

Title: Katherine Freese: The Dark Side of the Universe

Date: Mar 02, 2016 07:00 PM

URL: <http://pirsa.org/16030084>

Abstract: <p>The ordinary atoms that make up the known universe, from our bodies and the air we breathe to the planets and stars, constitute only 5 percent of all matter and energy in the cosmos. The remaining 95 percent is a recipe of 25 percent dark matter and 70 percent dark energy, both nonluminous components whose nature remains a mystery.</p>

<p>In her March 2 public lecture, Katherine Freese will recount the hunt for dark matter, from the discoveries of visionary scientists like Fritz Zwicky, the Swiss astronomer who coined the term "dark matter" in 1933, to the deluge of data today from underground laboratories, satellites in space, and the Large Hadron Collider.</p>



The Cosmic Cocktail: Three Parts Dark Matter

Katherine Freese



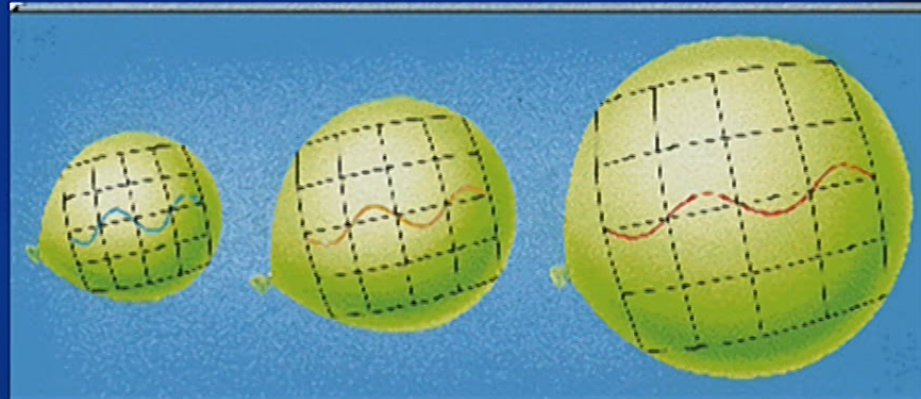
Origins of Modern Cosmology

- A scientific approach to the shape and evolution of the Universe date to the brilliant insights of Einstein's General Relativity in 1915.
- Friedmann, Robertson, Walker, Lemaitre (1920' s) applied Einstein' s theory to the universe as a whole.
- Several possible solutions to the equations existed: expanding, contracting, or static.
- Einstein preferred the extra symmetry of a static Universe. He postulated that it looks the same (on the average) at all times.

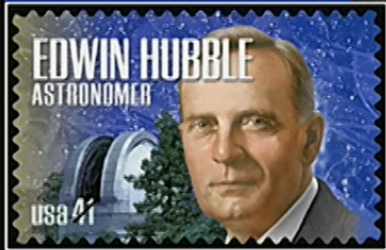
Hubble Expansion



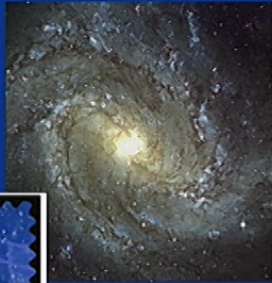
- In 1929 Edwin Hubble using the Mt. Wilson Observatory above Pasadena made an astonishing discovery. He observed light from galaxies at various distances away from Earth. The light waves are stretched, or redshifted, by the time they get to us. The reason is the expansion of space.
- THE UNIVERSE IS EXPANDING!!!
- Einstein abandoned the static Universe



Galaxies are expanding apart
from one another.
The Universe is expanding.

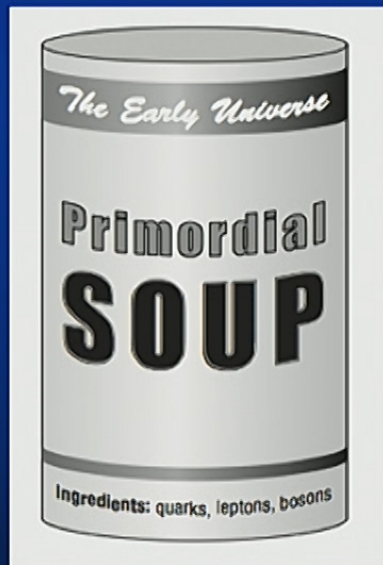


(1929)



THE BIG BANG

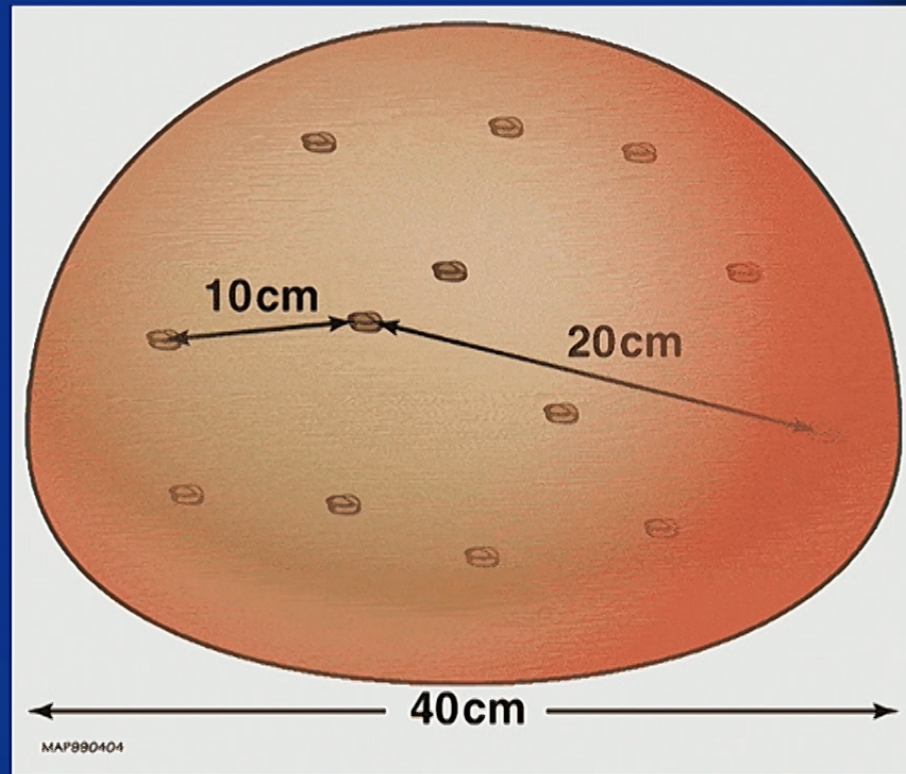
14 BILLION
YEARS AGO



The Universe started out hot;
It is cooling and expanding.

Raisin Bread Model of the Universe

- As the loaf rises, raisins move steadily apart from one another, with the loaf maintaining the same configuration.



As we look backwards in time:

- All points in infinite universe getting closer and closer
 - yet universe can still be infinite all the way back!
- Eventually, the density at each point is so great we lose description (maybe string theory?)

Big Bang at every point in the universe.

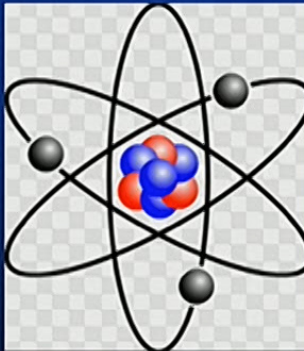
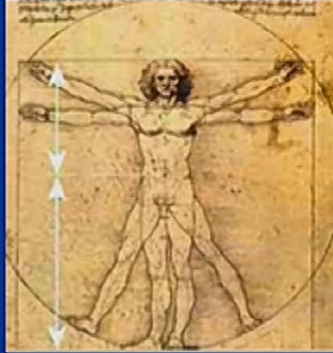
**Big Bang happens
everywhere at once (not at
a single point)**



What is the Universe made of?

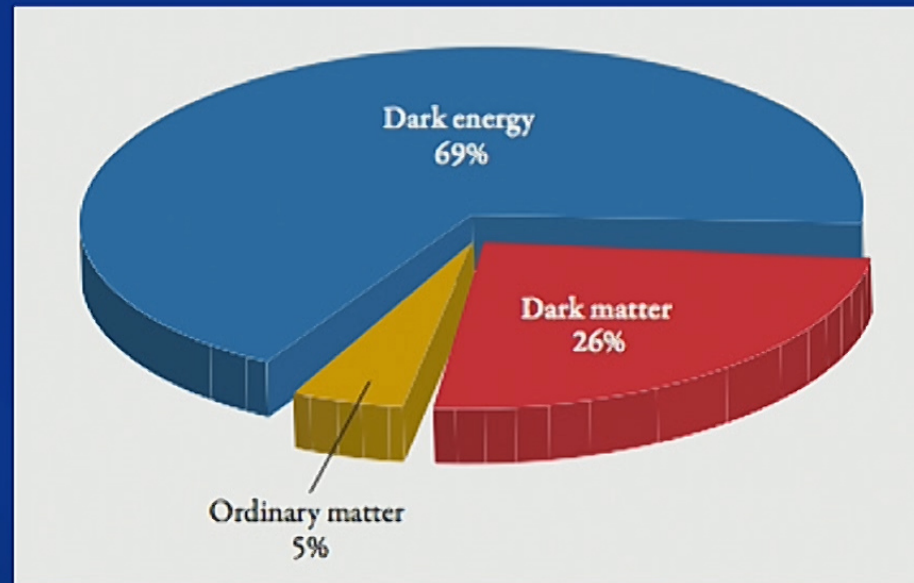
The answer is very SURPRISING!

All the objects of our daily experience:



ALL ADD UP TO ONLY 5% OF THE UNIVERSE!

Pie Chart of The Universe



Less than 5% ordinary matter.
What is the dark matter? What is the dark energy?

The Cosmic Cocktail: A Recipe for the Cosmos

3 oz. dark matter

7 oz. dark energy

1/2 oz. hydrogen and helium gas

3 thousandth oz. other chemical elements

5 hundredth oz. stars

5 hundredth oz. neutrinos

5 ten-thousandth oz. cosmic microwave background light

1 millionth oz. supermassive black holes

Shaken, not stirred.

Secret ingredient: dark matter



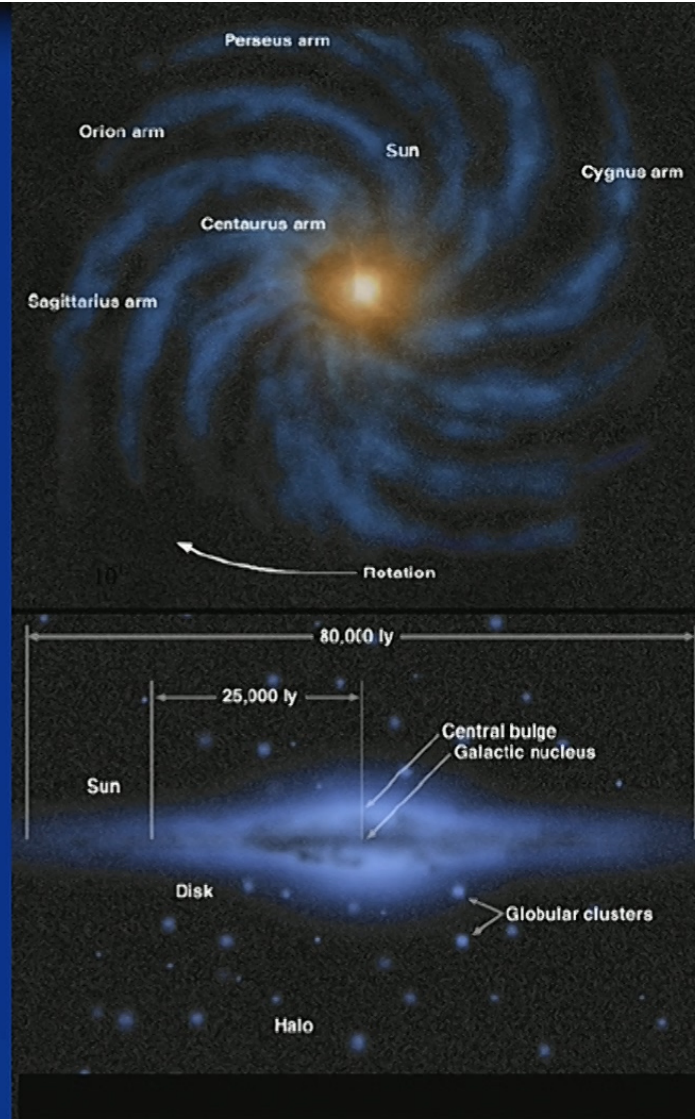
Dark Matter is the bulk of the mass in galaxies and clusters. How do we know?

- What do galaxies look like?
- Observational Evidence:
 - rotation curves
 - lensing
 - hot gas in clusters
 - Bullet Cluster

Our Galaxy: The Milky Way

The mass of the galaxy:

10^{12} solar masses



Galaxies have Dark Matter Haloes



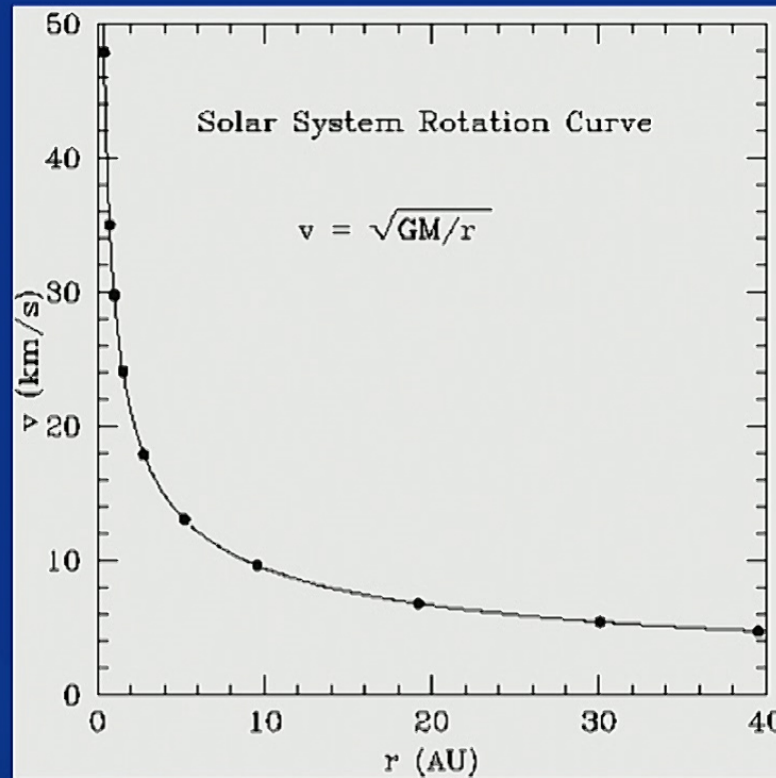
Rotation Curves

- How do we know that galaxies have dark matter haloes? Things are swirling around the center of the galaxy too fast: something is pulling on them!
- Rotation Curves.
- Example: Solar System Rotation Curve
- 95% of the mass of galaxies is made of an unknown component!!!

Solar System Rotation Curve

Average Speeds of the Planets

As you move out from the Sun, speeds of the planets drop.



Tyco Brahe (1546-1601)

Lost his nose in a duel,
and wore a gold and
silver replacement.

Studied planetary orbits.

Died of a burst bladder
at a dinner with the king.



Rotation Curves of Galaxies

Orbit of a star in a Galaxy: speed is Determined by Mass. Larger mass causes faster orbits.



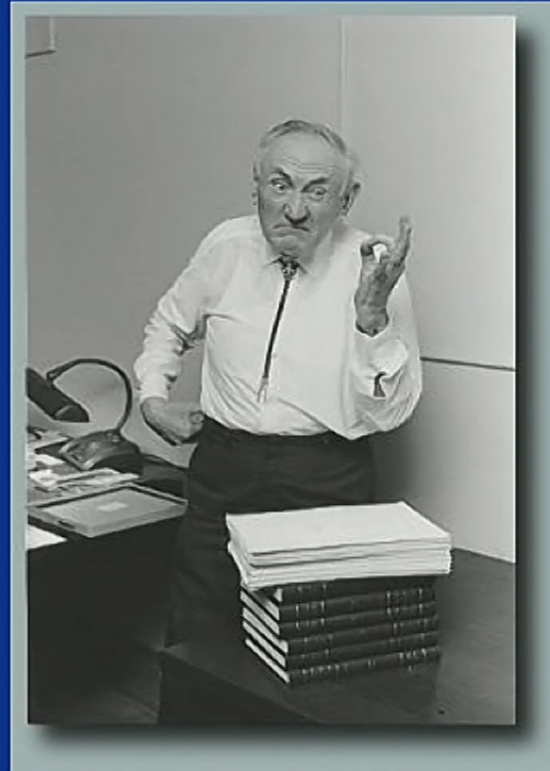
Fritz Zwicky in 1933

Galaxies in the
Coma cluster were
moving too rapidly.

He proposed
“Dunkle Materie”
as the explanation.

It's not stars, it doesn't shine.
It's DARK! It's mysterious!

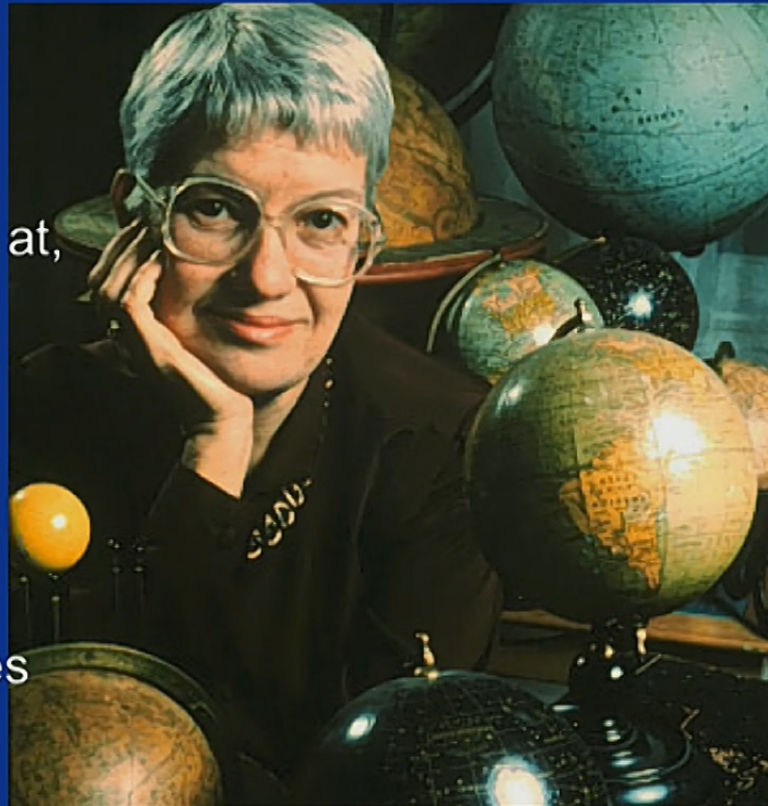
**THE BEGINNING OF
THE DARK MATTER
PROBLEM**



Vera Rubin in 1970s

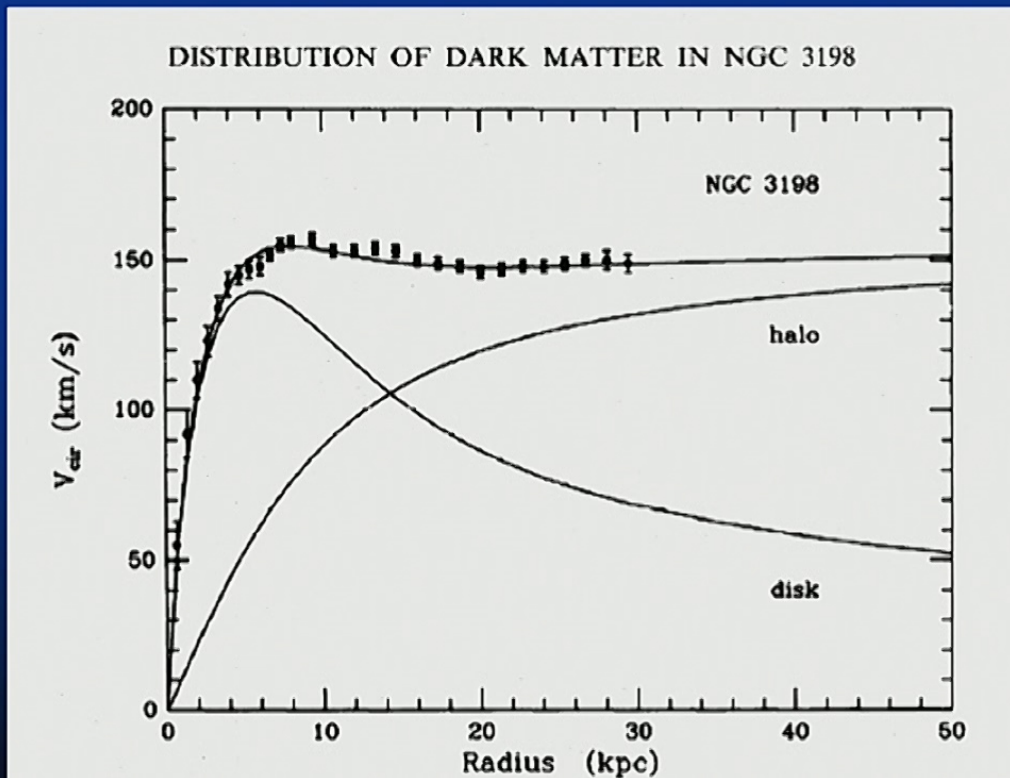
Found dark matter in all galaxies she looked at, and the scientific community became convinced that dark matter must exist.

She studied rotation curves of galaxies, and found that they are FLAT



95% of the matter in galaxies is unknown dark matter

- Rotation Curves of Galaxies:



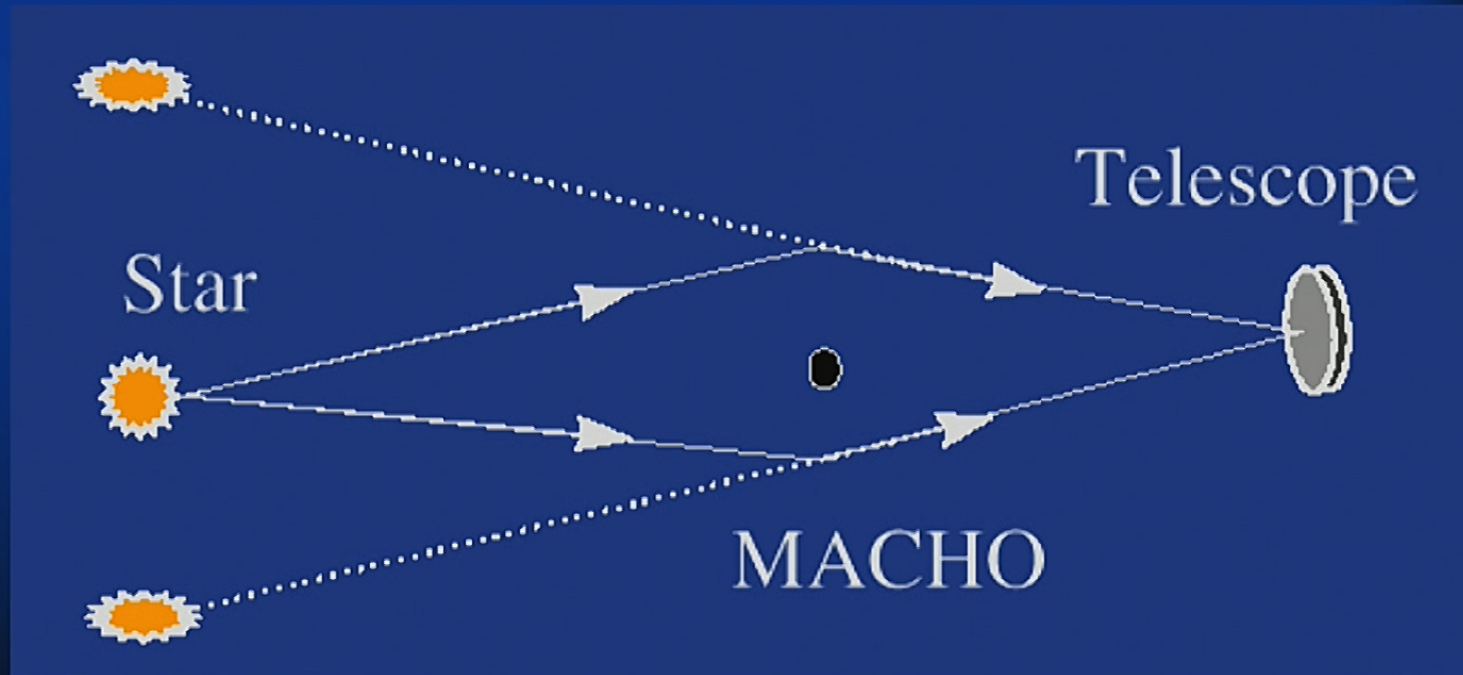
OBSERVED:
FLAT ROTATION
CURVE

EXPECTED
FROM STARS

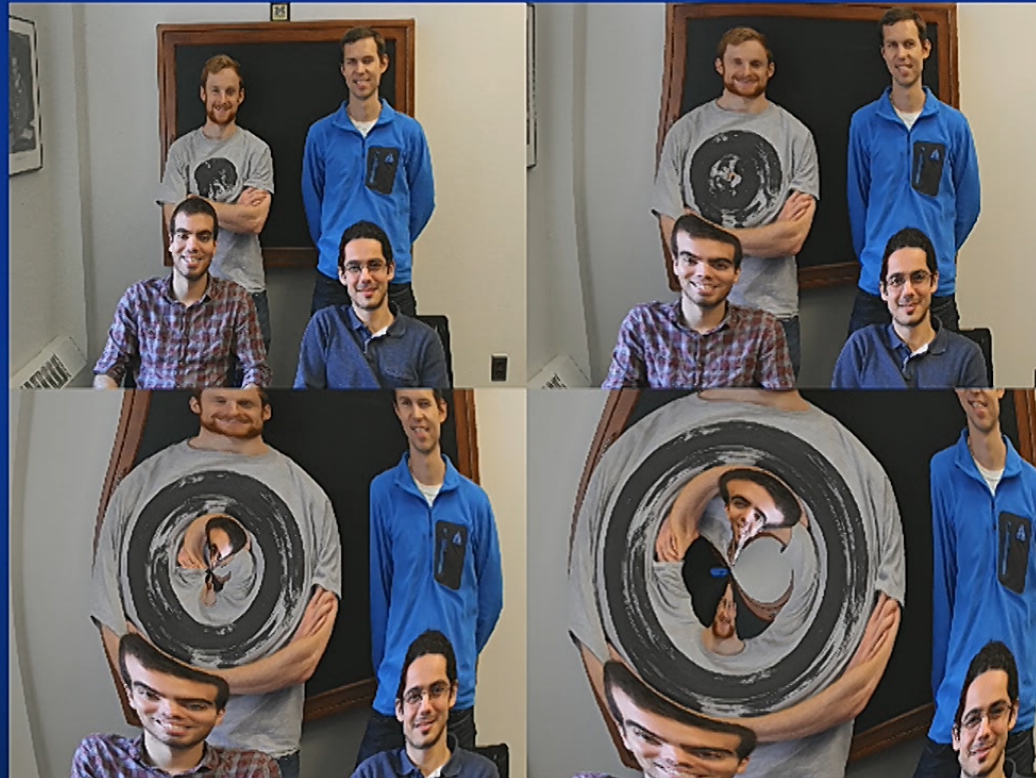
Galaxies have Dark Matter Haloes



Einstein's Lensing: Another way to detect dark matter: it makes light bend



Lensing of Michigan students



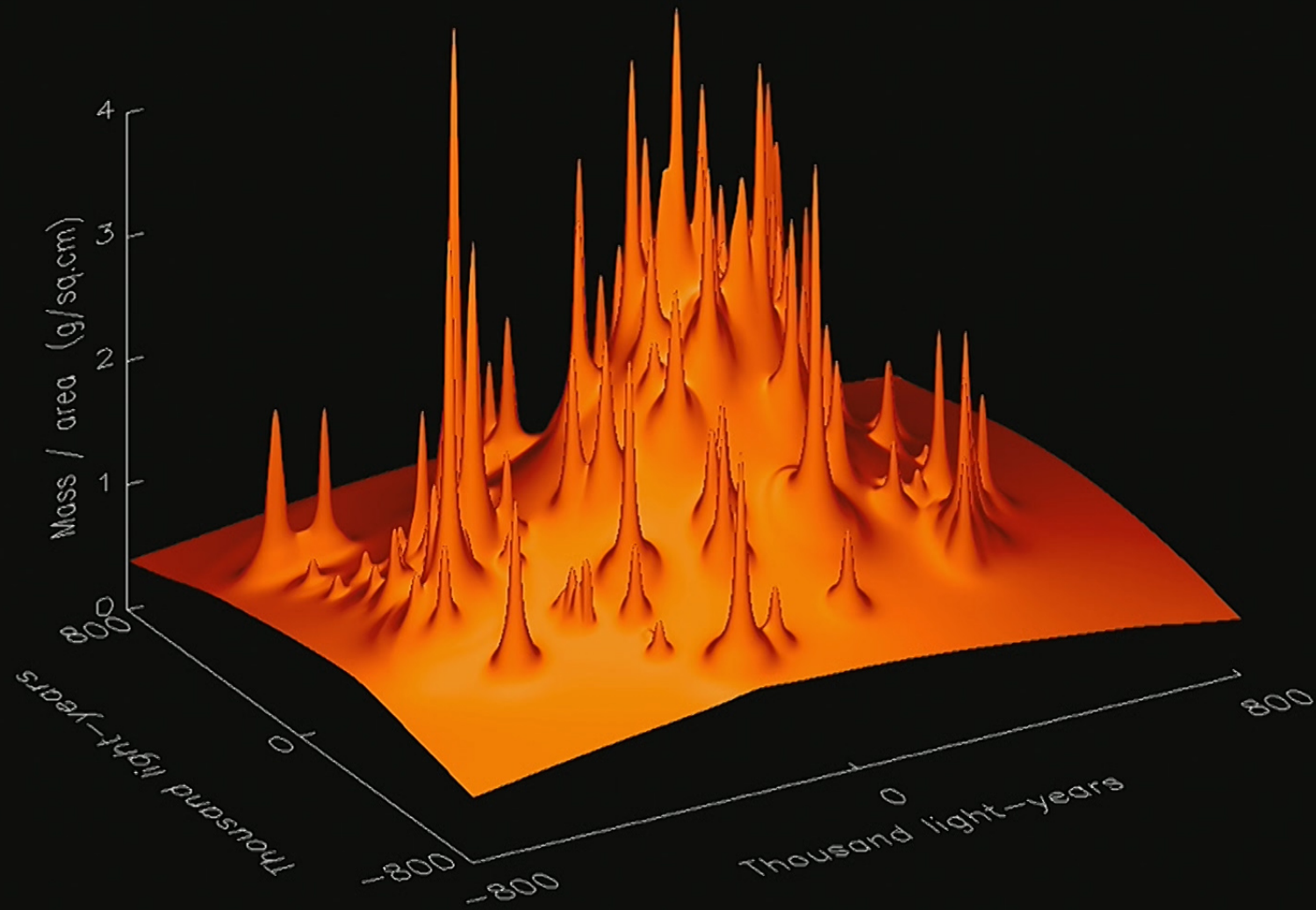
Strong lensing by dark matter



Gravitational Lens in Abell 2218

HST · WFPC2

PF95-14 · ST ScI OPO · April 5, 1995 · W. Couch (UNSW), NASA



The Bullet Cluster:

Two merging clusters: dark matter passes through while atoms get stuck

Atomic Matter ↘

Dark Matter ↘

The Dark Matter Problem

■
■

95% of the mass in galaxies and clusters of galaxies consists of an unknown dark matter component.

Known from:

rotation curves (out to tens kpc),
gravitational lensing (out to 200kpc),
hot gas in clusters.

Bullet Cluster.

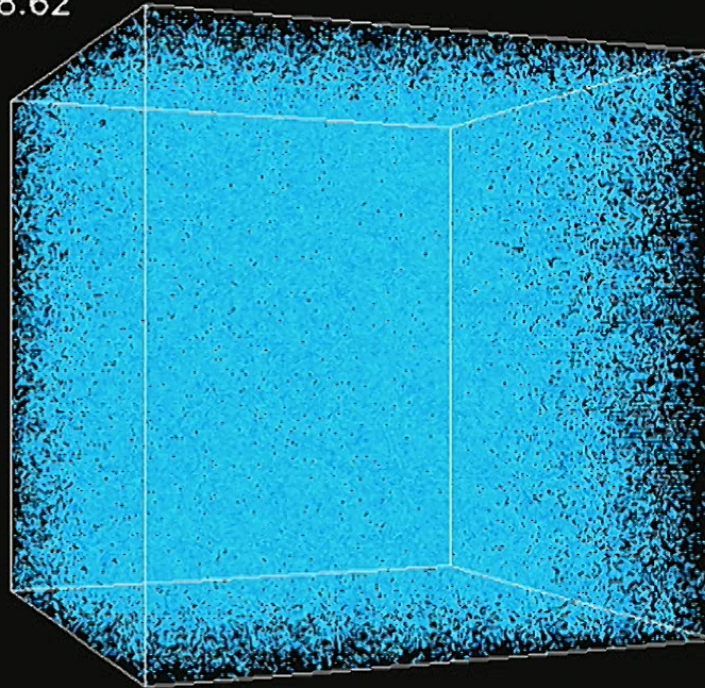
Evidence for Dark Matter: Formation of Structure, Computer Simulations

Initial conditions
from inflation

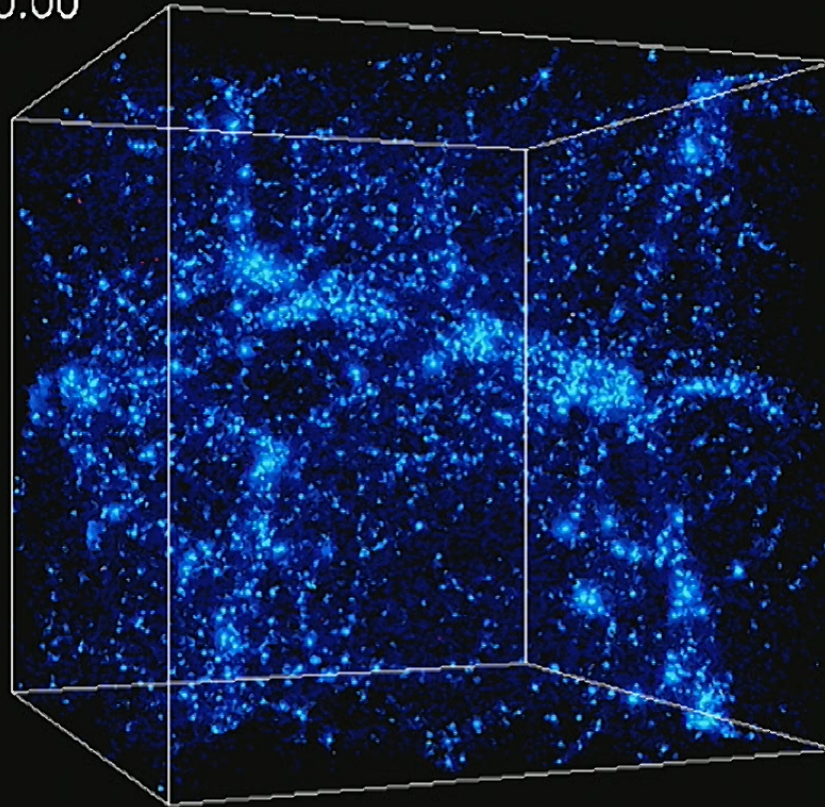
Dark Matter particles
come together to
make galaxies,
clusters, and larger
scale structures

Computer simulations
with dark matter
match the data

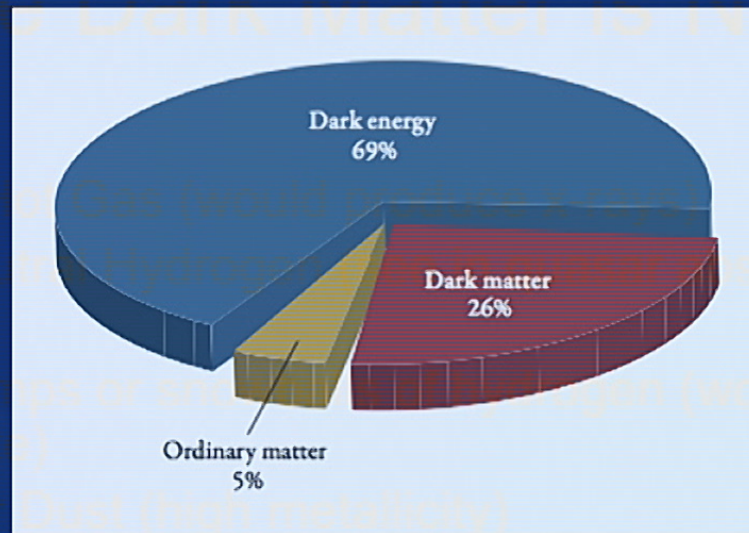
$Z=28.62$



$Z = 0.00$



WHAT IS THE DARK MATTER? PIE CHART OF THE UNIVERSE



WHAT ARE THE PIECES OF THE PIE???

WHAT IS THE DARK MATTER?

The Dark Matter is NOT

- Diffuse Hot Gas (would produce x-rays)
- Cool Neutral Hydrogen (see in quasar absorption lines)
- Small lumps or snowballs of hydrogen (would evaporate)
- Rocks or Dust (high metallicity)

(Hegyi and Olive 1986)

Fifteen Years ago, there were two camps

The believers in MACHOs (Massive
Compact Halo Objects)

vs.

The believers in WIMPs, axions and
other exotic particle candidates

MACHOS

(Massive Compact Halo Objects)

- Faint stars
- Substellar Objects (Brown Dwarfs)
- Stellar Remnants:
 - White Dwarfs
 - Neutron Stars
 - Black Holes

From a combination of observational and theoretical arguments, my student and I found that **THESE CANNOT EXPLAIN ALL THE DARK MATTER IN GALAXIES. STILL A POSSIBILITY: 15% OF THE MASS IN THE GALAXY CAN BE MADE OF WHITE DWARFS.**

Atomic Dark Matter is NOT enough



**Death of stellar baryonic dark matter candidates
(Fields, Freese, and Graff 2000)**

I HATE MACHOS!

DESPERATELY
LOOKING FOR WIMPS!

Scientists believe:
Dark Matter is some new kind
of elementary particle

- Not neutrons
- Not protons
- Something new.

What is the Dark Matter?

Candidates:

- WIMPs (SUSY or extra dimensions)
- Axions
- Neutrinos (too light, ruin galaxy formation)
- Sterile Neutrinos: no Standard Model interaction
- Primordial black holes
- WIMPzillas
- Mirror matter
- Axinos and gravitinos

The best bet for the Dark Matter Particle: WIMPs

- Weakly Interacting Massive Particles
- Billions pass through your body every second
- No strong nuclear forces
- No electromagnetic forces
- Yes, they feel gravity
- Of the four fundamental forces, the other possibility is weak interactions (also responsible for radioactivity)
- Weigh 1 to 10,000 times protons

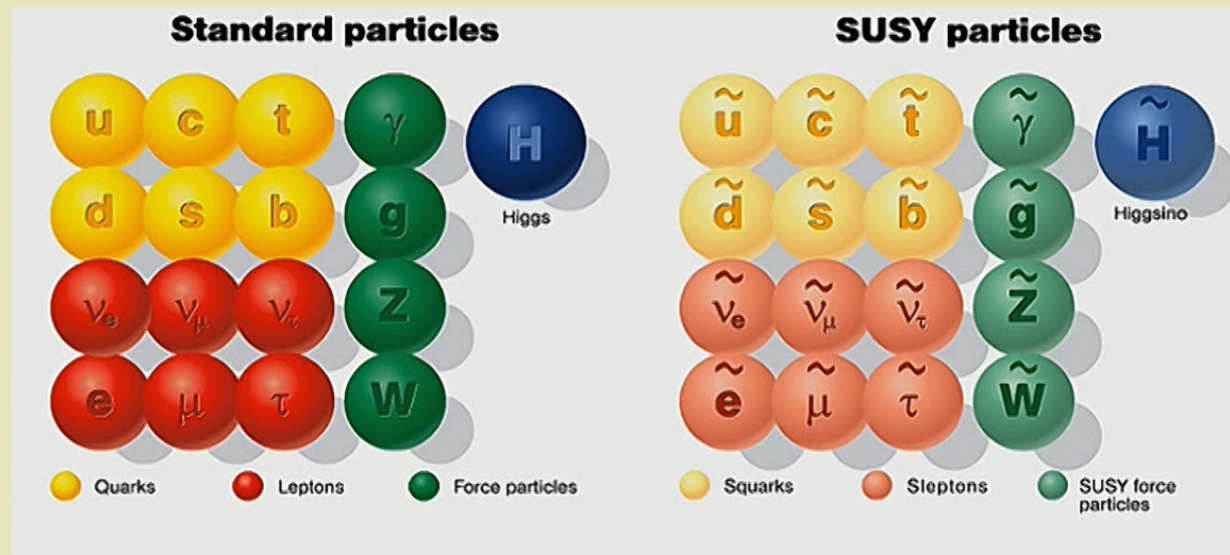
The best bet for the Dark Matter Particle: WIMPs

- THE WIMP MIRACLE: They are their own antiparticles and annihilate among themselves in the early universe, leaving behind the right numbers to explain the dark matter:
- They automatically are predicted by theories proposed for completely different reason, e.g. supersymmetry

WIMPs in particle theory: Supersymmetry

An extension of the standard model

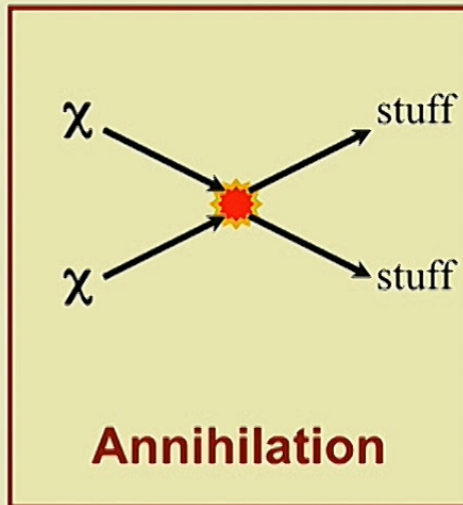
- Every particle we know has a partner



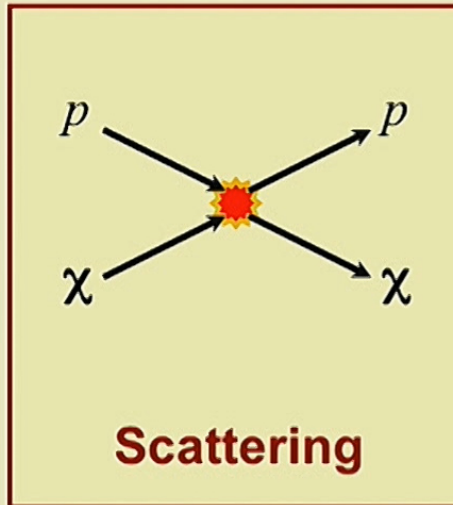
- The lightest supersymmetric particle may be the dark matter.

THREE PRONGED APPROACH TO WIMP DETECTION

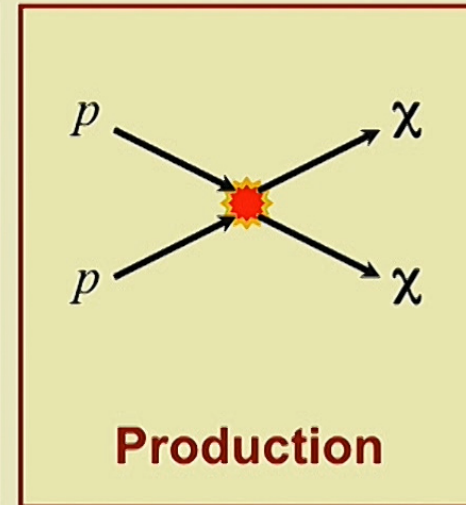
Interactions with Standard Model particles



Indirect Detection:
Halo (cosmic-rays))



Direct Detection:
Look for scattering
events in detector



Accelerators:
LHC

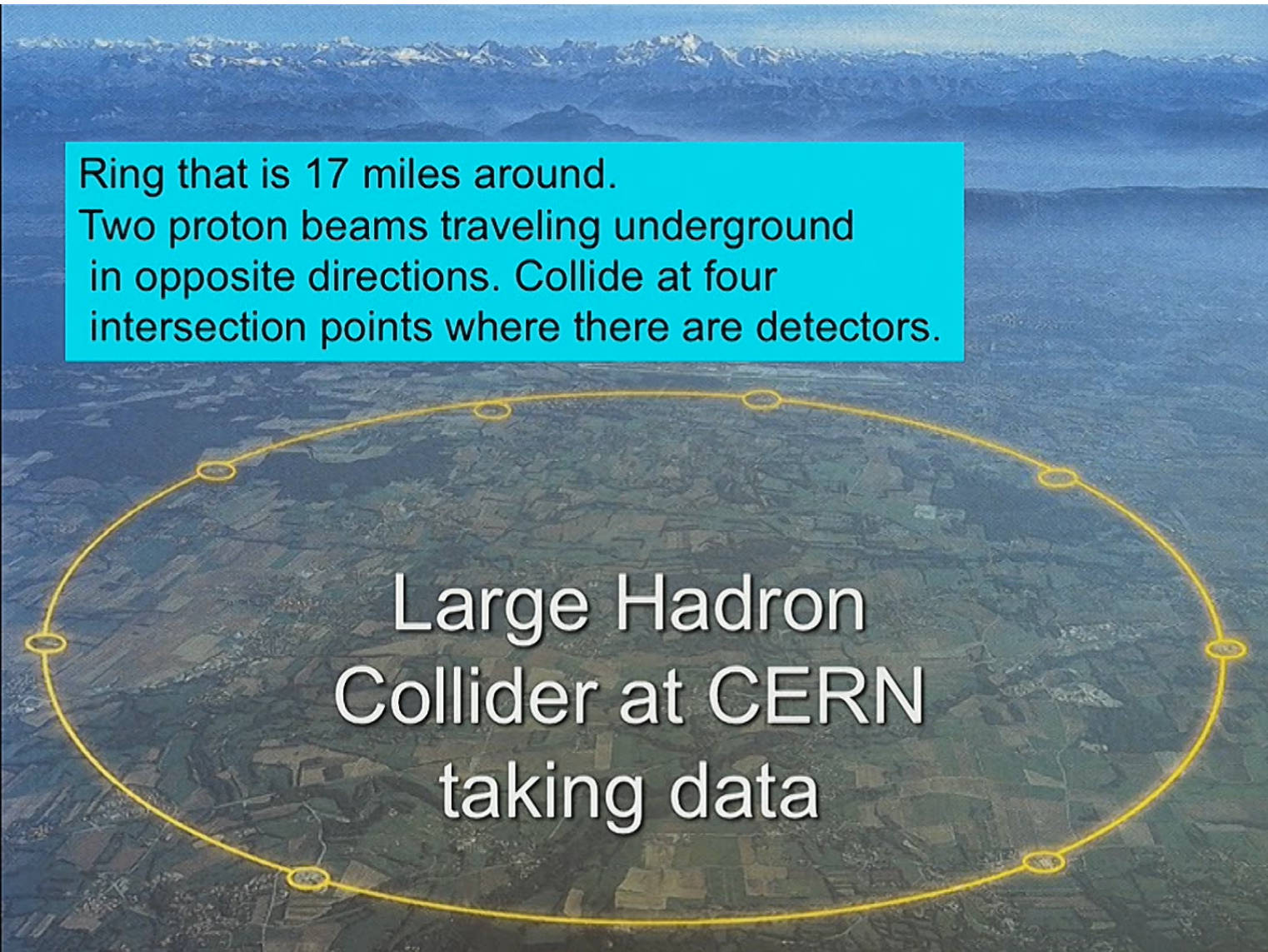
FOURTH PRONG: DARK STARS

EXCITING TIMES

- We made WIMP proposals twenty years ago:
- It is coming to fruition!
- My personal prediction: one of the anomalous results is right and we will know very soon.

FIRST WAY TO SEARCH FOR WIMPS

COLLIDERS:
Large Hadron Collider at
CERN

An aerial photograph of the CERN facility in Switzerland, showing the vast landscape and distant snow-capped mountains. A large yellow oval is superimposed on the image, representing the 17-mile circumference of the Large Hadron Collider (LHC) ring. Eight small yellow circles are placed along the perimeter of the oval, indicating the locations of the four main collision points and the four insertion points for the injector complex.

Ring that is 17 miles around.
Two proton beams traveling underground
in opposite directions. Collide at four
intersection points where there are detectors.

Large Hadron Collider at CERN taking data

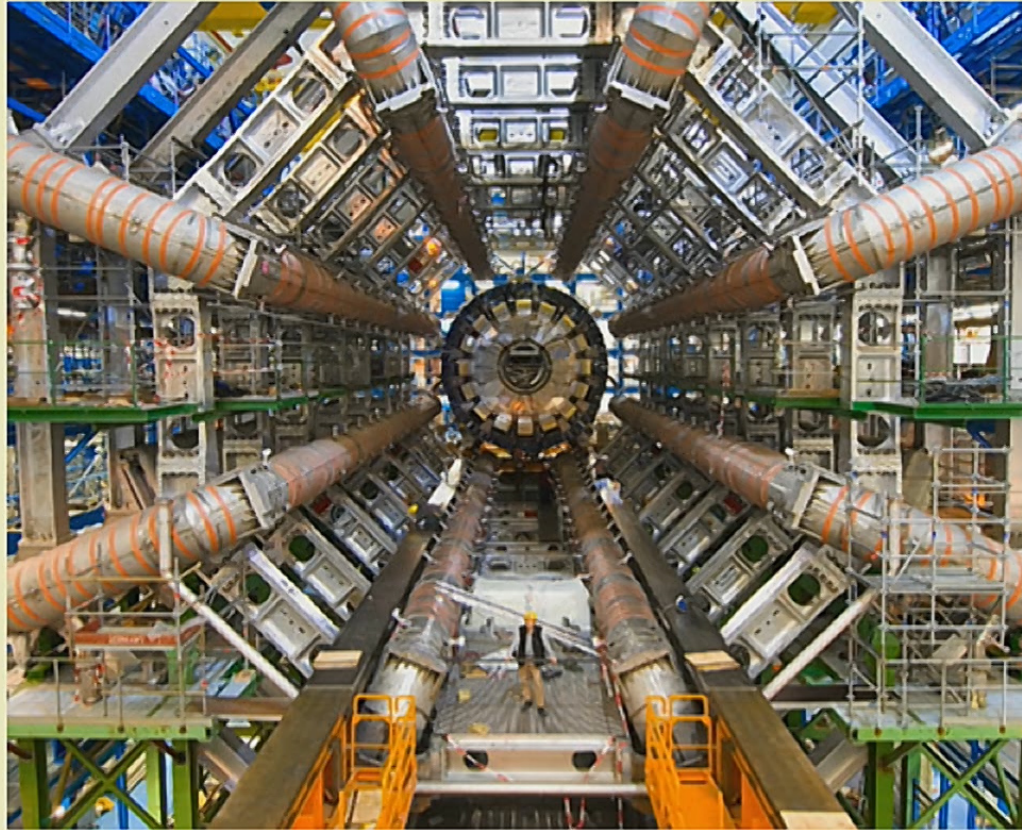
Underground beam pipe



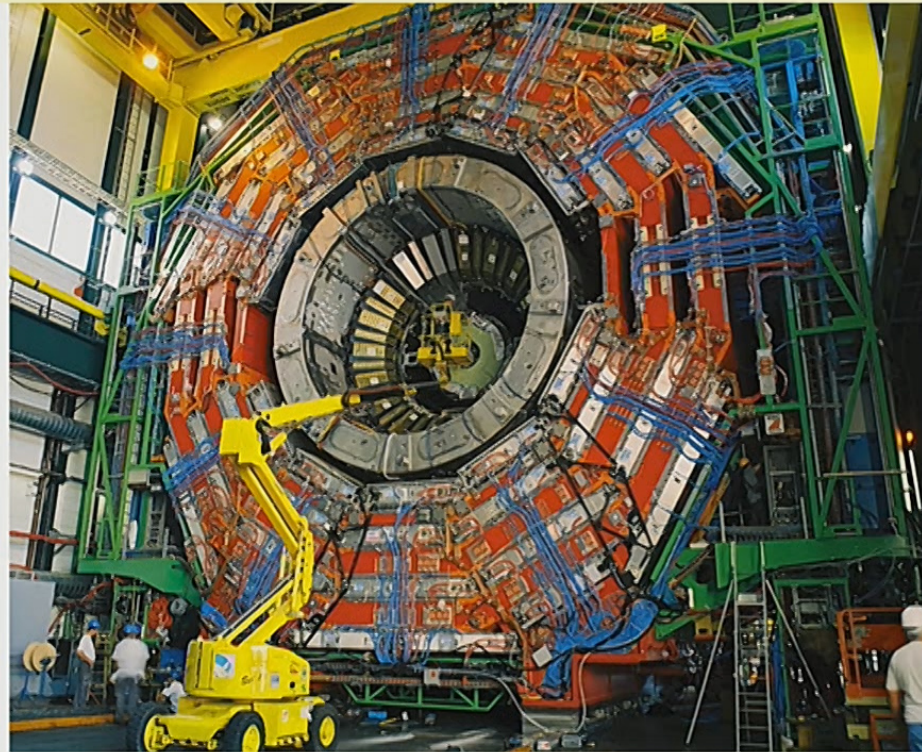
ATLAS detector: Fabiola Gianotti, spokesperson for 3000 scientists now Director General of CERN



ATLAS Detector at CERN

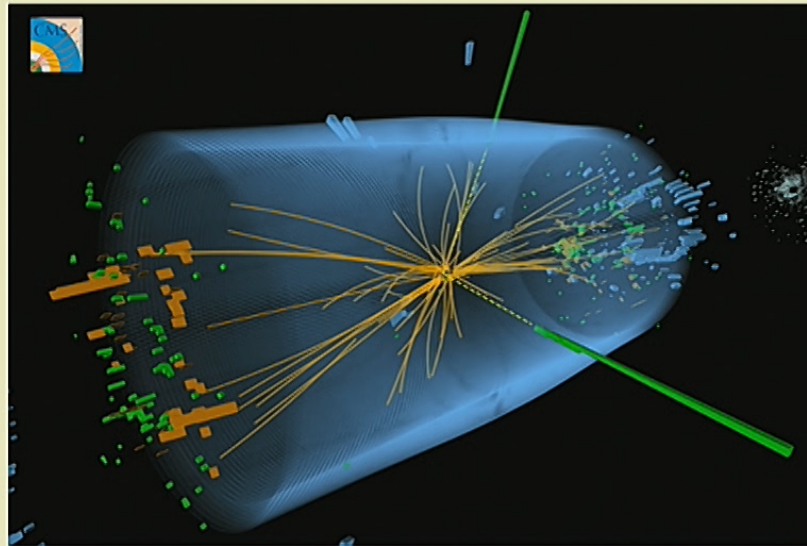


CMS detector during construction



Actual pp collision

- Higgs decays to two photons

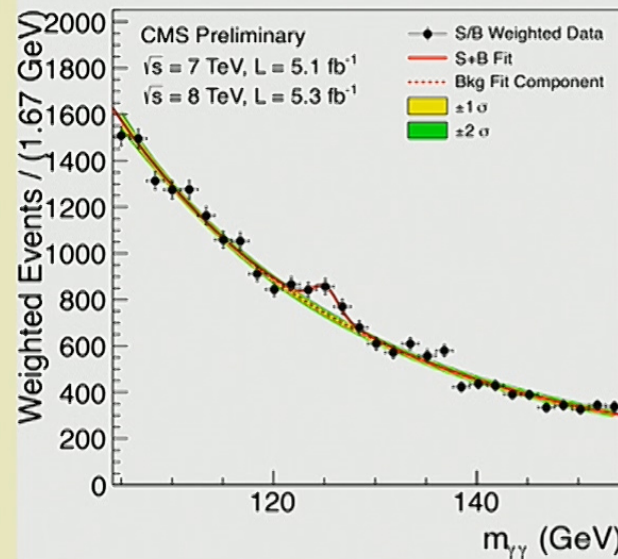


July 2012: Last missing piece of standard model of particle physics!!!

LHC's first success

Discovery of Higgs boson

weighing 125 GeV (125 proton masses)



Key role of Higgs: imparts mass to other particles



The Nobel Prize in Physics 2013

François Englert, Peter Higgs

The Nobel Prize in Physics 2013

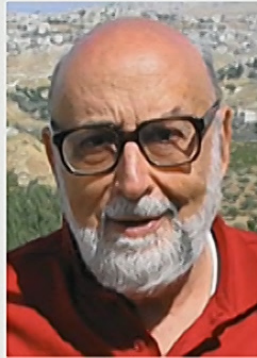


Photo: Pnicolet via
Wikimedia Commons

François Englert



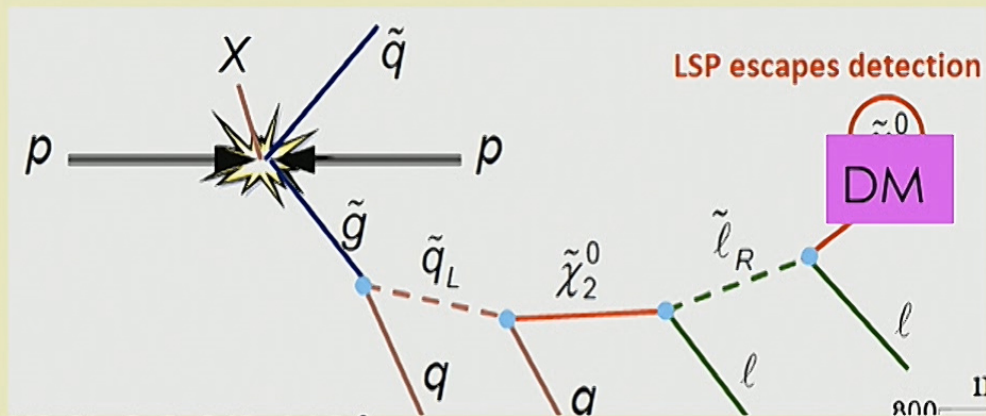
Photo: G-M Greuel via
Wikimedia Commons

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Second major goal of LHC: search for SUSY and dark matter

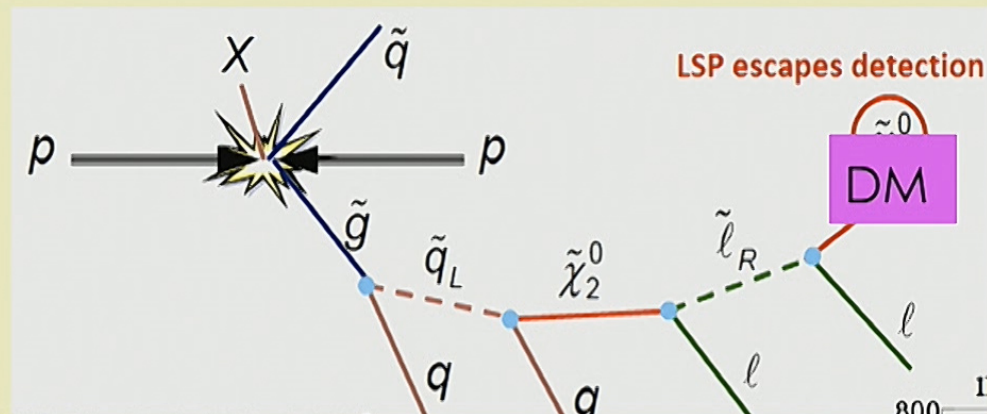
- Two signatures: Missing energy plus jets



- Nothing seen yet
- LHC just turned on again at higher mass
- Maybe it will discover something

Second major goal of LHC: search for SUSY and dark matter

- Two signatures: Missing energy plus jets



- Nothing seen yet
- LHC just turned on again at higher mass
- Maybe it will discover something

The Higgs Boson is NOT the Dark Matter

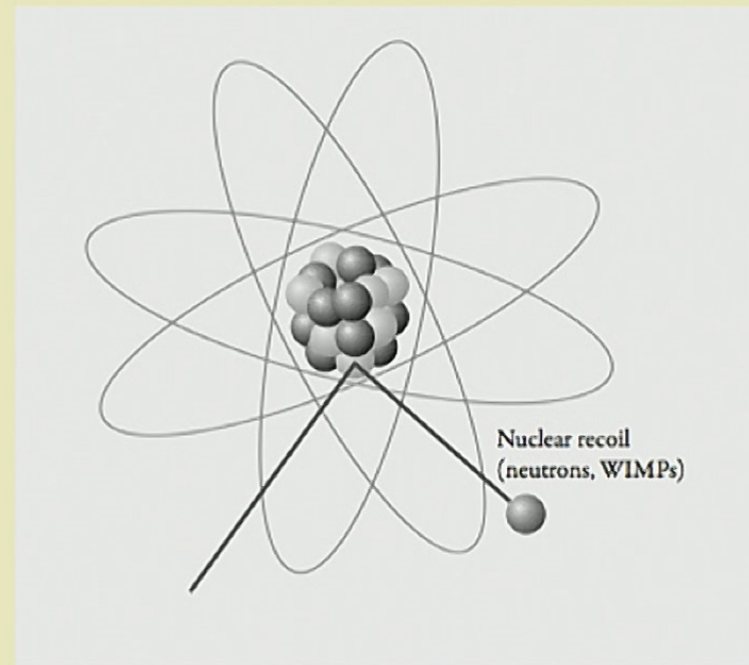
- Higgs particles are NOT the dark matter. They decay very quickly (they live only 10^{-22} seconds) and so cannot be the bulk of the mass in the Universe.
- The Large Hadron Collider at CERN will turn on again in March 2015, with double its previous energy, and will look for supersymmetry and dark matter.

SECOND WAY TO SEARCH FOR WIMPS

DIRECT DETECTION
Laboratory EXPERIMENTS

DIRECT DETECTION OF WIMP DARK MATTER

A WIMP in the Galaxy travels through our detectors. It hits a nucleus, and deposits a tiny amount of energy. The nucleus recoils, and we detect this energy deposit.



Expected Rate: less than one count/kg/day!

How did I get into Dark Matter?

COCKTAILS!

I was at a winter school in Jerusalem. This man (Andrzej Drukier) knew where to celebrate New Years: “Cinematheque”



He told me about his work with Leo Stodolsky on ideas for neutrino detection
We arranged a visit for him at Harvard
The same mechanism works for WIMPs!

Drukier, Freese, & Spergel (1986)

We studied the WIMPs in the Galaxy and the particle physics of the interactions to compute expected count rates, and we proposed annual modulation to identify a WIMP signal



WIMP detectors must be in underground laboratories

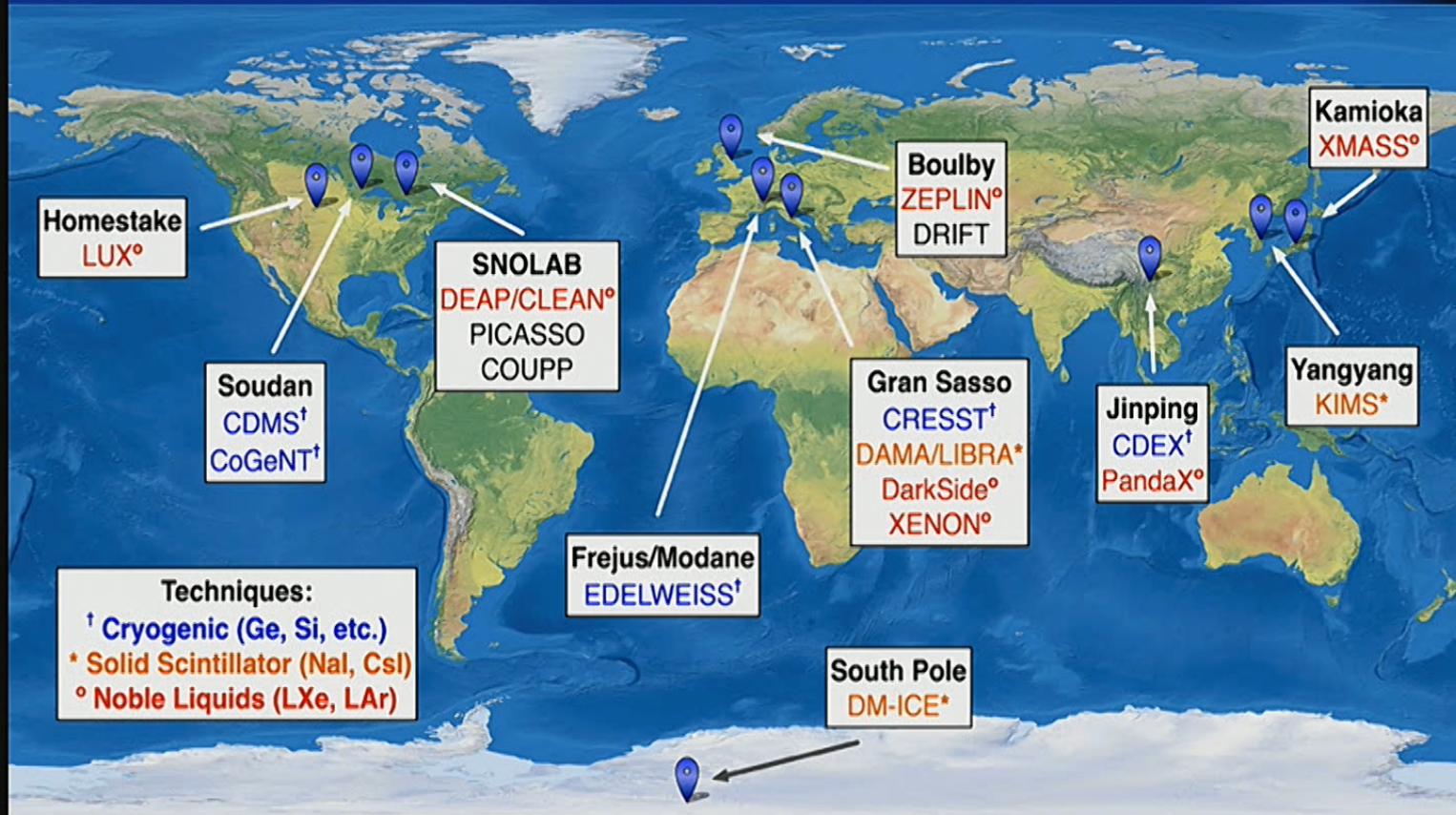
Davis Cavern



Need to shield
from
Cosmic Rays!

LUX Experiment in Sanford Mine in South Dakota

UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



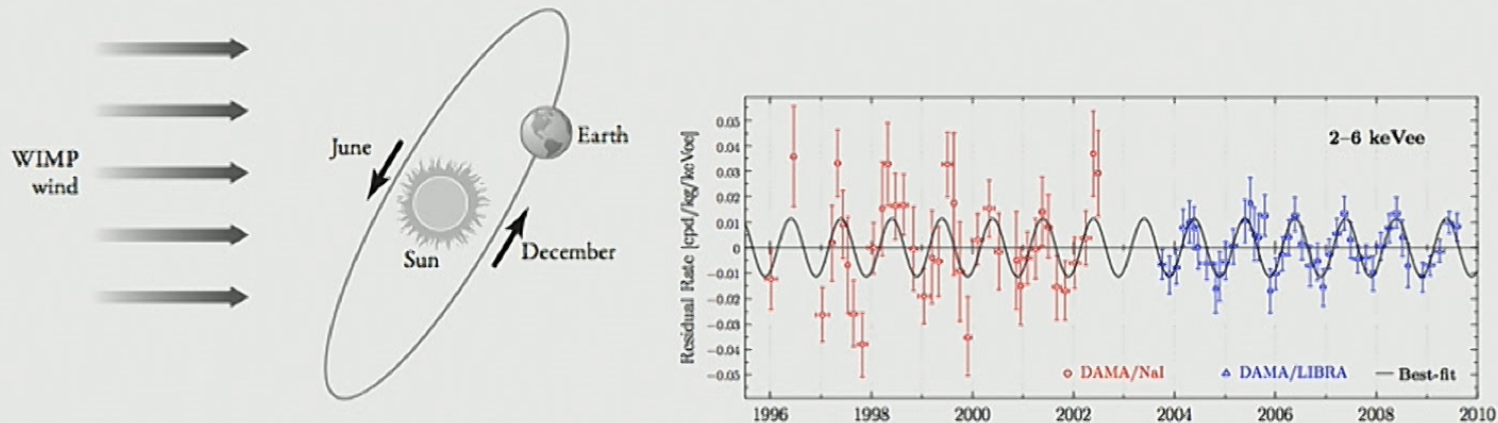
Many claims/hints of WIMP dark matter detection: how can we be sure?

- 1) The DAMA annual modulation
- 2) The HEAT, PAMELA, and AMS positron excess
- 3) Gamma-rays from Galactic Center (FERMI)

HAS DARK MATTER BEEN
DISCOVERED?

DAMA annual modulation

Drukier, Freese, and Spergel (1986);
Freese, Frieman, and Gould (1988)



Nal crystals in Gran Sasso Tunnel under the Apennine Mountains near Rome.

Data do show modulation! Peak in June, minimum in December (as predicted). **Are these WIMPs??**

“I’ m a Spaniard caught between two Italian women”



Rita Bernabei,
DAMA



Juan Collar, COGENT

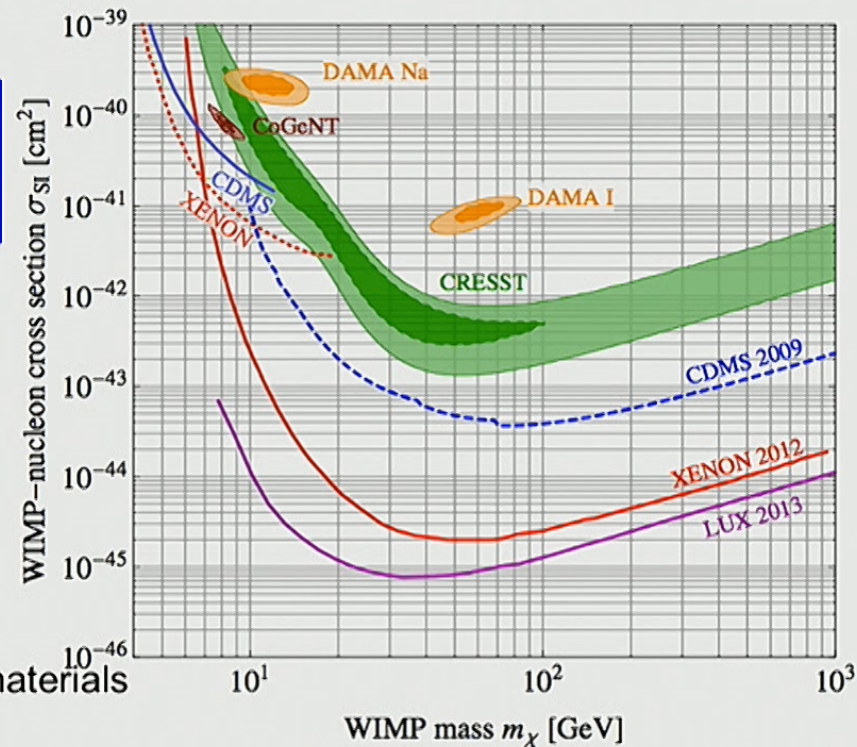


Elena Aprile, XENON

Data from Multiple Experiments for SI scattering

INTERACTION STRENGTH

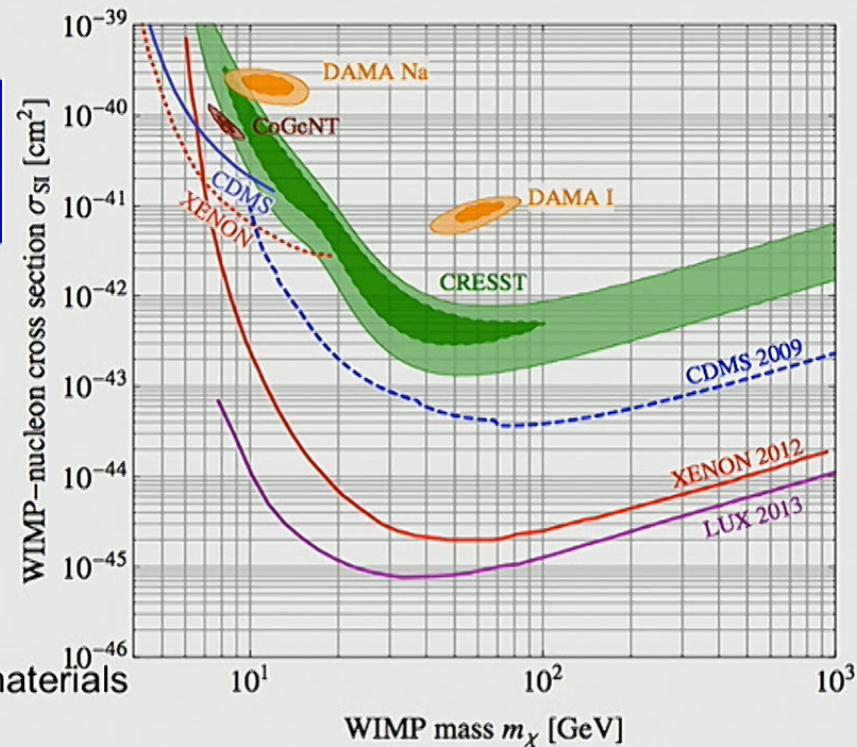
LUX Experiment 2013:
Must be below
the purple line.
Hard to reconcile
with DAMA and
CoGeNT.
BUT: different detector materials



Data from Multiple Experiments for SI scattering

INTERACTION STRENGTH

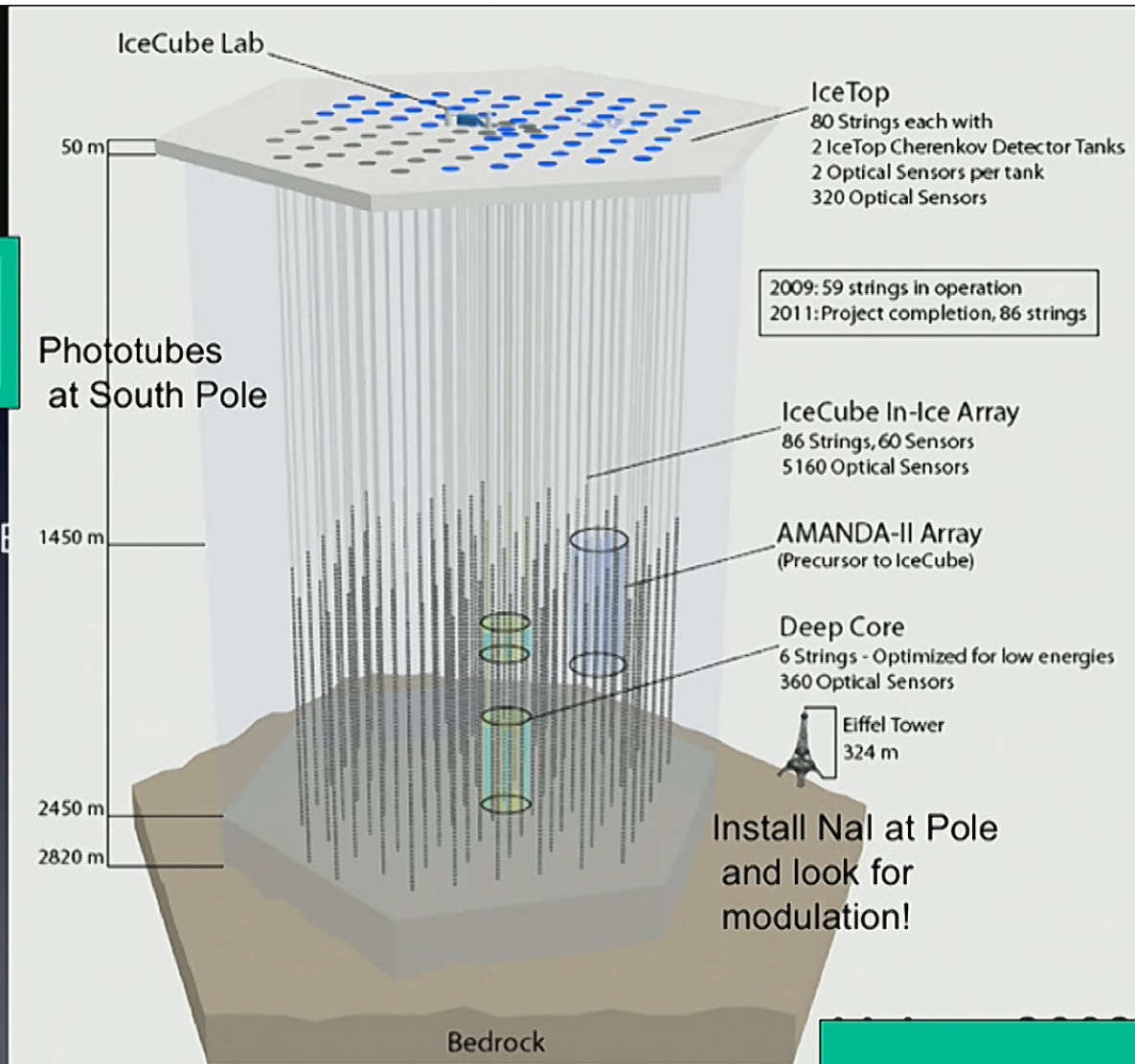
LUX Experiment 2013:
Must be below
the purple line.
Hard to reconcile
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CoGeNT.
BUT: different detector materials



DM-
ICE

TO TEST
DAMA


IceCube
DEEPCORE
experiment
at South
Pole has
installed
NaI xtals
to look
for annual
modulation
1) no T
variations
2) Southern
Hemisphere

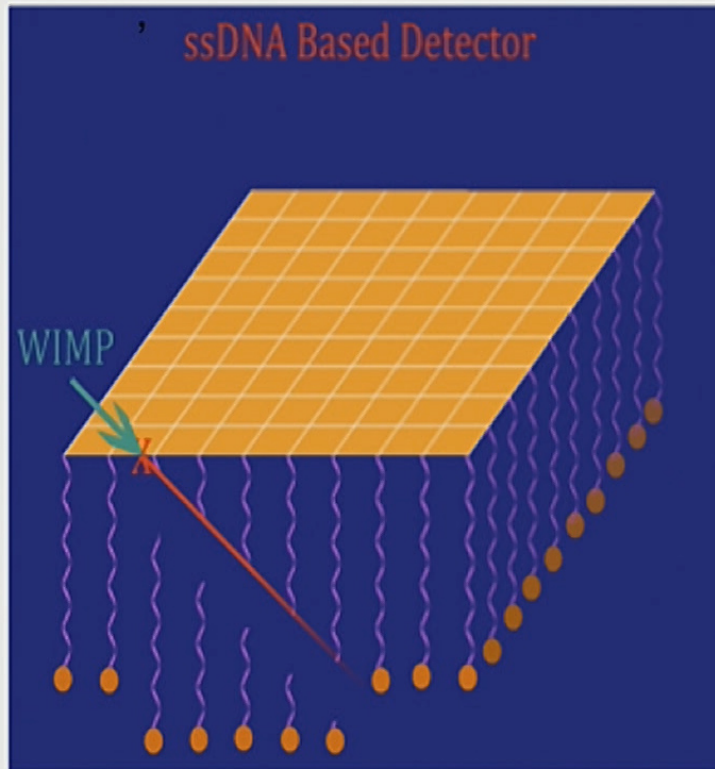


Postcards from the South Pole



DNA Tracker: nanometer resolution!

 1 kg Gold, 1 kg ssDNA, identical sequences of bases with an order that is well known



BEADED CURTAIN OF ssDNA

WIMP from galaxy knocks out Au nucleus, which traverses DNA strings, severing the strand whenever it hits.

We got 60K “MCUBED” money from U of MI to seed initial tests

THIRD WAY TO SEARCH FOR WIMPS

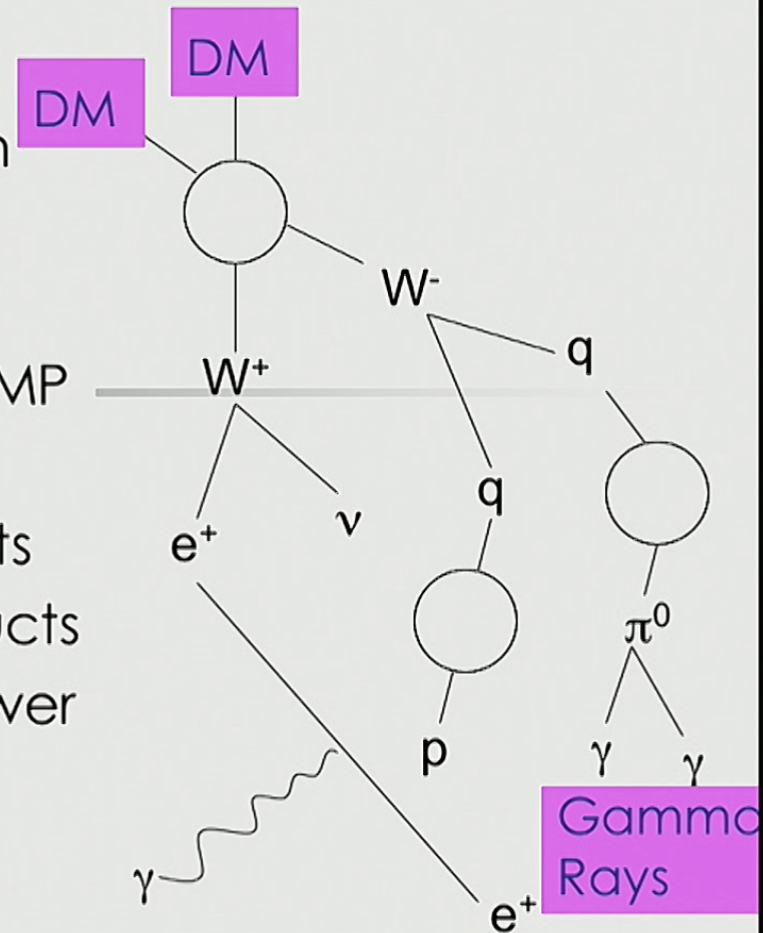


INDIRECT DETECTION:
searching for astrophysical
WIMP annihilation products

WIMP Annihilation

Many WIMPs are their own antiparticles, annihilate among themselves:

- 1) Early Universe gives WIMP miracle
- 2) Indirect Detection expts look for annihilation products
- 3) Same process can power Stars (dark stars)



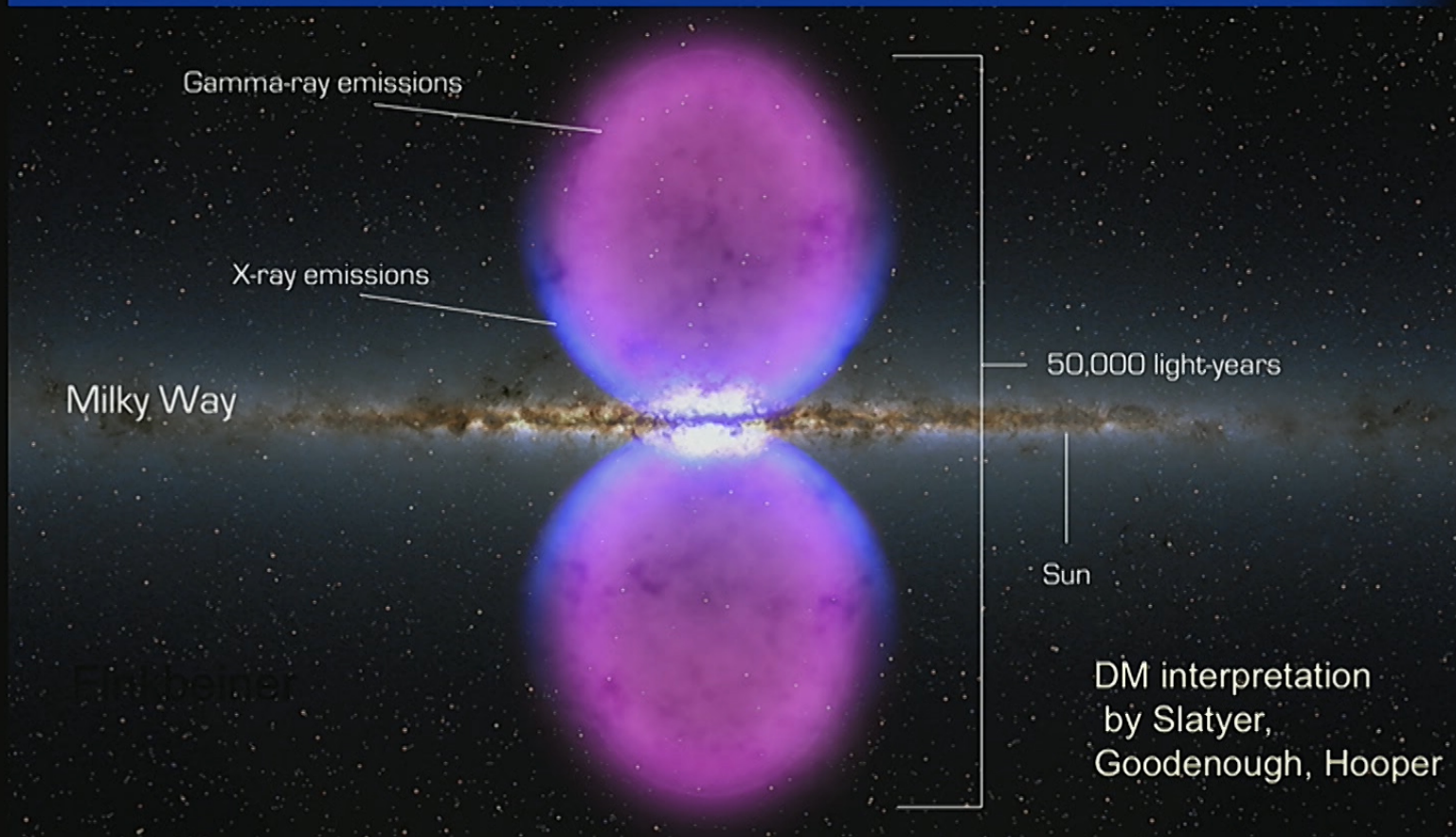
THE FERMI SATELLITE

SEARCHING FOR
HIGH-ENERGY
PHOTONS
(GAMMA-RAYS)
FROM DARK
MATTER
ANNIHILATION



FERMI Bubble

(Doug Finkbeiner)



Possible evidence for WIMP detection already now:

- Direct Detection:
 - DAMA annual modulation
 - COGENT, CRESST, CMDS-Si (but XENON, LUX)
- Indirect Detection:
 - The HEAT/PAMELA/FERMI/AMS positron excess
 - FERMI bubble near galactic center
- Theorists are looking for models in which some of these results are consistent with one another (given an interpretation in terms of WIMPs)



What will it take for us to believe DM has been found?

- Compatible signals in a variety of experiments made of different detector materials, and all the parties agree

FOURTH WAY TO SEARCH FOR WIMPS

Dark Stars:
Dark Matter annihilation can
power the first stars

DAVID GRANT presents
A JOHN CARPENTER film

From
ALAN DEAN FOSTER
FIRST
2001: A SPACE ODYSSEY

THEN
THE POSEIDON ADVENTURE
NOW

DARK STAR^A

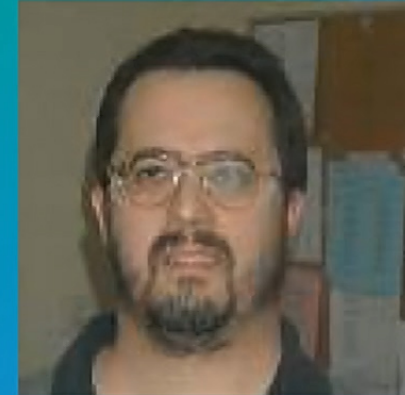
bombed out in space
with a spaced out bomb!

by OPPIDAN ENTERTAINMENTS Release of a JACK H. HARRIS Production Starring DAN O'BANNON and BRIAN NARELLE Produced & directed by JOHN CARPENTER

Collaborators



Doug Spolyar



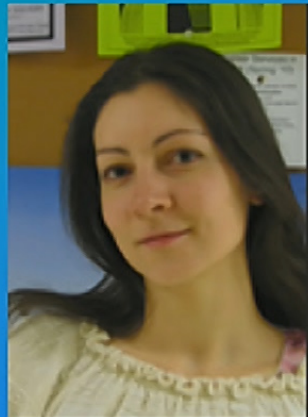
Paolo Gondolo



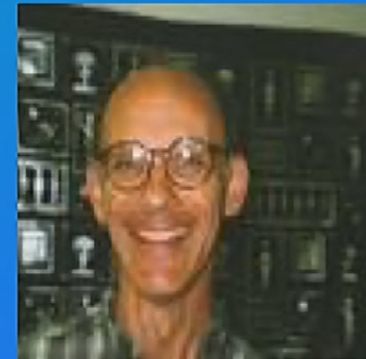
Dr. Monica Valluri



Pearl Sandick



Tanja Rindler-Daller

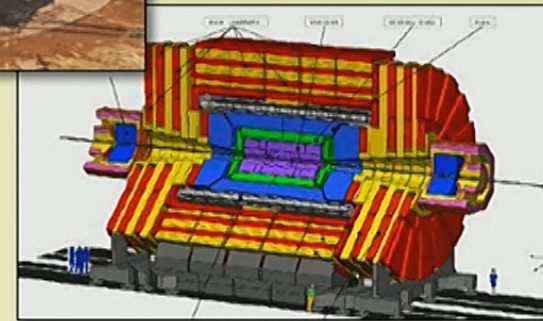
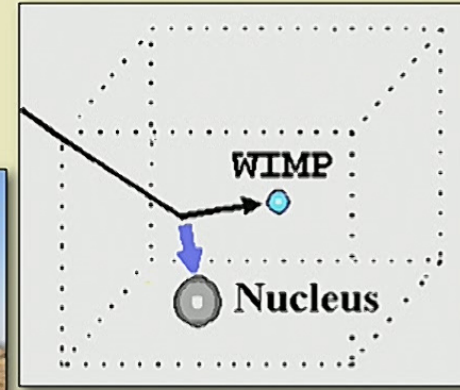


Peter Bodenheimer

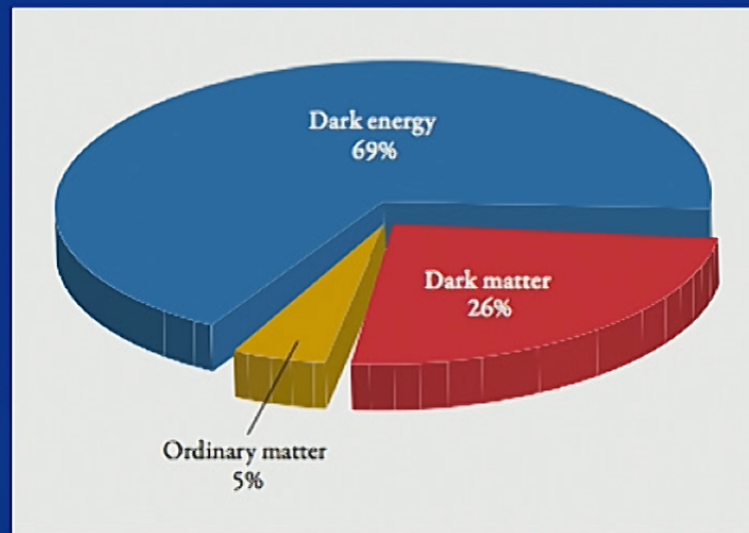
WIMP Hunting: Good chance of detection this decade

- Direct Detection
- Indirect Detection
- Collider Searches

Looking for Dark Stars



PIE CHART OF THE UNIVERSE



The panel on “The Dark Side of the Universe” at the World Science Festival in NY in June 2011



The three women representing Dark Matter are, from the right, Katherine Freese, Elena Aprile, and Glennys Farrar. Continuing to the left are three men representing Dark Energy: Michael Turner, Saul Perlmutter and Brian Greene (co-host of the Festival).

**“Dark matter is attractive, while
dark energy is repulsive!”**



