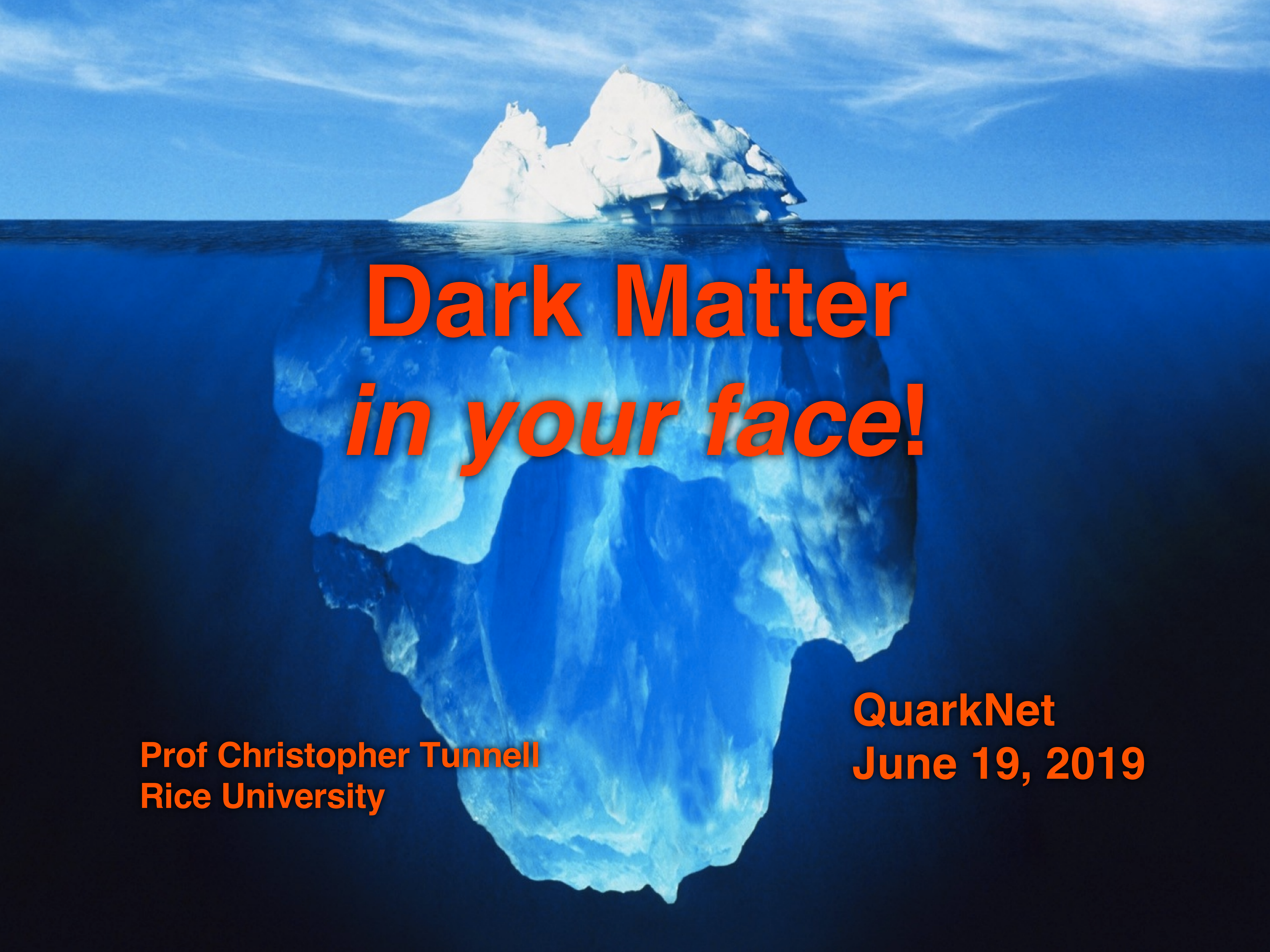
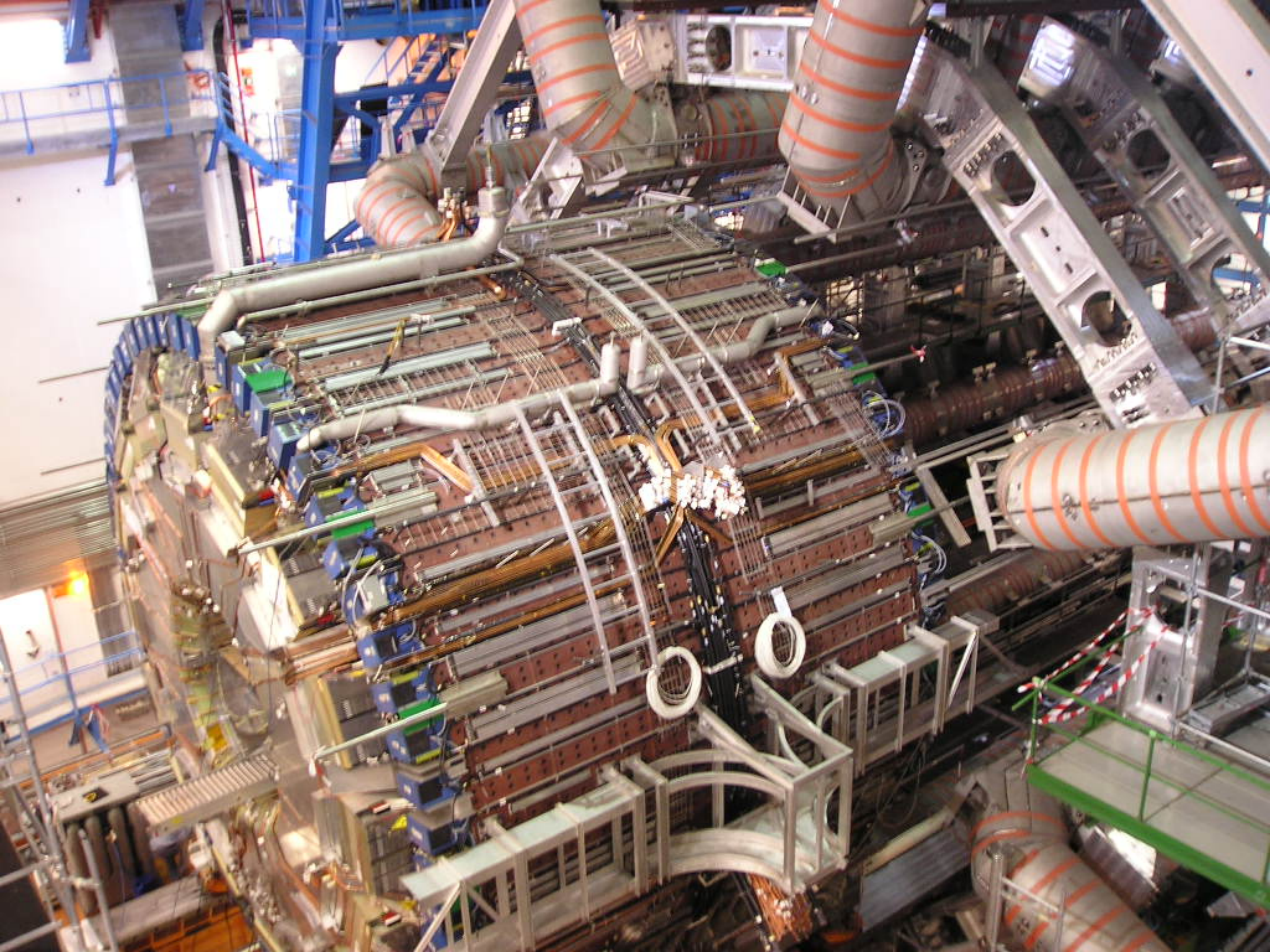


Dark Matter *in your face*!

Prof Christopher Tunnell
Rice University

QuarkNet
June 19, 2019

ARCTIC OCEAN
QUEEN ELIZABETH ISLANDS
Greenland
(DENMARK)
Beaufort Sea
Arctic Circle (66°33')
Baffin Bay
Davis Strait
Hudson Bay
Labrador Sea
Greenland Sea
Norwegian Sea
Barents Sea
North Sea
ICELAND
Reykjavík
NORWAY
SWEDEN
FINLAND
Oslo
Stockholm
Helsinki
U. S.
Anchorage
Fairbanks
CANADA
Edmonton
Calgary
Vancouver
Winnipeg
Ottawa
Toronto
Montréal
Québec
Island of Newfoundland
UNITED STATES
Seattle
Portland
San Francisco
Los Angeles
San Diego
Las Vegas
Phoenix
Salt Lake City
Denver
Kansas City
Saint Louis
Chicago
Milwaukee
Minneapolis
Indianapolis
Cincinnati
Cleveland
Pittsburgh
Buffalo
Boston
Providence
New York
Philadelphia
Baltimore
Washington D.C.
Nashville
Charlotte
Atlanta
Oklahoma City
Dallas
El Paso
Austin
San Antonio
Houston
New Orleans
Jacksonville
Tampa
Orlando
Miami
Bermuda
NORTH ATLANTIC OCEAN
Gulf of Mexico
MEXICO
Monterrey
Guadalajara
Mexico
Acapulco
THE BAHAMAS
Havana
CUBA
JAMAICA
HAITI
DOMINICAN REPUBLIC
Caribbean Sea
BELIZE
GUATEMALA
HONDURAS
EL SALVADOR
NICARAGUA
COSTA RICA
PANAMA
VENEZUELA
Caracas
COLOMBIA
Bogota
Quito
ECUADOR
GUYANA
SURINAME
French Guiana
(FRANCE)
PERU
Lima
BRAZIL
Manaus
Brasília
Rio de Janeiro
São Paulo
Salvador
Recife
Fortaleza
BOLIVIA
La Paz
PARAGUAY
Asunción
URUGUAY
Montevideo
CHILE
Santiago
ARGENTINA
Buenos Aires
Equator
SOUTH ATLANTIC OCEAN
St. Helena
(U.K.)
Ascension
(St. Helena)
CAPE VERDE
Praia
IRELAND
UNITED KINGDOM
London
FRANCE
Paris
PORTUGAL
Lisbon
SPAIN
Madrid
ITALY
Rome
GREECE
Athens
Berlin
Warsaw
POLAND
BELARUS
Minsk
UKRAINE
Kyiv
ROMANIA
Bucharest
Moscow
TURKEY
Ankara
Istanbul
Mediterranean Sea
Black Sea
SYRIA
IRAQ
IRAN
JORDAN
SAUDI ARABIA
Riyadh
YEMEN
MOROCCO
Rabat
ALGERIA
Algiers
TUNISIA
Tunis
LIBYA
Tripoli
EGYPT
Cairo
Western Sahara
MAURITANIA
MALI
NIGER
CHAD
SUDAN
Khartoum
SOUTH SUDAN
ETHIOPIA
Addis Ababa
SOMALIA
Mogadishu
KENYA
Nairobi
UGANDA
TANZANIA
SENEGAL
Dakar
GUINEA
SIERRA LEONE
LIBERIA
CÔTE D'IVOIRE
GHANA
NIGERIA
Abuja
CAMEROON
CENTRAL AFRICAN REPUBLIC
GABON
DEMOCRATIC REPUBLIC OF THE CONGO
Kinshasa
ANGOLA
Luanda
ZAMBIA
MALAWI
MOZAMBIQUE
ZIMBABWE
NAMIBIA
Windhoek
BOTSWANA
SOUTH AFRICA
Cape Town
Pretoria
MADAGASCAR
Antananarivo
SEYCHELLES
COMOROS



“What is Dark Matter and why are you going on about our faces?”

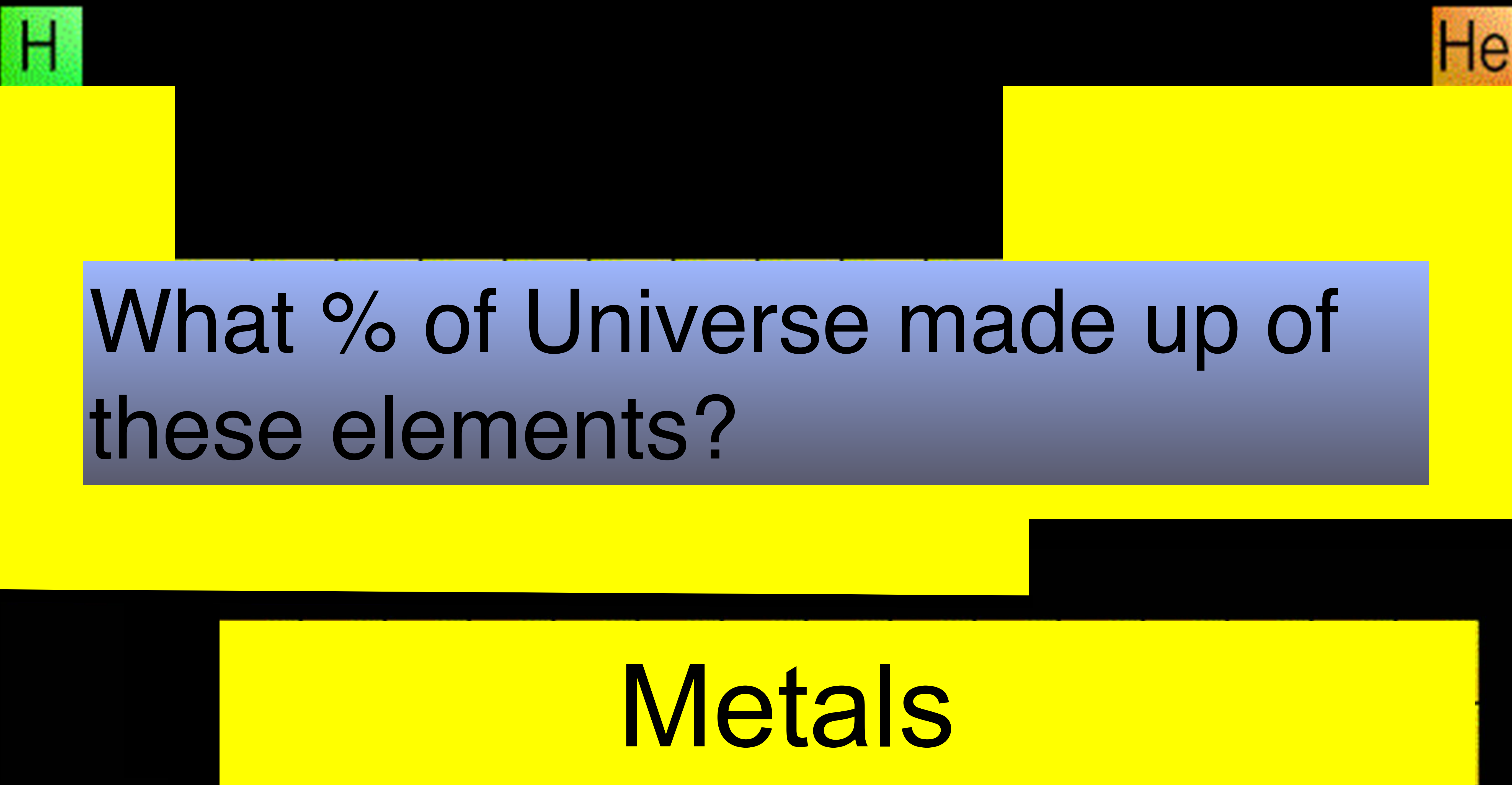
–Audience

Periodic Table – Chemist

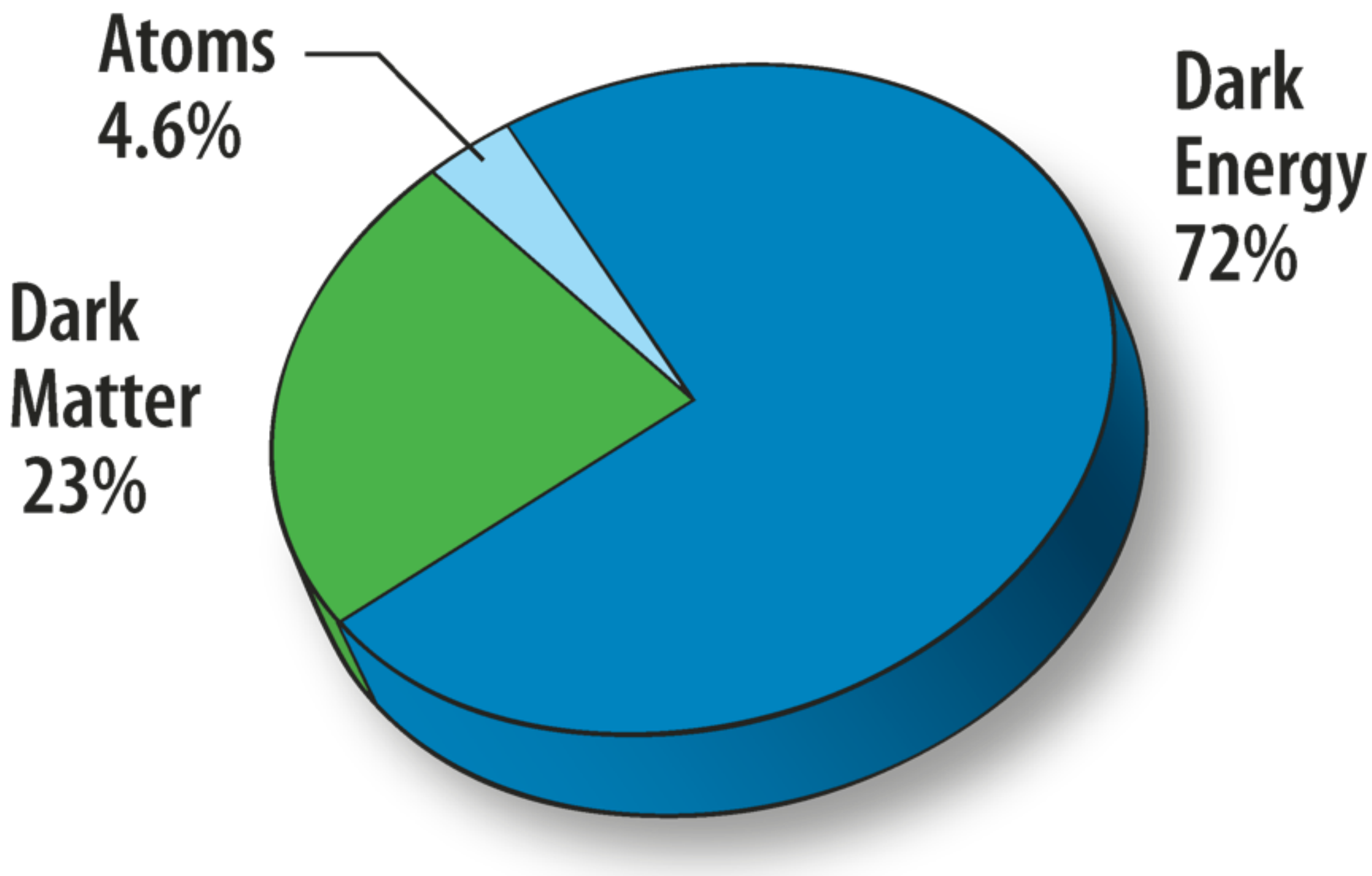
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Periodic Table – Cosmologist



Context: our *only* Universe



only studied 4.6% of the Universe!

95% of the mass is unknown…

Ninty-Five Percent of the Universe

Dark Matter (25%)	Dark Energy (70%)
Pulls things together	Pushes things apart
Attractive gravity	Repulsive gravity
New particle species?	Weight of space?

Astrophysics handbook:

1. Believe Newton
2. […]
3. Make discovery

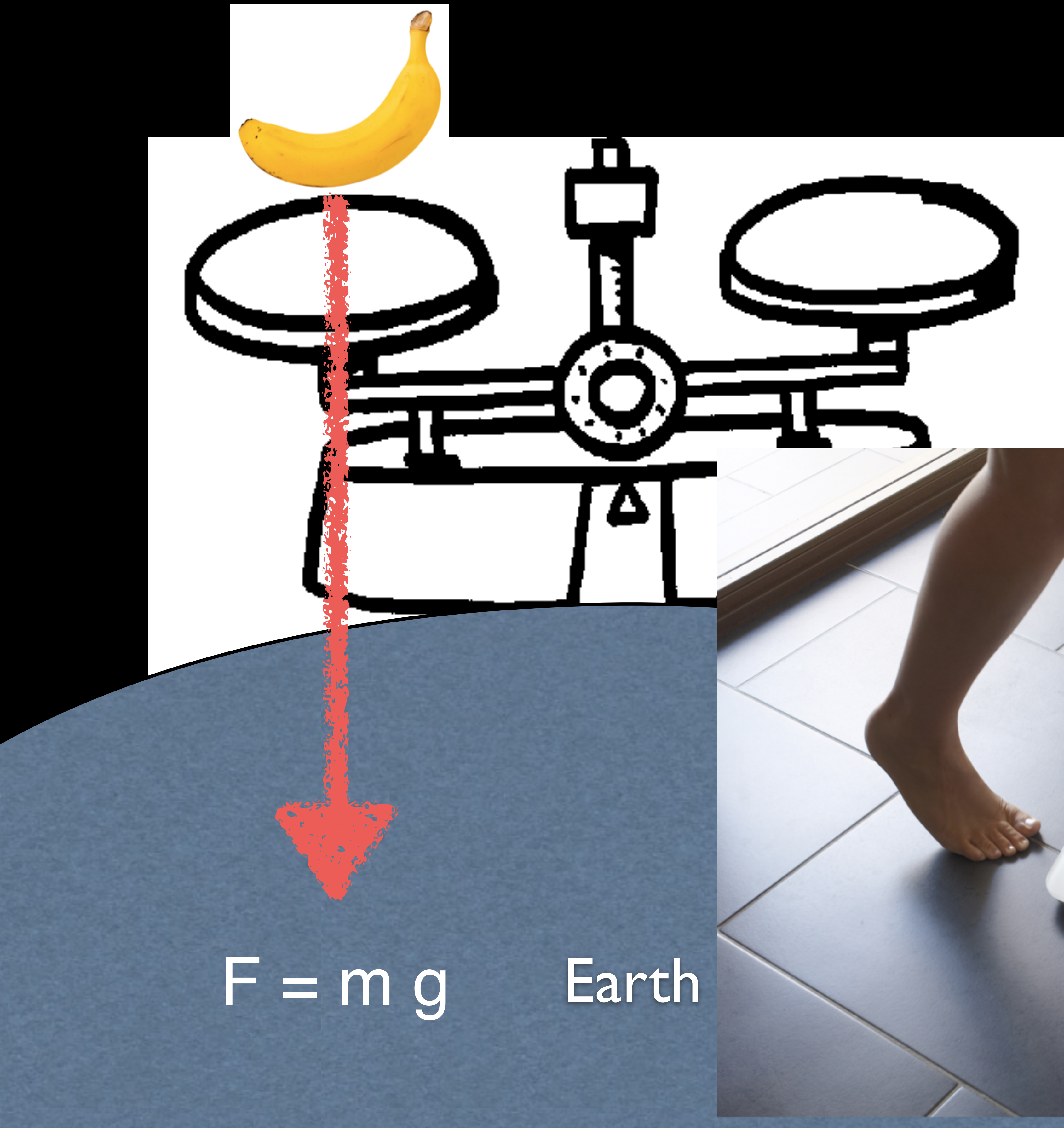
Apply this to a quick example…

23rd Sept 1846: Neptune right where scientists said it would be

Believing in Newton pays off!

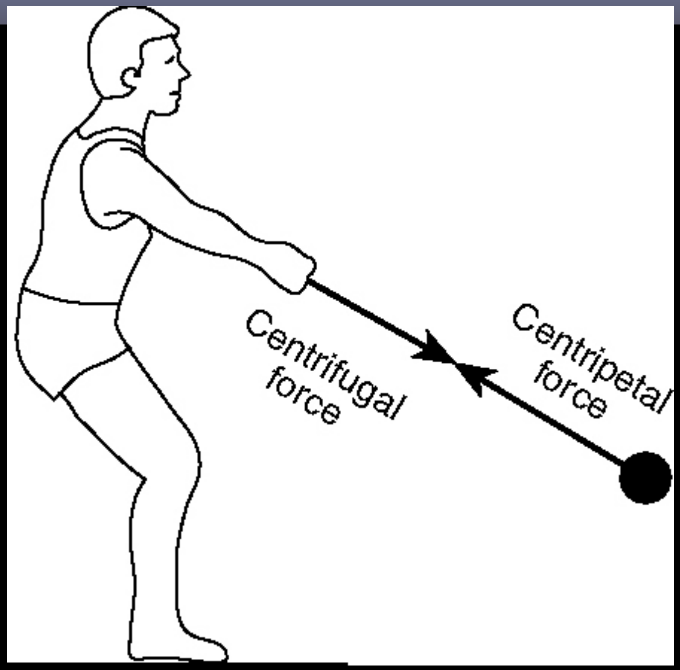
The planet Neptune was right where French mathematician Urban Le Verrier predicted it would be when German astronomer Johann Gottfried Galle looked for it

How to measure the mass of a banana?



$F = k\,x$

How to measure the mass of a GALAXY?



Centrifugal:

$$F = \frac{mv^2}{r}$$

Newton's law:

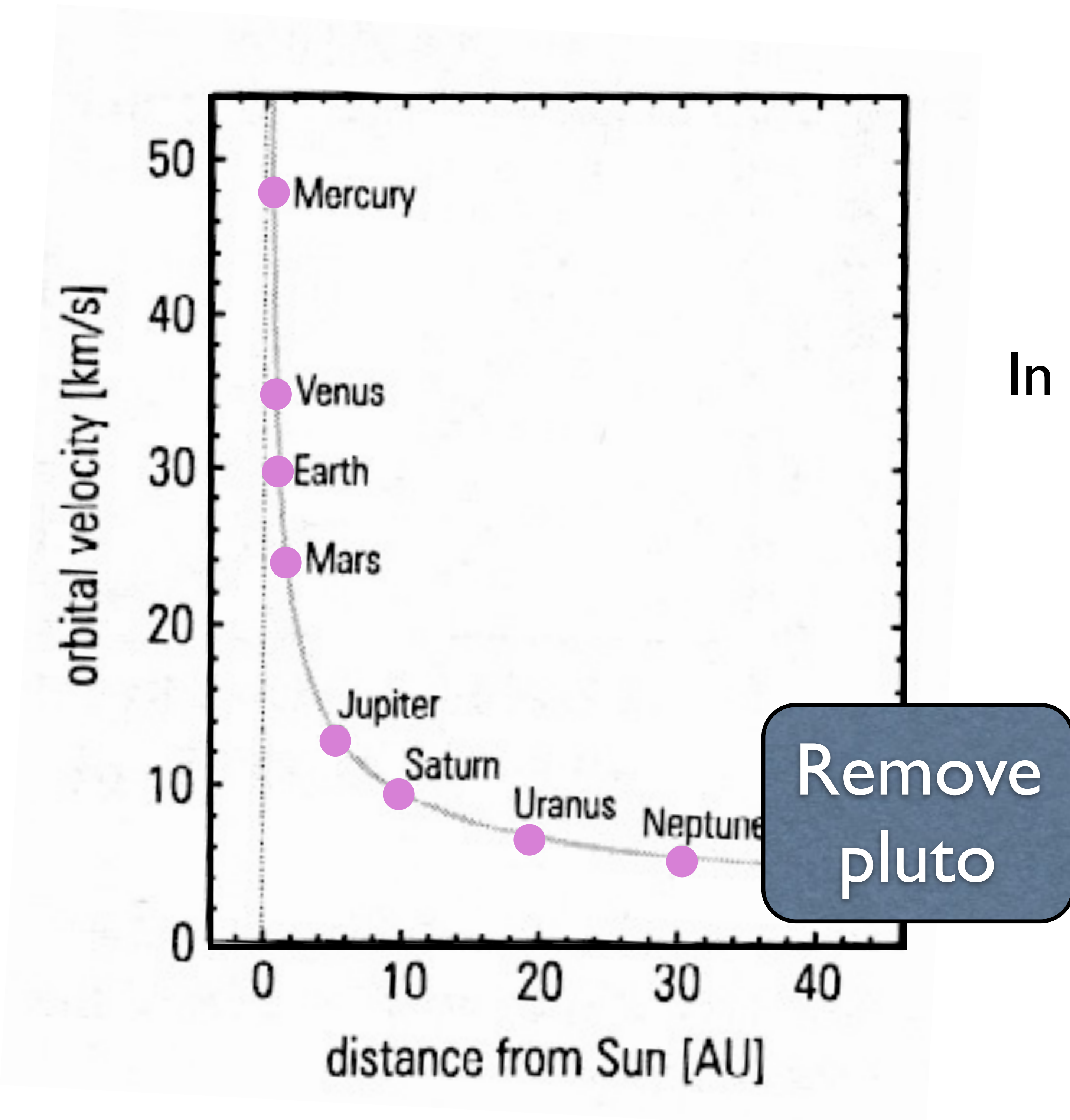
$$F = \frac{GM_1M_2}{r^2}$$

Triangulum galaxy M33 - can see with naked eye

$$\frac{M_1v^2}{r} = \frac{GM_1M_2}{r^2}$$

$$\implies v = \sqrt{\frac{GM_2}{r}} \sim r^{-1/2}$$

ex. rotation curve in our solar system



In our solar system: $v \sim r^{-1/2}$

Oort 1932

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

1932 August 17 | Volume VI. | No. 238.

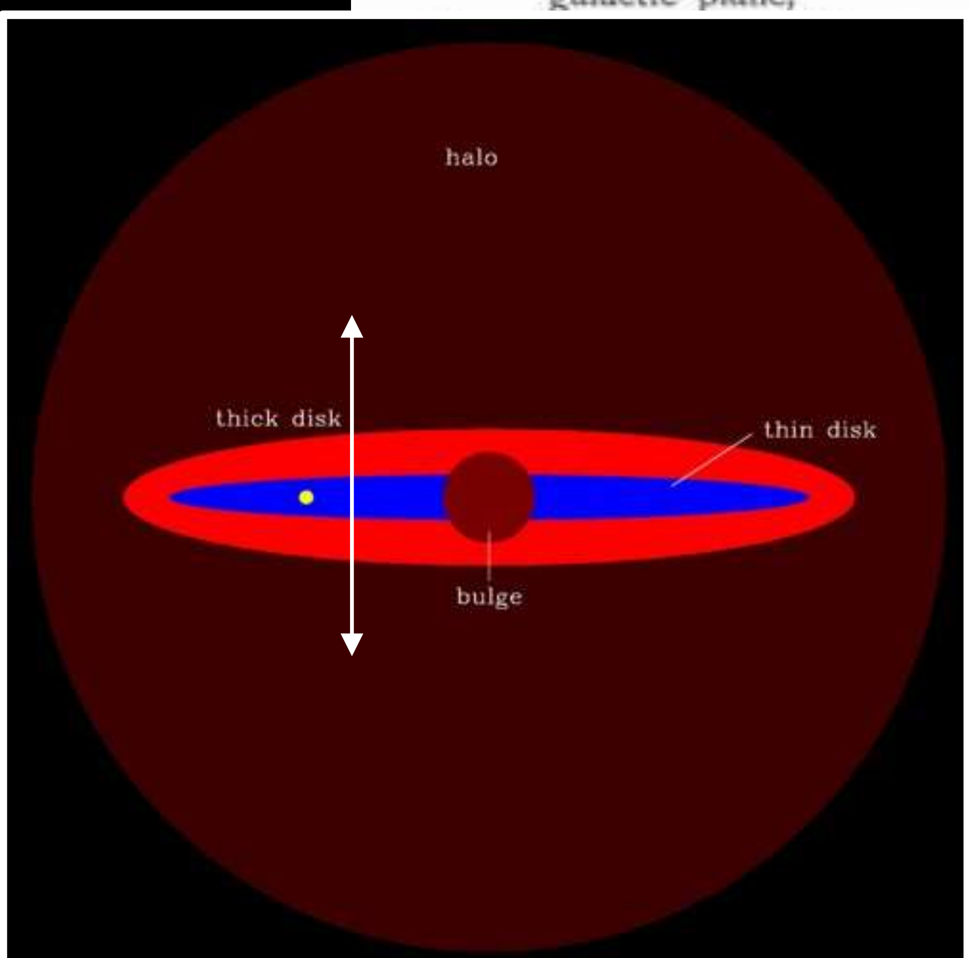
COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

Notations.
z distance from the galactic plane,
Z velocity component perpendicular to the galactic plane,
o,
component of the
la (5), p. 253),
direction of z,
rom the sun,
ubic parsec between

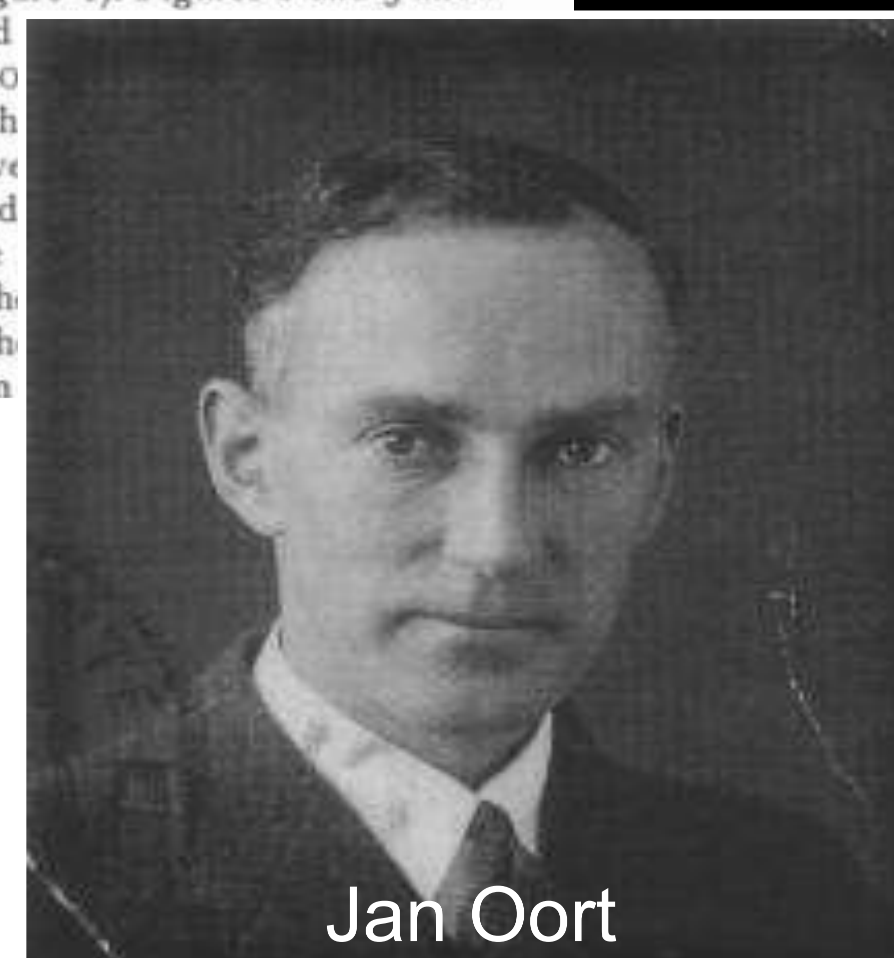
4. From VAN RHIJN's tables in *Groningen Publication* No. 38 the density distribution $\Delta(z)$ has been computed for four intervals of visual absolute magnitude (Table 13 and Figure 1). Figures 2 and 3 show log $\Delta(z)$ for A stars and LINDBLAD and PETERSSO

5. With the aid of th preceding sections I have $K(z)$ between $z = 0$ and were made by successive were eliminated first. Th Figure 4. $K'(z)$ giving th good agreement between

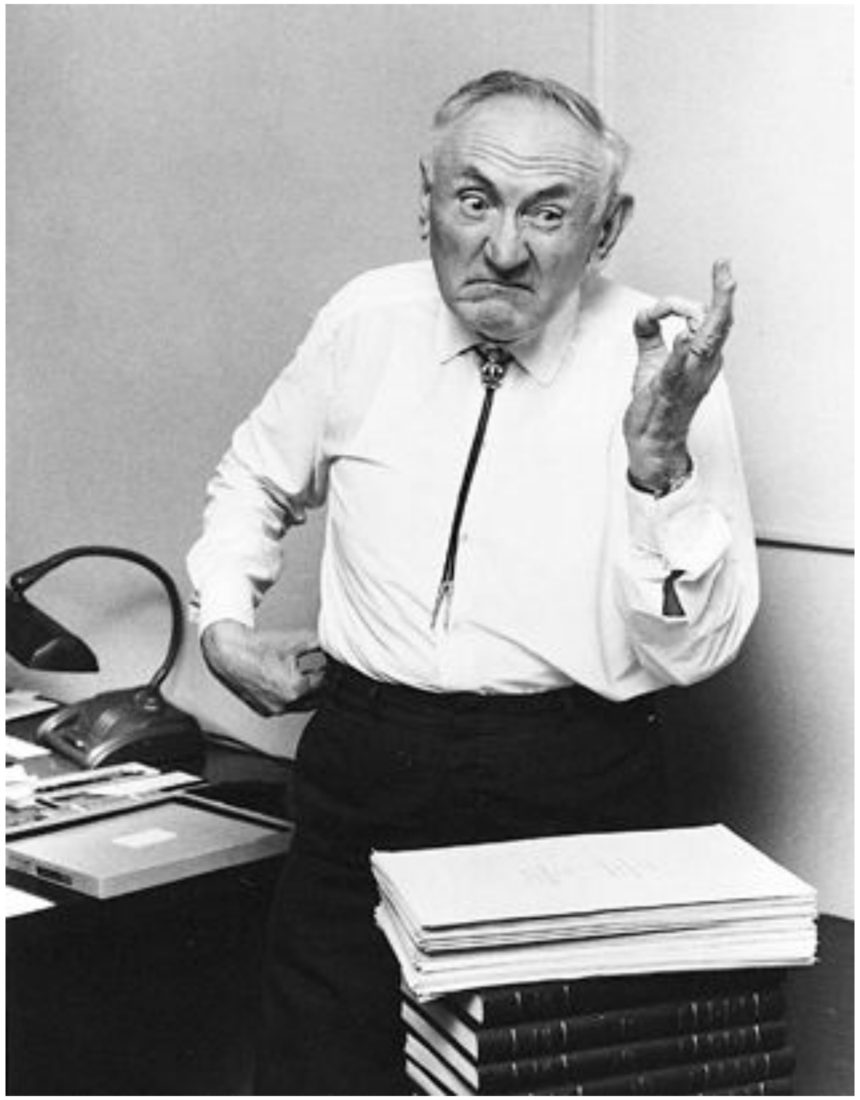


Infer surface mass density from dynamics of stellar motions.

Spoke of “Dark Matter” and “Invisible Matter”

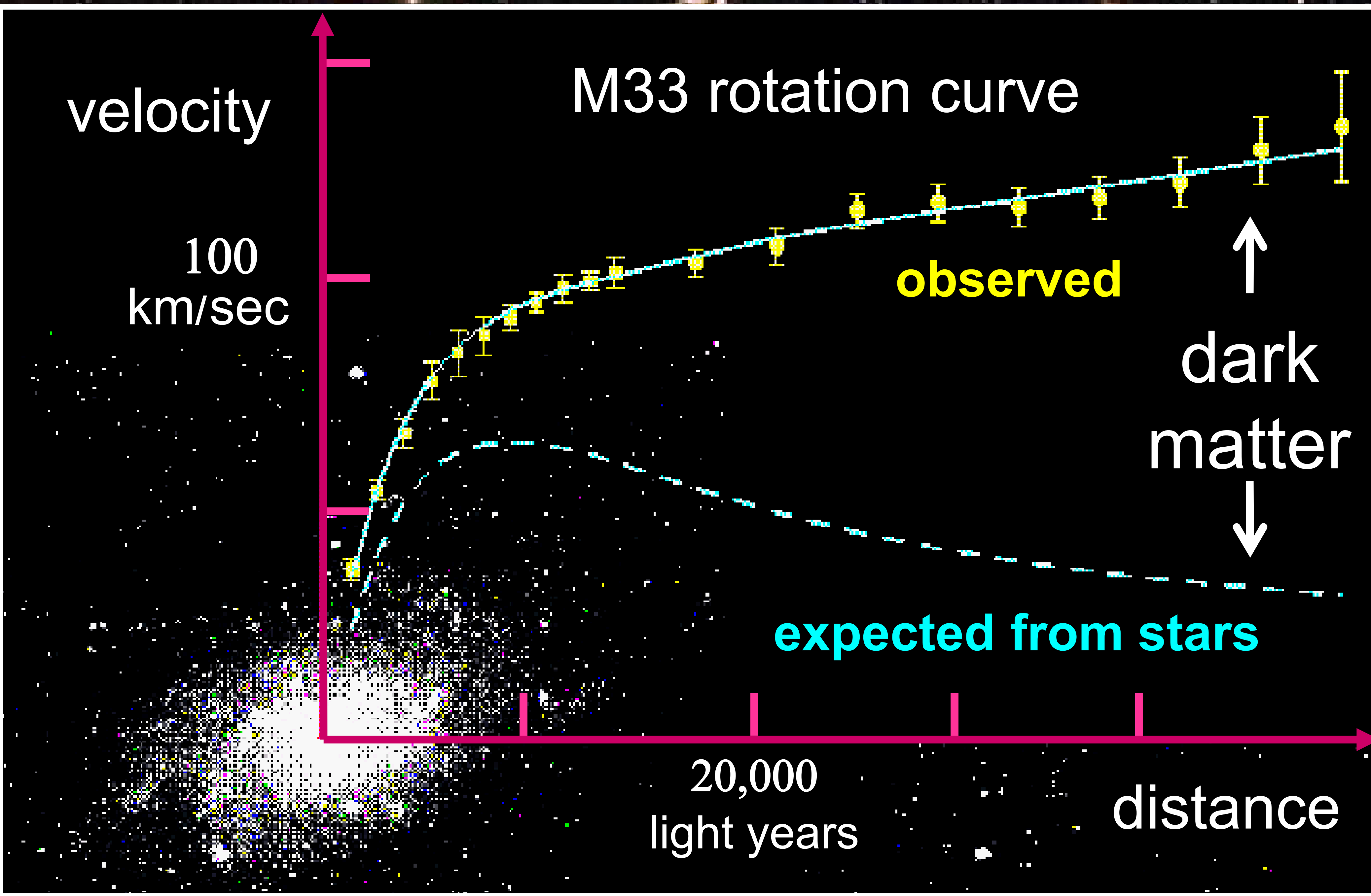


How to measure the mass of a GALAXY?



- Mass to luminosity ratio:
  - Our sun 5000 kg / W
  - Zwicky found in Coma cluster 400 times higher
- Coined term *dark matter*
- *But few people believed him… until*

Dark Matter

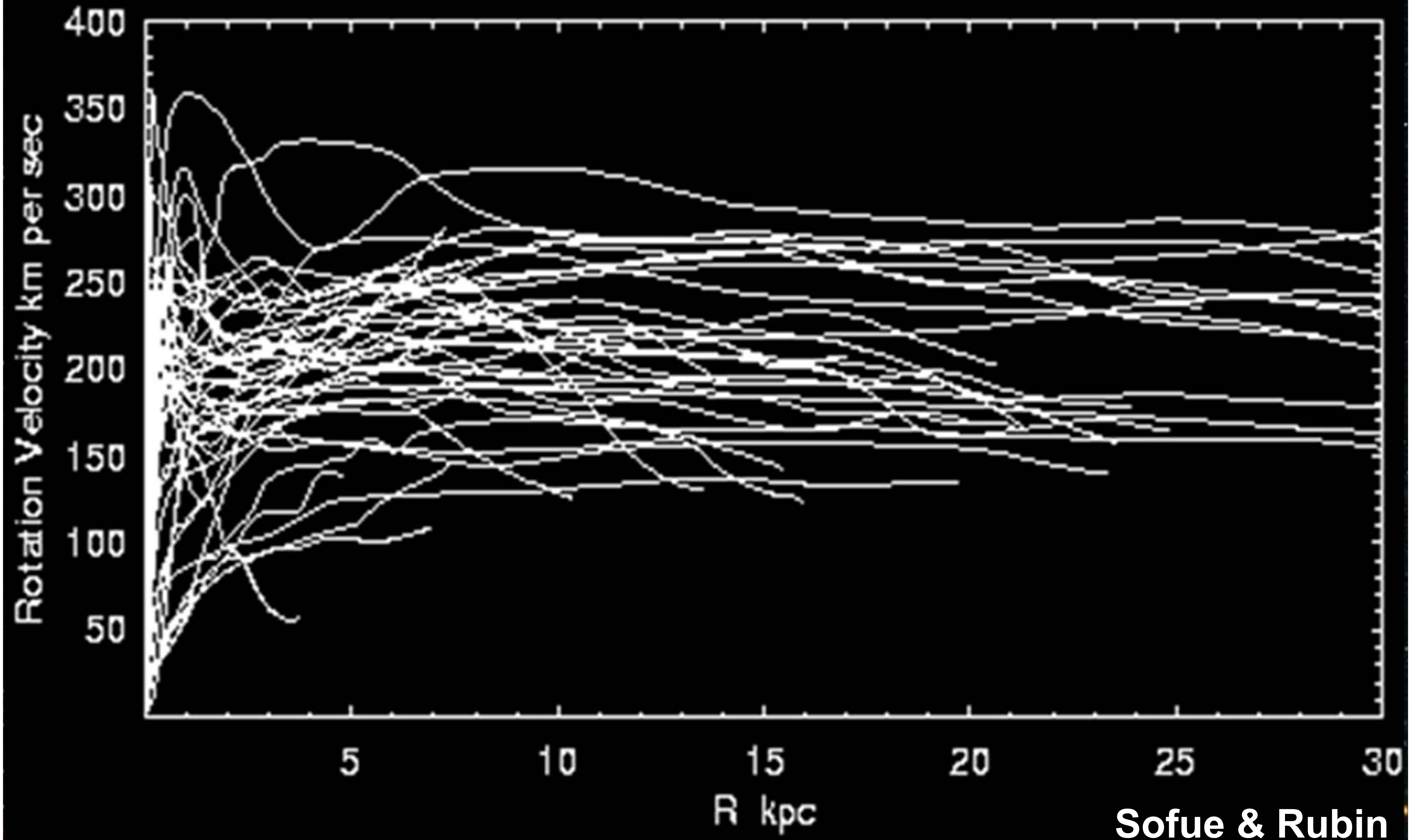


Vera Rubin 1970s

Individual Galaxies (e.g., M33)

Dark Matter

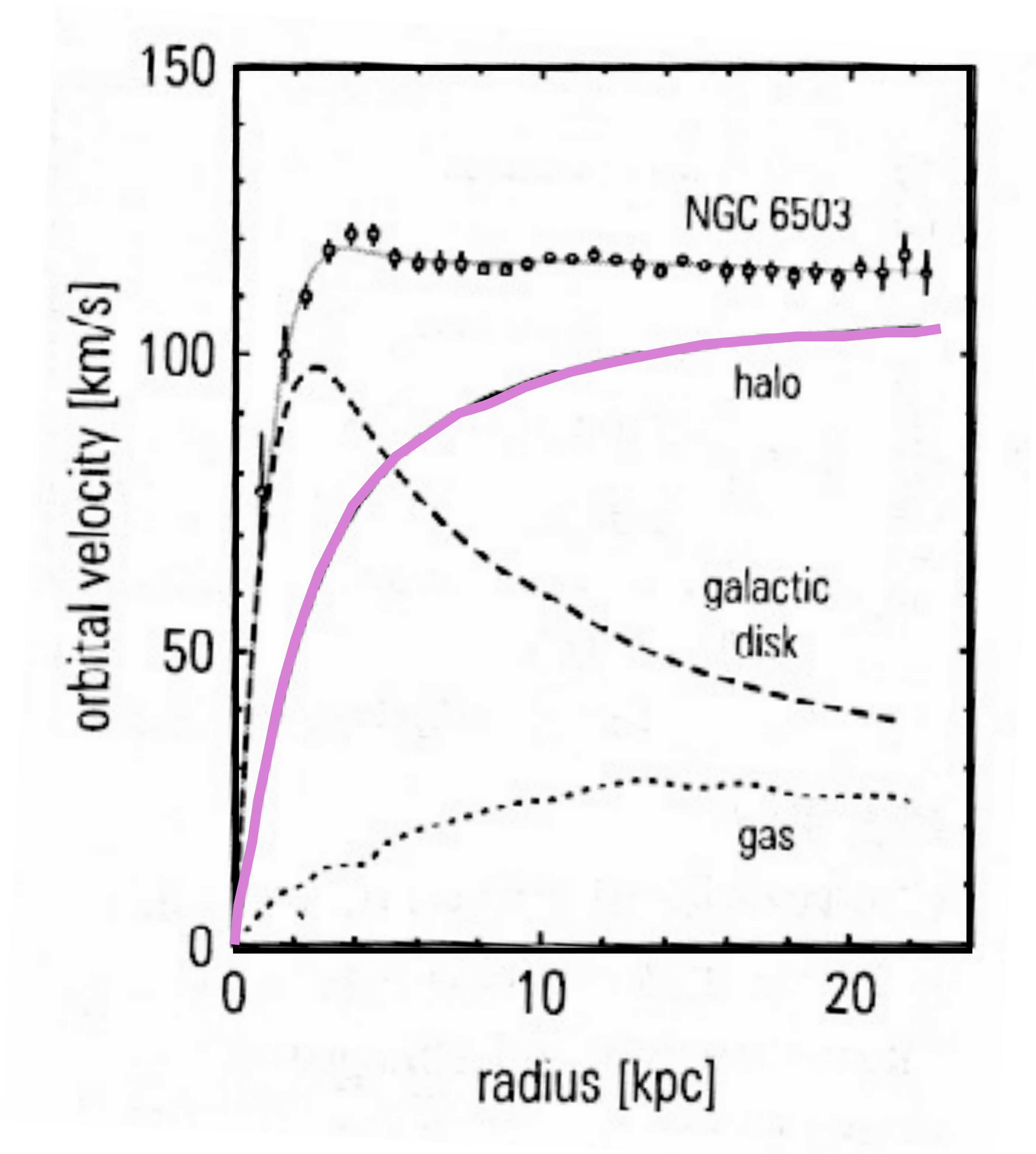
CO – central regions Optical – disks HI – outer disk & halo



Sofue & Rubin

Q: How do you measure the velocity curve of a galaxy?

Invisible mass



You need more mass to explain rotational curves → Dark Matter halo

If $\rho_{DM} \sim r^{-2}$:

$$\frac{mv^2}{r} = G\frac{m\int_0^r \rho dV}{r^2}$$

$$\sim G\frac{m\int_0^r r^{-2}r^2 dr}{r^2}$$

$$\sim G\frac{mr}{r^2}$$

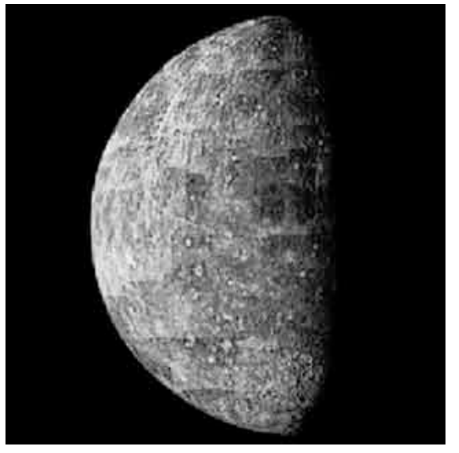
→ v^2 = const

Our location in the Milky Way $\rho_{DM} \sim 0.3$ GeV/cm^3

Inferences of dark matter are not always right … it may instead be a change in the dynamics

2 Jan 1860: "Gentlemen, I Give You the Planet Vulcan" French mathematician Urbain Le Verrier announces the discovery of a new planet between Mercury and the Sun, to members of the Académie des Sciences in Paris (following up on his earlier successful prediction of Neptune in 1856).

Some astronomers even see Vulcan in the evening sky!



But the precession of Mercury is not due to a dark planet …
but because Newton is superseded by Einstein

Skeptic: What if this isn't dark matter?

- Modified newtonian gravity
- Black holes
- Rocky planets
- Dwarf (or politically correct: light and mass challenged) stars
- WIMPzilla

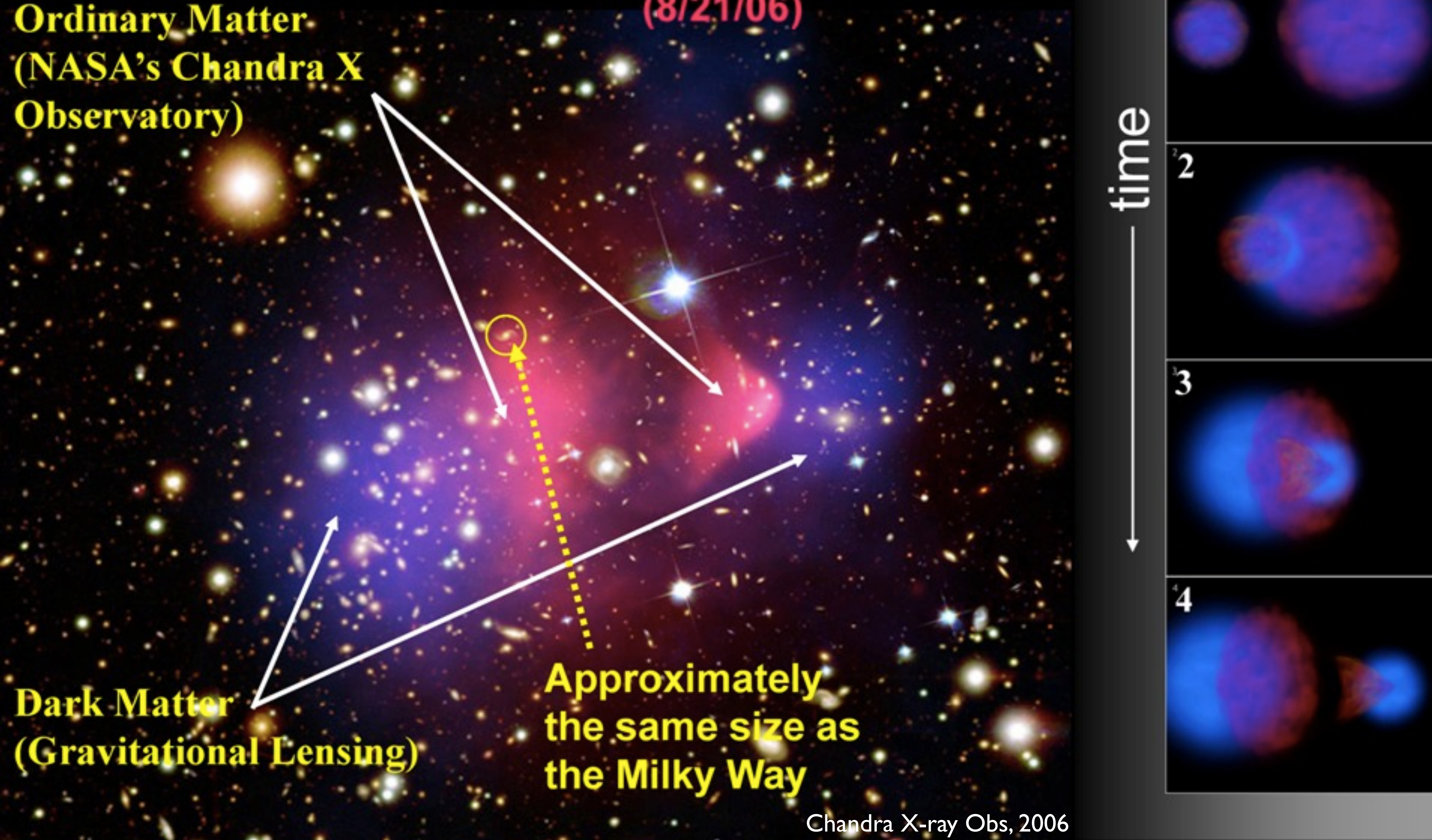
MAssive
Compact
Halo Objects

Seemingly endless reasons to believe dark matter is ‚stuff'

DARK MATTER IN THE UNIVERSE

splitting normal matter and dark matter apart

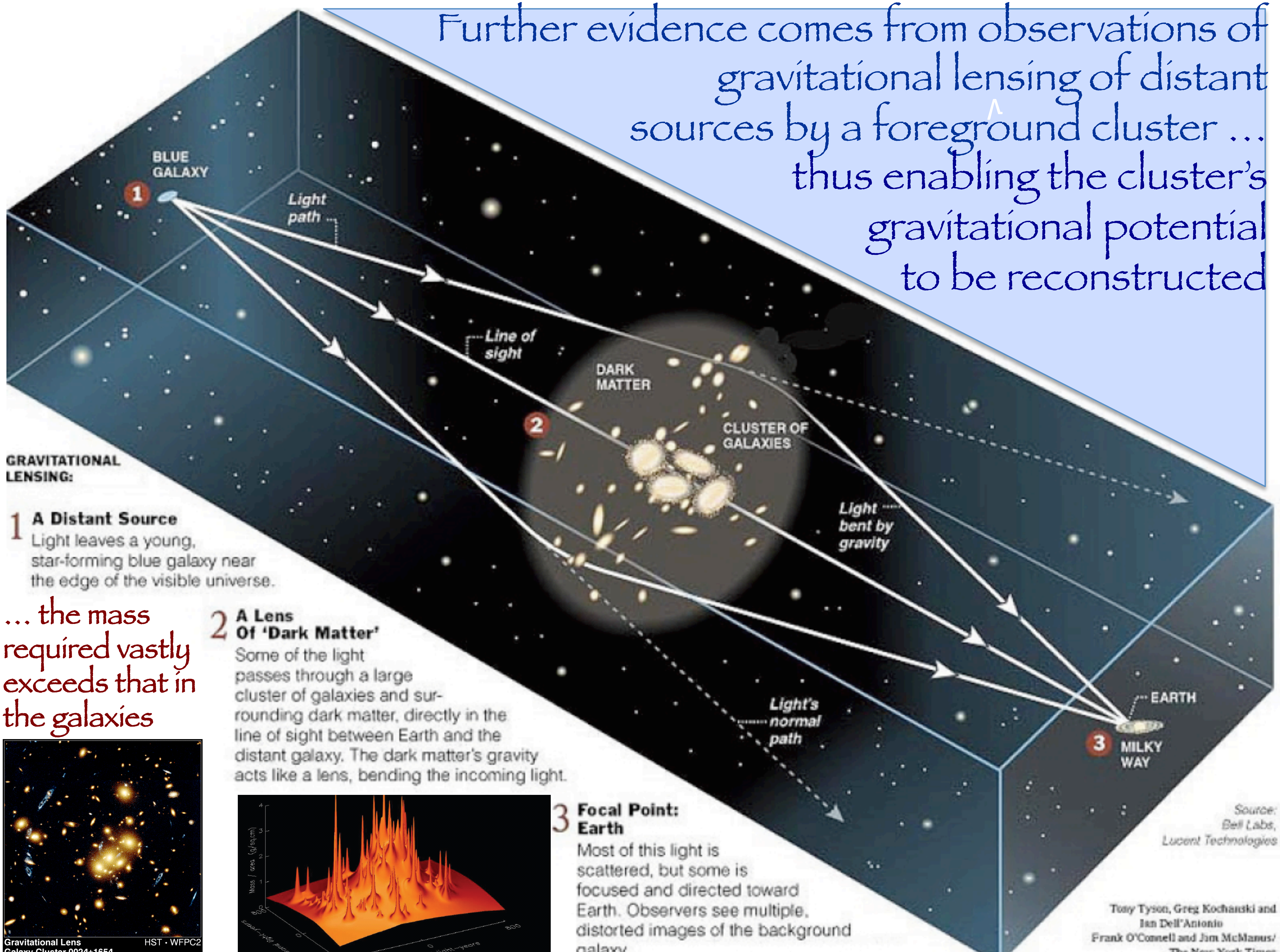
– Another Clear Evidence of Dark Matter –
(8/21/06)



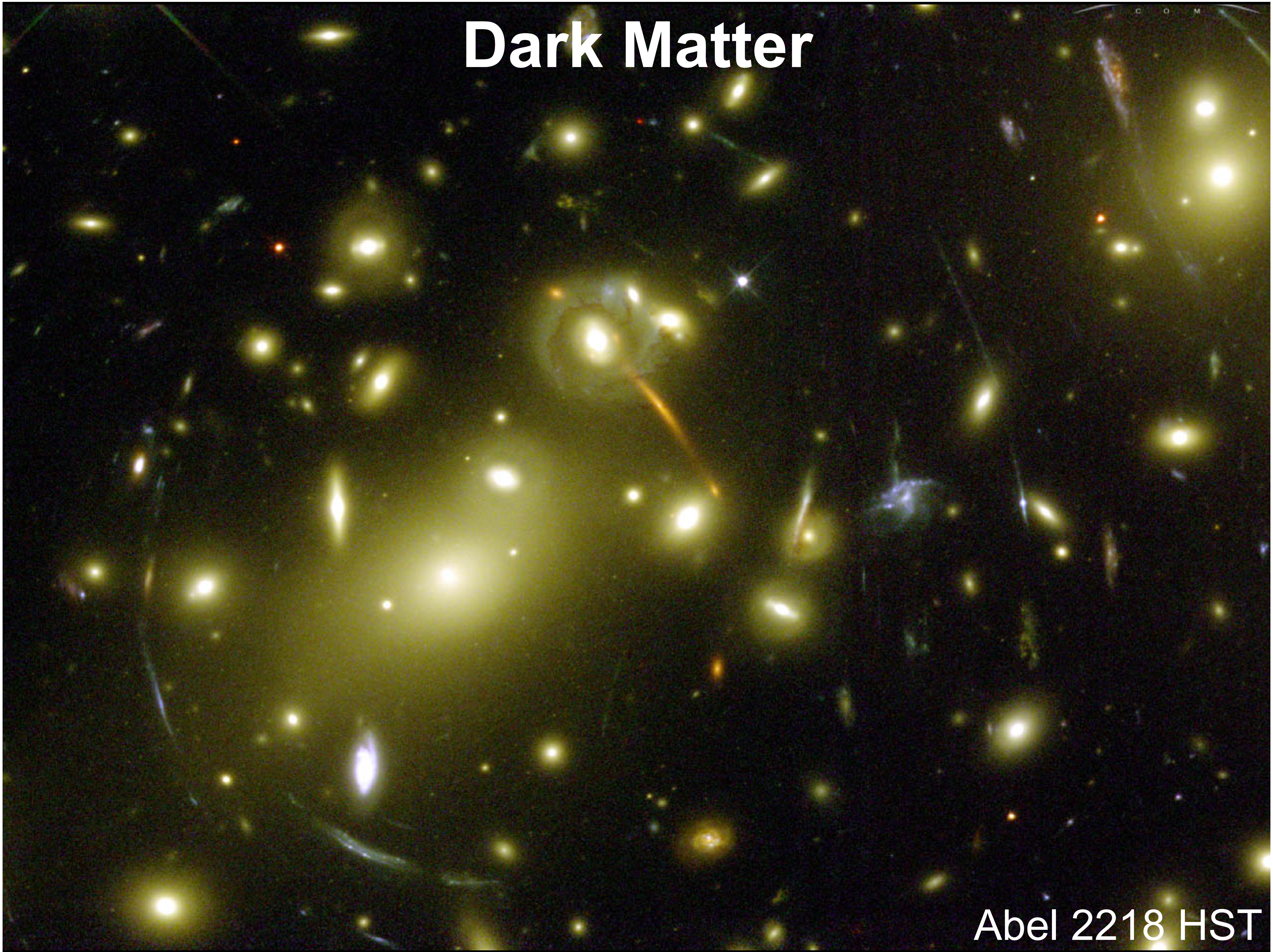
Chandra X-ray Obs, 2006

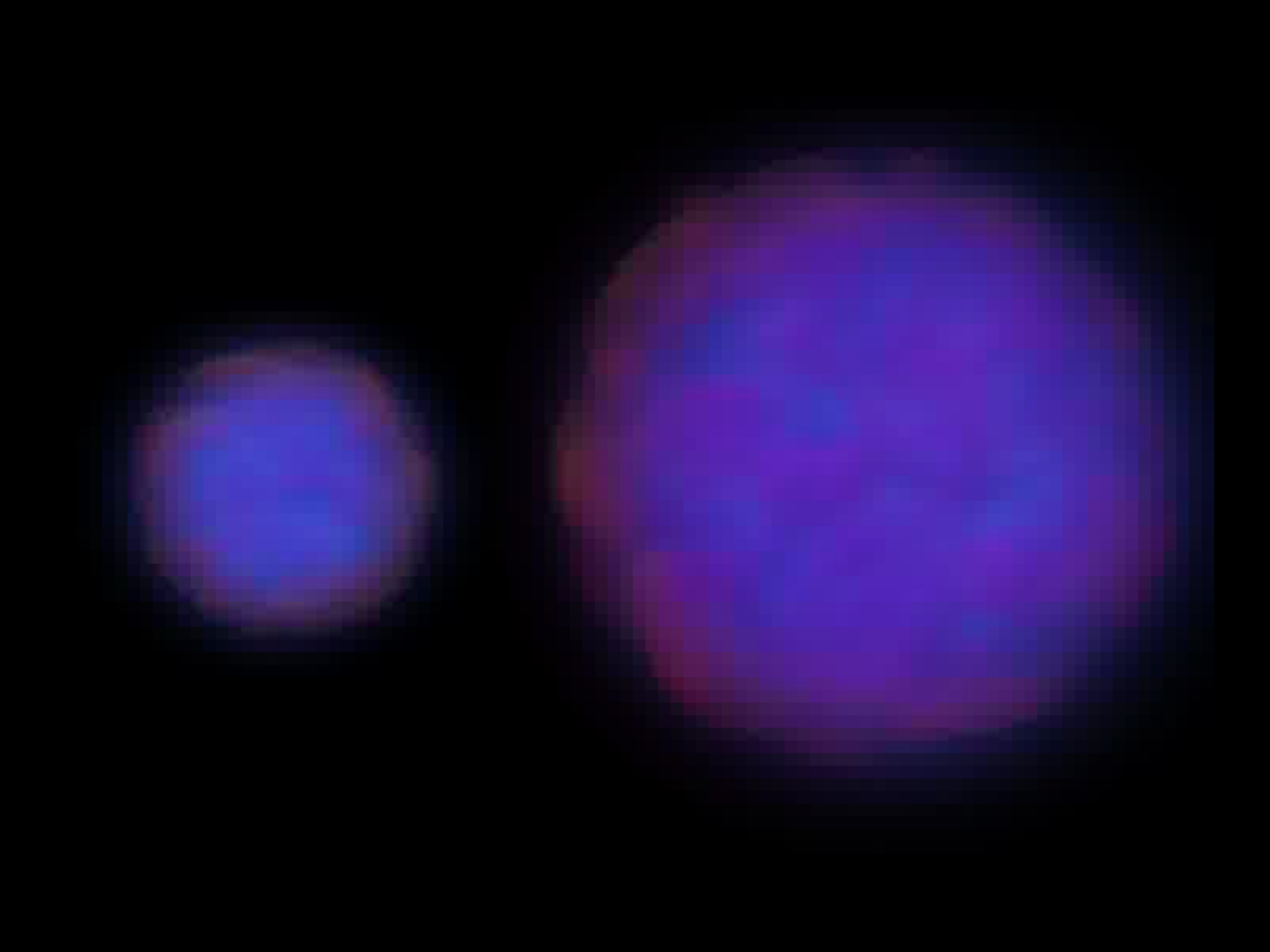
Further evidence comes from observations of gravitational lensing of distant (background) sources by a foreground cluster … thus enabling the cluster's gravitational potential to be reconstructed

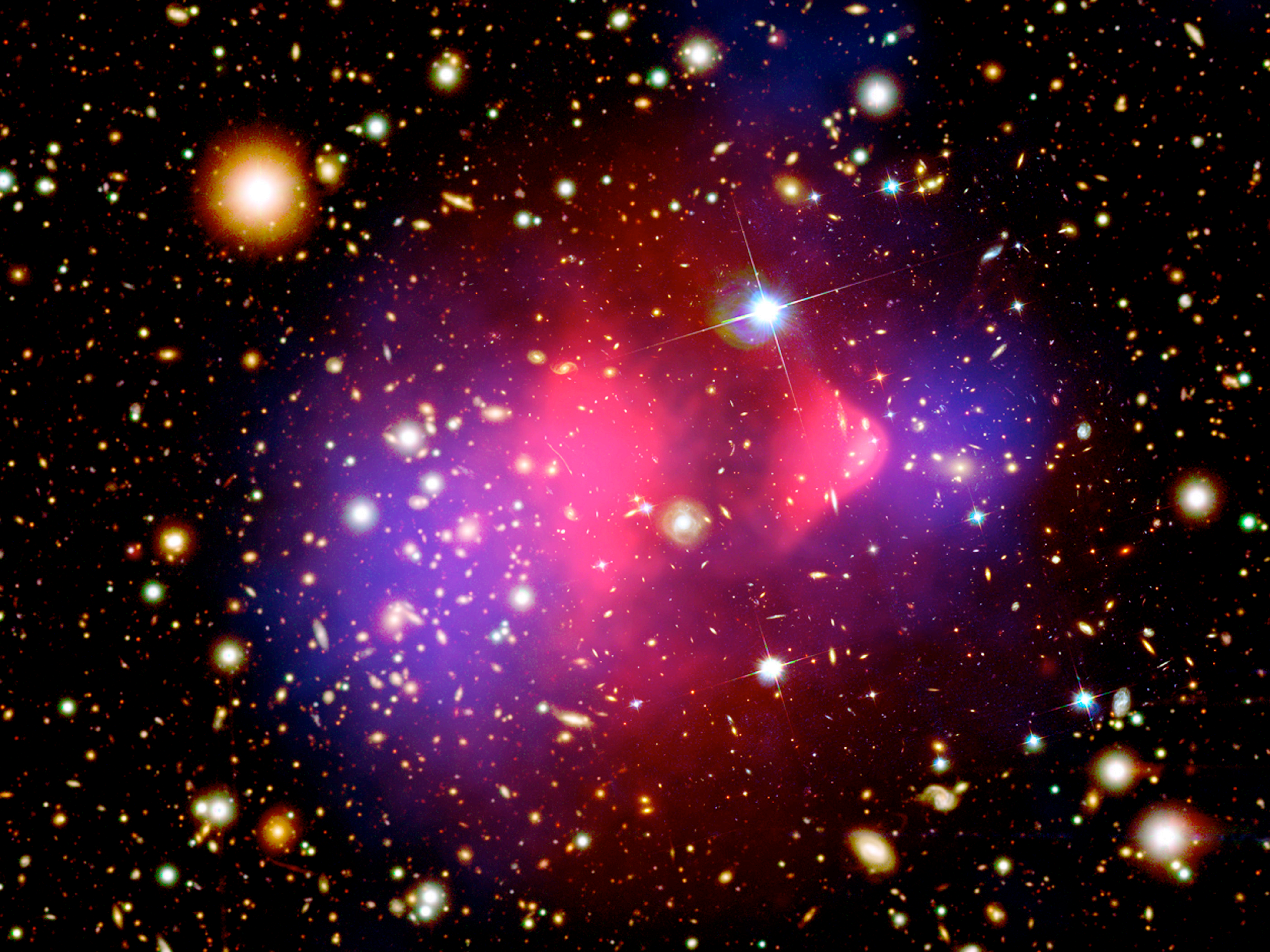
… the mass required vastly exceeds that in the galaxies



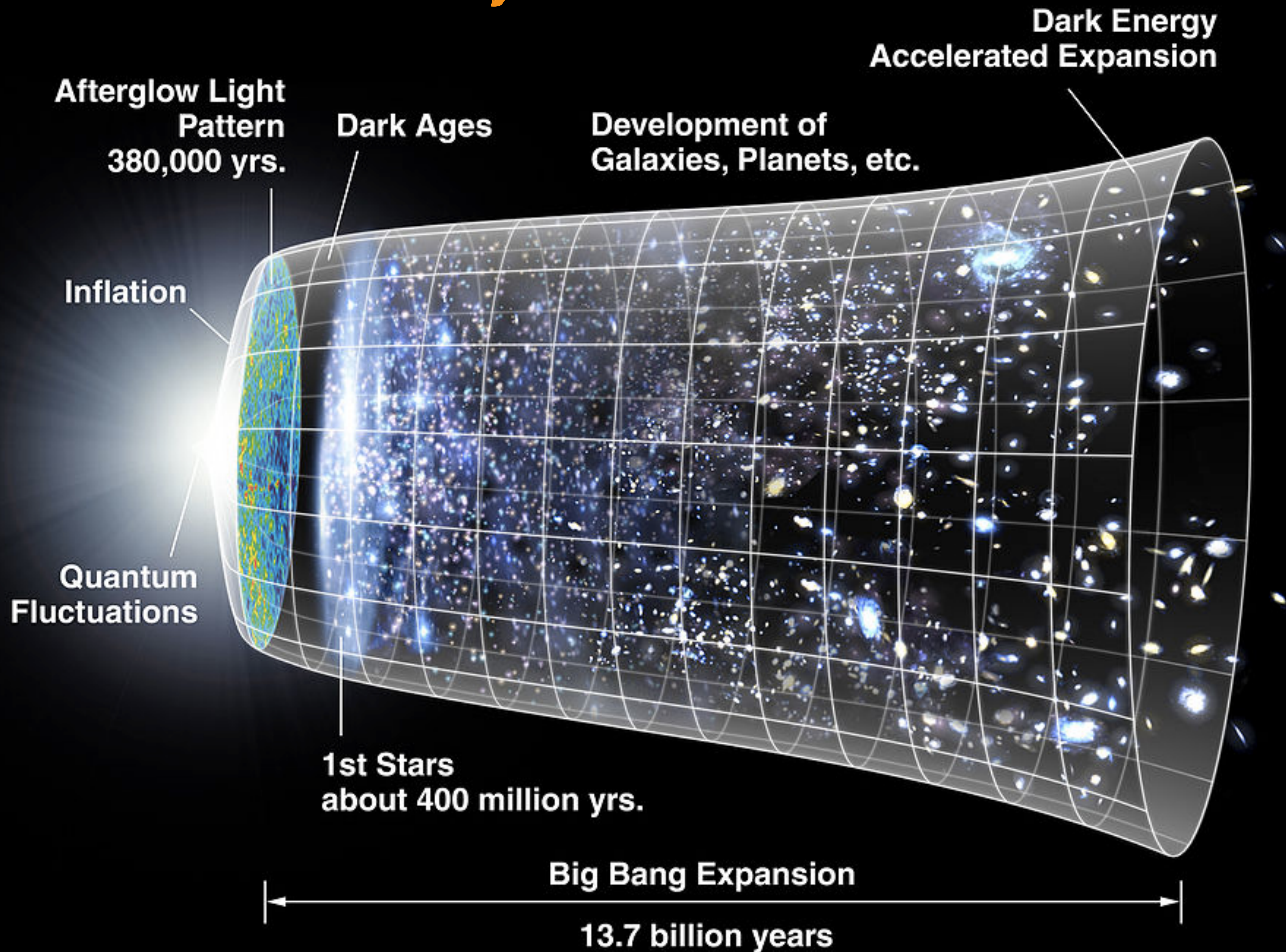
Dark Matter



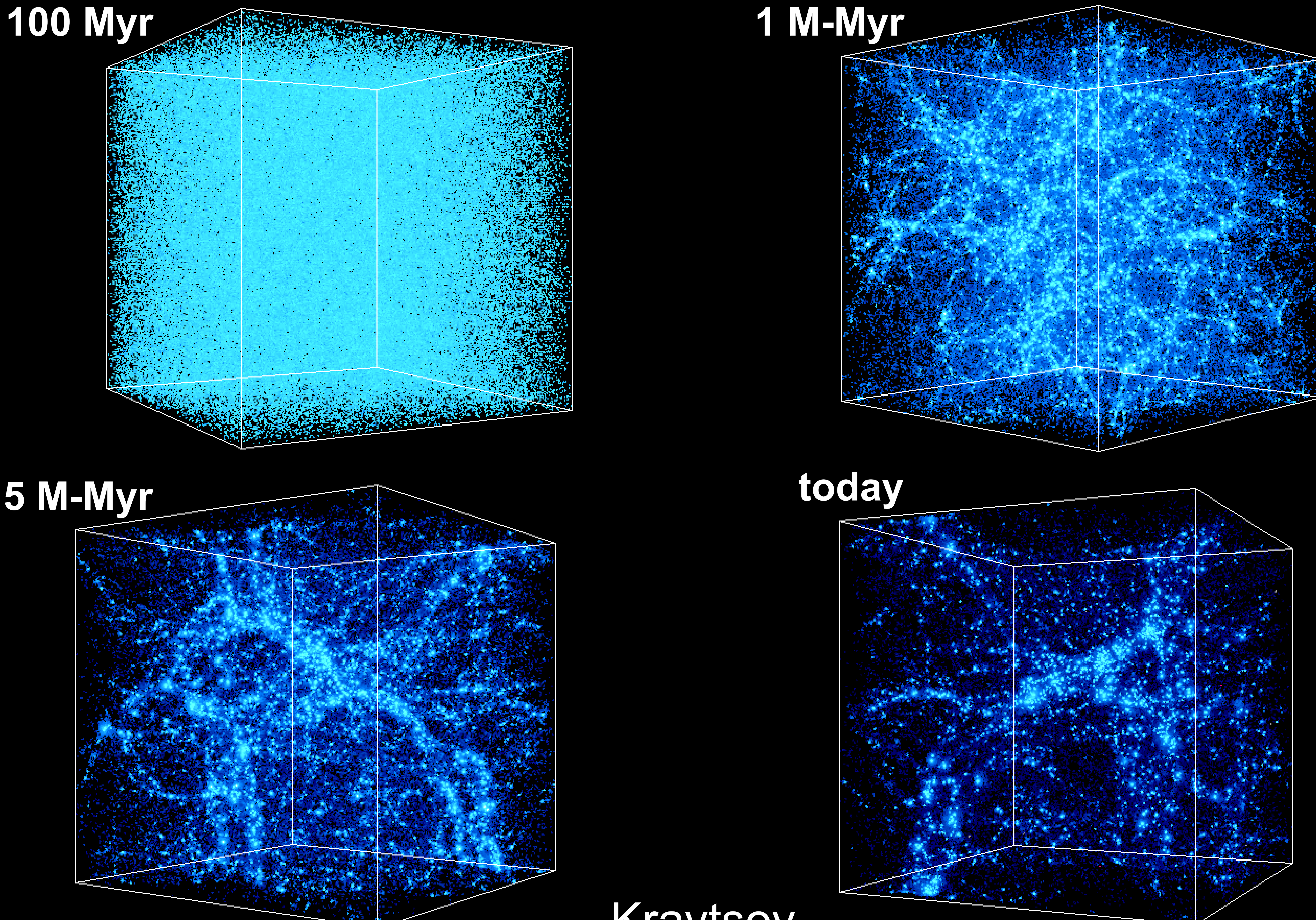




History of our Universe

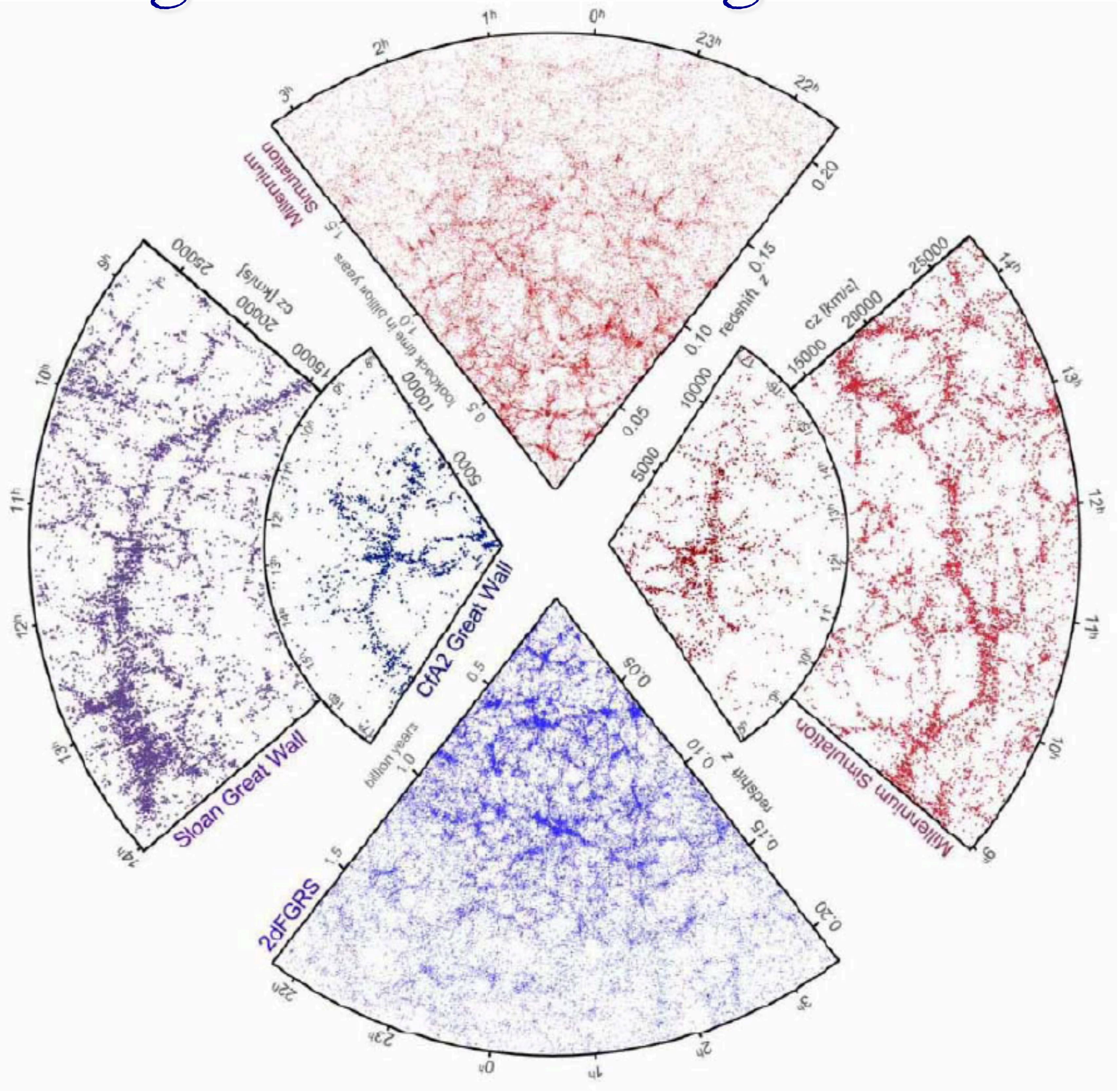


Structure Formation



Kravtsov

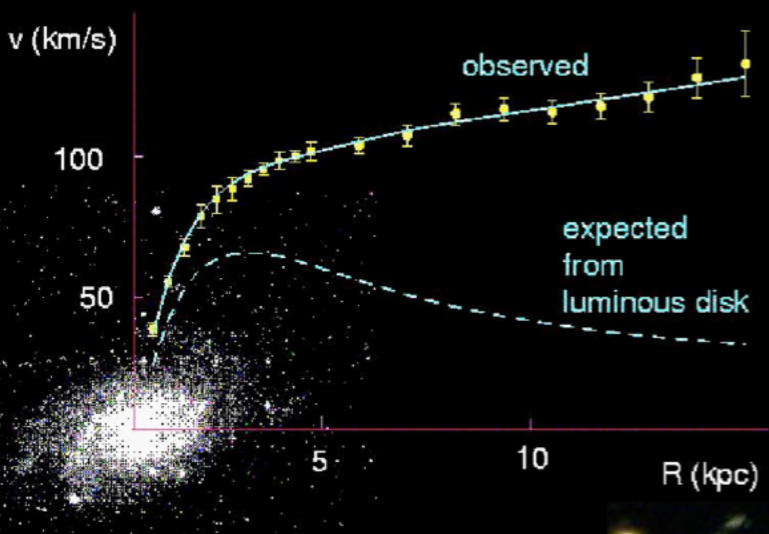
Such numerical simulations provide a pretty good match to the observed large-scale structure of galaxies in the universe



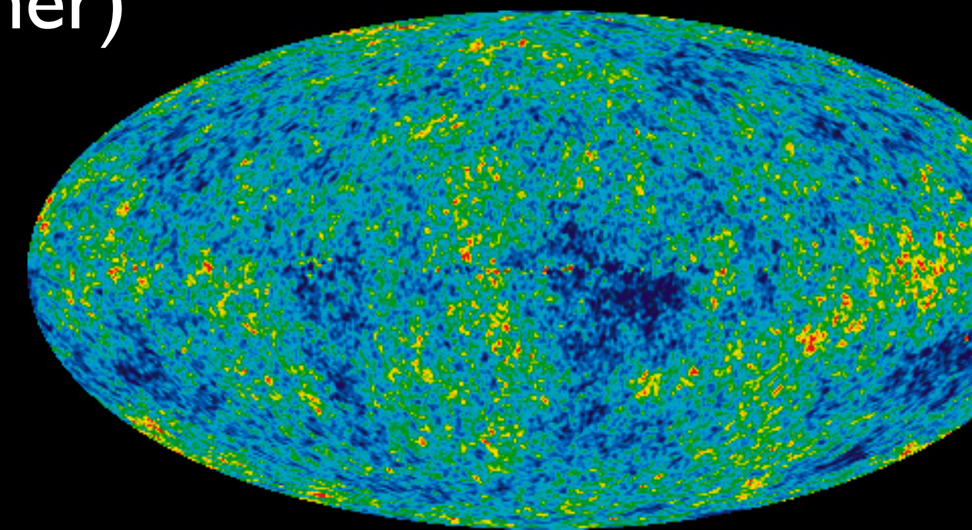
Springel, Frenk & White, Nature **440**:1137,2006

Much Astronomical Evidence for DM

At **all** scales (for astronomer)
in the Universe!

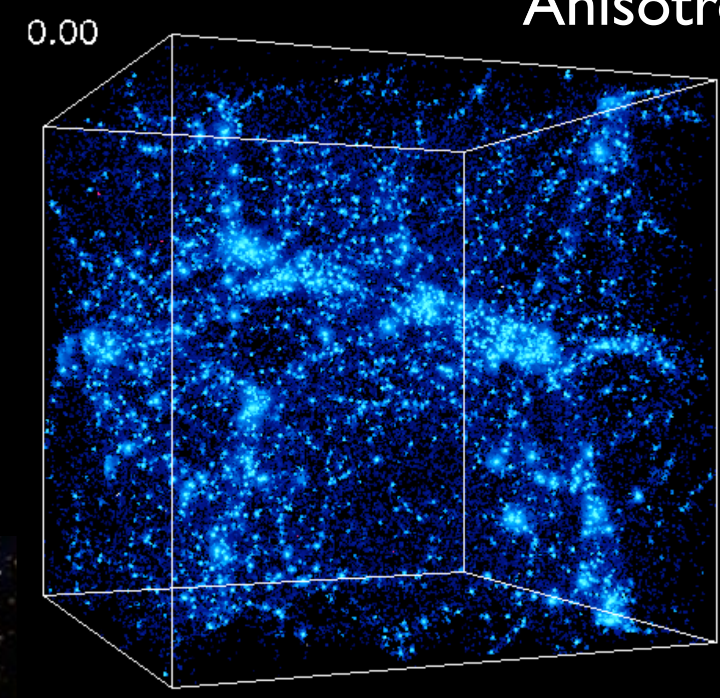


Rotational Curves



Anisotropy in CMB

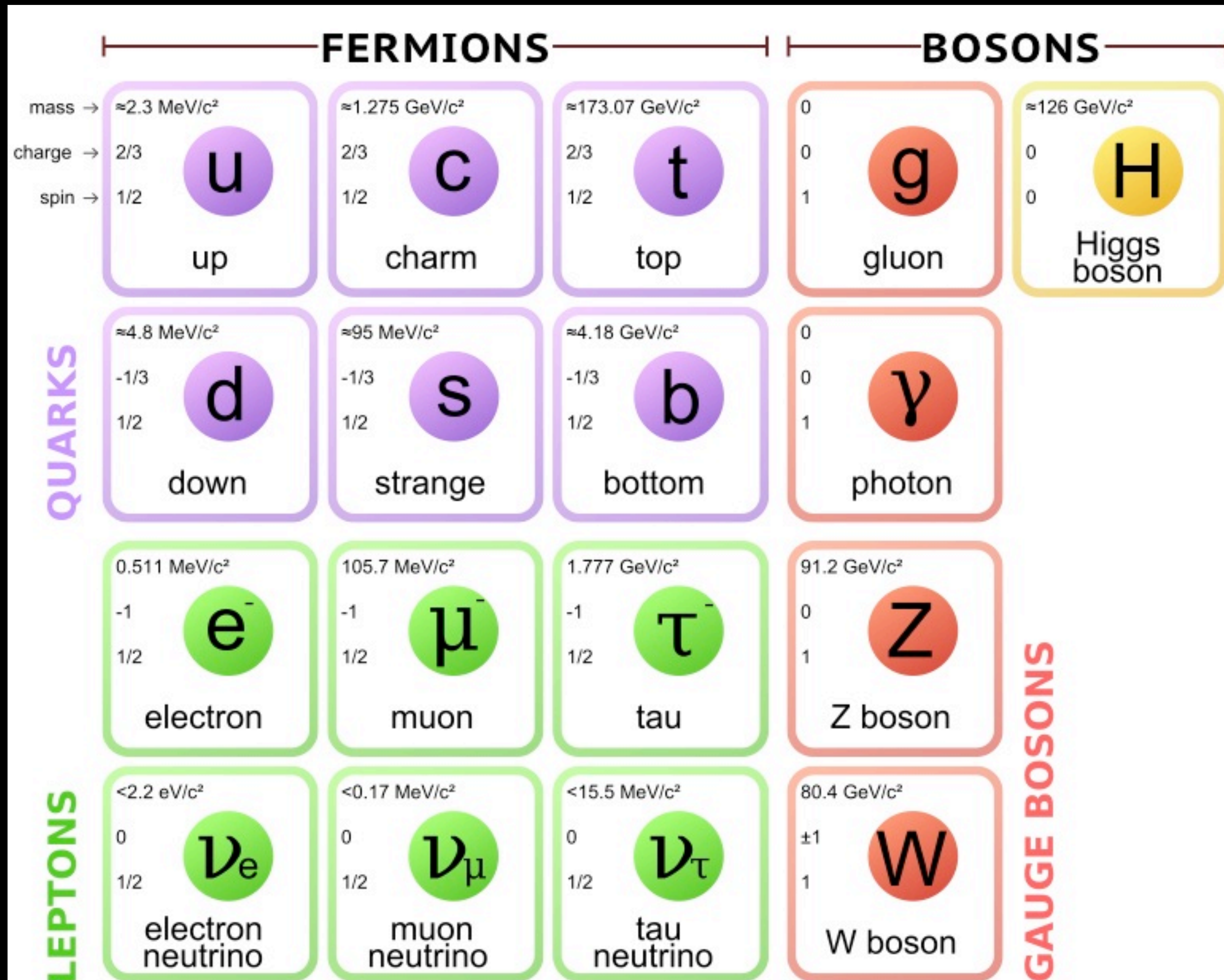
Weak Lensing



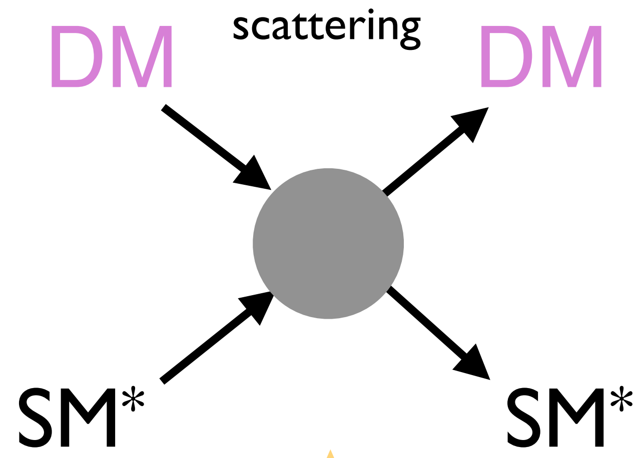
Large Scale Structure

Galaxy Clusters

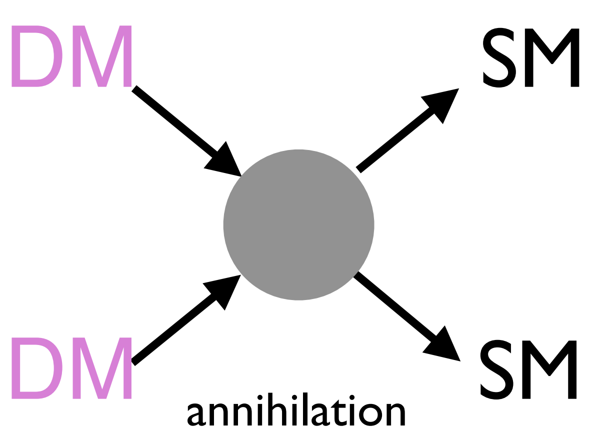
The Standard Model of Particle Physics

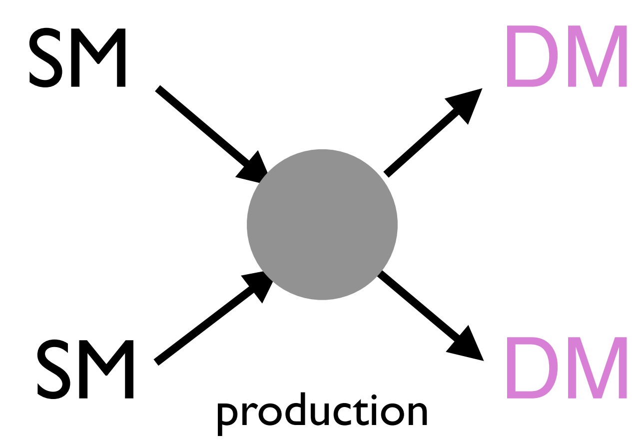


Three ways to find Particle Dark Matter



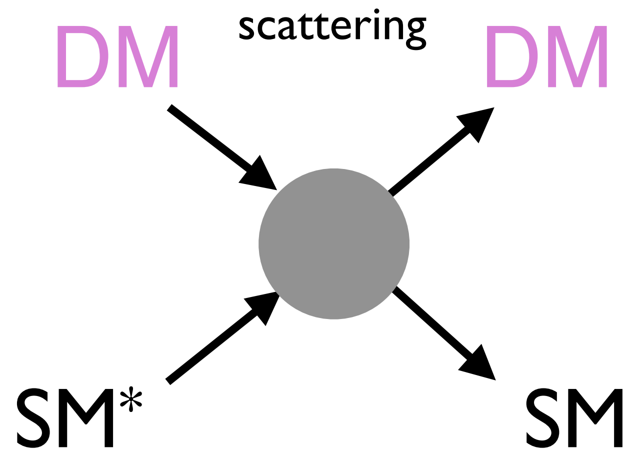
Three different ways how Dark Matter particles may interact with Normal Matter





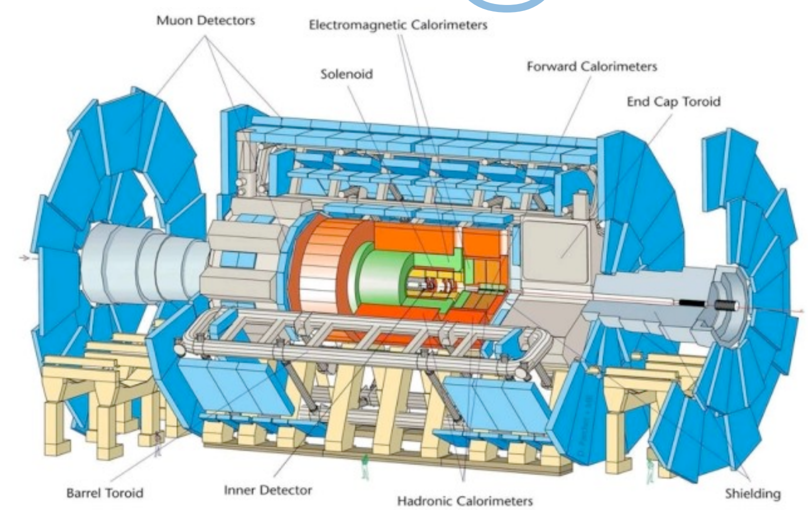
*SM = Standard Model

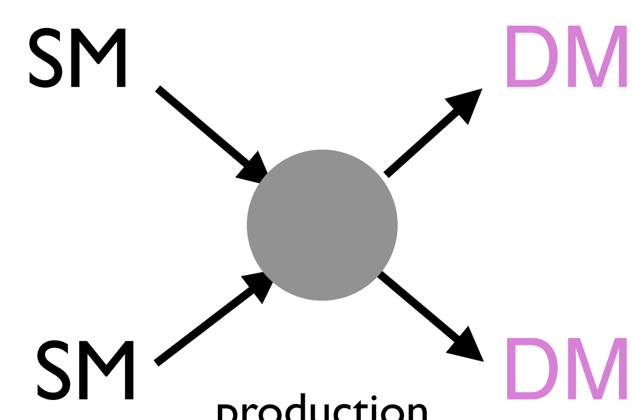
Three ways to find Particle Dark Matter



XENON

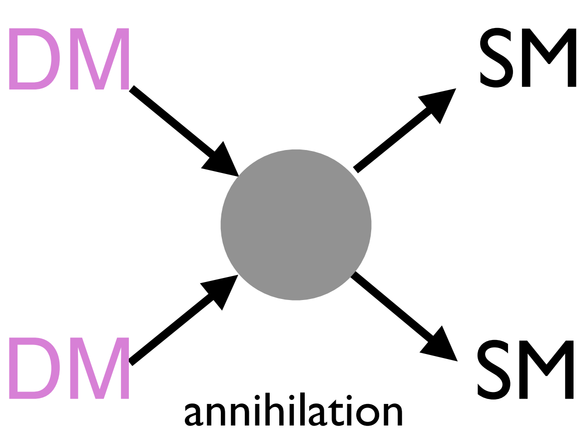
ATLAS @ LHC

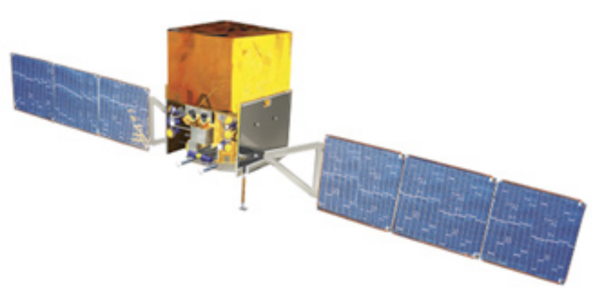




Different Approaches to look for Dark Matter!

FERMI Satellite





DM cheat sheet

- If we had a quiz on what the contents of the Universe were, we'd fail.
- Some "stuff" is out there
  - We know it's why we're here (holds University together)
  - We don't know what it is or how it interacts with other material

Can we measure Dark Matter?


Cool places


PASSAT
DS·726ZV
BE 902KK

Finding faint signals

Historical notes

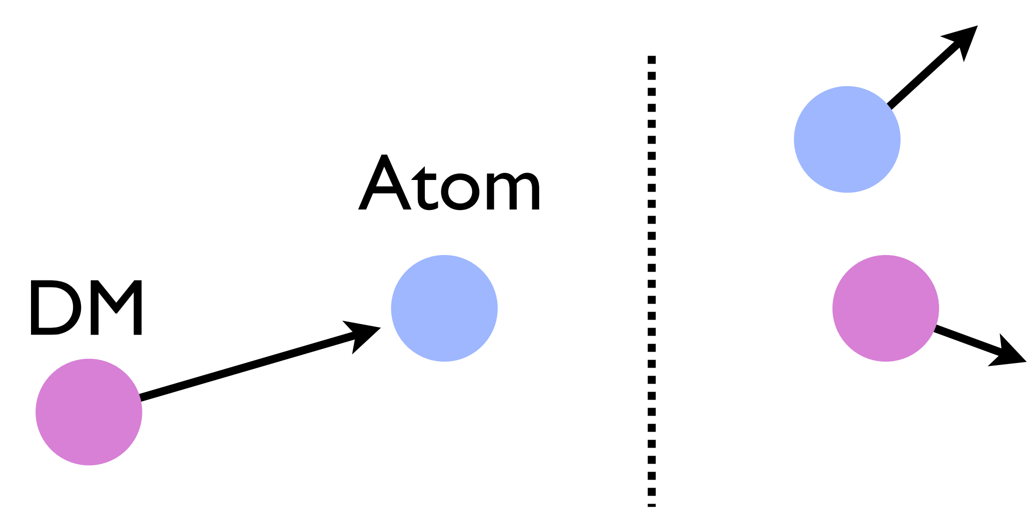
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

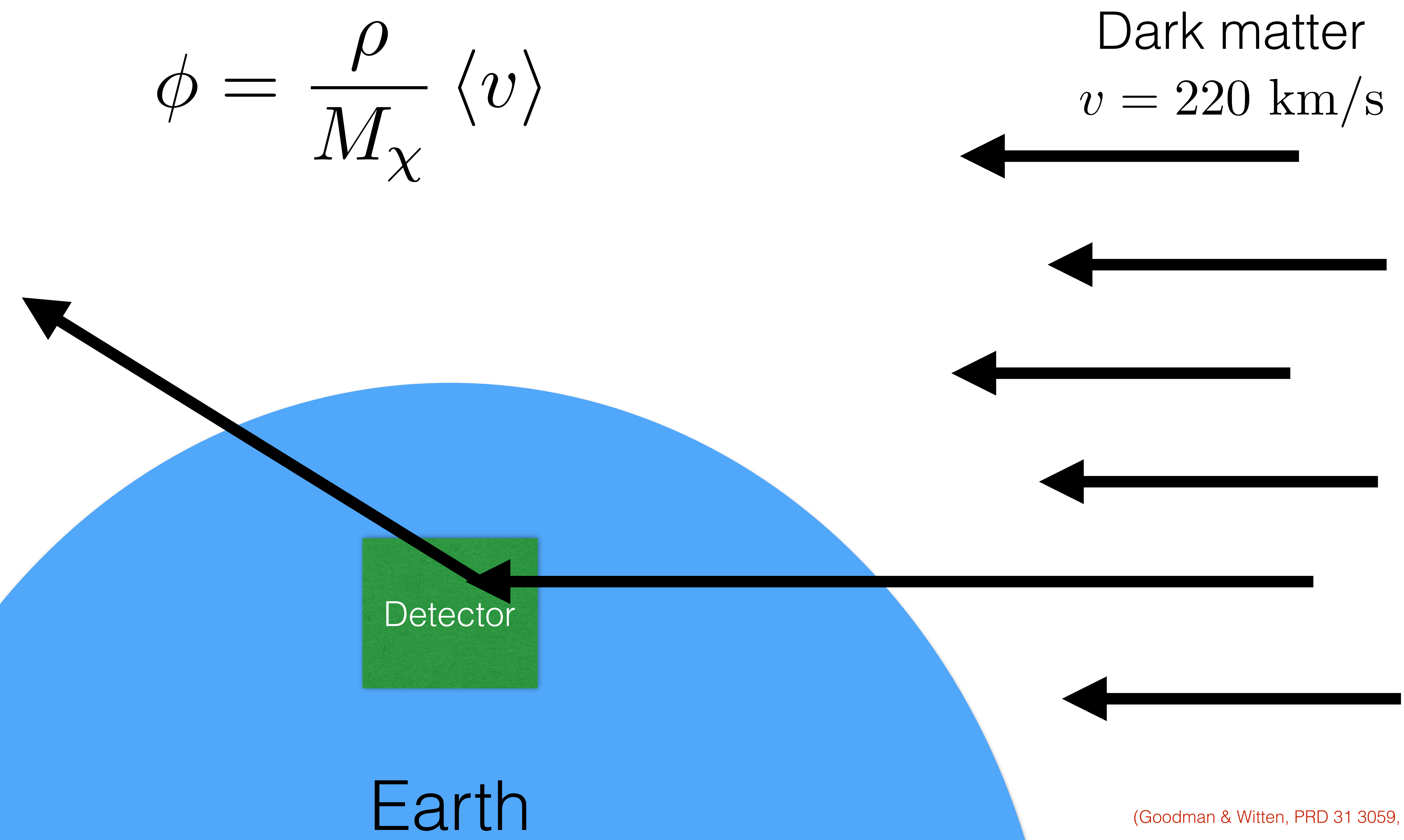
Elastic scattering:



Think billiard balls: want M_WIMP ~ M_atom

Direct-detection concept

$$\phi = \frac{\rho}{M_\chi} \langle v \rangle$$



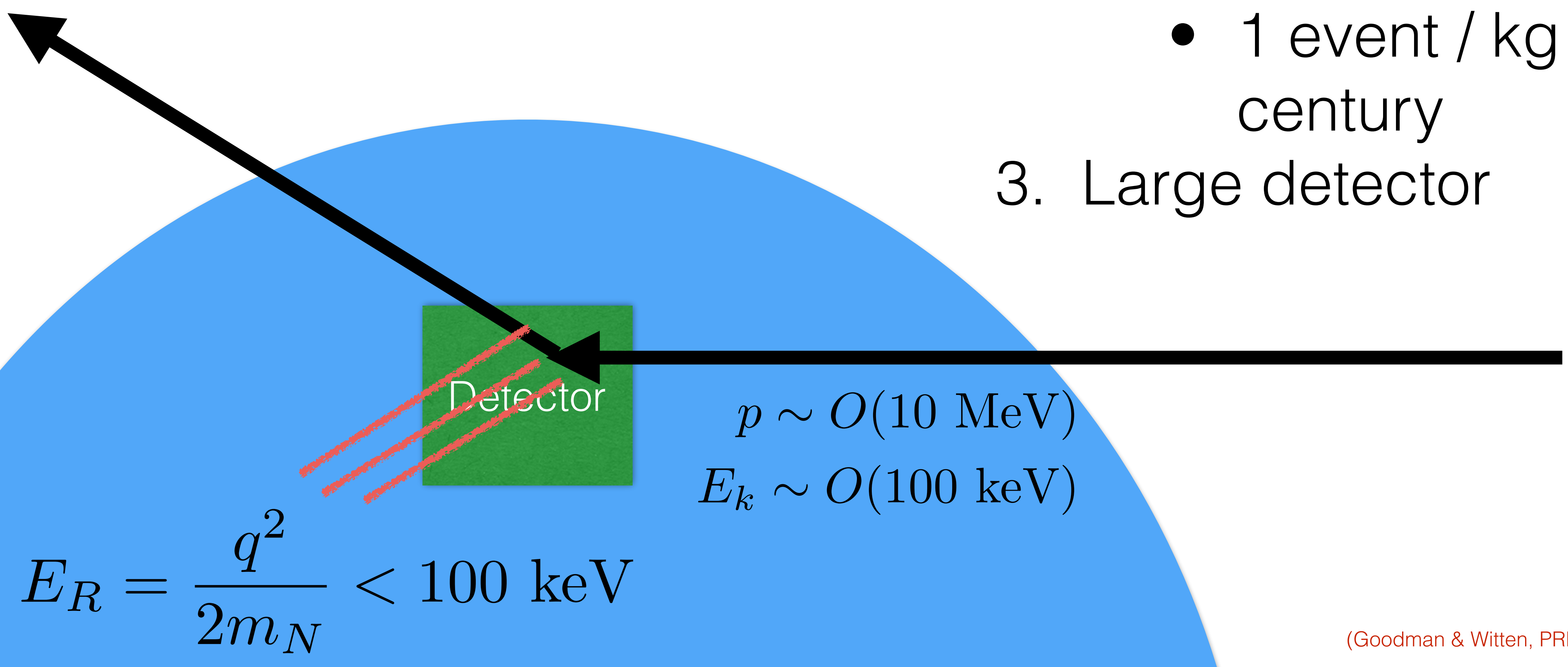
(Goodman & Witten, PRD 31 3059, 1985)

We can detect this bump.

$$\phi = \frac{\rho}{M_\chi} \langle v \rangle$$

Goals:

1. Low threshold
2. Low backgrounds
    - rare-event search
    - no *beam off*
    - 1 event / kg / century
3. Large detector



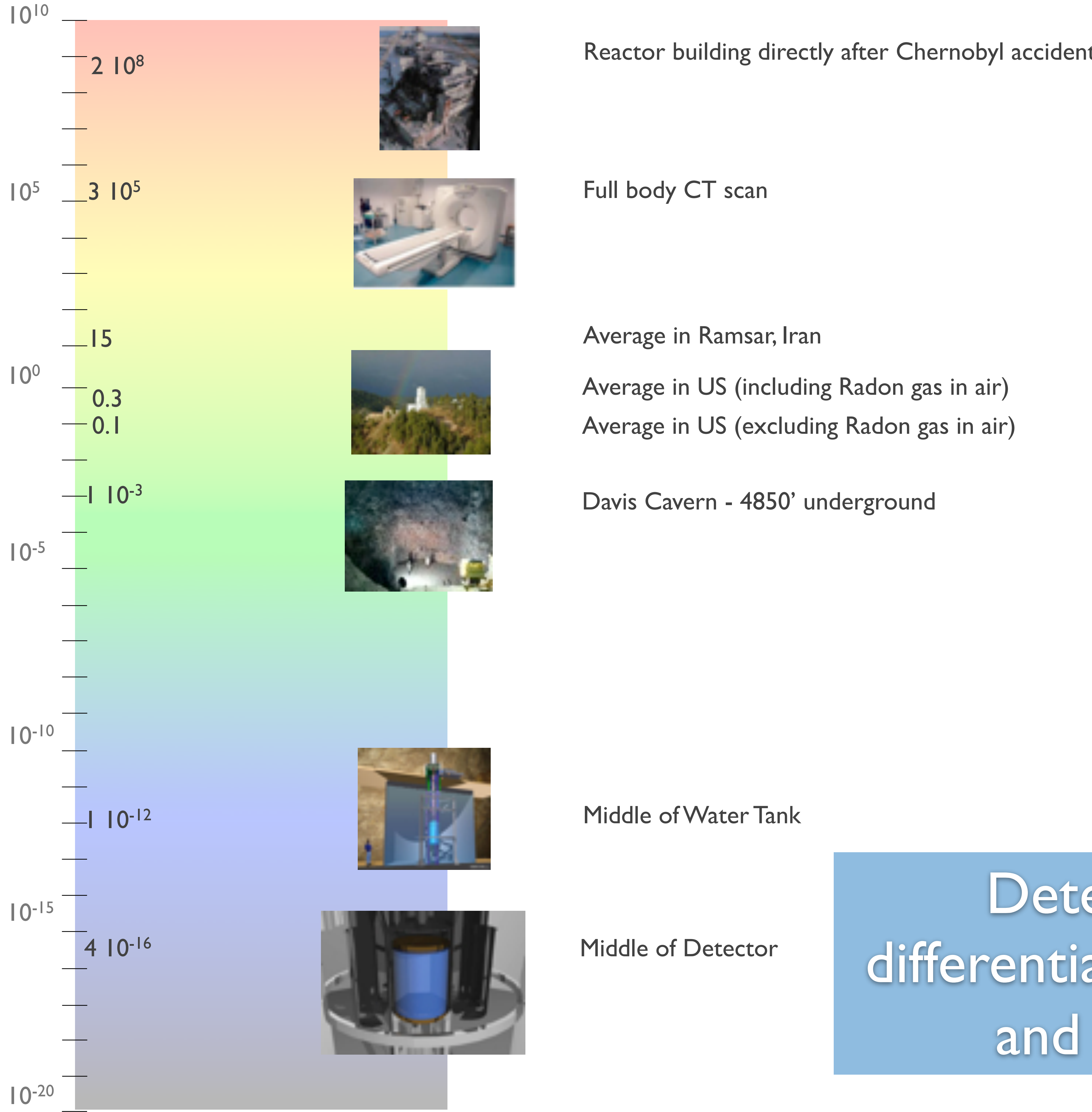
$$p \sim O(10\ \mathrm{MeV})$$

$$E_k \sim O(100\ \mathrm{keV})$$

$$E_R = \frac{q^2}{2m_N} < 100\ \mathrm{keV}$$

(Goodman & Witten, PRD 31 3059, 1985)

Effective Radiation Exposure per Hour from Gamma Rays

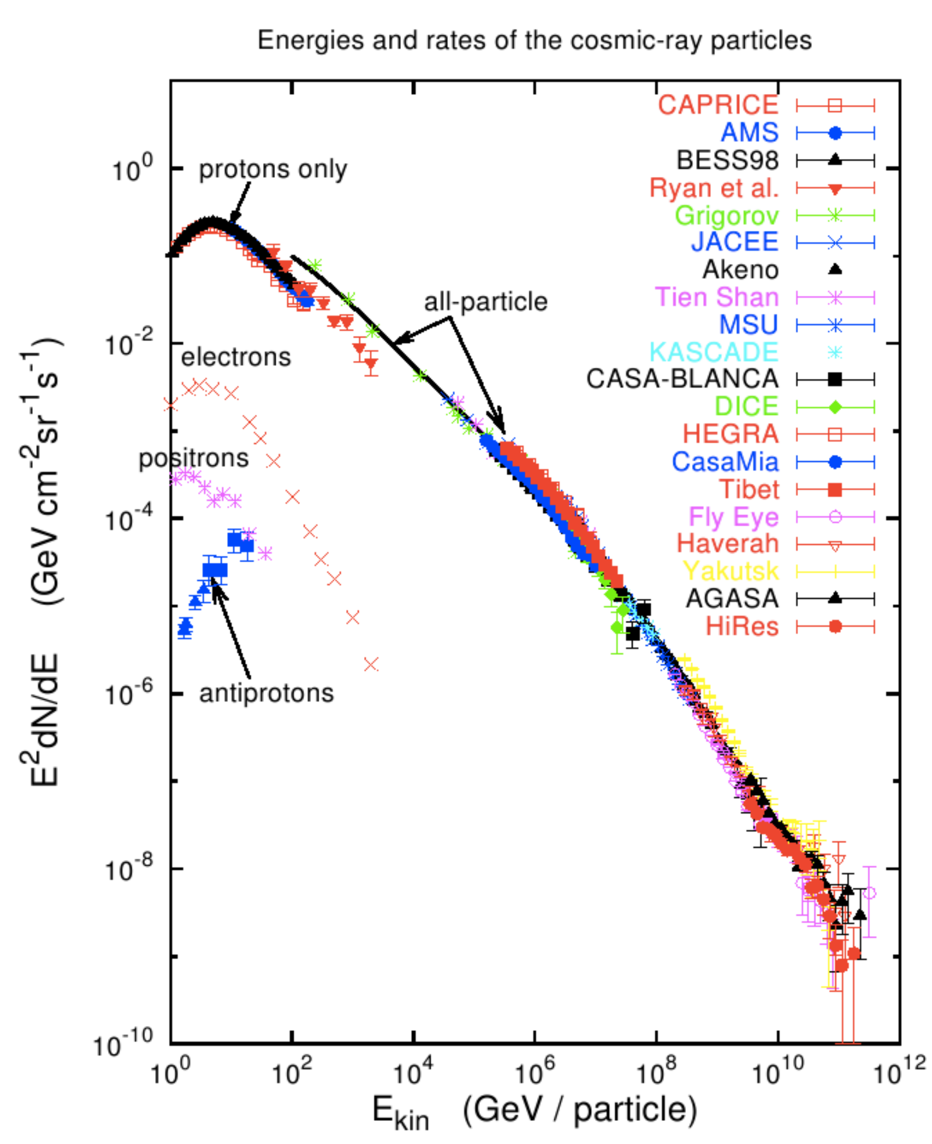


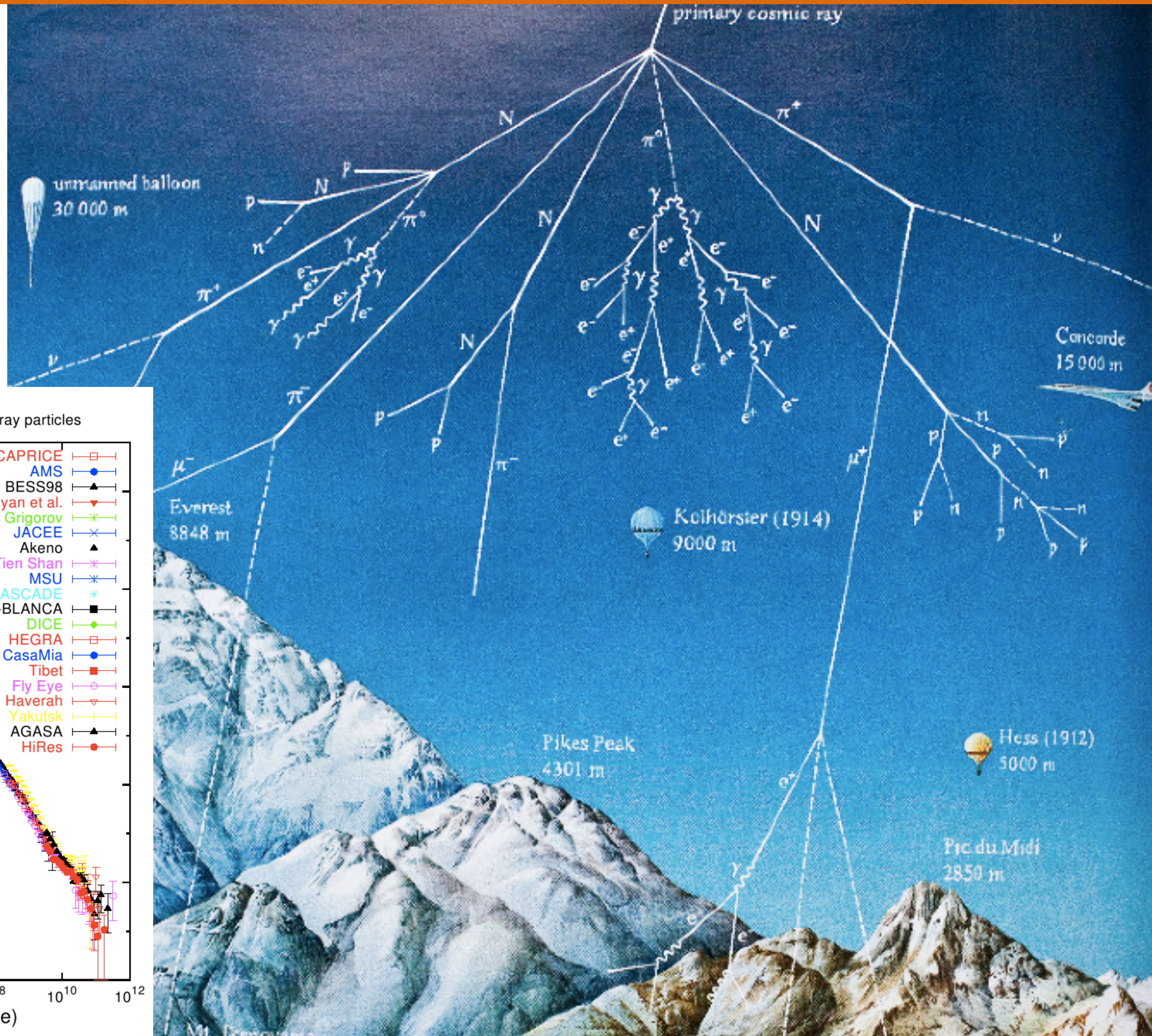
Detectors can also differentiate between WIMPs and γ at 99% level

*1 Gy = 1 J/kg = 100 rad

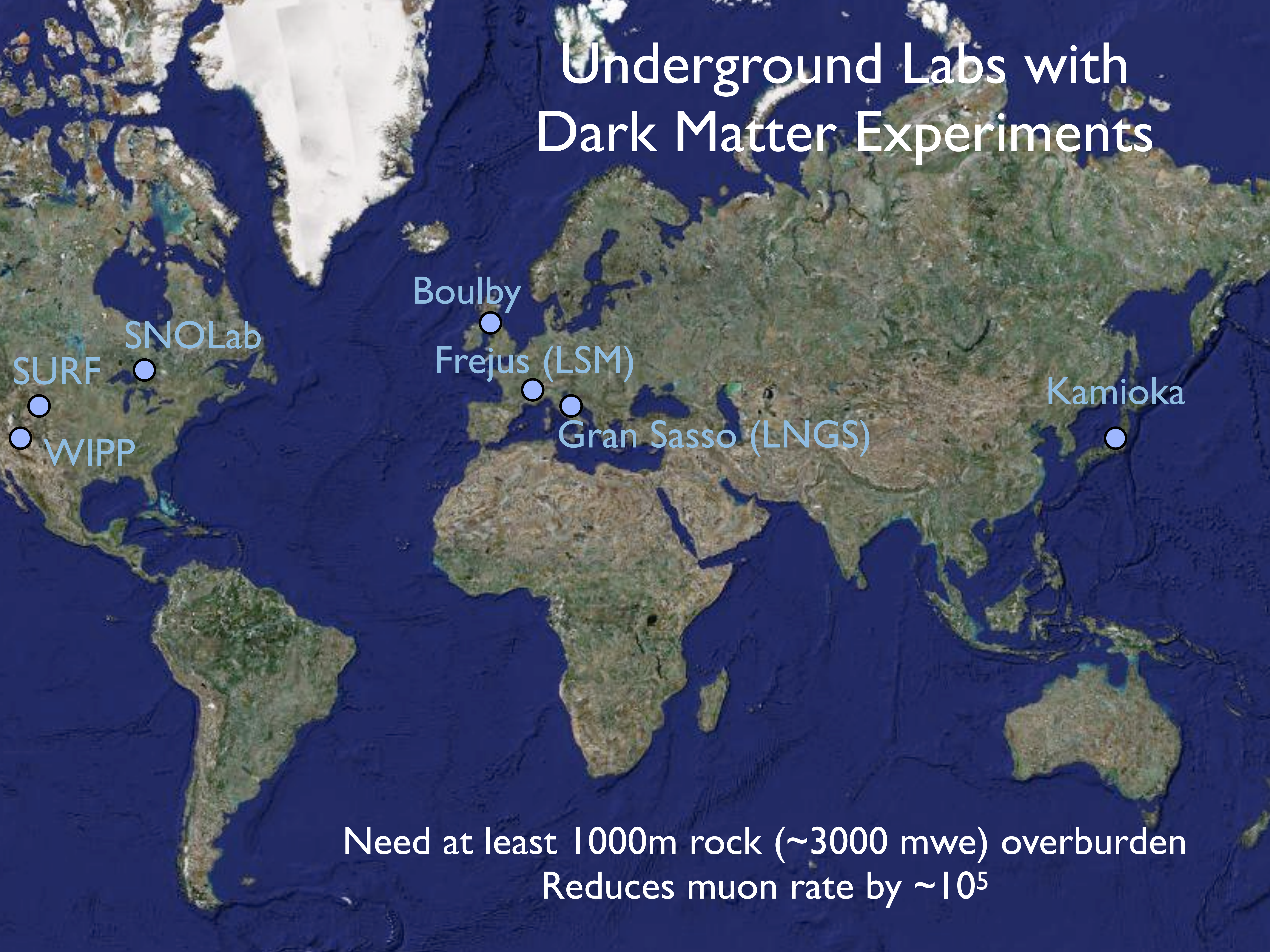
Cosmic rays go kilometers

Cosmic rays go kilometers



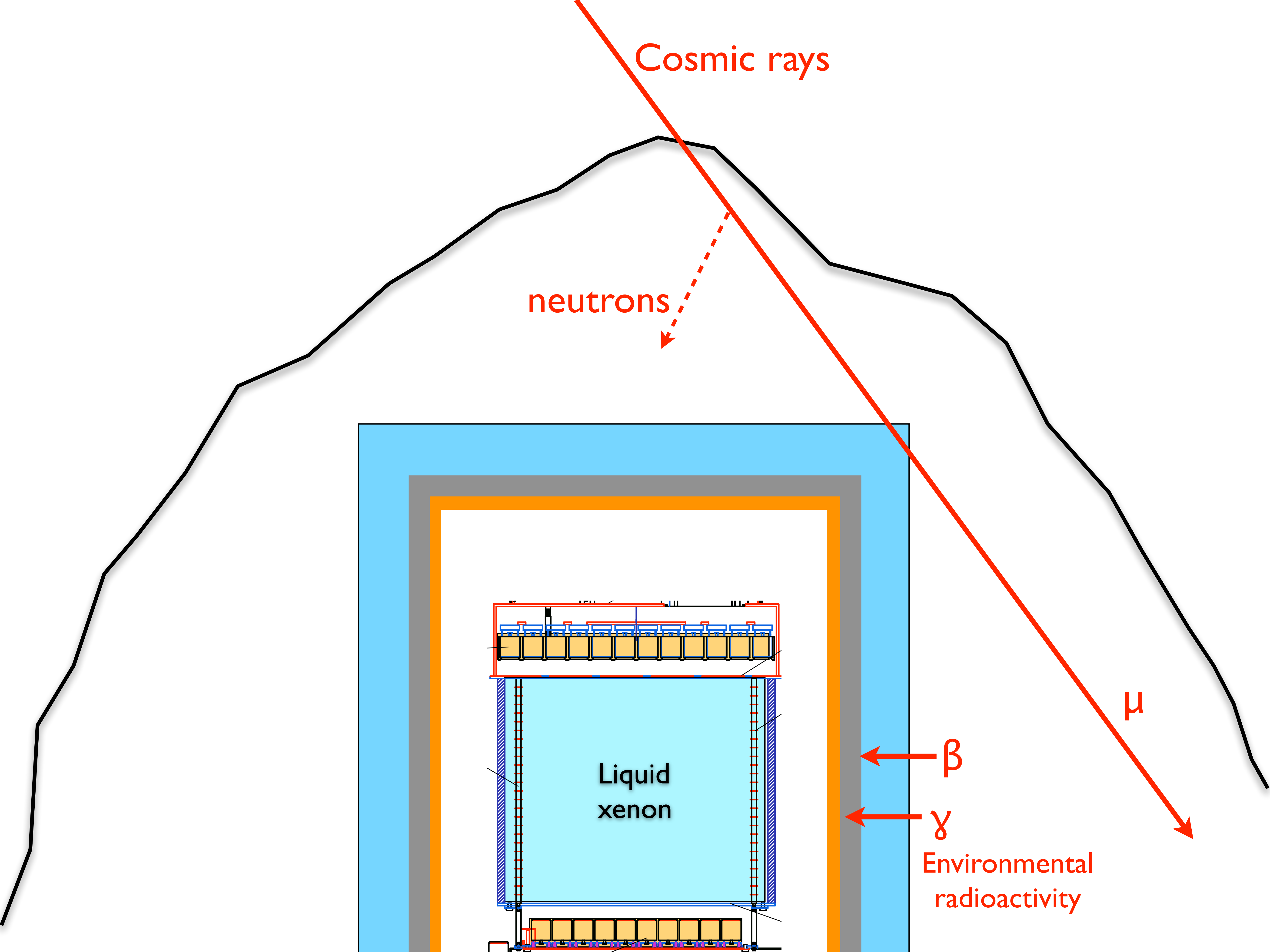


Underground Labs with Dark Matter Experiments

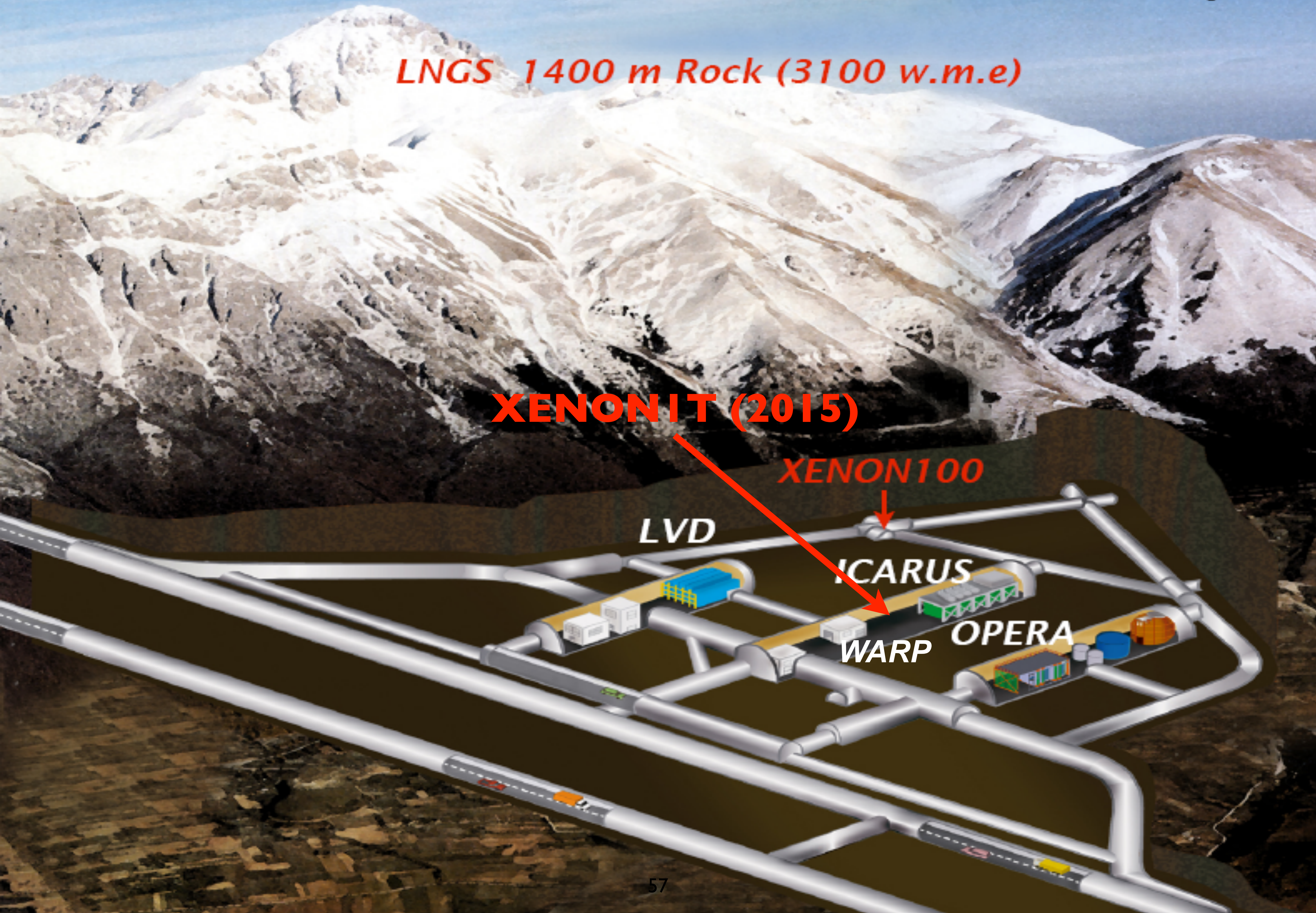


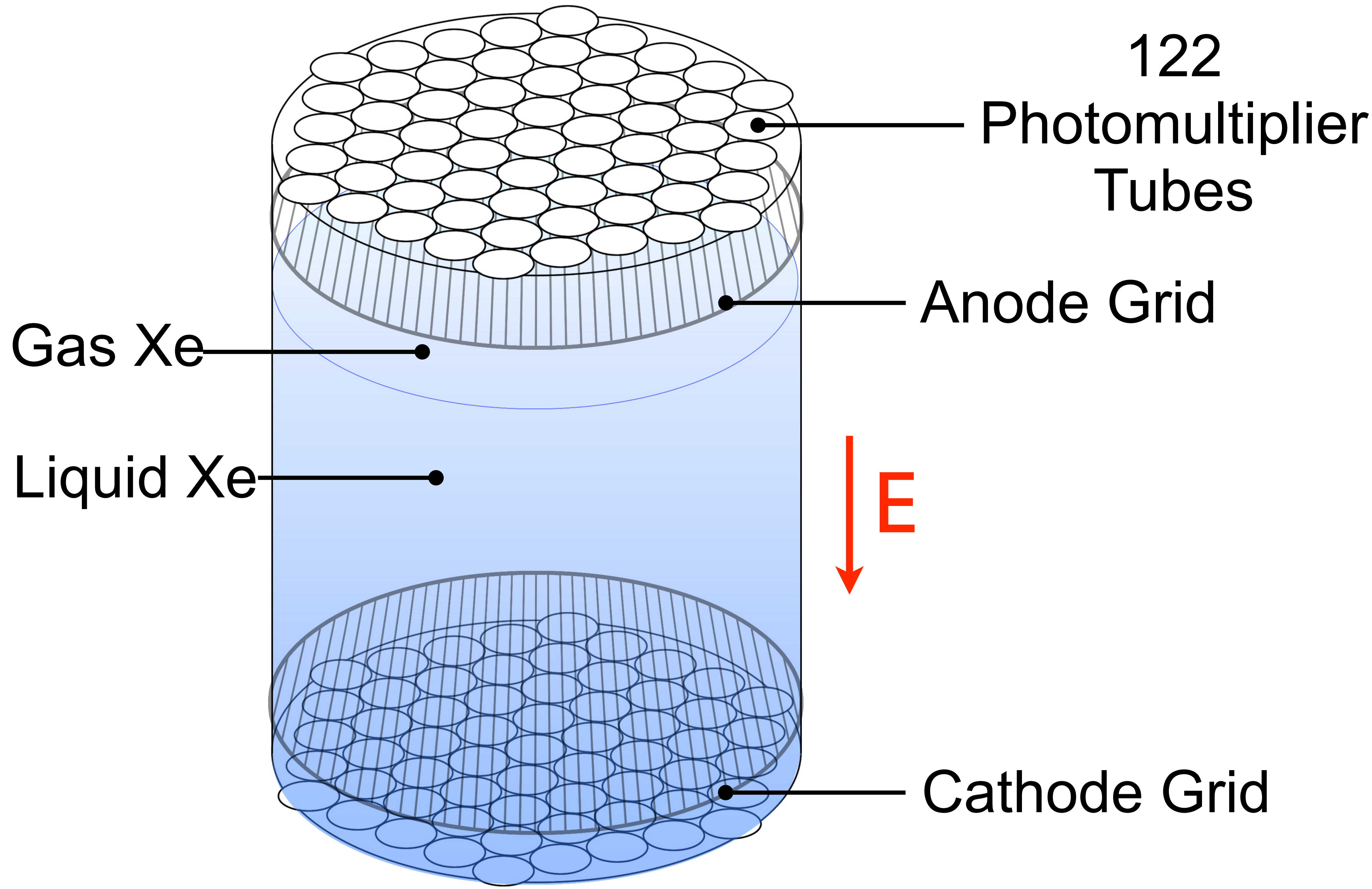
Need at least 1000m rock (~3000 mwe) overburden

Reduces muon rate by ~10^5

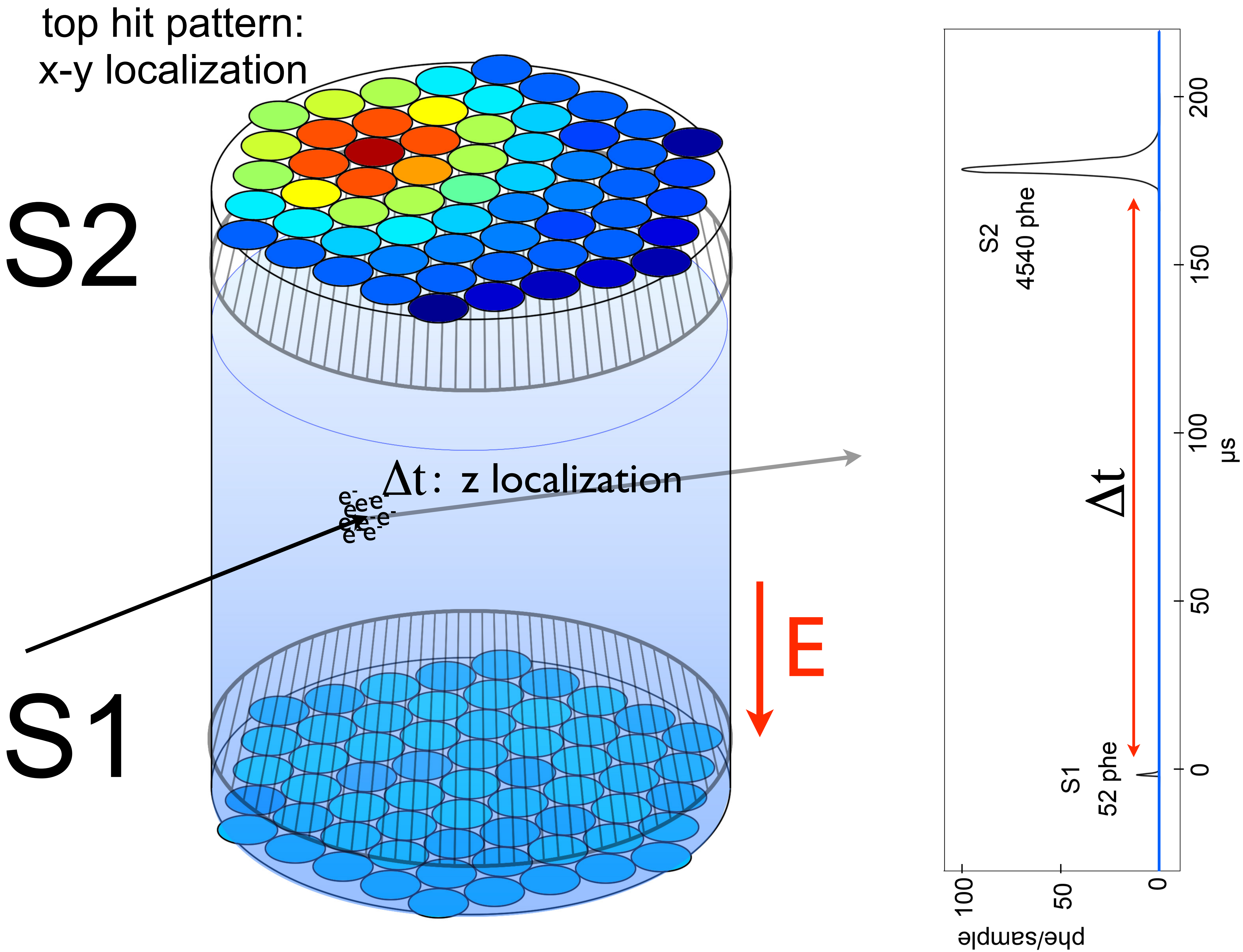

Cosmic rays
neutrons
Liquid
xenon
μ
β
γ
Environmental
radioactivity

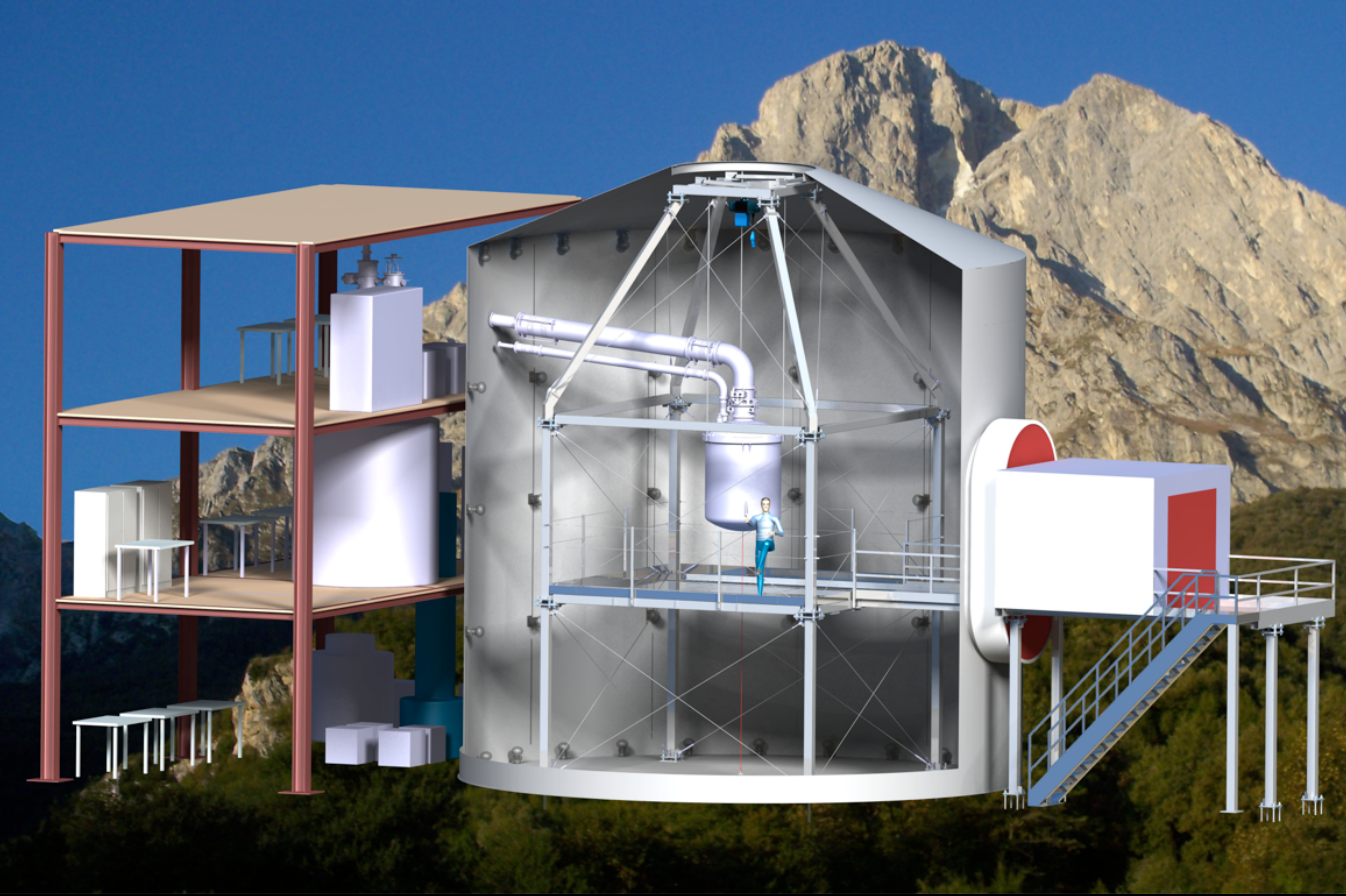
Laboratori Nazionali del Gran Sasso, Italy





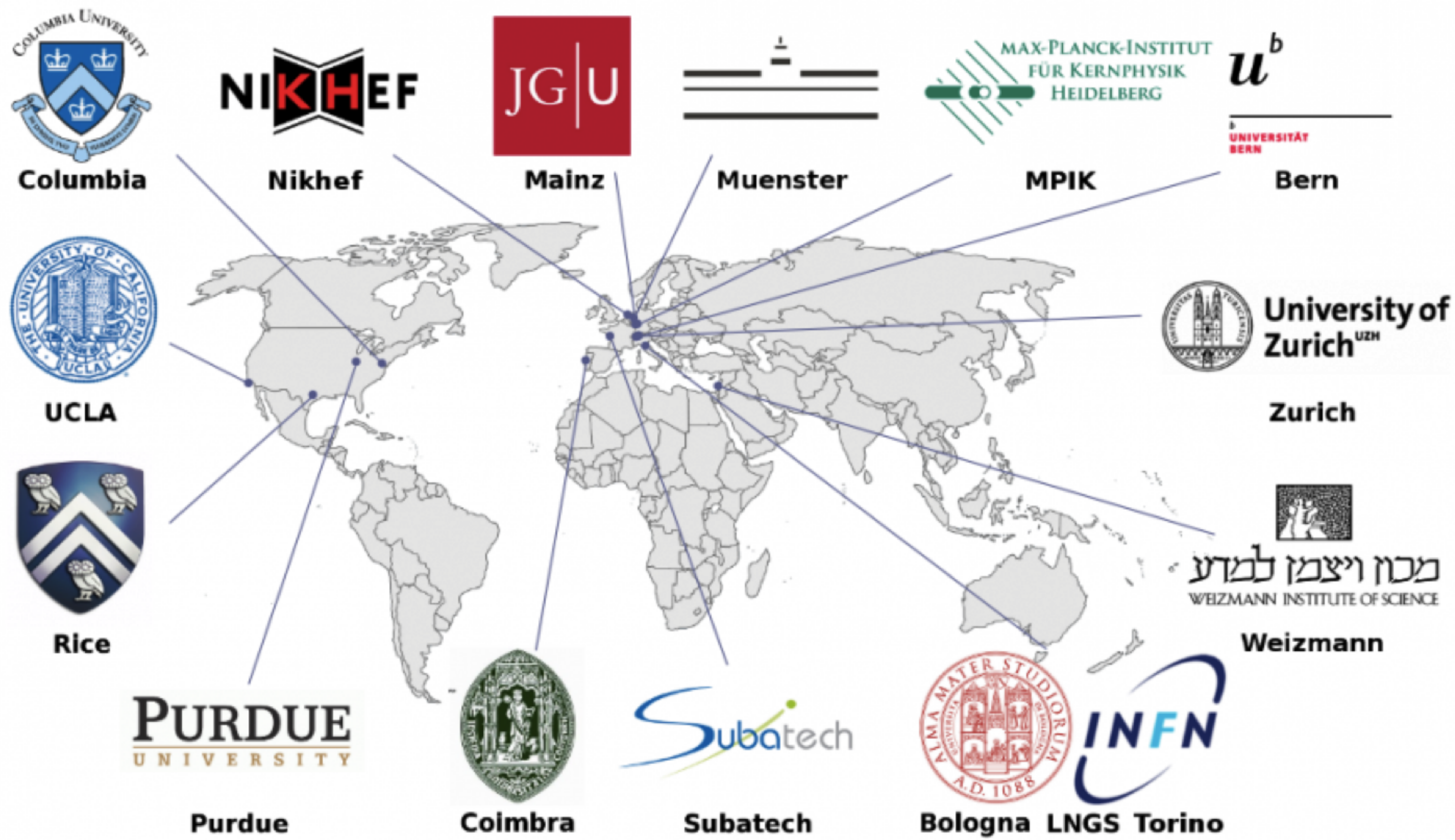
122
Photomultiplier
Tubes
Anode Grid
Gas Xe
Liquid Xe
E
Cathode Grid

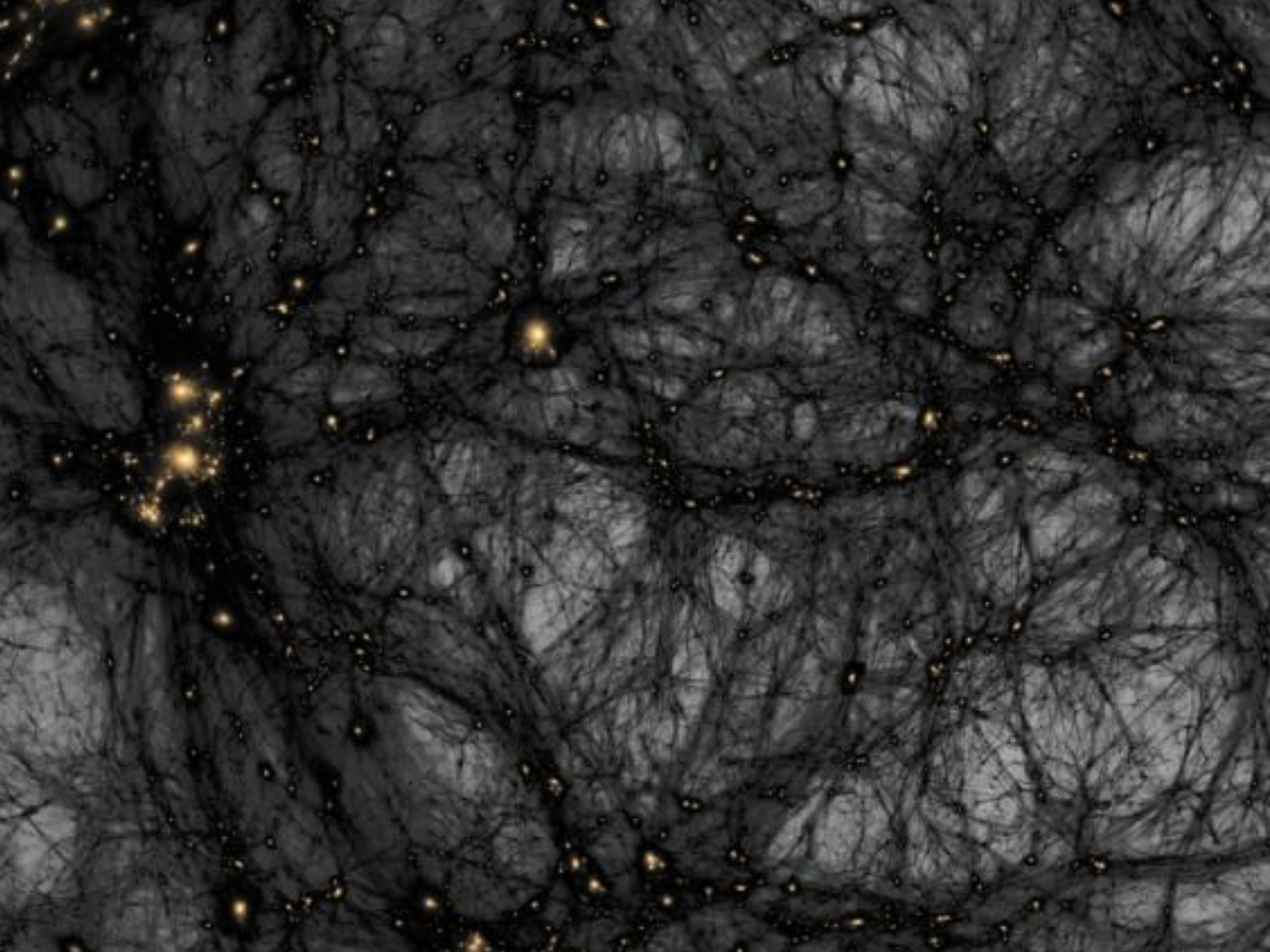

top hit pattern:
x-y localization
S2
S1
Δt : z localization
E
S2
4540 phe
S1
52 phe
Δt
phe/sample
μs
0
50
100
150
200
100
50
0



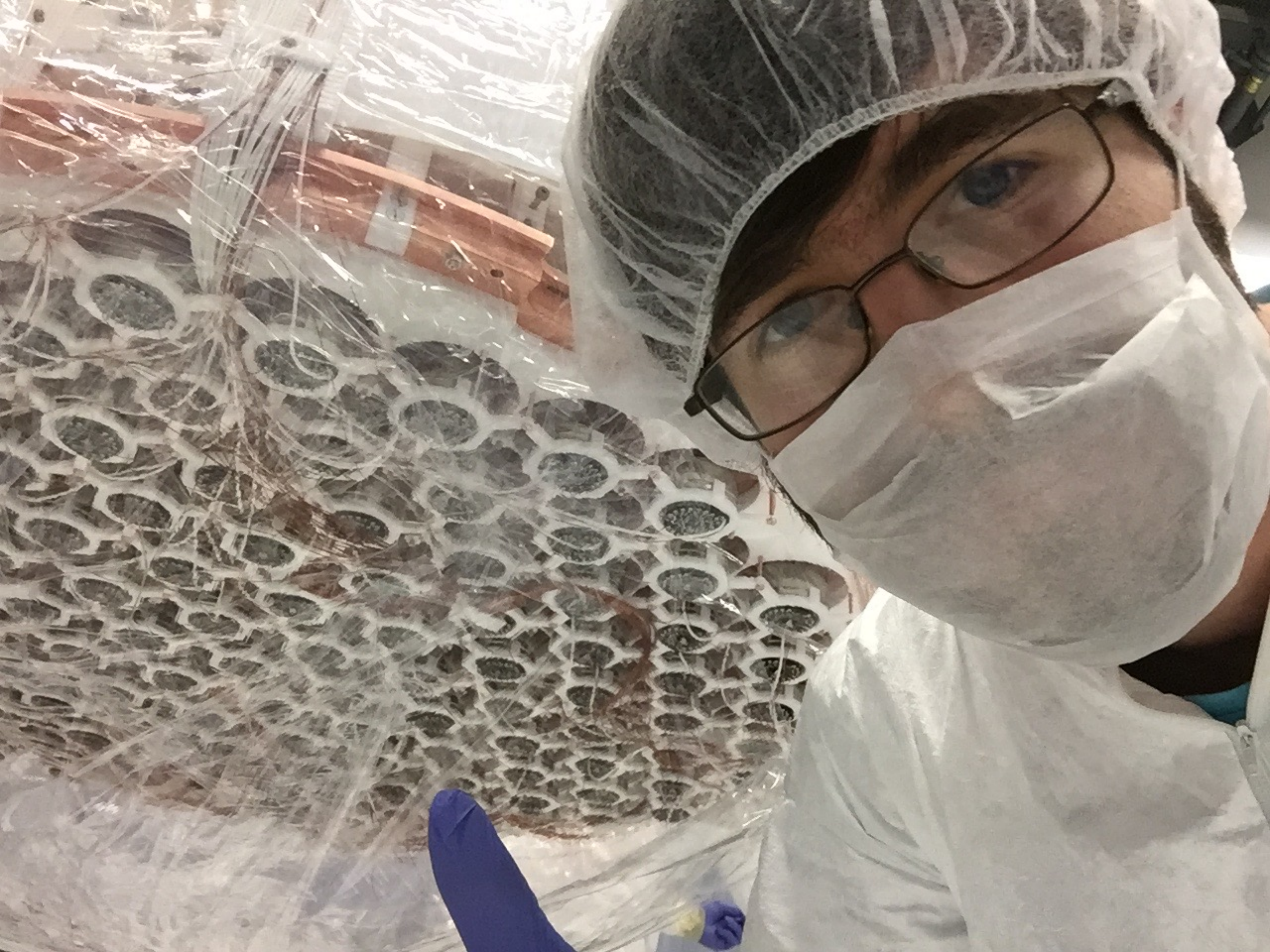
The XENON Collaboration

currently ~ 100 scientists from 15 institutions
US led and NSF supported since project start in 2002





Assembling XENON1T

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The underground lab

My experiment: XENON1T