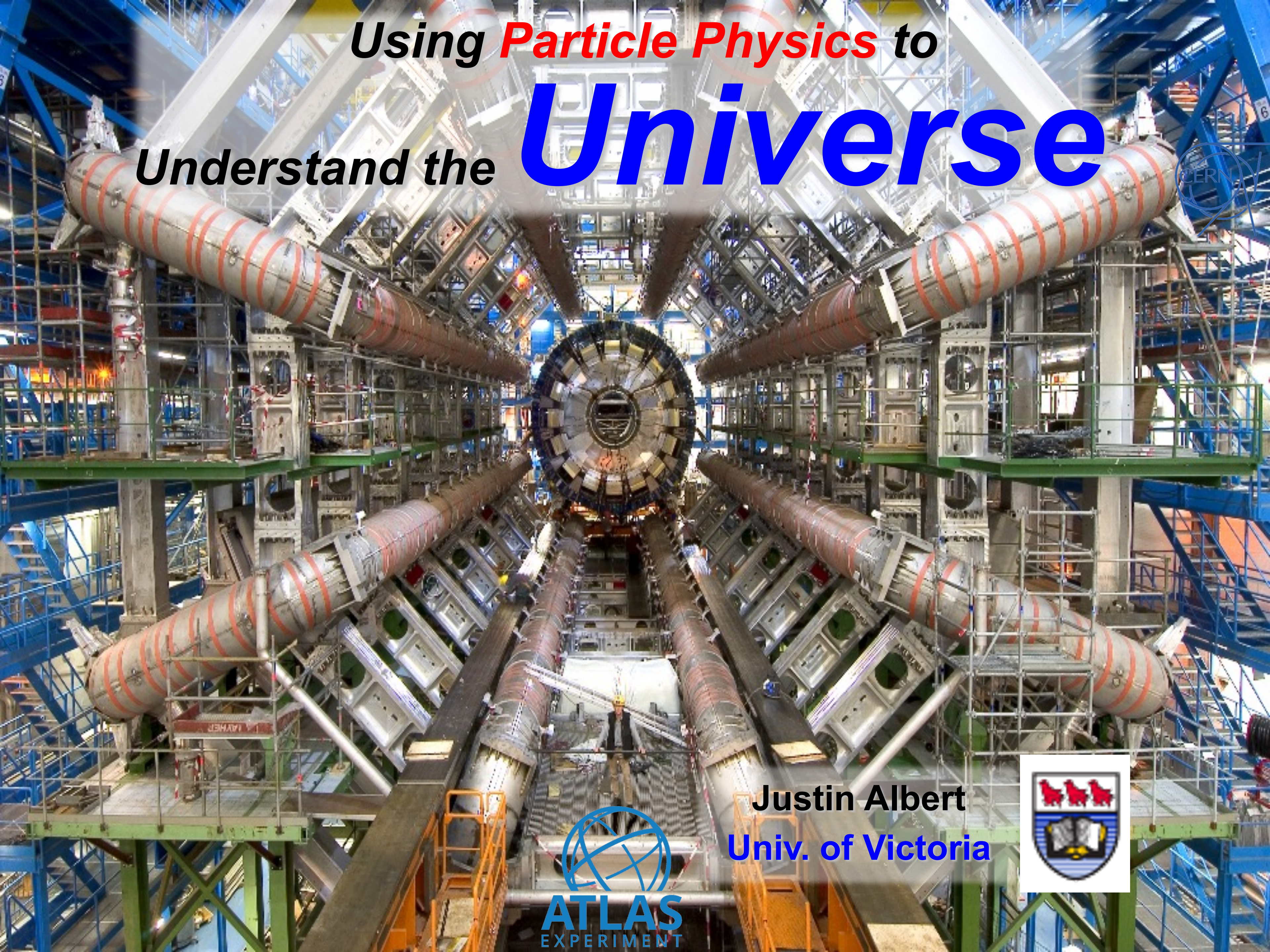


Using Particle Physics to Understand the Universe

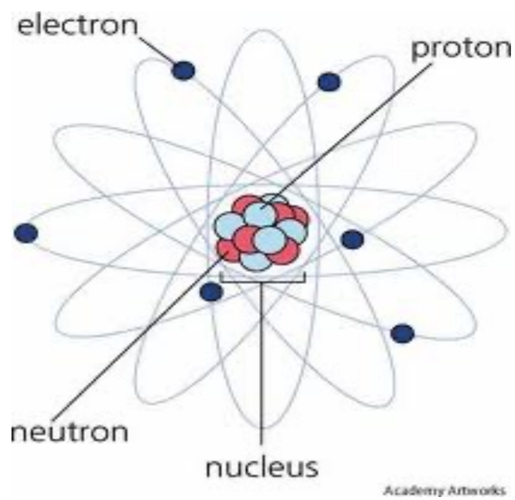
Justin Albert
Univ. of Victoria

ATLAS EXPERIMENT

CERN July 4th 2012 (ATLAS and CMS)

"A new particle of mass 125 GeV"

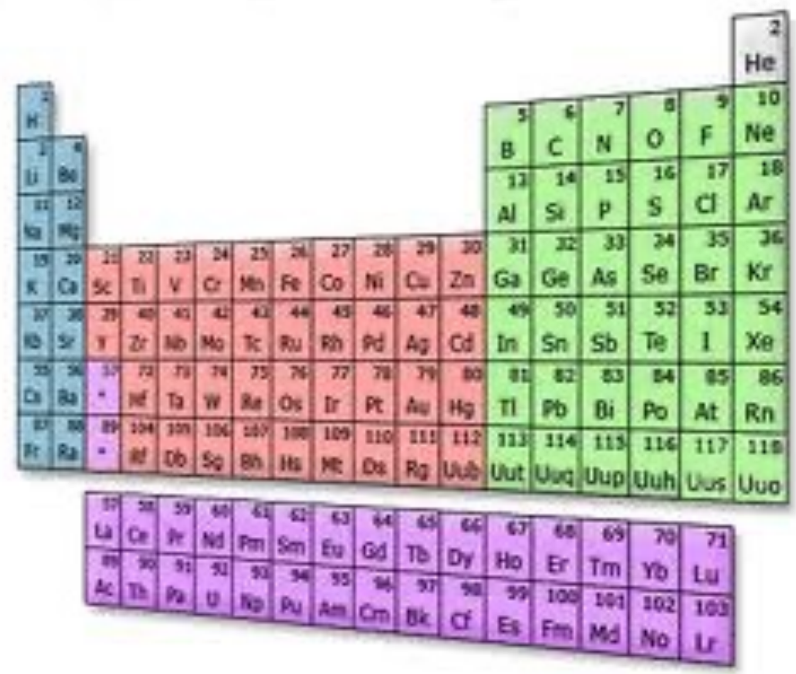
Atoms and chemistry



- **Discovery of the proton** (1918)
  There are particles of positive charge inside nuclei.
  (Discovered via scattering of "alpha decays.")

- **Helps explain periodic table**
  Atoms of different elements have different number of protons in nucleus

  Number protons = number electrons (Z).
  Determines chemical properties.



- **Discovery of the neutron** (1932)
  Uncharged particle in nucleus.
  Explains atomic masses and isotopes.
  <u>What holds nucleus together???</u>

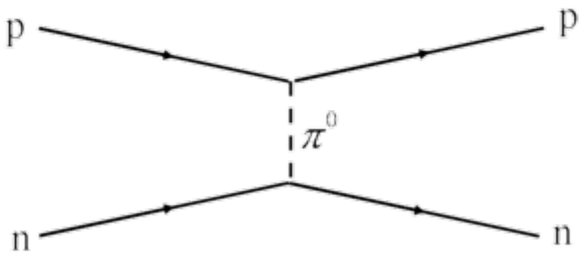
Strong nuclear force (1934)

- New force >> electromagnetic
- Independent of electric charge (p+, n)
- Extremely short range

- Quantum theory
- New particle associated with force
- Acts on protons and neutrons

Hideki Yukawa

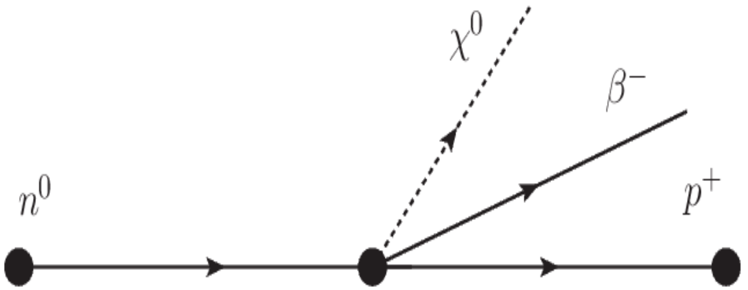
Yukawa pion π^-, π_0, π^+



Discovered 1947 (cosmic rays)

Weak nuclear force (1934)

- Radioactive decay of nucleus
- Increases number of protons in nucleus!
- Neutrons changing to protons?
- Beta decay of the neutron



$$\boldsymbol{n \rightarrow p^+ + e^- + v}$$

- New particle: neutrino
- Discovered 1956
- Fermi's theory of the weak force
- Four interacting particles

Enrico Fermi

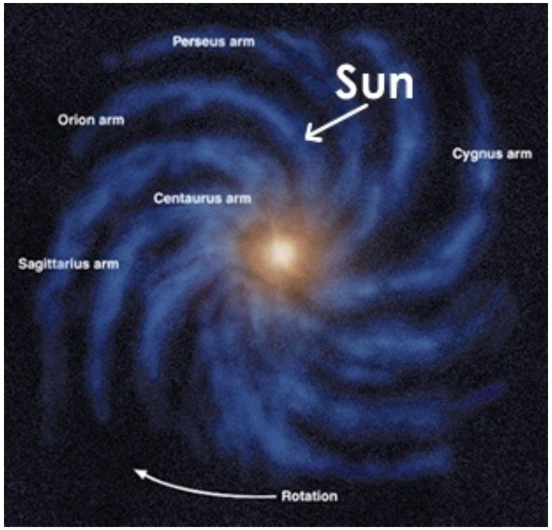
Four forces of nature (1930s)

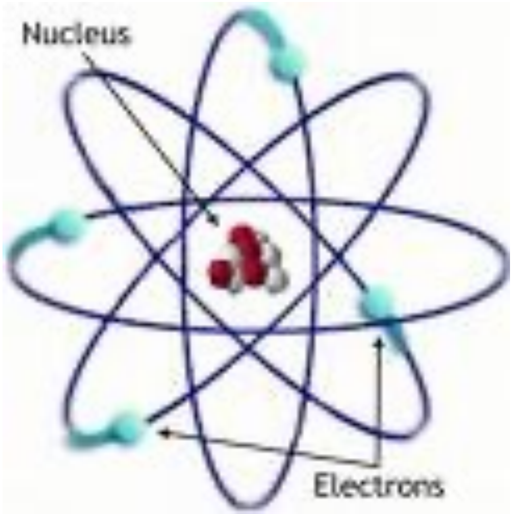
- **Force of gravity**
  Long range
  Holds cosmos together

- **Electromagnetic force**
  Electricity + magnetism
  Holds atoms together

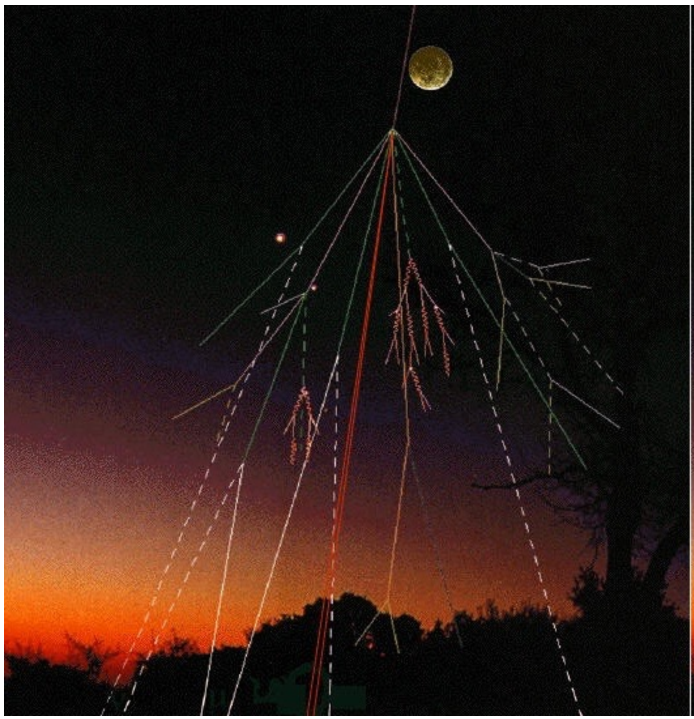
- **Strong nuclear force**
  Holds nucleus together

- **Weak nuclear force**
  Responsible for radioactivity (Fermi)



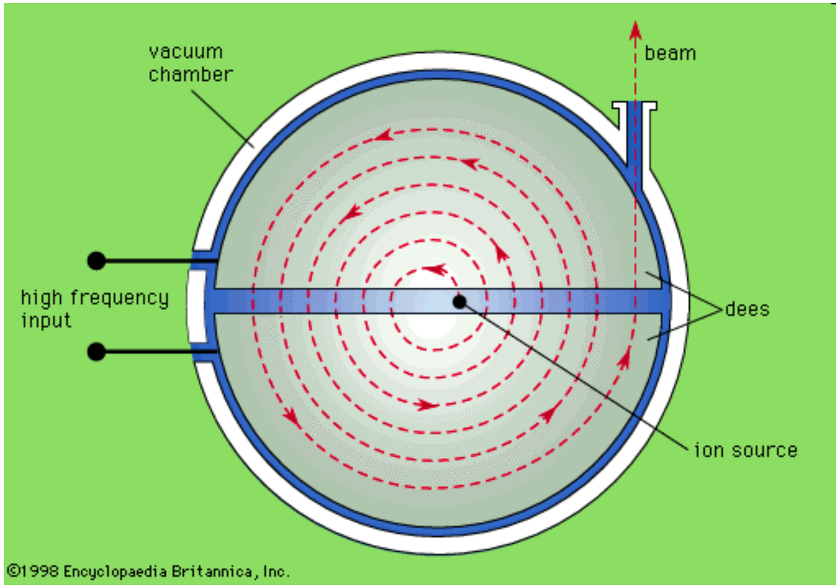


New elementary particles (1940-50)



Cosmic rays

$\pi^+ \rightarrow \mu^+ + \nu$



Particle accelerators

Pions, muons, neutrinos, antiparticles

High-energy physics

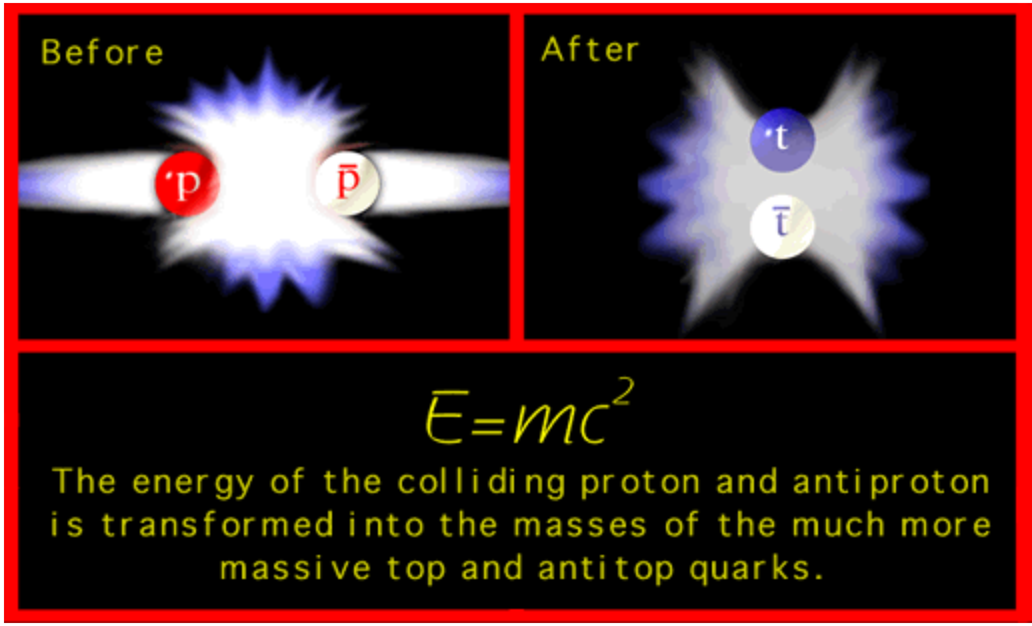
- Accelerate charged particles to high velocity

  High voltage

- Collisions
- High energy density
- New particles observed
- Not ‘inside’ original particles

$$m = E/c^2$$

$$E = mc^2$$



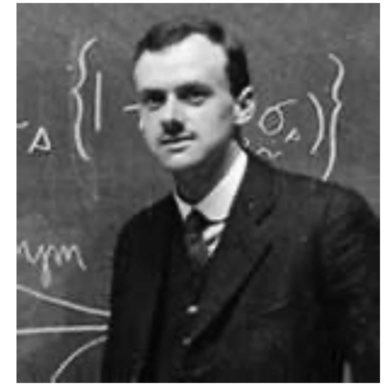
Particle Zoo (1950s, 1960s)

BARYONS		MESONS		LEPTONS		PHOTON	
Symbol	Charge	Symbol	Charge	Symbol	Charge	Symbol	Charge
p	+1	π^+	+1	e^-	−1	γ	0
$\bar{p}$	−1	π^-	−1	e^+	+1		
n	0	π^0	0	ν_e	0		
Δ	0	K^+	+1	$\bar{\nu}_e$	0		
		K^-	−1				
		K^0	0				

Over 100 “elementary” particles

Anti-particles

- Dirac equation for the electron
- Twin solutions
- Negative energy values?

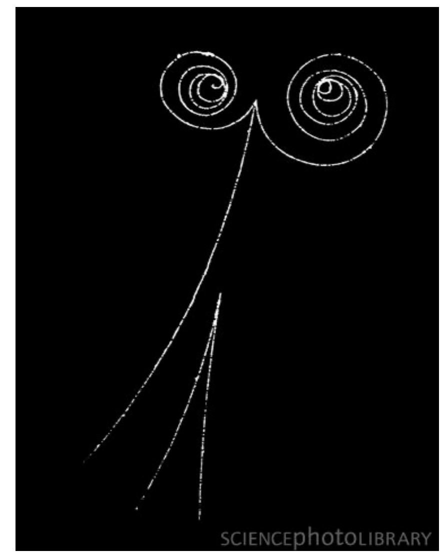


Paul A.M. Dirac 1902-84

- Particles of opposite charge (1928)
- Anti-electrons (detected 1932)
- Anti-particles for all particles

- Energy creates matter and anti-matter

Why is the universe made of matter?

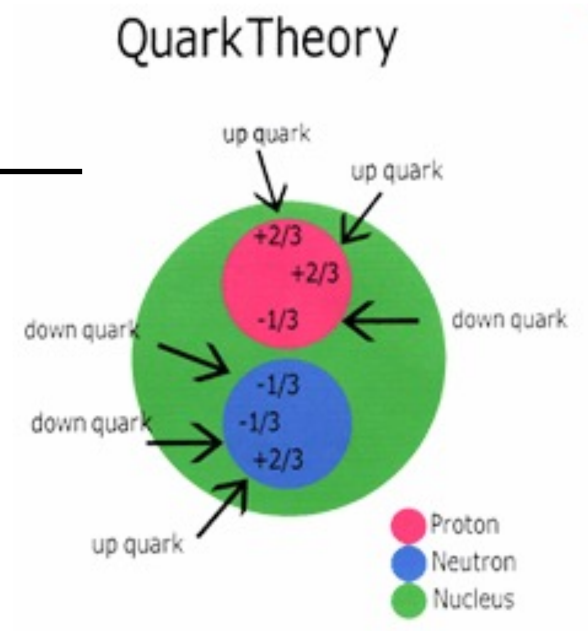


$E= mc^2$

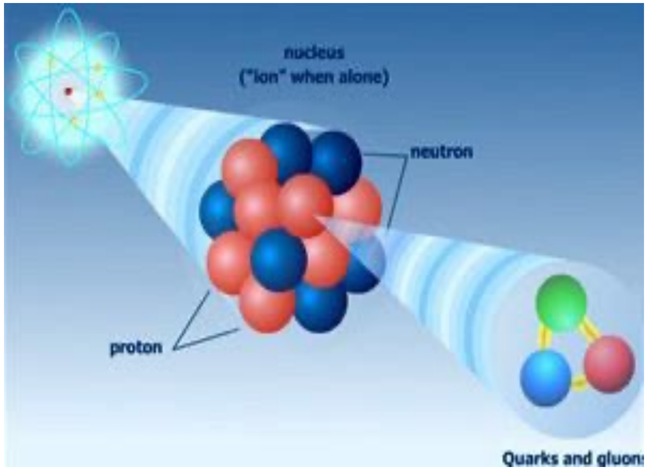
New model: Quarks (1964)

- **Too many particles**
- Protons not fundamental
- Made up of smaller particles
- New fundamental particles
  Quarks *(fractional charge)*
- Hadrons: particles containing quarks
  Baryons (3 quarks) mesons (2 quarks)

Prediction of Ω^-



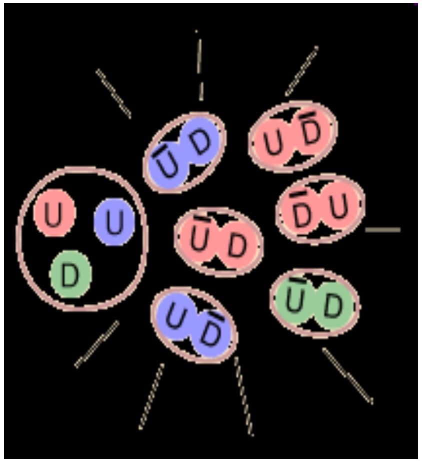
Gell-Mann, Zweig



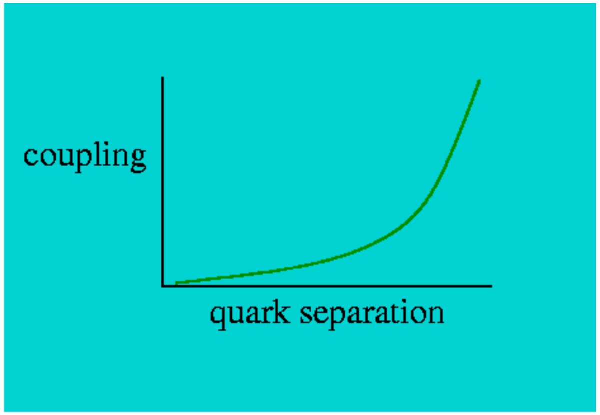
Finding Quarks

Stanford/MIT experiments in 1969

- Scattering experiments (very similar to Rutherford scattering)
- Three centres of mass inside proton
- Strong force = inter-quark force!



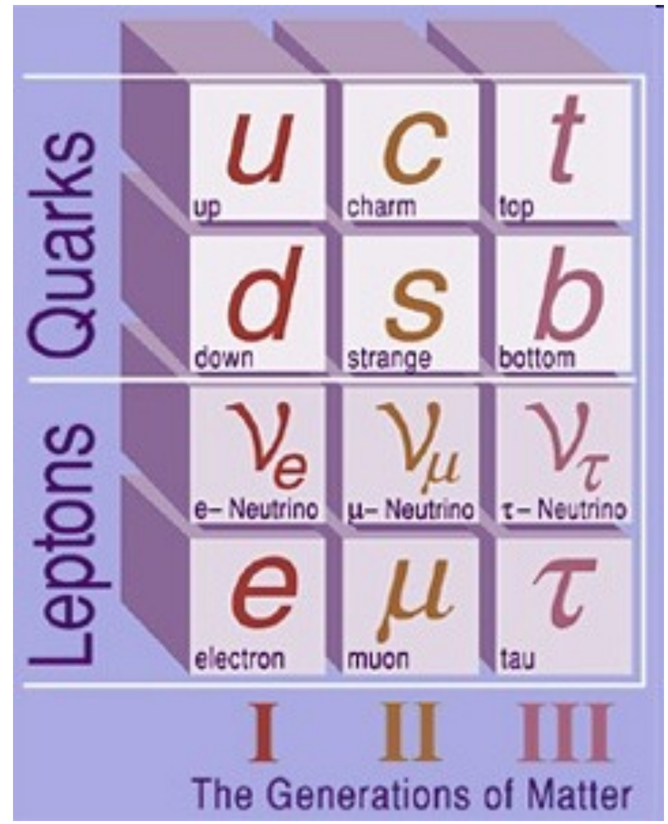
- Defining property = ***colour***
- Strange behaviour
- Quark confinement



The energy required to break apart the proton far exceeds the pair production energy of a quark-antiquark pair

Six quarks (1970s –1990s)

- 30 years of experiments
- Six different quarks **(u,d,s,c,b,t)**
- Six corresponding leptons **(e, μ, τ, υ_e, υ_μ, υ_τ)**
- Gen I: all of ordinary matter
- Gen II, III – why are they there? Why 3?



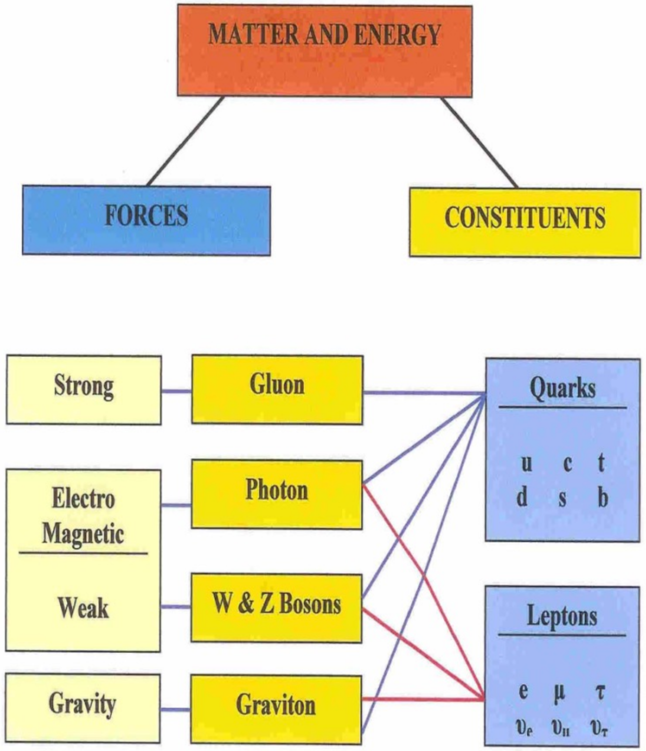
New periodic table

Bosons and the Standard Model

Satyendra Nath **Bose**

Bosons: particles associated with forces

- Electromagnetic force mediated by *photons*
- Strong force mediated by *gluons*
- Weak force mediated by *W* and *Z bosons*
- Problems constructing theory of weak force…

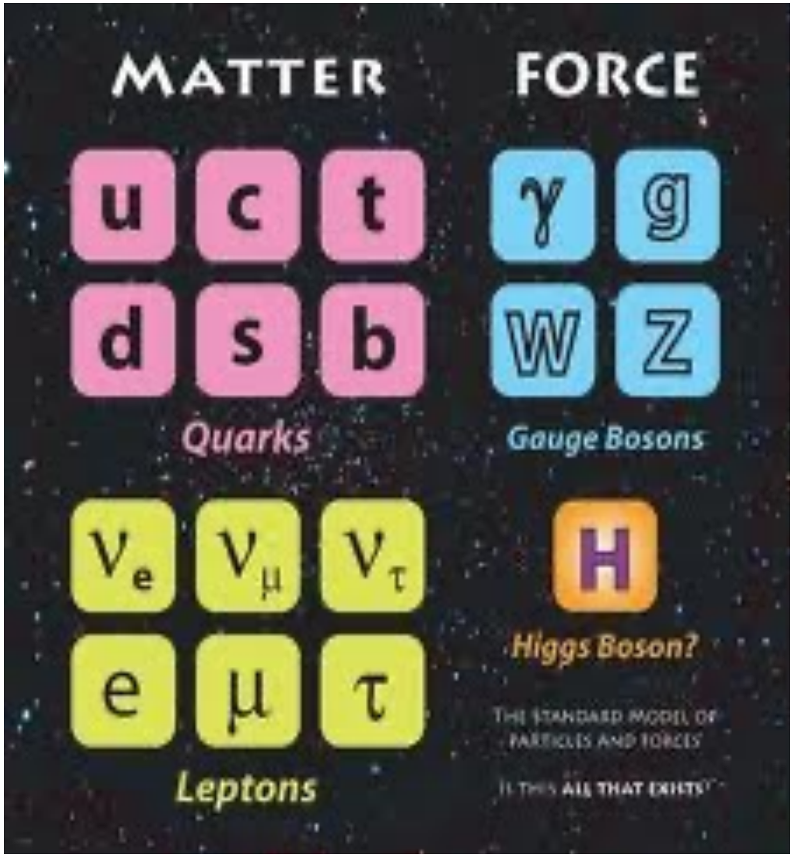


- *EM* + *weak*: single interaction above 100 GeV
- Quantum field causes symmetry breaking
- Separates *EM*, weak interactions
- Endows *W*, *Z bosons* with mass
- Called the Higgs field

The Standard Model (1970-90s)

- Strong force = quark force (QCD)
- EM + weak force = electroweak force
- Higgs field causes e-w symmetry breaking
- Gives particle masses

- Matter particles: fermions (1/2 integer spin)
- ‘Force’ particles: bosons (integer spin)

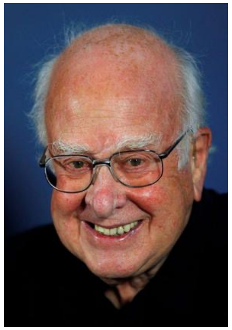


<u>Experimental tests</u>

- *Top, bottom , charm, strange quarks*
- *Leptons*
- *W^{+-},Z^0 bosons*

<u>Higgs boson</u> outstanding

The Higgs field



Peter Higgs

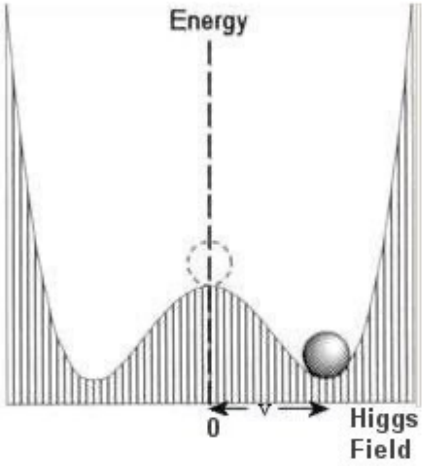
- Electro-weak symmetry breaking
- Mediated by scalar field
- Higgs field
- Generates mass for W, Z bosons

W and Z bosons (CERN, 1983)

Kibble, Guralnik, Hagen, Englert, Brout

- Generates mass for all massive particles
- Associated particle : scalar boson
- Higgs boson

Particle masses not specified



The Higgs field

- Particles acquire mass by interaction with the field
- Some particles don't interact (massless)

  Photons travel at the speed of light
- Heaviest particles interact most

  Top quarks
- Self-interaction = Higgs boson

Mass not specified by SM

II The Large Hadron Collider

$E = mc^2$

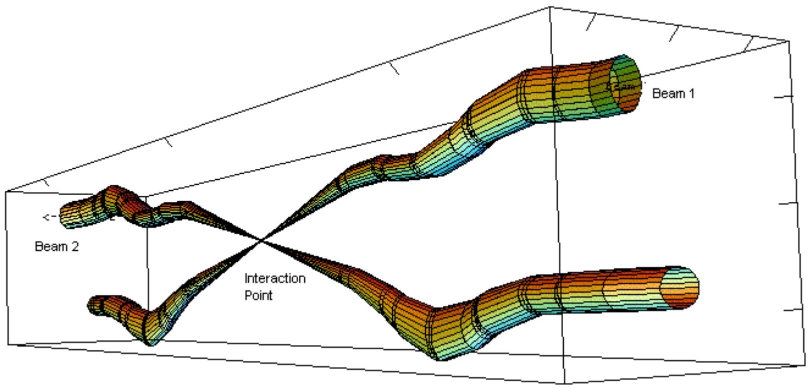
- Particle accelerator (8TeV)
- High-energy collisions (10^{12}/s)
- Huge energy density
- Create new particles

  $m = E/c^2$

- <u>Detect particle decays</u>
- Four large particle detectors

How?

- Two proton beams
- *E* = (4 + 4) TeV (now is (6.5 + 6.5) TeV)
- speed ≈ (very very close to) speed of light
- 10^{12} collisions/sec



Relative beam sizes around IP1 (Atlas) in collision

- Ultra-high vacuum
- Low temp: 1.6 K
- Superconducting magnets

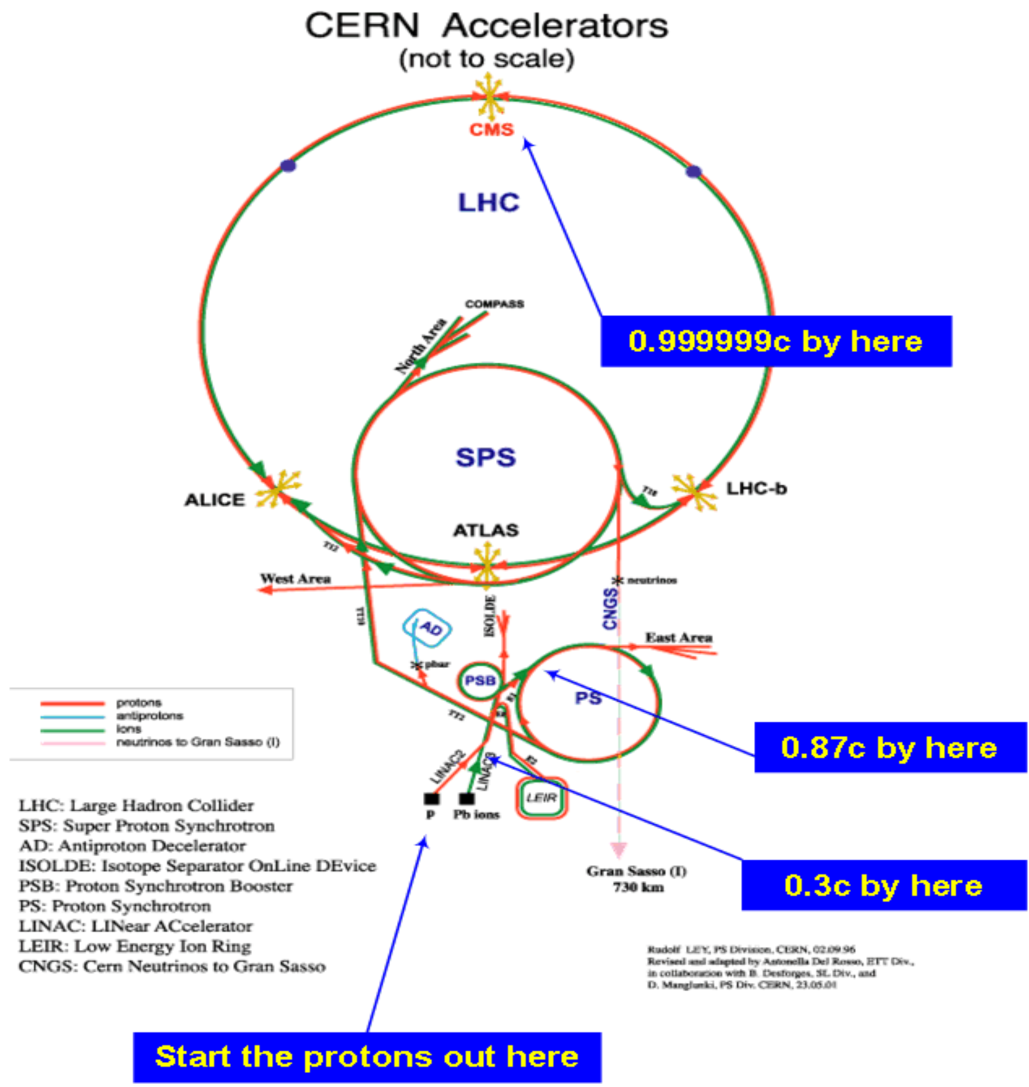
LEP tunnel: 27 km

Total "Integrated luminosity" (up to now): ~ 150 fb^{-1}

Around the ring at the LHC

- Nine accelerators
- Cumulative acceleration
- Velocity increase
- $K.E = 1/2mv^2$
- Effective mass increase *x8000*

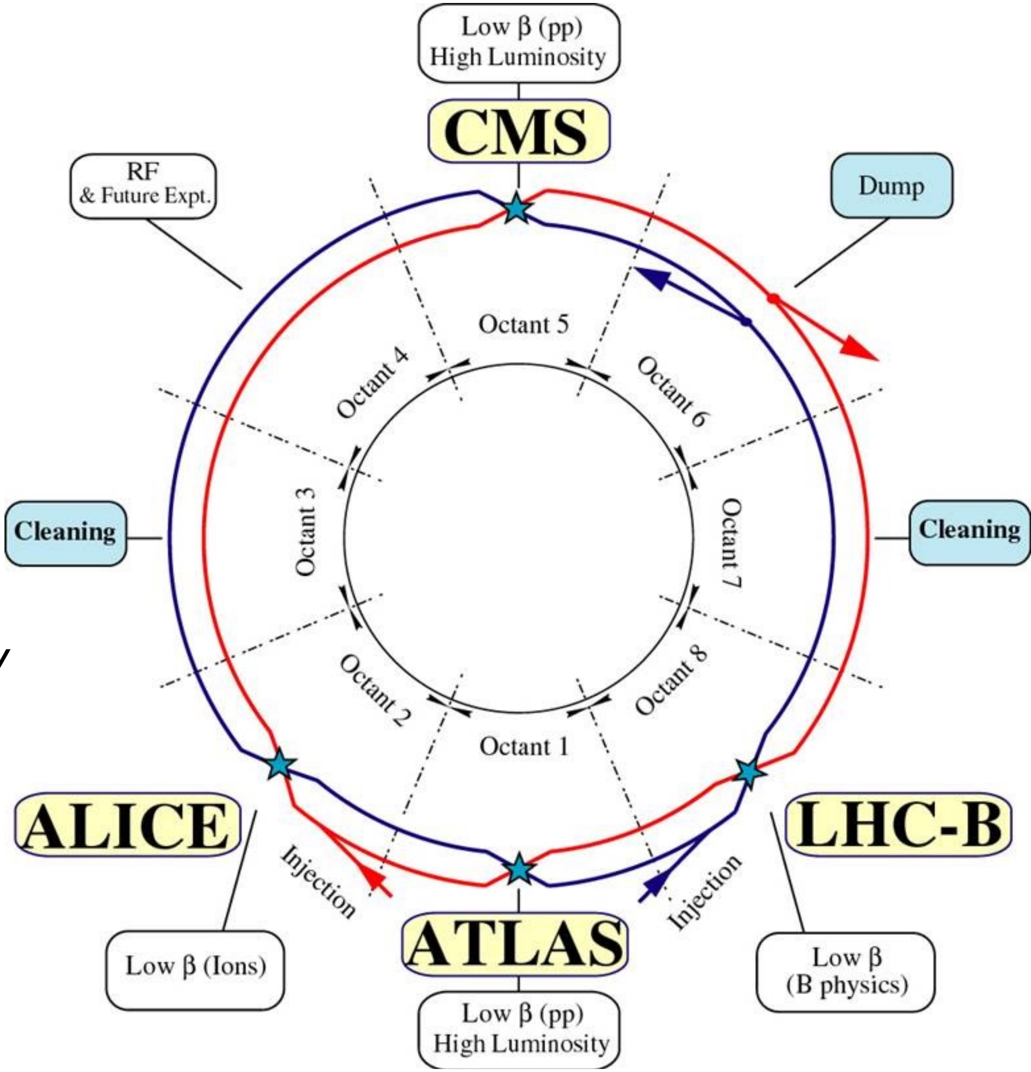
$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$



Particle detectors

<u>Detectors at crossing pts</u>

- **CMS** *multi-purpose*
- **ATLAS** *multi-purpose*
- **ALICE** *quark-gluon plasma*
- **LHC-b** *matter-antimatter asymmetry*



Particle detection

- Tracking device

  Measures particle momentum

- Calorimeter

  Measures particle energy

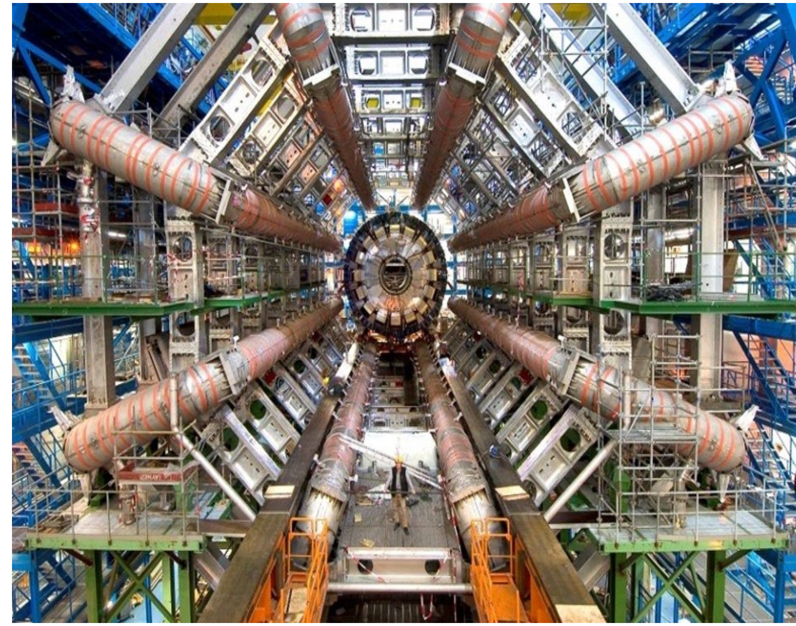
- Identification detector

  Measures particle velocity

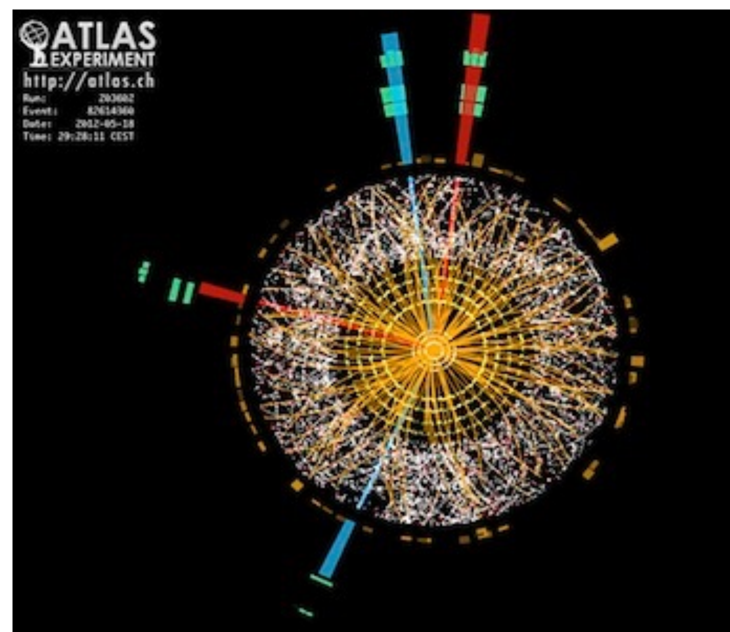
  Cerenkov radiation

- Analysis of decay tracks

  GRID computing



ATLAS



III A Higgs at the LHC?

- <u>Search for excess events</u>

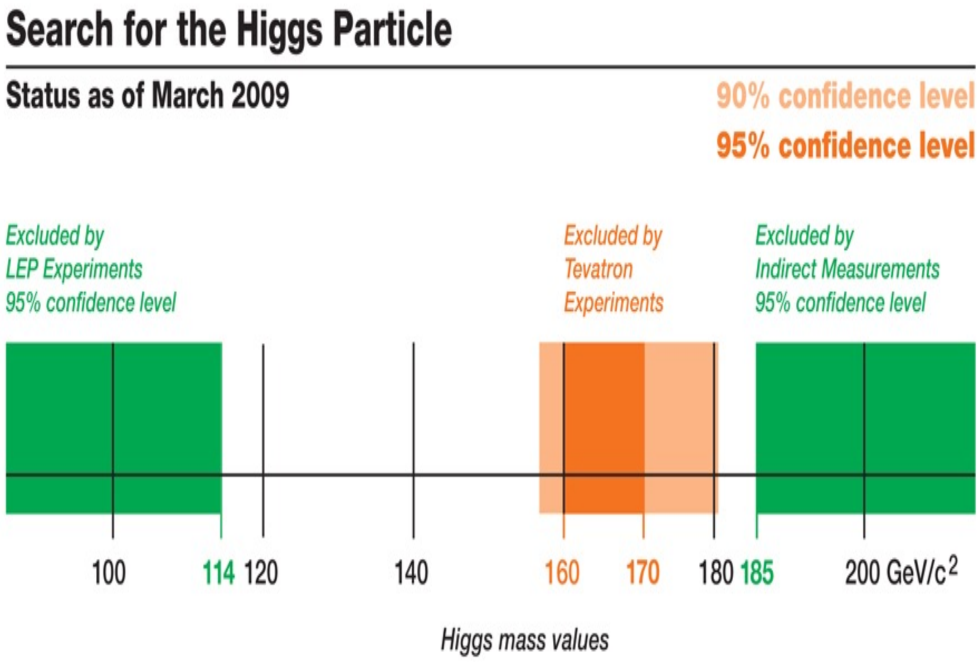
  Mass not specified?

- Close windows of possibility

- 120-160 GeV (1999)

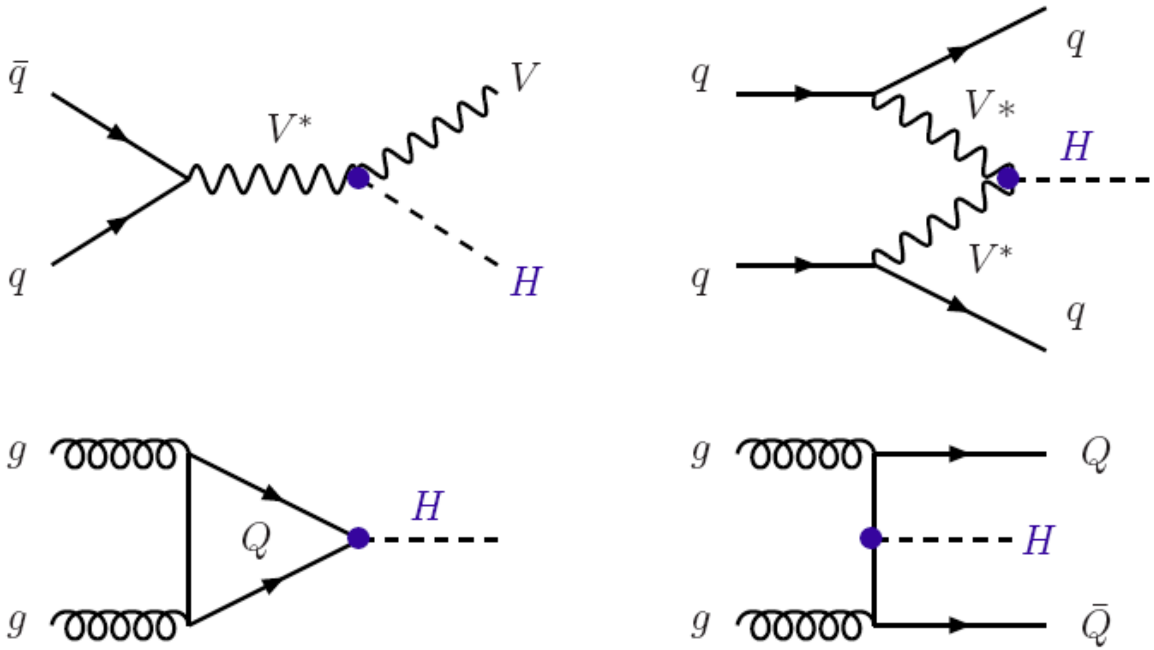
- Set by mass of top quark, W boson

- Search…running out of space!



Higgs production in LHC collisions

$$\begin{aligned}
\text{associated production with } W/Z: &\quad q\bar{q} \longrightarrow V + H \\
\text{vector boson fusion}: &\quad qq \longrightarrow V^*V^* \longrightarrow qq + H \\
\text{gluon} - \text{gluon fusion}: &\quad gg \longrightarrow H \\
\text{associated production with heavy quarks}: &\quad gg, q\bar{q} \longrightarrow Q\bar{Q} + H
\end{aligned}$$



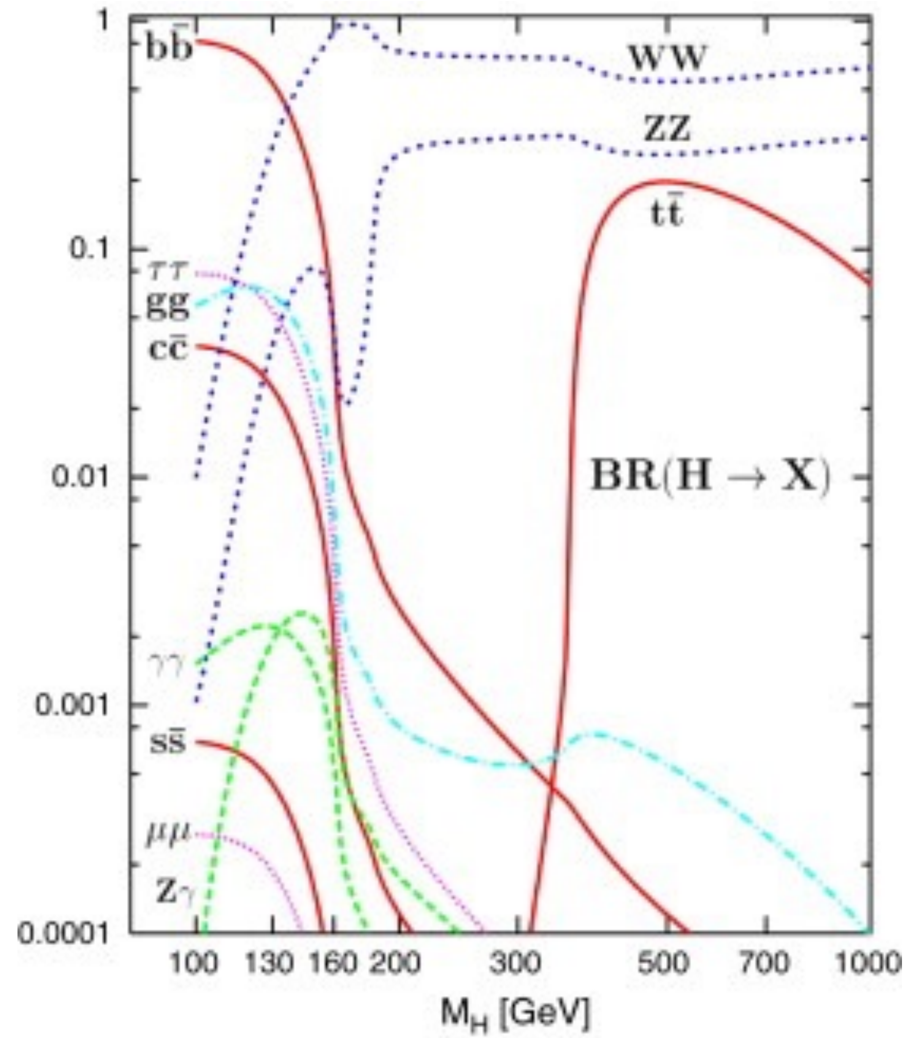
<u>*1 in a billion collisions*</u>

Detect Higgs by decay products

- Most particles interact with Higgs
- Variety of decay channels
- Massive particles more likely
- Difficult to detect from background
- Needle in a haystack

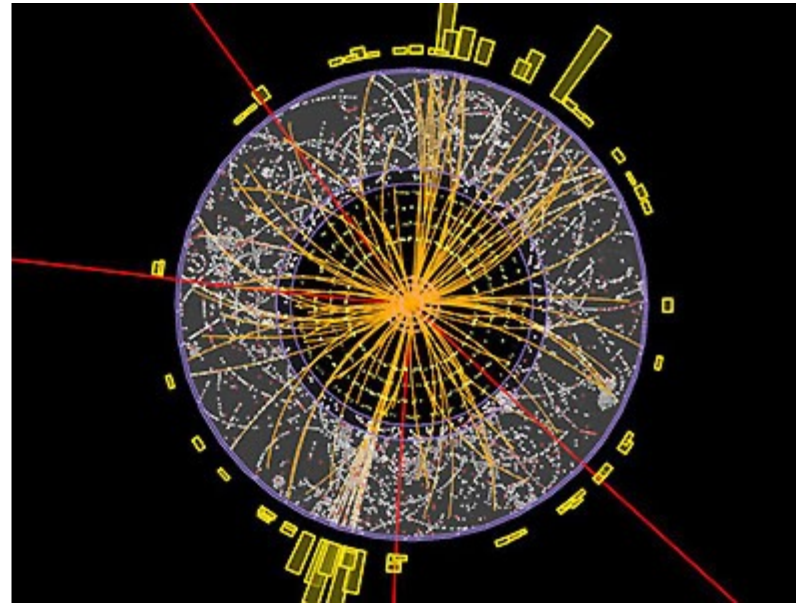
Needle in haystack of needles

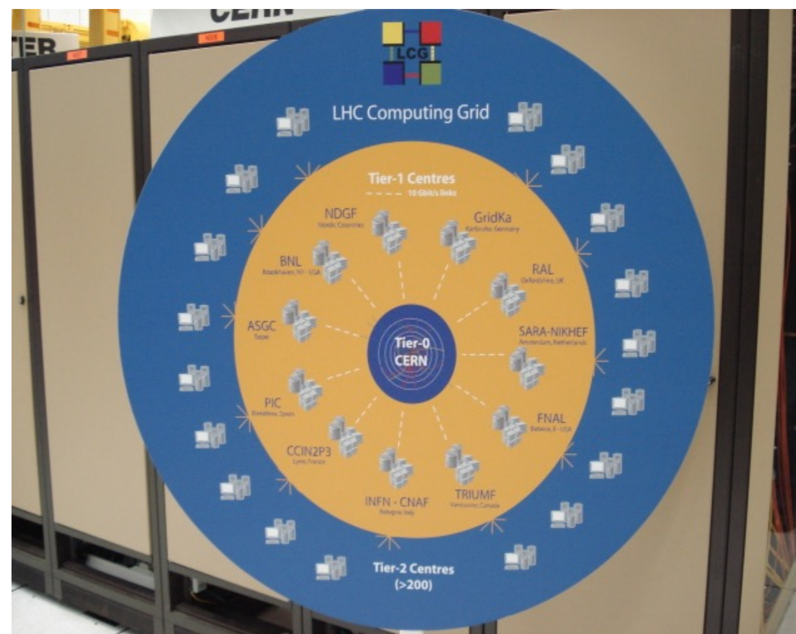
High luminosity required



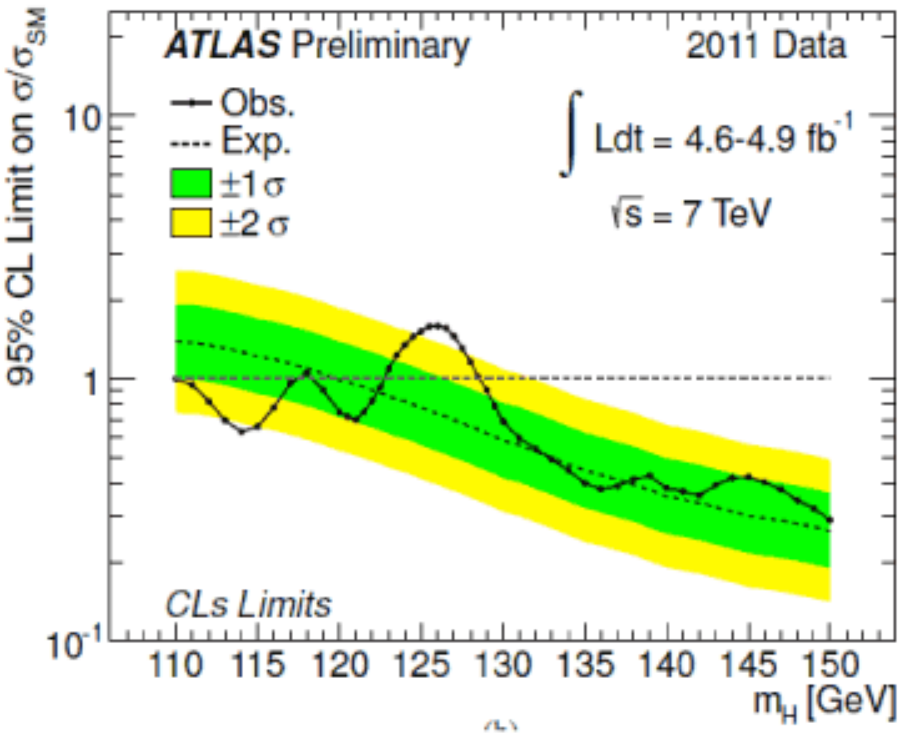
Analysis: Grid

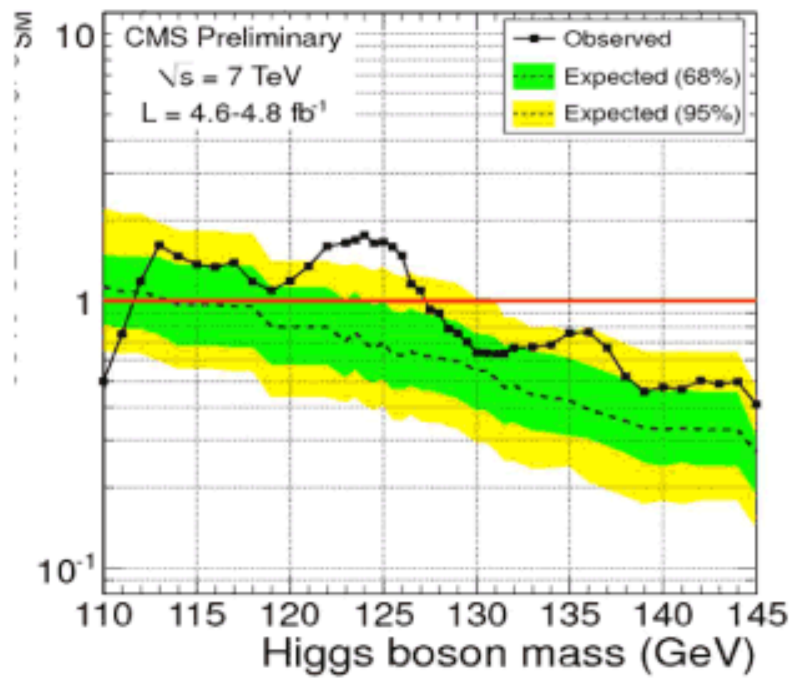
- Huge number of collisions
  Data analysis
- World Wide Web (1992)
  Platform for sharing data
- Grid (2012)
  Distributed computing
- World-wide network
- Huge increase in computing power





Higgs search at LHC (Dec. 2011)

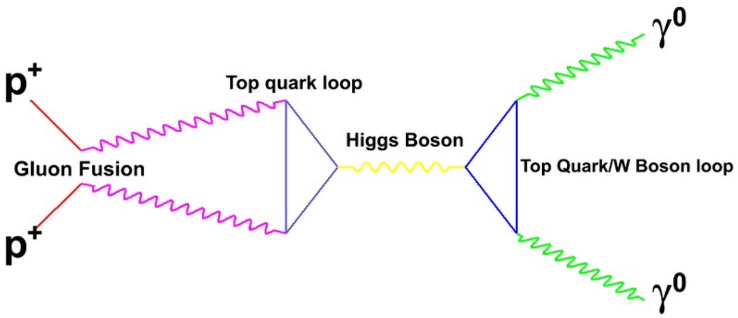


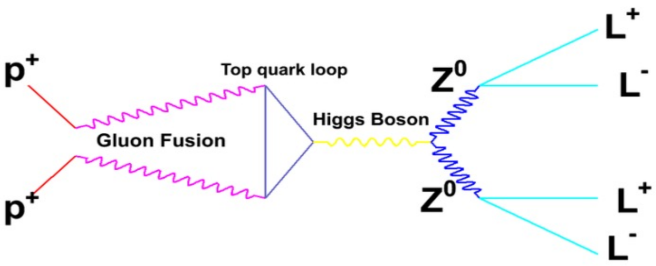


Excess events at 125 GeV in ATLAS and CMS detectors

Higher luminosity required (4.8 fb^{-1} at that time)

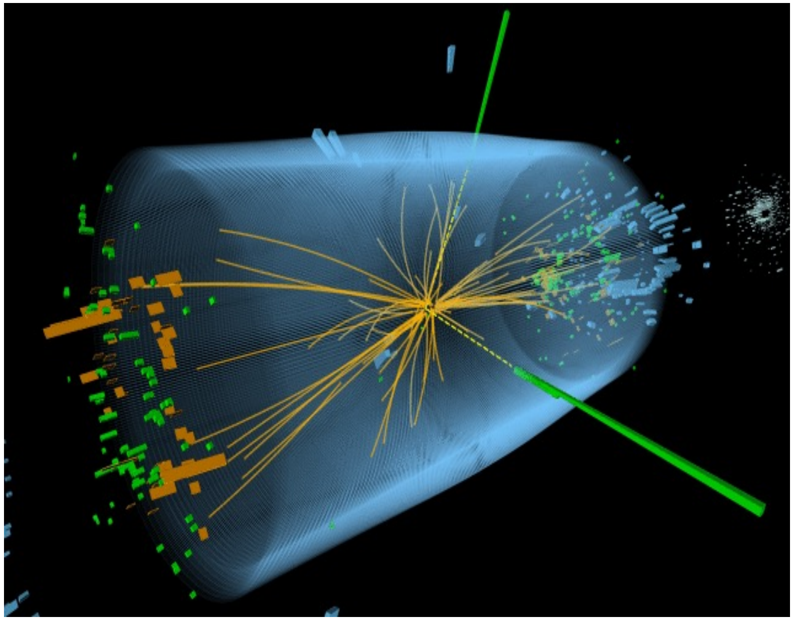
April-July 2012: add *5.9* fb^{-1} at *8 TeV*

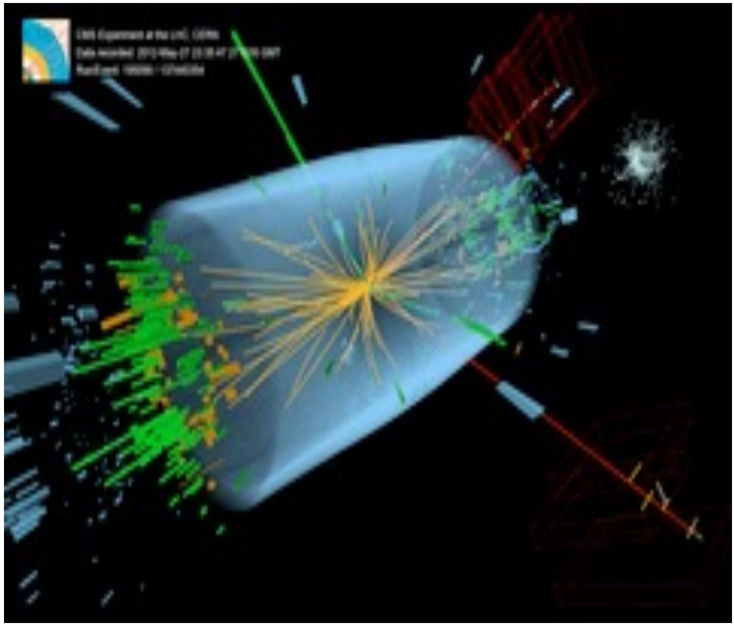




Measure energy of photons emitted

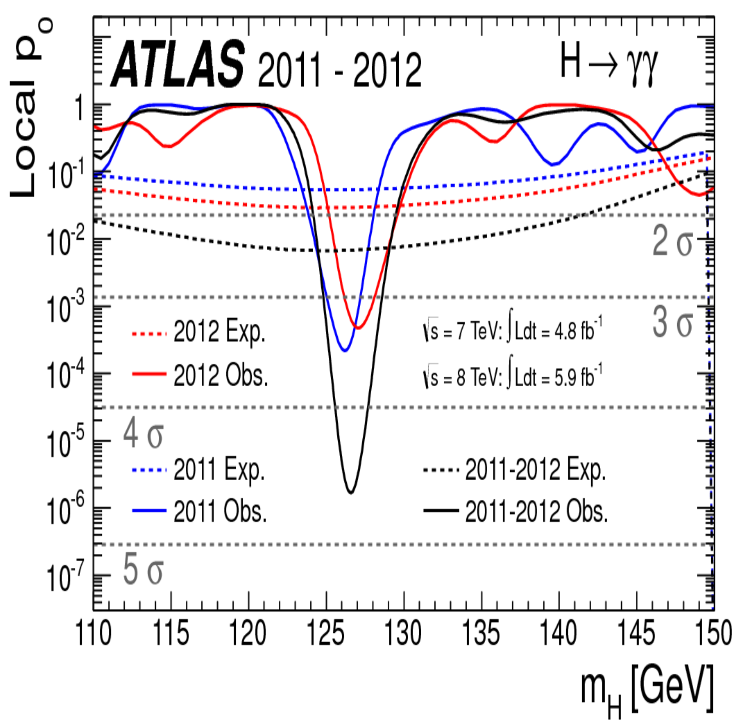
Measure decay products of Z bosons

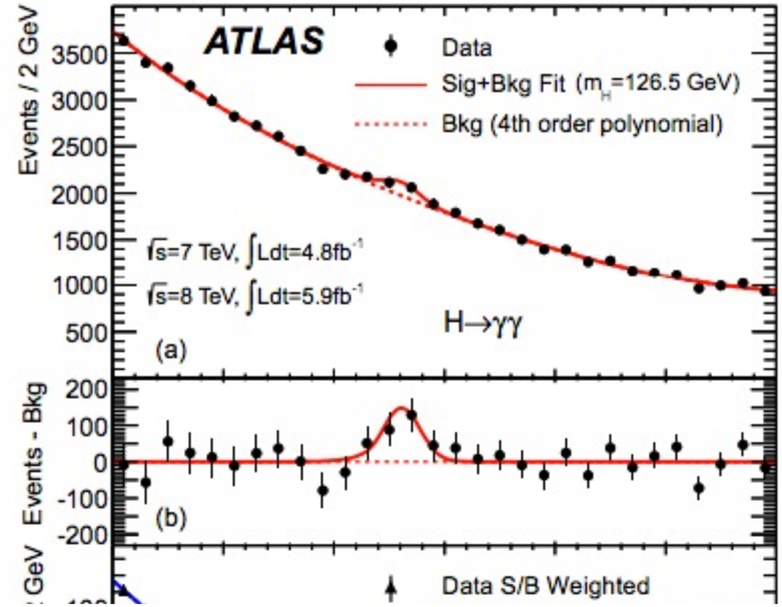


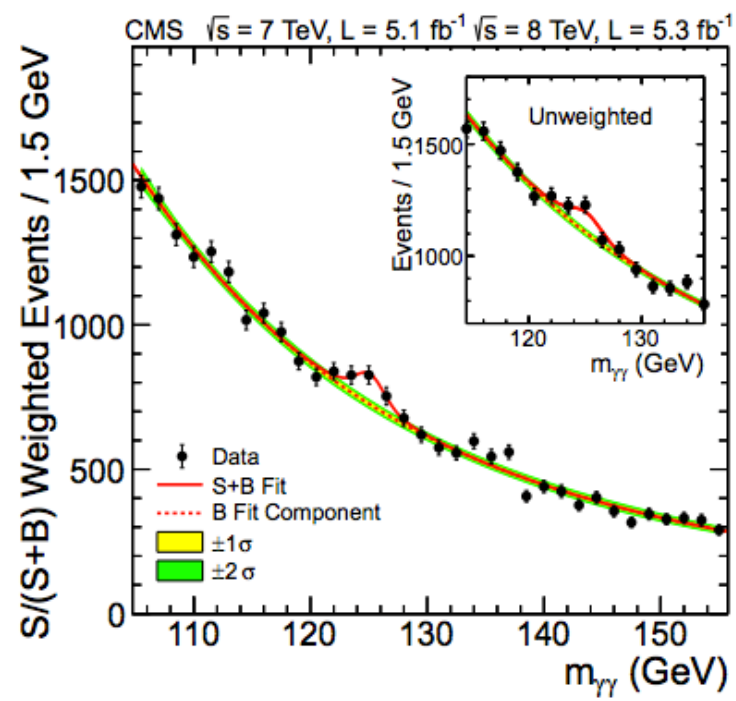


Results (July, 2012)

H→ γγ (*7 TeV,* 4.8 fb^{-1} + *8 TeV,* 5.9 fb^{-1})

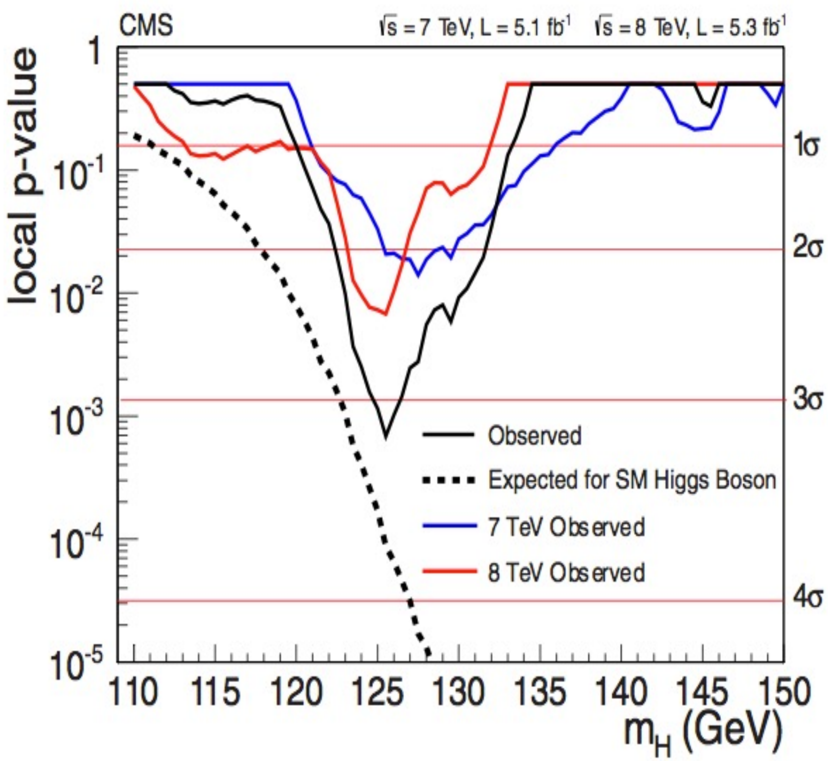


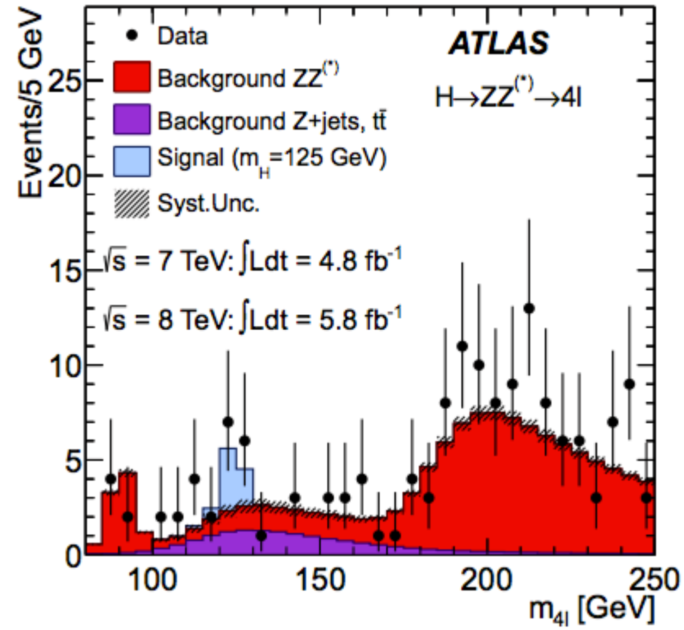


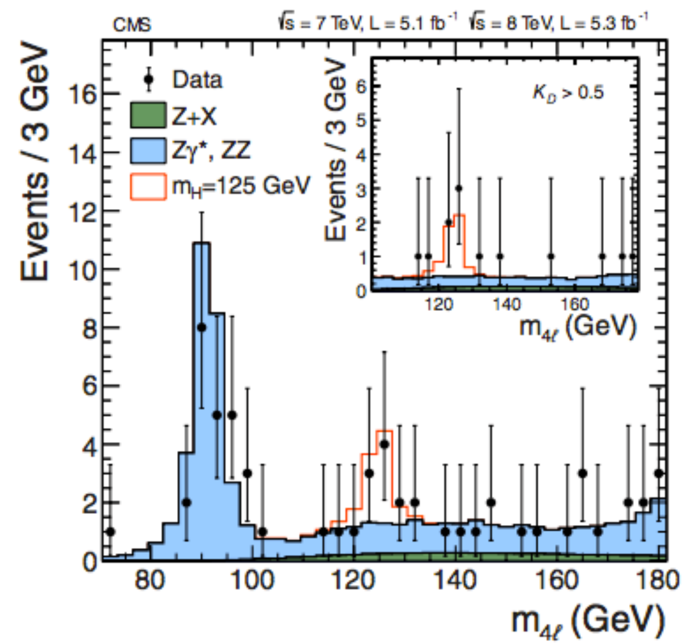


Results (July, 2012)

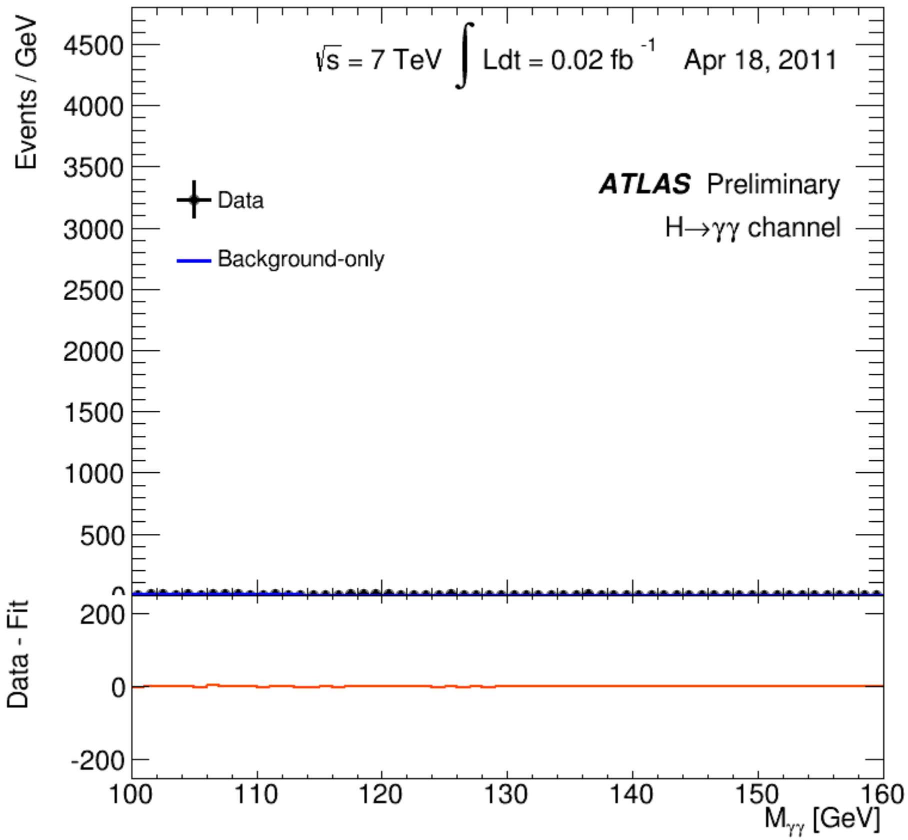
H→ZZ (8 TeV, 5.3 fb^{-1})

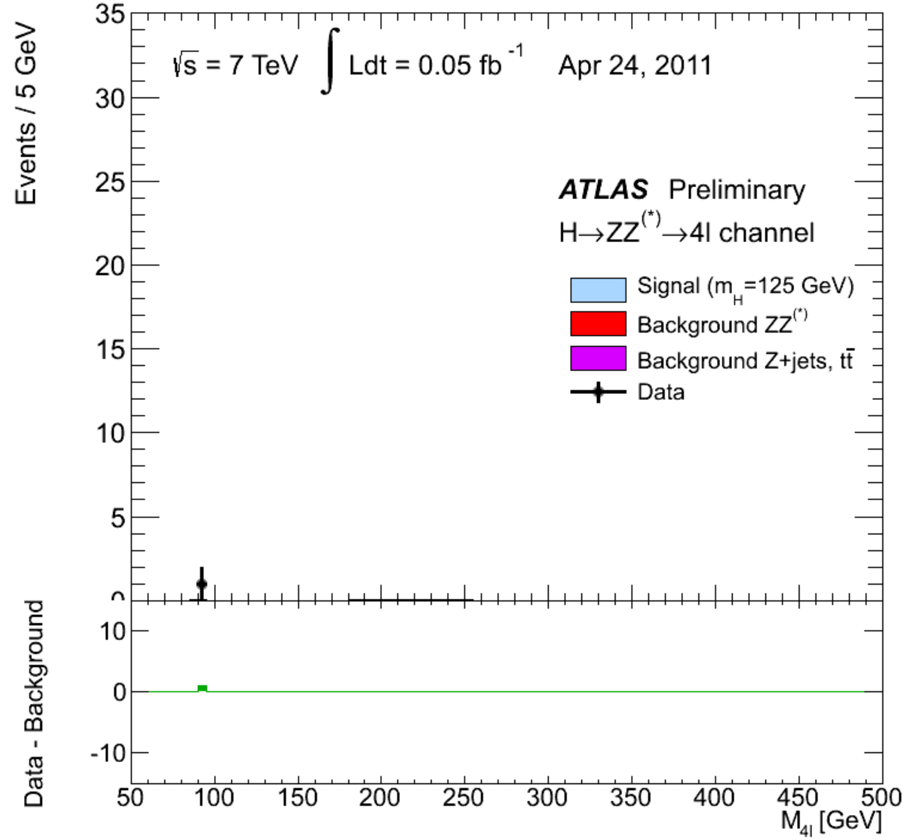




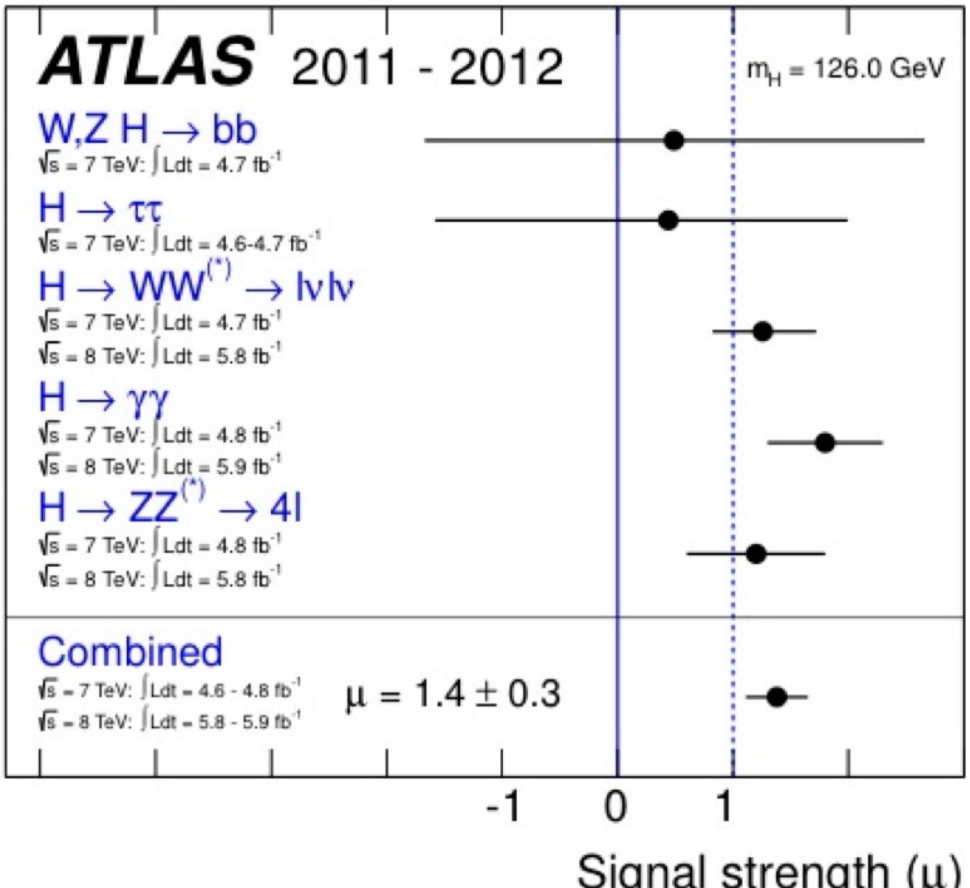


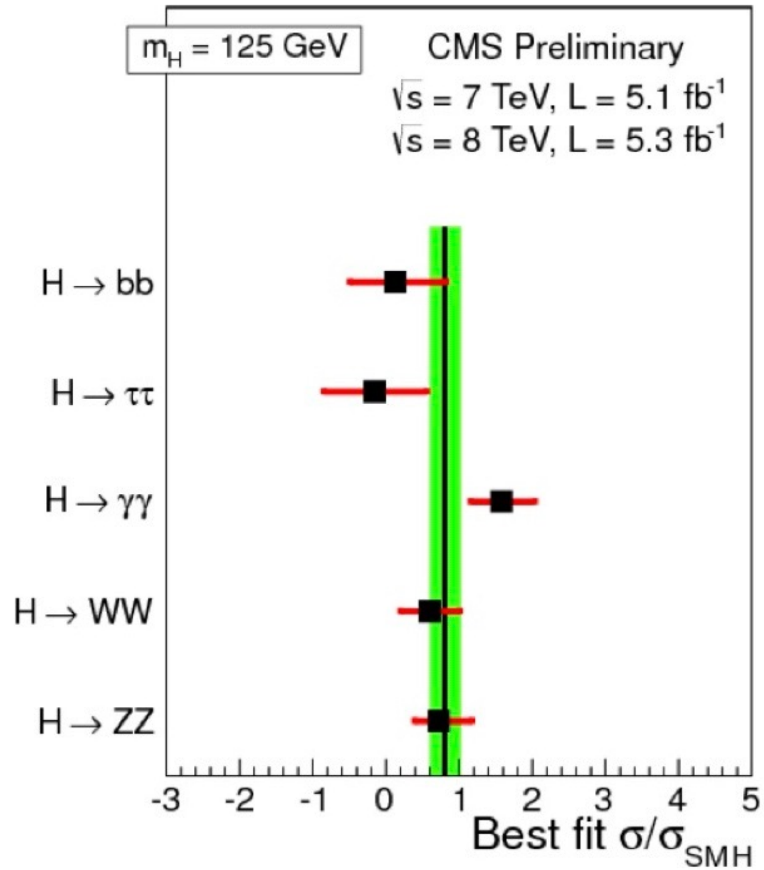
Add new data from late 2012 (8 TeV)





Results: all decay channels

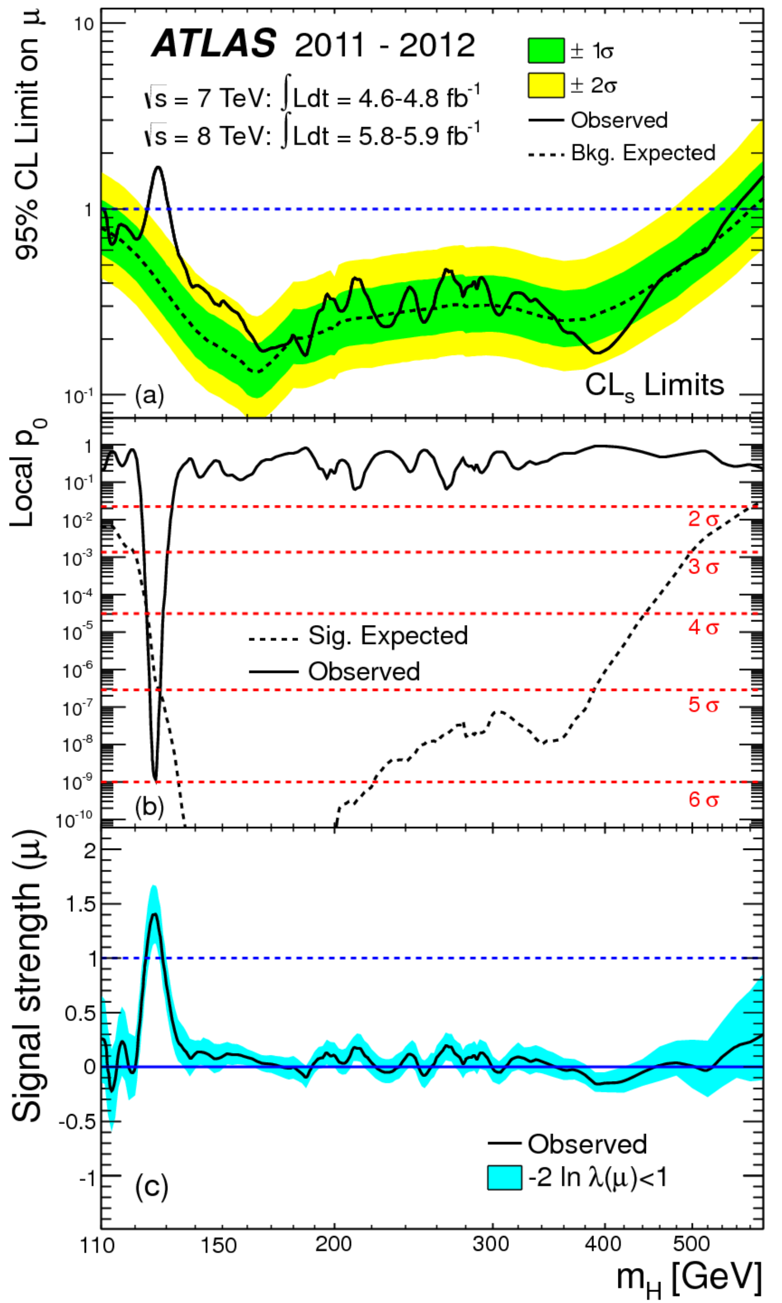




Results summary

- New particle
- Mass 126 +/- 0.5 GeV
- Zero charge
- Integer (zero or two) spin (is it zero?)
- Scalar boson
- 6 sigma signal (August, 2012)

__Higgs boson?!__

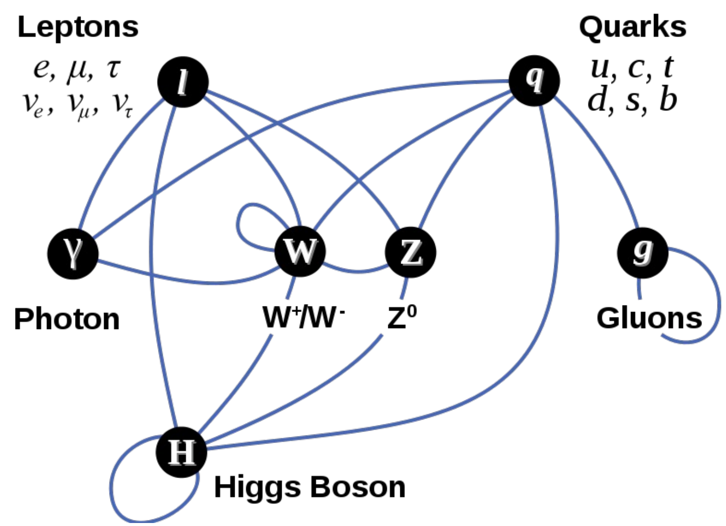


IV Next at the LHC

- **Characterization of new boson**
  Branching ratios, spin
  Deviations from theory?

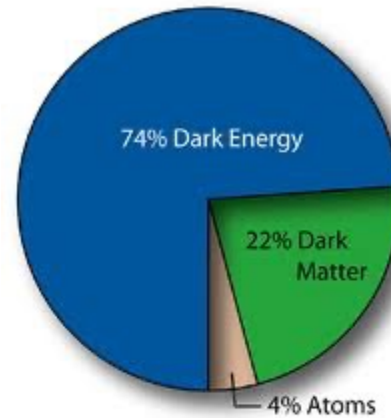
- **<u>Supersymmetry</u>**
  Numerous Higgs?
  Supersymmetric partner particles
  Implications for unification

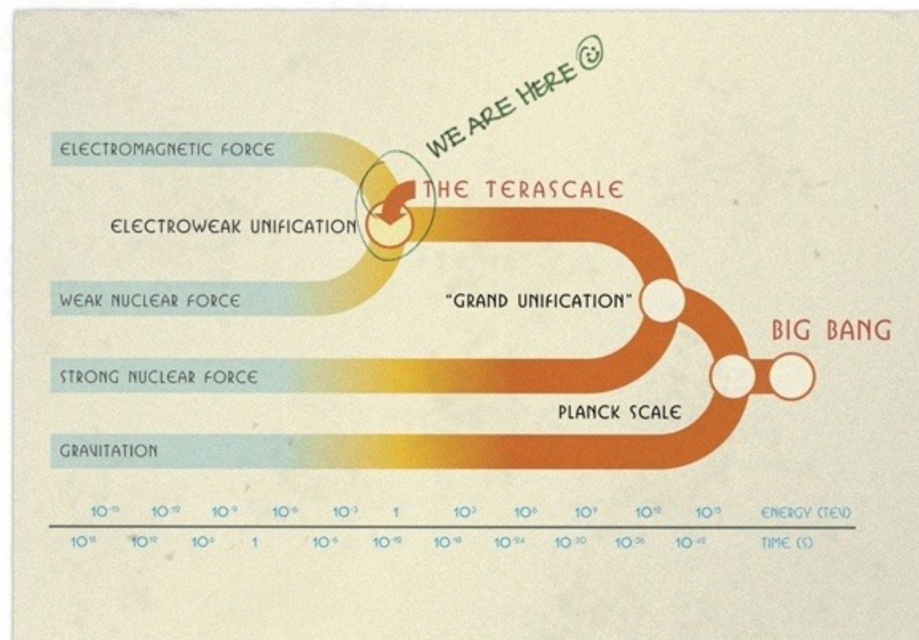
- **<u>Cosmology</u>**
  Dark matter particles?
  Dark energy?
  Higher dimensions?



Cosmology at the LHC

- **Snapshot of early universe**
  Highest controlled energy density since BB
- **Dark matter particles?**
  Neutralinos (supersymmetry)
- **Dark energy ?**
  Scalar field
- **Higher dimensions?**
  Kaluza Klein particles
- **String theory?**



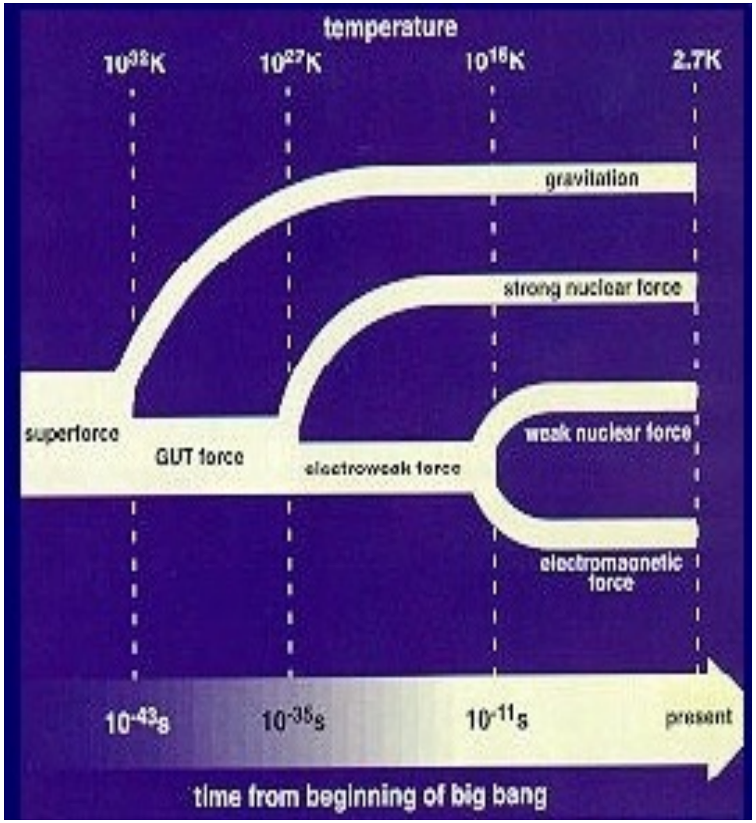


Summary (2019)

- New particle detected at LHC
- Mass 125.1 ± 0.2 GeV
- Zero charge, zero spin
- **<u>Appears</u>** <u>**(so far, at the O(5% – 10%) level…) consistent with Standard Model Higgs boson**</u>

  Appears (so far) to be confirmation of electroweak unification
- Fundamental particle theory right so far

En route to a theory of everything ?



Space Expands

Edwin Hubble
1929

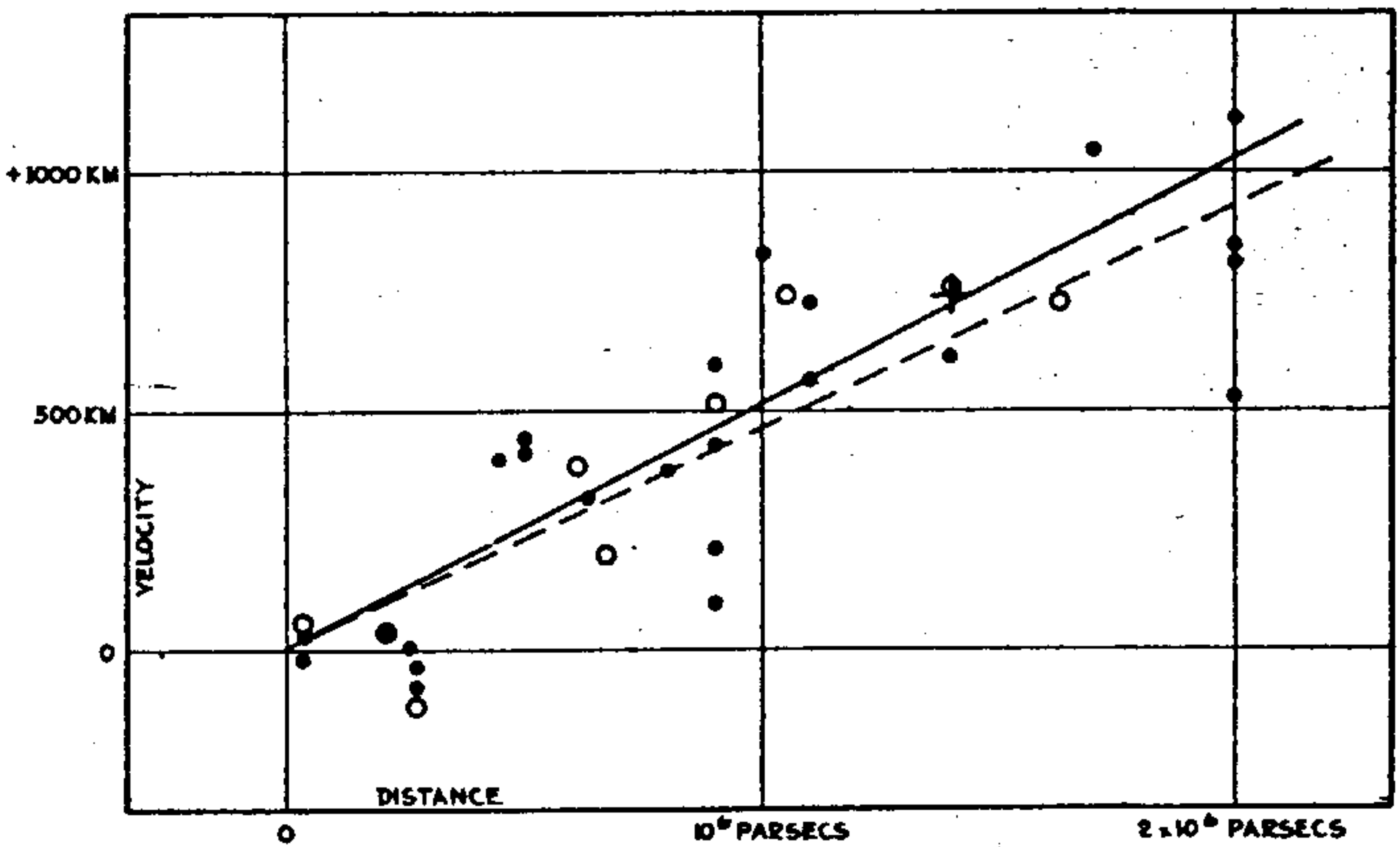
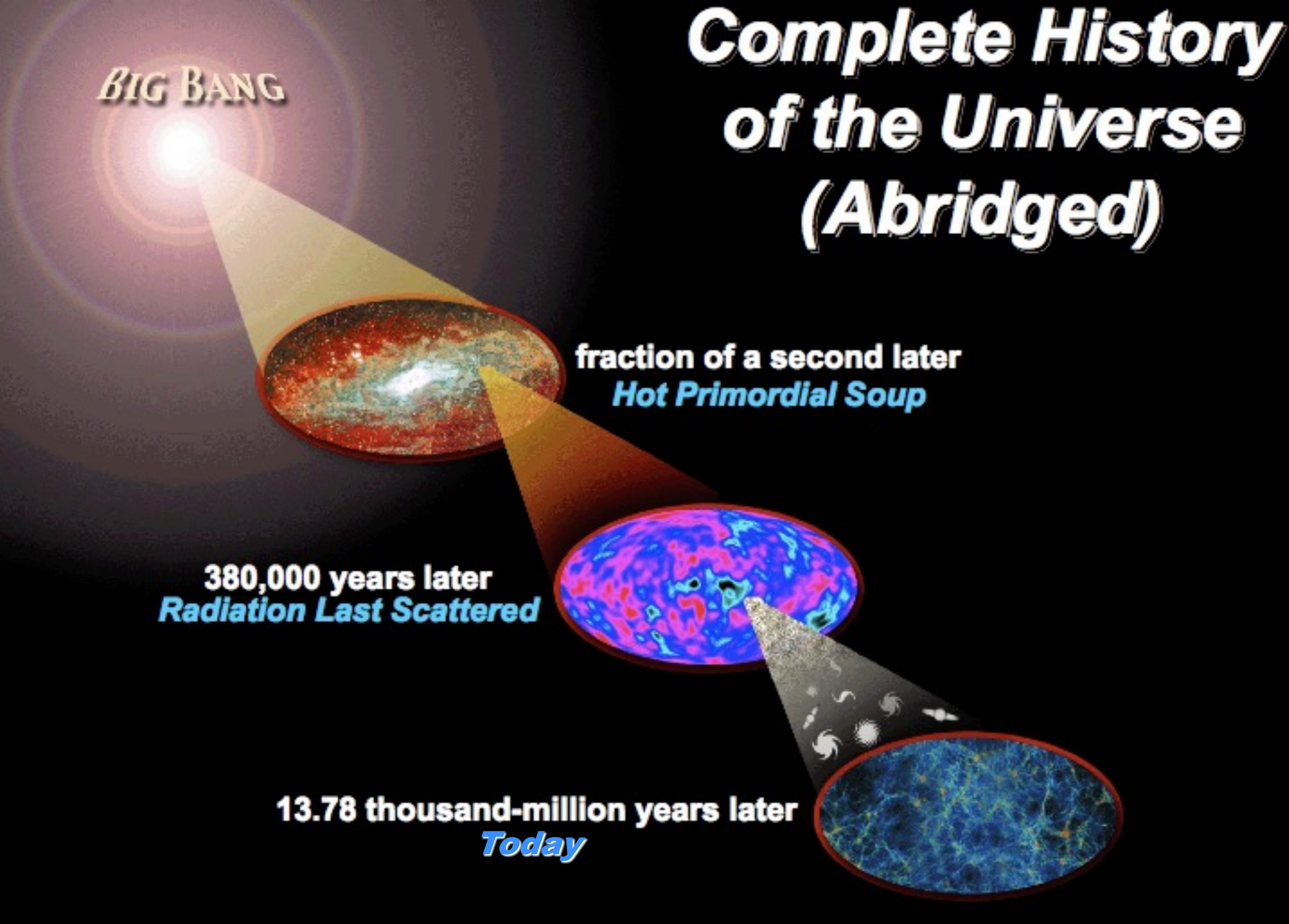

+1000 KM
500 KM
0
VELOCITY
DISTANCE
0
10^6 PARSECS
2×10^6 PARSECS

FIGURE 1

The Universe Is Radiant

Penzias & Wilson 1965

Temperature of the Universe is 3K (–270C)


Complete History of the Universe (Abridged)
BIG BANG
fraction of a second later
Hot Primordial Soup
380,000 years later
Radiation Last Scattered
13.78 thousand-million years later
Today

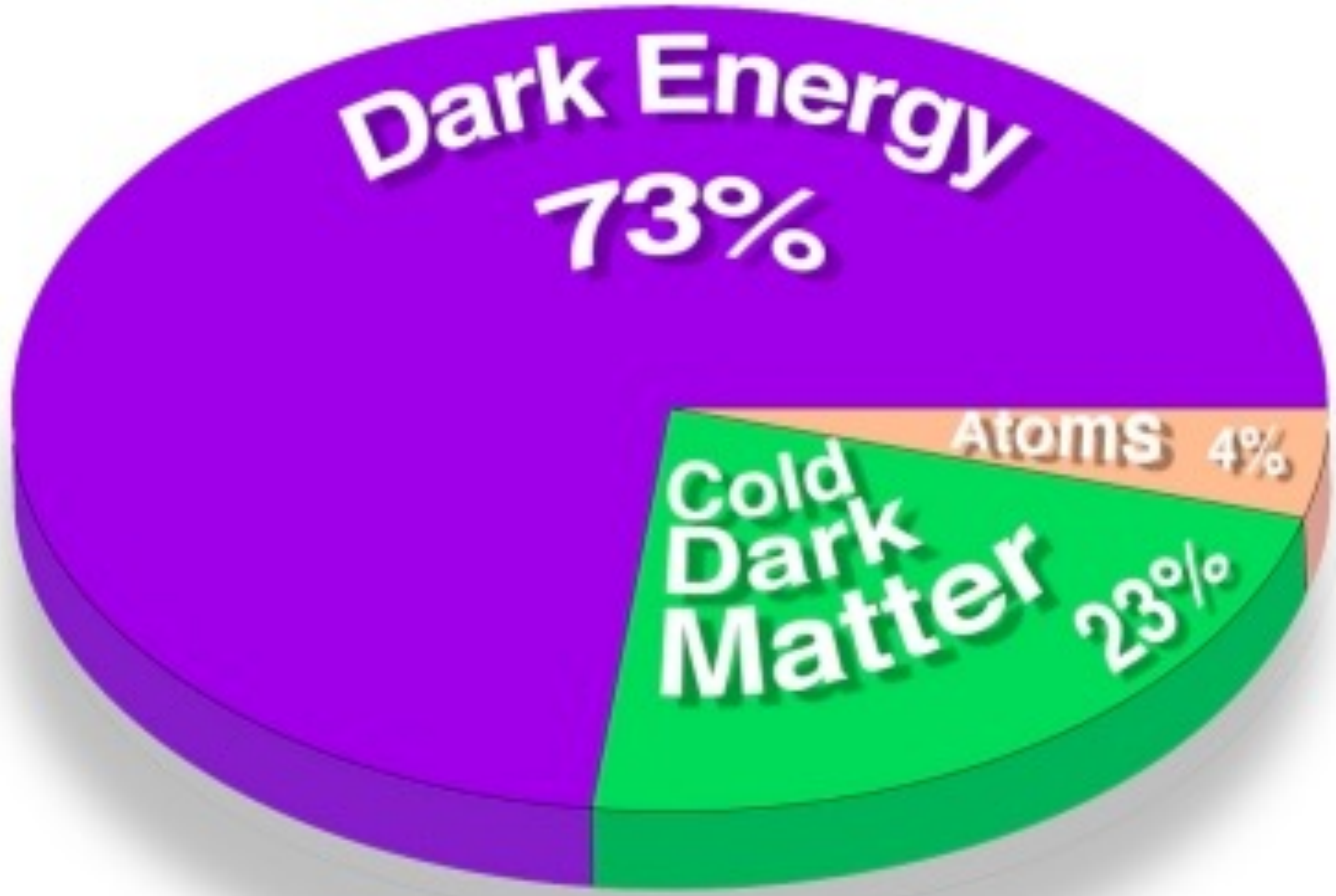
Composition

Hubble Ultradeep Field

10,000 galaxies →

50 thousand million visible to HST over entire sky

We live in a Universe of galaxies

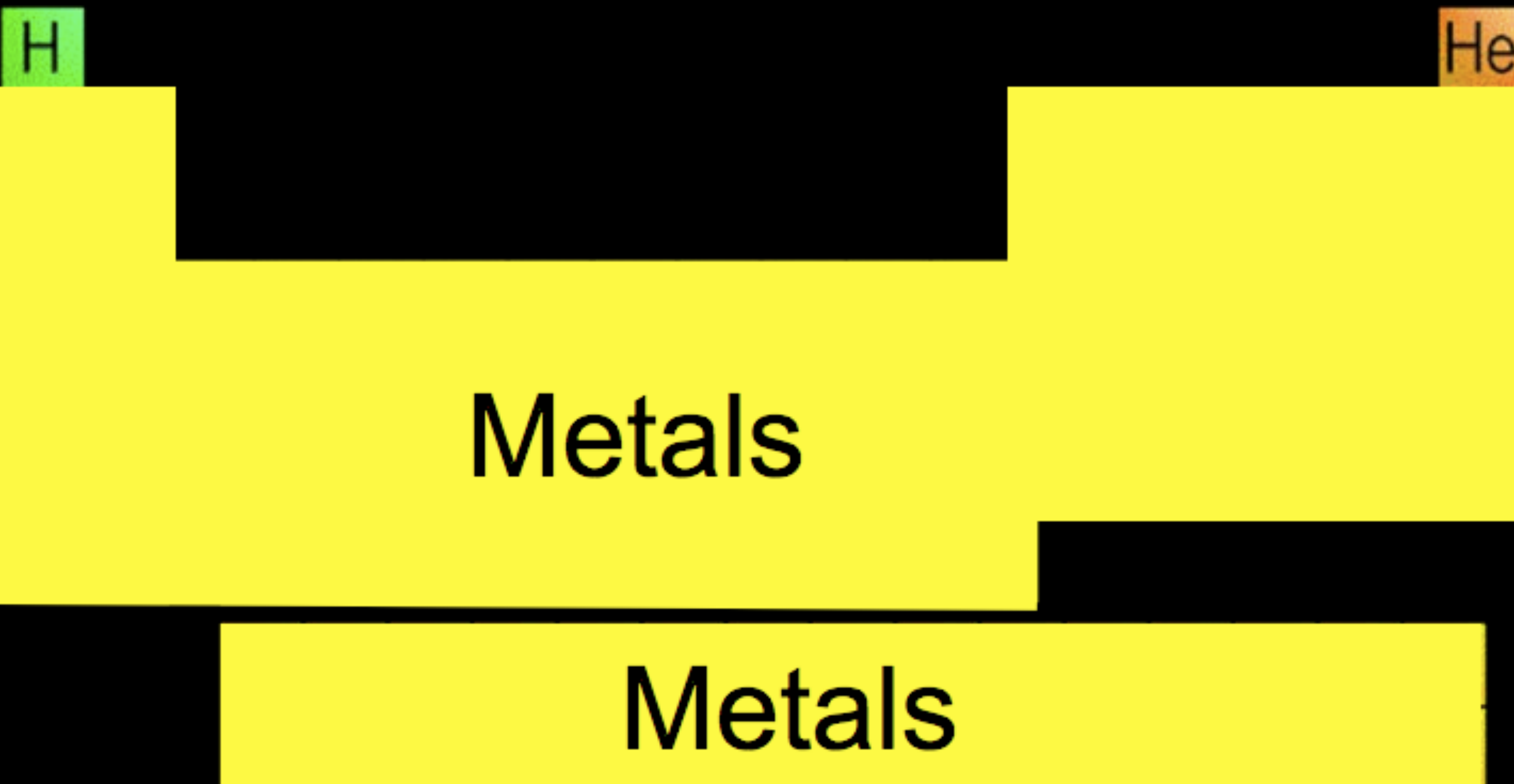

Dark Energy
73%
Atoms 4%
Cold
Dark
Matter
23%

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



Visible Matter

Today:

73% Hydrogen (10^{-5} deuterium)
26% Helium (10^{-5} ^{3}He)
1% Metals

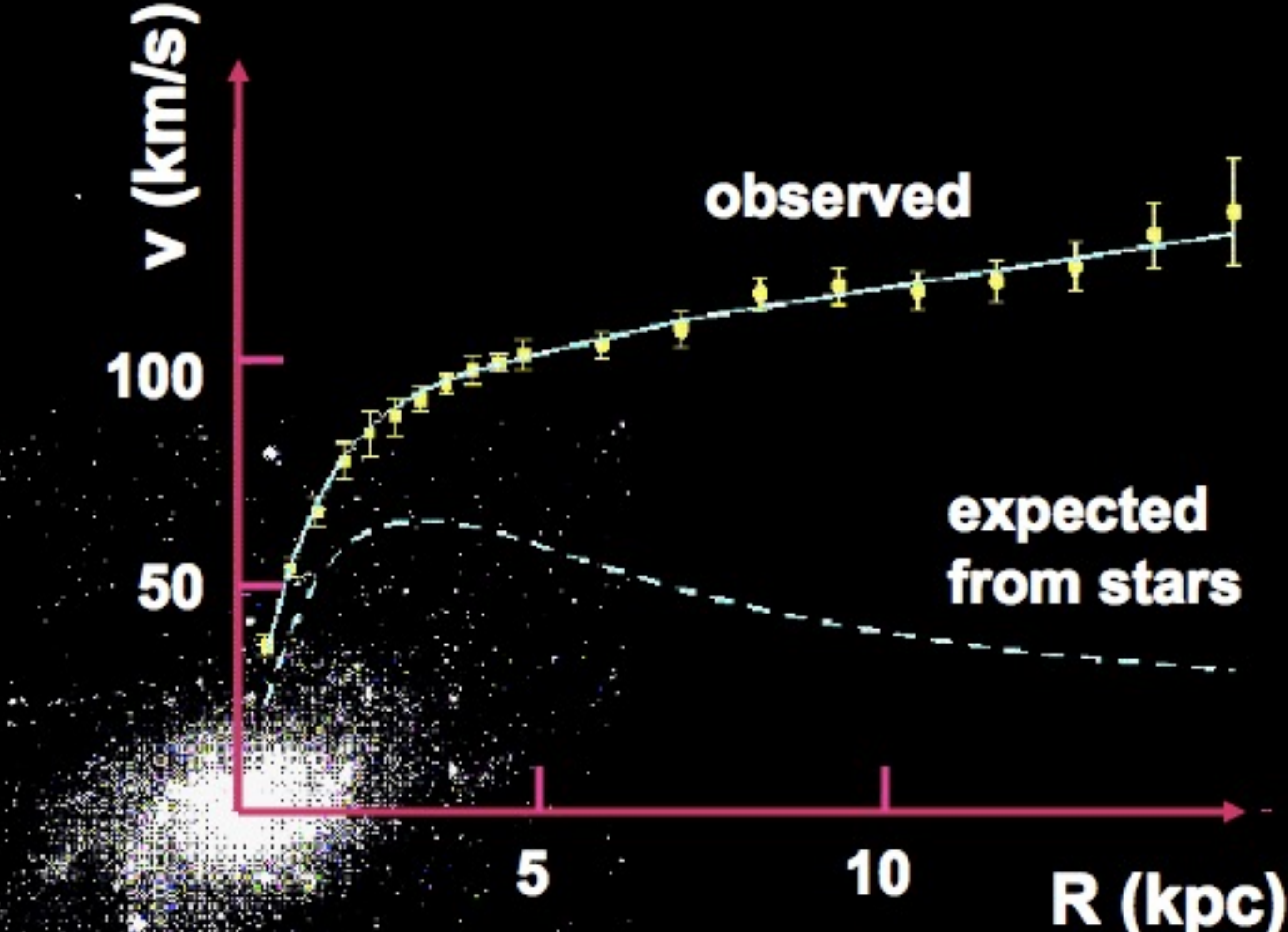
Three minutes AB:

76% Hydrogen (10^{-5} deuterium)
24% Helium (10^{-5} ^{3}He)
10^{-8}% Lithium

The Visible Universe

The Invisible Universe

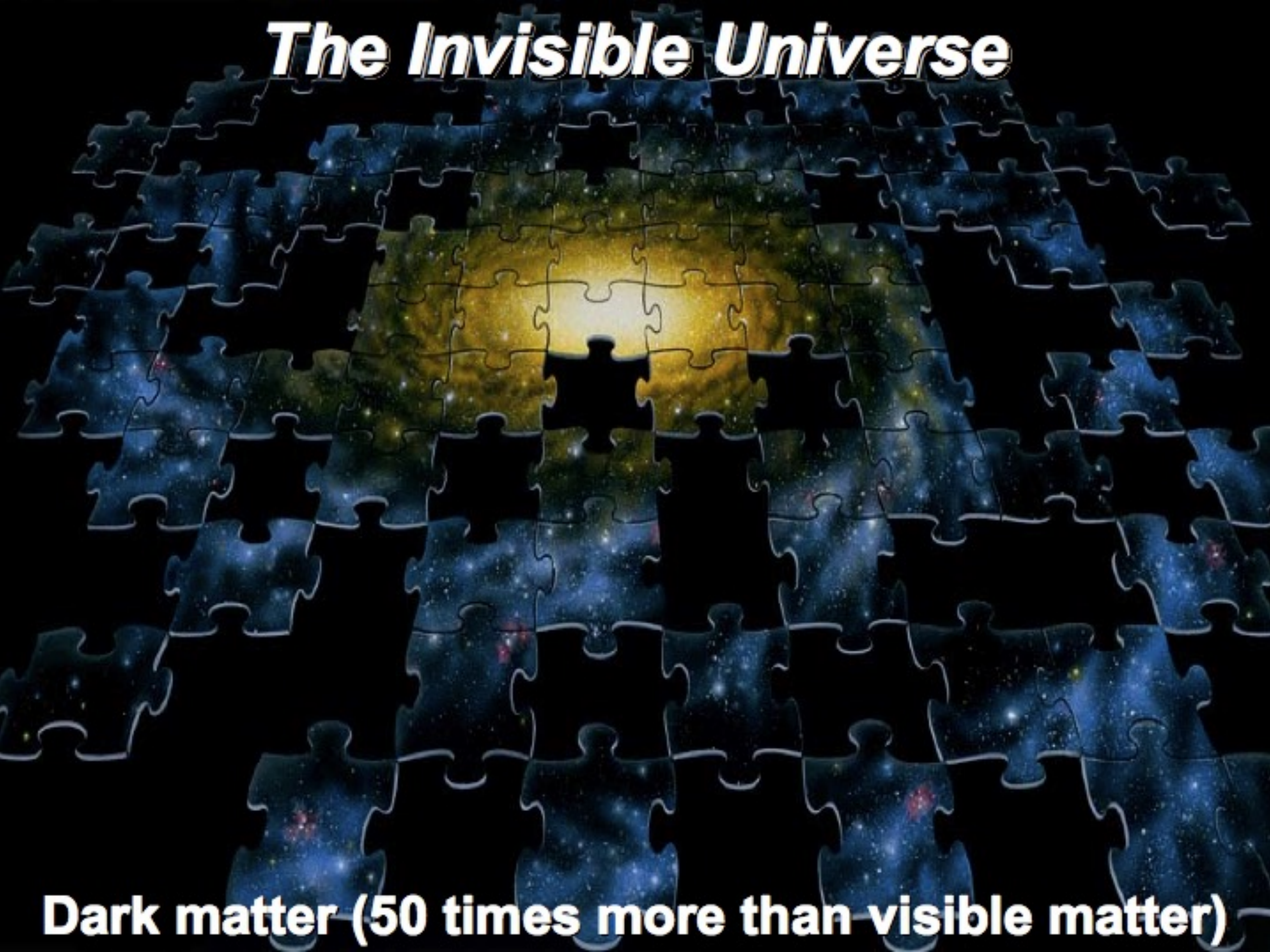
Vera Rubin



M33 rotation curve

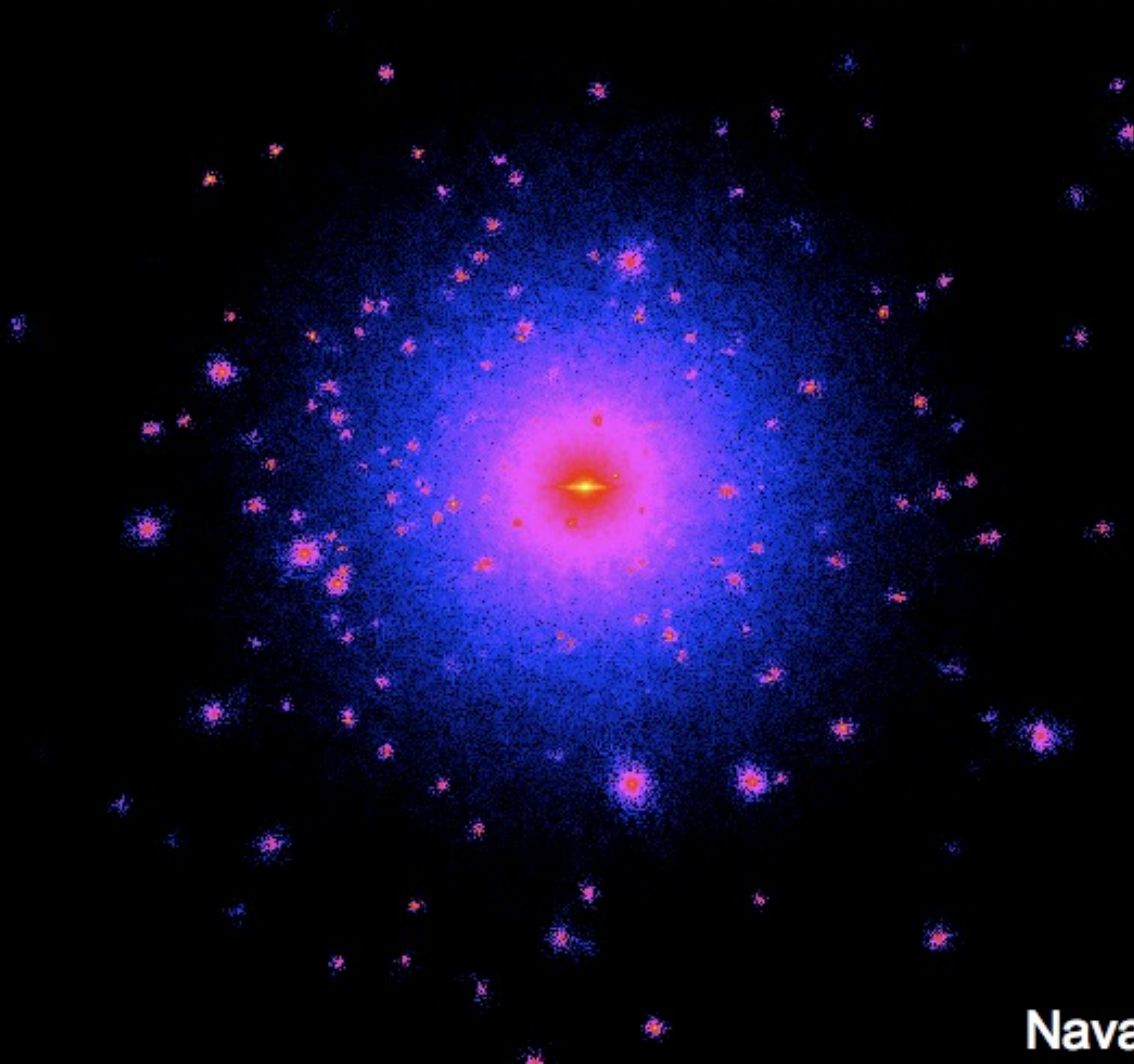

The Invisible Universe
Abel 2218 HST

The Invisible Universe



Dark matter (50 times more than visible matter)

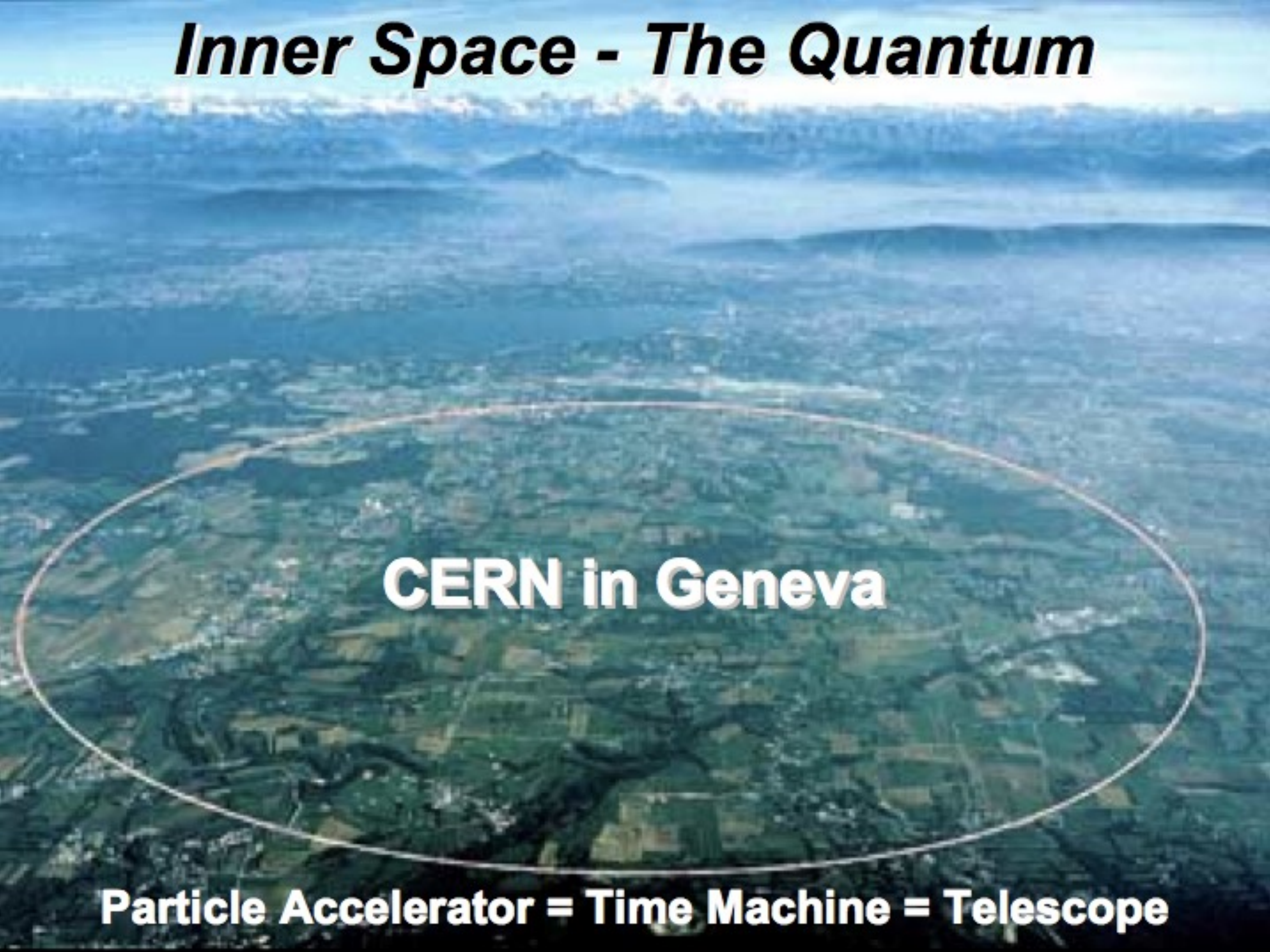
If We Could "See" Dark Matter



Navarro, et al.

Dark Matter?

- Newton's (or Einstein's) law of gravity is wrong
- MACHOS (massive astronomical compact halo objects)
  - planets
  - dwarf stars (white, red, brown)
  - black holes
- WIMPS (weakly interacting massive particles)
  - a new type of particle relic from the big bang


Inner Space - The Quantum
CERN in Geneva
Particle Accelerator = Time Machine = Telescope

Large Hadron Collider (LHC)

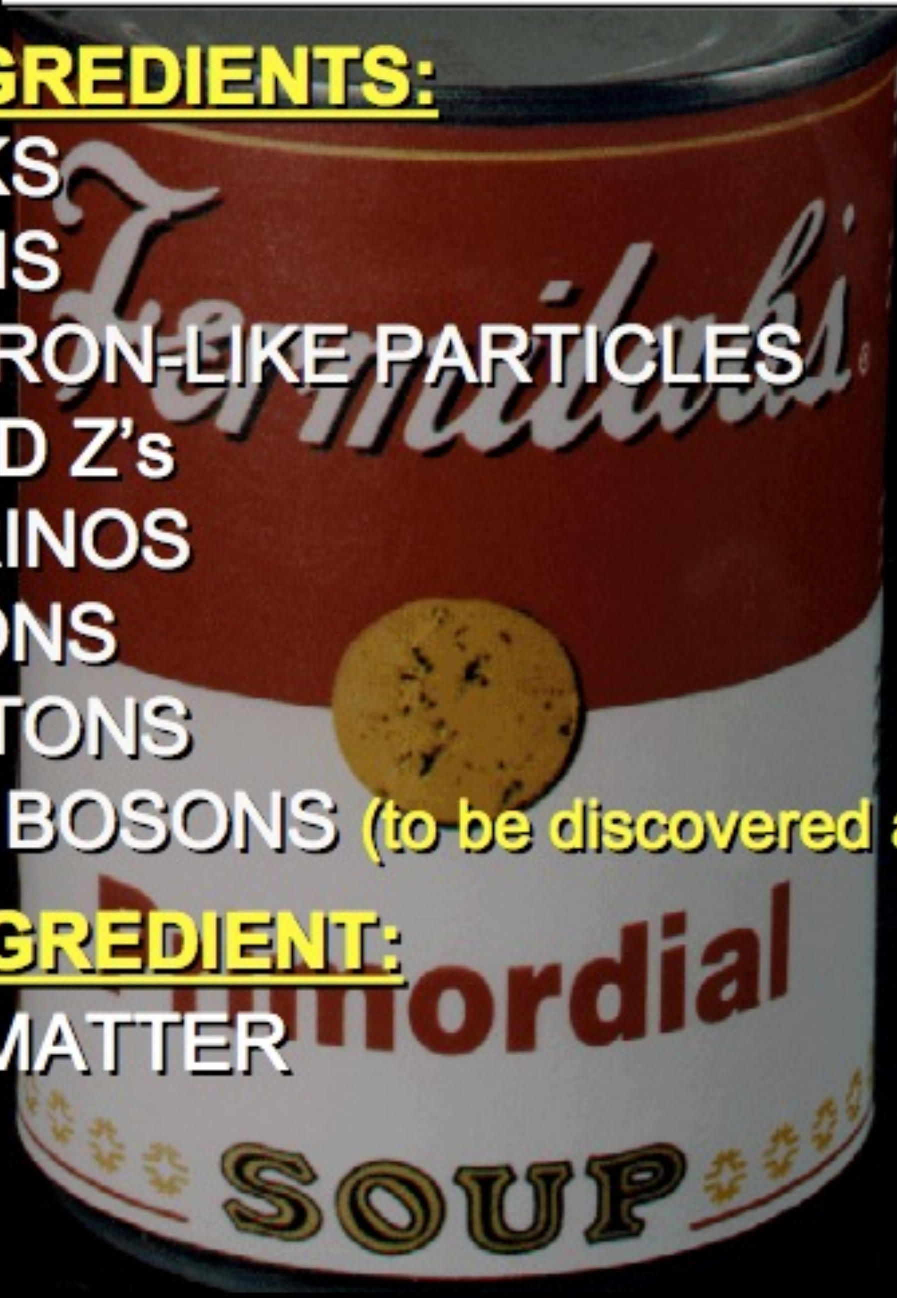
Primordial Soup

KNOWN INGREDIENTS:

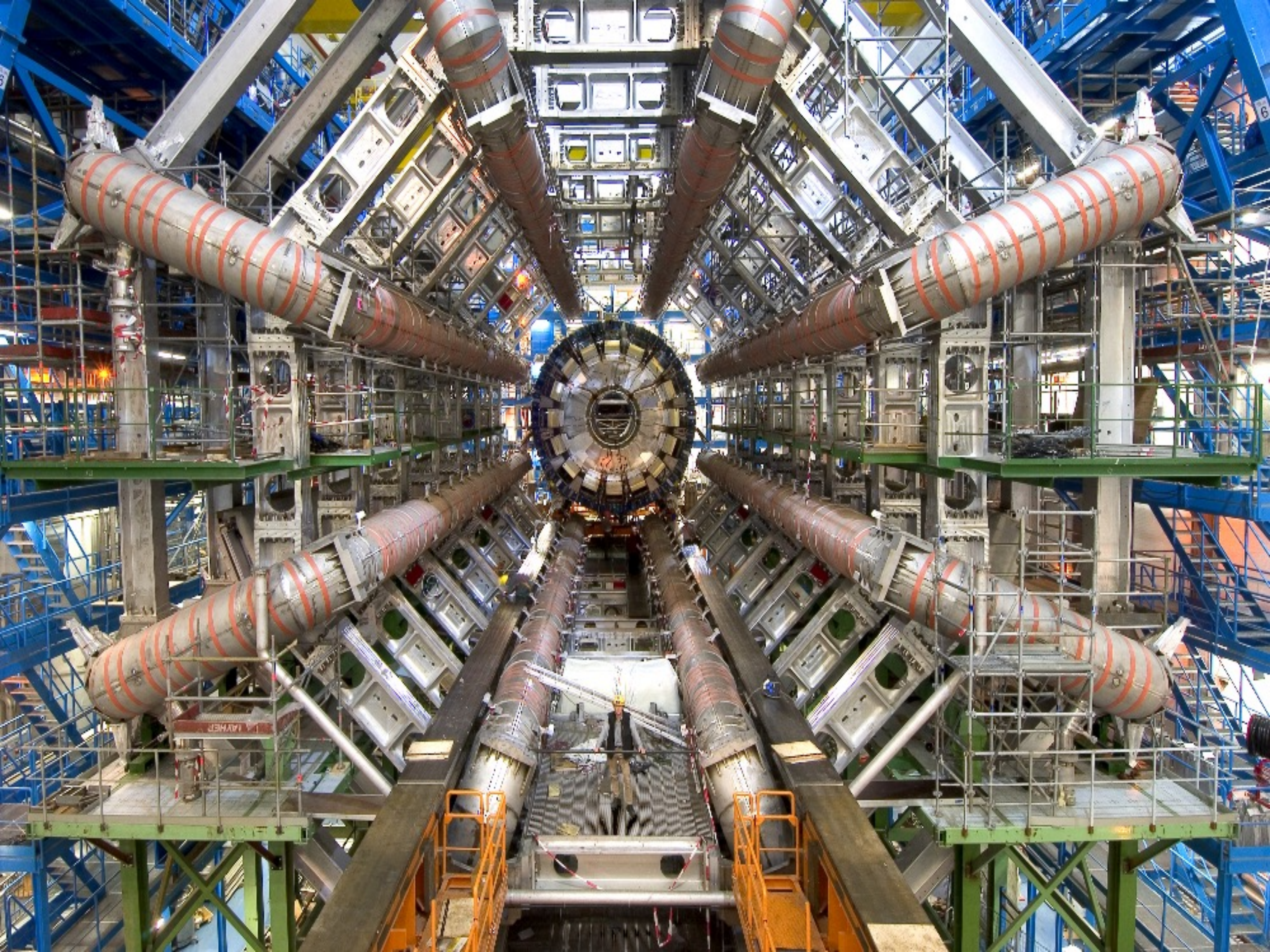
56% QUARKS
16% GLUONS
9% ELECTRON-LIKE PARTICLES
9% W's AND Z's
5% NEUTRINOS
2% PHOTONS
2% GRAVITONS
1% HIGGS BOSONS (to be discovered any day)

SECRET INGREDIENT:

DARK MATTER



Make WIMPS in the Laboratory



Yet More To The Dark Side

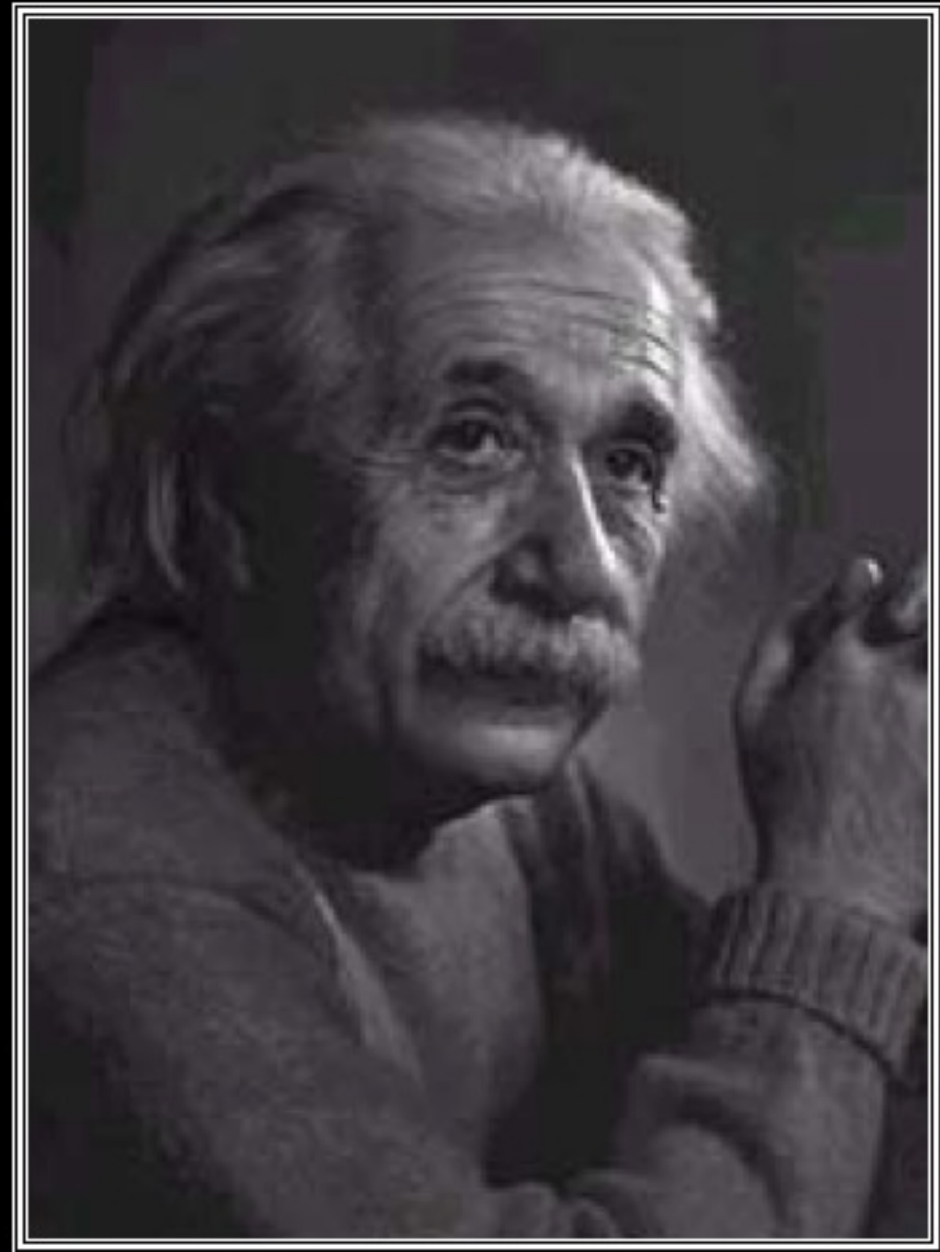
Dark Energy

<u>1917</u> Einstein proposed cosmological constant.

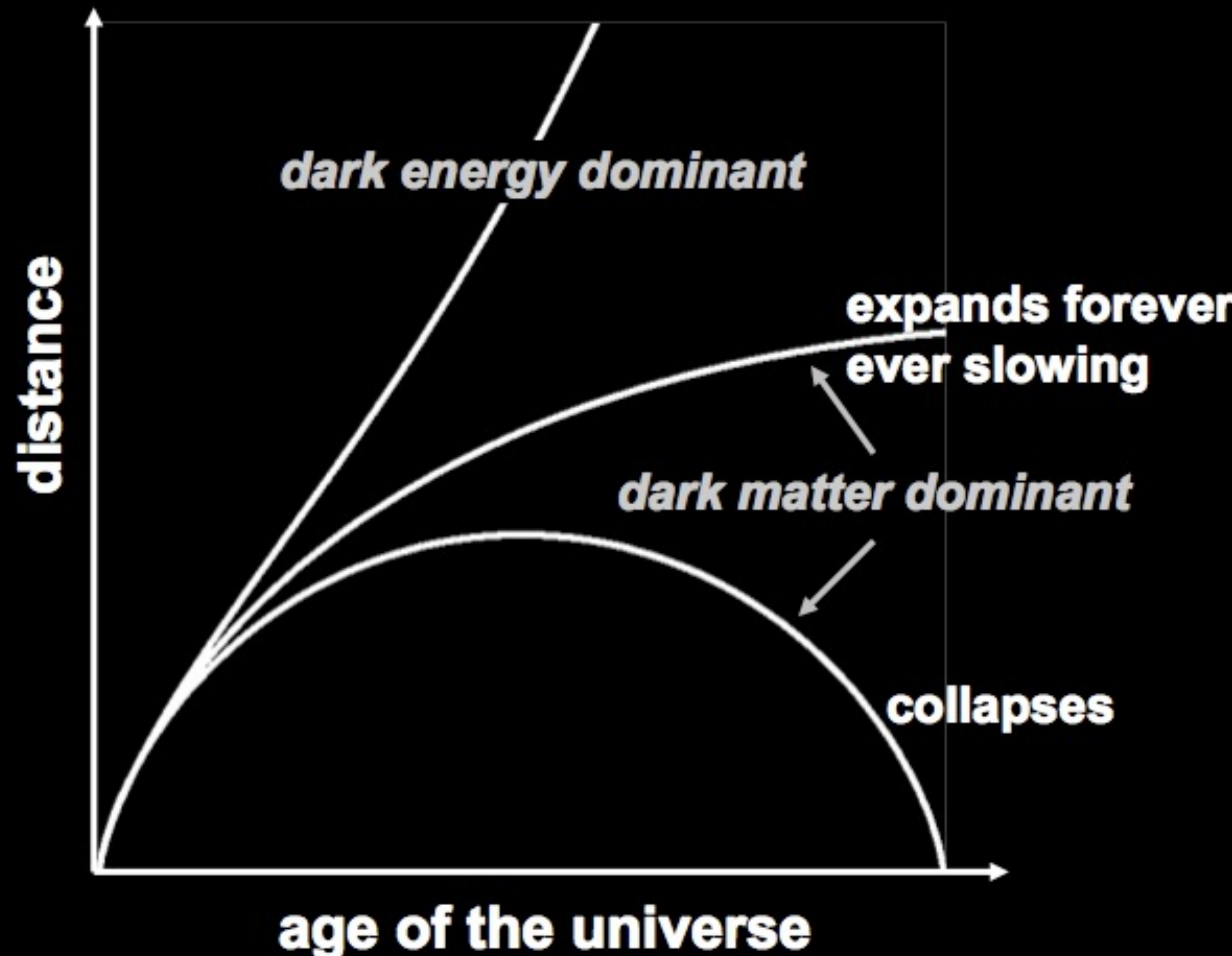
<u>1929</u> Hubble discovered expansion of the Universe.

<u>1934</u> Einstein called it "my biggest blunder."

<u>1998</u> Astronomers found evidence for it.



The Dark Side of the Universe



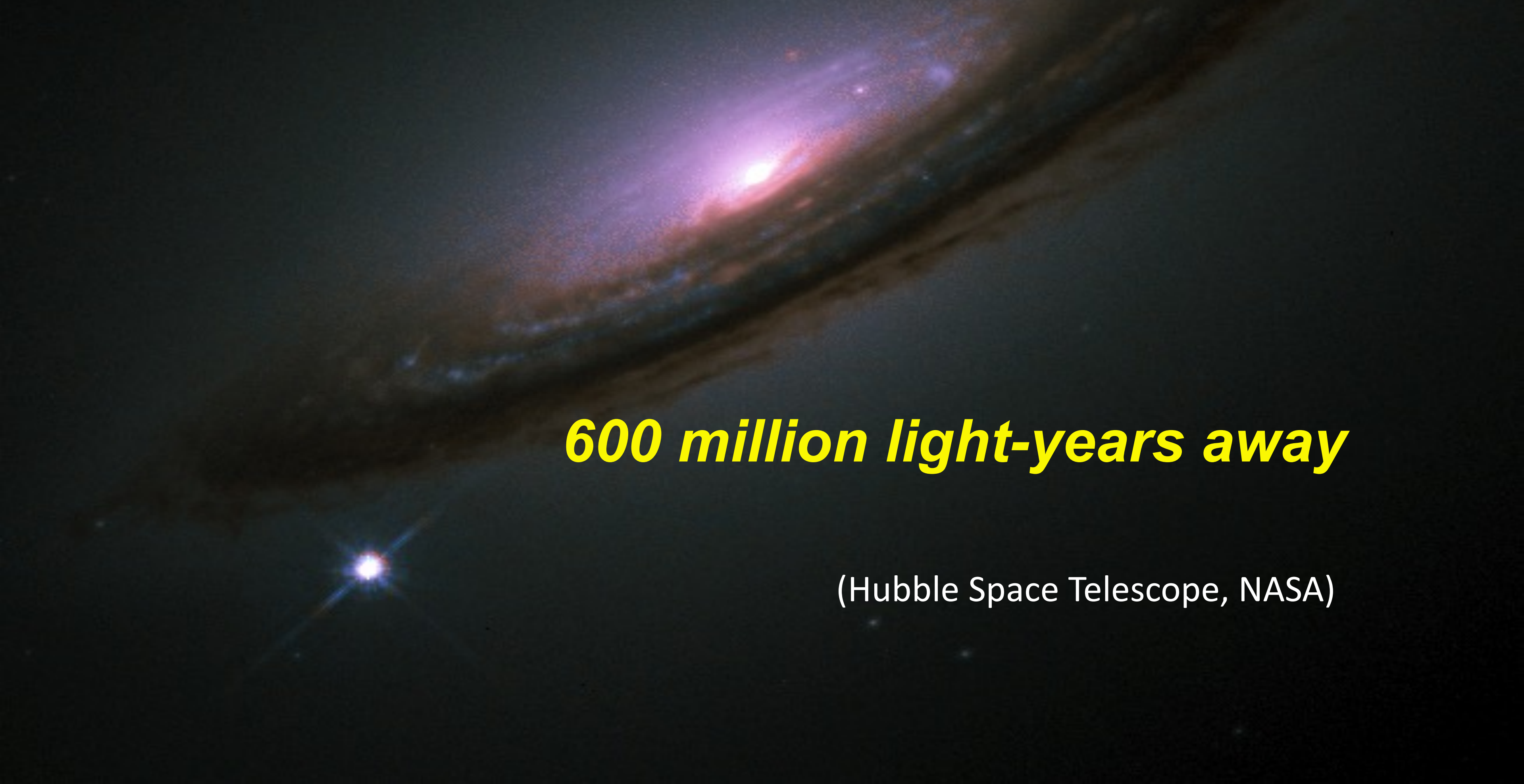
Unbearable Lightness of Nothing

10^{-30} grams per cc

Supernovae are one of the powerful probes for understanding the eventual fate of the Universe

Distances to ~6% from brightness

Redshifts from features in spectra



600 million light-years away

(Hubble Space Telescope, NASA)

Cosmic Arithmetic

General Relativity, isotropy, and homogeneity require that (in the relevant units)

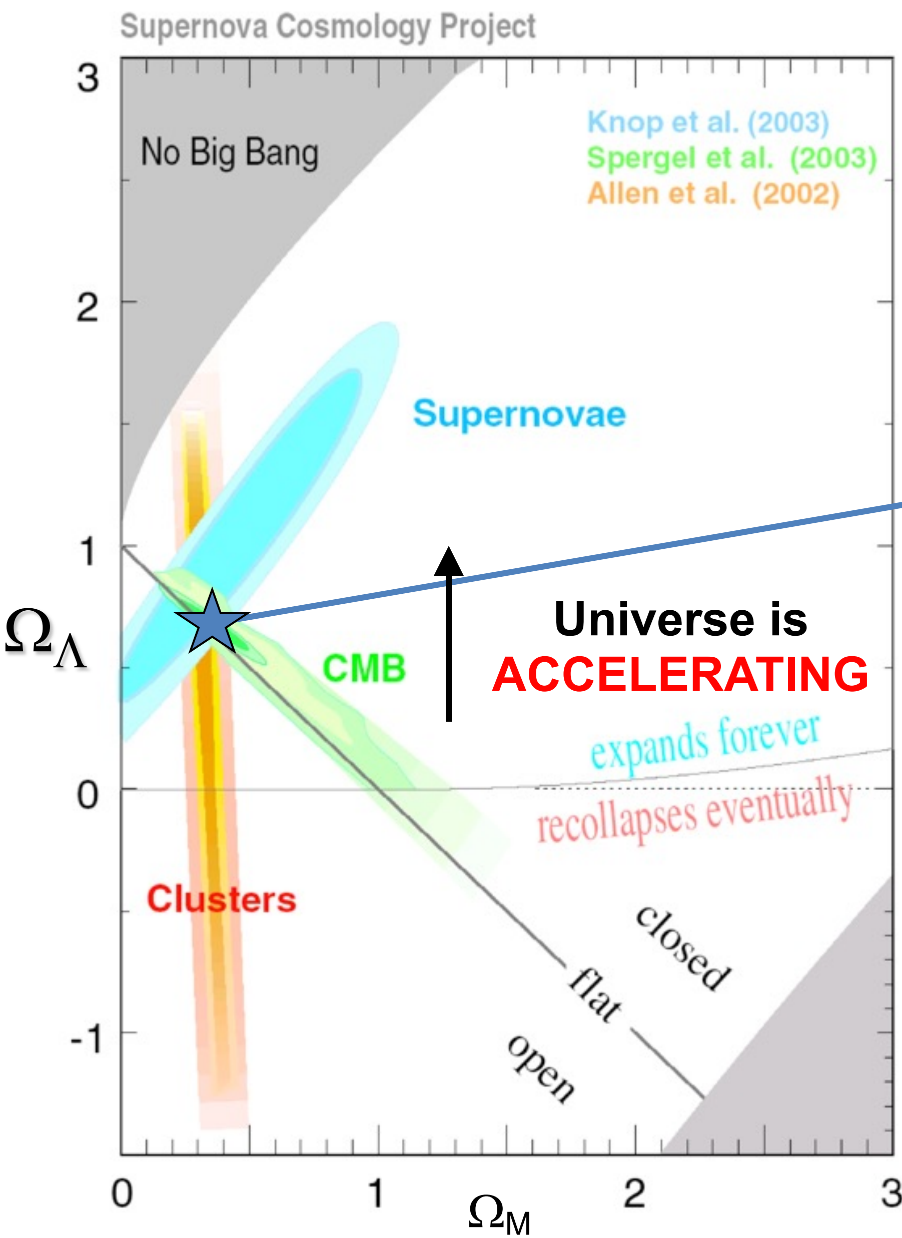
$$\boxed{\Omega_{\text{geometry}} + \Omega_{\text{matter\&radiation}} + \Omega_{\Lambda} = 1}$$

If the underlying geometry is flat ($\Omega_{\text{geom}} = 0$), & if $\Omega_{\text{m\&r}} < 1$ then Ω_{Λ} ("cosmological constant term") *must* be non-zero.

Cosmic microwave background (CMB) measurements demonstrate the geometry is flat, $\Omega_{\text{geometry}} = 0$.

Mass inventories fall short of $\Omega_{\text{matter\&radiation}} = 1$

($\Omega_{\text{matter}} \approx 0.3$, and the radiation contribution is tiny)



Insufficient mass to halt the expansion…

“Best Fit”
at
$\Omega_{mass} \sim 0.3$
$\Omega_\Lambda \sim 0.7$

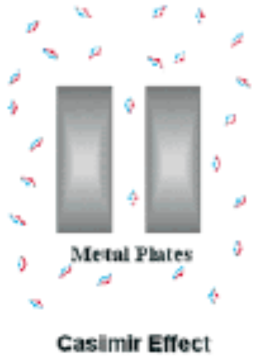
Rate of expansion is increasing…

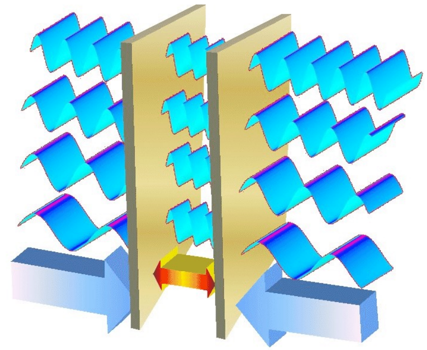
<u>What does this mean?</u>

A Perplexing Result

- Expansion of Universe is *accelerating*!(?)
- Implies something new: "Dark Energy"
- <u>Regions of empty space *repel* each other!</u>
  - "Cosmological constant"…

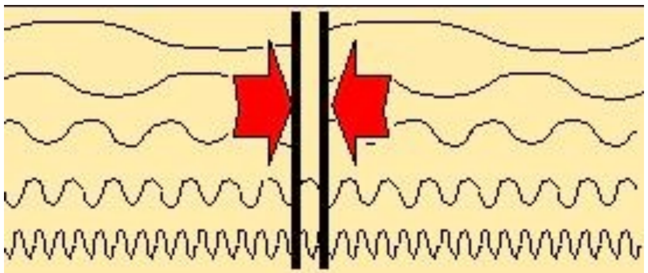
    Einstein's greatest blunder?
  - **What's going on in the vacuum?**

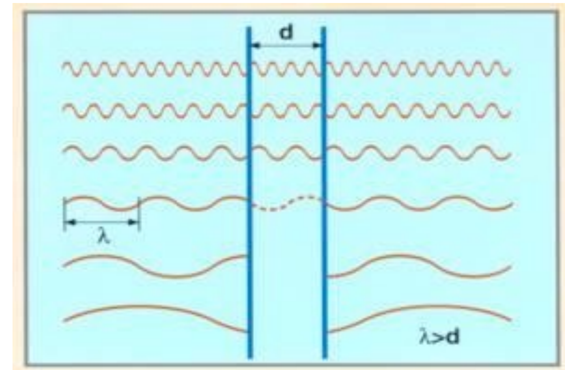




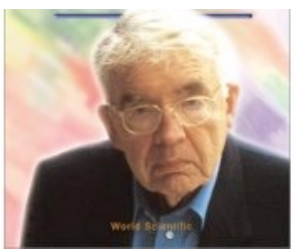
Vacuum Energy and the Casimir Effect

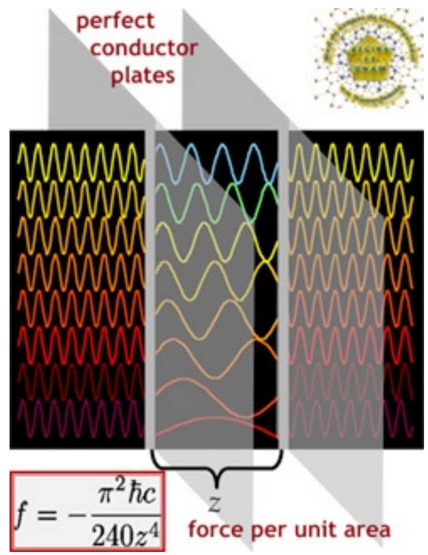
- Vacuum energy is real -- we can *see* it:





- Predicted in 1948 by H.B.G. Casimir

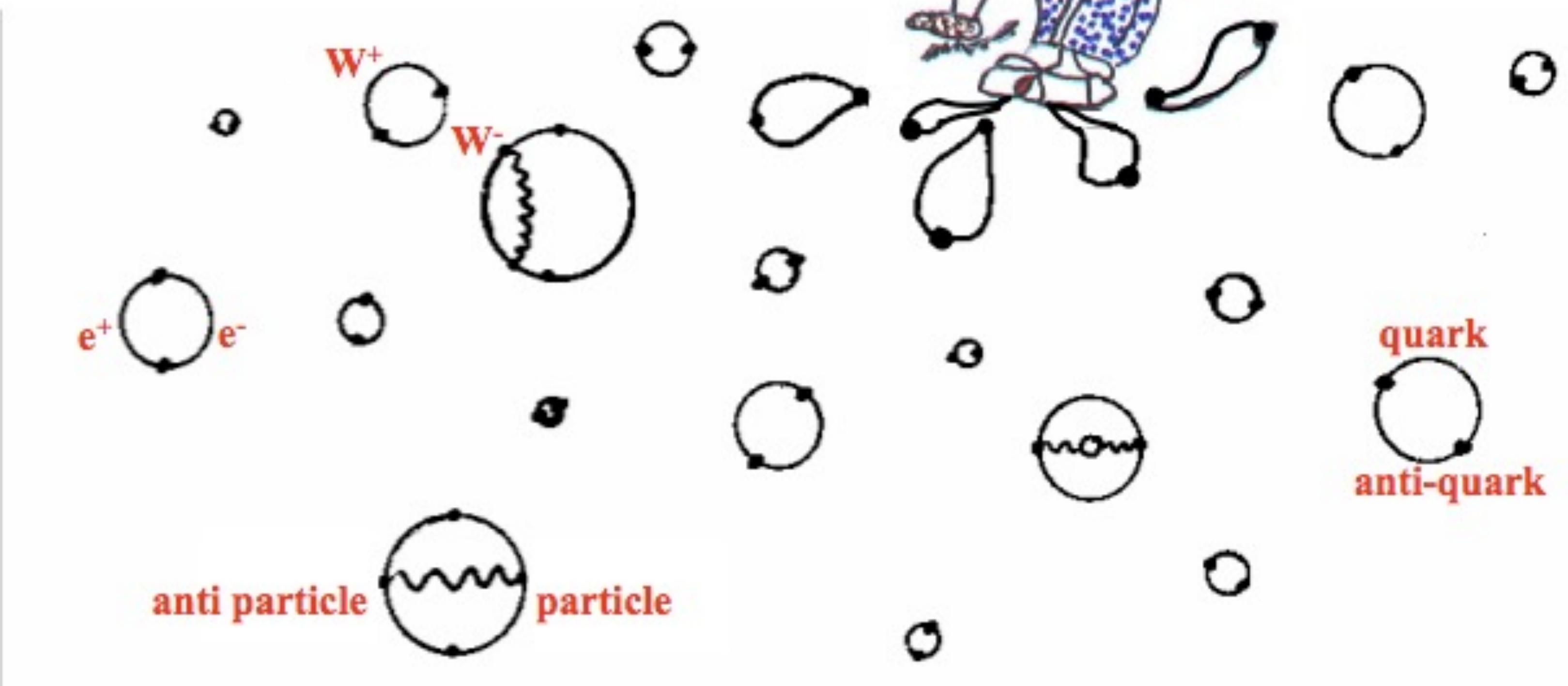




- Since measured to better than 5% precision

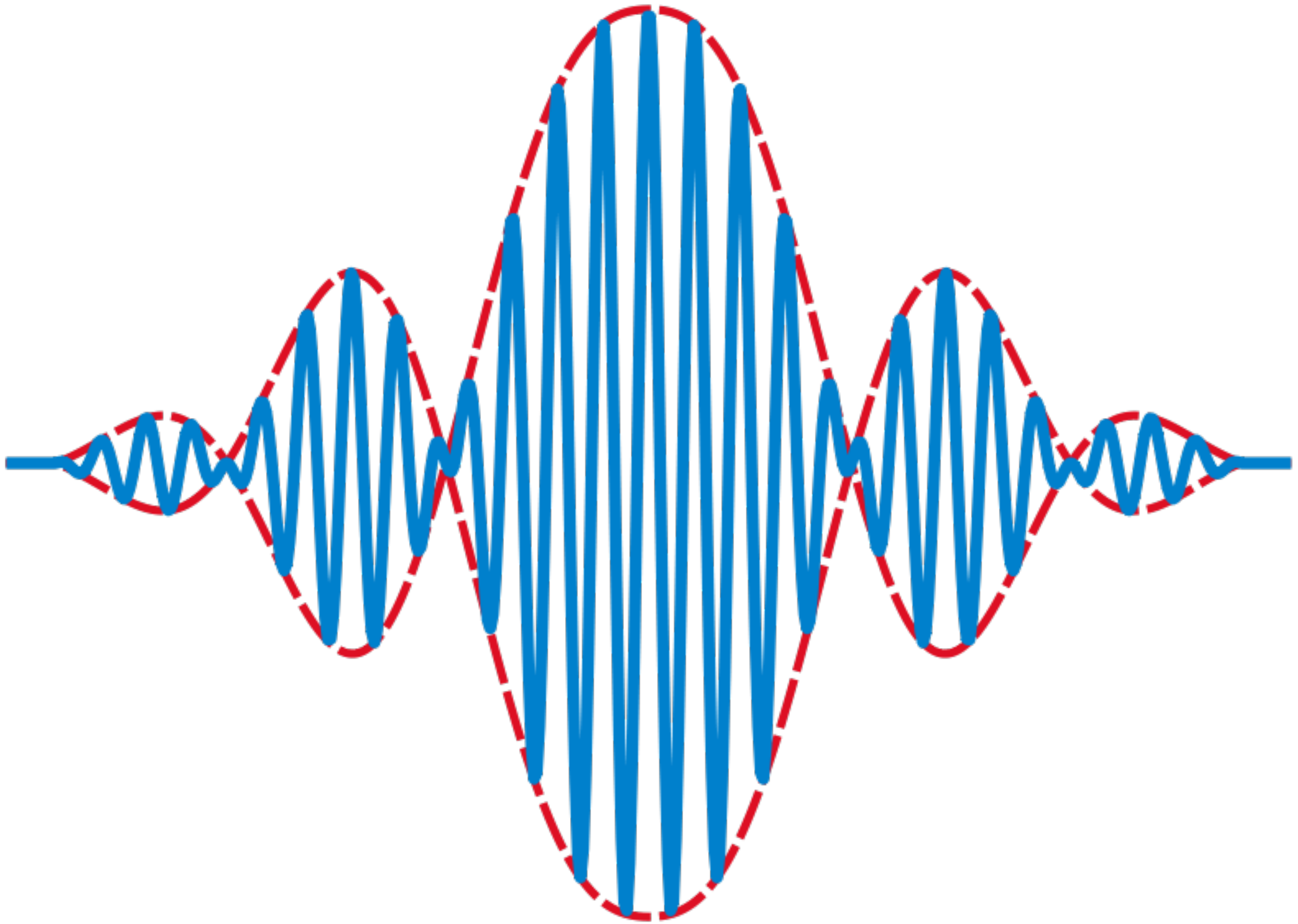
- **So -- since vacuum fluctuations are real, why isn't dark energy *enormous* (*10^{120} times larger*)???**

Uncertainty in the Quantum Vacuum

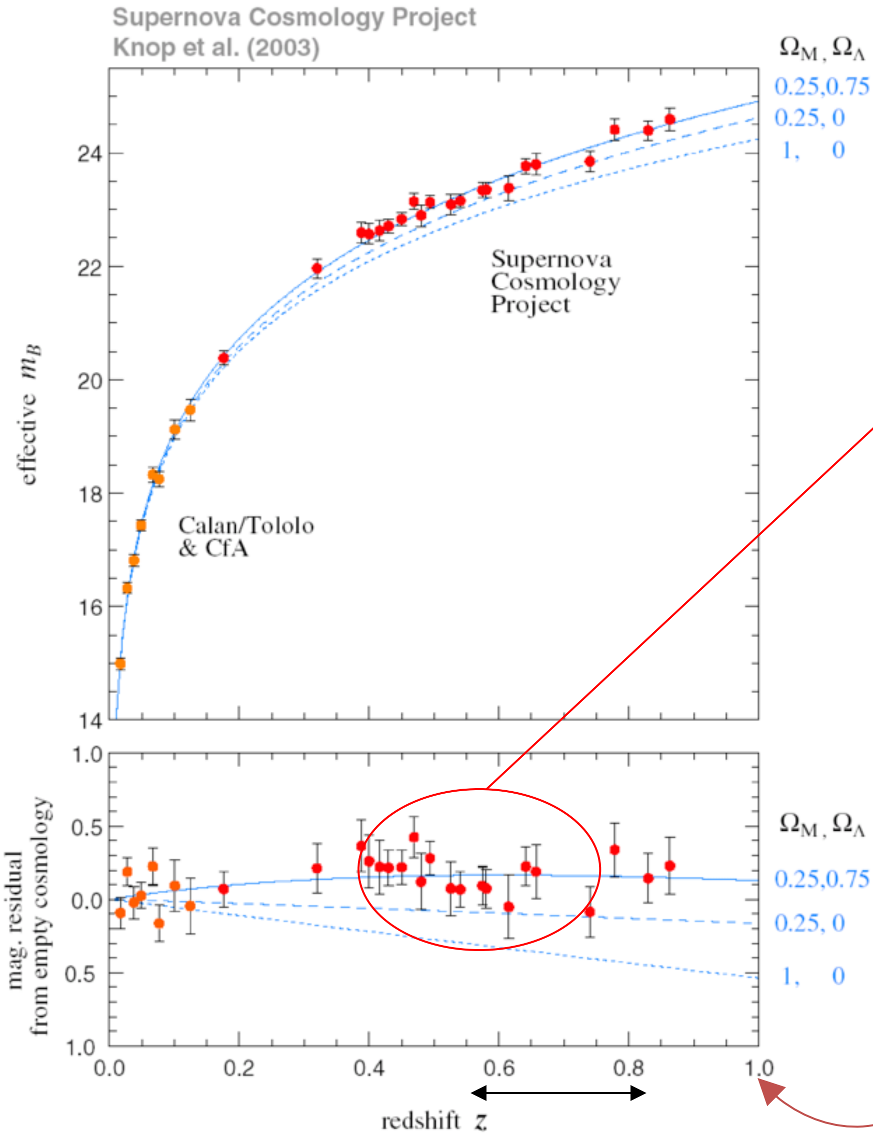


Nothing is Something!

The Music of Quantum Fields



Limitations on our Knowledge of Dark Energy



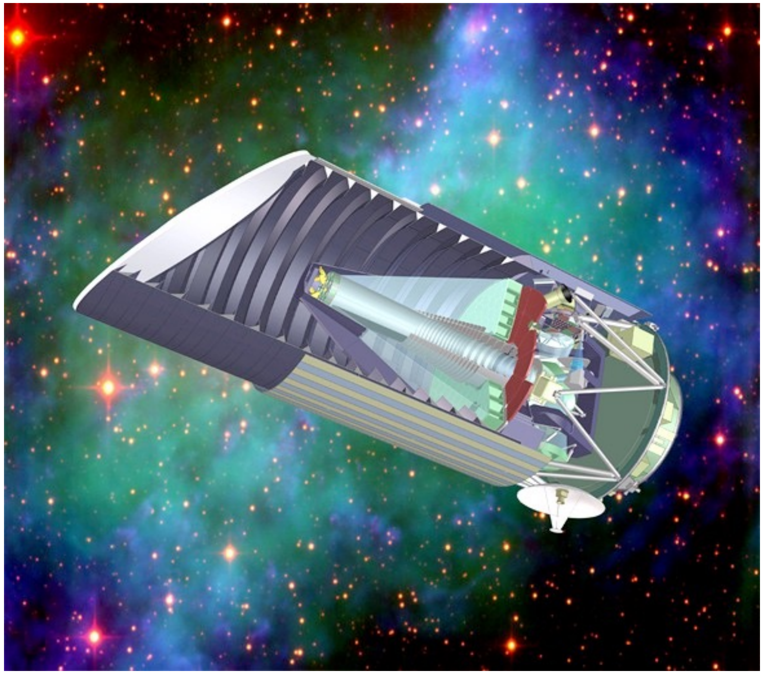
→ Calibration of, and corrections to, brightness measurements are a significant source of uncertainty in measured cosmological parameters.

↓ Unless we improve calibration standards (for flux as a function of color) to < 1%, this will be a limiting systematic uncertainty for upcoming projects …

7.7 billion light-years from Earth

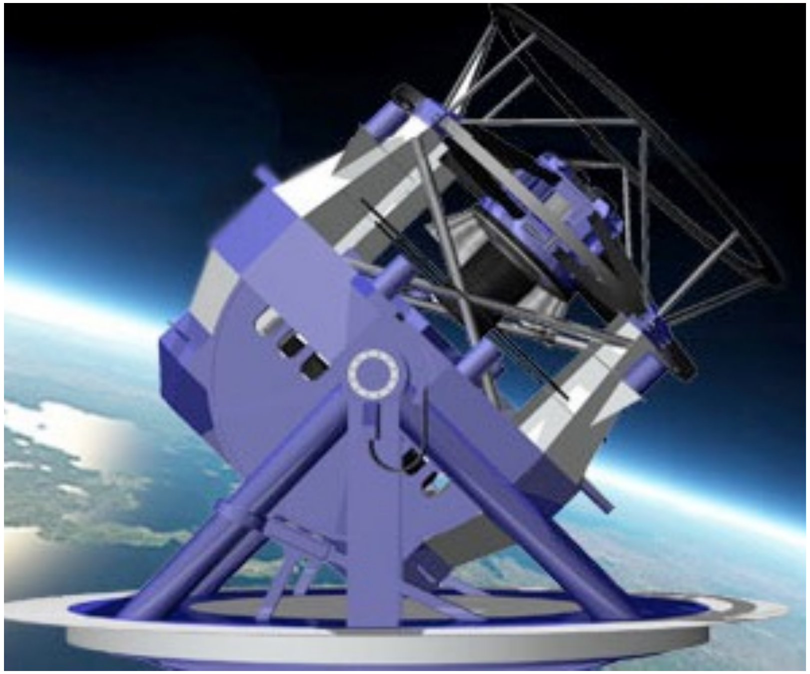
Understanding the Acceleration of the Universe

JDEM
The Joint Dark Energy Mission



Launch date ~2015

LSST
Large Synoptic Survey Telescope

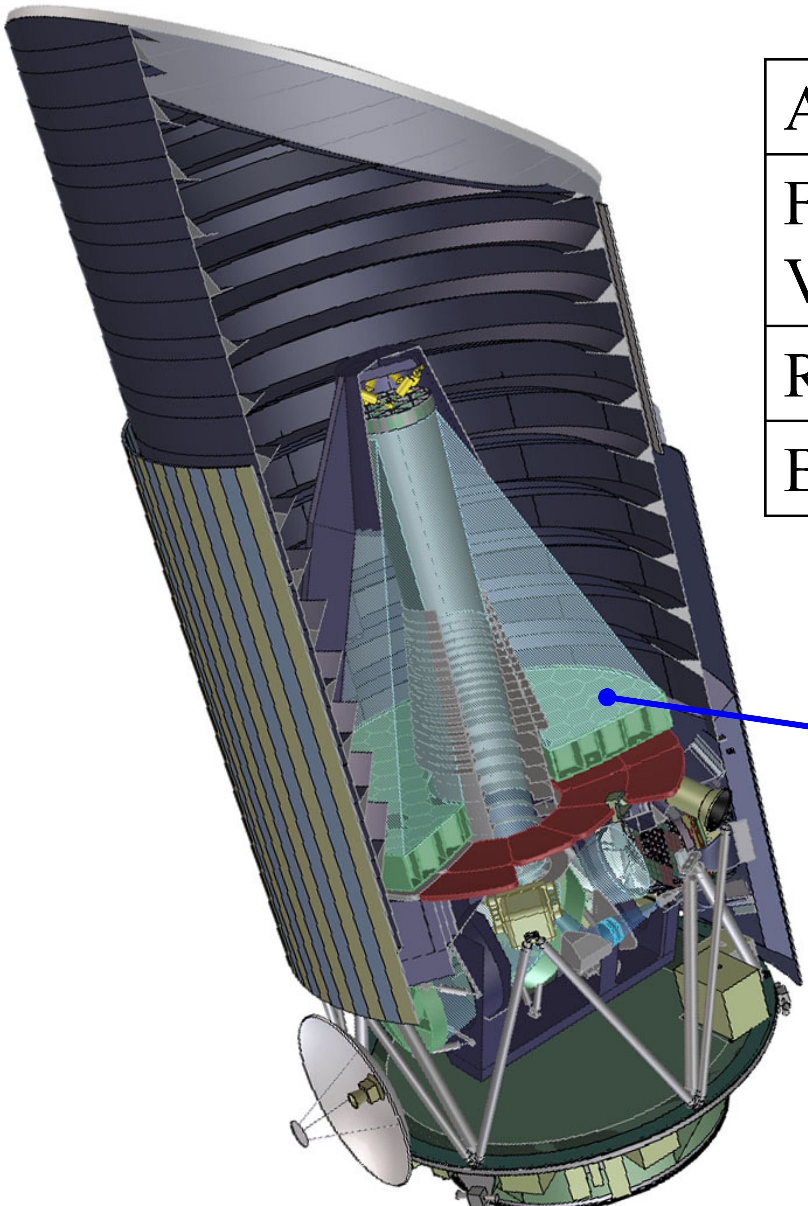


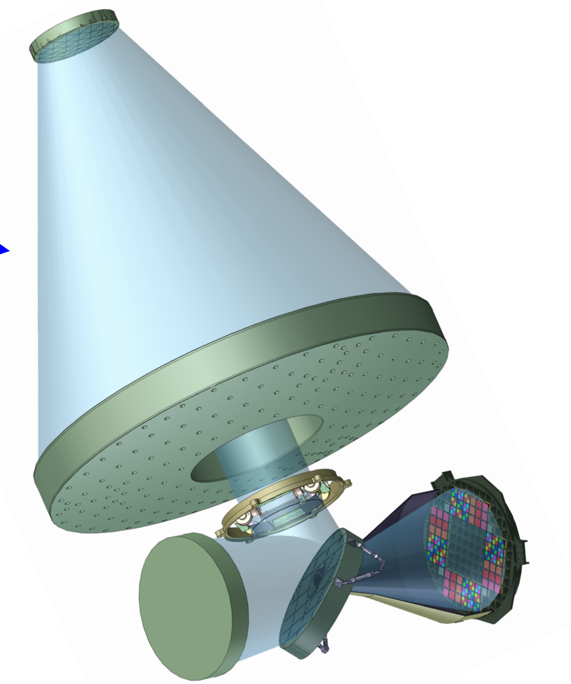
First data ~2013

… and others

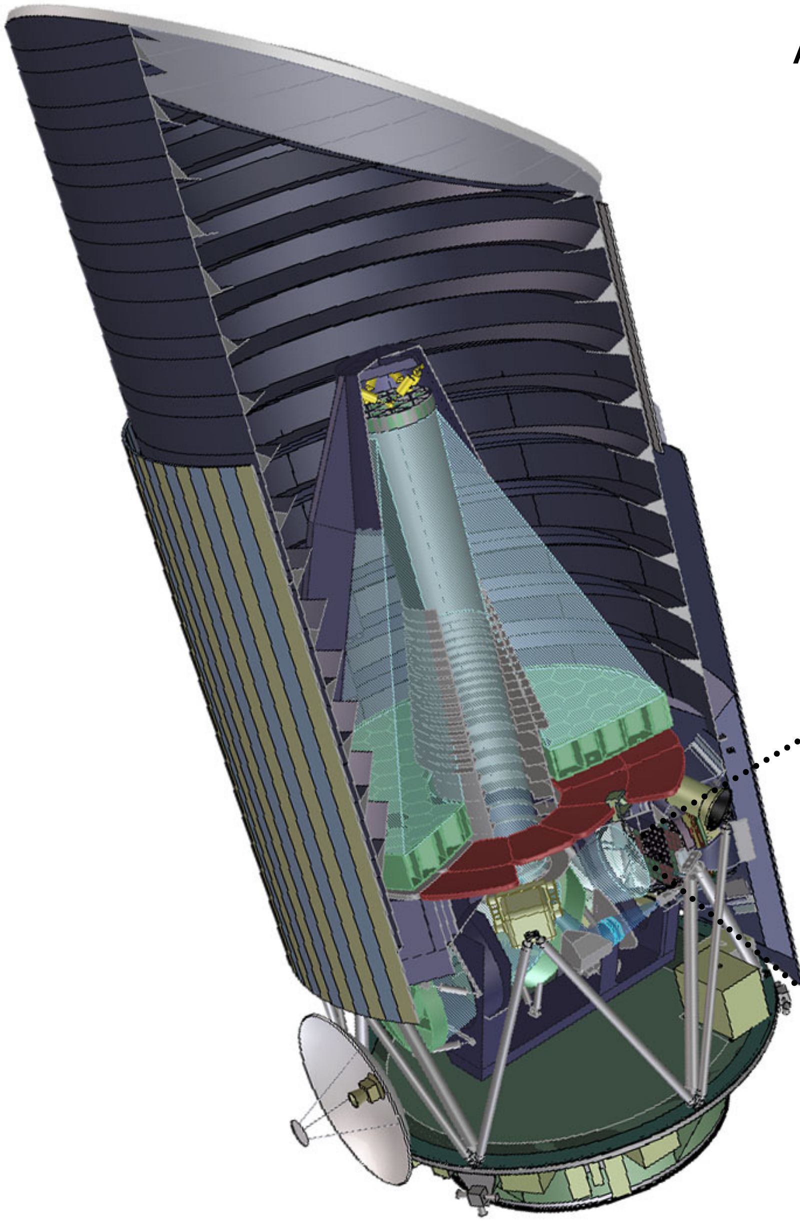
JDEM Concept

Aperture	1.8 meter
Field of View	1.37 square deg
Resolution	< 0.06 arcsec FWHM blur
Bandpass	0.35-1.7 µm



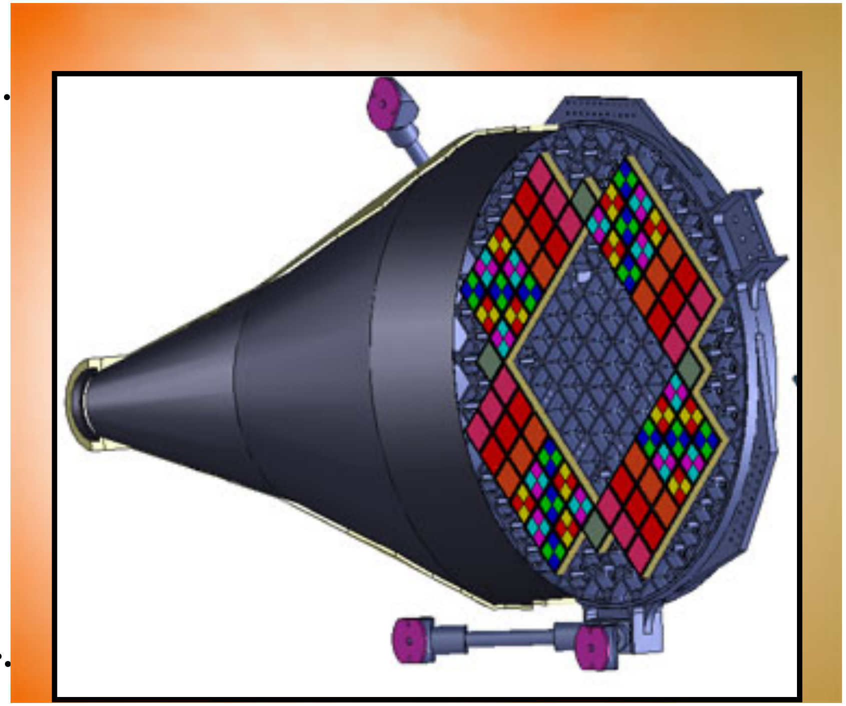


JDEM Concept

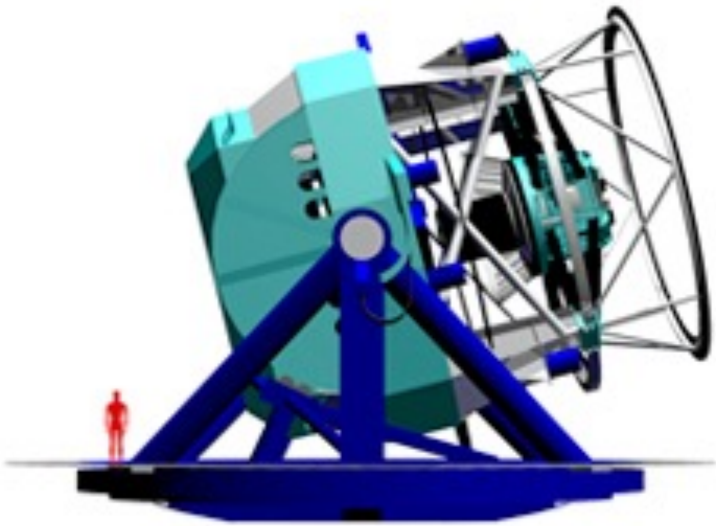


All instruments/detectors on single focal plane.

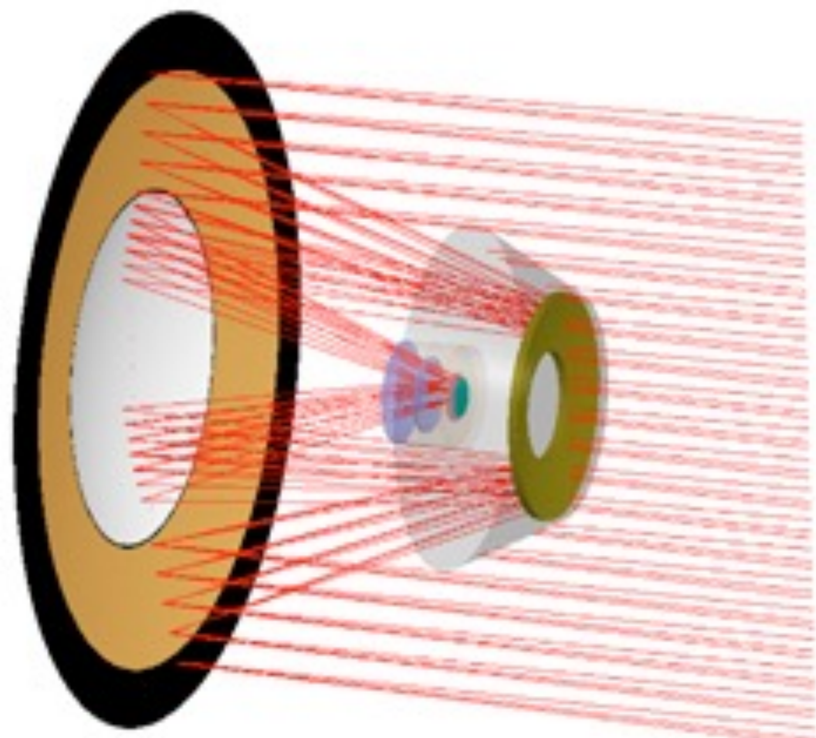
- Passively cooled to 140K
- 0.7 square degrees instrumented FOV
- 9 fixed filters from 350nm to 1700nm
- 36 CCDs. 36 HgCdTe detectors



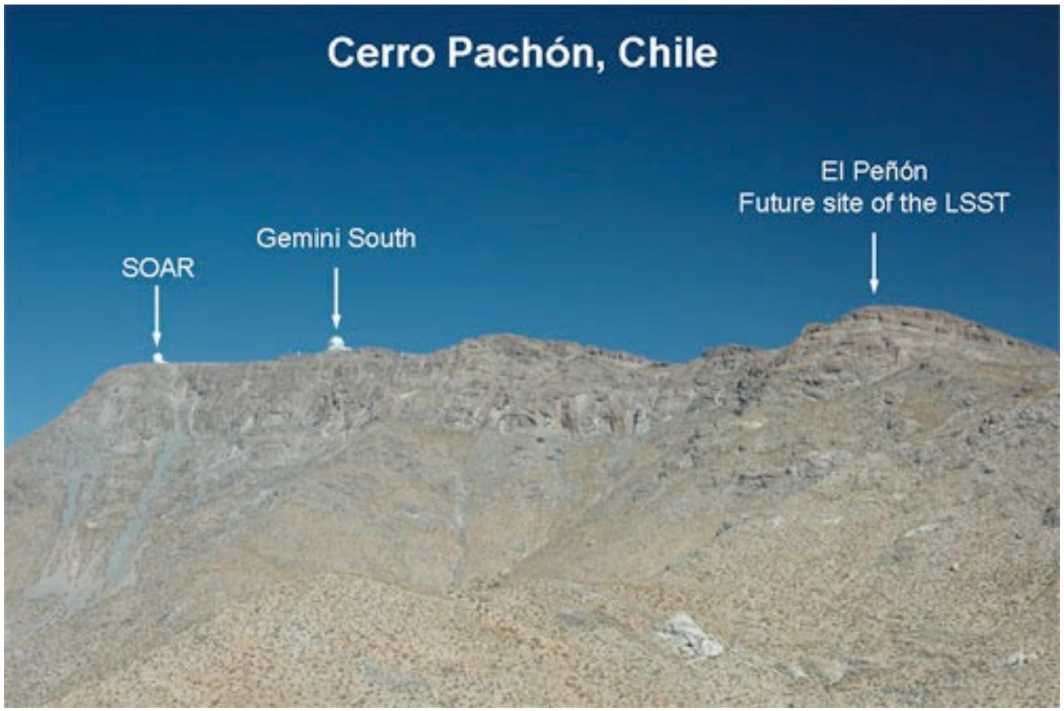
The Large Synoptic Survey Telescope (LSST)

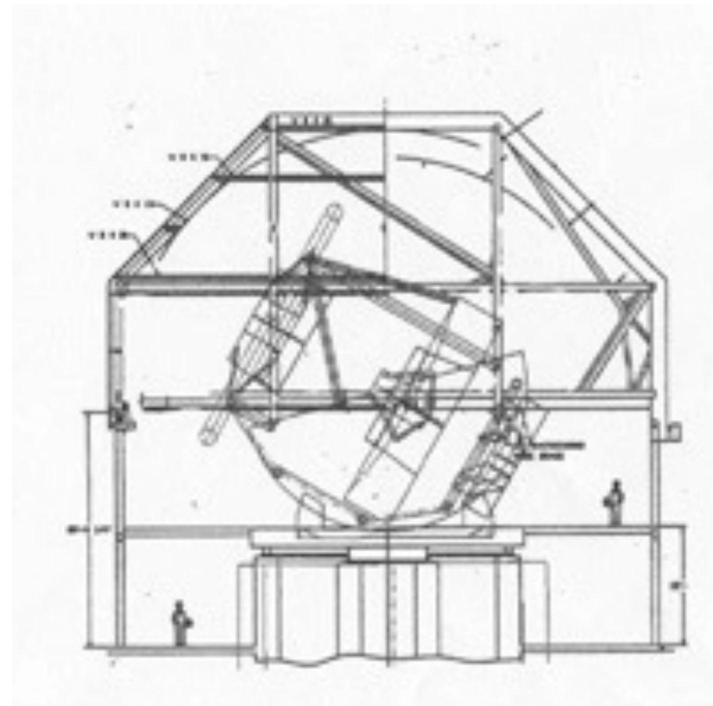


- 8.4 m aperture
- Survey: 20,000 sq. degrees
- 9.6 sq. degree field-of-view
- 6 filters from 320nm to 1060nm
- Site: Cerro Pachon, Chile



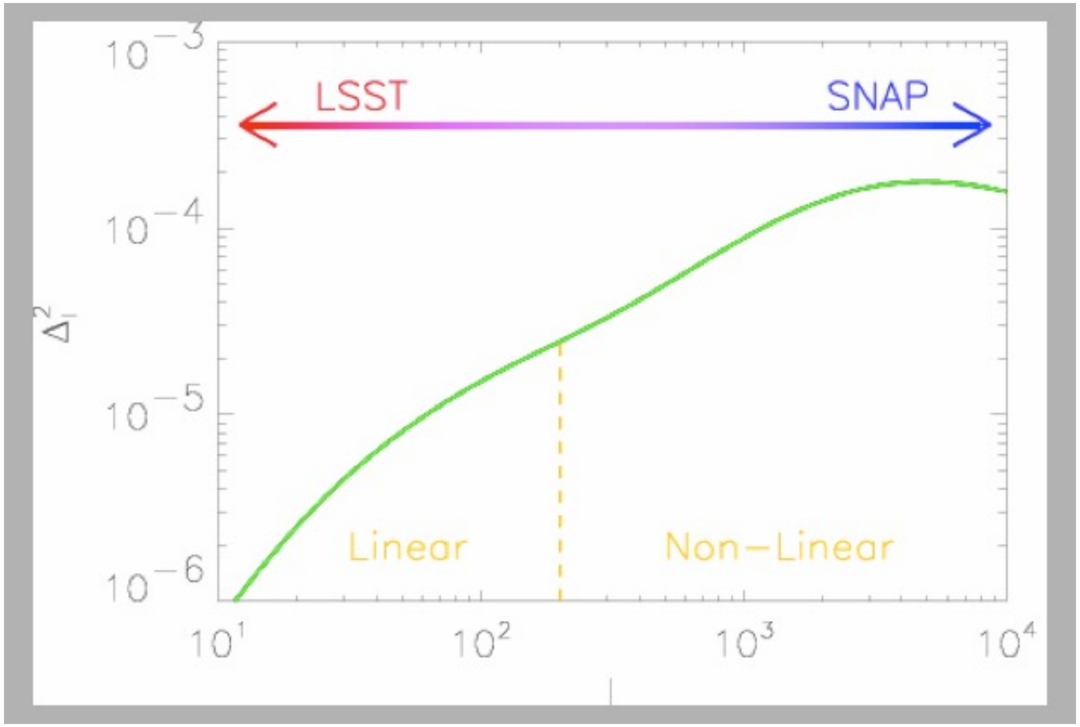
The Large Synoptic Survey Telescope (LSST)

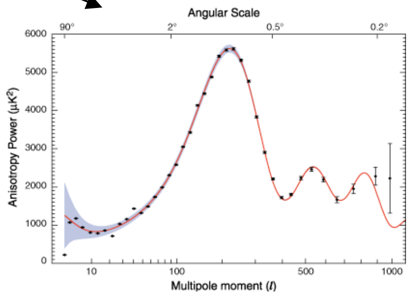




Complementarity of JDEM and LSST

- The power spectrum of matter in the Universe (analogous, e.g., to the power spectrum of the CMB)

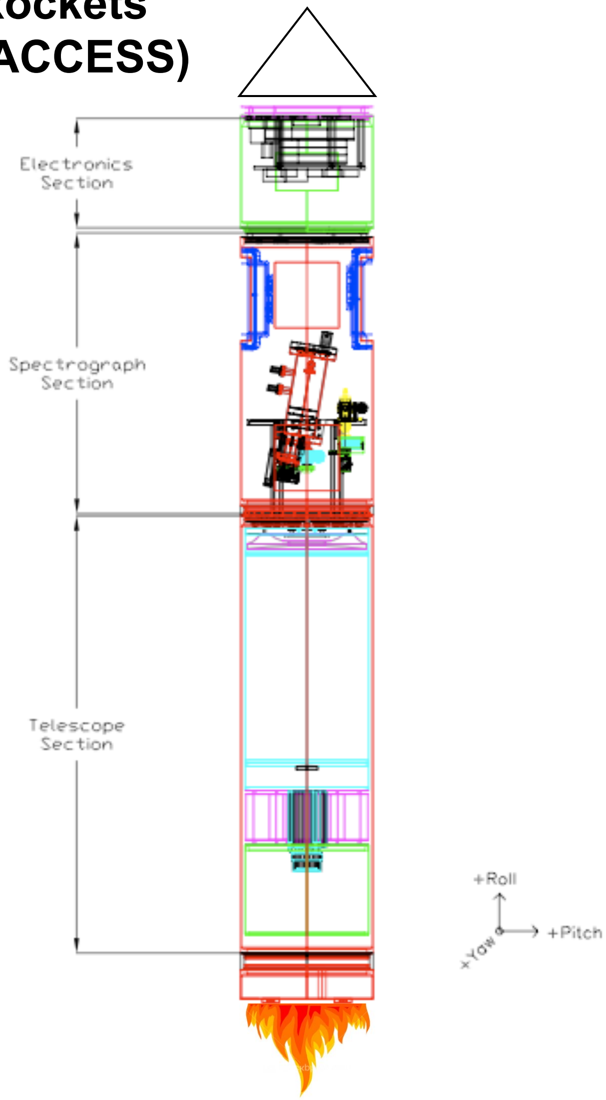




- Ground can survey whole sky, space can probe deeper in selected areas.
- Space data with lower systematics and higher redshift accuracy can calibrate ground surveys.

Improving Fundamental Calibration

Rockets (ACCESS)



Not Easy

<u>**Need to get above the ATMOSPHERE**</u>

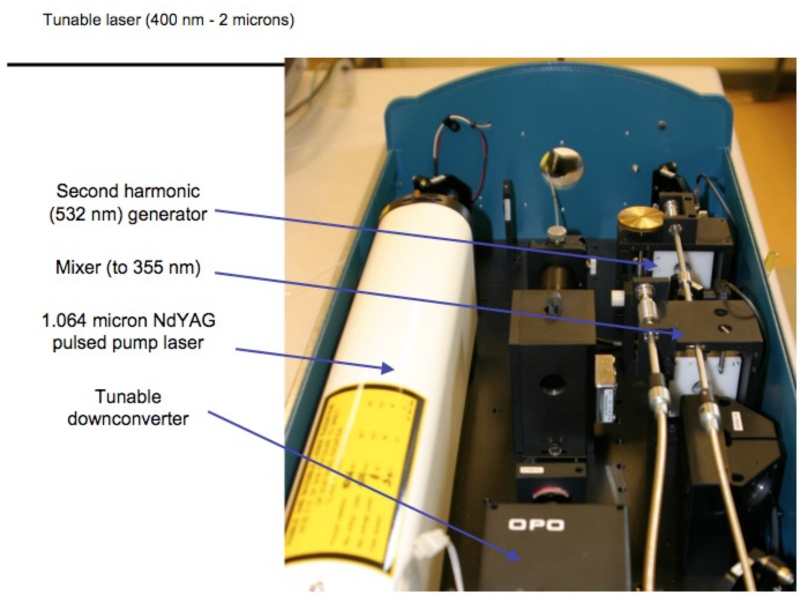
Another possibility: Balloons

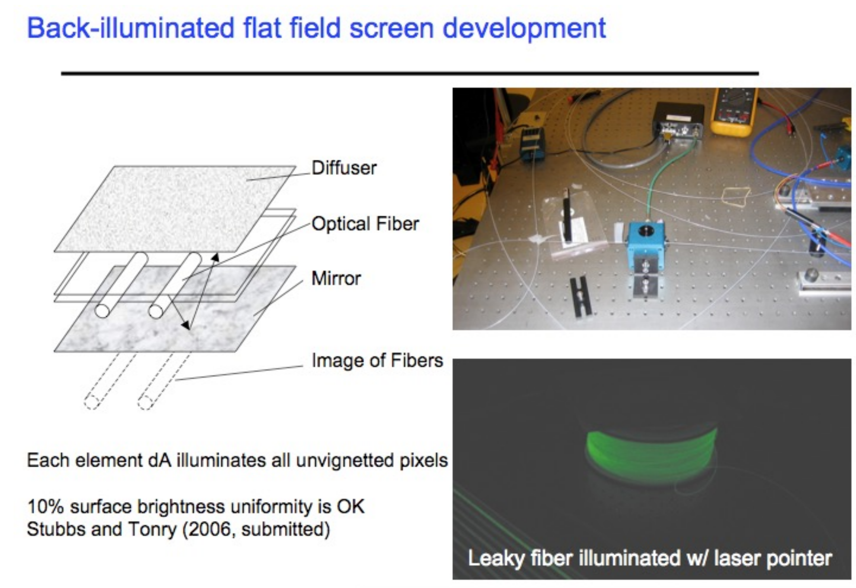
But even after you very carefully calibrate them, stars are <u>VARIABLE</u> (majority on the > 1% scale).

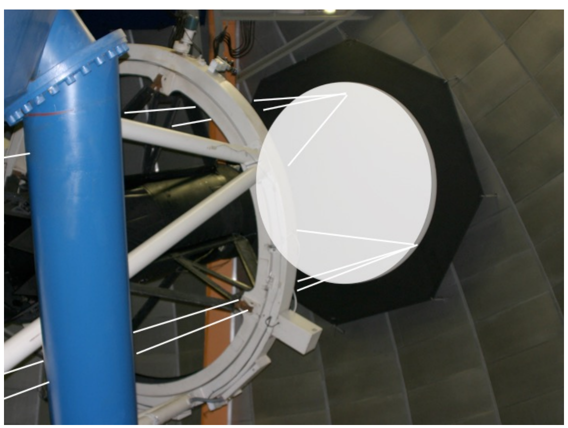
<u>*Wouldn't it be nice to just have a (man-made) source up there … ?*</u>

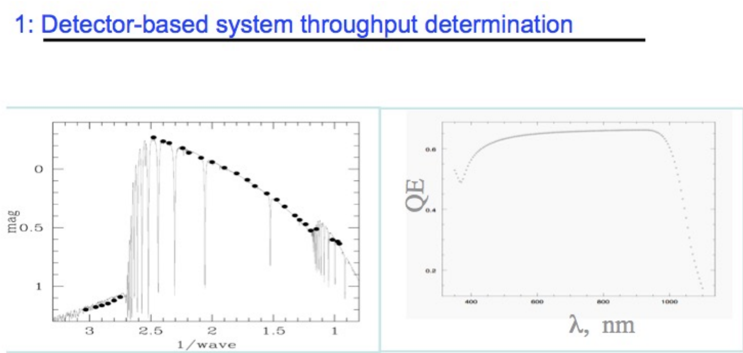
Using a Tunable Laser on the Ground

- Use tunable laser to calibrate *telescope optical throughput* (Stubbs & Tonry):

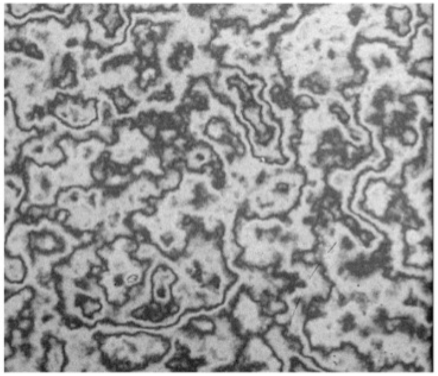






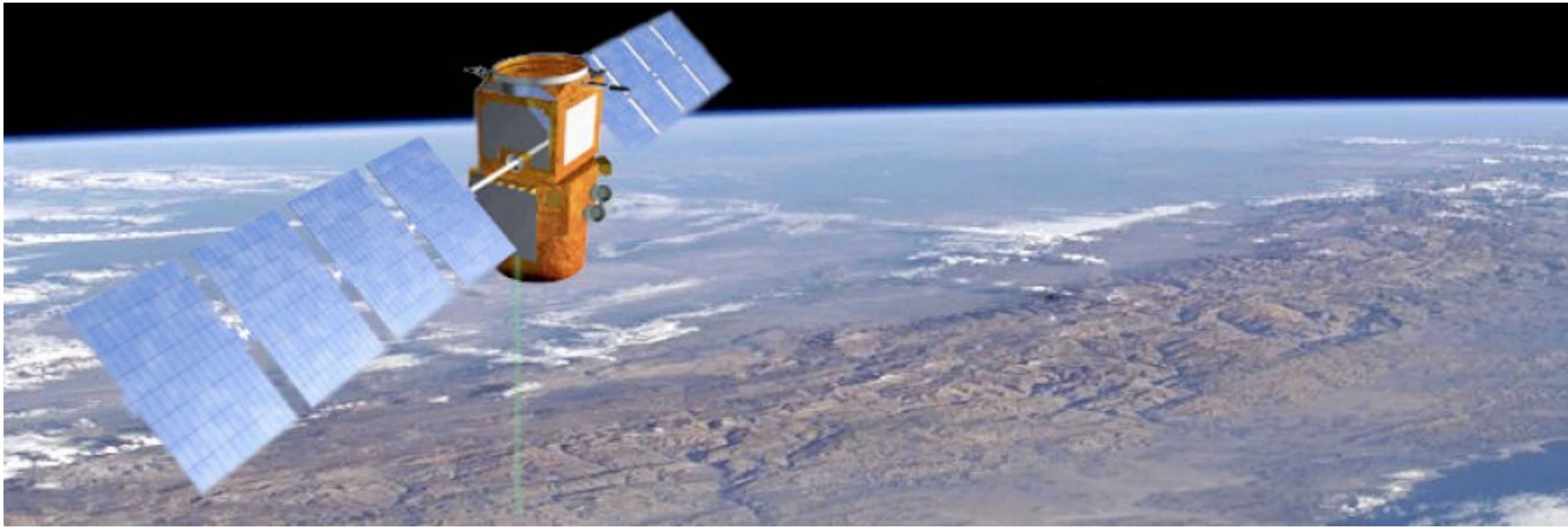


Spectrum of Vega NIST photodiode QE



960 nm

A (Non-Tunable) Laser in Space…



- The CALIPSO satellite (launched on Apr. 23, 2006) uses an Nd:YAG LIDAR laser at 1064 and 532 nm to measure the properties of clouds and the atmosphere. A tunable laser (and LIDAR receiver) could provide information in a *far* greater range of wavelengths.

A Tunable Laser in Space

1) **Would allow atmospheric calibration for all major ground-based observatories (without any worries of stellar variability).**

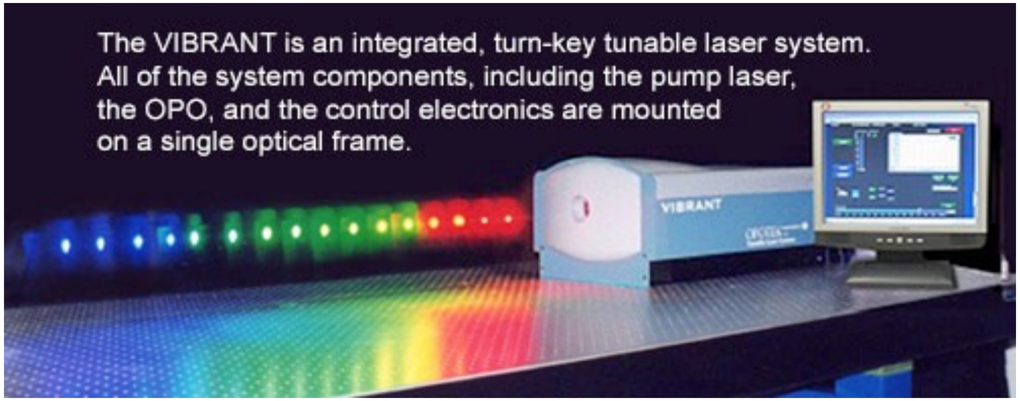
2) **A monochromatic source that covers the entire wavelength range (250 to 2500 nm) -- avoids worries about differences between stars and galaxies.**

3) **Would provide an always-available fundamental spectrophotometric standard source for space-based observatories (e.g. SNAP).**

4) **Minimizes calibration transfers; precision is limited essentially only by radiometer uncertainty (only 0.01% !!)**

Tunable laser

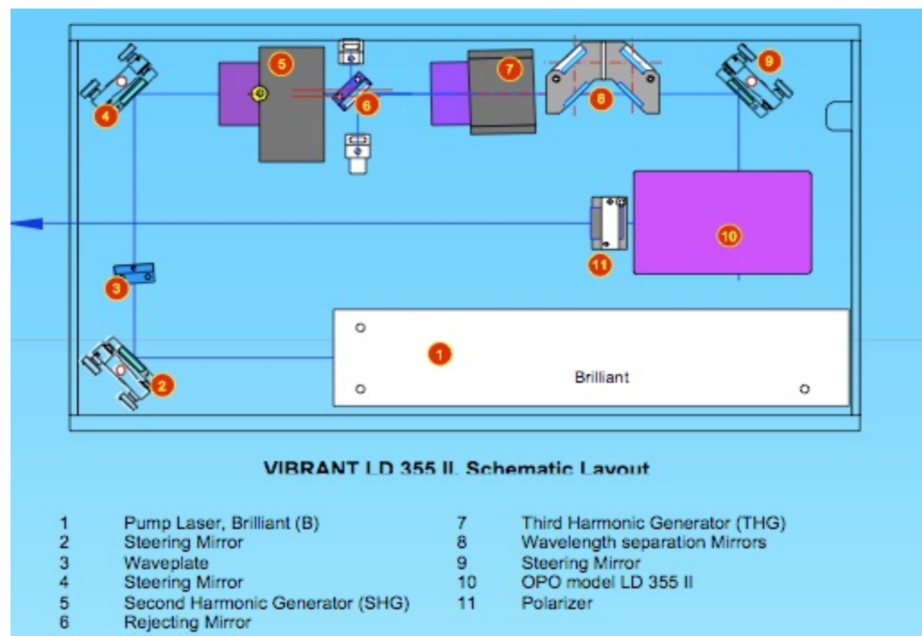
Opotek Vibrant LD 355 II



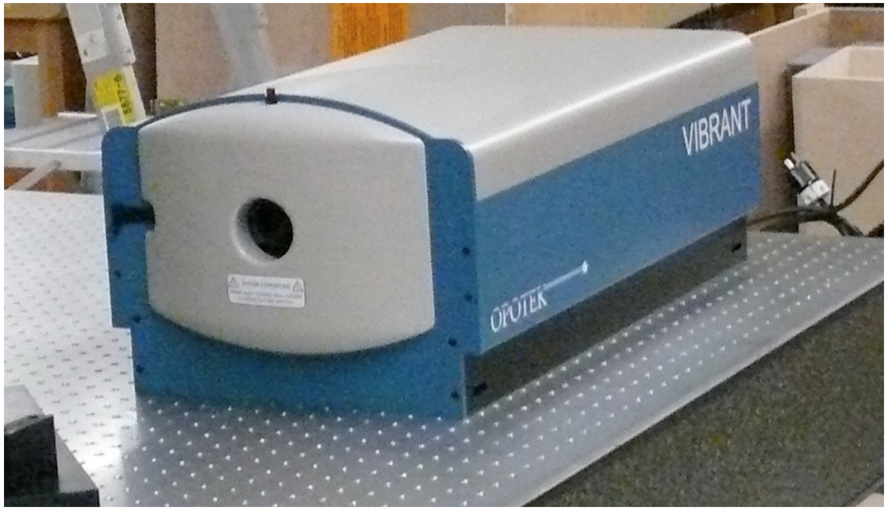
→ **Recently purchased**

VIBRANT LD 355 II	Specifications	Comments
Pump Laser	Nd:YAG, Q-Switched	Brilliant, by Quantel
Pump Wavelength	355 nm	Nominal Energy 100 mJ
Pulse Repetition Rate (PRR)	Variable, Single pulse to 10 Hz	Computer Controlled
Pulse length	5 ns	Nominal
Beam Diameter	6 mm	Nominal
External Trigger	Lamp and Q-Switch	Lamp has to operate at designed PRR
OPO Parameters		
Wavelength Tuning Range	410 – 2400 nm	No gap
OPO Peak Energy	25 mJ	See tuning graph
Spectral Linewidth	4 – 7 cm^{-1}	
Beam Divergence	< 2mRad	FWHM
Polarization	Linear	Signal: Horizontal Idler: Vertical
Computer Control	All the laser and OPO functions	ON, OFF, Power, Rep-Rate, Tuning

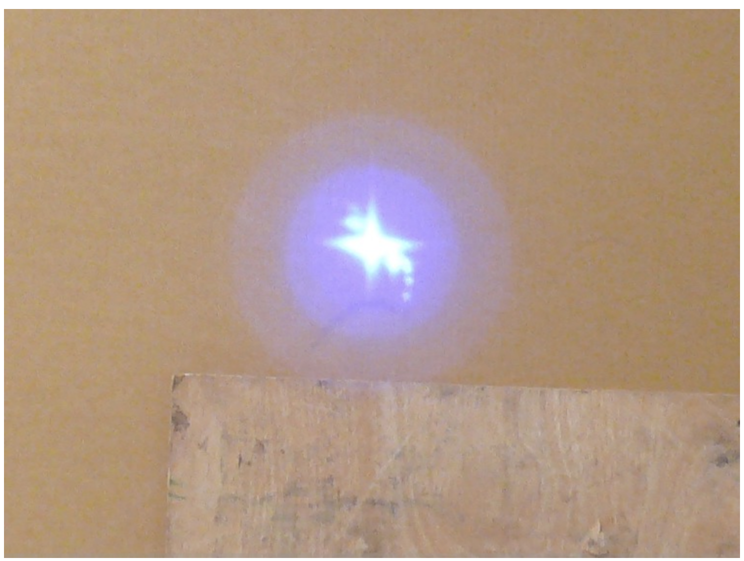
Options	Comments
UV Doubling Modules	Tuning range: 210 – 410 nm
Access to Laser Wavelengths	355, 532, and 1064 nm
Fiber Delivery	2 m fiber, mounted lenses, polishing kit
Comptroller for real time wavelength monitoring	OPO wavelength, auto calibration
Computer controlled Harmonics and polarizer	Automatic selection of tuning range
Variable Power Attenuator	Computer controlled 0 – 100% output power
266 nm output	Integrated Fourth Harmonic Generator

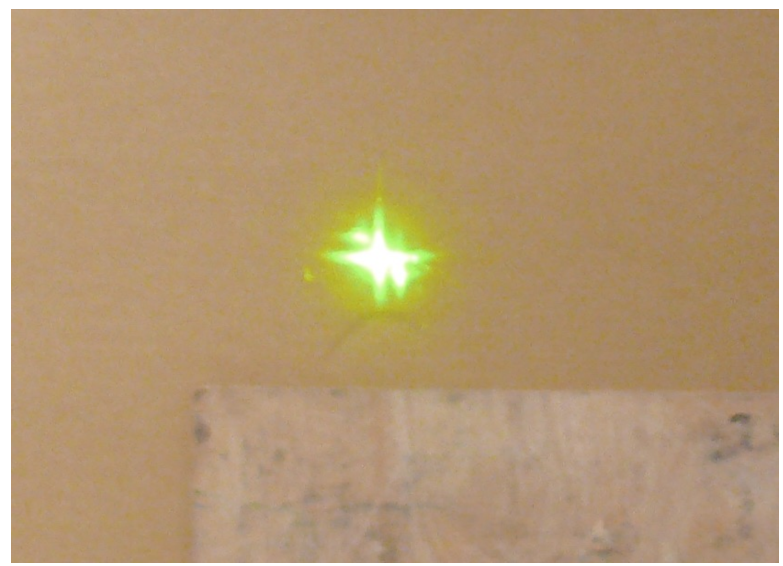


Tunable Laser Setup

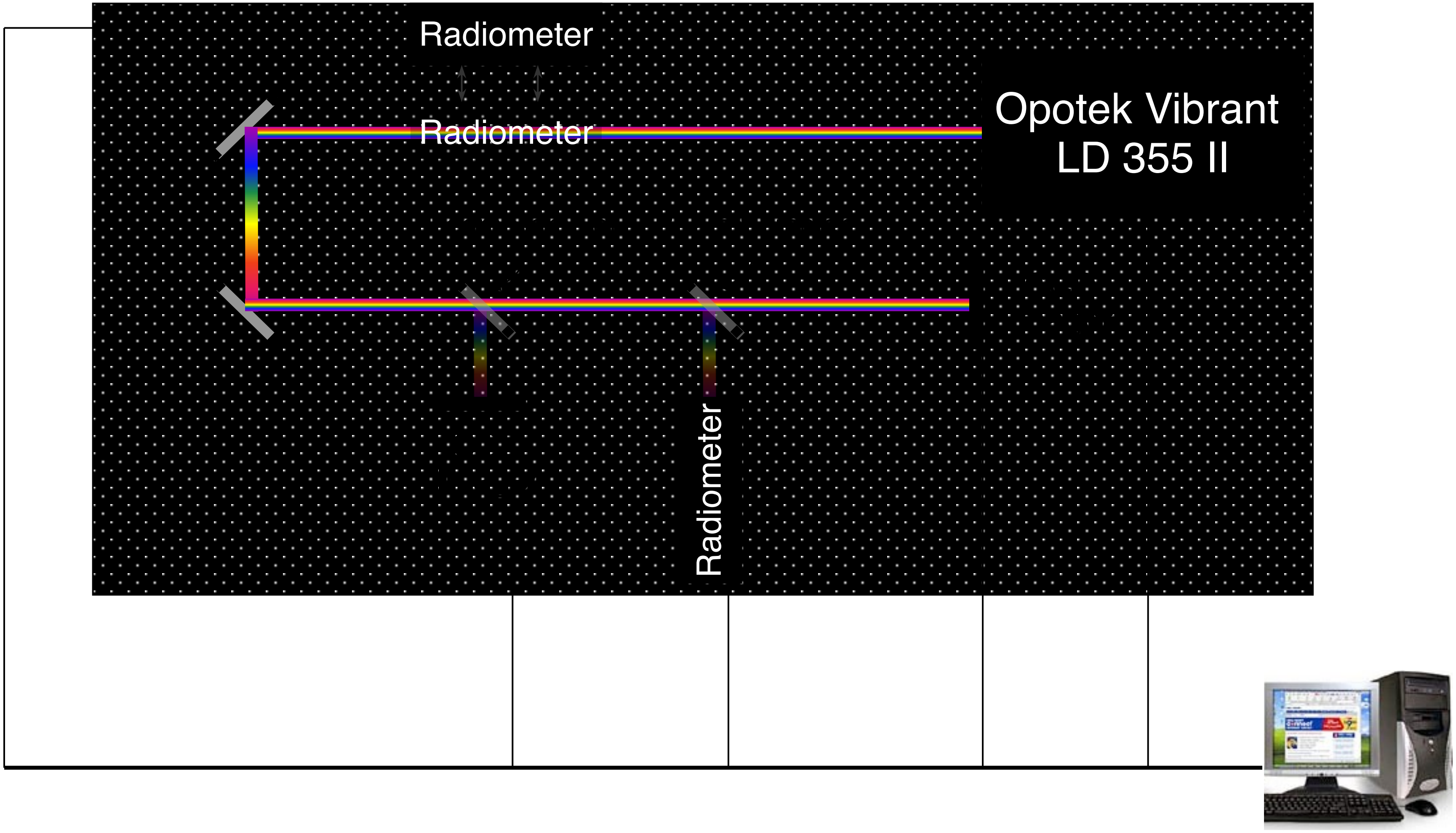


Safety barrier

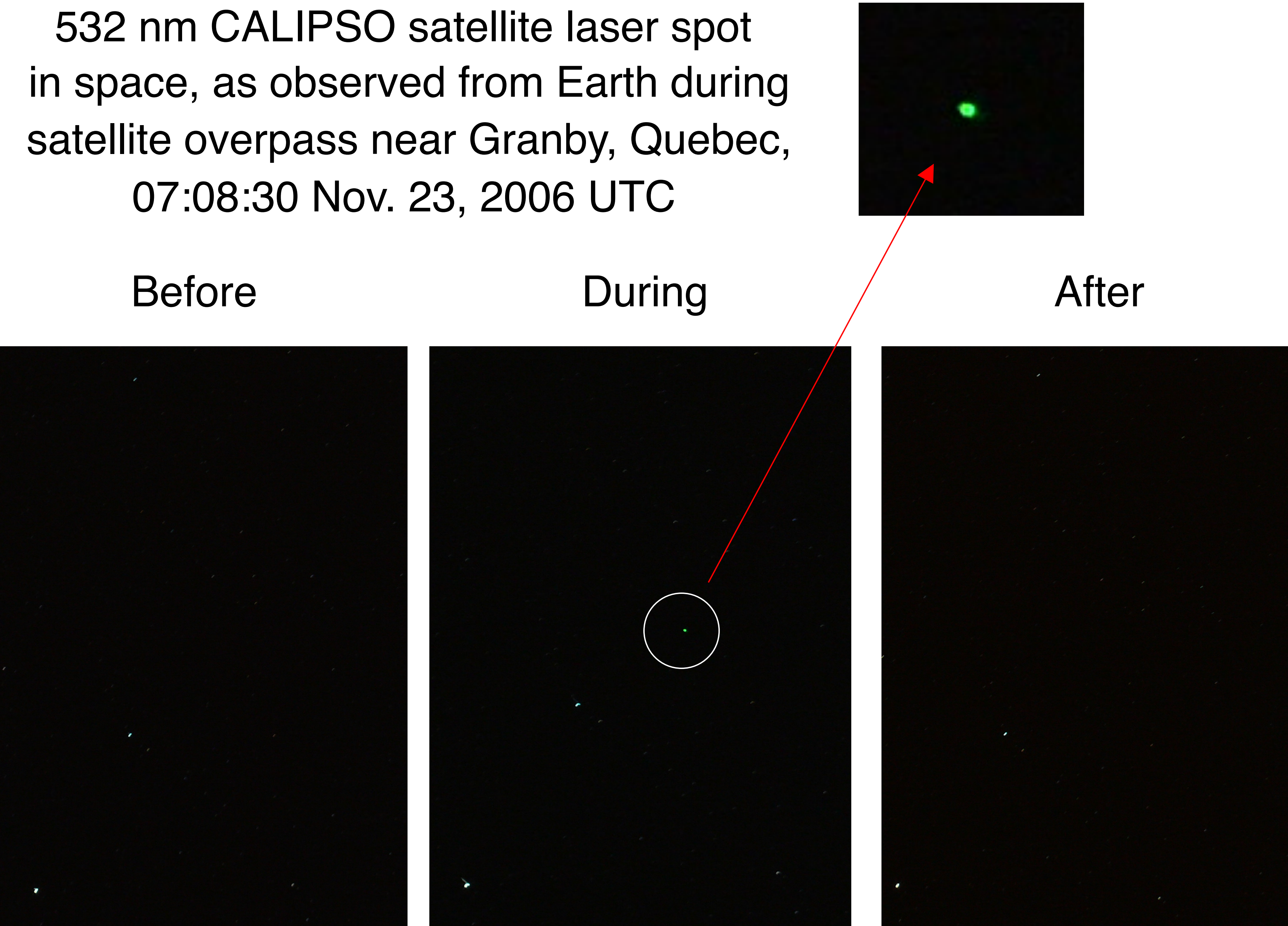




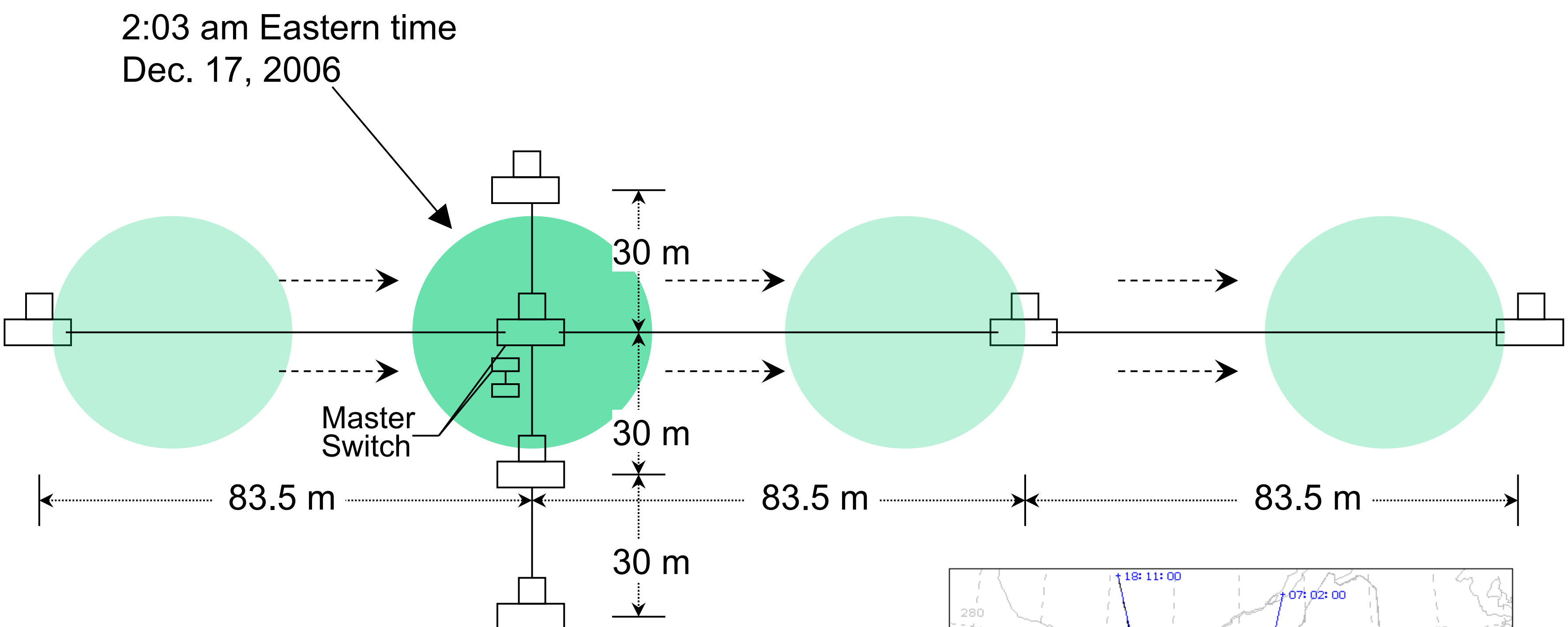
Tunable Laser Setup



532 nm CALIPSO satellite laser spot in space, as observed from Earth during satellite overpass near Granby, Quebec, 07:08:30 Nov. 23, 2006 UTC

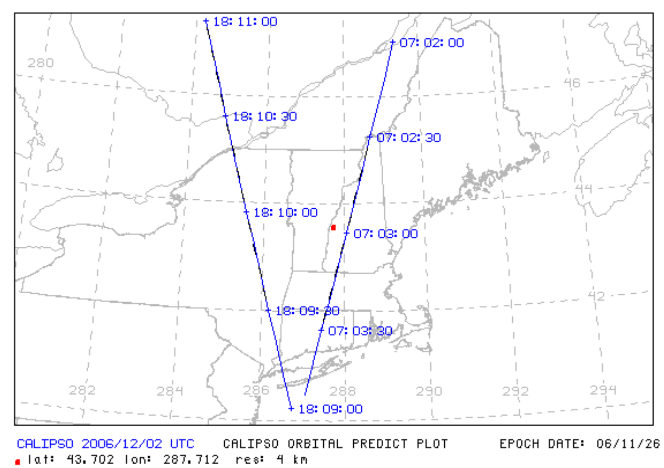


Setup for Calibrated CALIPSO Observations



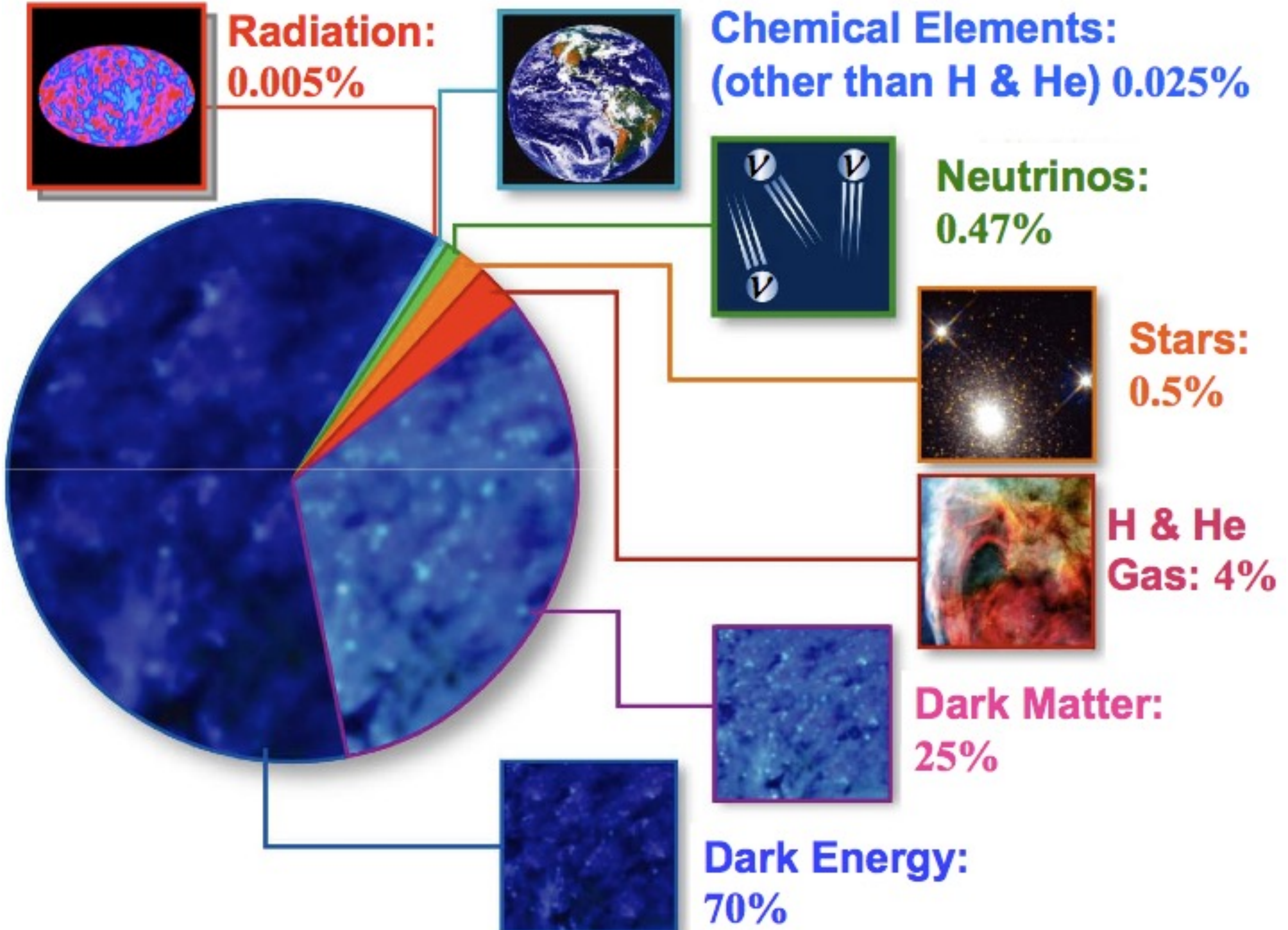
= calibrated photodiode (with 532 nm notch filter)

= Panasonic FZ50 digital camera



The Dark Side of the Universe

95% of the Universe Is Dark!


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.47%
Stars:
0.5%
H & He
Gas: 4%
Dark Matter:
25%
Dark Energy:
70%

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

– T. S. Eliot

How Understanding Fundamental Particle Interactions Helps us Understand the Universe

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