Initiative for the Theoretical Sciences, The CUNY Graduate Center

Adventures in the Theoretical Sciences
An informal, online summer school.

June 4 and 5
Few-body and many-body chaos
Vladimir Rosenhaus

June 11 and 12
Multi-parameter models and information geometry
Katherine Quinn

June 25 and 26
Big universe, big data: Emerging challenges in astrophysics
Viviana Acquaviva

June 18 and 19
Statistical physics and machine learning
David J. Schwab

July 2 and 3
Precision and emergence in the physics of life
William Bialek

July 9 and 10
Driven quantum systems
Vadim Oganesyan

Six lecturers will present four hours of lecture and discussion each, touching a wide range of topics. Our goal is to introduce students to the excitement of our fields, and to encourage thinking about theory as a unifying activity. We expect students to have solid backgrounds in statistical physics and quantum mechanics; more specialized topics will be introduced as needed. Our target audience overlaps advanced undergraduates and beginning graduate students in the US, and MSc students abroad.

Registration: itsatcuny.org/summerschool

Lectures from 11am-1pm (EDT)

Questions: info@itsatcuny.org

BIG UNIVERSE, BIG DATA: EMERGING CHALLENGES IN ASTROPHYSICS

Viviana Acquaviva

CUNY / Universitat de Barcelona

vacquaviva@citytech.cuny.edu

2-DAYS PLAN

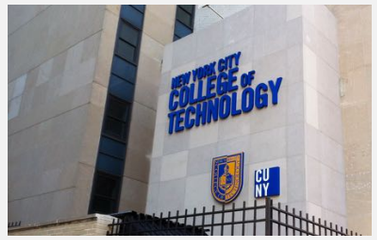
- Today: Cosmology mini primer + Data Science in Astro
- Tomorrow: How to measure the physical properties of galaxies with Bayesian inference and Machine Learning
- Slides/links and videos will be posted

ABOUT THE SESSIONS

- Feel free to use video or not
- For questions: please use the "Chat" (not private chat, not raise your hand) option
- I'll review and answer them, in real time if I can, and if not the allocated slots. I apologize in advance if I miss some/can't answer all.
- To encourage participation I'll try to answer questions from different people before multiple questions from the same person.
- Approx. schedule:
  - Me talking 11.05 -11.50
  - Break 11.50-12
  - Q/A 12-12.10
  - Me talking 12.10-12.45
  - Q/A 12.45-1 (tomorrow a longer one and open to general career/work-life questions)

A FEW WORDS ABOUT ME

Associate Prof @ City Tech



From Lecce, Italy ☺

An improbable Astrophysicist

Constantly on the verge of quitting my job

Also, a mom

AND ABOUT THE STUFF I WORK/WORKED ON

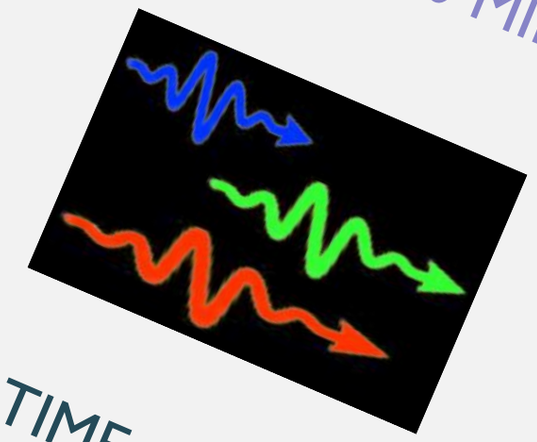
- The super early Universe (inflation) — Master's
- Weak lensing and Cosmic Acceleration — PhD
- Modified theories of gravity and their phenomenology — Postdoc I
- Cosmic Microwave Background (early Universe, but not as early as inflation) — Postdoc I
- Galaxy physical properties — Postdoc II, Faculty
- Machine Learning/Data Science x Astronomy — Faculty
- Training modern physicists (academia + industry) — Faculty

LET'S HAVE A LITTLE ANONYMOUS POP QUIZ AND SEE IF THIS ZOOM POLLING REALLY WORKS!

A TINY COSMOLOGY PRIMER

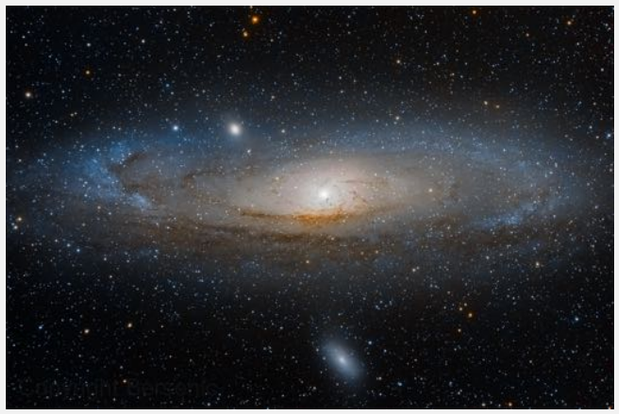
THE MOST AMAZING FACT EVER

DISTANCE = 150 MILLION KM

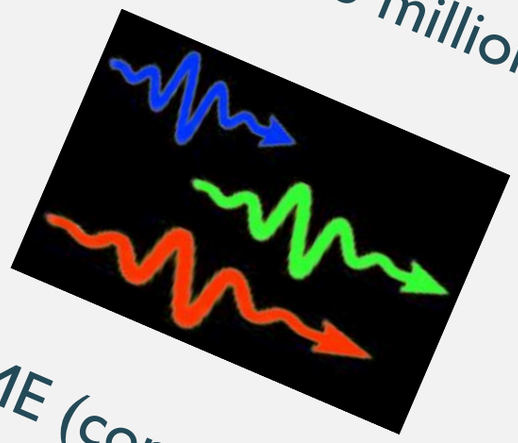


TIME = D/V =
150 MILLION KM/(300,000 KM/S) =
500 S ~ 8 MINUTES

THE MOST AMAZING FACT EVER



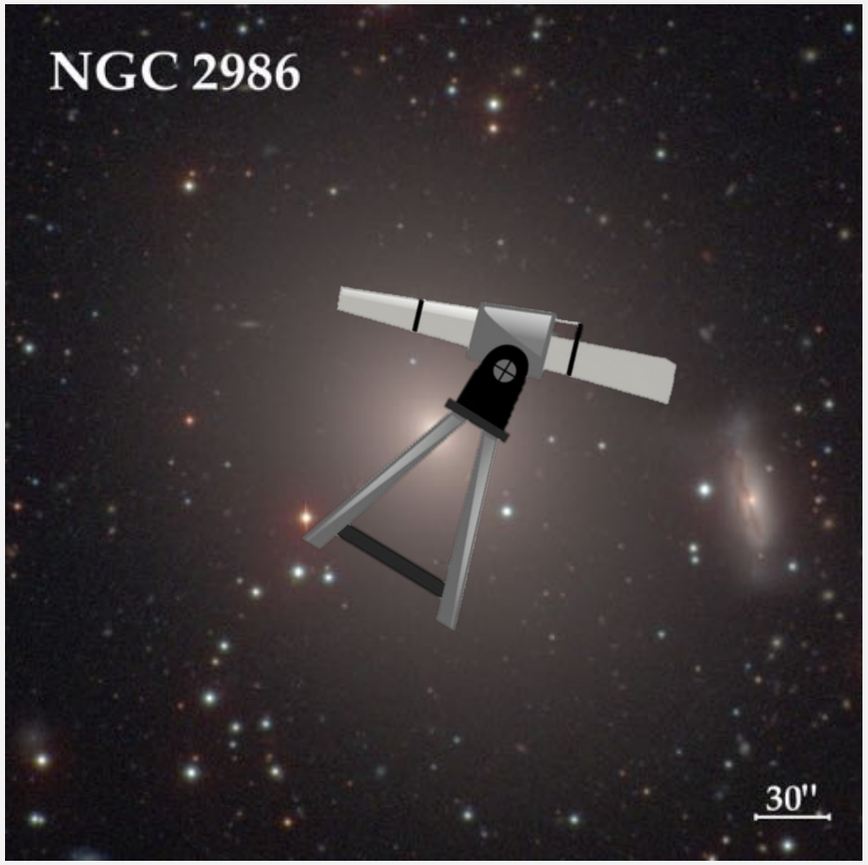
DISTANCE = 2.5 million light years



TIME (conveniently) = 2.5 million years

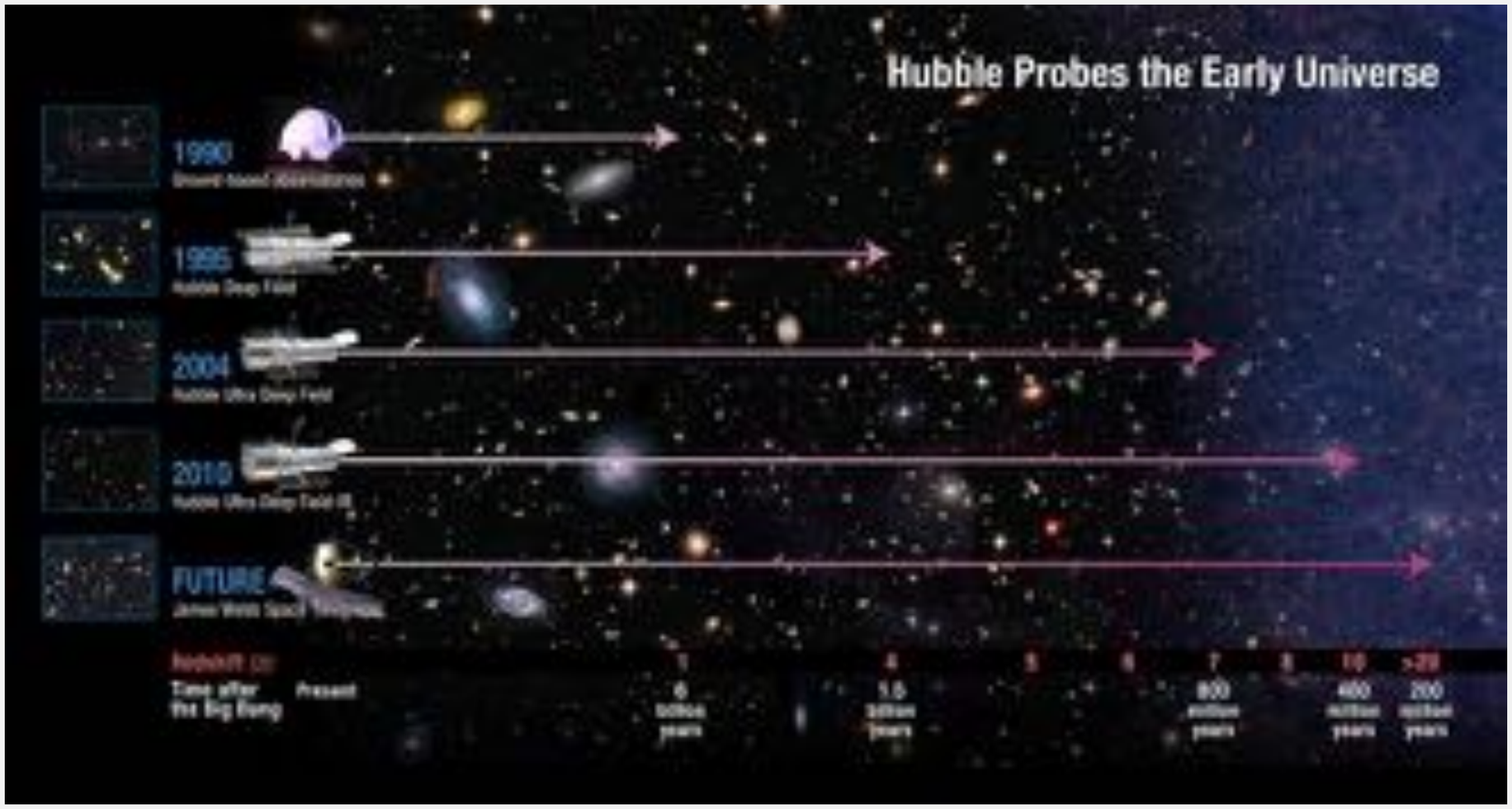
By looking far away we can look back in time

THE MOST AMAZING FACT EVER



A galaxy about
100 million light years away.

THE SKY IS THE LIMIT!

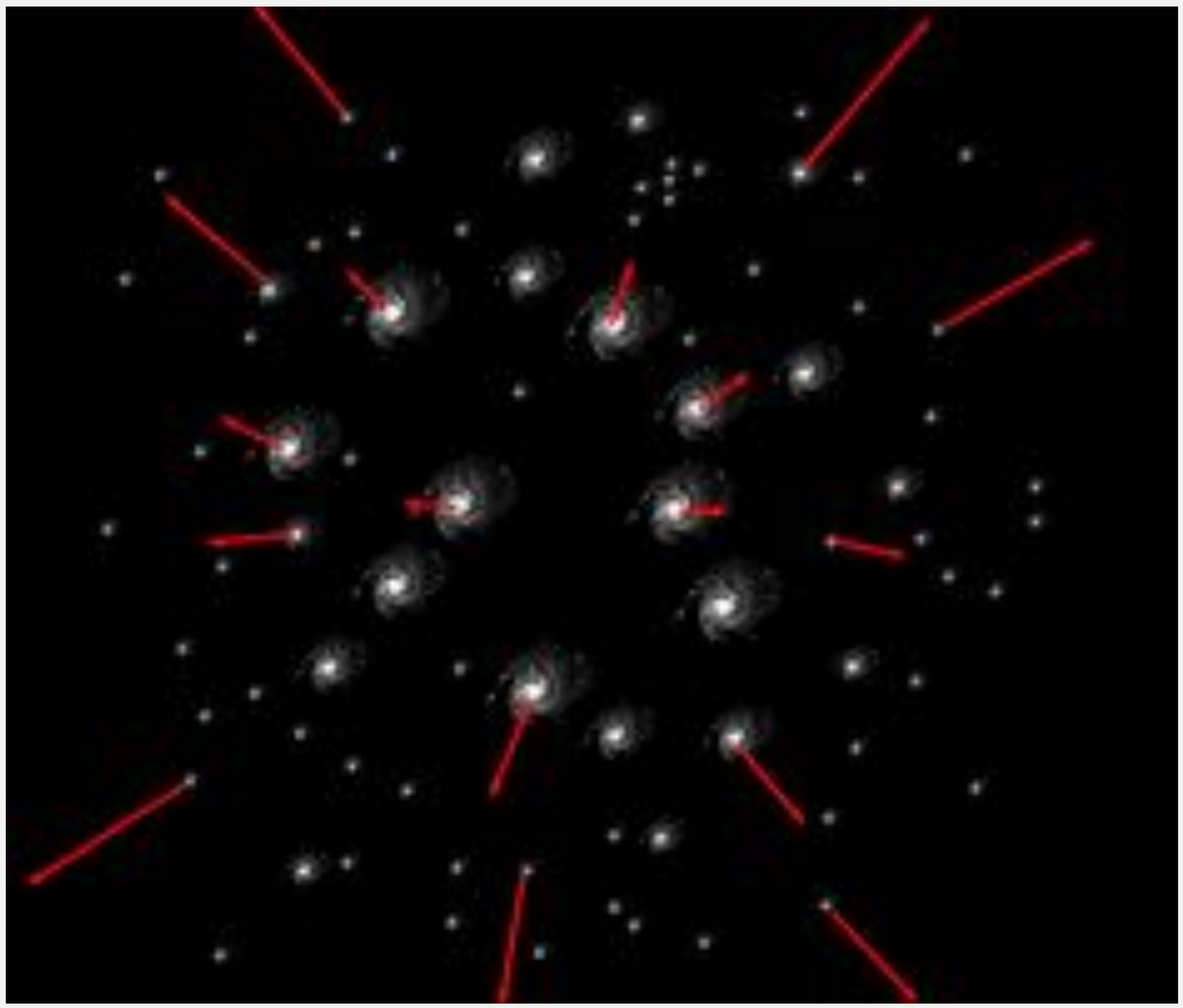


Better telescopes and longer exposures

give us the chance to OBSERVE the history of the Universe.

SO WHAT HAVE WE DISCOVERED?

All (faraway) galaxies are moving away from us.



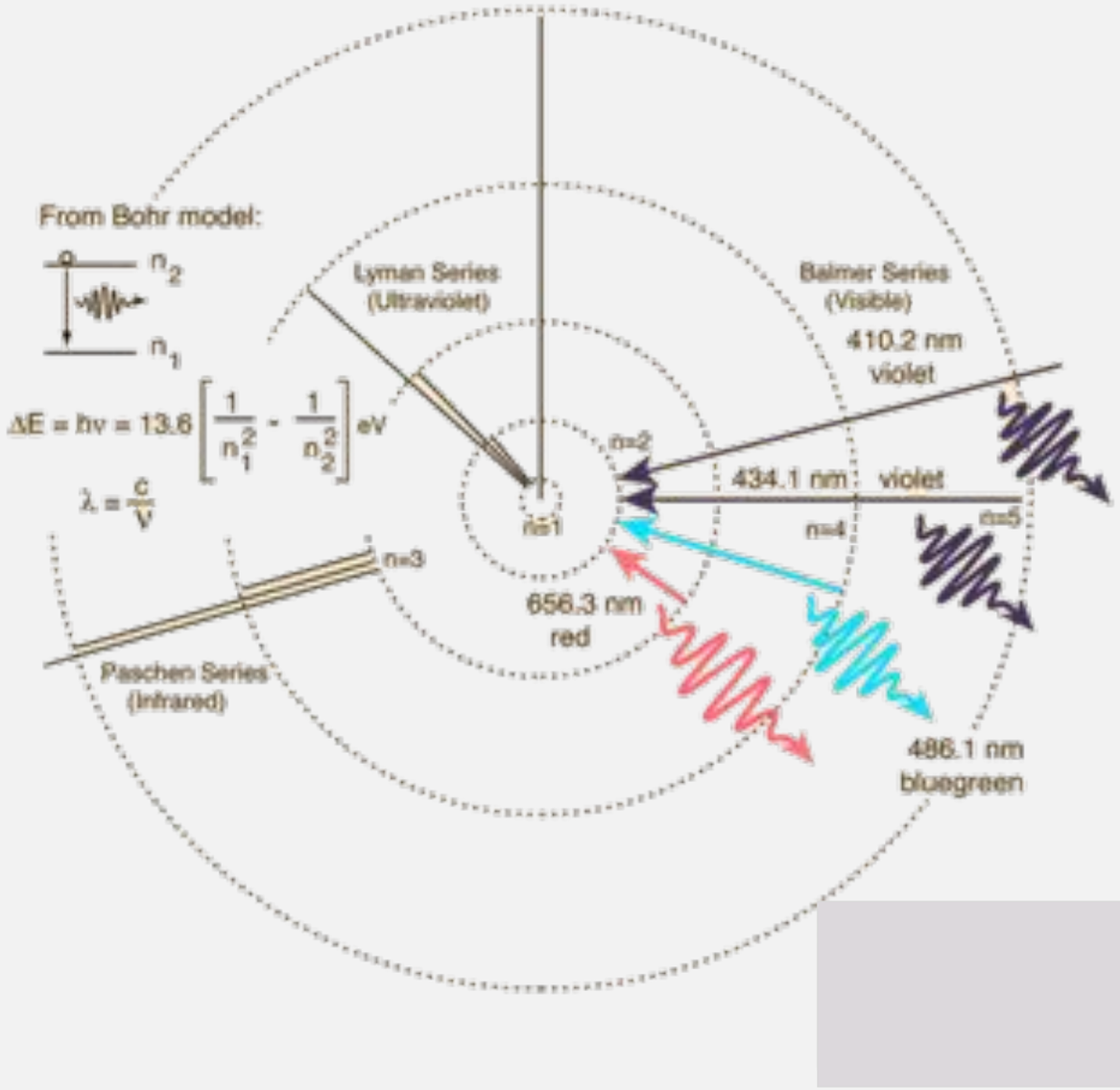
How do we know?

THE DOPPLER EFFECT

The same shift in frequency happens with light.
On Earth, it's not noticeable because $c >> c_s$
but in space, relative speeds are large even compared to c.

THIS IS CALLED COSMOLOGICAL REDSHIFT.

IN PRACTICE, WE OFTEN MEASURE EMISSION SPECTRA OF HYDROGEN (~90%!)



Measured in the lab

1) All emission lines are shifted towards the red.
2) The farther away objects are, the faster they are moving away from us.

SO PERHAPS 1. WE ARE SPECIAL AND 2. NOBODY LIKES US, SO ALL GALAXIES ARE RUNNING AWAY.

Aristarchus, proposed the idea of non-geocentricity

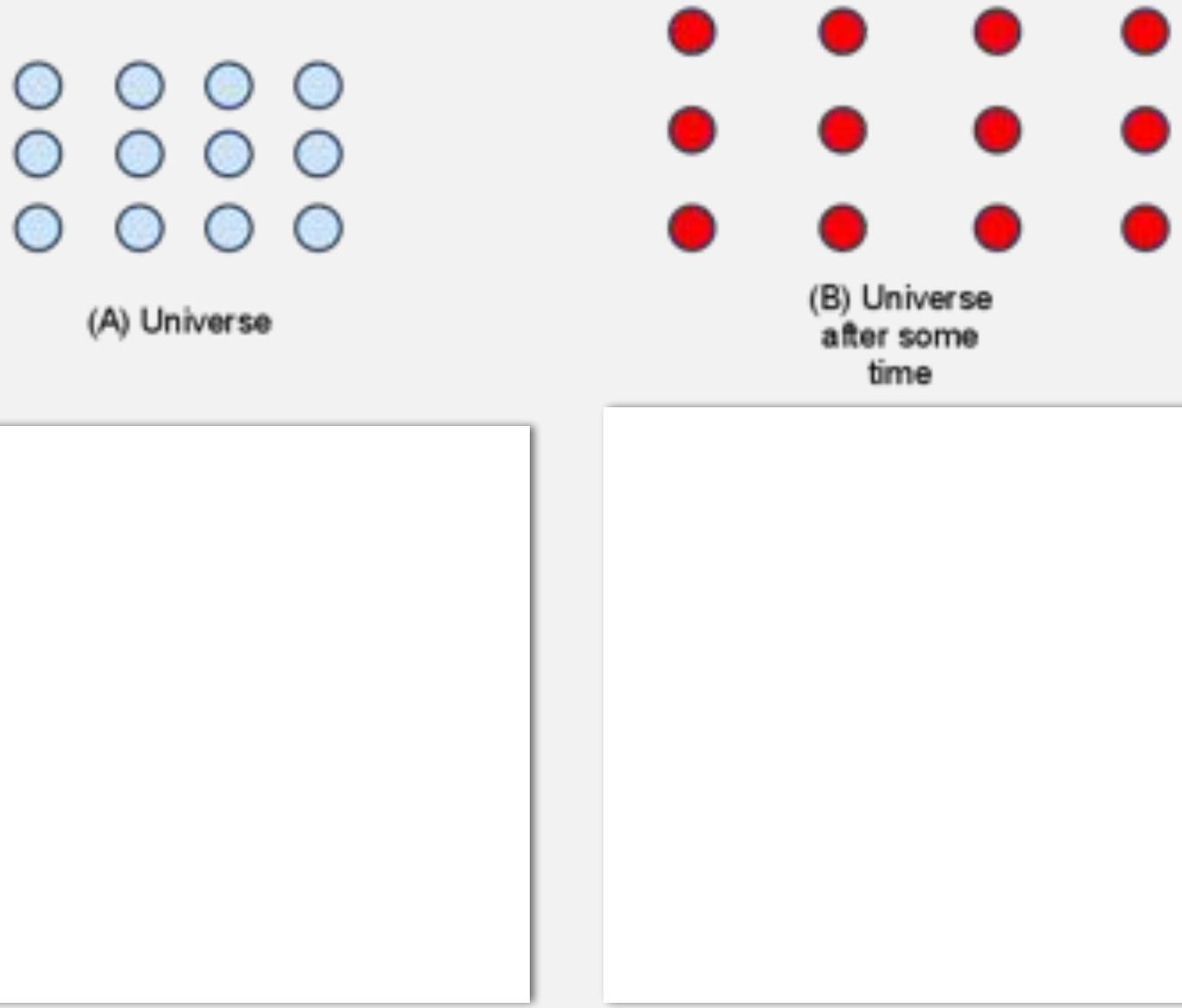
Copernicus, popularized the heliocentric model

Herschel, mapped the Milky Way Galaxy and found we are not at the center

Hubble, found other galaxies

But this is hard to reconcile with everything we have learned along the way.

THE ALTERNATIVE IS THAT SPACE ITSELF IS EXPANDING.

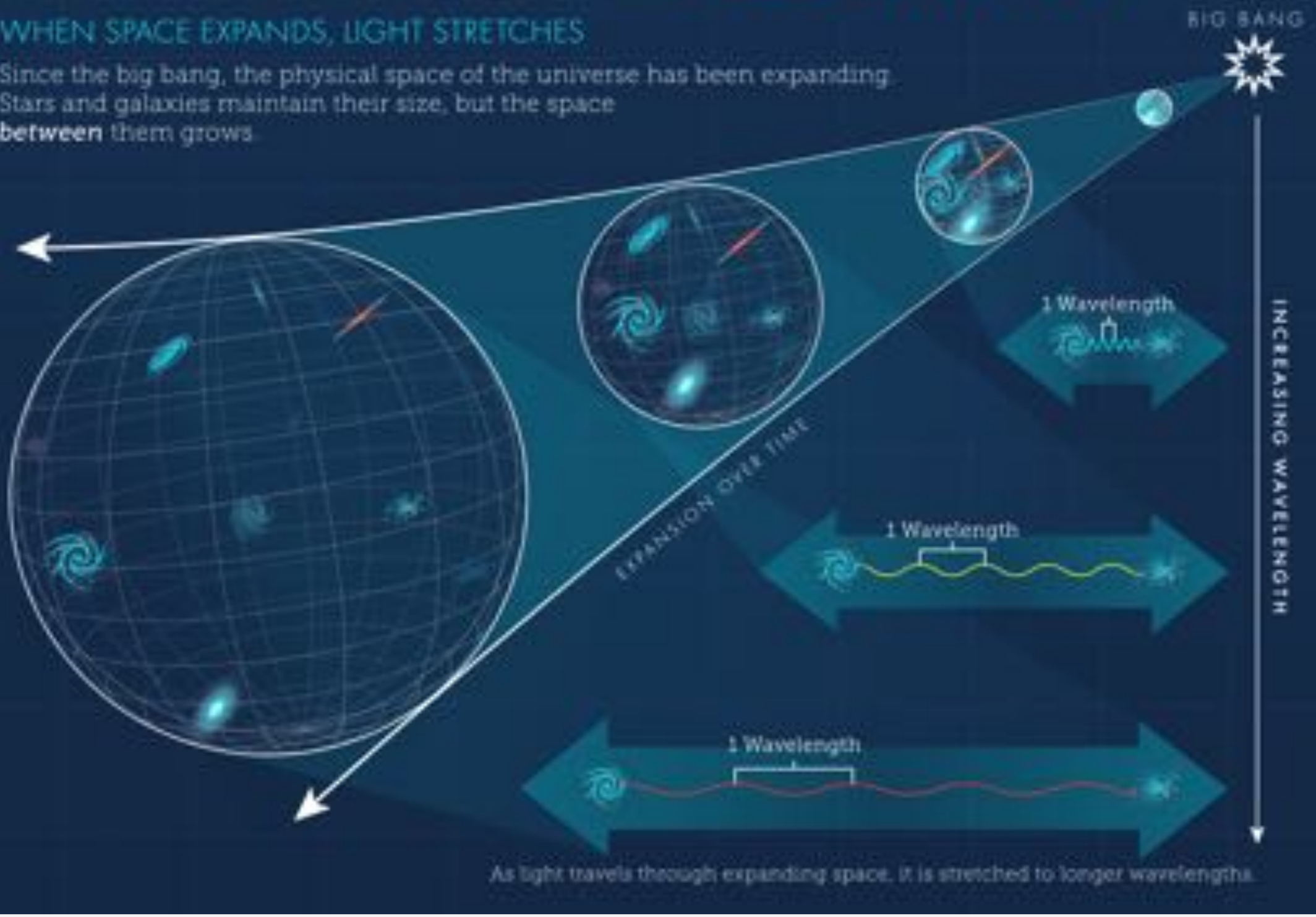


This model explains why galaxies are moving away from us, and why the farther they are, the faster they move.

WHAT IS COSMOLOGICAL REDSHIFT?

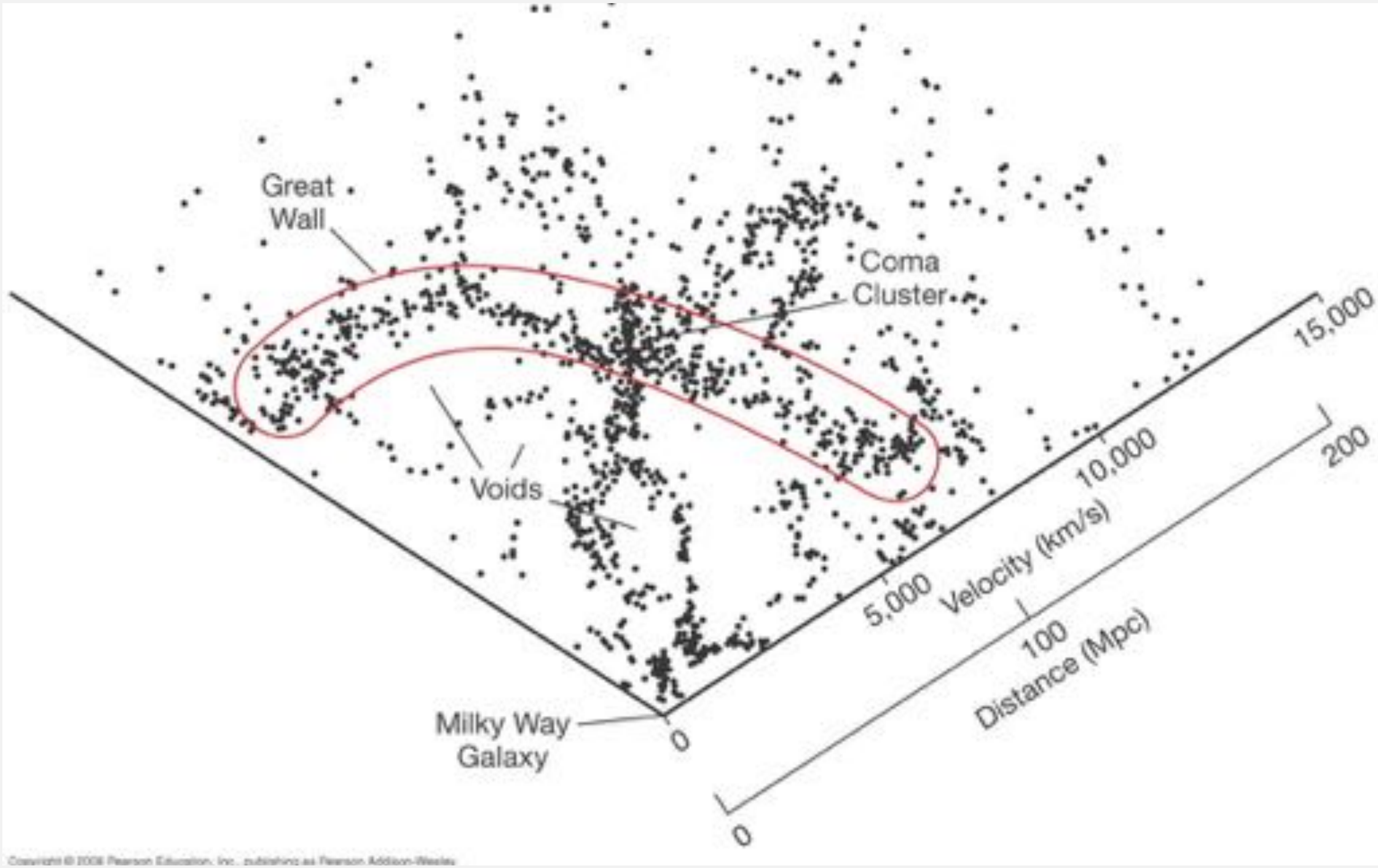
WHEN SPACE EXPANDS, LIGHT STRETCHES

Since the big bang, the physical space of the universe has been expanding
Stars and galaxies maintain their size, but the space
between them grows



As light travels through expanding space, it is stretched to longer wavelengths.

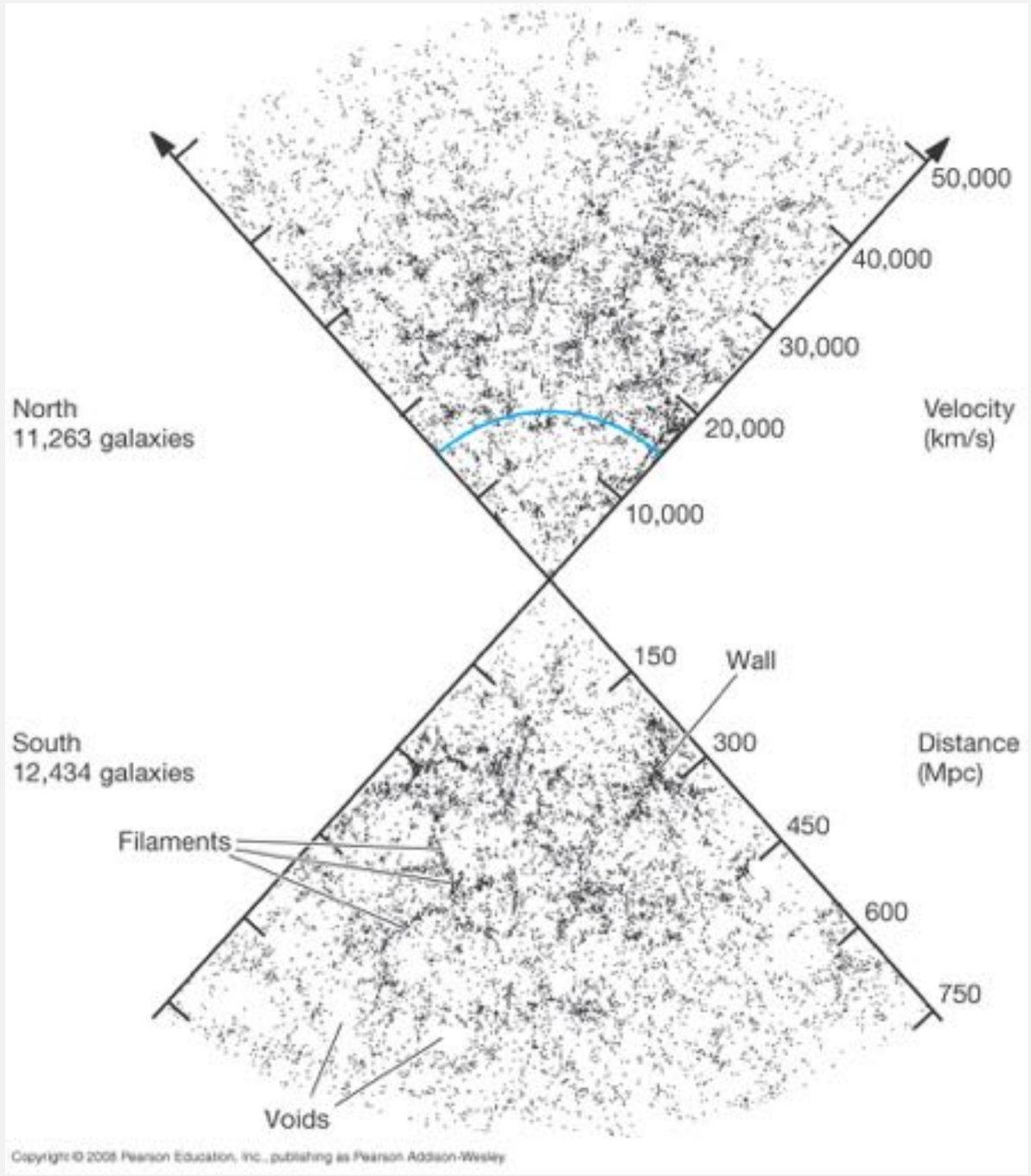
WE HAVE OTHER EVIDENCE THAT WE ARE NOT IN A SPECIAL PLACE.



WE HAVE OTHER EVIDENCE THAT WE ARE NOT IN A SPECIAL PLACE.

On the largest scales, structures begin to repeat themselves.

And they look the same no matter what direction we are looking.



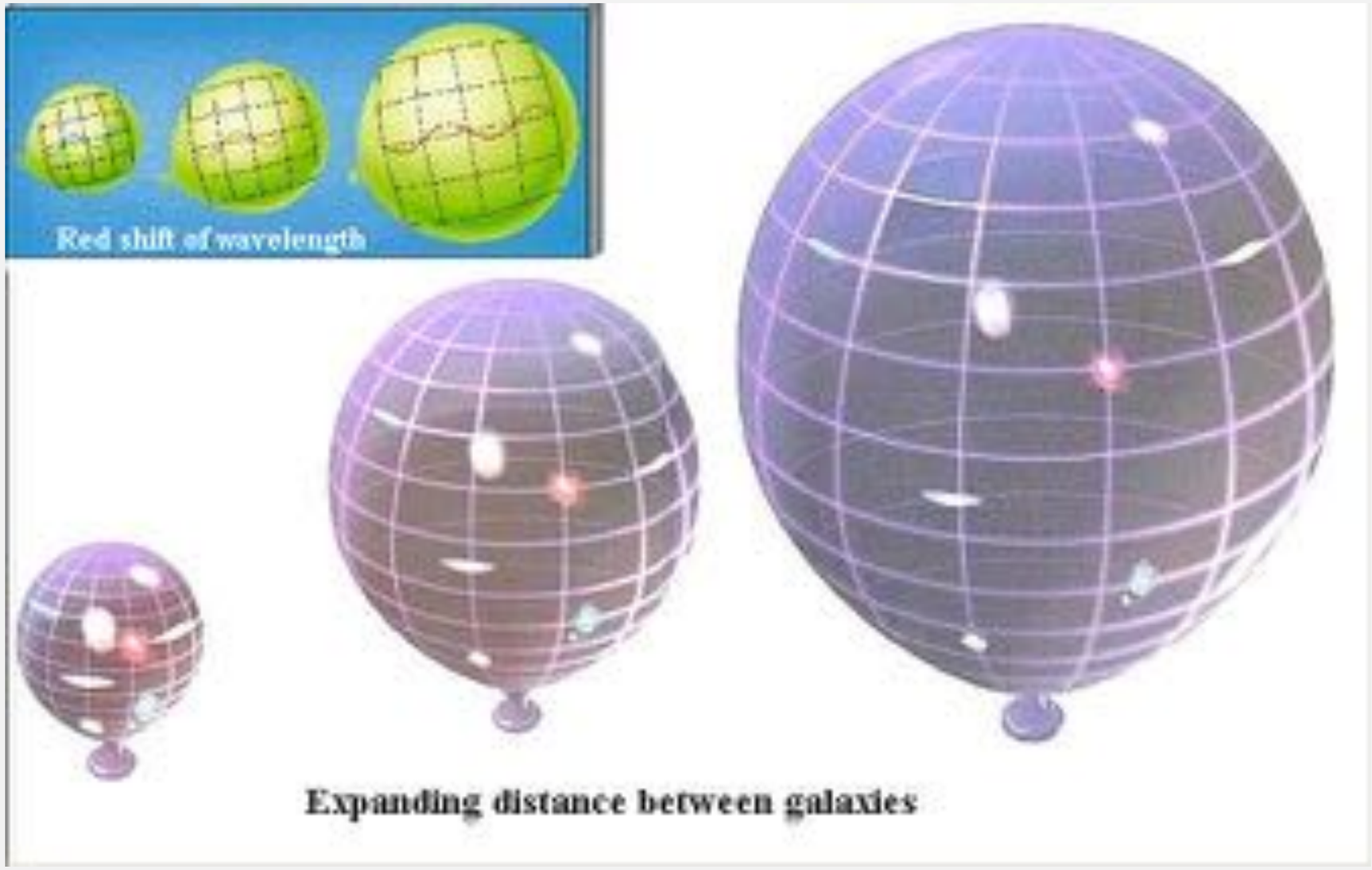
THE COSMOLOGICAL PRINCIPLE

The train of thought initiated by Aristarchus and continued by Copernicus and Herschel ends here.

The idea that on large enough scales (on a statistical basis), the Universe is the same in every direction (isotropic) and from every point of view (homogeneous) is called the cosmological principle.

It means that astronomers in another galaxy far, far away will measure the same density of the Universe, the same amount of matter and energy, and so on.

AN UNAVOIDABLE CONCLUSION



time

The Universe had a beginning!

Viviana Acquaviva (CUNY) Lecture 1 - April 20

THE BIG BANG THEORY

We have to conclude that:

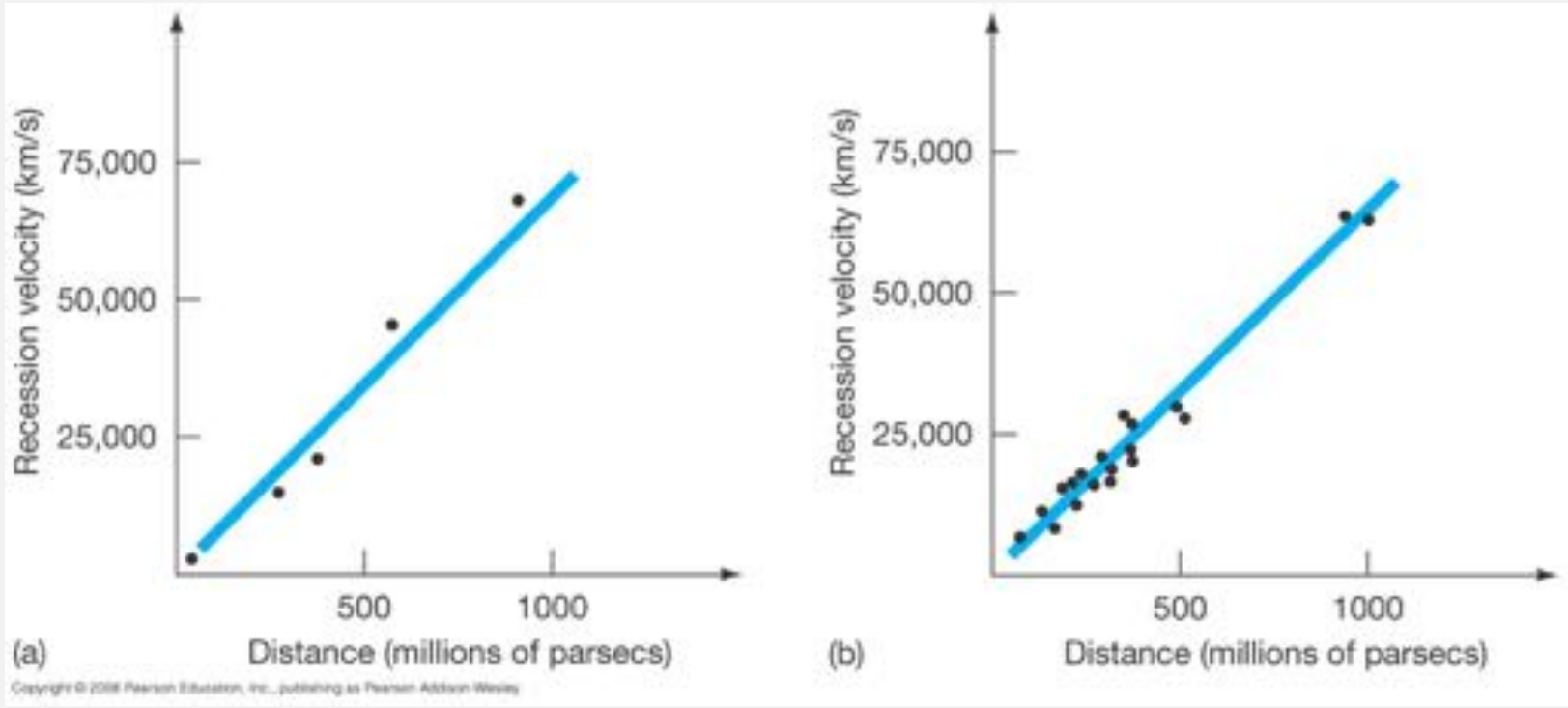
1. There was a time in the past were the space between all galaxies is reduced to zero. The Universe is finite in time.

2. This is what we call the Big Bang: an initial time when the Universe was hot and dense, not an explosion.

3. How about space? Is the Universe finite, or infinite? The observable Universe is finite, and its size is given by the maximum distance that light can have traveled from the Big Bang to today.

4. The Hubble expansion has no center and no edge.

THE AGE OF THE UNIVERSE



Remember how we said that the farther away galaxies are, the faster they are moving away? This is known as Hubble law:

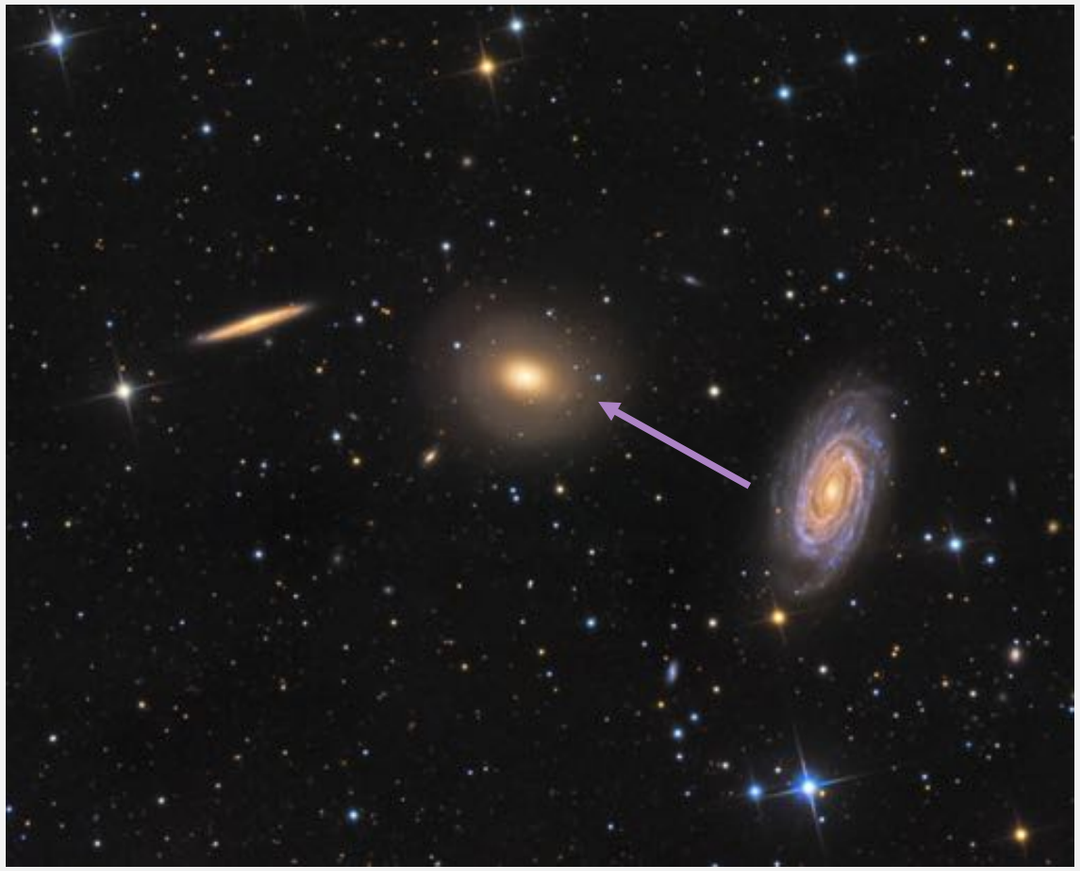
$$v = H_0 \times d$$

where H_0 is the slope of that line you see above.

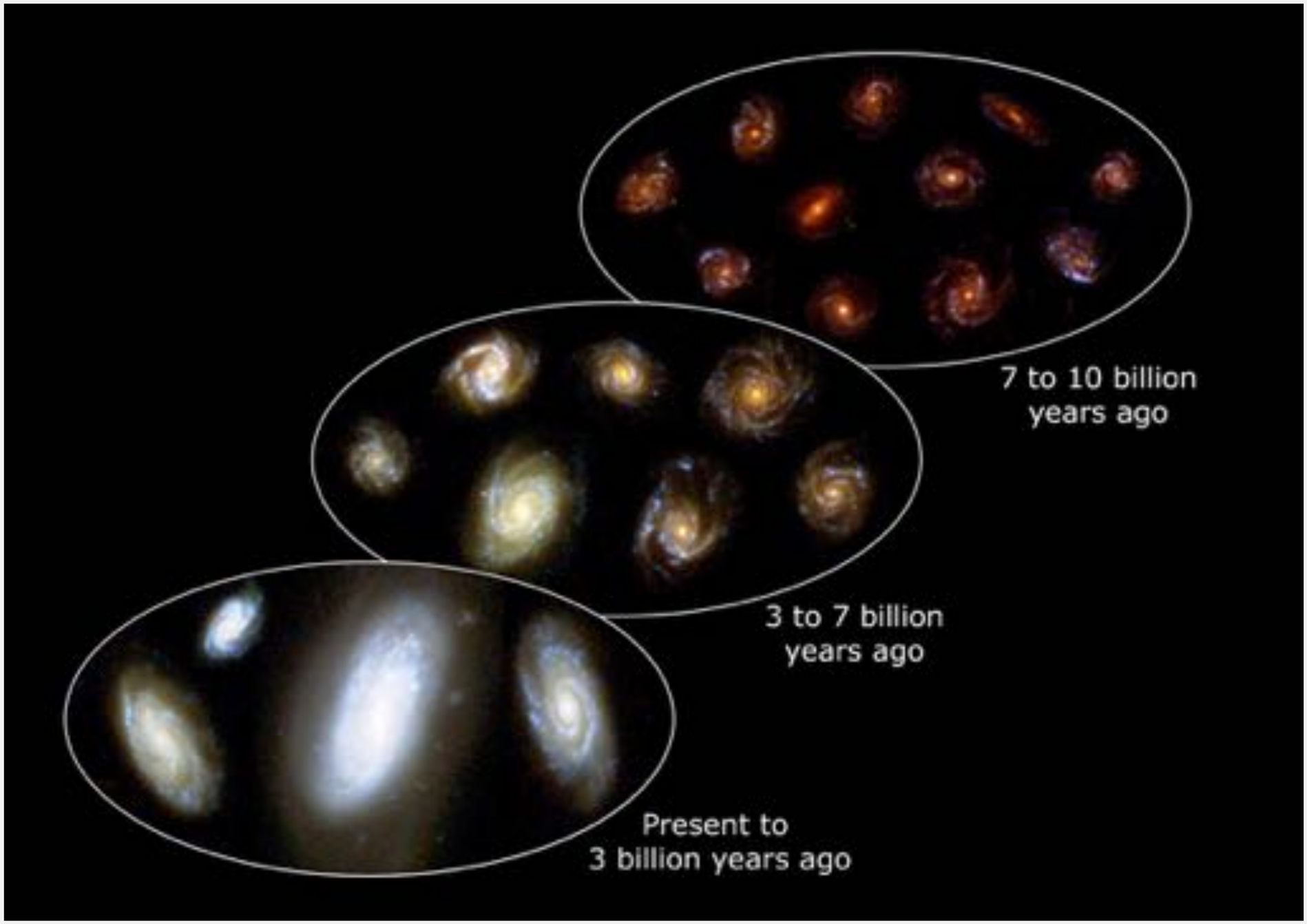
This gives us a quick and remarkably accurate (by coincidence) estimate of the age of the Universe as $t = d/v = 1/H_0 \sim 14$ Gyr

WE ALSO FOUND (AND WE CAN'T EXPLAIN) THAT GALAXIES EXISTED ALREADY IN THE BABY UNIVERSE!

AND THEY CAN CHANGE SHAPE!



WE DON'T SEE IT IN REAL TIME, BUT WE CAN COMPARE DIFFERENT EPOCHS



credit: NASA Hubble website

ALSO, THERE ARE ~ 200 BILLION GALAXIES IN THE UNIVERSE.

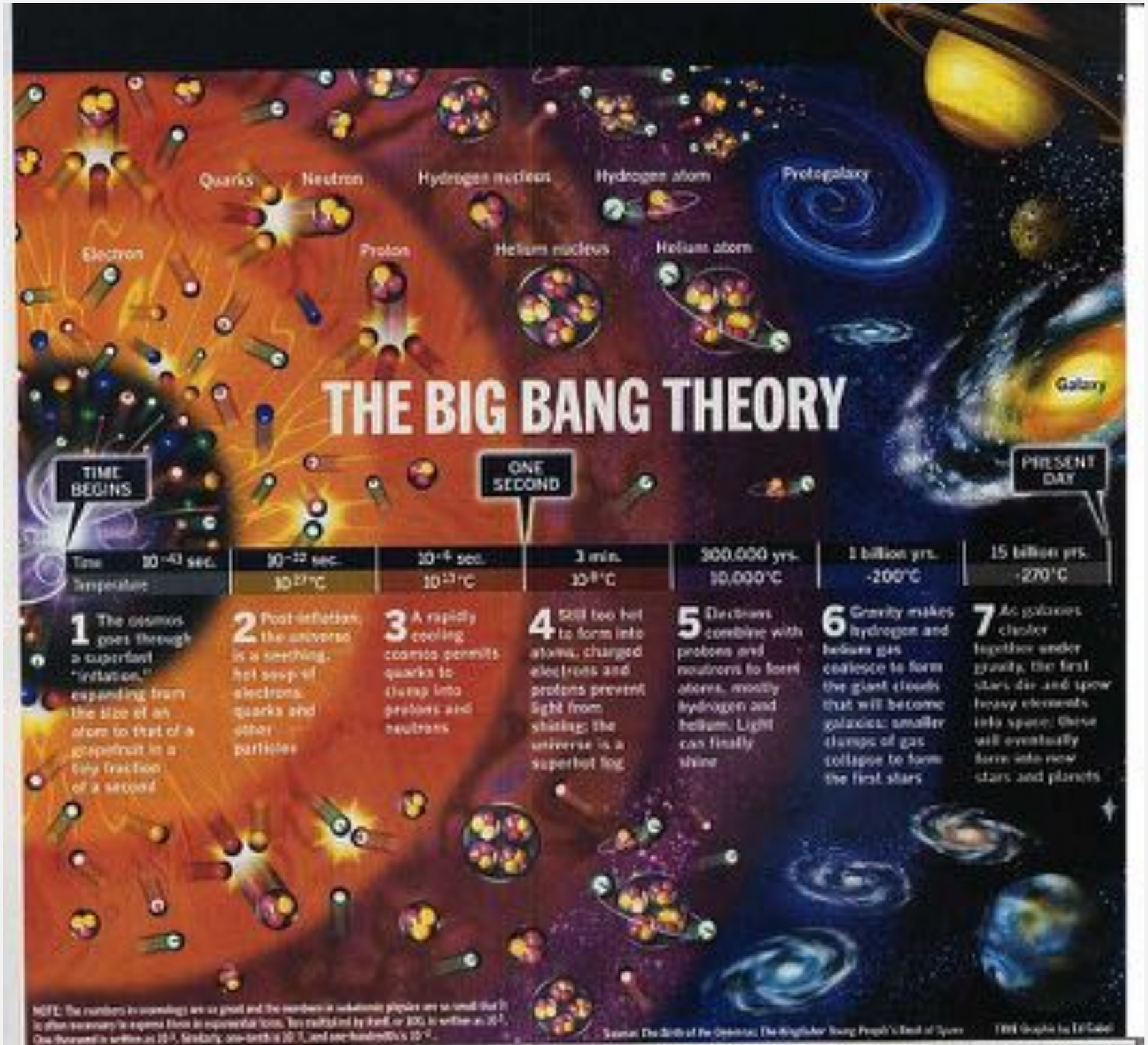
Yes, it makes you feel small.

TO CHEER YOU UP, HERE IS A REAL FLY BACK THROUGH THE UNIVERSE (FROM PRESENT TIME TO BIG BANG), STARTING FROM AN AREA ABOUT 1/100TH OF A FULL MOON

OK, NOW IT'S TIME FOR SOME

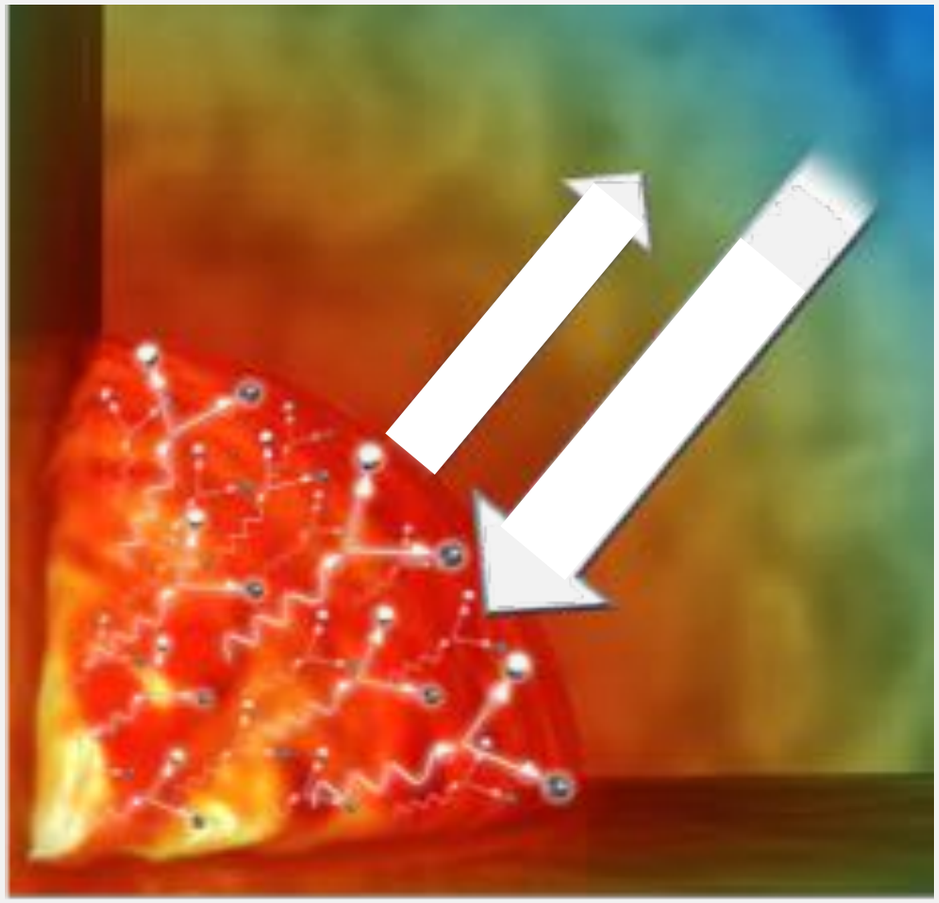
DIRTY LAUNDRY.

OUR MAIN PREDICTION IS THAT THE UNIVERSE HAS BEEN EXPANDING.



BUT WHY?

"section"
of the young,
hot
Universe



The balance between pressure (initial momentum)
and gravity tells us the rate of the expansion of the Universe

Can you predict what happens with more/less matter?

Would the expansion be accelerating or slowing down?

QUICK POLL

(I WILL LOOK AT FIRST 5 ANSWERS IN THE CHAT!)

THE MORE MATTER IN THE UNIVERSE, THE MORE ITS EXPANSION WILL…

A) SLOW DOWN

B) ACCELERATE

You can weigh the Universe
by measuring distance!

Smaller distance ⇔ Slower expansion

Stars have different
luminosities, and measuring
how bright they appear
is not enough to know their distance ☹

What if he had light bulbs, instead of stars?

Would he be able to know
how far the light bulbs are
from their apparent brightness?

YES!
Because all the light bulbs
have the same luminosity,
and so the dimmer ones must be farther away.

ARE THERE ASTRONOMICAL LIGHT BULBS?

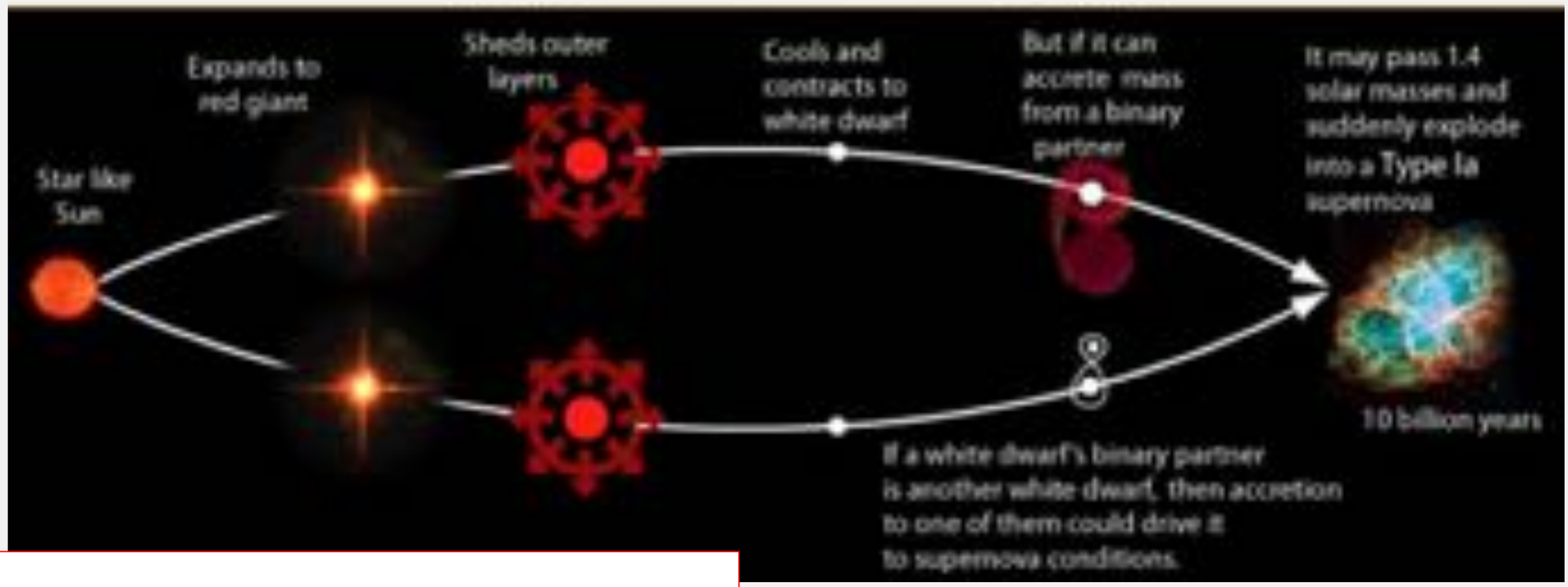
YES! The brightest ones are called SUPERNOVAE Type Ia.

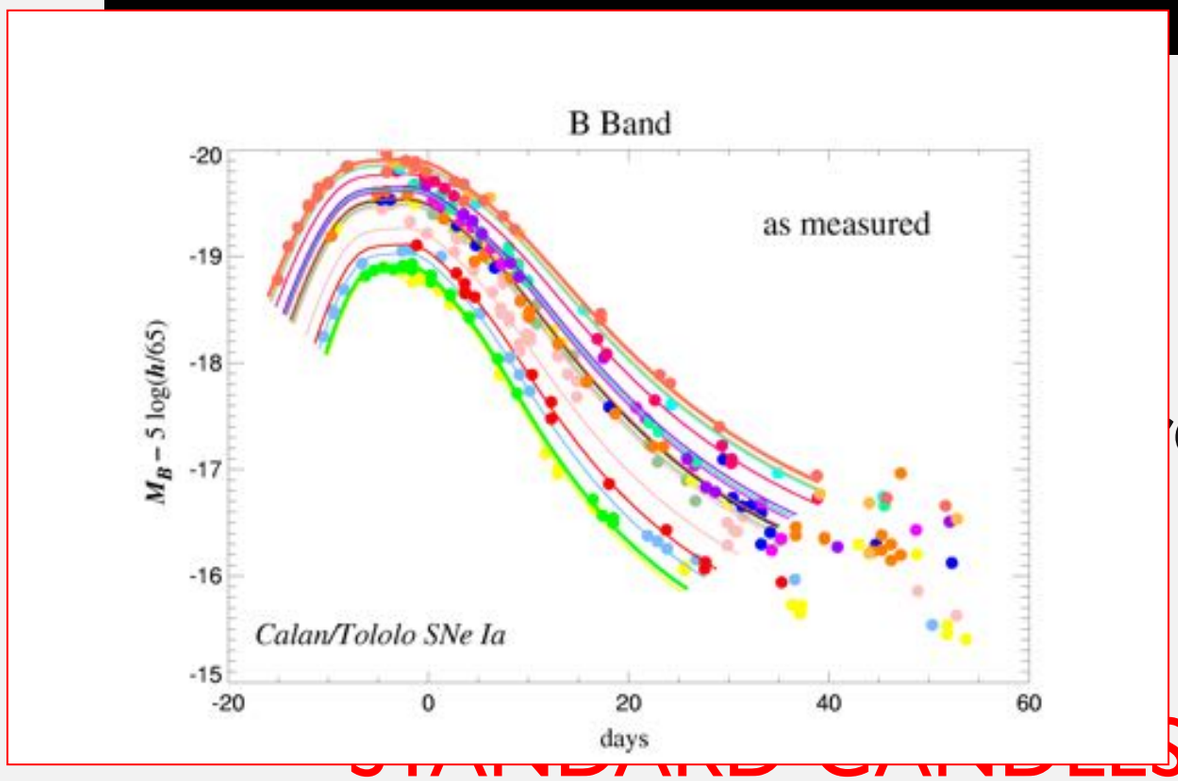
A supernova is an explosion from either
a massive star or from a white dwarf (Type Ia)

It is really bright, and it is visible for months or years.

But why is it so special?

THE SPECIAL THING IS THAT THEY ARE ALL BORN EQUAL

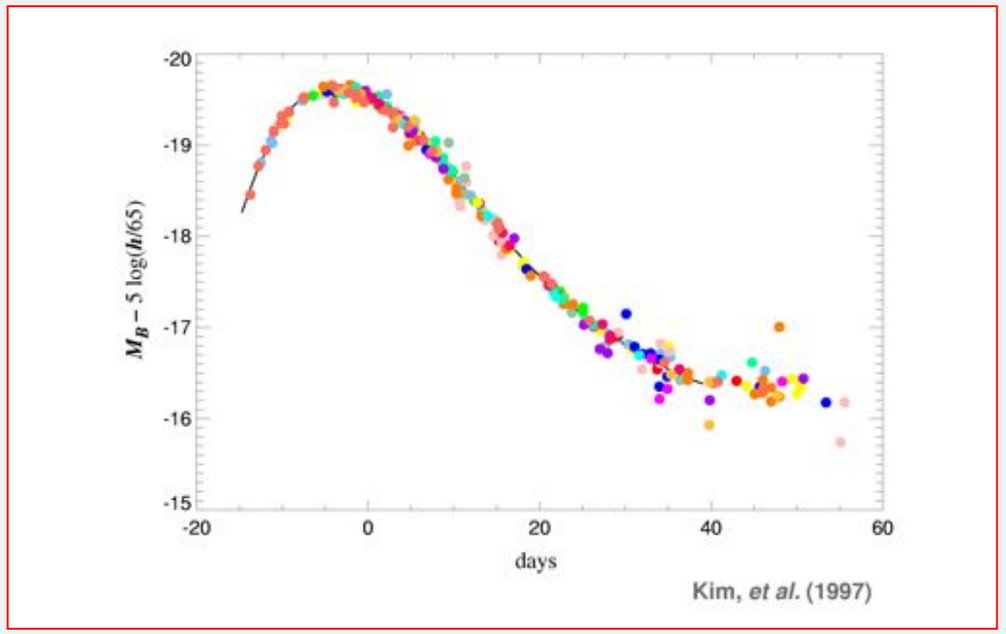




mass

efore,

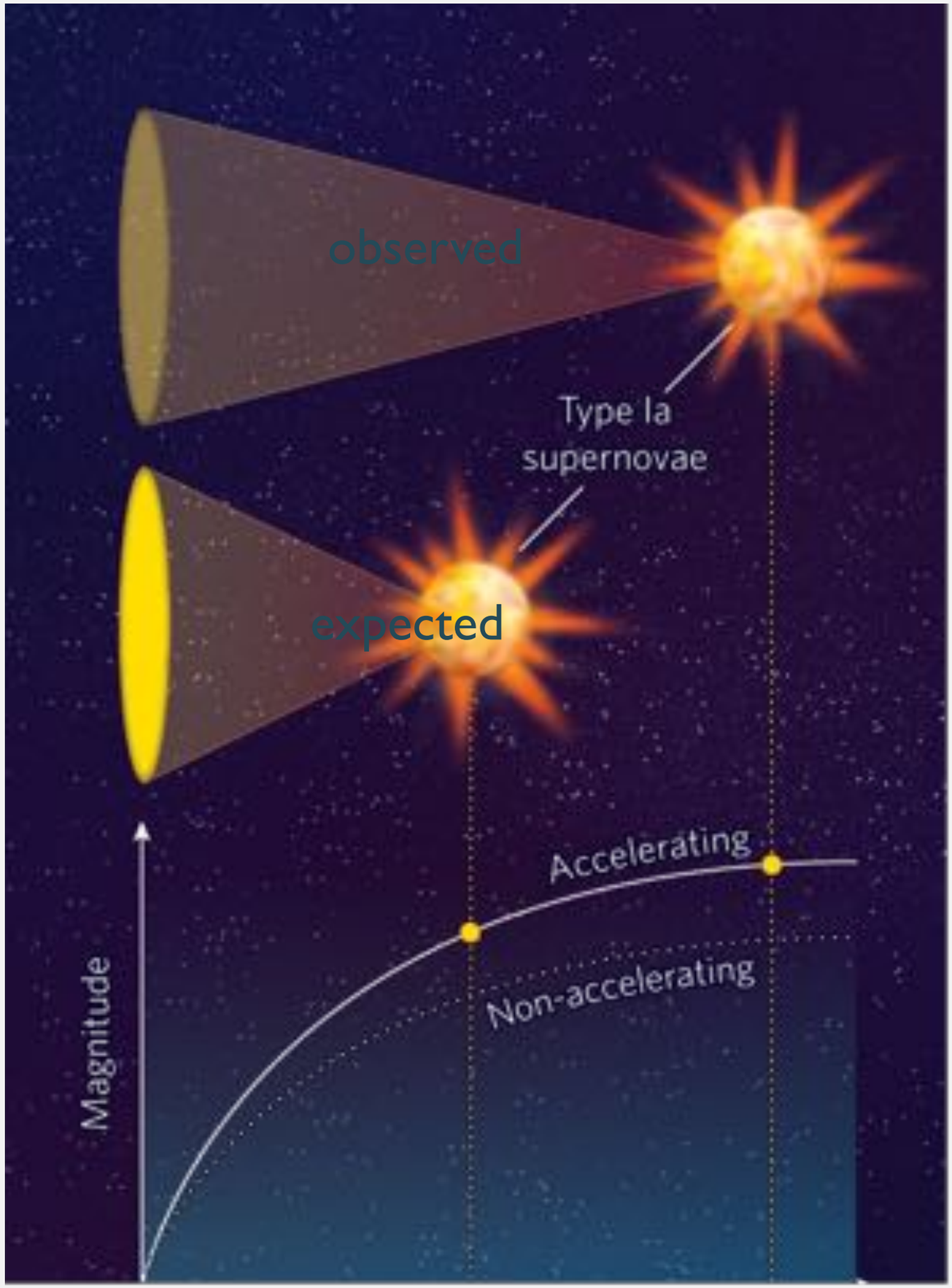
STANDARD CANDLES.



Astronomers decided to use these SNe to measure the rate of the expansion…

And found that they were ALL dimmer than expected, suggesting that the expansion was proceeding at a much higher rate than previously thought.

NOW, THIS WAS A BIG SHOCK.



http://hubblesite.org/hubble_discoveries/dark_energy/

UNFORTUNATELY THIS SITE DOESN'T EXIST ANY MORE

THIS IS THE NEW VERSION

HTTPS://HUBBLESITE.ORG/CONTENTS/NEWS-RELEASES/2006/NEWS-2006-52.HTML

The Shock Heard Round the World

Shocked team members sent a flurry of e-mails around the world, trying to make sense of their discovery. Could it truly be that the universe's expansion was speeding up, that an unknown force, created by some kind of "dark energy," was accelerating the growth? The astronomers were excited, but worried. If the data were correct they could announce an astounding discovery … but what if they were wrong?

Astronomers on the teams voiced their amazement in e-mail.

REPLAY

"The results are very surprising, shocking even. I have avoided telling anyone about them for a few reasons. I wanted to do a few cross checks (I have) … Approach these results not with your heart or head but with your eyes. We are observers after all!" — Adam Riess

Astronomers Struggle With the News

"A reasonable position for someone to take is that the observations are wrong."
– *Andreas Albrecht, University of California at Davis physicist (The New York Times)*

In 1998, both teams released their findings to widespread curiosity and caution. By proposing that the universe was speeding up, not slowing down, the teams were calling into doubt the established understanding of how the universe worked. Scientists worldwide were open to the possibility, but expressed deep qualms.

Scientists expressed concerns about the discovery to the press

PLAY ▶

Astronomers Struggle With the News

"Its implications are so profound that they really need to assemble a more solid case."
— David Spergel, Princeton University astrophysics professor (The Age)

"[illegible] of the unexpected."
- Brian Schmidt, team leader (The New York Times)

1 2 3

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Scientists expressed concerns about the discovery to the press. PAUSE II

CONTINUE

"My own reaction is somewhere between amazement and horror. Amazement, because I just did not expect this result, and horror in knowing that it will likely be disbelieved by a majority of astronomers - who, like myself, are extremely skeptical of the unexpected"
- *Brian Schmidt, team leader*
(The New York Times)

In 1998, both teams released their findings to widespread curiosity and caution. By proposing that the universe was speeding up, not slowing down, the teams were calling into doubt the established understanding of how the universe worked. Scientists worldwide were open to the possibility, but expressed deep qualms.

Scientists expressed concerns about the discovery to the press

PLAY

CONTINUE

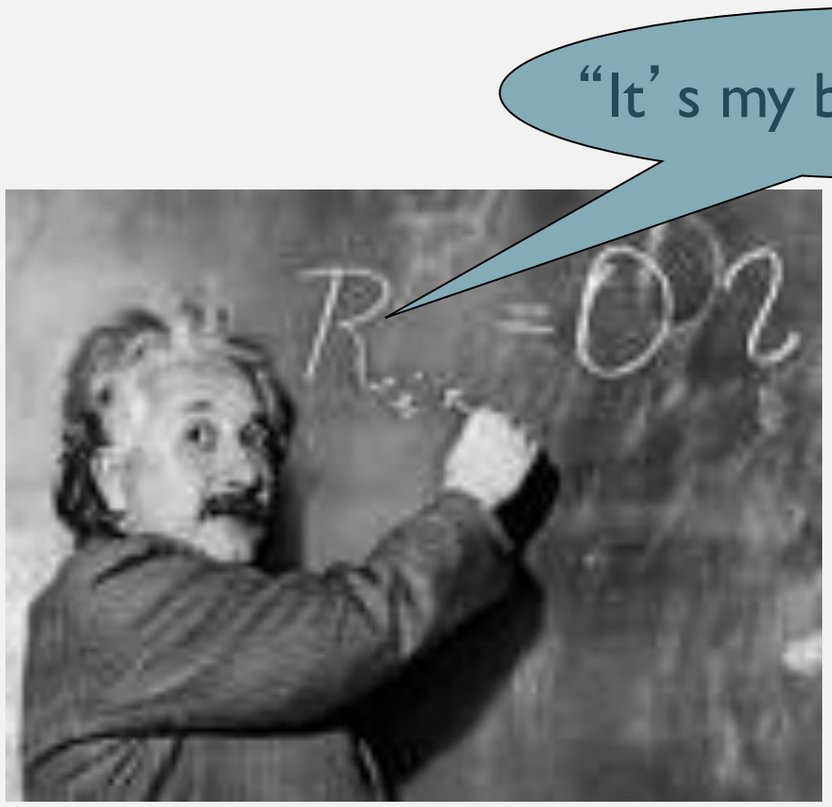
Supernovae data forced us to think about
a new component,
accounting for ~ 75% of the total
current energy density of the Universe.

DARK (INVISIBLE) ENERGY

"something" that speeds up the expansion,
stretching the very fabric of the spacetime.

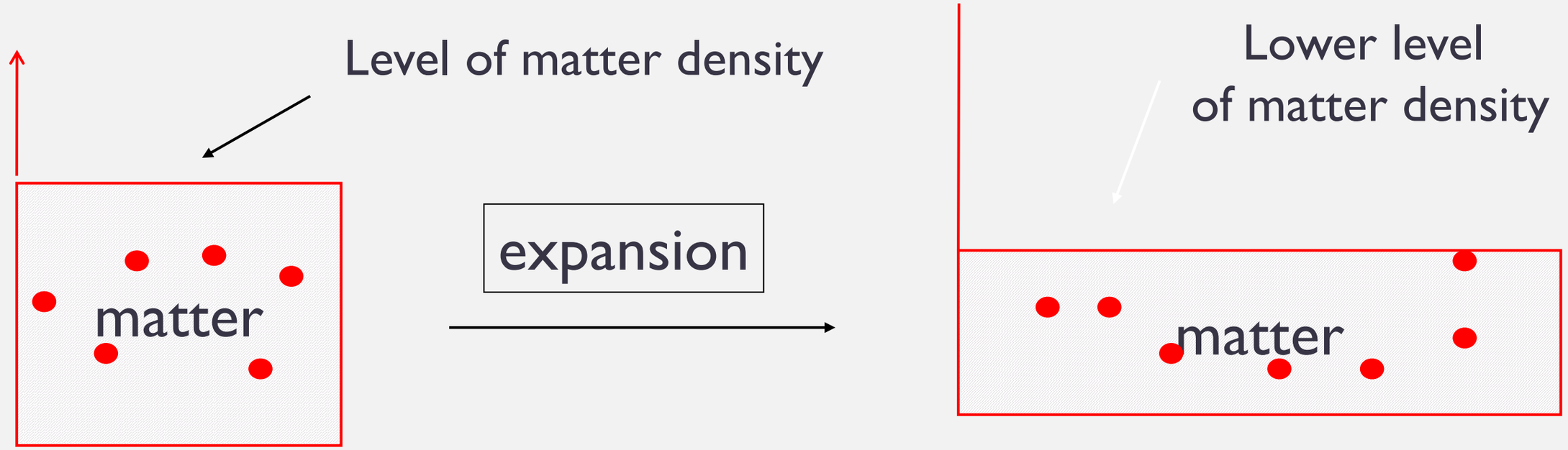
WHAT IS THE DARK ENERGY?

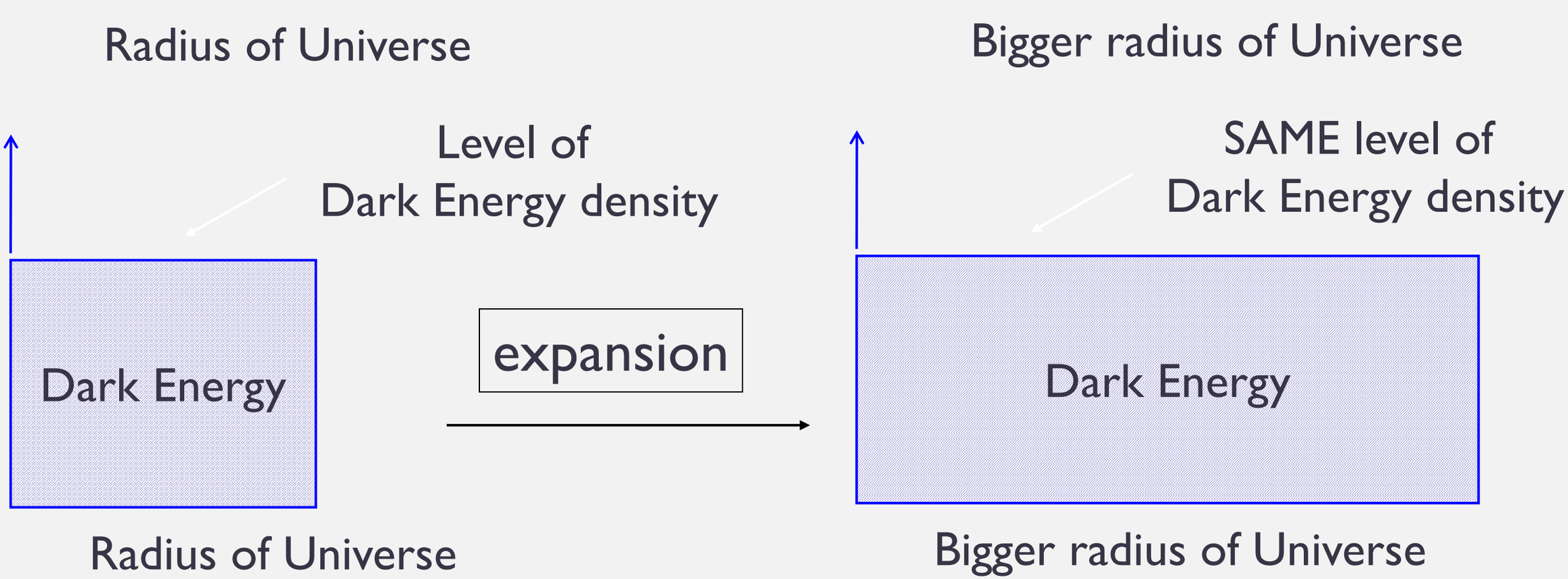
Maybe it is something called a Cosmological Constant:
A uniform layer of energy that fills space everywhere,
sometimes also called vacuum energy.



Einstein had predicted it,
and rejected it.
But he might have been right.

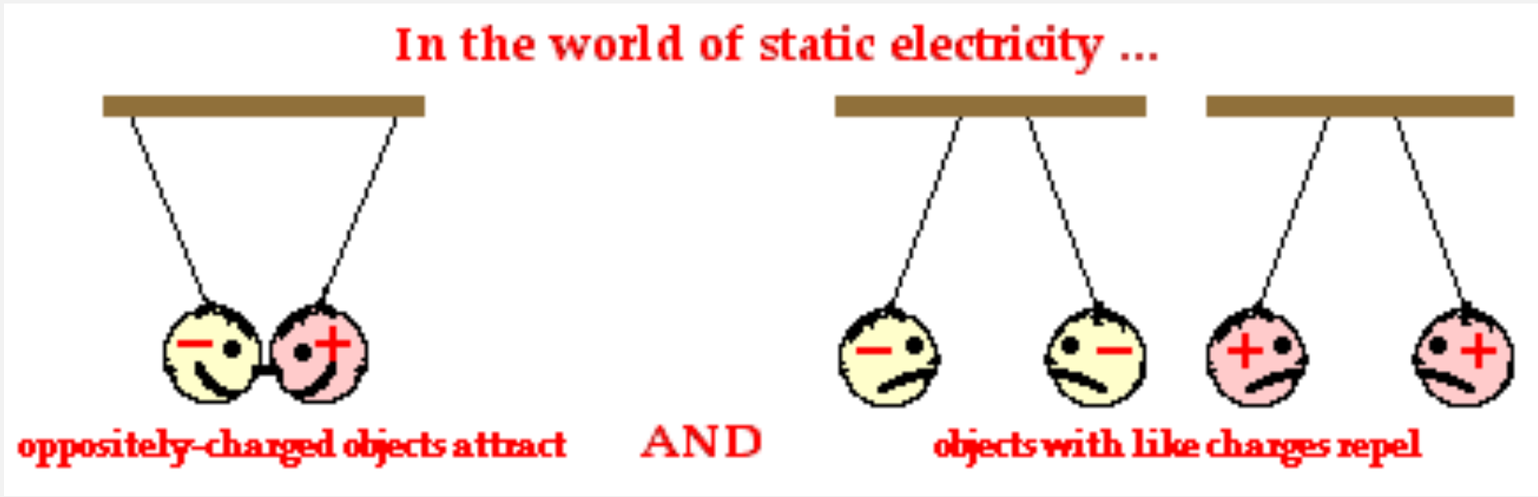
PARADOX # 1 ABOUT THE DARK ENERGY





PARADOX # 2 ABOUT THE DARK ENERGY

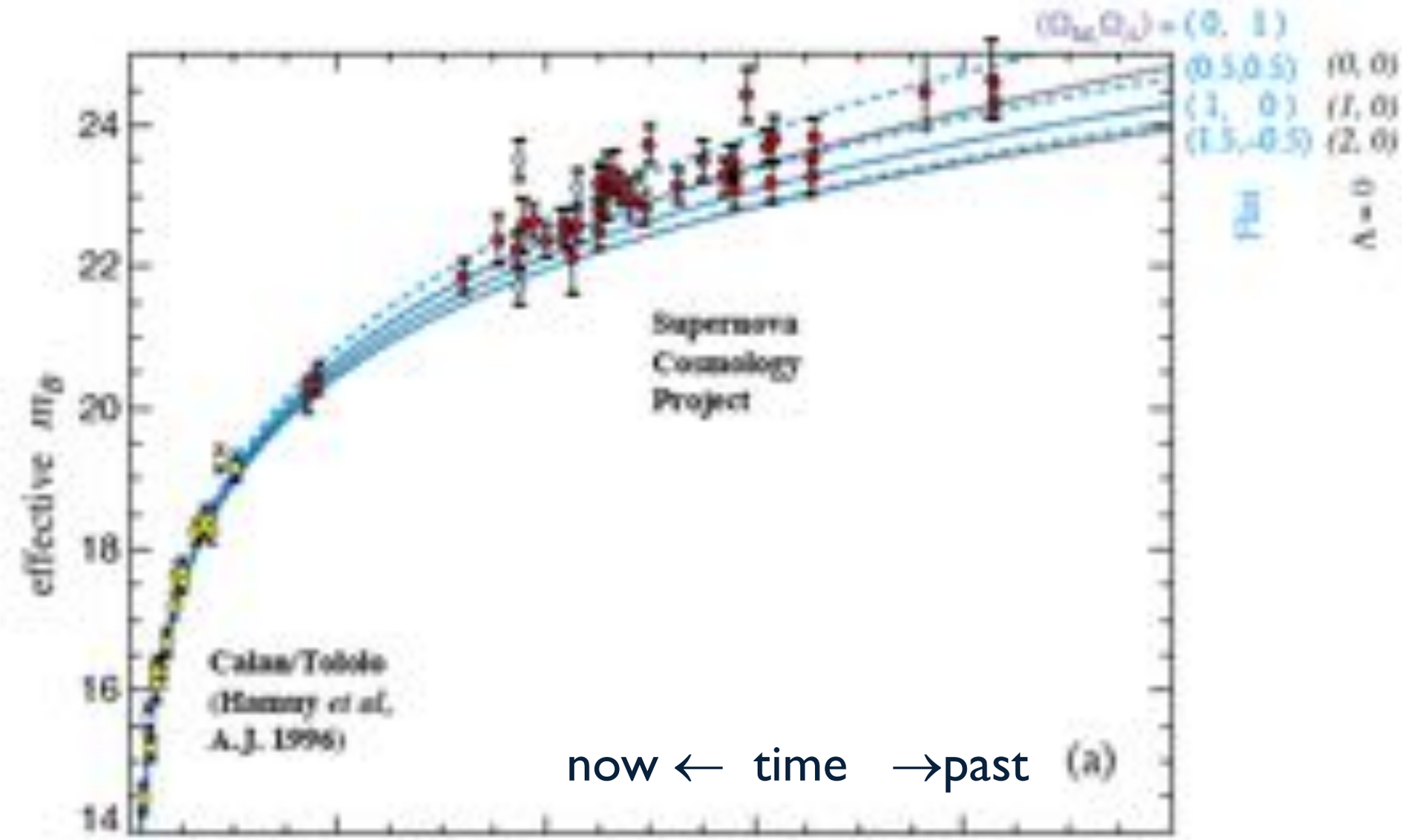
We are used to forces that can be attractive or repulsive.



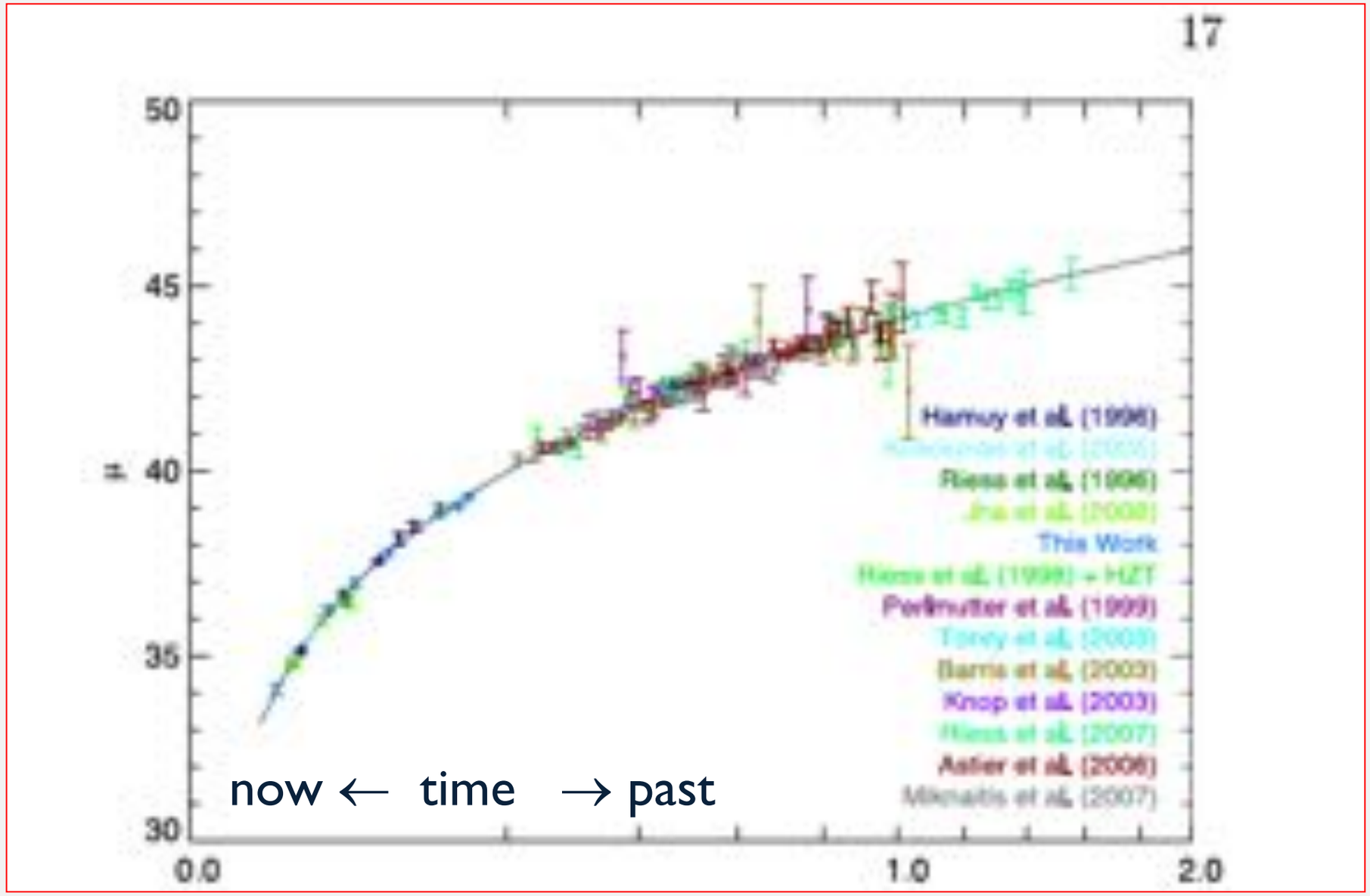
But could this just be anti-gravity?

No, because it does not depend on the involved masses (or any other property, like every well-behaved force!)

Supernovae data then…



and now!

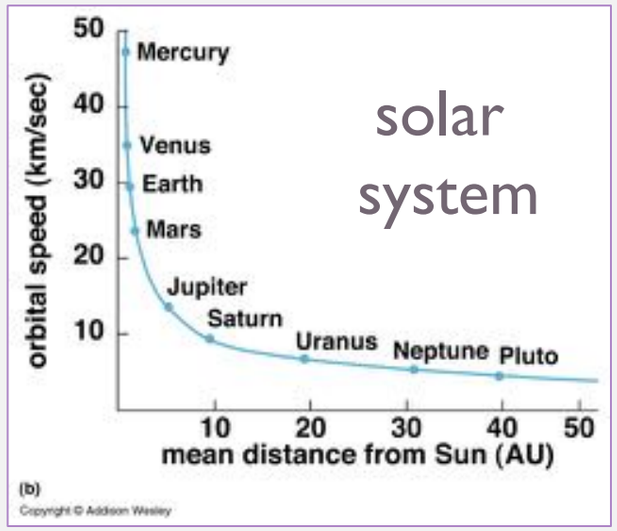


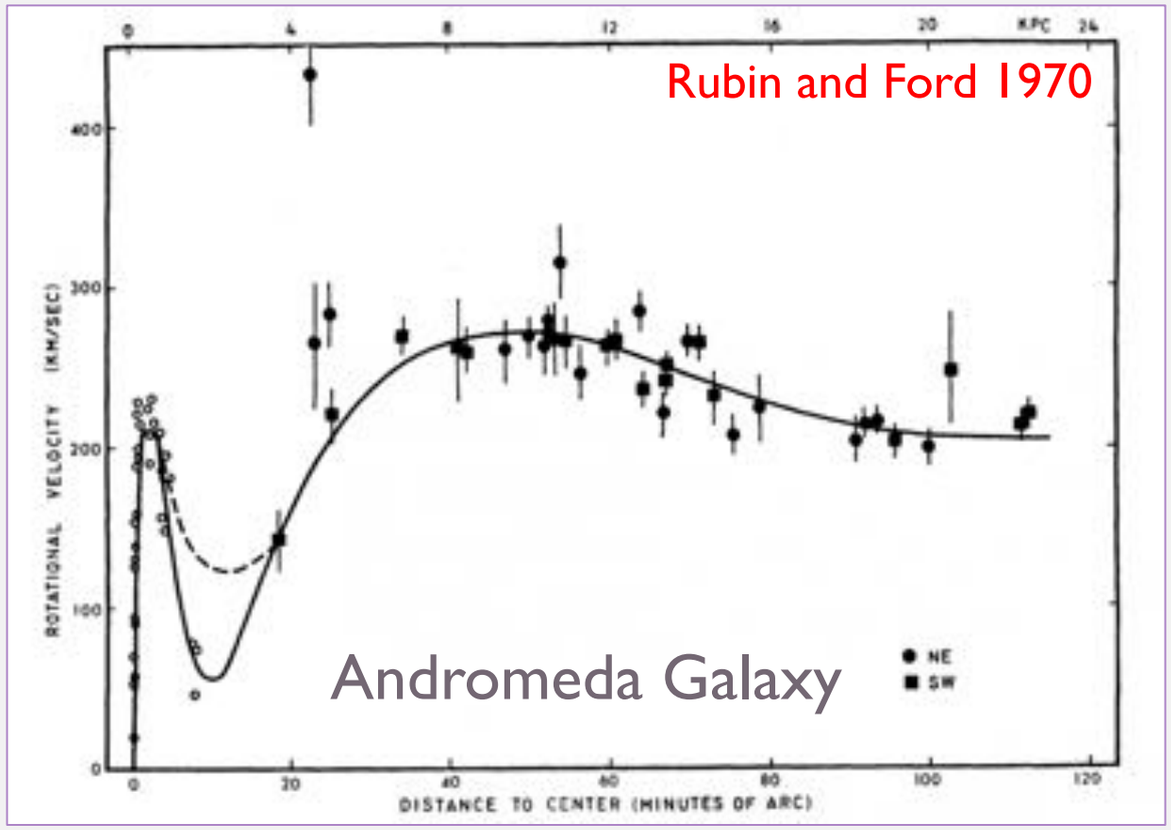
We have since then learned that the acceleration only started a few billion yrs ago (as expected from Λ) although we do have some hints of incompatibility (H_0)

AND I'M NOT GONNA LIE,

DARK ENERGY IS NOT
OUR ONLY PROBLEM.

TURNS OUT THAT WE ARE IN THE DARK ABOUT MATTER, TOO.



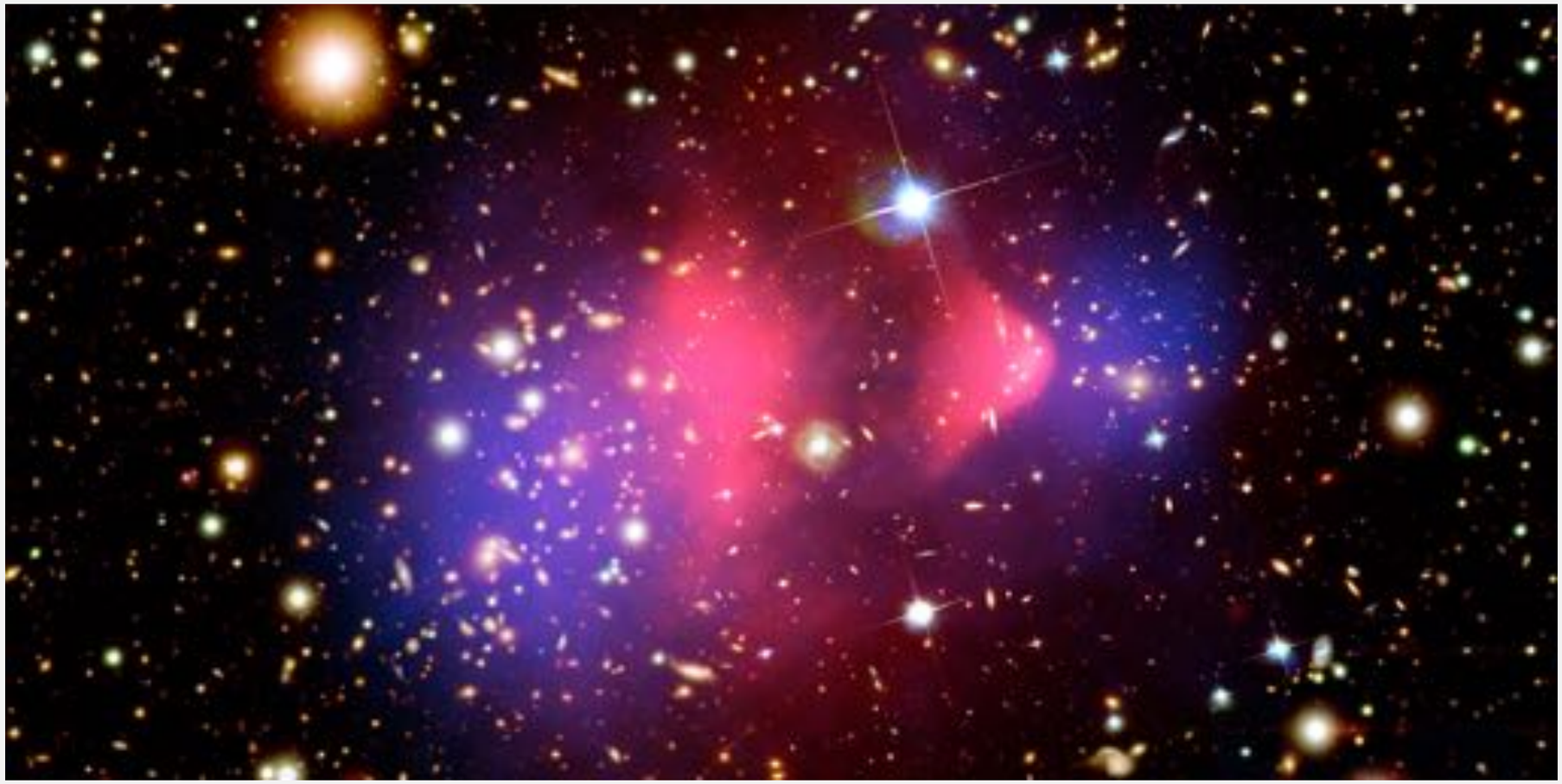


First, we started noticing that the rotational velocities of stars in galaxies (here shown for Andromeda) did not agree with the "planetary system" model of most matter in the center.

This could also be explained by a different law of gravity.

https://www.space.com/vera-rubin.html

TURNS OUT THAT WE ARE IN THE DARK ABOUT MATTER, TOO.



Then we found objects like the Bullet Cluster (above), a system in which we can trace the total mass distribution from gravitational lensing (blue), the visible matter (galaxies, stars), and the hot X-ray (pink).

They are not aligned with one another, suggesting the presence of additional matter that doesn't interact electromagnetically.

SO HERE IS A SUMMARY

- The Universe is really huge.
- It's been around for about 13.8 billion years, and expanding ever since, first slowing down, then accelerating.
- There are ~200 billion galaxies in the Universe, and each one can have a few hundred billion stars.
- More stars than grains of sand in all beaches of Earth.
- And each star can host its own planetary system… but I digress.
- However all this stuff makes up only 5% of the Universe!
- The remaining 95% is dark: dark energy and dark matter.
- How can we learn about it, if we can't observe it?

LET'S TAKE A BREAK, AND THINK OF SOME QUESTIONS!

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An informal, online summer school.

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Registration: itsatcuny.org/summerschool

Lectures from 11am-1pm (EDT)

Questions: info@itsatcuny.org

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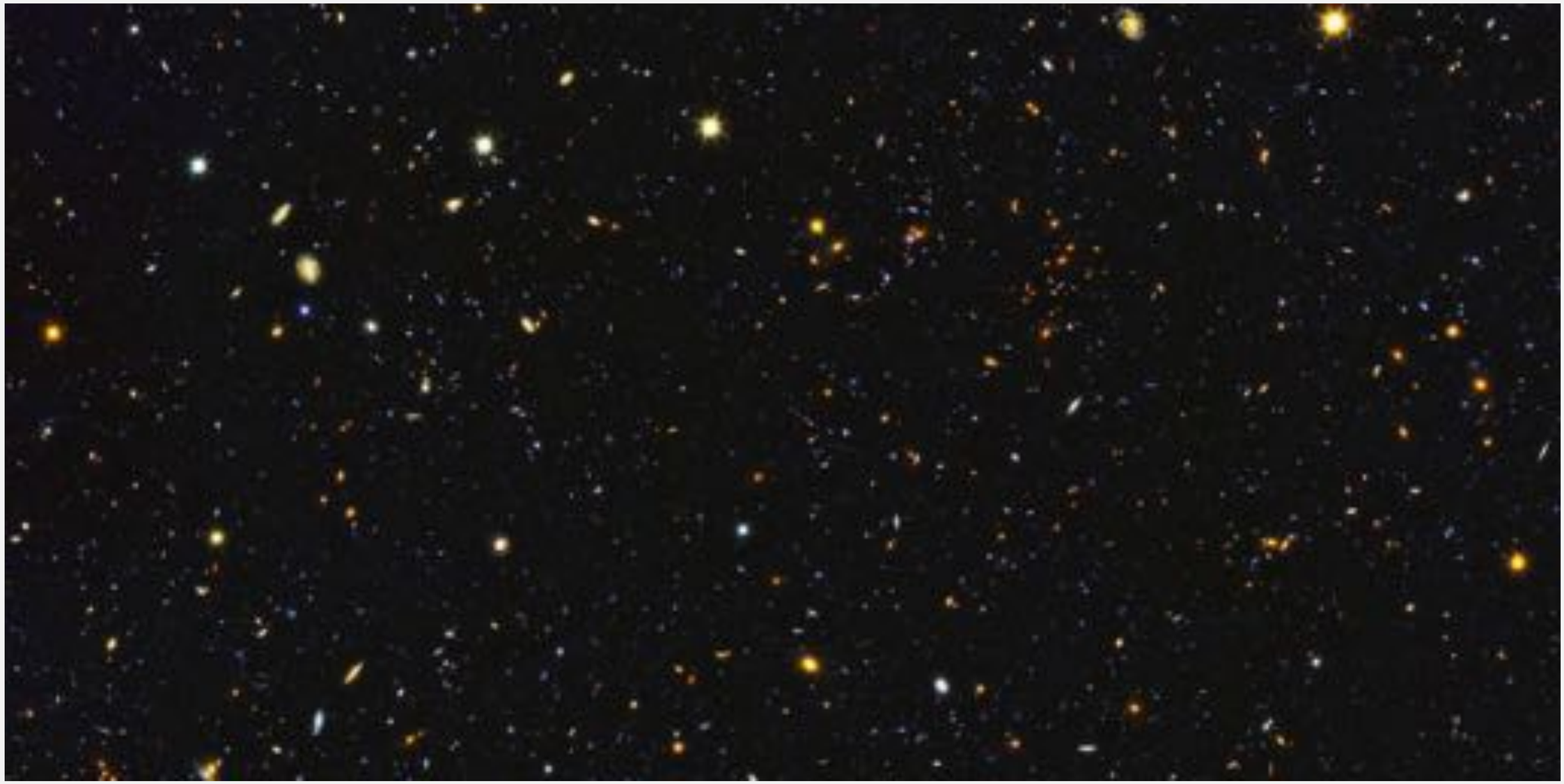
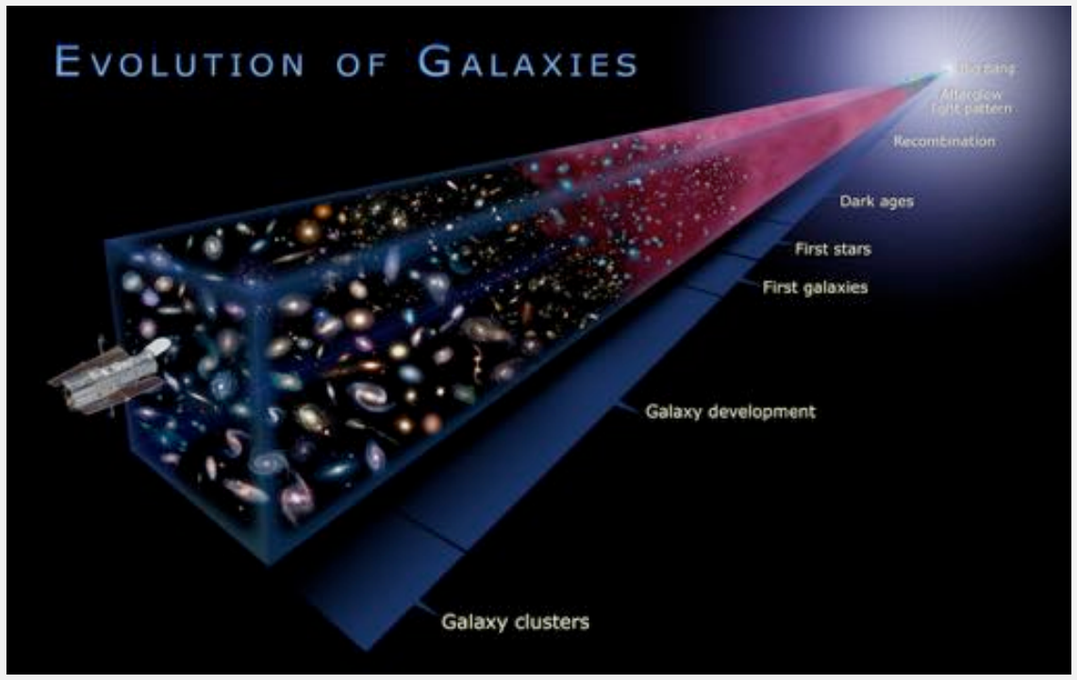
- It's been around for about 13.7 billion years, and expanding ever since.
- There are ~200 billion galaxies in the Universe, and each one can have a few hundred billion stars.
- More stars than grains of sand in all beaches of Earth.
- And each star can host its own planetary system… but I digress.
- However all this stuff makes up only 5% of the Universe!
- The remaining 95% is dark: dark energy and dark matter.
- How can we learn about this stuff?



GALAXIES, OF COURSE!
(THIS IS GOODS-N, ABOUT 15K GALAXIES IN THIS PICTURE ALONE)

WHY?

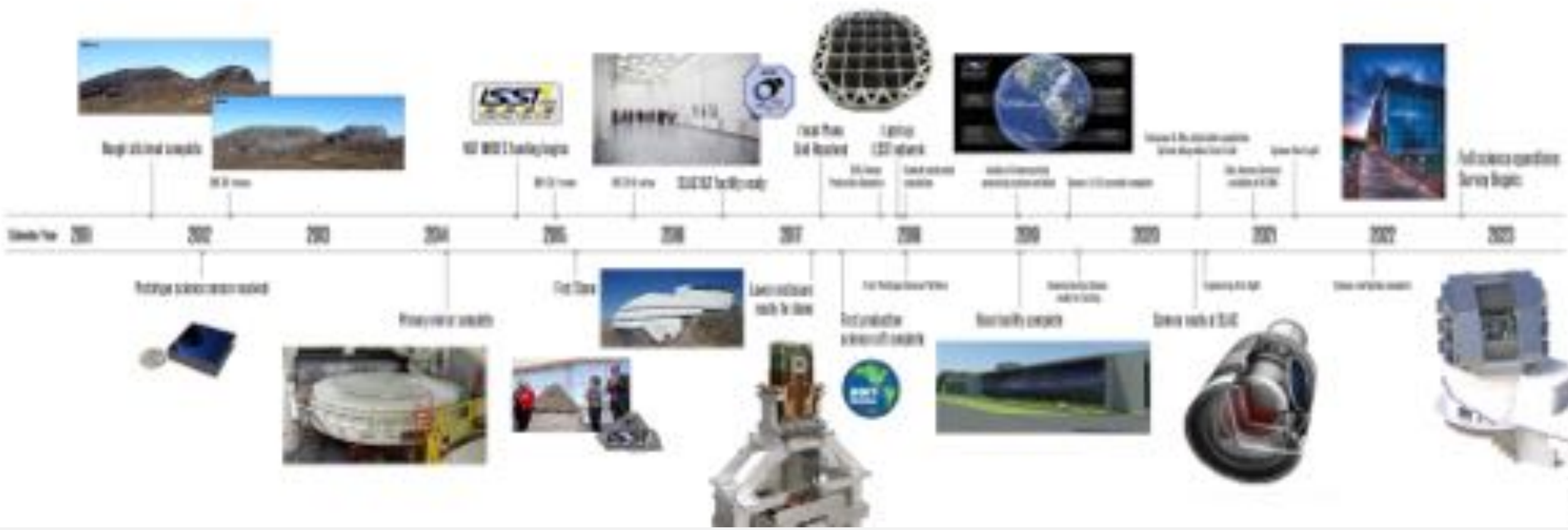


Galaxies are awesome!

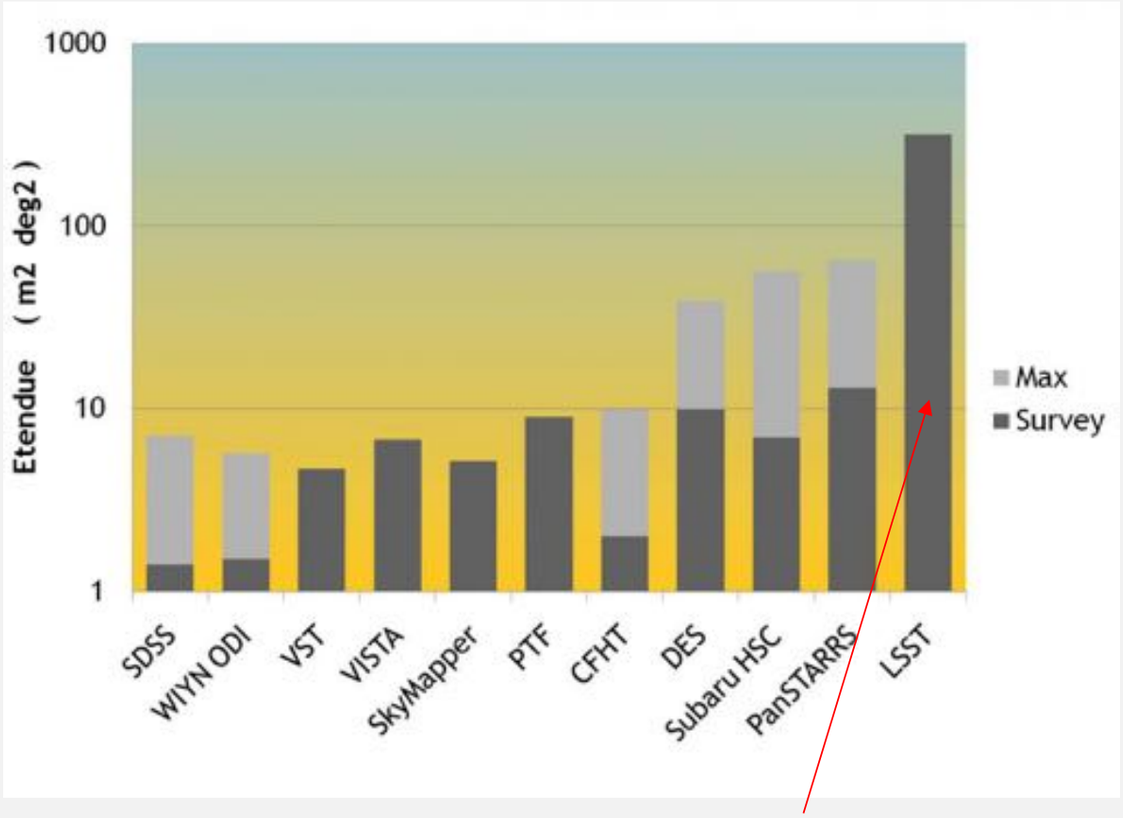
1. They are very bright, so can be seen from very far
2. they have been around for > 95% of the life of the Universe
3. they are sensitive to cosmological expansion history H(z) AND gravity!
4. The evolution of galaxy properties through cosmic time teaches us about galaxy formation and evolution

SO WHAT PLANS DO WE HAVE FOR GALAXY SURVEYS?

THE NEXT BIG PROJECT:
VERA RUBIN OBSERVATORY
(PREVIOUSLY LARGE SYNOPTIC SURVEY TELESCOPE)



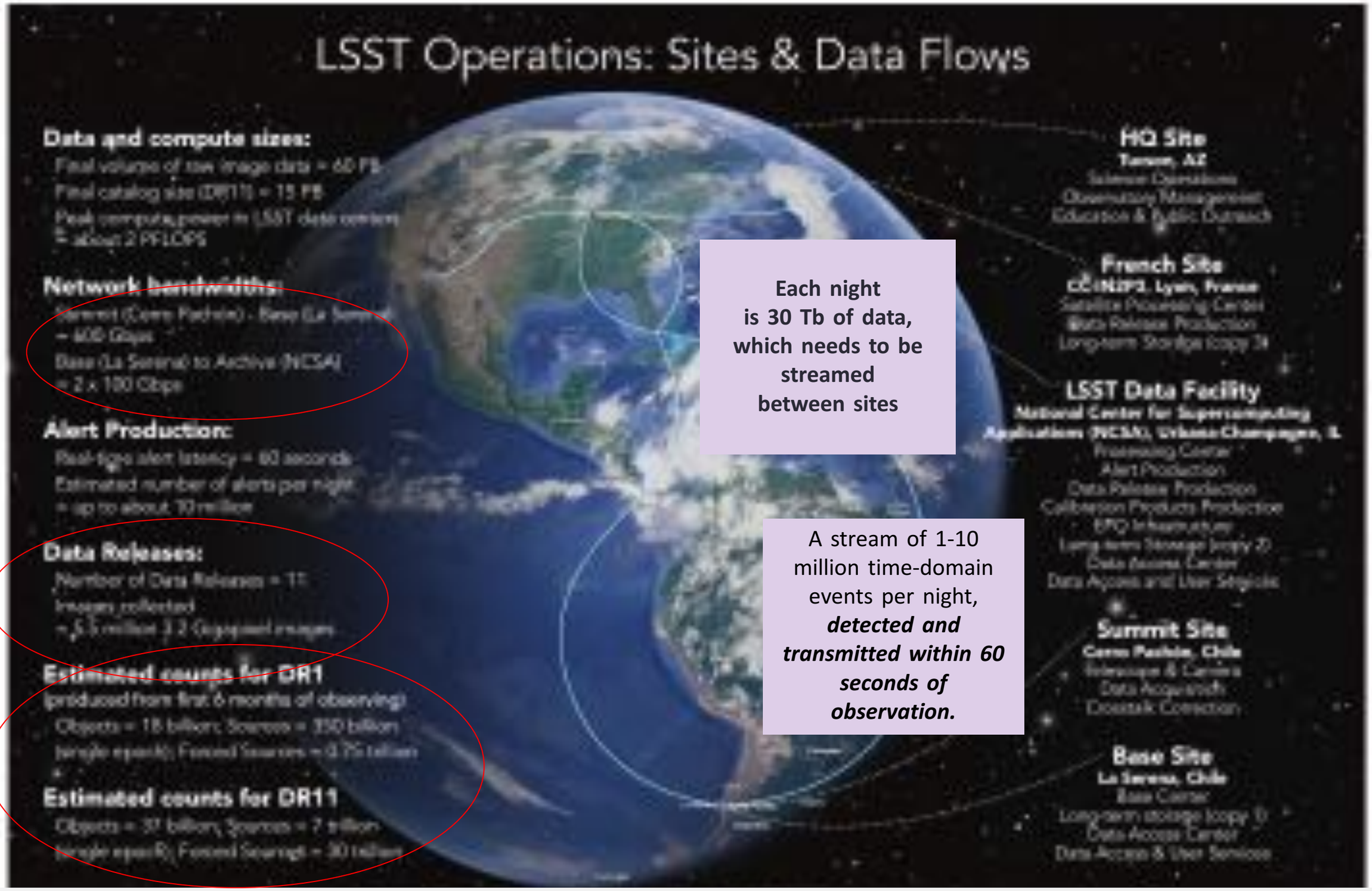
IMPRESSIVE ENOUGH ON PAPER



Roughly, amount of data scales with field of view x size of primary mirror

A catalog of ~ 37 billion objects (20B galaxies, 17B stars), observed in six bands (u g r i z y) over 18,000 square degrees (almost half of the sky!)

THE RUBIN OBSERVATORY DATA

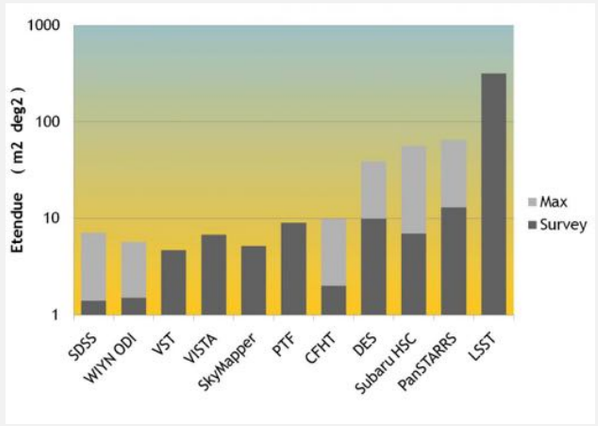


Each night is 30 Tb of data, which needs to be streamed between sites

A stream of 1-10 million time-domain events per night, ***detected and transmitted within 60 seconds of observation.***

HOW DOES IT COMPARE WITH THE PREVIOUS GENERATION OF SURVEYS?

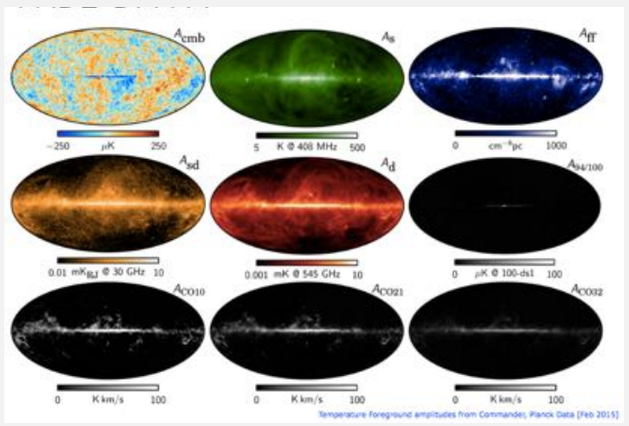
https://classic.sdss.org/dr7/



big
data

WHEN WE TALK OF BIG DATA, IT'S NOT JUST ABOUT SIZE.

DATA IS ALSO BECOMING MORE COMPLEX; I LIKE TO CALL IT RICH DATA



wide
data

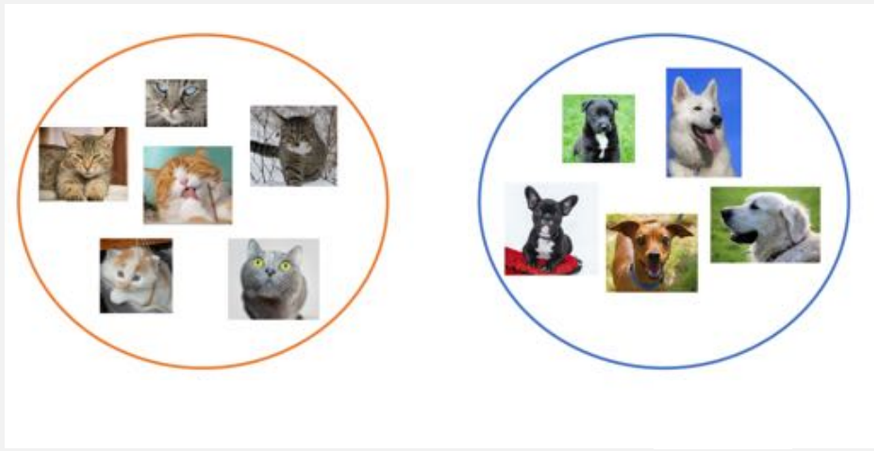
new
data

MACHINE LEARNING

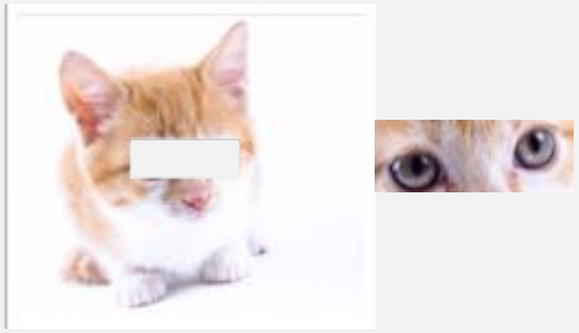
THE ART OF TEACHING A MACHINE TO MAKE DECISIONS

Recognize

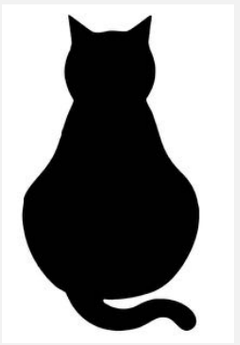
Group together



Predict



Simplify



WHAT DO WE USE ML FOR IN ASTRONOMY?

1. SAVE TIME

Galaxy morphology

Trained humans are the best classifiers.
But what to do when
you have millions of objects?

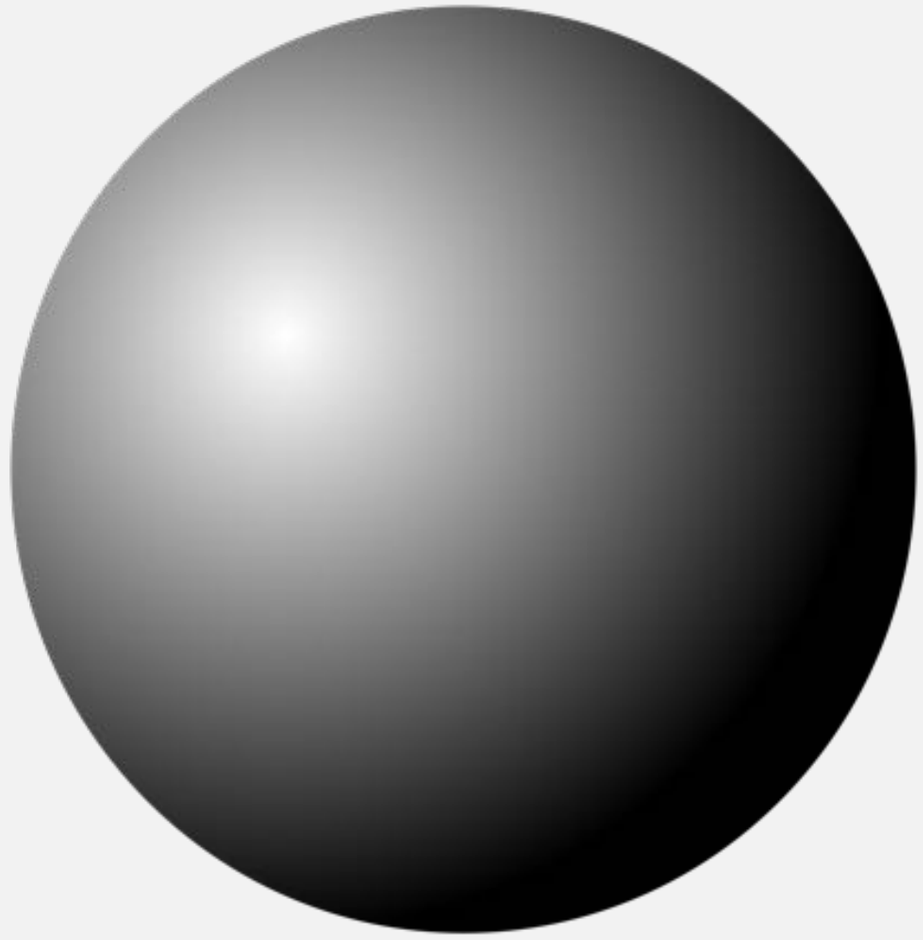
Citizen science

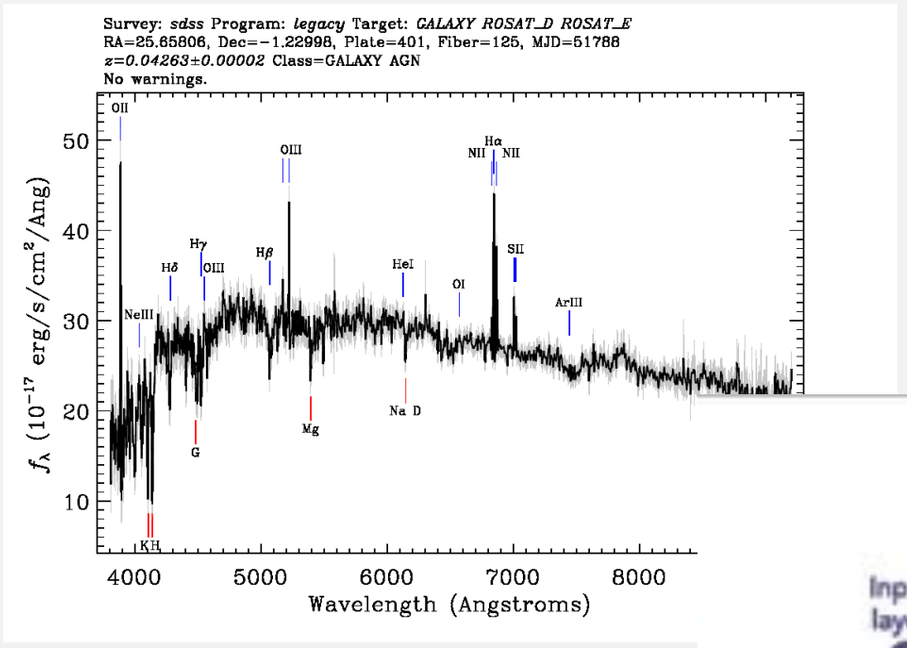
Automated Classification
via Machine Learning

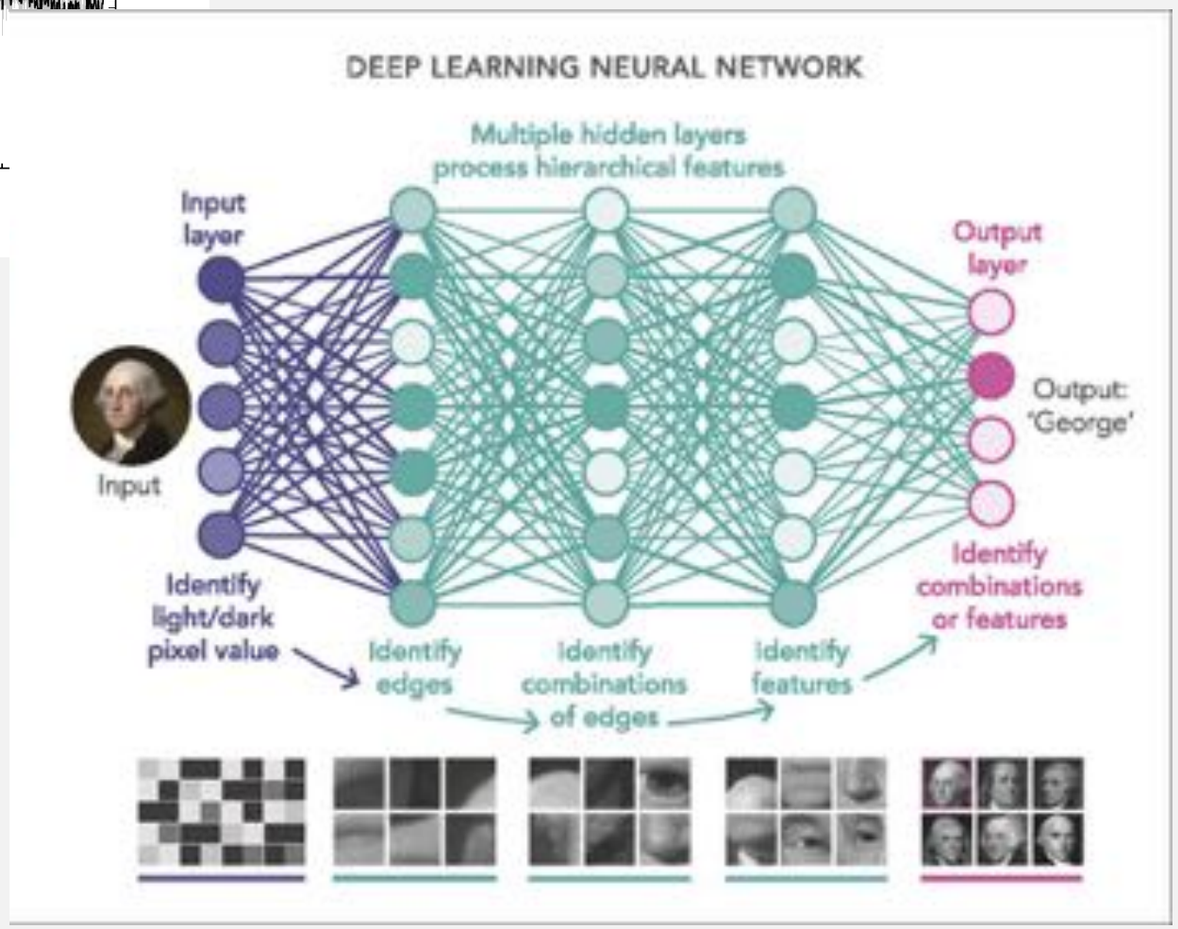
(supervised/unsupervised
approach, see e.g. Hocking et al 2017)

2. MAKE MODEL-FREE INFERENCE (ELIMINATING BIASES)

≠







Capture complex relationships between input and output without a model or a likelihood

redshift (distance)

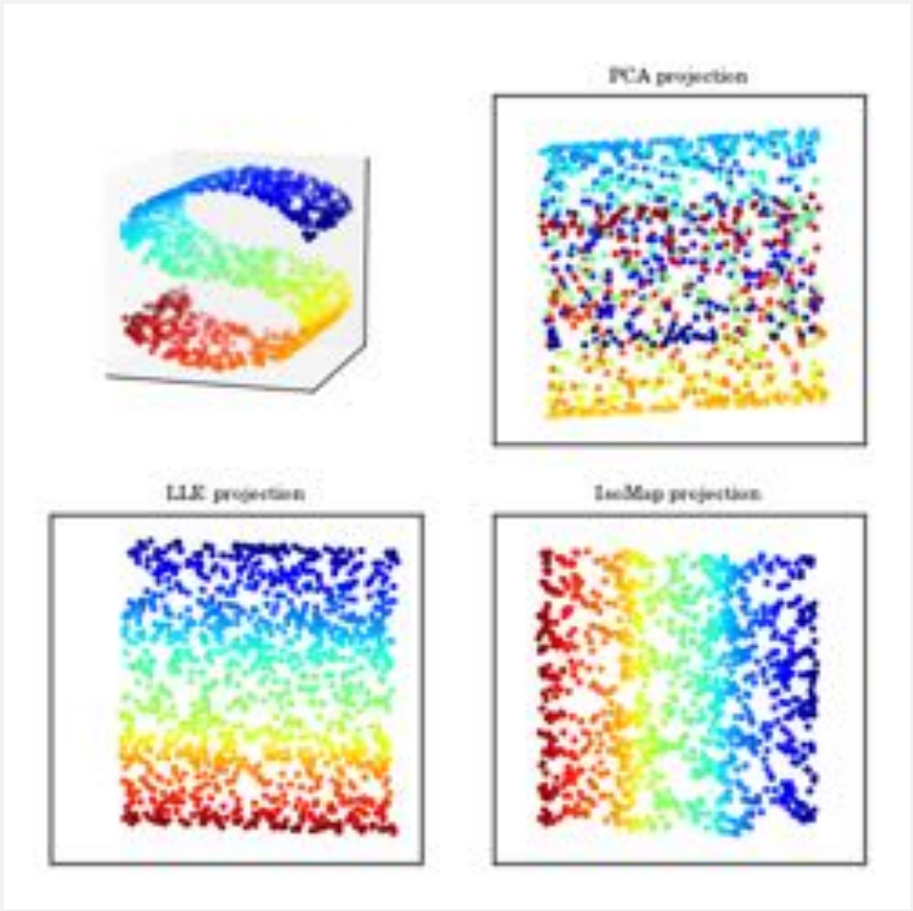
3. USE HIGHER-LEVEL DATA PRODUCTS

Model based inference:
P(model | image) = mess ☹

Machine Learning

4. MAKE PROBLEMS TRACTABLE

via dimensionality reduction



3D -> 2D with different degrees of information loss

By allowing us to transfer knowledge

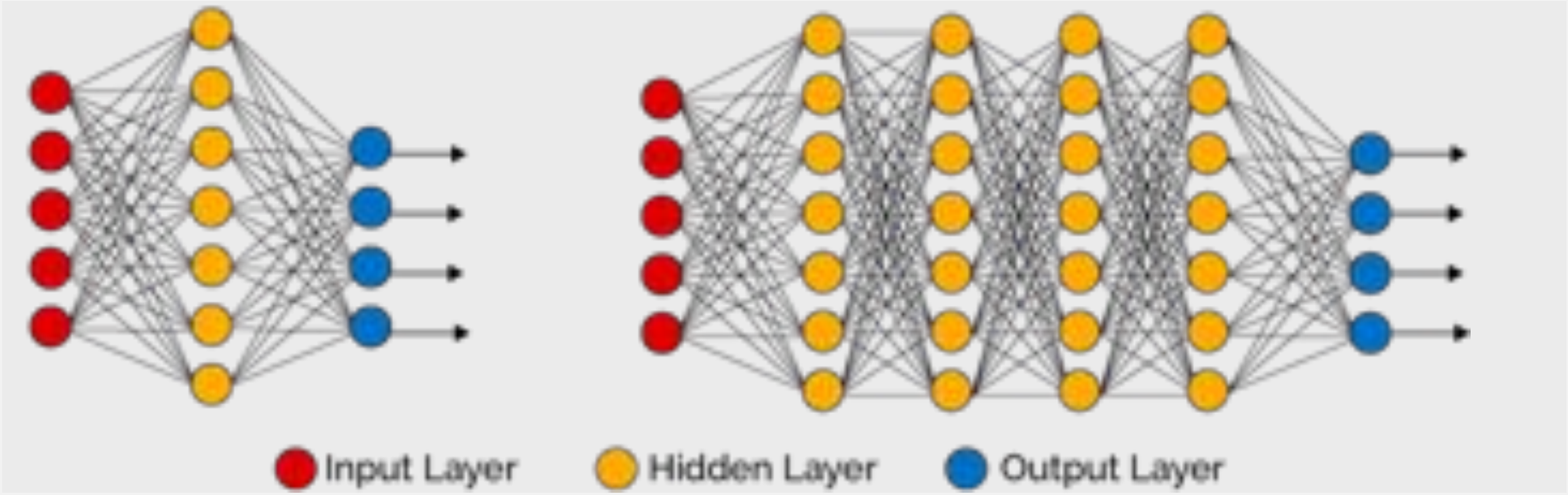
TRAINING DOMAIN (e.g., sims)

APPLICATION DOMAIN (e.g. data)

feature space

feature space

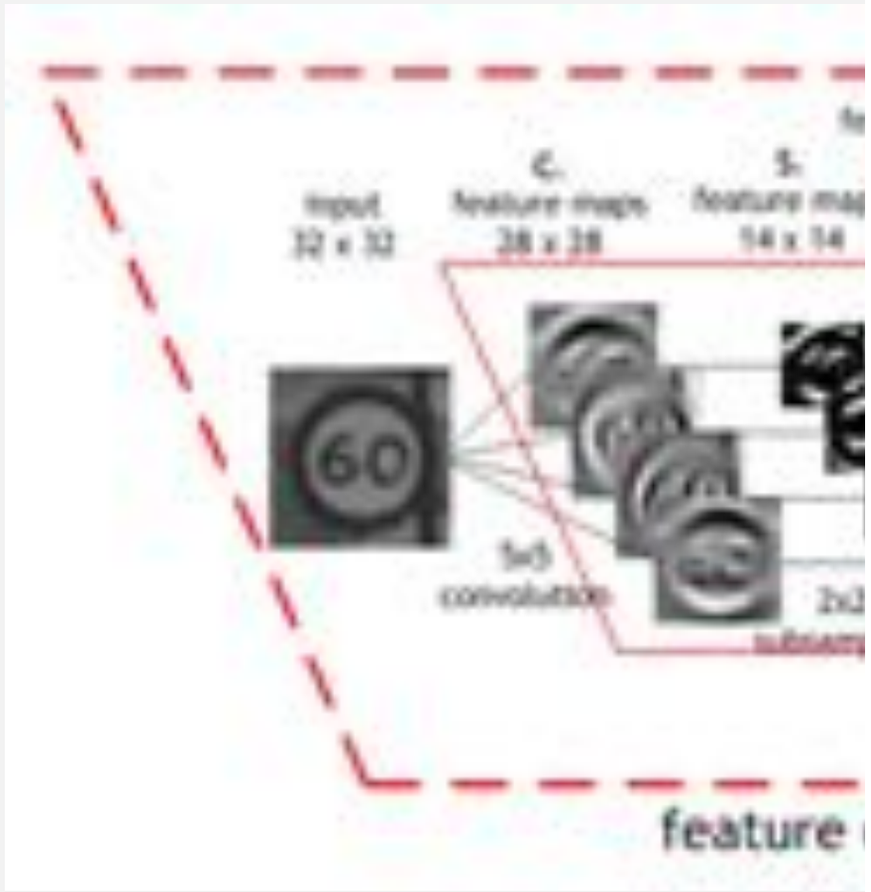
LAST 5 YEARS:
A LOT OF DEEP LEARNING

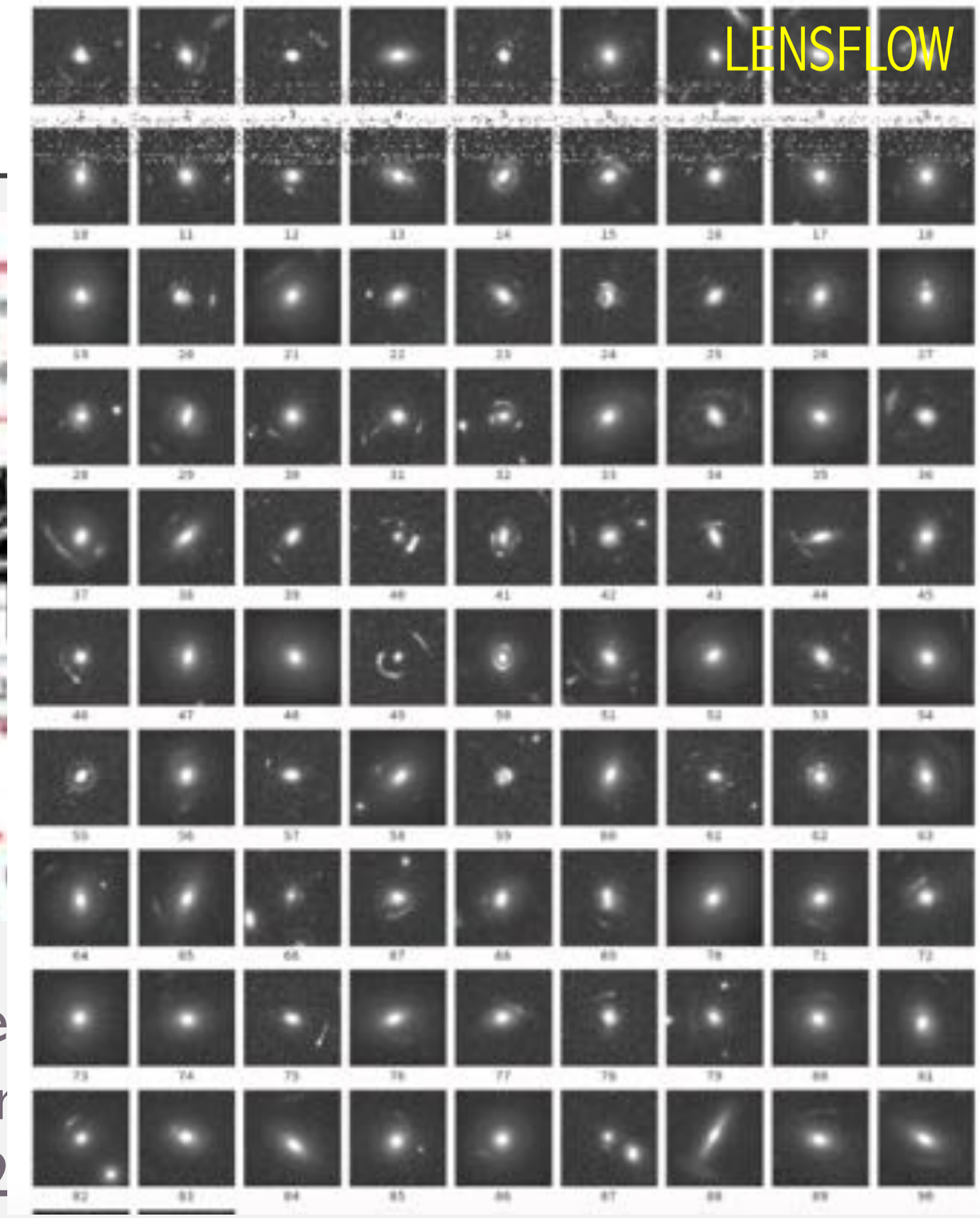


Why?

Well, it works.

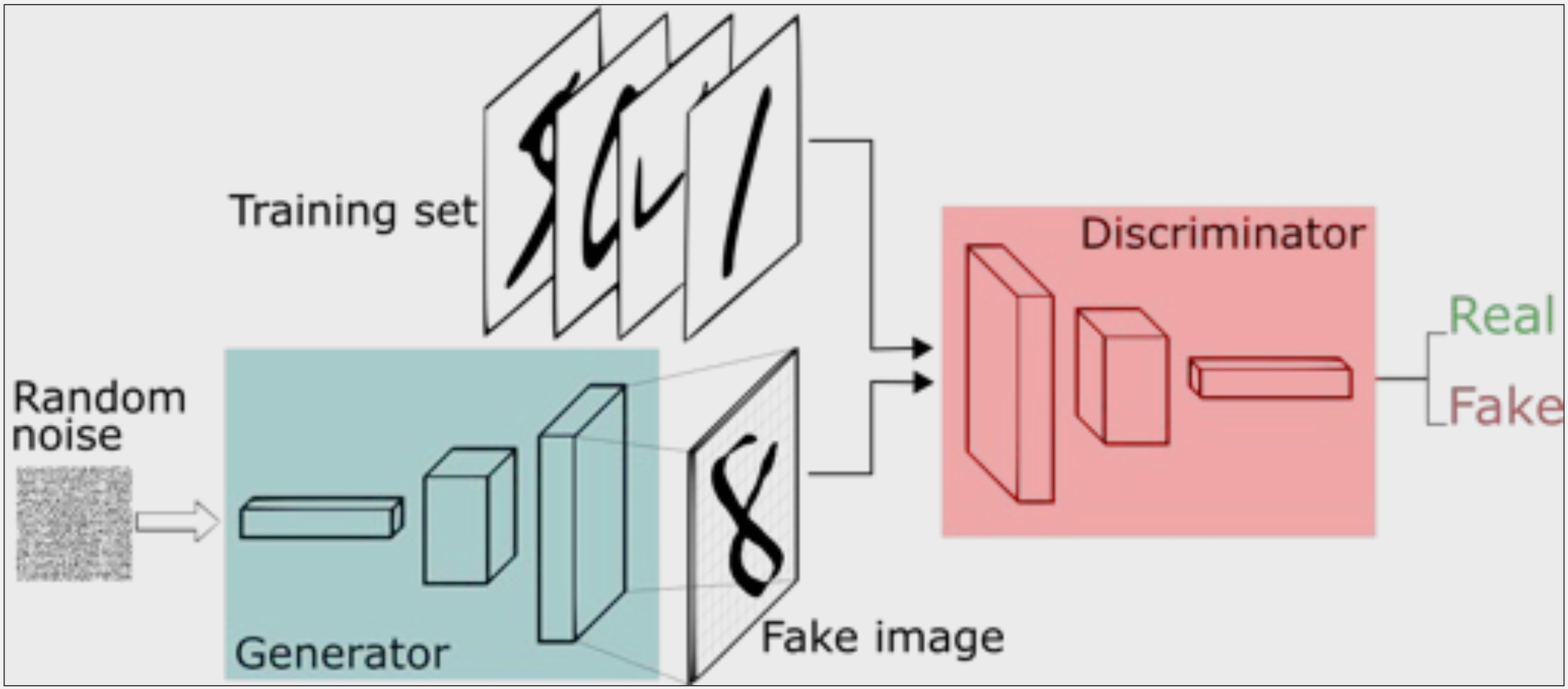
CONVOLUTIONAL NEURAL





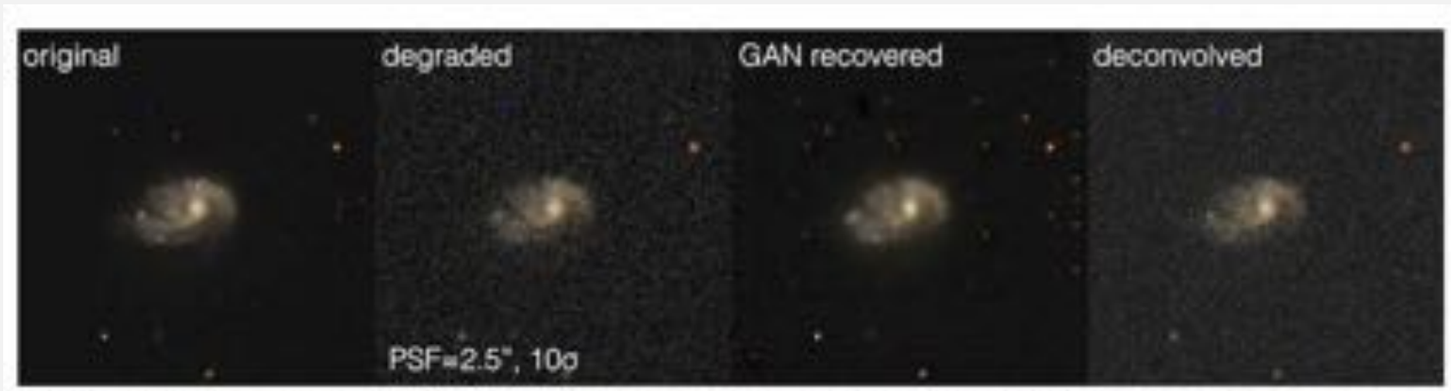
Built-in feature e
makes it perfect for
(e.g. Kim et al 2
Itam+Pasquet 2017, Flamary 2017, Pourrahmani et al 2018, Lovell, VA+ 2019)

GENERATIVE ADVERSARIAL NETWORKS



GENERATIVE ADVERSARIAL NETWORKS

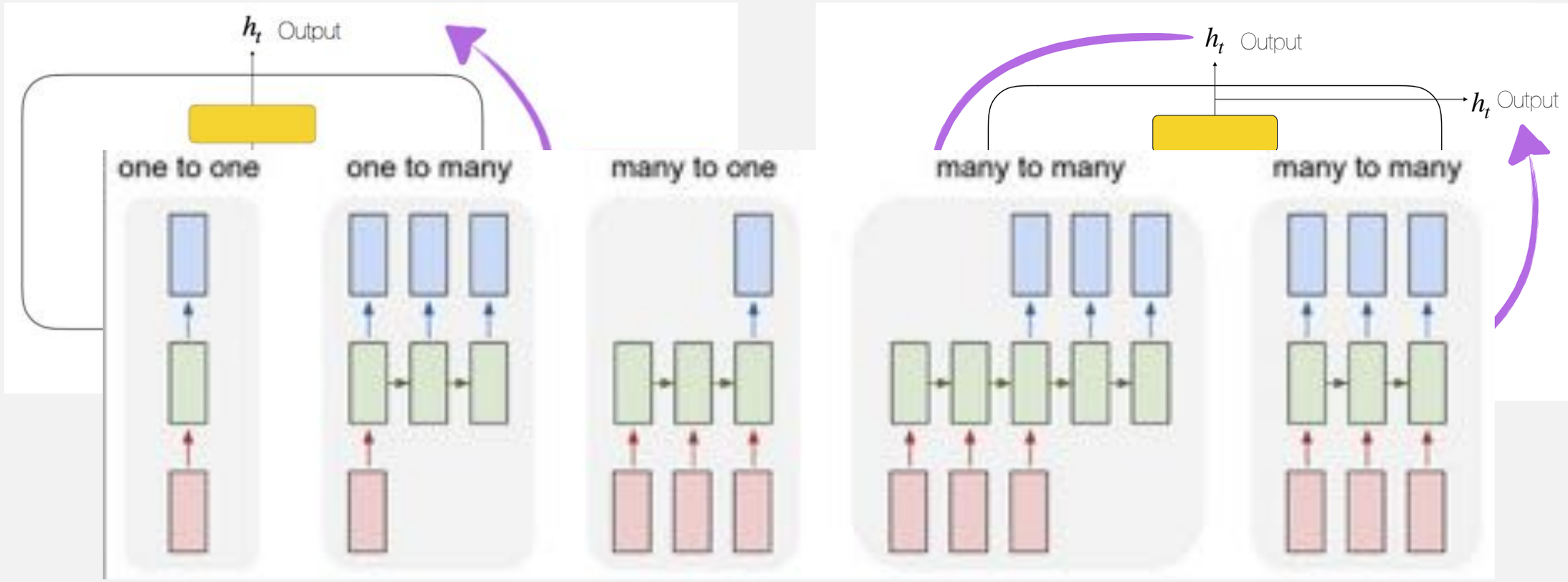
Use: Upsample resolution of galaxy images (Shawinski et al 2017)



Example results achieved with the GAN. From left to right: the original SDSS image, the degraded image with a worse PSF and higher noise level (indicating the PSF and noise level used), the image as recovered by the GAN, and for comparison, the result of a deconvolution. This figure visually illustrates the GAN's ability to recover features which conventional deconvolutions cannot.

Generate simulated galaxies (Fussell and Meows 2018)

RECURRENT NEURAL NETWORKS



source: http://karpathy.github.io/2015/05/21/rnn-effectiveness/

Next word prediction example: Let's feed an RNN some bio information about me, train it, then ask to complete the sentence:
I was born in...

Now imagine doing the same for any time-ordered data!
(Naul et al 2018, Zhang et al 2018)

NEURAL NETWORKS HAVE BEEN AROUND SINCE THE 1960S

WHY ARE THEY EXPLODING NOW?

https://colab.research.google.com/drive/

TOMORROW: SQUEEZING INFORMATION ABOUT GALAXIES USING BAYESIAN INFERENCE AND ML

QUESTIONS TIME