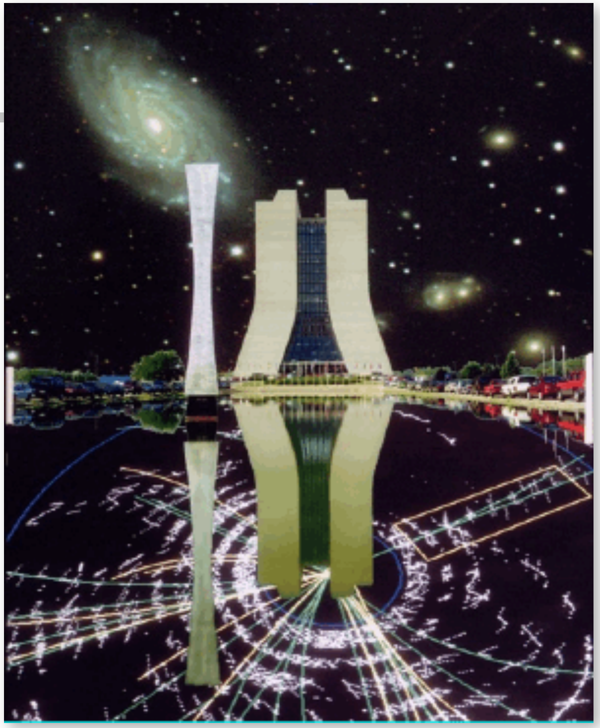
A Quick Look At The History of Dark Matter



Dan Hooper

Fermilab/University of Chicago

Cosmology Short Course For Museum and Planetarium Staff

September 2010


Democritus philozoph⁹

Periodic Table of the Elements

- ■ Alkali metals
- ■ Alkaline earth metals
- ■ Transition metals
- ■ Lanthanide series
- ■ Actinide series
- ■ Poor metals
- ■ Nonmetals
- ■ Noble gases

- **C** Solid
- **Br** Liquid
- **H** Gas
- **Tc** Synthetic

New Original	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA	
1	1 **H** Hydrogen 1.00794 1																	2 **He** Helium 4.002602 2	K
2	3 **Li** Lithium 6.941 2 1	4 **Be** Beryllium 9.012182 2 2											5 **B** Boron 10.811 2 3	6 **C** Carbon 12.0107 2 4	7 **N** Nitrogen 14.00674 2 5	8 **O** Oxygen 15.9994 2 6	9 **F** Fluorine 18.9984032 2 7	10 **Ne** Neon 20.1797 2 8	K L
3	11 **Na** Sodium 22.989770 2 8 1	12 **Mg** Magnesium 24.3050 2 8 2											13 **Al** Aluminum 26.981538 2 8 3	14 **Si** Silicon 28.0855 2 8 4	15 **P** Phosphorus 30.973761 2 8 5	16 **S** Sulfur 32.066 2 8 6	17 **Cl** Chlorine 35.453 2 8 7	18 **Ar** Argon 39.948 2 8 8	K L M
4	19 **K** Potassium 39.0983 2 8 8 1	20 **Ca** Calcium 40.078 2 8 8 2	21 **Sc** Scandium 44.955910 2 8 9 2	22 **Ti** Titanium 47.867 2 8 10 2	23 **V** Vanadium 50.9415 2 8 11 2	24 **Cr** Chromium 51.9961 2 8 13 1	25 **Mn** Manganese 54.938049 2 8 13 2	26 **Fe** Iron 55.8457 2 8 14 2	27 **Co** Cobalt 58.933200 2 8 15 2	28 **Ni** Nickel 58.6934 2 8 16 2	29 **Cu** Copper 63.546 2 8 18 1	30 **Zn** Zinc 65.409 2 8 18 2	31 **Ga** Gallium 69.723 2 8 18 3	32 **Ge** Germanium 72.64 2 8 18 4	33 **As** Arsenic 74.92160 2 8 18 5	34 **Se** Selenium 78.96 2 8 18 6	35 **Br** Bromine 79.904 2 8 18 7	36 **Kr** Krypton 83.798 2 8 18 8	K L M N
5	37 **Rb** Rubidium 85.4678 2 8 18 8 1	38 **Sr** Strontium 87.62 2 8 18 8 2	39 **Y** Yttrium 88.90585 2 8 18 9 2	40 **Zr** Zirconium 91.224 2 8 18 10 2	41 **Nb** Niobium 92.90638 2 8 18 12 1	42 **Mo** Molybdenum 95.94 2 8 18 13 1	43 **Tc** Technetium (98) 2 8 18 13 2	44 **Ru** Ruthenium 101.07 2 8 18 15 1	45 **Rh** Rhodium 102.90550 2 8 18 16 1	46 **Pd** Palladium 106.42 2 8 18 18 0	47 **Ag** Silver 107.8682 2 8 18 18 1	48 **Cd** Cadmium 112.411 2 8 18 18 2	49 **In** Indium 114.818 2 8 18 18 3	50 **Sn** Tin 118.710 2 8 18 18 4	51 **Sb** Antimony 121.760 2 8 18 18 5	52 **Te** Tellurium 127.60 2 8 18 18 6	53 **I** Iodine 126.90447 2 8 18 18 7	54 **Xe** Xenon 131.293 2 8 18 18 8	K L M N O
6	55 **Cs** Cesium 132.90545 2 8 18 18 8 1	56 **Ba** Barium 137.327 2 8 18 18 8 2	57 to 71	72 **Hf** Hafnium 178.49 2 8 18 32 10 2	73 **Ta** Tantalum 180.9479 2 8 18 32 11 2	74 **W** Tungsten 183.84 2 8 18 32 12 2	75 **Re** Rhenium 186.207 2 8 18 32 13 2	76 **Os** Osmium 190.23 2 8 18 32 14 2	77 **Ir** Iridium 192.217 2 8 18 32 15 2	78 **Pt** Platinum 195.078 2 8 18 32 17 1	79 **Au** Gold 196.96655 2 8 18 32 18 1	80 **Hg** Mercury 200.59 2 8 18 32 18 2	81 **Tl** Thallium 204.3833 2 8 18 32 18 3	82 **Pb** Lead 207.2 2 8 18 32 18 4	83 **Bi** Bismuth 208.98038 2 8 18 32 18 5	84 **Po** Polonium (209) 2 8 18 32 18 6	85 **At** Astatine (210) 2 8 18 32 18 7	86 **Rn** Radon (222) 2 8 18 32 18 8	K L M N O P
7	87 **Fr** Francium (223) 2 8 18 32 18 8 1	88 **Ra** Radium (226) 2 8 18 32 18 8 2	89 to 103	104 **Rf** Rutherfordium (261) 2 8 18 32 32 10 2	105 **Db** Dubnium (262) 2 8 18 32 32 11 2	106 **Sg** Seaborgium (266) 2 8 18 32 32 12 2	107 **Bh** Bohrium (264) 2 8 18 32 32 13 2	108 **Hs** Hassium (269) 2 8 18 32 32 14 2	109 **Mt** Meitnerium (268) 2 8 18 32 32 15 2	110 **Ds** Darmstadtium (271) 2 8 18 32 32 17 1	111 **Rg** Roentgenium (272) 2 8 18 32 32 18 1	112 **Uub** Ununbium (285) 2 8 18 32 32 18 2	113 **Uut** Ununtrium (284)	114 **Uuq** Ununquadium (289)	115 **Uup** Ununpentium (288)	116 **Uuh** Ununhexium (292)	117 **Uus** Ununseptium	118 **Uuo** Ununoctium	K L M N O P Q

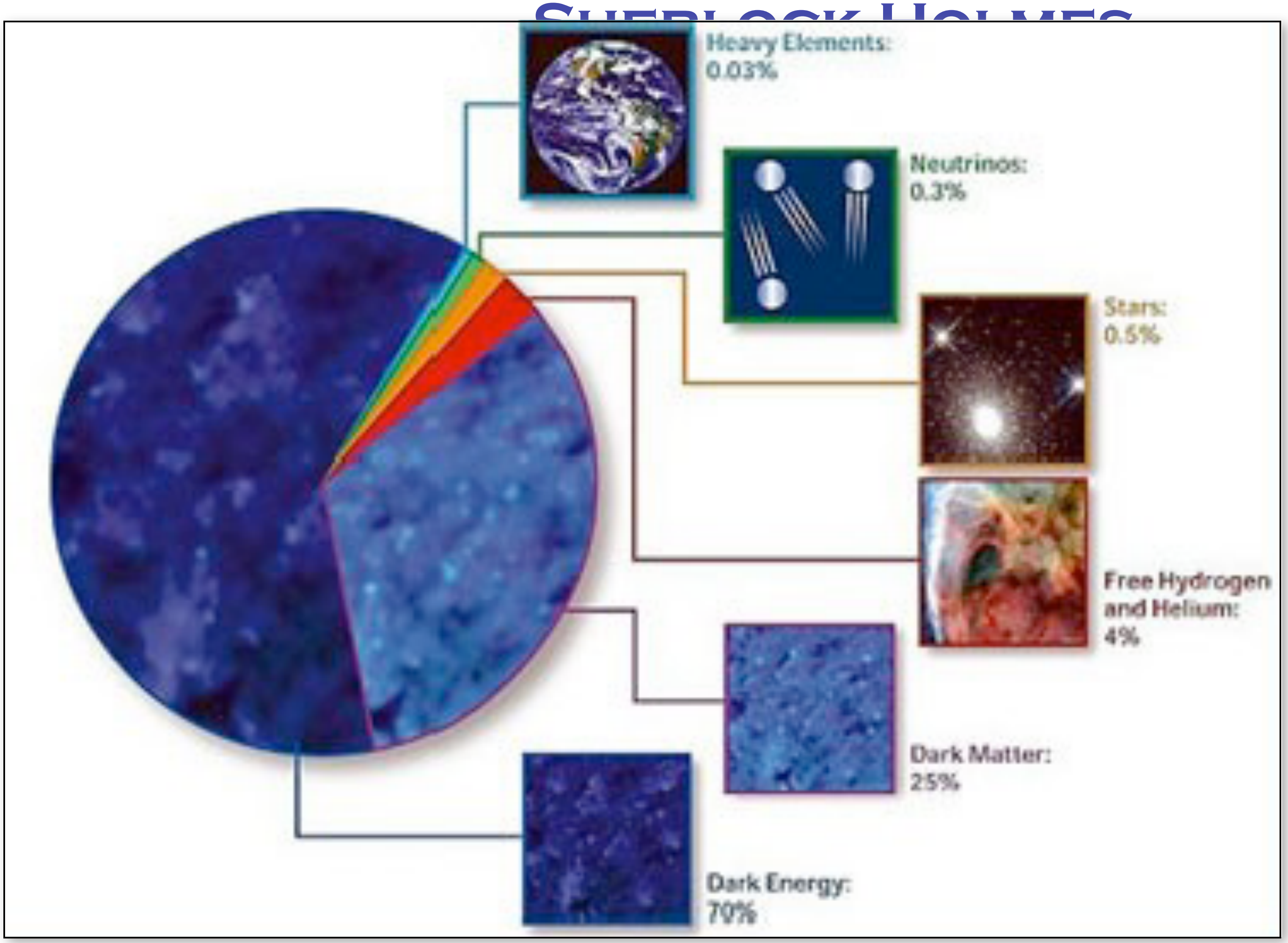
Atomic masses in parentheses are those of the most stable or common isotope.

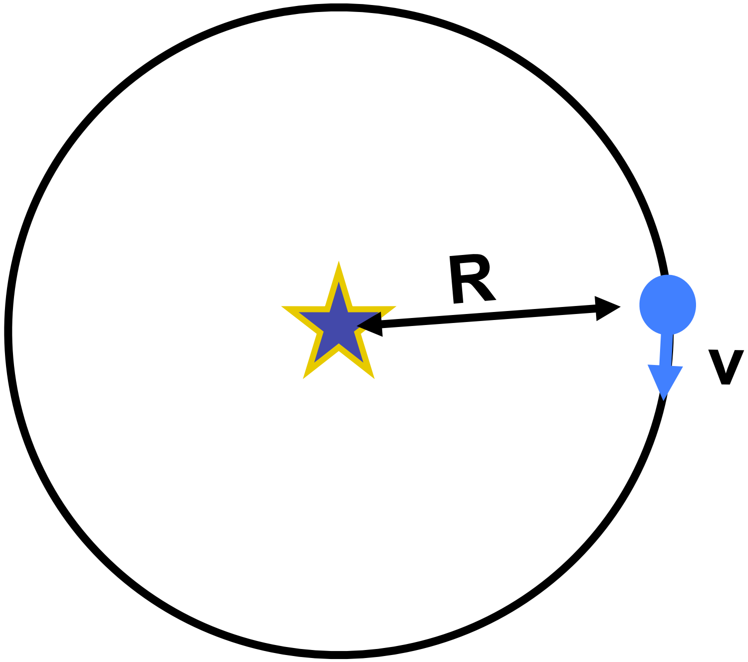
57 **La** Lanthanum 138.9055 2 8 18 18 9 2	58 **Ce** Cerium 140.116 2 8 18 19 9 2	59 **Pr** Praseodymium 140.90765 2 8 18 21 8 2	60 **Nd** Neodymium 144.24 2 8 18 22 8 2	61 **Pm** Promethium (145) 2 8 18 23 8 2	62 **Sm** Samarium 150.36 2 8 18 24 8 2	63 **Eu** Europium 151.964 2 8 18 25 8 2	64 **Gd** Gadolinium 157.25 2 8 18 25 9 2	65 **Tb** Terbium 158.92534 2 8 18 27 8 2	66 **Dy** Dysprosium 162.500 2 8 18 28 8 2	67 **Ho** Holmium 164.93032 2 8 18 29 8 2	68 **Er** Erbium 167.259 2 8 18 30 8 2	69 **Tm** Thulium 168.93421 2 8 18 31 8 2	70 **Yb** Ytterbium 173.04 2 8 18 32 8 2	71 **Lu** Lutetium 174.967 2 8 18 32 9 2
89 **Ac** Actinium (227) 2 8 18 32 18 9 2	90 **Th** Thorium 232.0381 2 8 18 32 18 10 2	91 **Pa** Protactinium 231.03588 2 8 18 32 20 9 2	92 **U** Uranium 238.02891 2 8 18 32 21 9 2	93 **Np** Neptunium (237) 2 8 18 32 22 9 2	94 **Pu** Plutonium (244) 2 8 18 32 24 8 2	95 **Am** Americium (243) 2 8 18 32 25 8 2	96 **Cm** Curium (247) 2 8 18 32 25 9 2	97 **Bk** Berkelium (247) 2 8 18 32 27 8 2	98 **Cf** Californium (251) 2 8 18 32 28 8 2	99 **Es** Einsteinium (252) 2 8 18 32 29 8 2	100 **Fm** Fermium (257) 2 8 18 32 30 8 2	101 **Md** Mendelevium (258) 2 8 18 32 31 8 2	102 **No** Nobelium (259) 2 8 18 32 32 8 2	103 **Lr** Lawrencium (262) 2 8 18 32 32 9 2

Note: The subgroup numbers 1-18 were adopted in 1984 by the International Union of Pure and Applied Chemistry. The names of elements 112-118 are the Latin equivalents of those numbers.

“THE WORLD IS FULL OF THINGS WHICH NOBODY BY ANY CHANCE EVER OBSERVES.”

SHERLOCK HOLMES





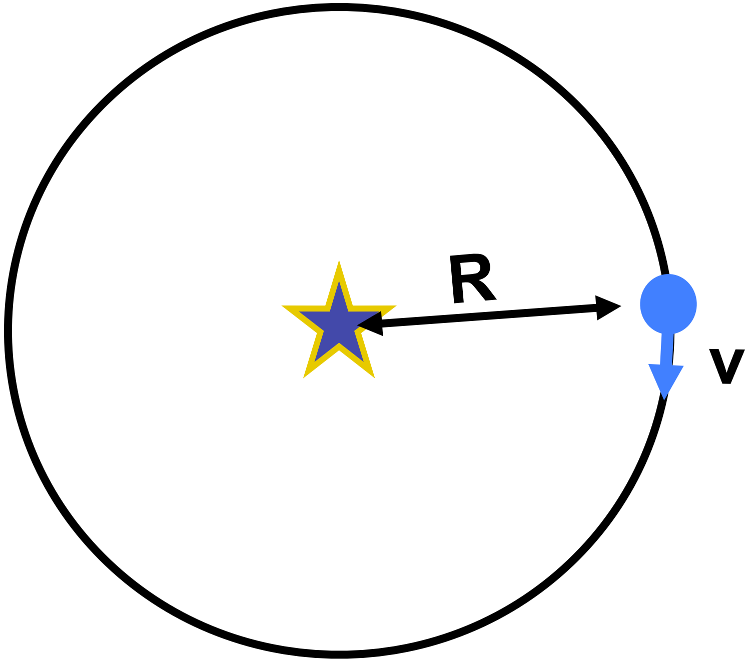
$$m_{pl}\,\frac{v^2}{R} = \frac{G\,M_{Sun}}{R^2}\,m_{pl}$$

Centrifugal
Force

Gravitational
Force

Measure the speed
at which planets orbit
around the Sun → The Sun’s Mass

ANDROMEDA
GALAXY



$$\frac{v^2}{R} = \frac{G\, M_{Sun}}{R^2}$$

$$\frac{v^2}{R} = \frac{G\, M_{GALAXY}}{R^2}$$

Measure the speeds of stars ⇒ Determine the mass of their galaxy

FRITZ ZWICKY

VERA RUBIN

FRITZ ZWICKY

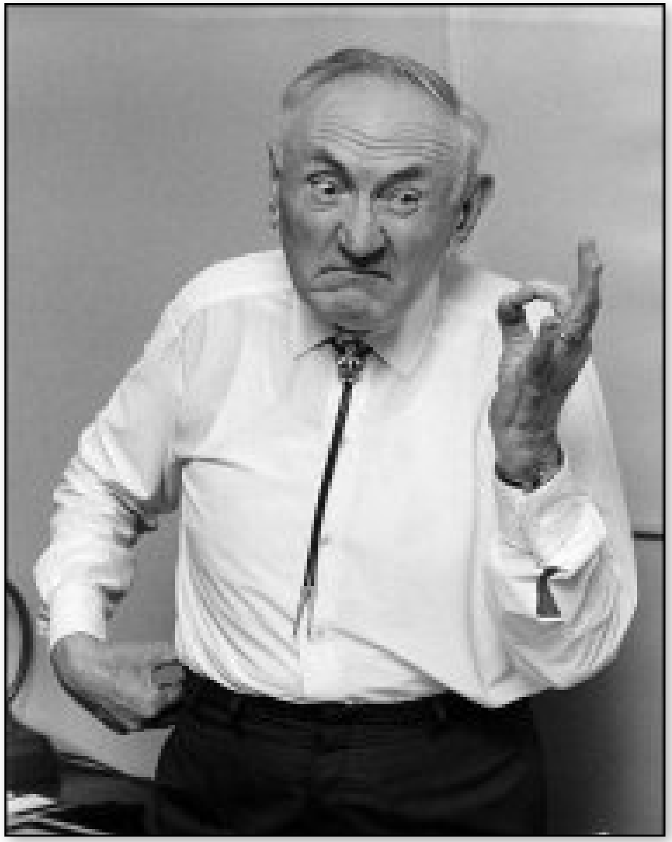
- Swiss astronomer (emigrated to the US in 1925)
- Major accomplishments include:

-First to realize that supernovae were the result of a star transitioning into a neutron star (coined the term supernova in 1934)

-Proposed using supernovae as standard candles to measure cosmological distances

-Proposed the use of galaxy clusters as gravitational lenses

-Identified the presence of missing matter (dark matter) in the Coma cluster



THE COMA CLUSTER

- Cluster of at least ~1000 galaxies
- About 100 Mpc (325,000,000 light years) distant
- In 1933, Zwicky studied the motions of these galaxies (using the virial theorem) to determine the average mass of the galaxies within the cluster

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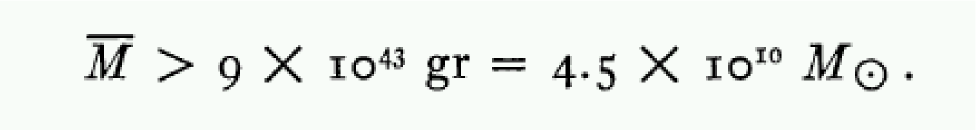
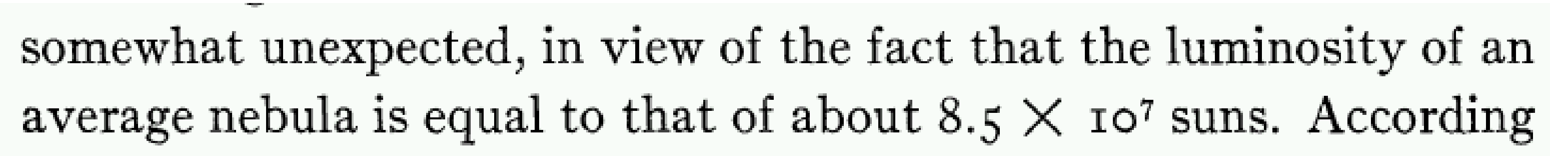


$$\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_{\odot} .$$

which, he pointed out, was…



somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According

⇒ Mass-to-light ratio of ~500

(per mass, 1/500th as luminous as the sun)

The Coma Cluster

- How might this be explained?

1) Stars are different (less luminous) in the Coma cluster than in our galaxy

2) Coma cluster is not in equilibrium (galaxies are in the process of flying

3) The laws of physics are different in the Coma cluster than in our galaxy

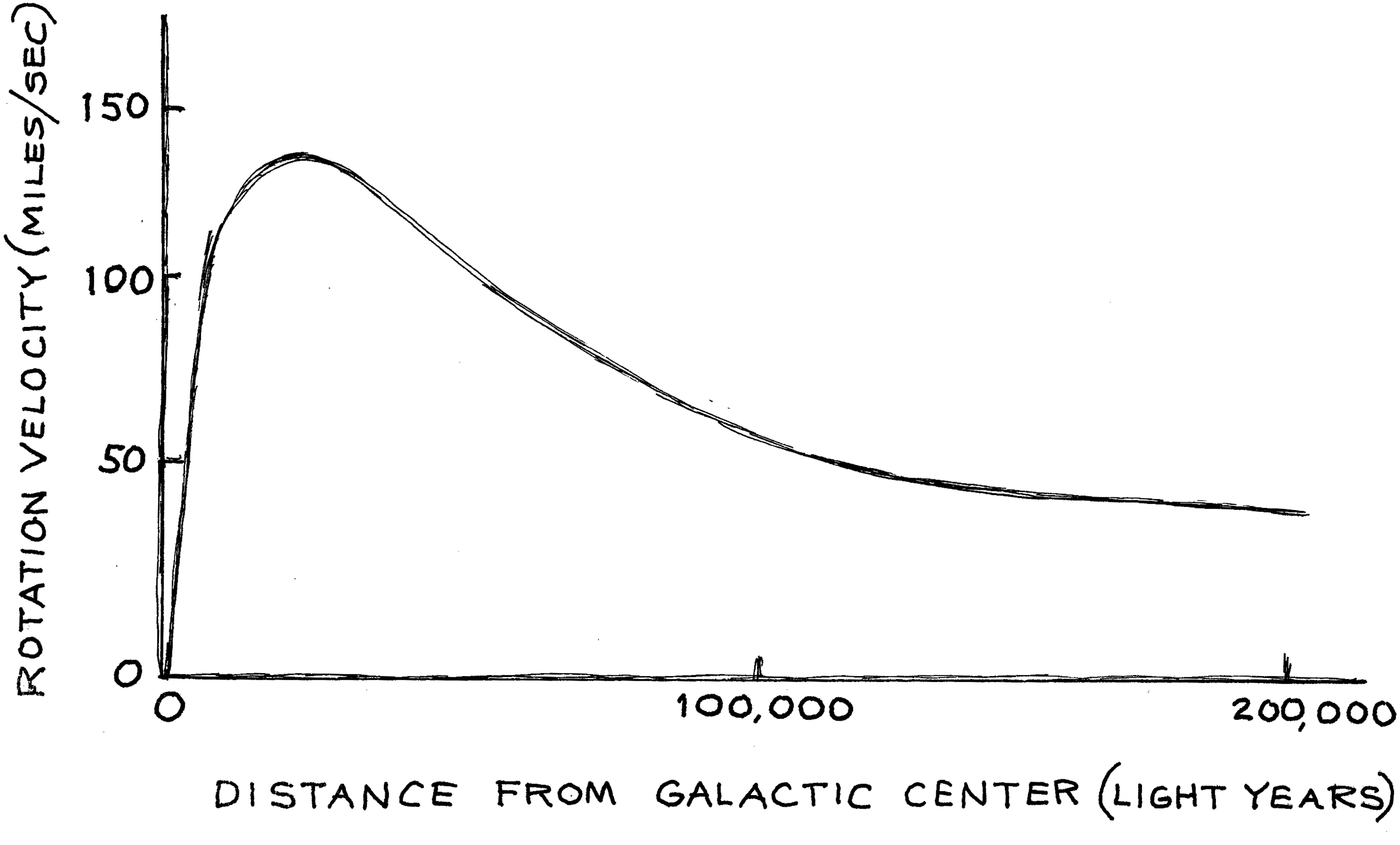
4) The vast majority of the Coma cluster’s mass is in non-luminous material (dark matter)

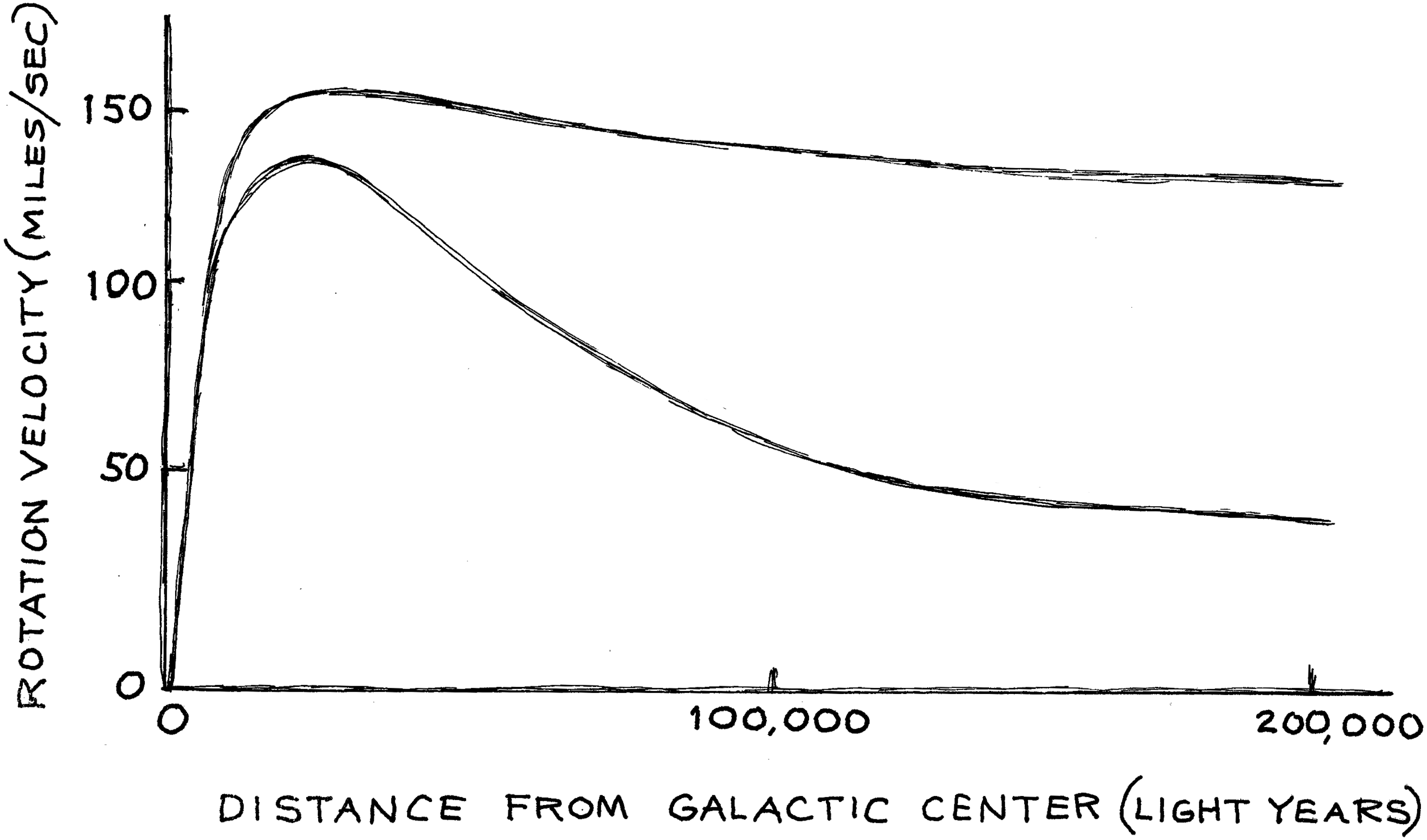
- To discriminate between these various possibilities, it would be necessary to study other clusters and see if they too had large mass-to-light ratios (Sinclair Smith, in 1936, found similar results for the Virgo cluster)

- Over time, options 1, 2 and 3 would become increasingly untenable

VERA RUBIN

- American astronomer
- Between roughly 1950 and 1980, carried out many of the most detailed and influential studies of the dy s
- In particular, she published a key paper in 0 (with W.K. Ford) on the motions of stars n the Andromeda galaxy, revealing a large mass-to-light ratio
- By 1980 or so, the conclusion that galaxies and clusters of galaxies were much more massive than their luminosities would suggest had become broadly accepted among astronomers


ROTATION VELOCITY (MILES/SEC)
150
100
50
0
0
100,000
200,000
DISTANCE FROM GALACTIC CENTER (LIGHT YEARS)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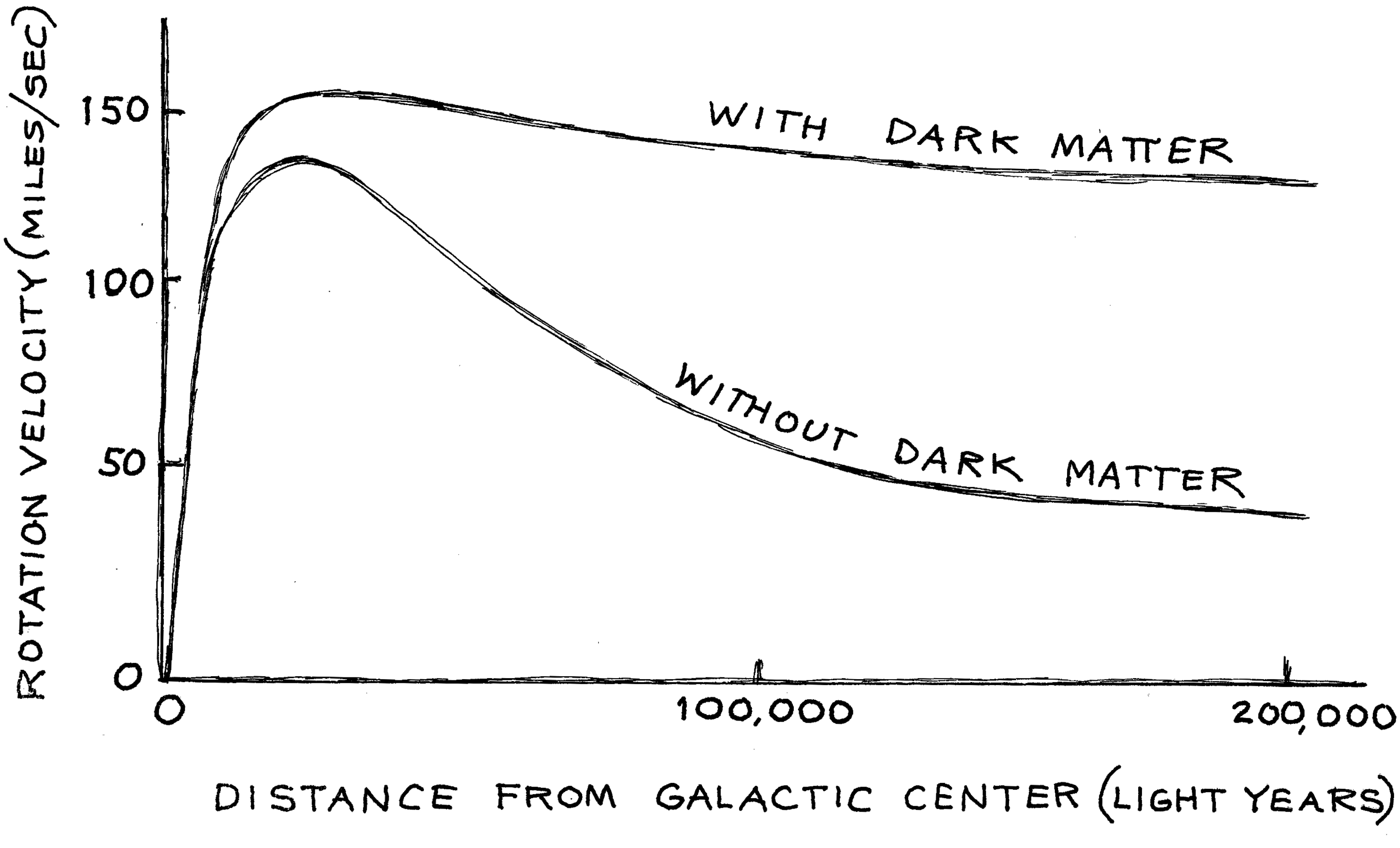

Most of the mass is invisible!

Three Possibilities

1) Galaxies are mostly made up of very non-luminous objects (black holes, neutron stars, white dwarf stars, large planets, etc.)

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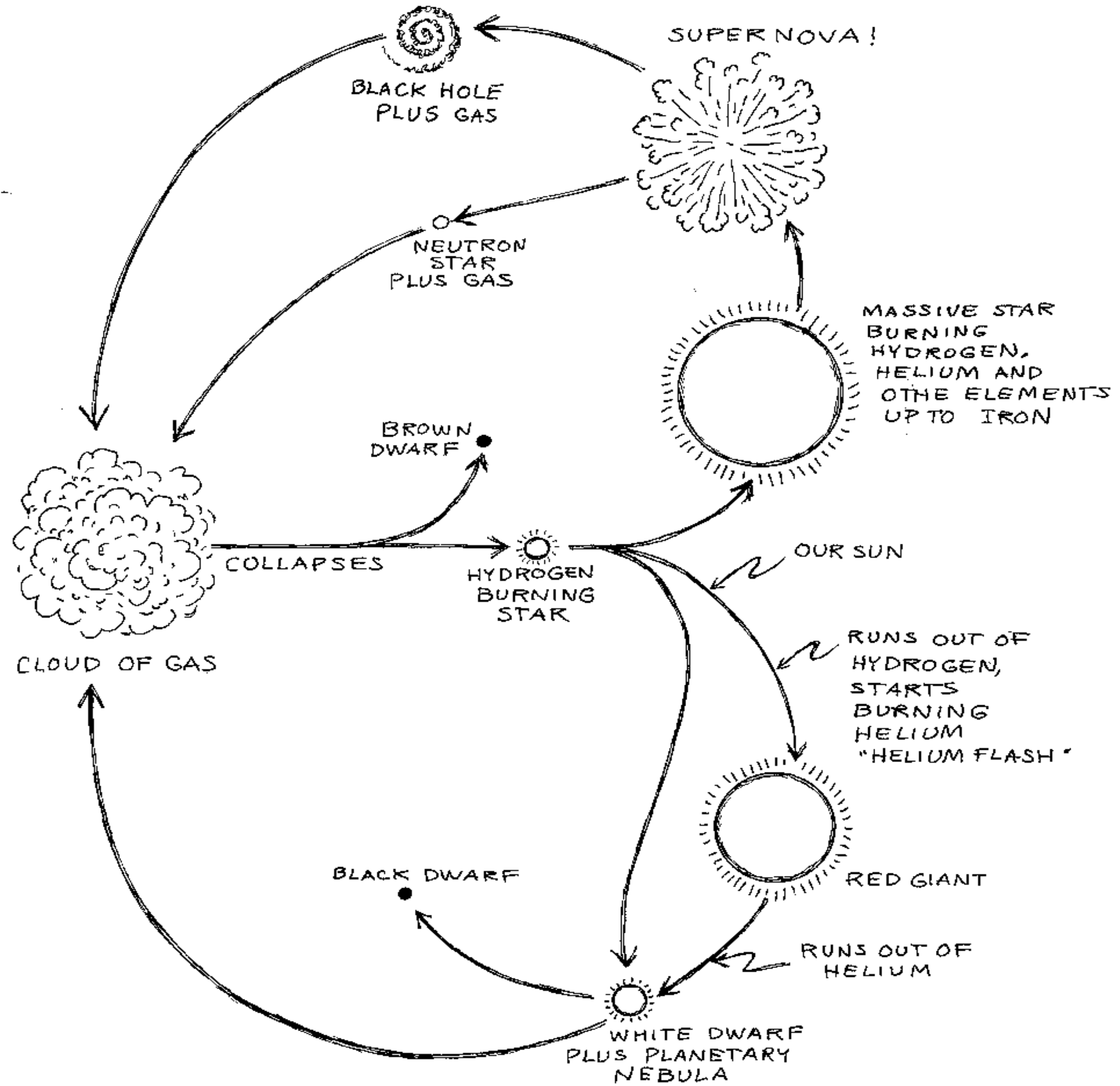
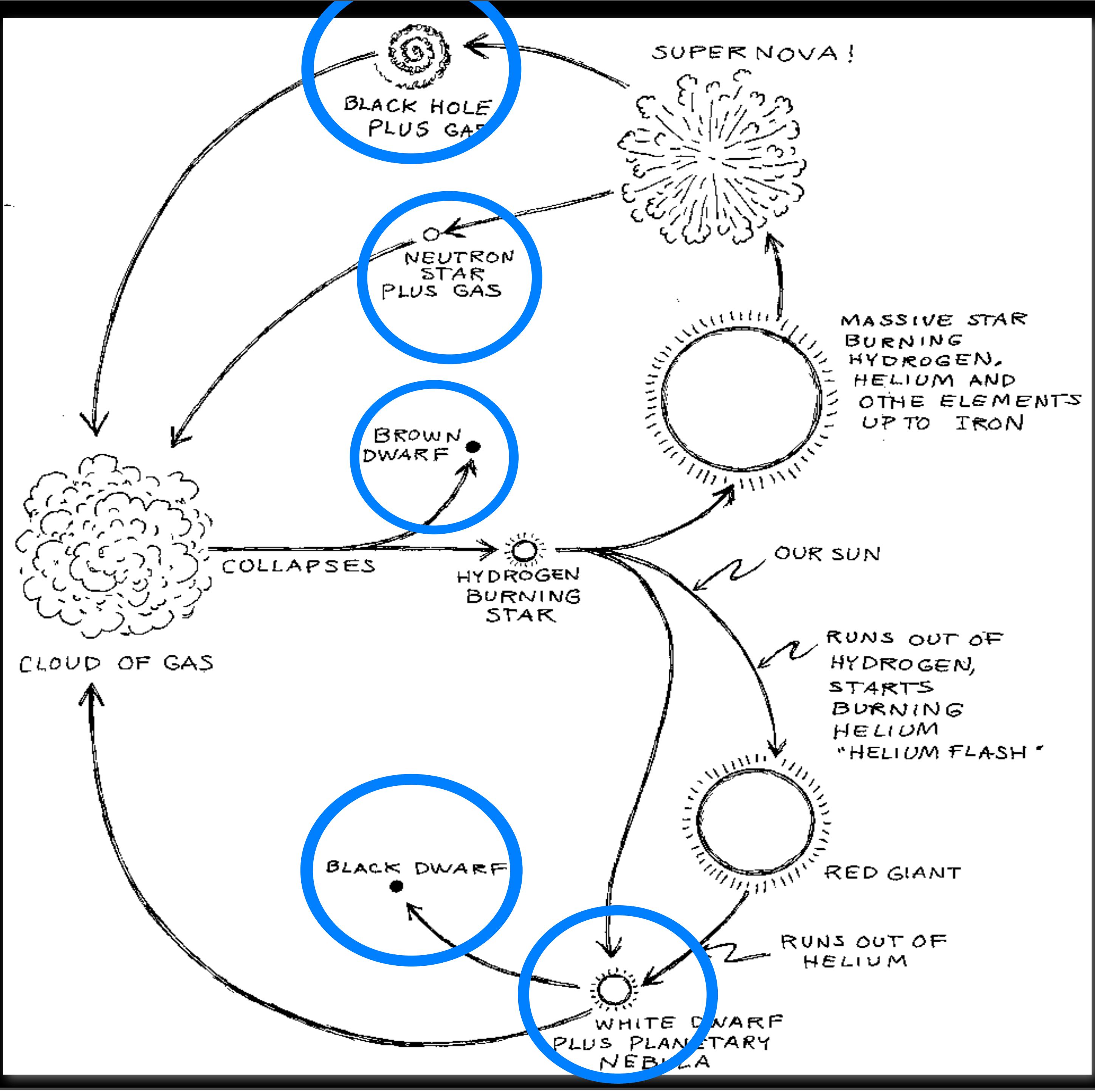

SUPER NOVA !
BLACK HOLE PLUS GAS
NEUTRON STAR PLUS GAS
MASSIVE STAR BURNING HYDROGEN, HELIUM AND OTHE ELEMENTS UP TO IRON
BROWN DWARF
CLOUD OF GAS
COLLAPSES
HYDROGEN BURNING STAR
OUR SUN
RUNS OUT OF HYDROGEN, STARTS BURNING HELIUM "HELIUM FLASH"
RED GIANT
RUNS OUT OF HELIUM
BLACK DWARF
WHITE DWARF PLUS PLANETARY NEBULA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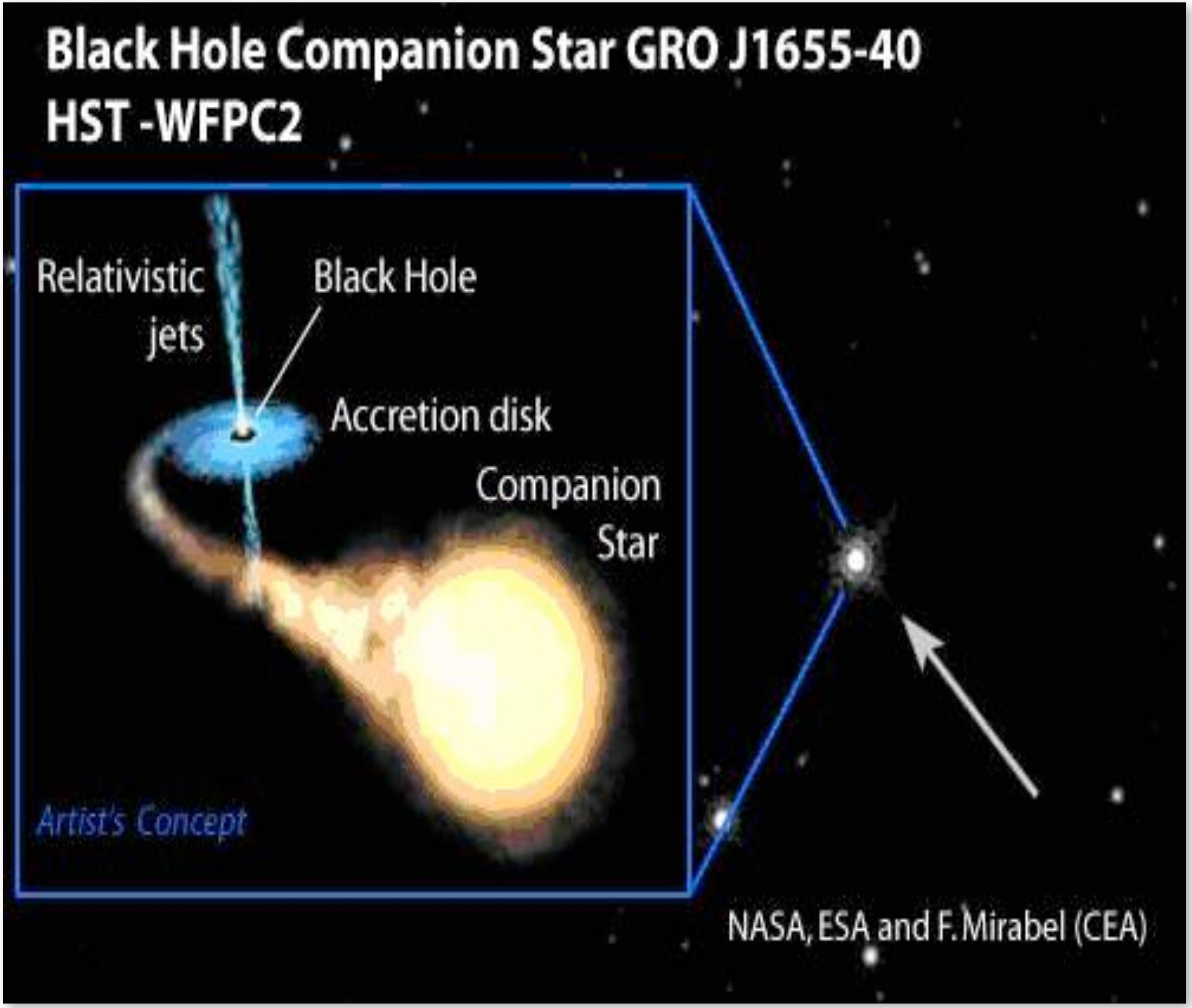
NEBULA

FAINT STARS

- When most (~97%, including the Sun) stars run out of nuclear fuel, they compress into objects about the size of the Earth - white dwarfs
- White dwarfs become fainter as they age; most are 20% to 0.03% as luminous as the Sun

- When massive stars (~3%) run out of fuel, they explode as supernovae, leaving behind either a neutron star or a black hole
- Neutron stars are objects made up almost entirely f neutrons (few protons, electrons); they consist f a solar mass worth of material within a radius kilometers
- Black holes are remnants of stars so massive t they collapse to a single point of space, with density; nothing (including light) can escape gravitational pull

“SEEING” BLACK HOLES



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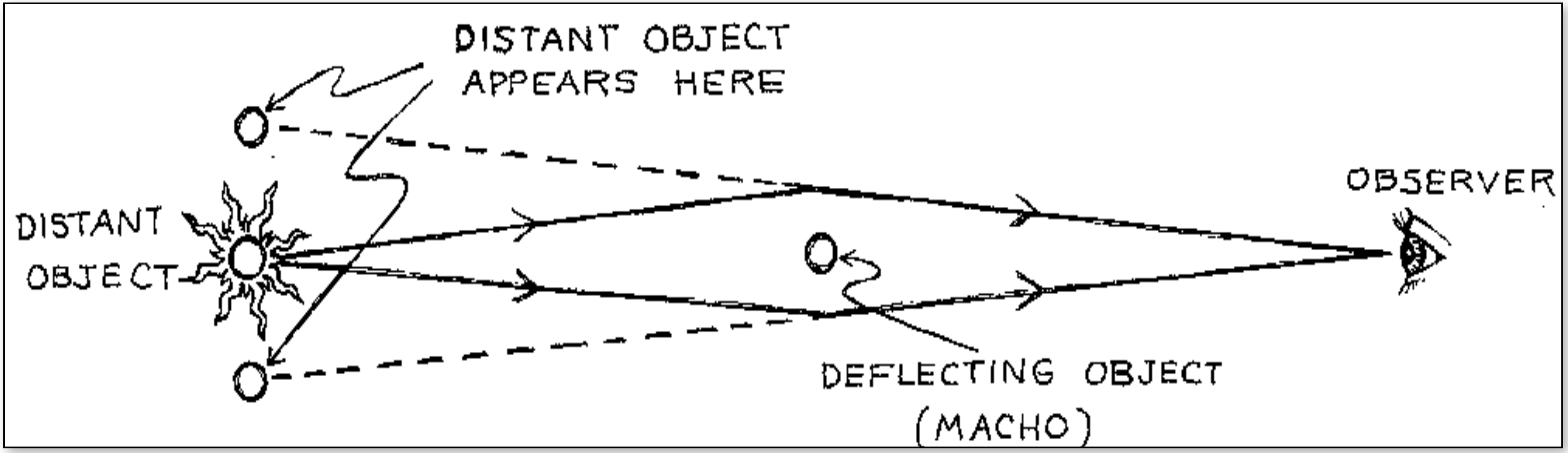
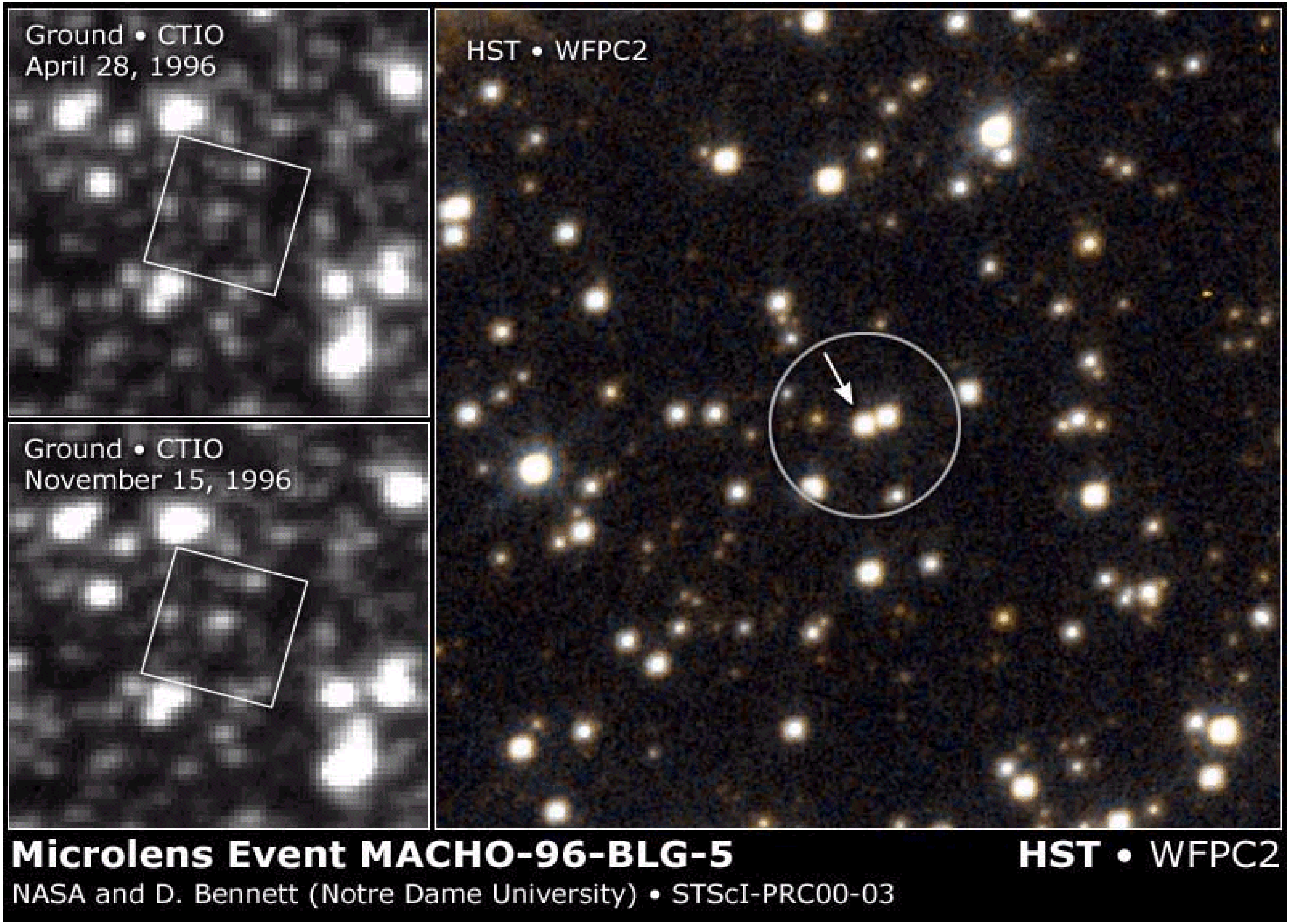


Massive objects can be detected as gravitational lenses, even if they are themselves non-luminous

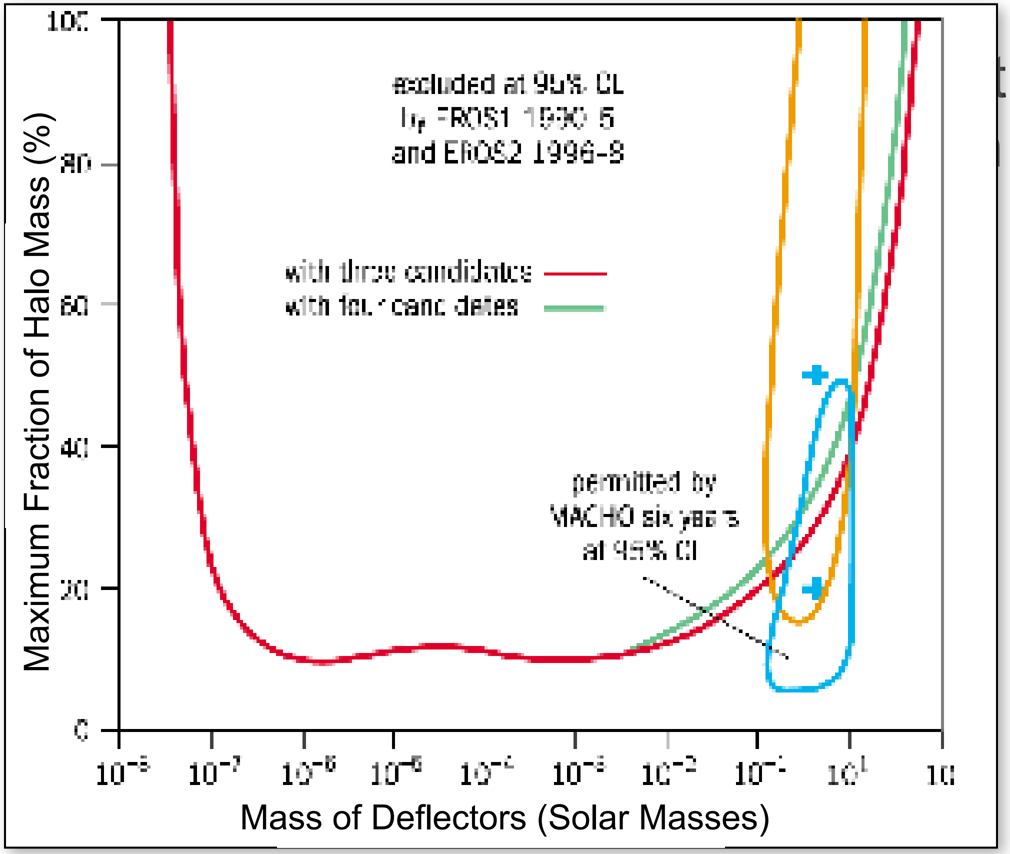


Caused by a black hole six times more massive than the Sun

SEARCHES FOR DARK MATTER WITH GRAVITATIONAL MICROLENSING

- Although microlensing searches have found some faint and compact objects, they seem to be far too rare to make up much of the missing matter

- Whatever the dark matter is, does not consist of objects masses between about 10^{-8} and 100 solar masses



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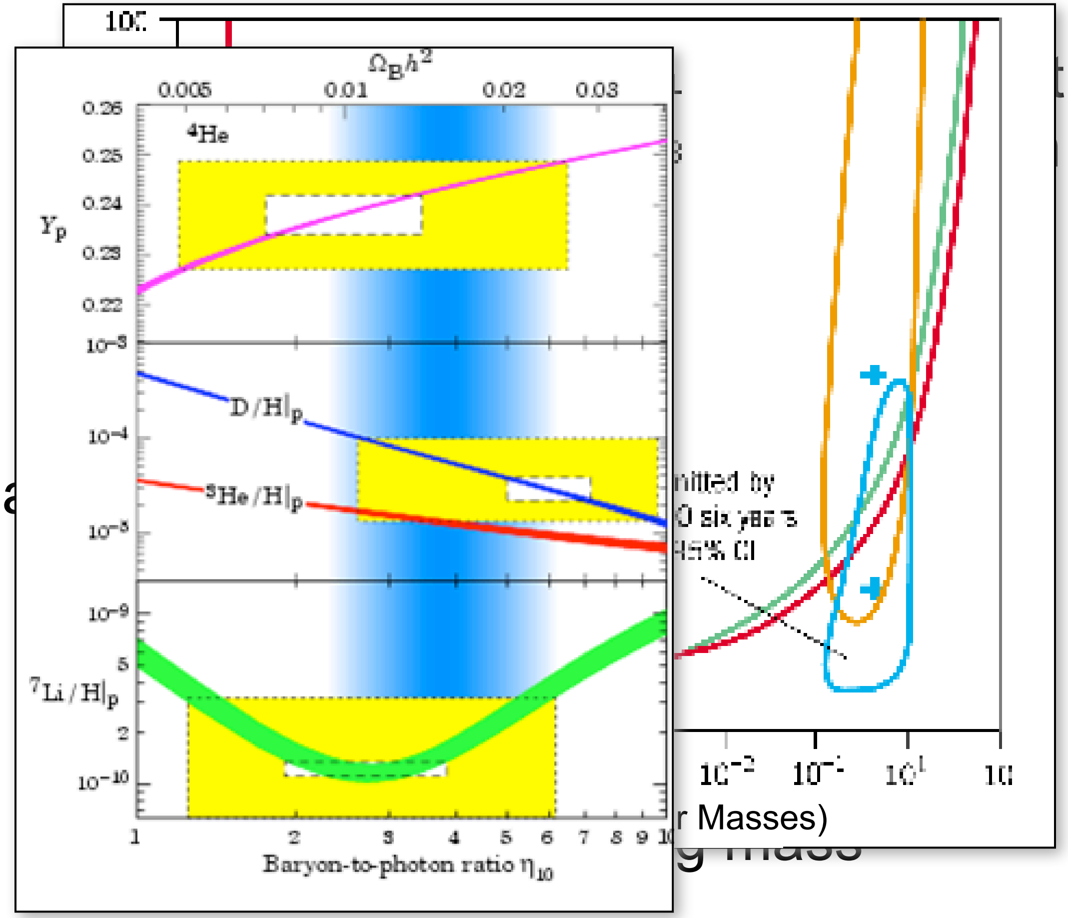
- Furthermore, our current understanding of the ea

far

would

of



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~~1) Galaxies are mostly made up of very non-luminous objects (black holes, neutron stars, white dwarf stars, large planets, etc.)~~

2) Gravity does not work in galaxies and clusters the way in does on Earth or in our Solar System

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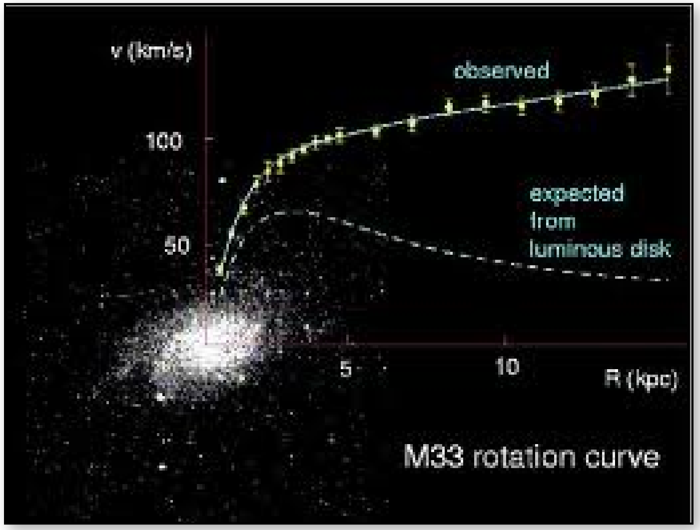
Modified Newtonian Dynamics (MOND)

- Begin by modifying Newtonian dynamics as follows:

$$F = ma \longrightarrow F = ma \times \mu(a)$$

where $\mu \approx 1$, except at small accelerations, at $\mu = a/a_0$



- For a circular orbit,

$$F = \frac{GMm}{r^2} = ma\mu$$

Which in the low-acceleration limit yields:

$$a = \frac{\sqrt{GMa_0}}{r} = \frac{v^2}{r} \quad \Longrightarrow \quad v = (GMa_0)^{1/4}$$

Rotational velocity independent of galactic radius (flat rotation curve)

Modified Newtonian Dynamics (MOND)

- MOND has been quite successful in explaining galactic dynamics of galaxies, and provides an explanation for the Tully-Fisher relationship
- Galaxy clusters have been less well described by MOND

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PROPERTIES OF DARK MATTER

1) Not made of baryons (protons, neutrons)

2) Comes in “small” pieces (relative to stars, planets)

3) Does not significantly emit, reflect, or absorb light (electrically neutral)

4) Stable

5) Massive

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Massive Astrophysical Halo Objects (MACHOs)

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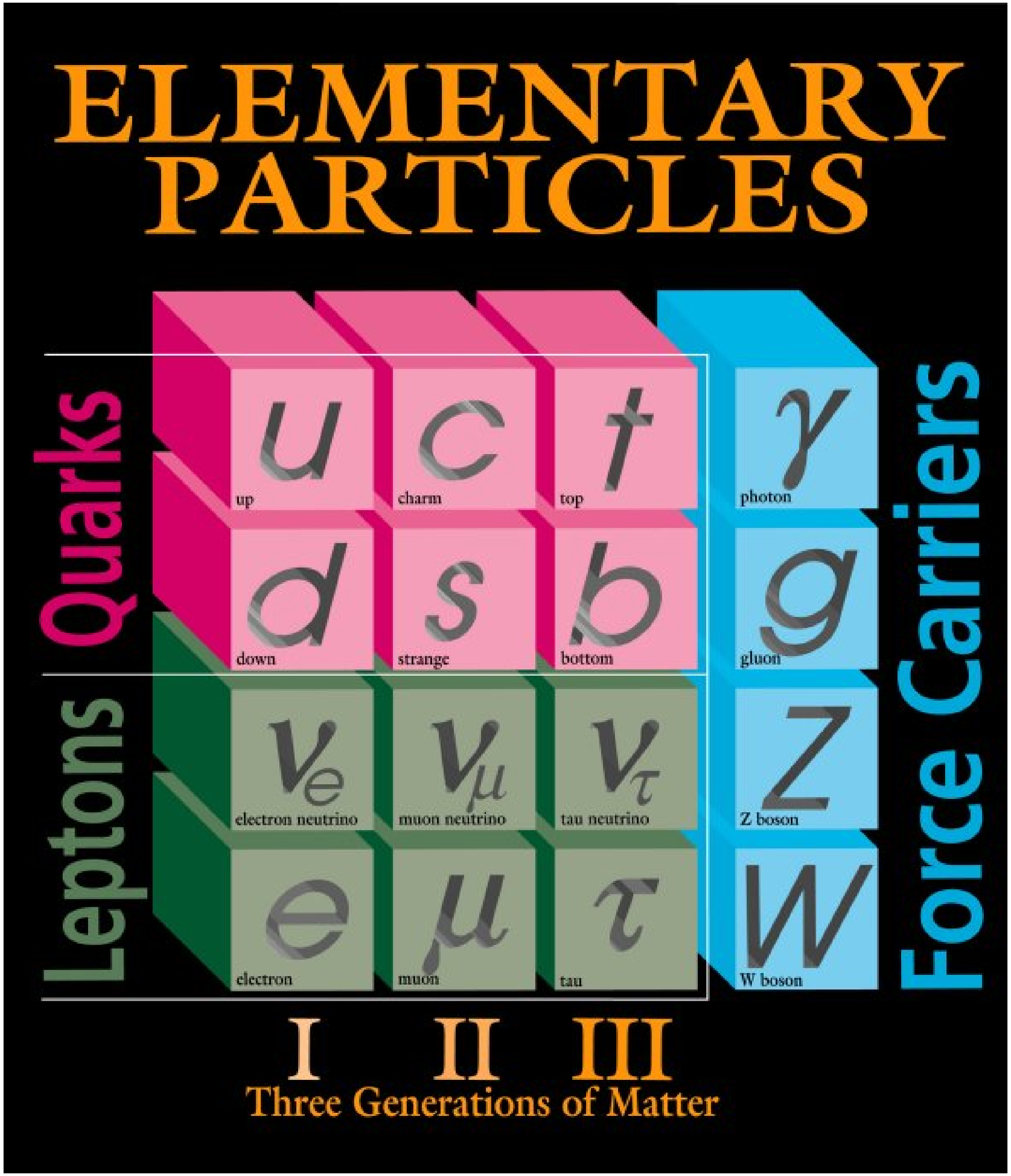
Weakly Interacting Massive Particles
(WIMPs)

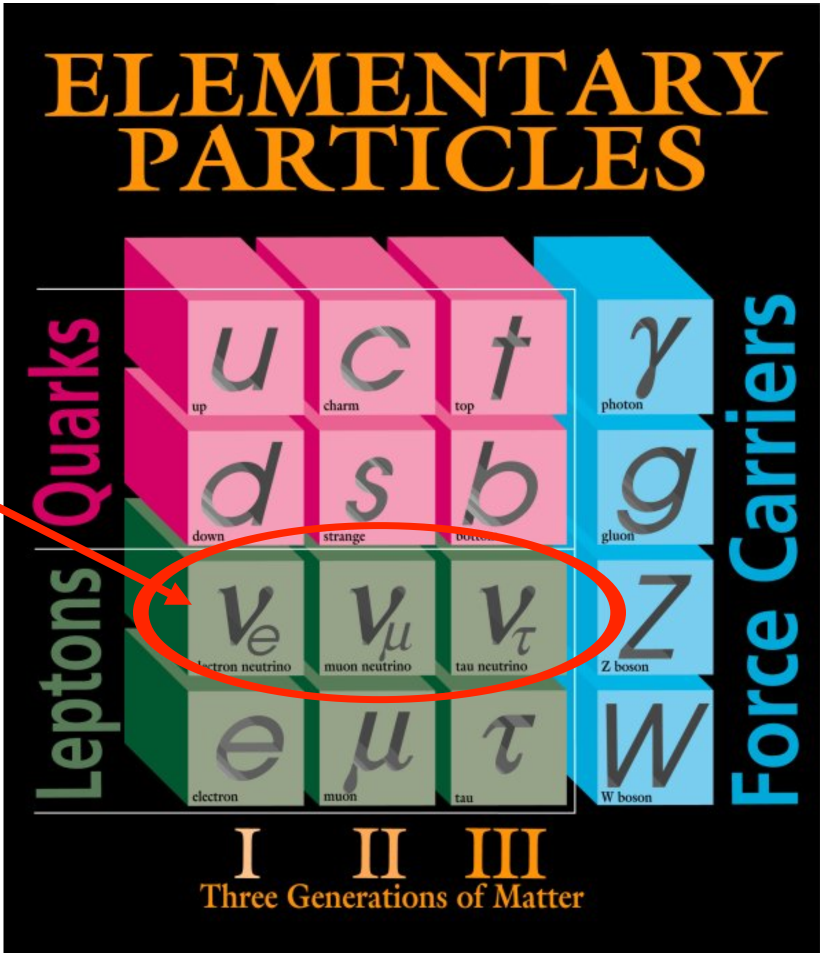
But what are the WIMPs?


ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
d
down
s
strange
b
bottom
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
e
electron
μ
muon
τ
tau
γ
photon
g
gluon
Z
Z boson
W
W boson
I
II
III
Three Generations of Matter

WIMPs

Weakly Interacting Massive Particles

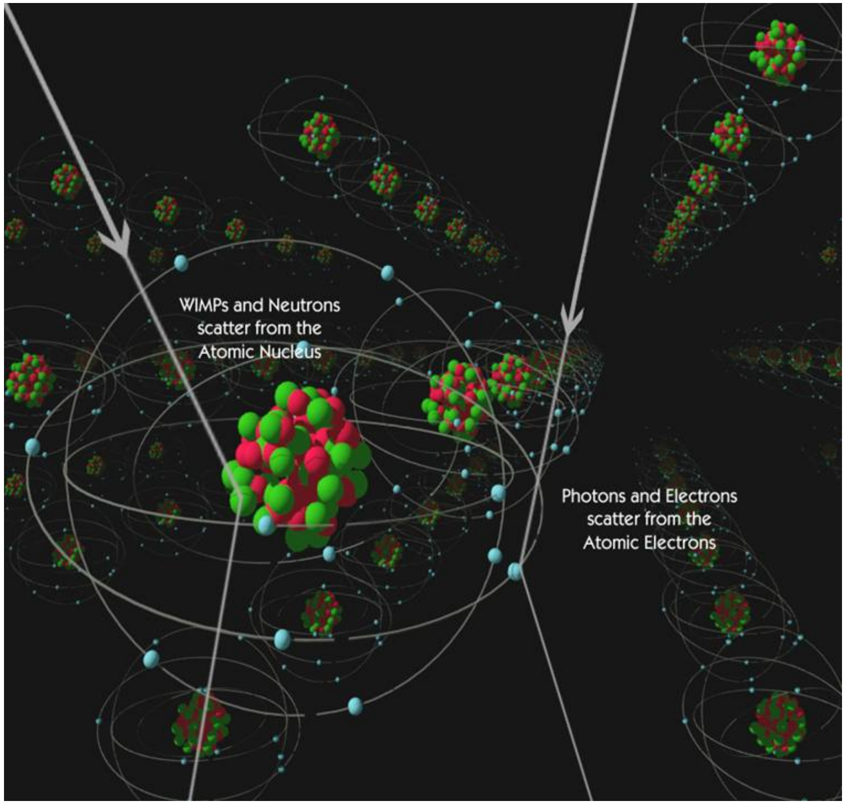
- There are known particles with most of the properties required of WIMPs, called neutrinos
- But neutrinos are too light and quick moving to make up the dark matter



How to search for WIMPs?

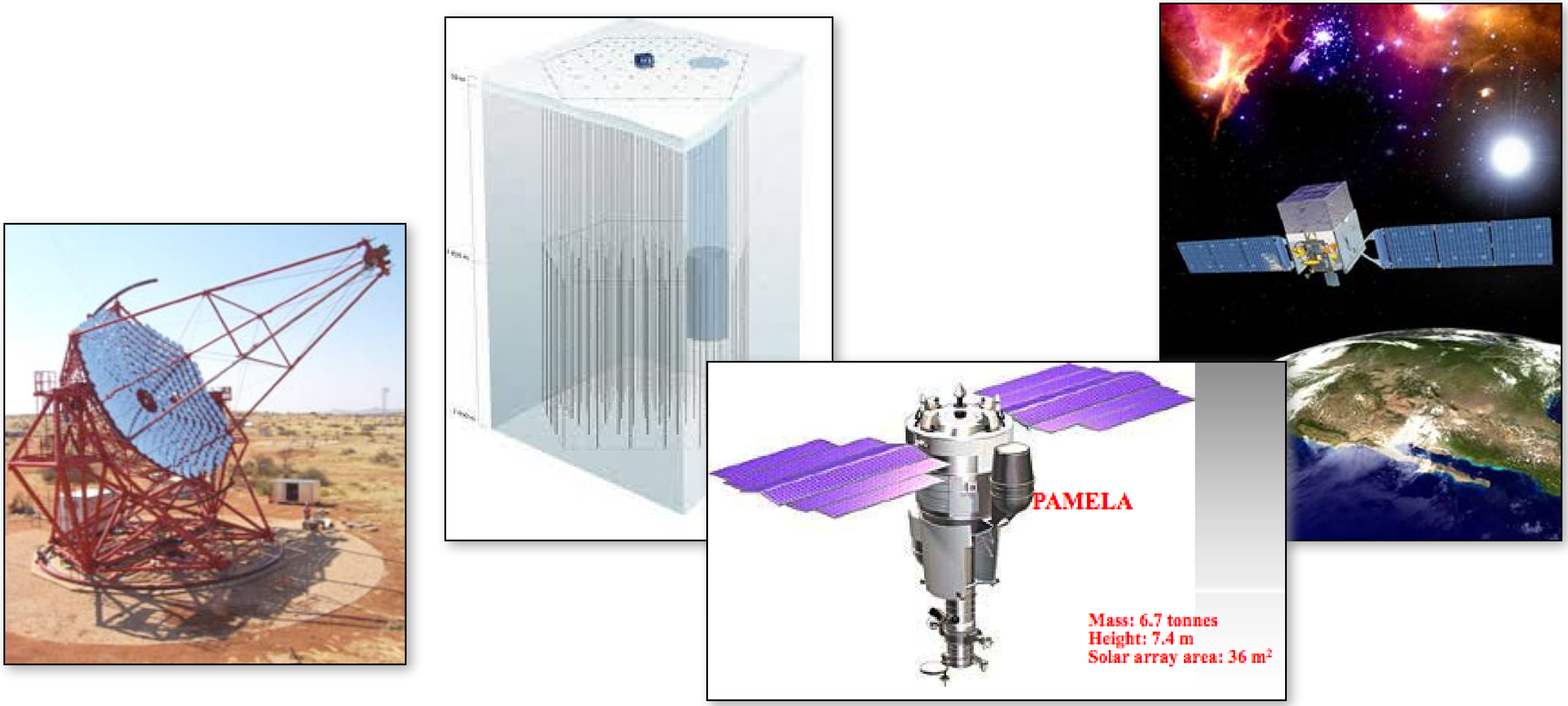
1) Go deep underground and wait for WIMPs to hit your detector

The Soudan Mine



How to search for WIMPs?

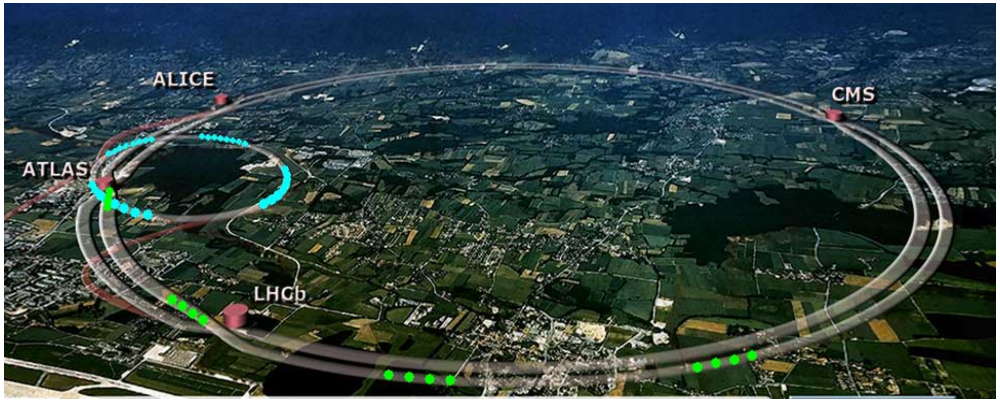
2) Use “telescopes” to look for energetic particles that are produced when dark matter particles annihilate



How to search for WIMPs?

3) Create it using a particle accelerator

The Fermilab Tevatron



The Large Hadron Collider (LHC)

DARK MATTER IN THE 21ST CENTURY

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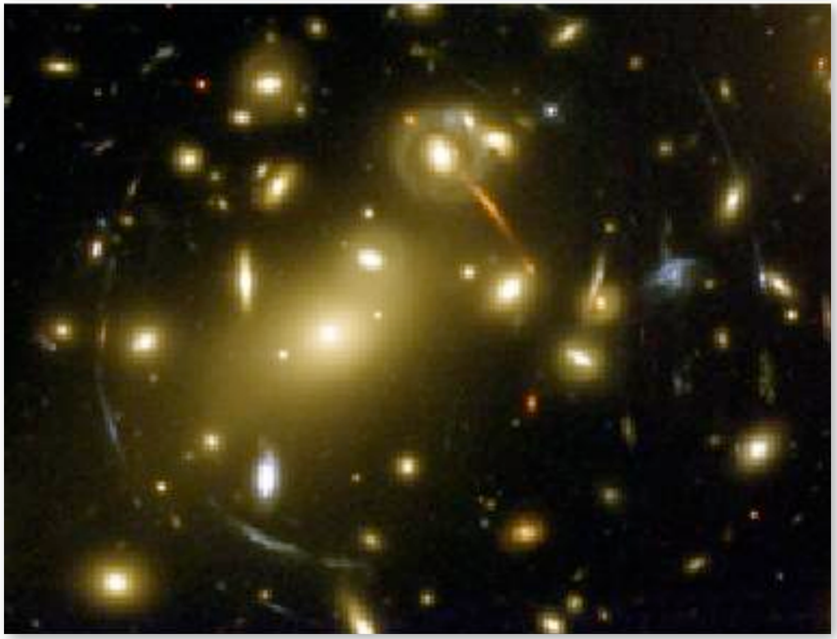
- Astrophysicists see its imprint in many different ways:
  - -Gravitation lensing of clusters



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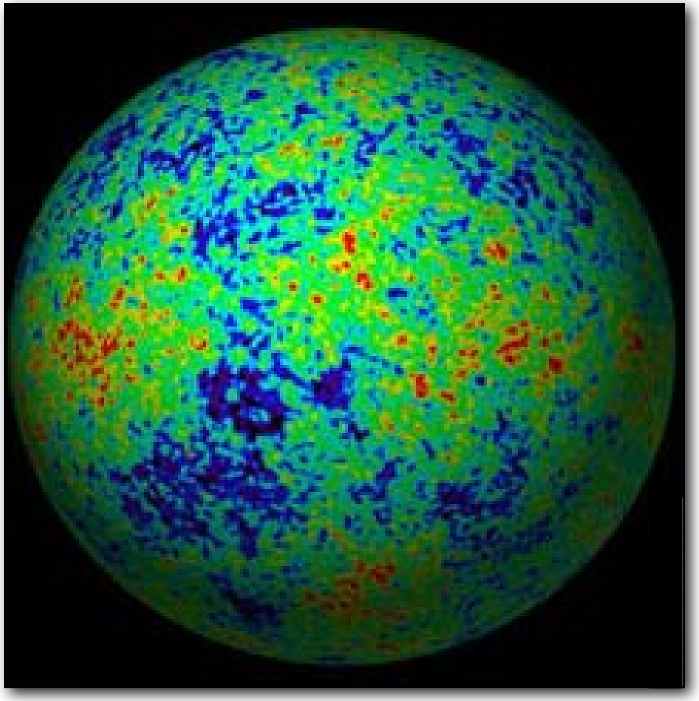
  - -The cosmic microwave background radiation



DARK MATTER IN THE 21ST CENTURY

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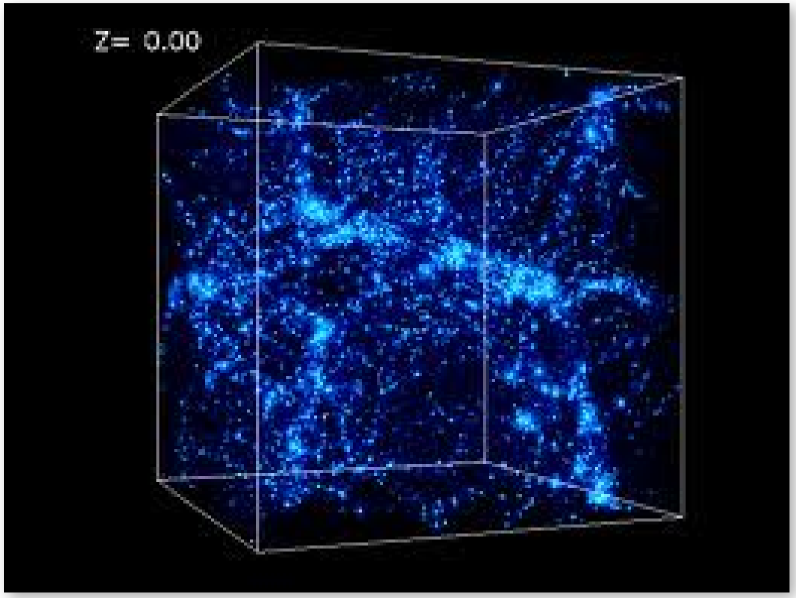
    - -The cosmic microwave background radiation
    - -The large scale structure of our universe



DARK MATTER IN THE 21ST CENTURY

- Dark matter’s nature remains a mystery
- Astrophysicists see its imprint in many different ways
- The WIMP-paradigm for dark matter has held up to much scrutiny, but what WIMPs actually are remains to be discovered