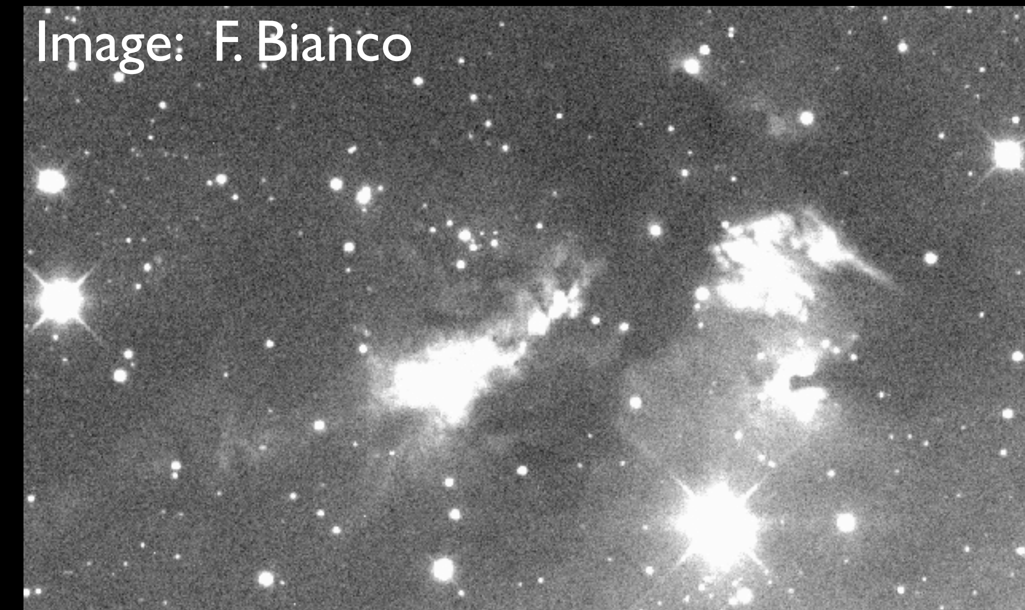
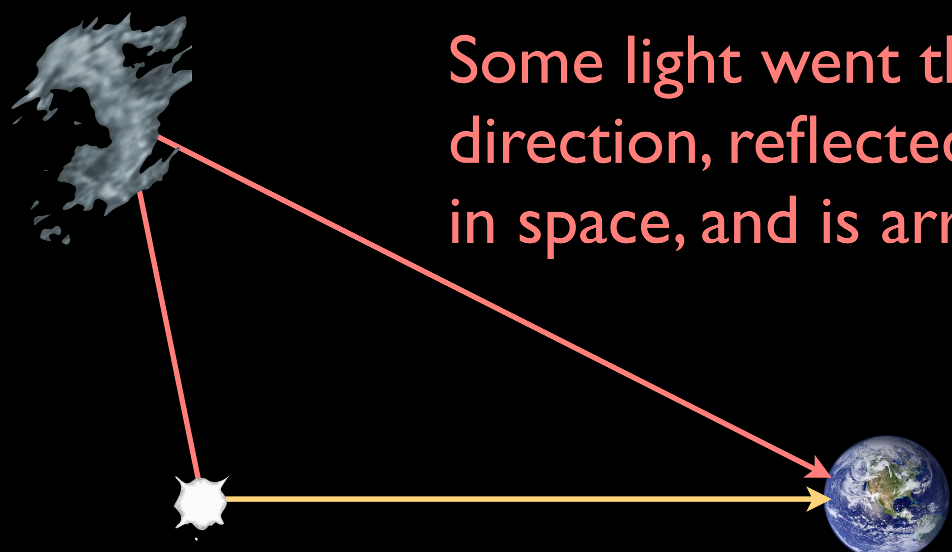



Image: Mark Elphick &
Rachel Ross

Aside: How do we know Tycho's SN (1572) was a SN Ia?

So we can re-watch the explosion 440 years later!

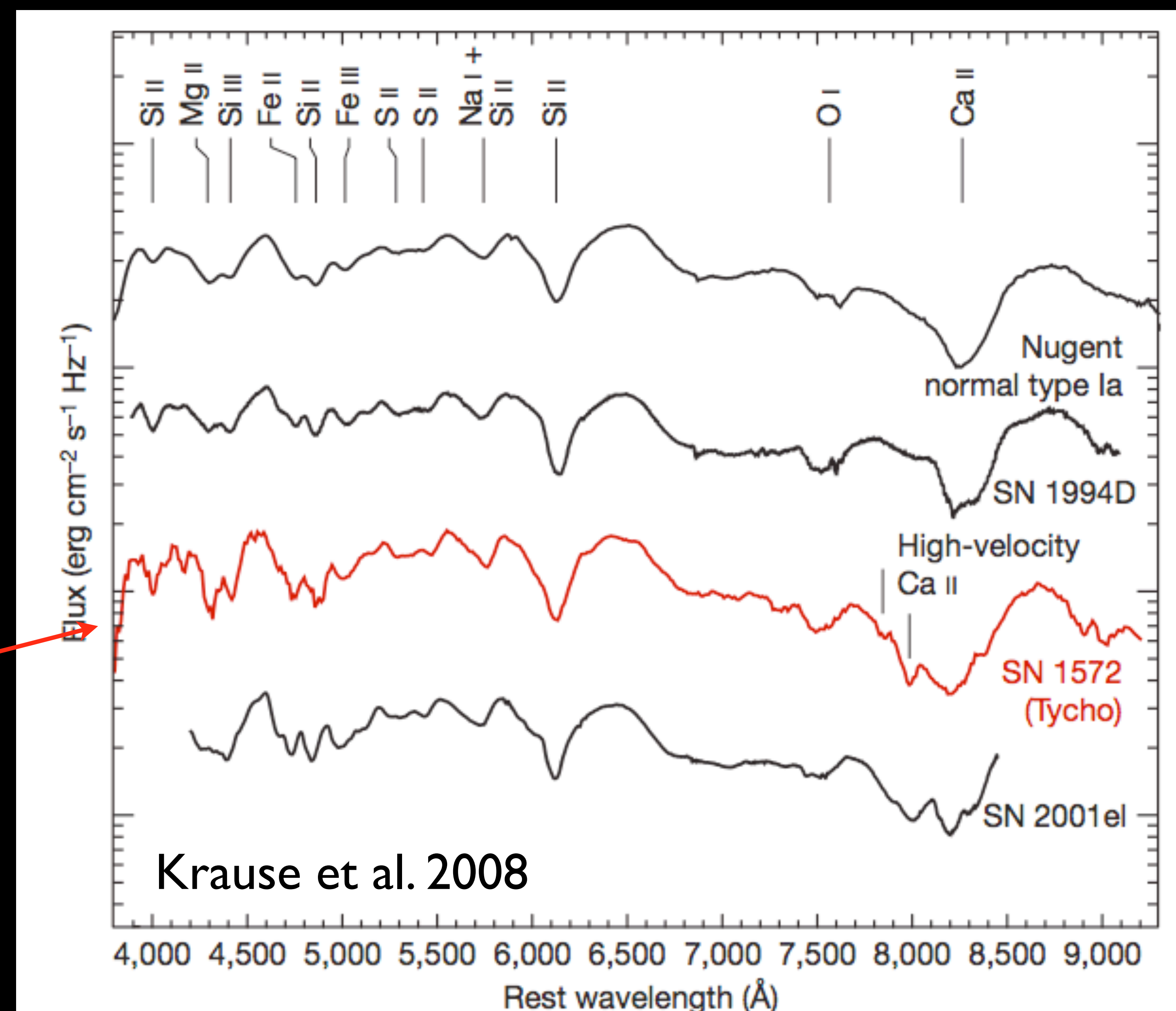




Some light went the other direction, reflected off a gas cloud in space, and is arriving now.

Some light from the supernova came straight to Earth, was seen by Tycho in 1572

Light from the peak of the explosion, seen by Tycho, delayed 436 years.



Dark Energy: effect on distances

Measuring w does require precision.

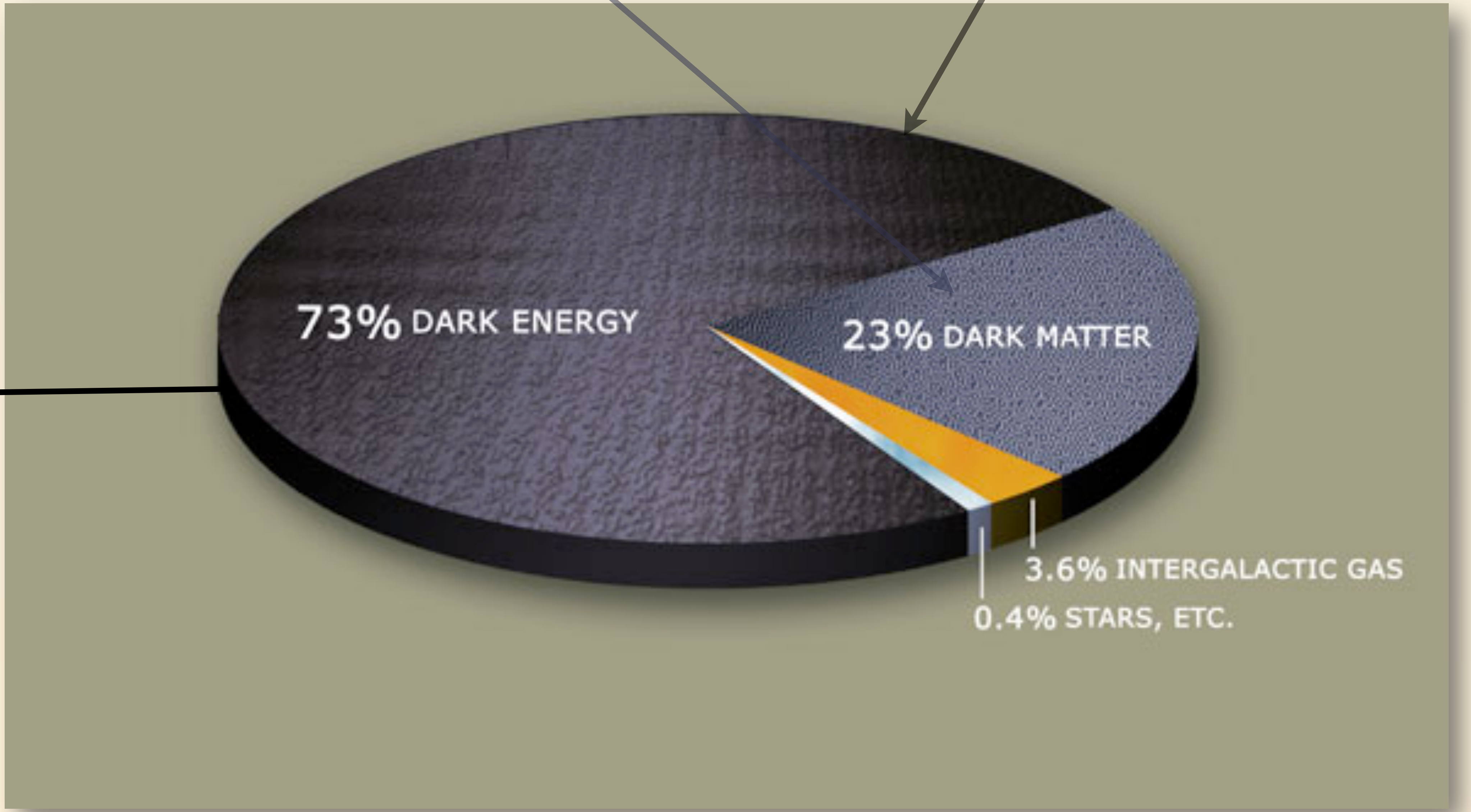
Friedmann equation can be written as

$$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_X a^{-3(1+w)}\right]$$

Matter   Radiation   Curvature   Dark Energy

a: scale factor   **w**: equation of state =P/ρ

The dark energy signal is so obvious, you can see it without any corrections to SNe to make them better standard candles.



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Matter Radiation Curvature Dark Energy

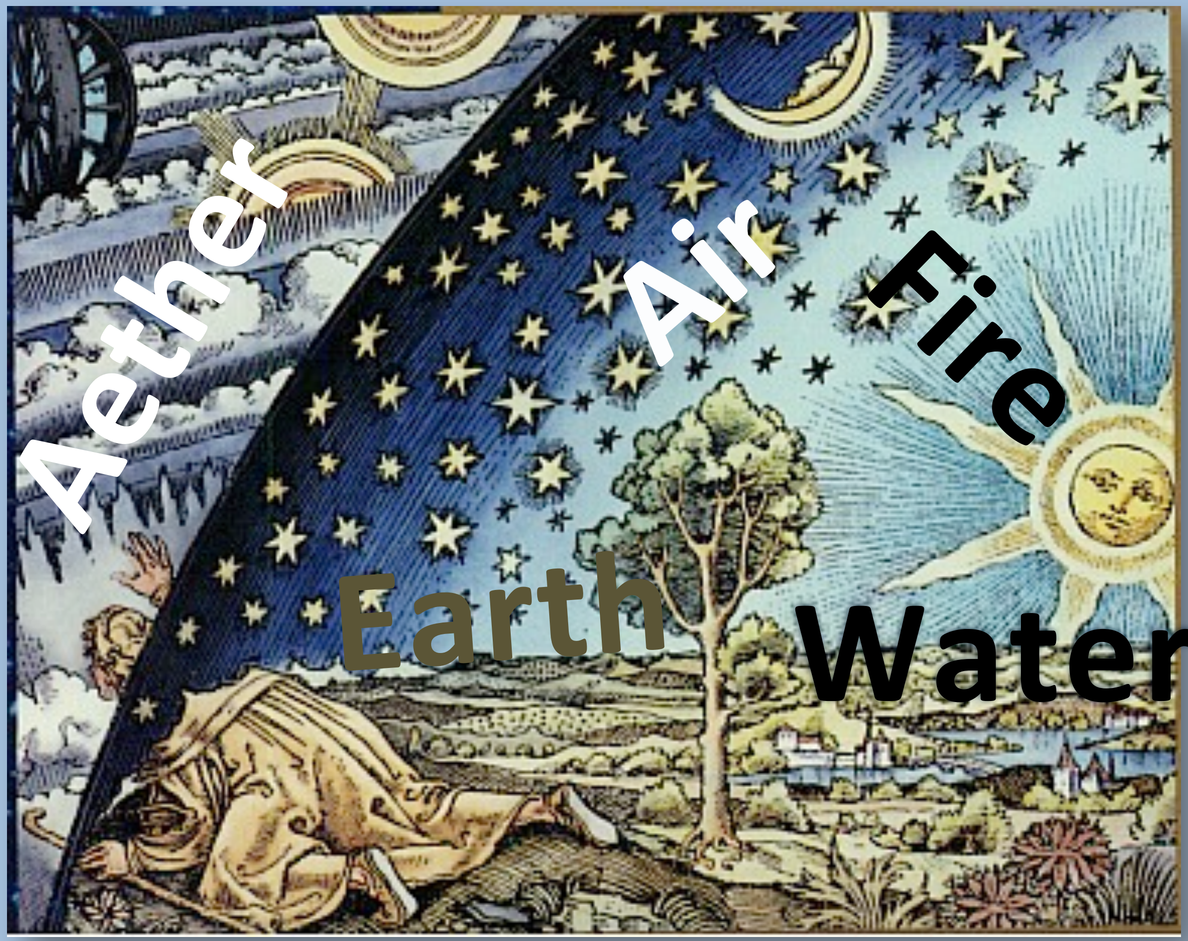
a: scale factor **w**: equation of state =P/ρ

w > -1

Quintessence: A scalar field that fills space. Can evolve with time.

Plato had 4 terrestrial elements: fire, earth, air, and water.

Aristotle added aether, the substance of the heavens. From *quinta essentia*, "fifth element"



Dr. Andrew Howell

Dr. Andrew Howell is a staff scientist at the Las Cumbres Observatory Global Telescope Network, Adjunct Professor in the Department of Physics at the University of California Santa Barbara, and was a host of the third season of the National Geographic Channel series "Known Universe." He is a member of the Palomar Transient Factory (PTF), the Supernova Legacy Survey, and Pan-STARRS1, three teams which have found and followed thousands of explosive and transient events in the universe, providing our best measurement of the mysterious dark energy. This followed his work with the Supernova Cosmology Project, whose leader, Saul Perlmutter, was awarded the 2011 Nobel Prize in physics, along with Brian Schmidt and Adam Riess, for the discovery of the acceleration of the universe. Dr. Howell recently published some of his research on Type Ia Supernovae as Stellar Endpoints and Cosmological Tools in Nature Communications, and the PTF team's recent discovery of the supernova in M101 was reported worldwide in the summer of 2011.