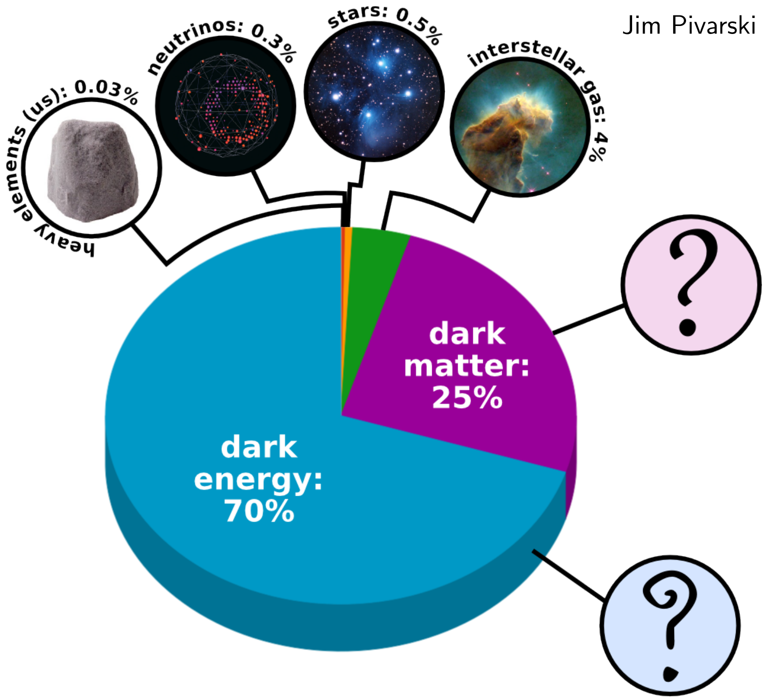
Dark Matter and Dark Energy

Jim Pivarski

March 4, 2012

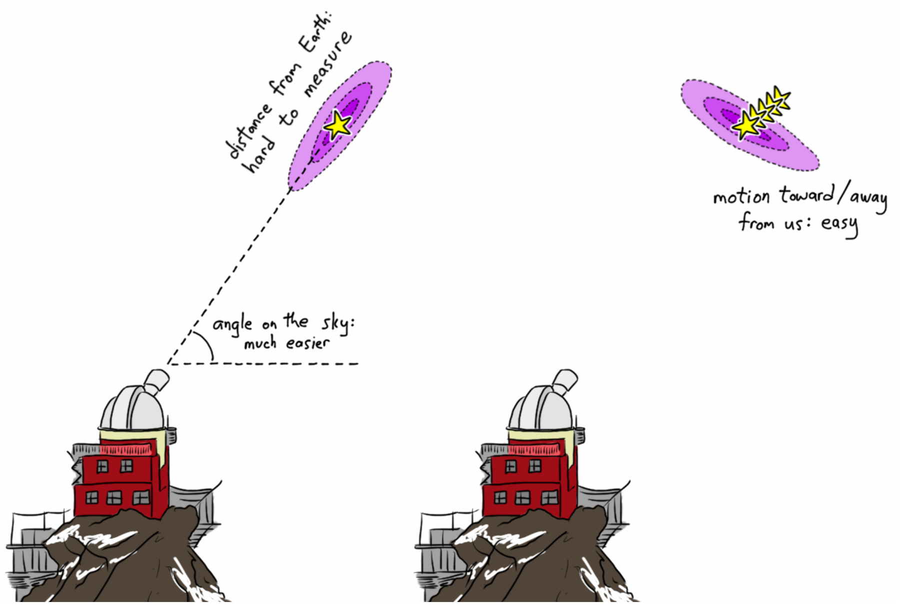
Matter as we know it is
a minority of the universe.

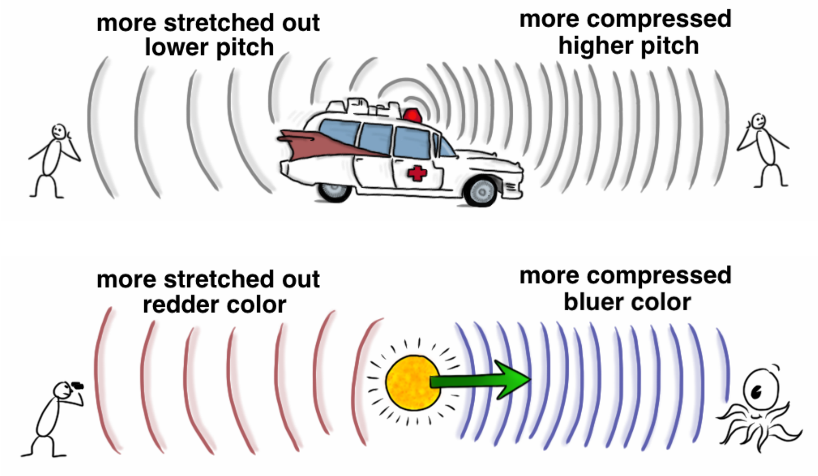

heavy elements (us): 0.03%
neutrinos: 0.3%
stars: 0.5%
interstellar gas: 4%
dark matter: 25%
dark energy: 70%
?
?

This talk:

- What is dark matter?
  - The astronomer's toolbox: how we measure the sky
  - More mass than expected
  - What is it? (narrowing the options)
- What is dark energy?
  - How space-time curves
  - Expansion of the universe
  - Accelerating expansion: what is it???

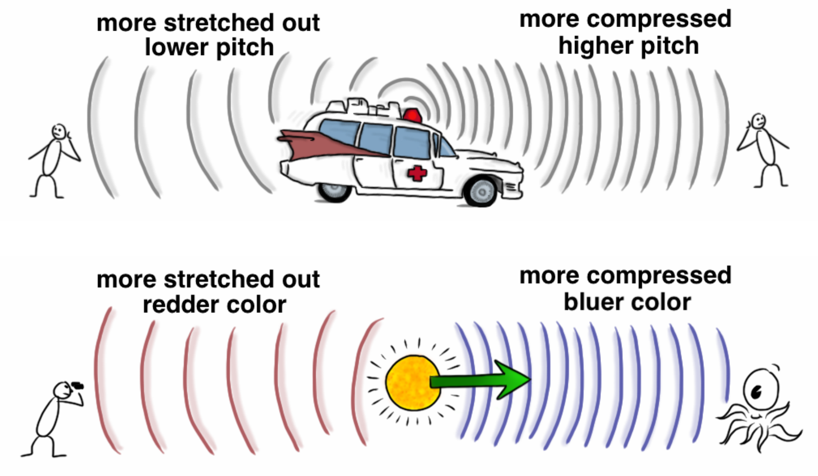
The astronomer's toolbox





By comparing the observed color of the star with its actual color, we can determine how fast it's moving.

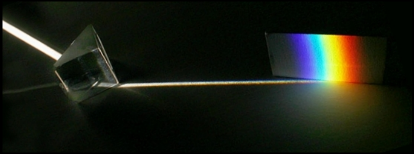
The astronomer's toolbox



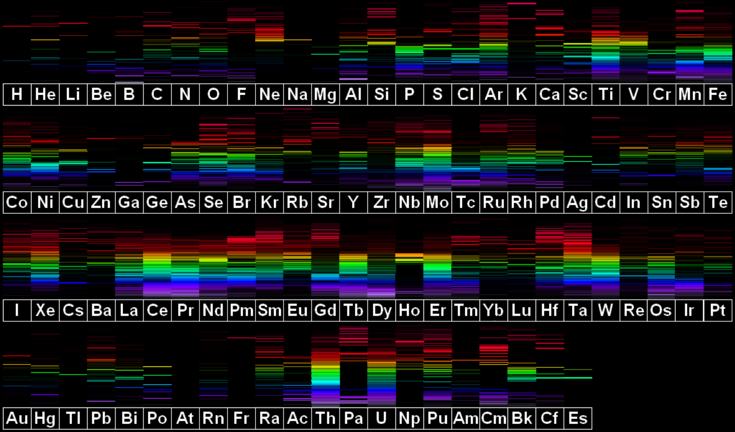
By comparing the observed color of the star with its actual color, we can determine how fast it's moving.

But how do we know the actual color of the star?

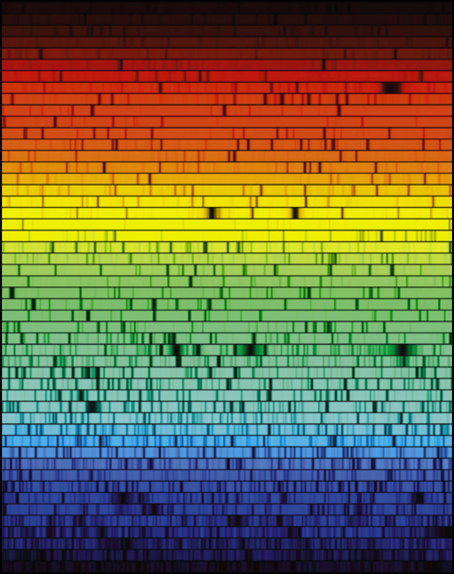
Chemical fingerprints



Every element has a unique set of spectral lines.



Chemical fingerprints



The Sun

The spectrum of each star is a combination of these lines, in proportion to the abundance of the elements in the star.

If the star is moving toward or away from us, the whole spectrum is merely shifted to the right (bluer) or the left (redder).

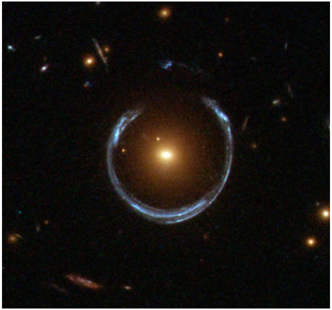
The combinations of lines are distinct enough to be recognized in spite of the shift.

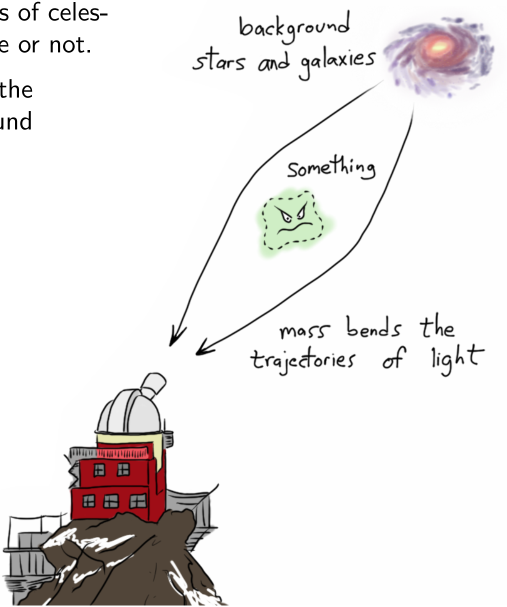
Another tool: measuring mass

Astronomers can measure the mass of celestial objects whether they are visible or not.

Mass bends space-time, distorting the paths of light rays from background stars and galaxies.

On earth, we see multiple images or even connected rings of the background galaxies.





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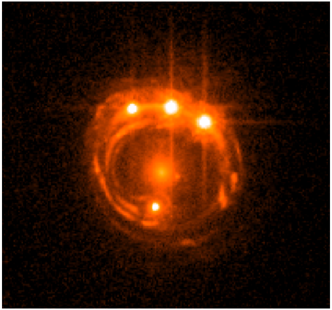
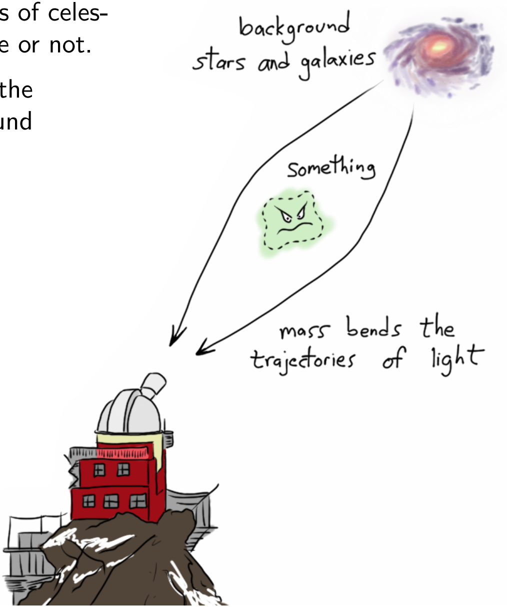
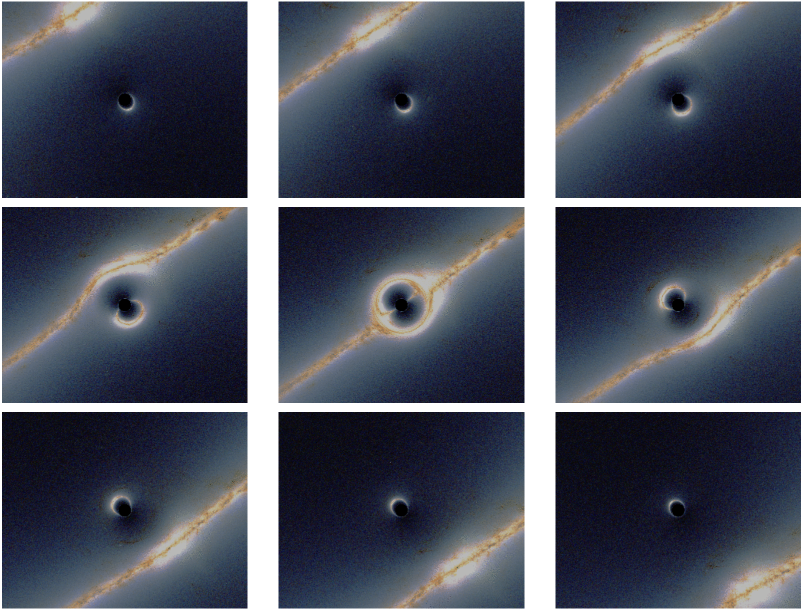




Simulated lensing of a black hole

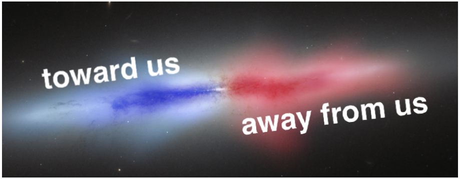


Dark Matter

Newton and Einstein's theories of gravity were developed and tested in the solar system: do they work for larger objects?

- Measure orbital velocities of stars in the disks of galaxies (from red/blueshifts).

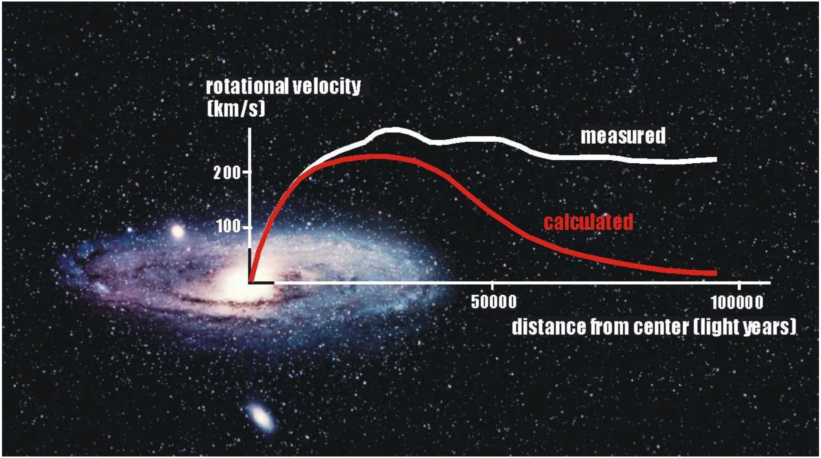
edge-on galaxy with exaggerated colors



- Newton's law predicts orbital velocity versus distance from the center, assuming knowledge of the mass distribution.

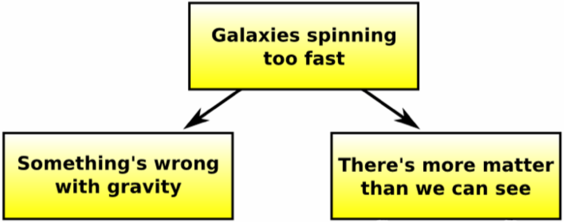
  (Einstein's corrections are negligible.)
- Assume that the mass is primarily due to observed stars and gas.

The result (same for most galaxies)

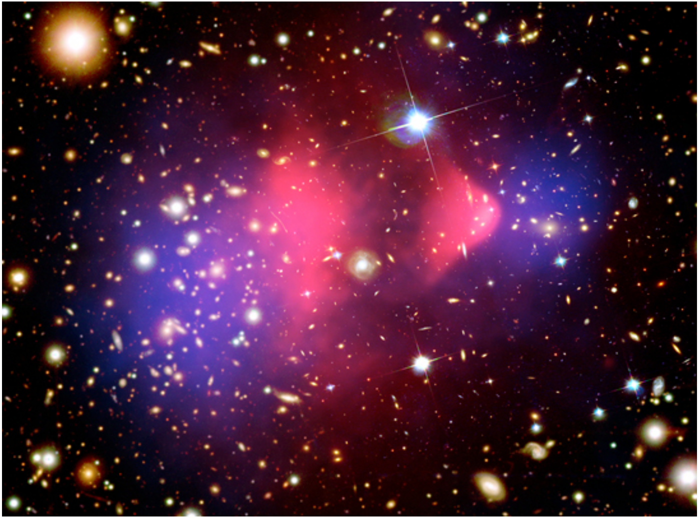


- Stars are orbiting the galactic core too fast.
- If both assumptions were valid (theory of gravity and mass distribution), galaxies would have spun apart long ago.

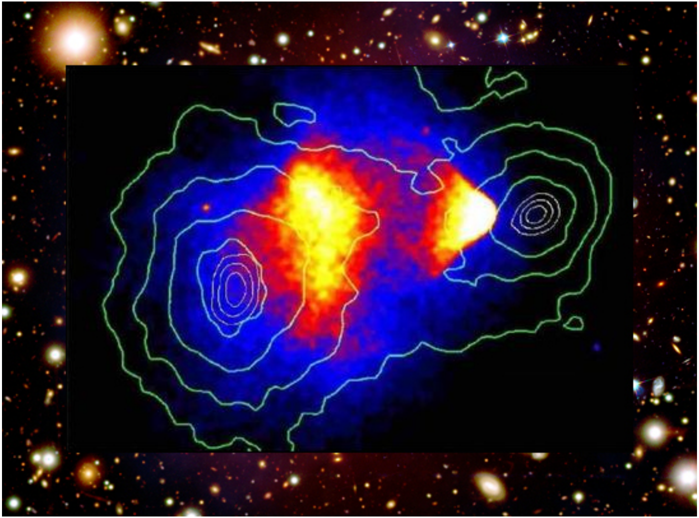
What could it be?



Modify gravity or missing matter?



Color: X-ray observations of hot gas (majority of normal matter).
Contours: mass distribution determined from gravitational lensing.



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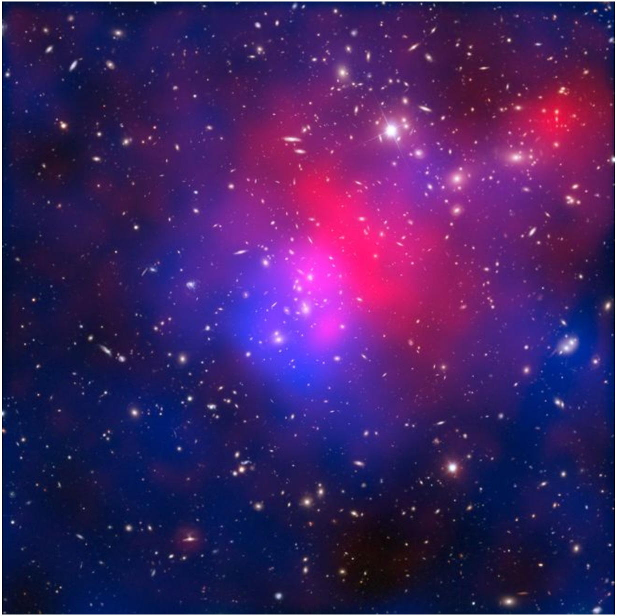
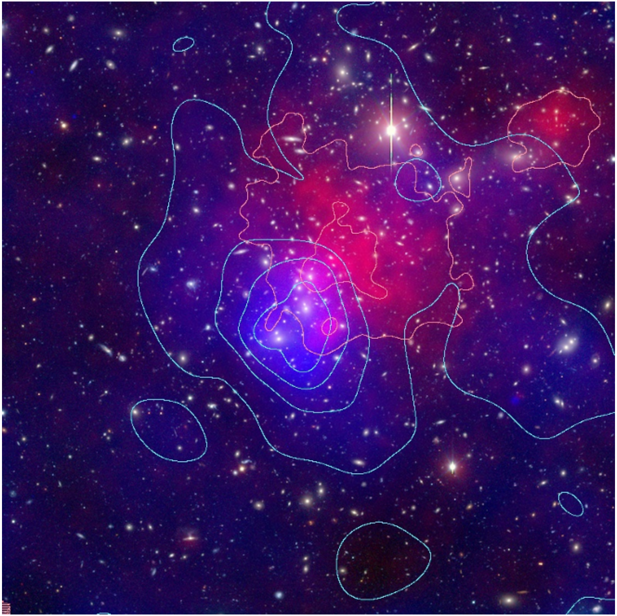


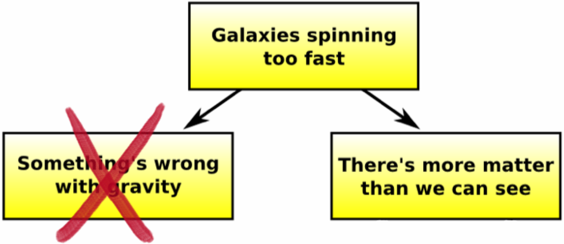
Modify gravity or missing matter?



After colliding, most of the mass of the galaxy clusters (blue) is light years away from the visible gas (red).

Strongly suggests that another *material* is present, not a modification of the gas's gravitational pull.

What could it be?



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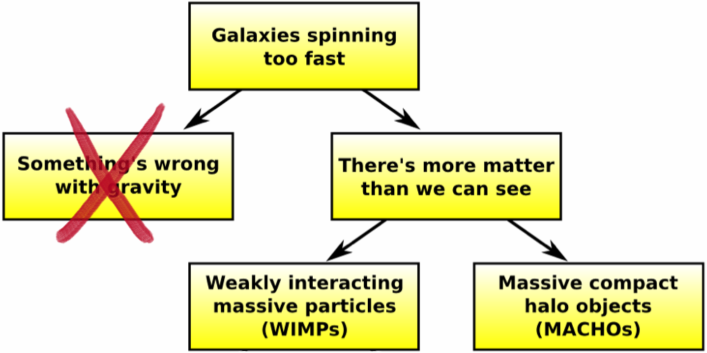
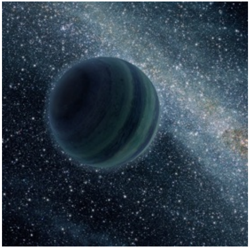


Massive Compact Halo Objects



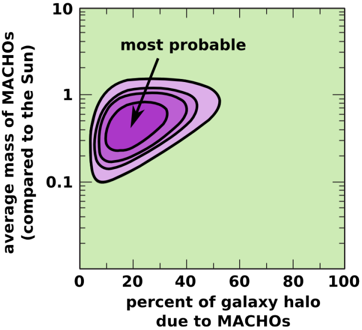
Types of MACHOs

- Free-floating planets and brown dwarfs
- Old white dwarfs that have ceased glowing
- Neutron stars
- Black holes

Search with microlensing: luminosity of background star briefly spikes when a MACHO passes in front of it.

Decades of searches, tens of microlensing events observed.

Some of the unseen mass was due to MACHOs, but not the majority of it.



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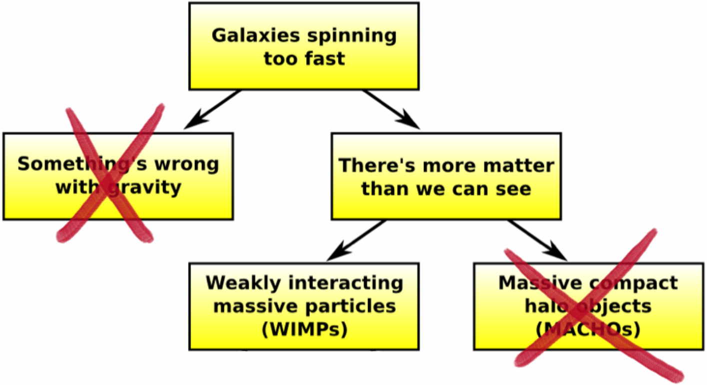

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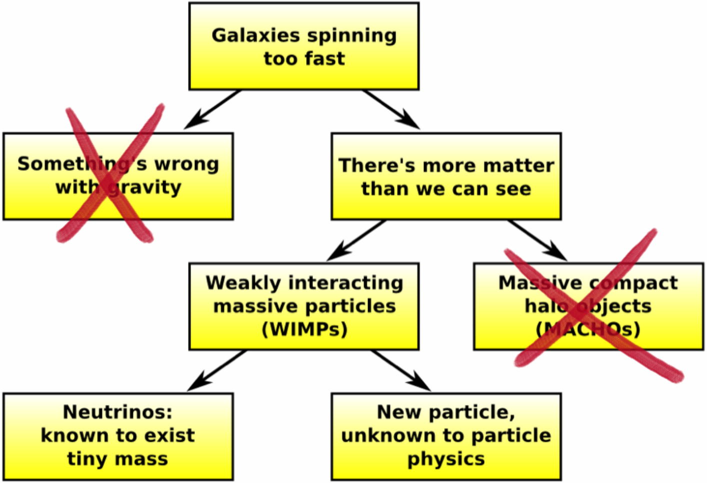


Neutrinos: oddballs of particle physics

- Nearly but not exactly massless, invisible, and intangible.
- Three "flavors," but spontaneously change flavor when travelling long distances.

- They probably do not travel faster than the speed of light.

  (Two errors were found in last year's apparent discovery.)
- Hard to detect; many of their basic parameters are still unknown or not well known.
- They swarm through space in vast numbers without our noticing: could this be the dark matter we're looking for?

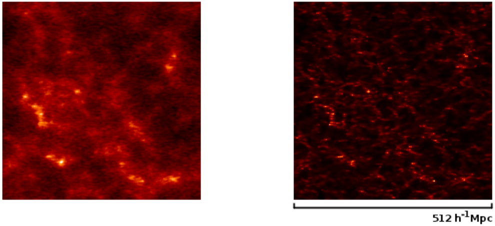
Dark matter determined the development of large-scale structure (galaxies and clusters of galaxies) in the universe.

Neutrinos are always traveling close to the speed of light.

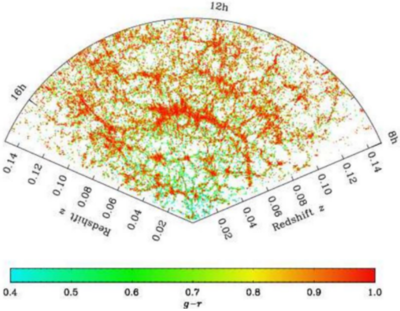
If most of the dark matter were neutrinos, they wouldn't stay put long enough to let those structures form.

What the universe would look like:

with neutrinos as dark matter **with slower dark matter**



What the universe looks like:



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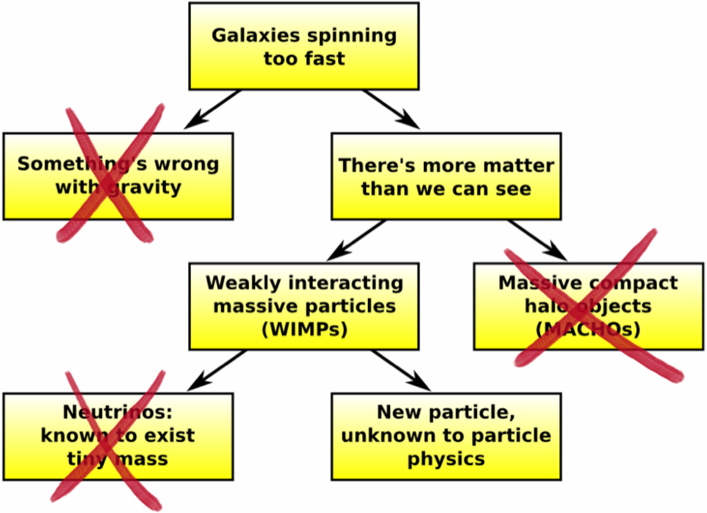
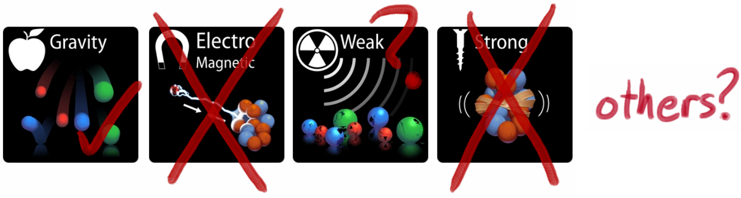
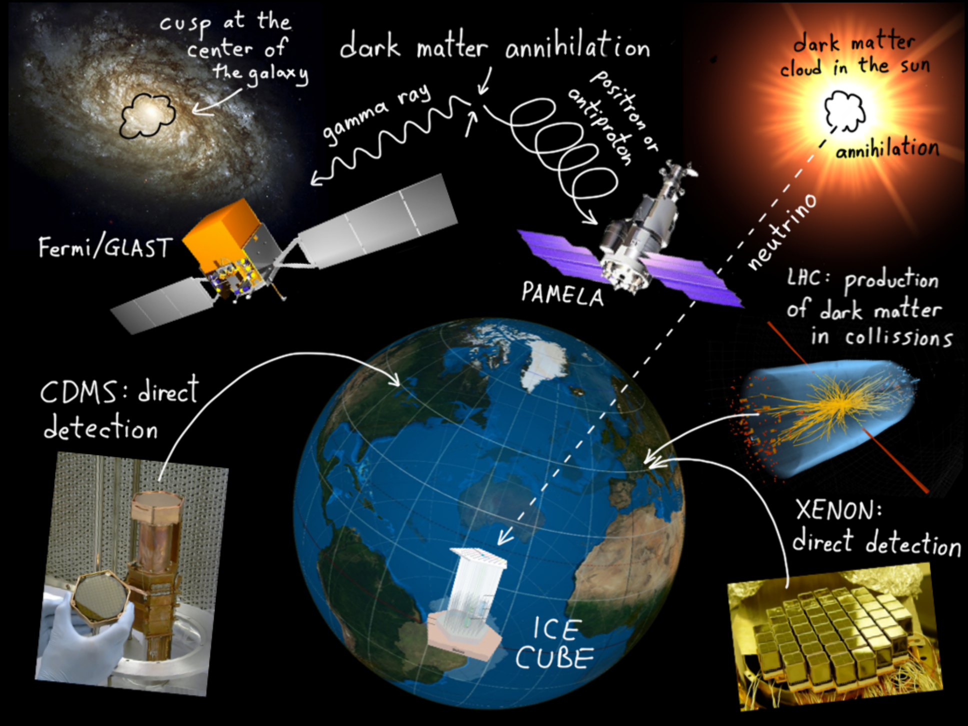


The nature of dark matter is one of the foremost mysteries in physics.

- Force laws obeyed:



- Speed: less than 95% of the speed of light.
- Mass: maybe 10^{11} eV (weak force scale) if thermally produced in the Big Bang. Maybe as low as 10^{-5} eV (axion) or as high as 10^{19} eV (WIMPZILLA) if not thermally produced.
- Connection to other mysteries of particle physics: maybe supersymmetry, extra dimensions, strong CP problem, inert Higgs doublet, sterile neutrinos, left-right symmetry. . .


cusp at the center of the galaxy
dark matter annihilation
dark matter cloud in the sun
gamma ray
positron or antiproton
annihilation
neutrino
Fermi/GLAST
PAMELA
LHC: production of dark matter in collissions
CDMS: direct detection
XENON: direct detection
ICE CUBE

Dark Energy

Dark energy resembles dark matter in that it has “dark” in its name and it’s not well understood.

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This name can be applied to anything that addresses the fact that the expansion of the universe is accelerating.

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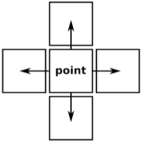
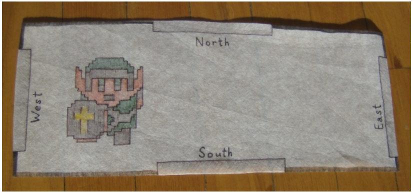
Universal expansion is an example of space-time curvature, so let’s start with that.

Space-time curvature in three steps

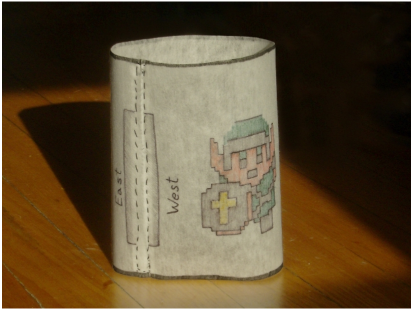
Step 1: Consider unusual connections between space points

Normal:





Unusual:



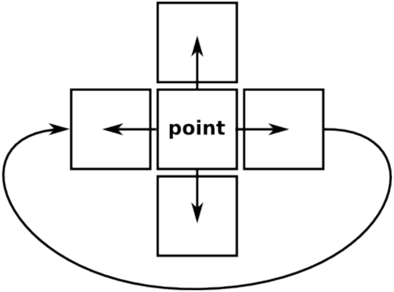
Space-time curvature in three steps

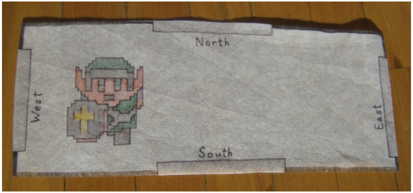
Step 1: Consider unusual connections between space points

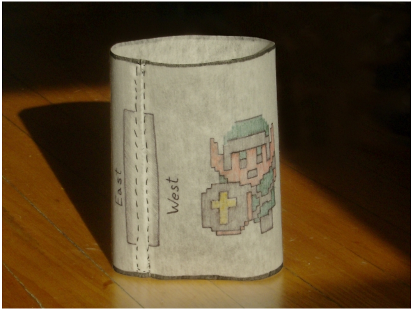
The cloth is just a metaphor: what is important is how each point in space is connected to all of the other points in space.

With cloth, we can sew together any stitch to any other stich.

With space, we can only imagine it.

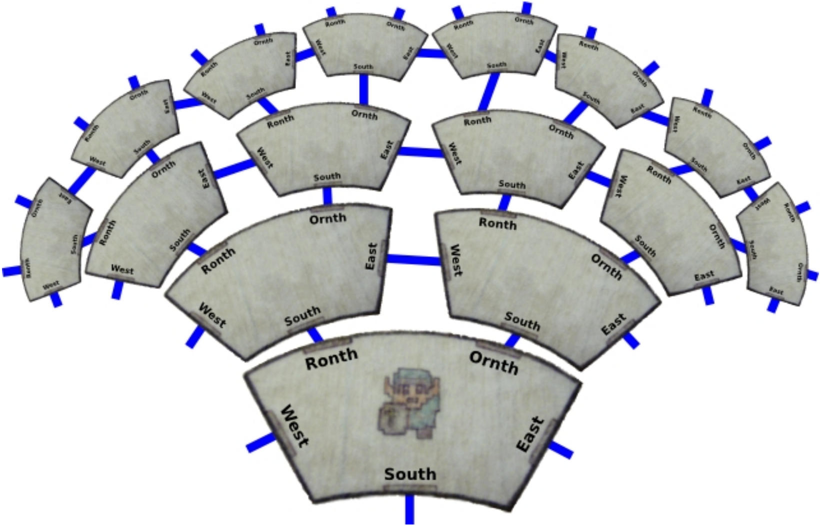






Space-time curvature in three steps

Step 2: Rewire nearby points with a repeating pattern



Space-time curvature in three steps

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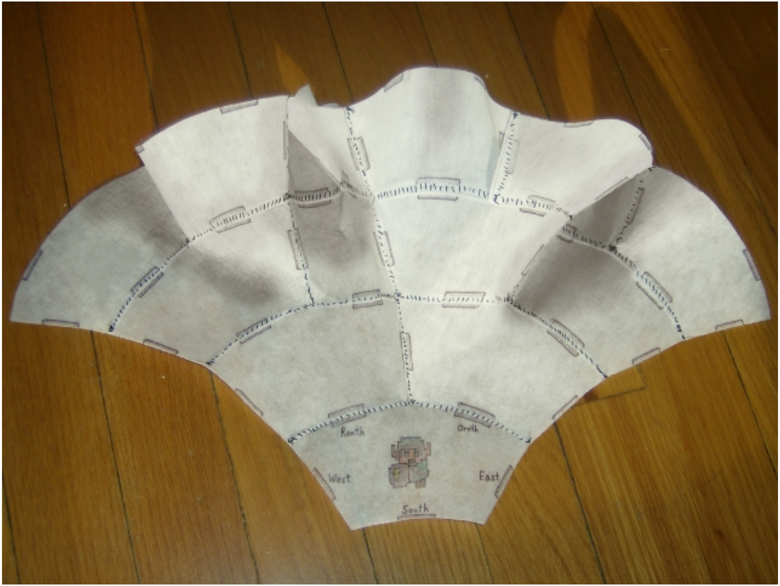

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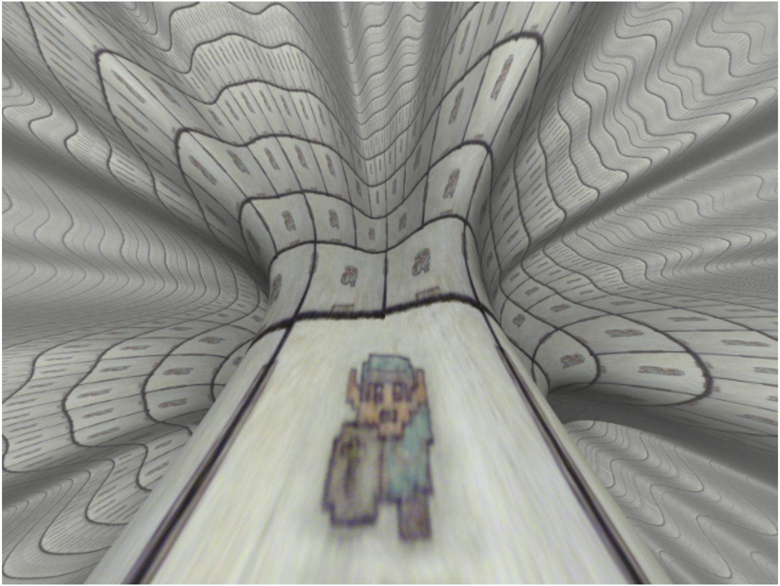
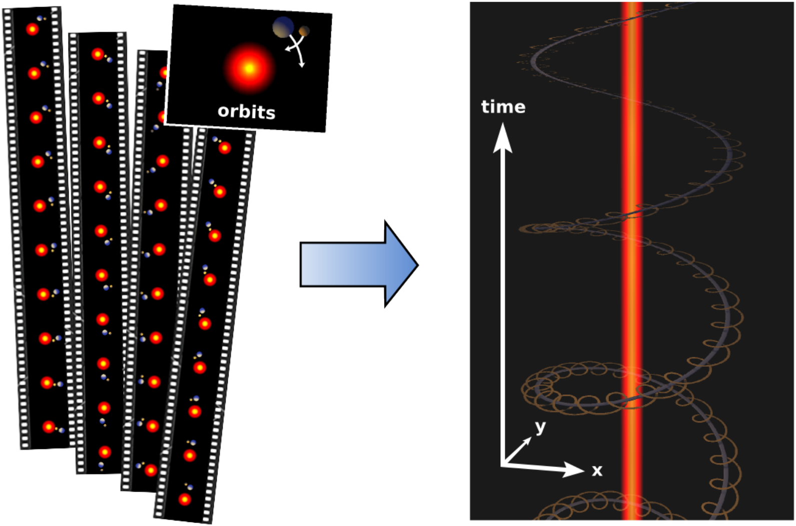


Space-time curvature in three steps

Step 3: Think of time as a dimension



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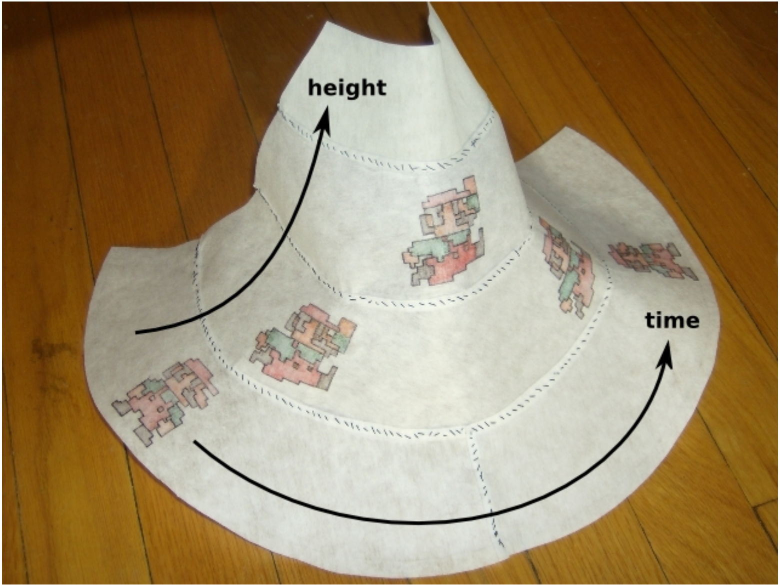
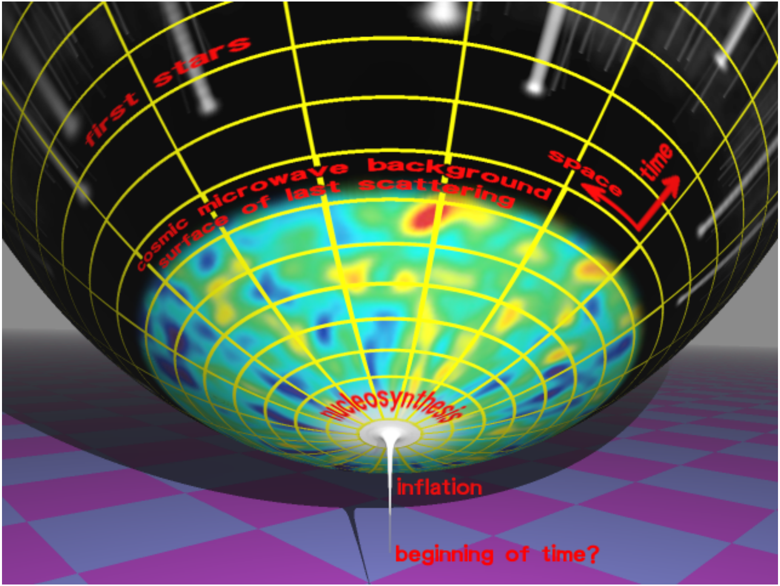
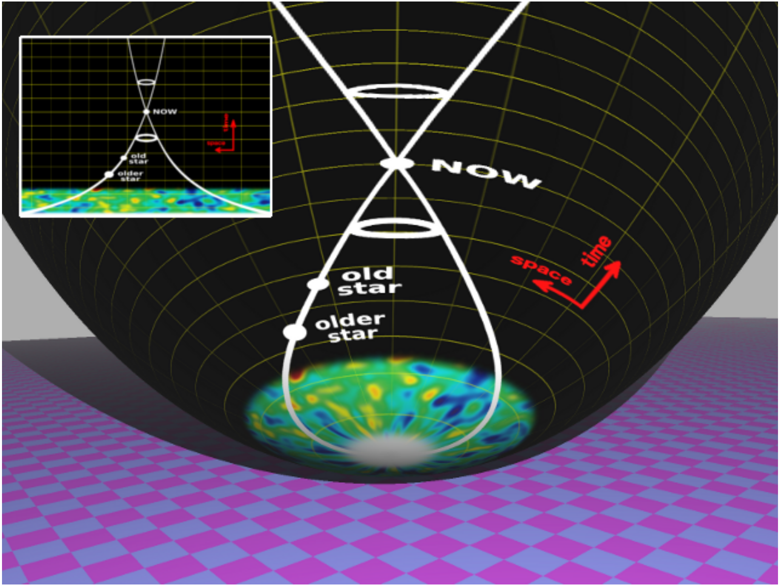
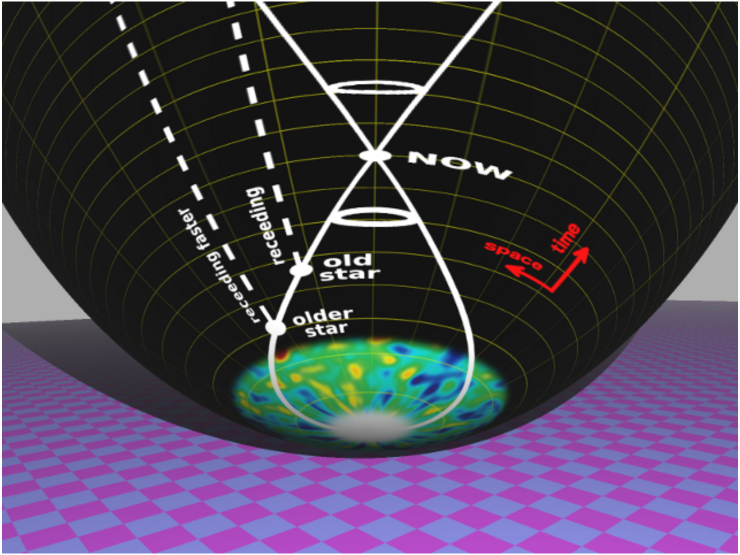



first stars
cosmic microwave background
surface of last scattering
space
time
nucleosynthesis
inflation
beginning of time?


NOW
old star
older star
space
time



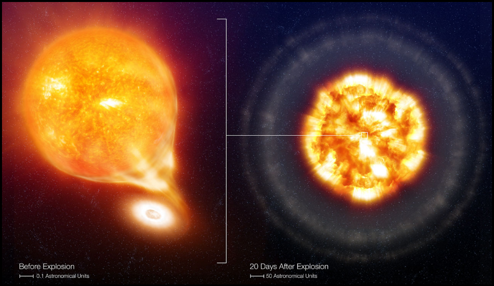
The shape can be measured with recession speed versus distance.

Type 1-A supernovae are a tool for measuring distance.

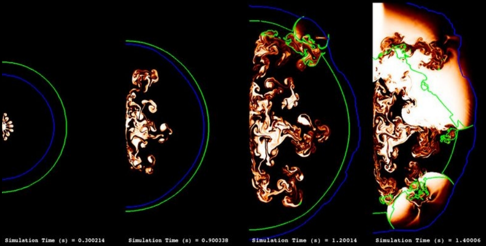
A white dwarf star accretes matter from its giant companion and explodes the moment it has acquired the critical mass.

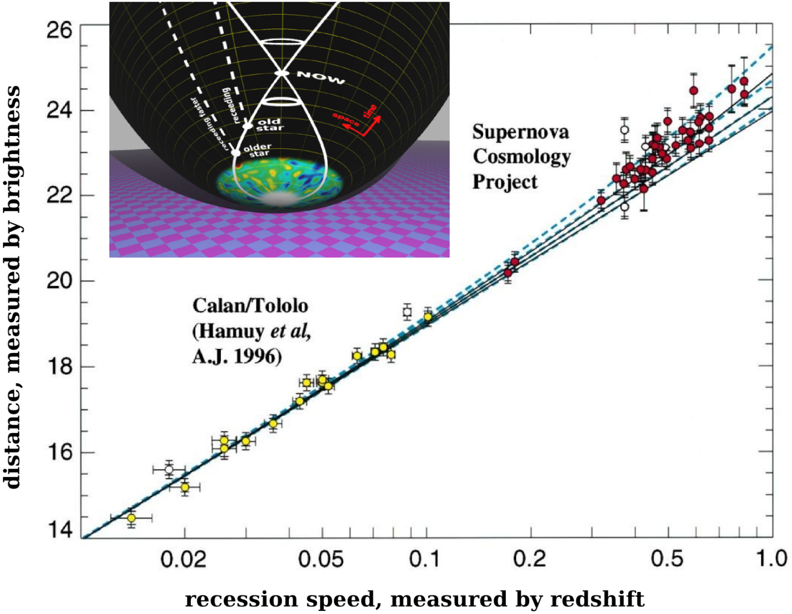
Thus, we know exactly how large and how bright it was.

Artist's conception



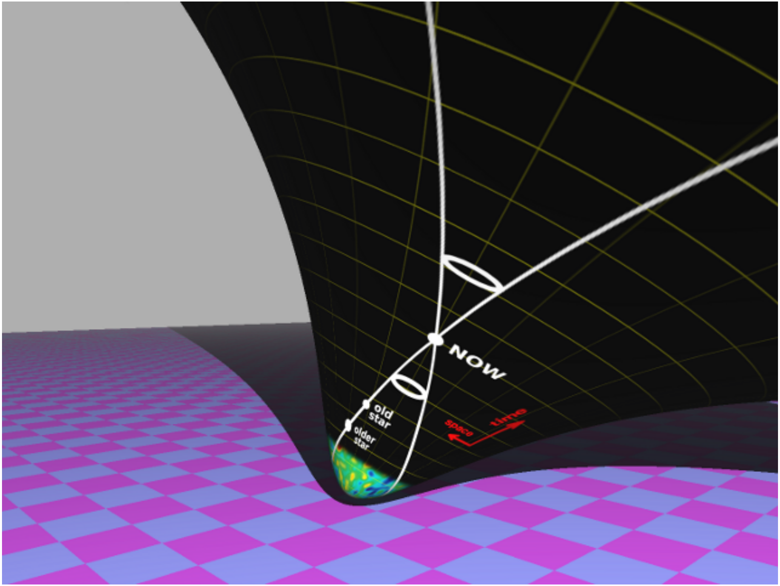
Computer simulation





NOW
receeding faster
receeding
old star
older star
space
time
Supernova Cosmology Project
Calan/Tololo (Hamuy et al, A.J. 1996)
distance, measured by brightness
recession speed, measured by redshift
14
16
18
20
22
24
26
0.02
0.05
0.1
0.2
0.5
1.0

Surprise: it's accelerating!



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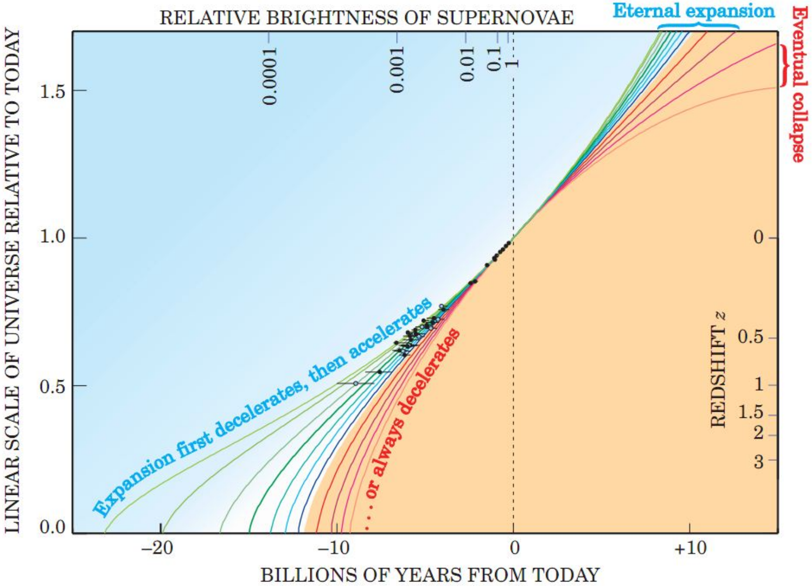
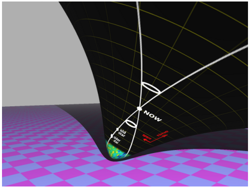
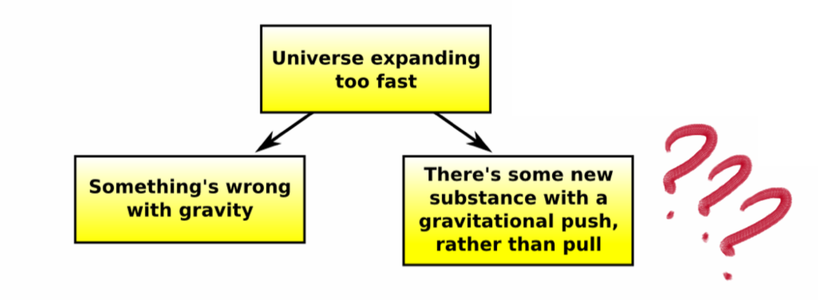




Accelerating expansion: what could it mean?

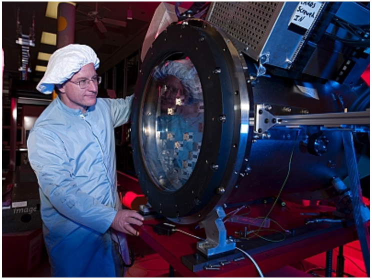
- Matter curves space-time in such a way that massive objects move toward each other (gravity).
- From all the matter in the universe, including dark matter, we would expect the universe to curve inward: *decelerating* expansion.



Dark Energy Survey, built at Fermilab

- Survey telescope to study dark matter and dark energy:
  - count galaxy clusters and use gravitational lensing to map the mass/dark matter distribution,
  - collect thousands of supernovae to map expansion history.
- Extremely wide field of view: 2.2 degrees, extremely deep: 570 megapixel camera, extremely fast: 17 seconds per image.
- Camera is being installed in Chile *right now.*

building the camera at Fermilab



Blanco observatory in Chile

Coffeeshop Physics
by Jim Pivarski

Why coffee? Why physics?

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Spinning Tops, Protons, and Planets

14 Jan 2012

When I was little, I tried to make an electromagnet by winding a thin wire around a nail and connecting it to a battery. I must have seen this on *Mr. Wizard's World*. But instead of magically picking up paper clips, it just got hot and wasted the battery. What I didn't understand is that the wire must be insulated, not bare metal: instead of flowing around the nail in many circular loops, the electric current flowed through the whole thing as a bumpy metal blob.

This fact that circulating electric currents produce magnetic fields can be seen everywhere in nature. Electromagnets, whether they flip bits in a hard drive or cars in a junkyard, are essentially just (insulated) wires wound around nails. Neutron stars spin faster and faster as they collapse, generating the strongest magnetic fields known in the universe. Elementary particles such as electrons are haloed by tiny magnetic fields due to their intrinsic spin, a kind of internal rotation they can never stop. Even refrigerator magnets are not as stationary as they seem: their magnetic fields are due to a partial alignment of electron spins.

Sometimes, though, the flow can be so turbulent and complicated that its dynamics are a mystery. The underlying equations are known, but even supercomputers are not powerful enough to determine the implications of those equations. Only simplified versions of these systems can be calculated, so the predictions don't exactly match the real systems in all their messy glory. The two examples I have in mind are a proton's magnetic field and the Earth's. **read more »**

The Crunchy Star

14 Oct 2011

A voyage to the sun would not be a pleasant trip. While still a million miles away, the tungsten hull of our spacecraft would start to melt. At half a million miles, it evaporates. A little farther and we'd be nothing but swirling plasma, mixing into a nuclear furnace so vast that "oceans" would be an understatement.

Though we could never touch the sun, there are stars that you can touch— former stars, anyway— and one has recently been discovered [link to paper]. It is only four thousand light-years away (16.1 years traveler time; see "We Can Get There from Here"). This star has been transformed by its neighbor into a husk of cold diamond. Since it's solid, some astrophysicists are calling it a planet, but it's not clear that the word applies to an object with such a bizarre history.

Suppose that we take the 16-year trip to visit this world: what would it look like? Could we really stand on the heart of a dead star? **read more »**

We Can Get There From Here

23 Sep 2011

"Have you heard about this? Opera says neutrinos travel faster than light!"

I was in a conversation at Fermilab yesterday when I first heard about it. "Is that like one of those things where astrophysicists say that quasar jets travel faster than light, but only because they're leaving out some projection effect?" I said.

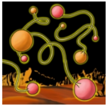
"No, this is for real. Except— I think so. I can't really tell; the article doesn't say very much."

I shrugged. I have no nose for news. It was only when my wife asked me about it that I knew it was a big story. She usually hears too much physics from me, so she doesn't actively seek it out. By that point, it was in all the newspapers, the experimenters made their paper public, and CERN's director general sent out a general e-mail.

If it's true that neutrinos travel faster than light, it would be a huge upset. Some may take it to mean that relativity is overturned, Einstein rolls in his grave, and there's no longer

Quirky Science Fiction

16 Sep 2011



I like old science fiction. The stories from the first half of the twentieth century didn't always get the science right, but they incorporated a lot of the latest ideas of their time. For example, *When Worlds Collide*, a 1934 novel about the Earth colliding with a roving exoplanet, had this description of the rocket that would save a remnant of humanity:

"Each of these tubes generates the rays that split atoms of beryllium into their protons and nuclei. The forces engendered in the process, which is like a molecular explosion, but vastly greater, together with the disrupted matter, is then discharged through this gun..."

Splitting atoms? Vast forces? They're talking about nuclear energy ten years before the world knew about the atom bomb. But more surprisingly, the authors knew that beryllium might be a good atom to do it. Leó Szilárd's secret patent two years later was based on the idea that beryllium or uranium might start a chain reaction— beryllium didn't work, but uranium did.

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