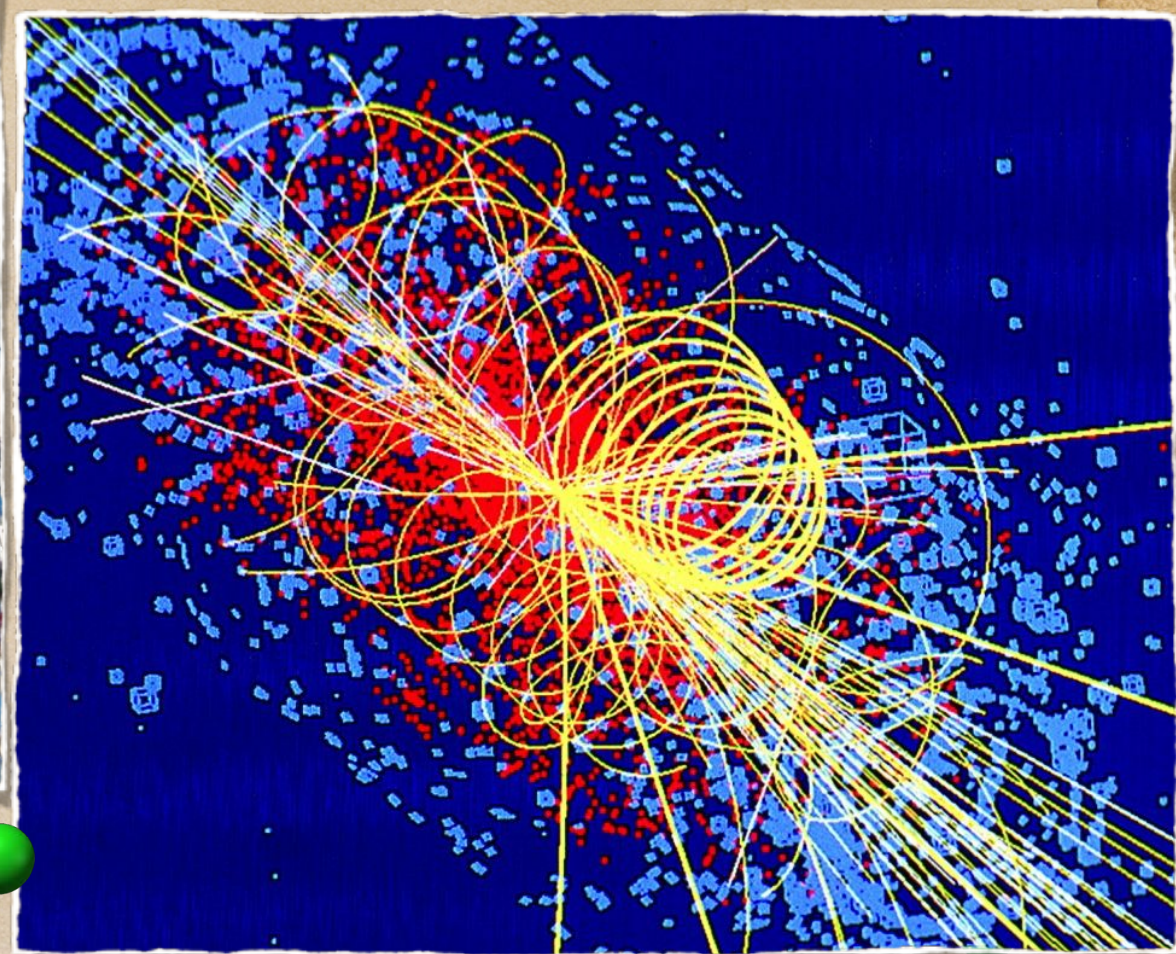
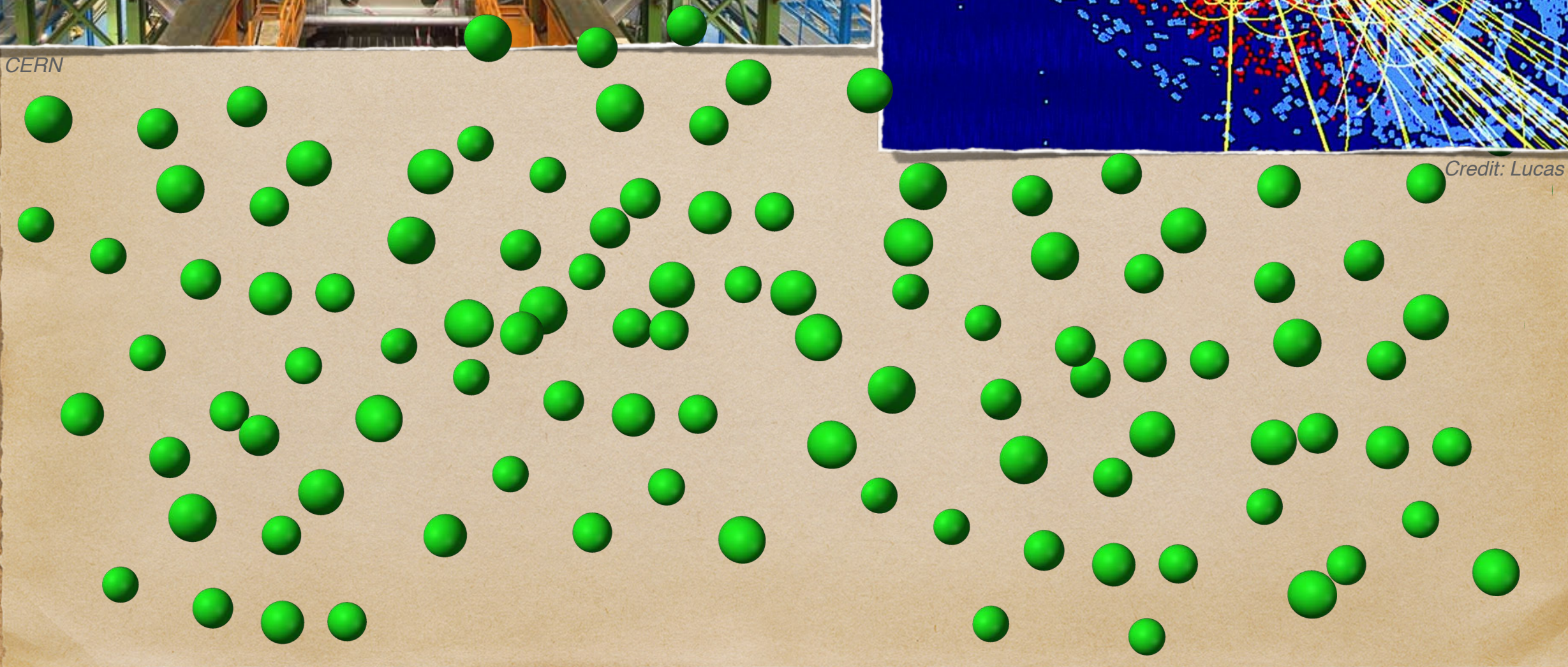


Credit: CERN

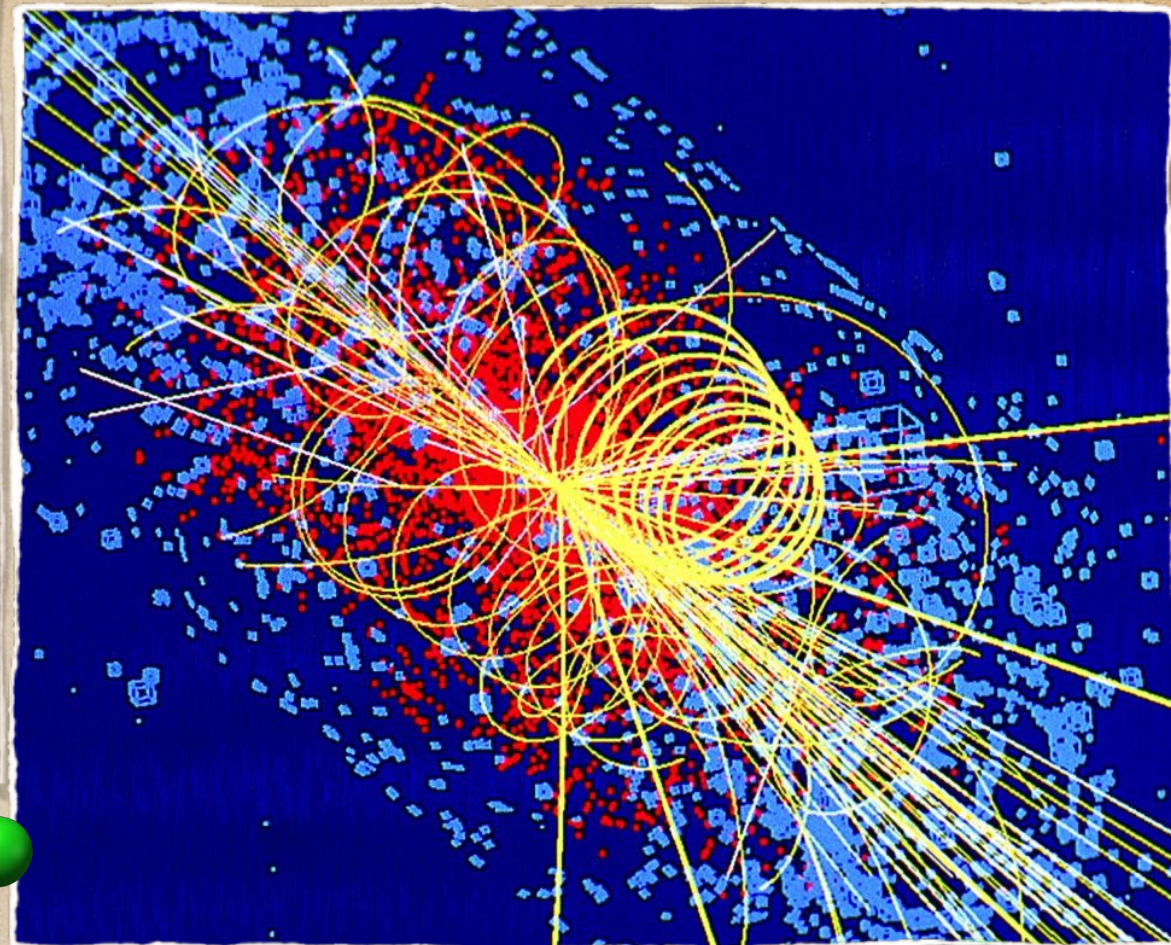


Credit: Lucas Taylor

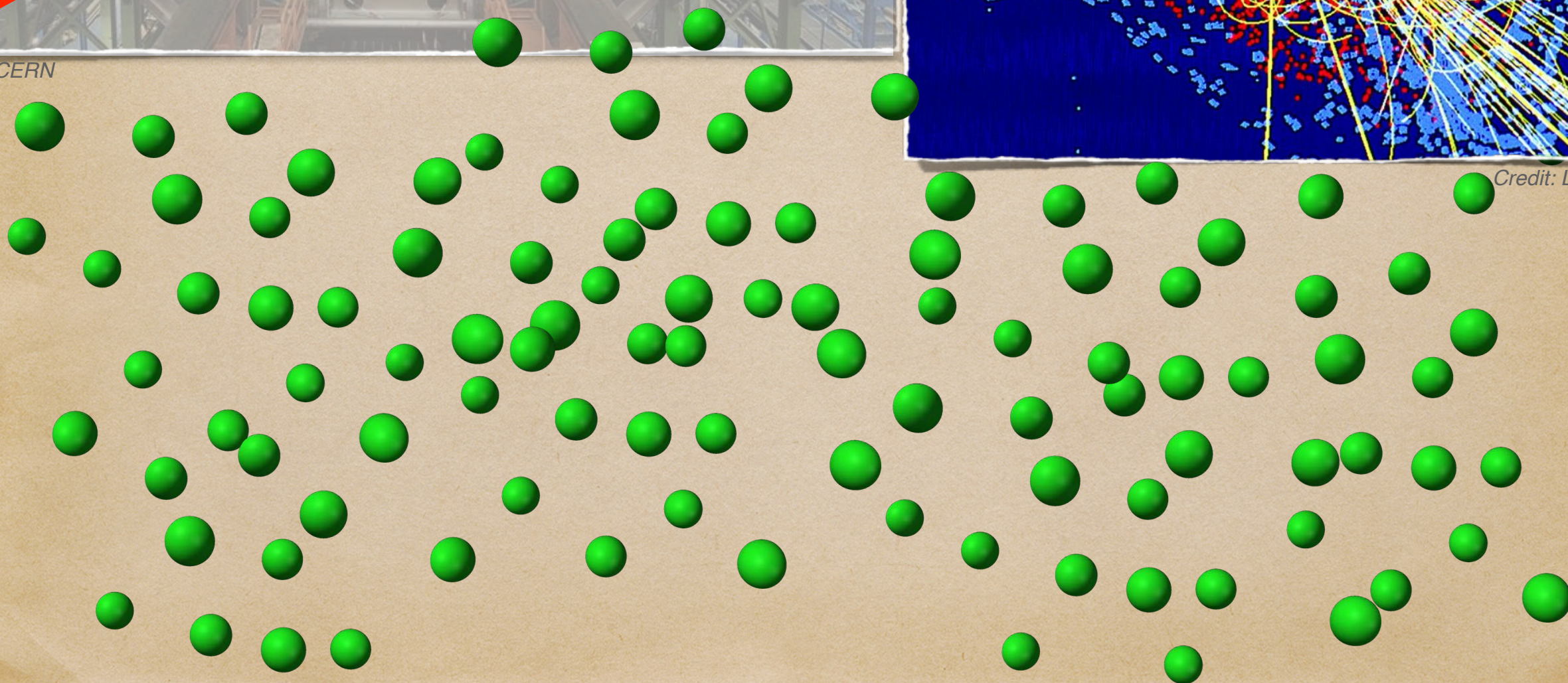


Big Machines

Credit: CERN



Credit: Lucas Taylor

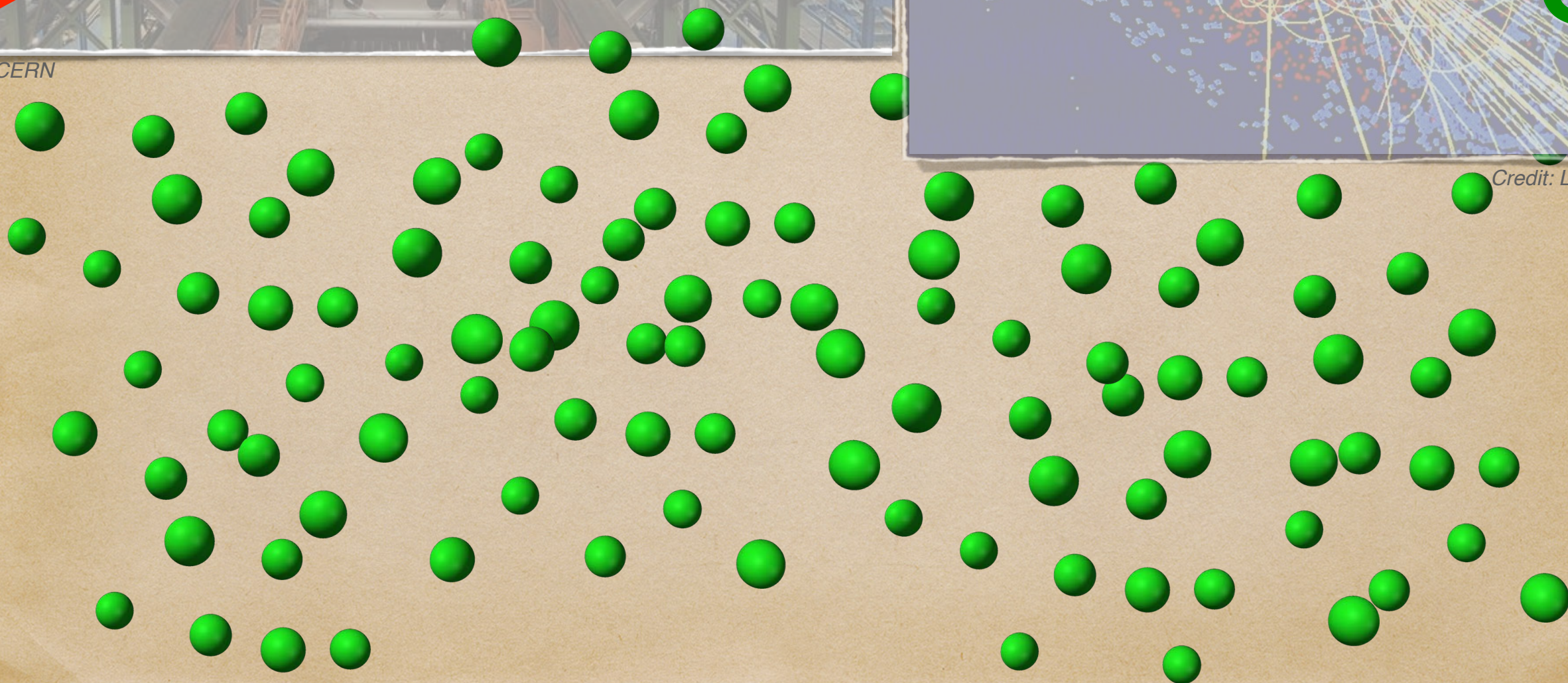


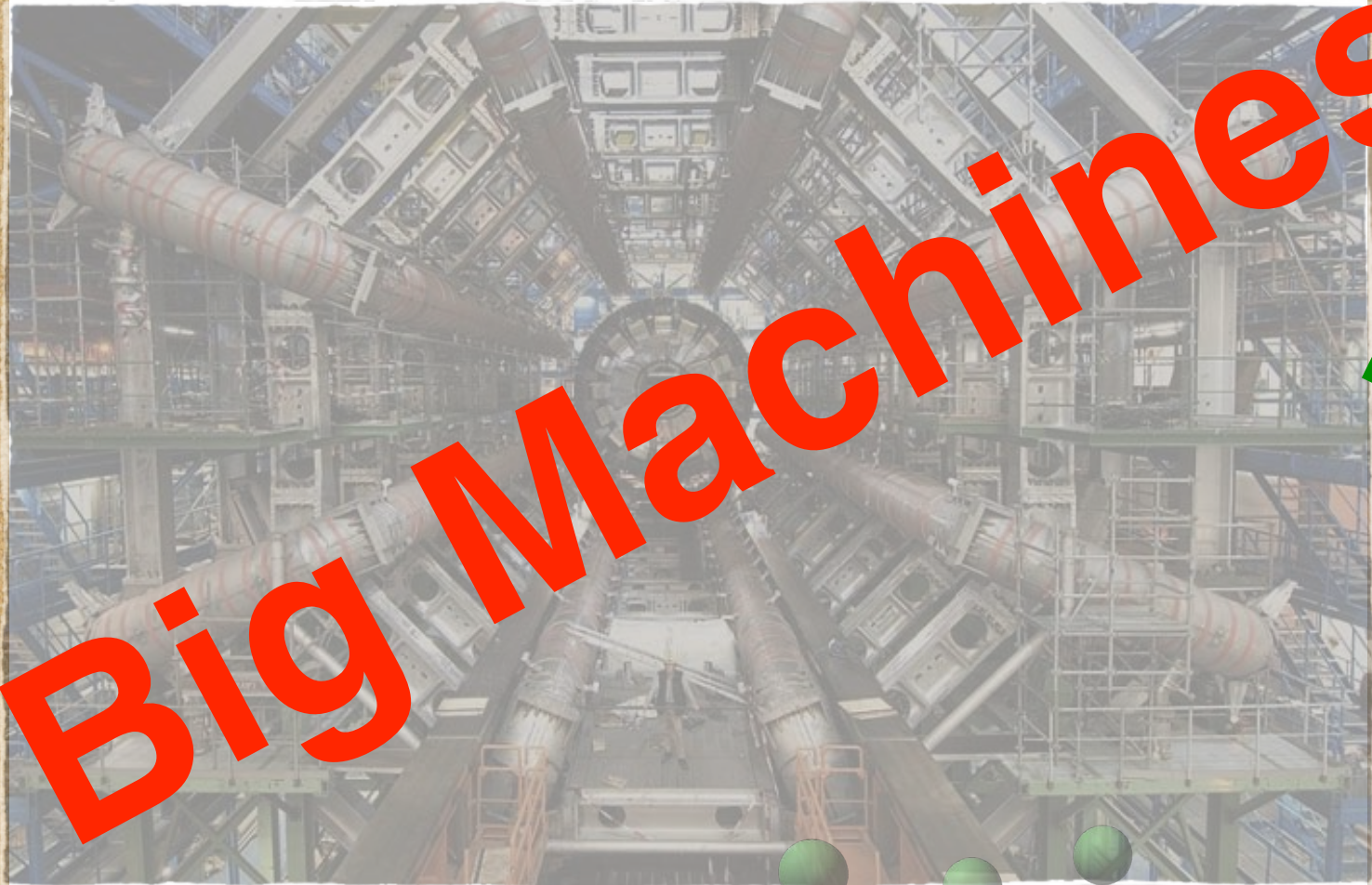
Big Machines

Credit: CERN

High Energies

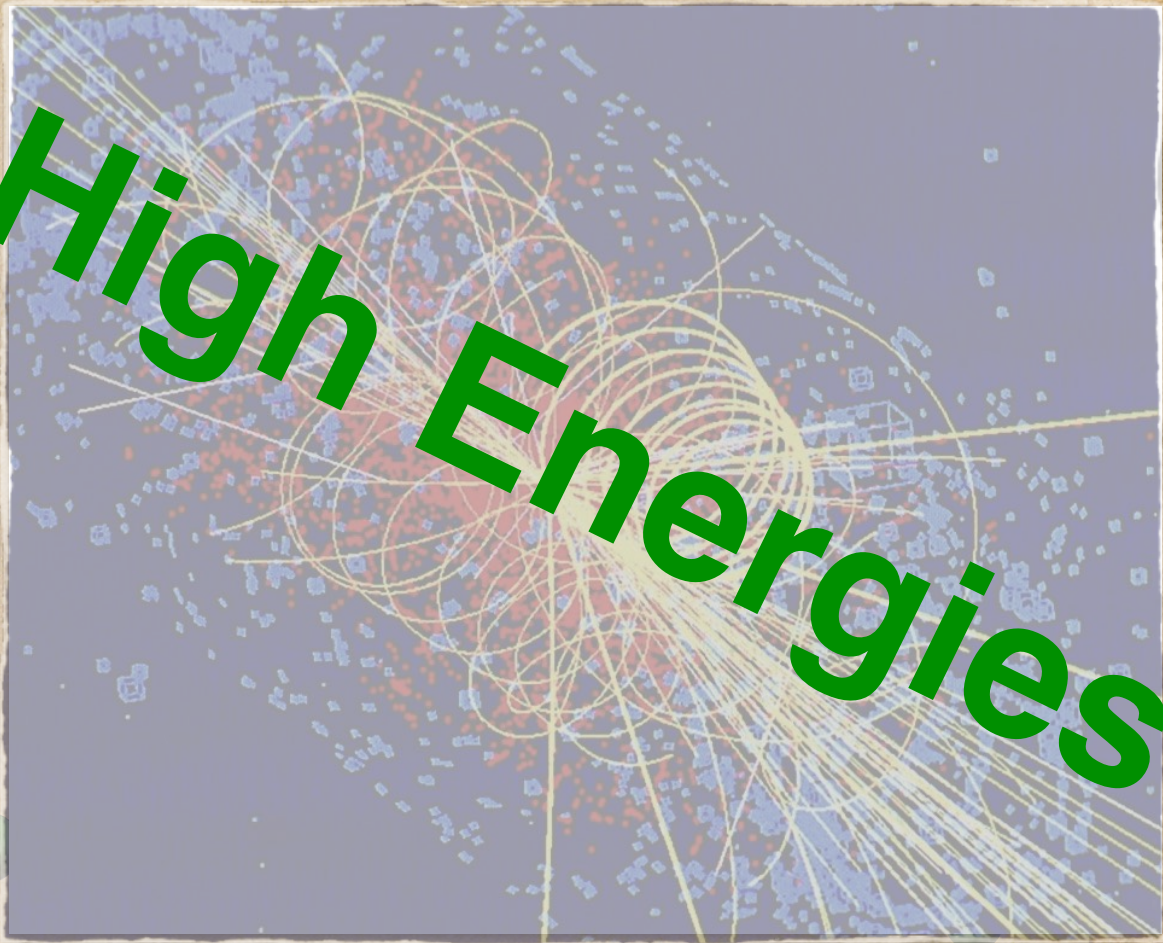
Credit: Lucas Taylor





Big Machines

Credit: CERN



High Energies

Credit: Lucas Taylor

and Tiny Particles

Physics at the Femtoscale

Frederik Van der Veken

INSPYRE 2020

frederikvanderveken@gmail.com

1

What scale... ?

Matter

Atom

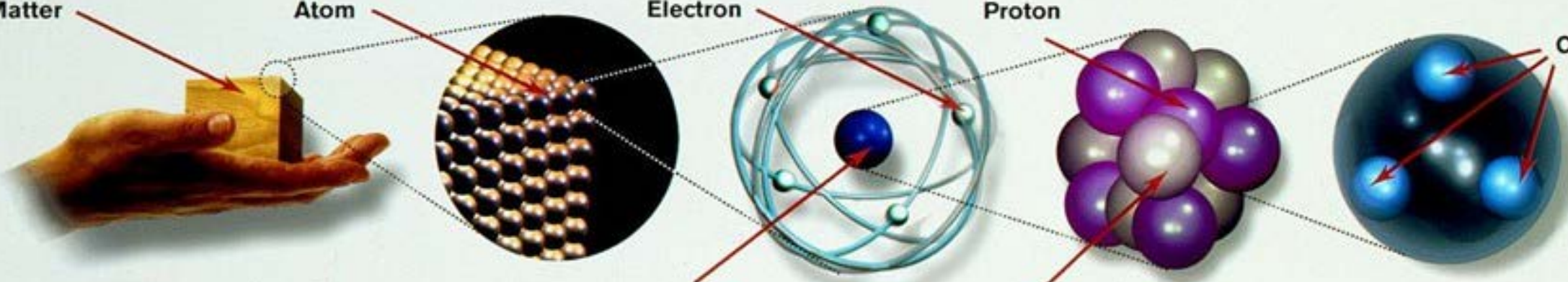
Electron

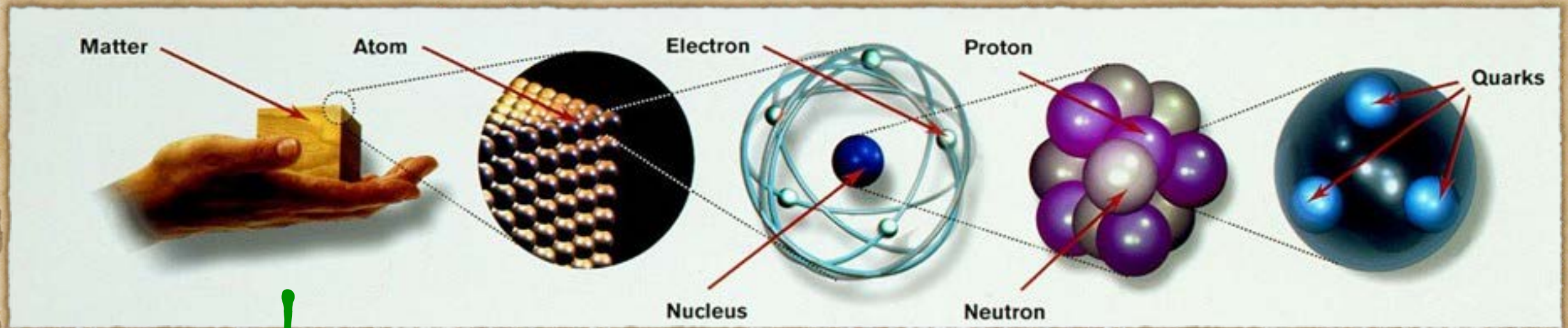
Proton

Quarks

Nucleus

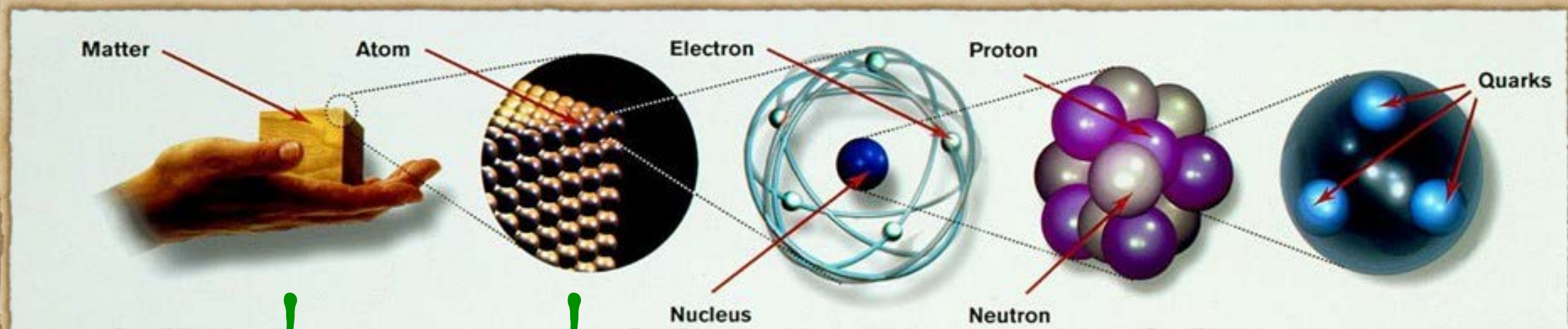
Neutron





5cm

(10^{-2}m)

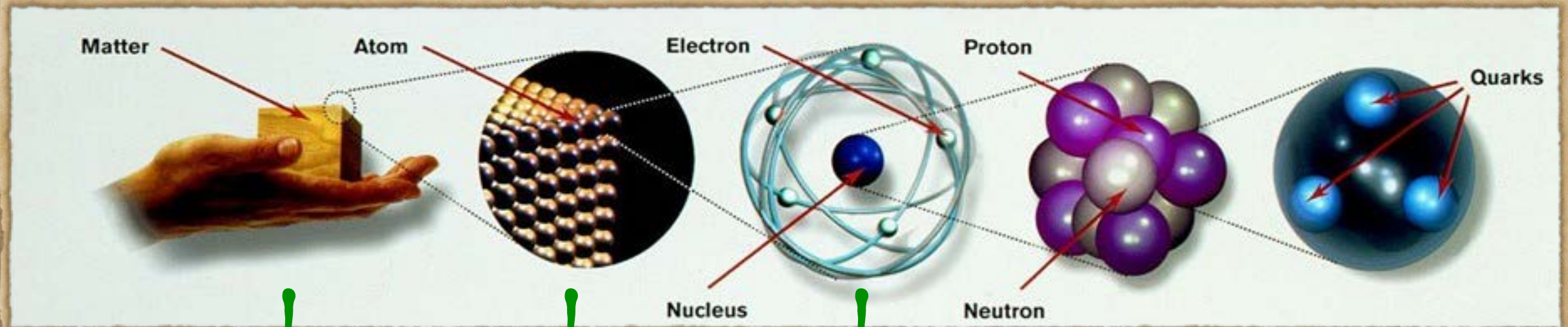


5cm

(10^{-2}m)

1Å

(10^{-10}m)



5cm

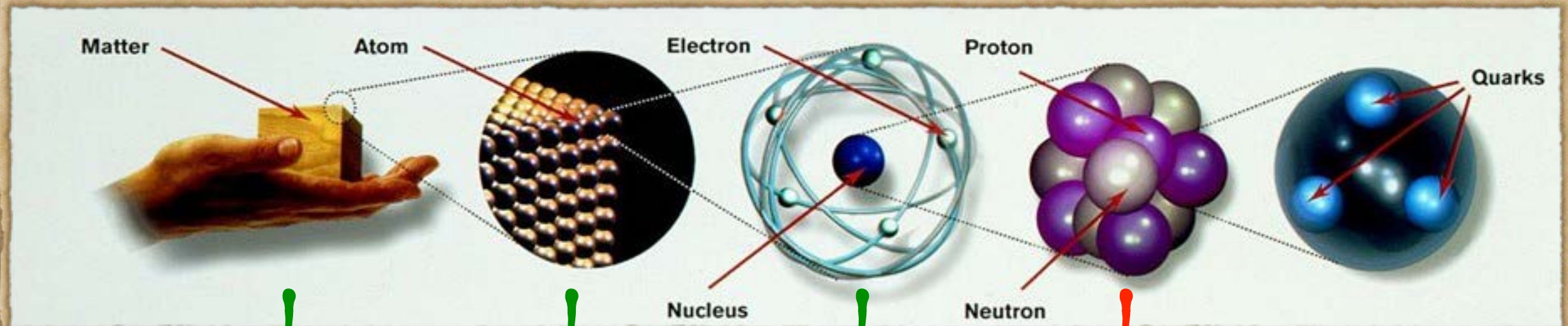
1Å

0.01pm

(10^{-2}m)

(10^{-10}m)

(10^{-14}m)



5cm

(10^{-2}m)

1Å

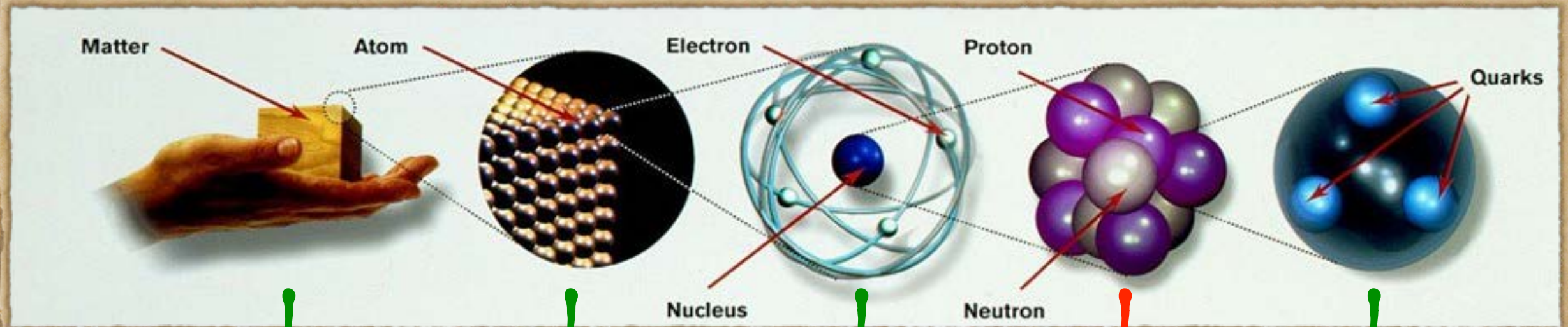
(10^{-10}m)

0.01pm

(10^{-14}m)

Femto!

(10^{-15}m)



5cm

(10^{-2}m)

1Å

(10^{-10}m)

0.01pm

(10^{-14}m)

1am

(10^{-18}m)

Femto!

(10^{-15}m)

Matter

Atom

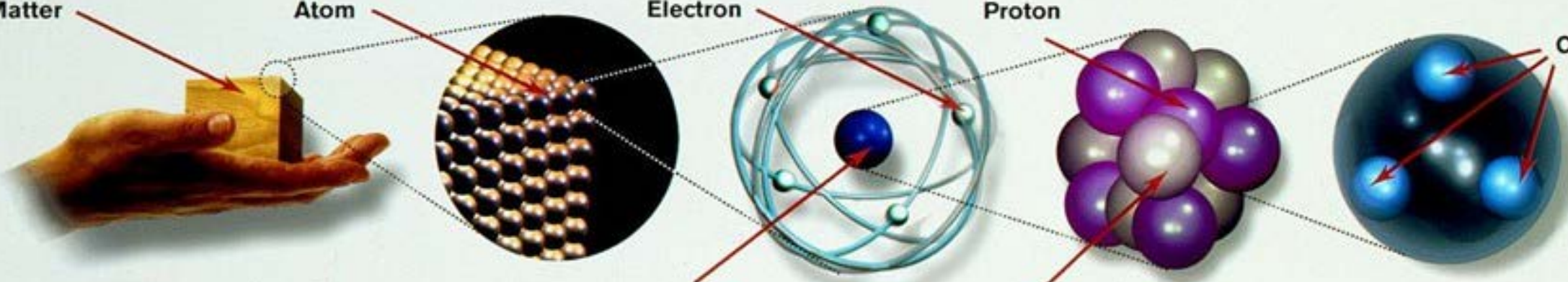
Electron

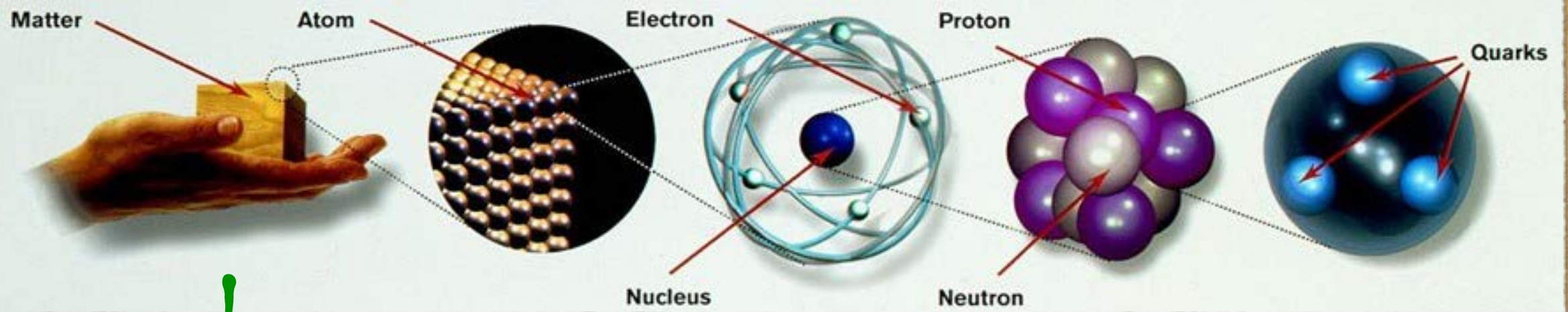
Proton

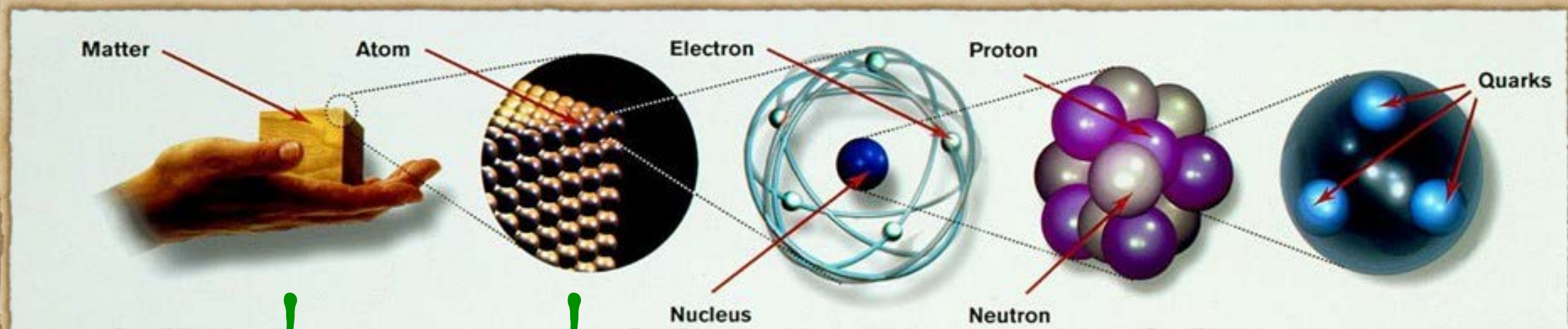
Quarks

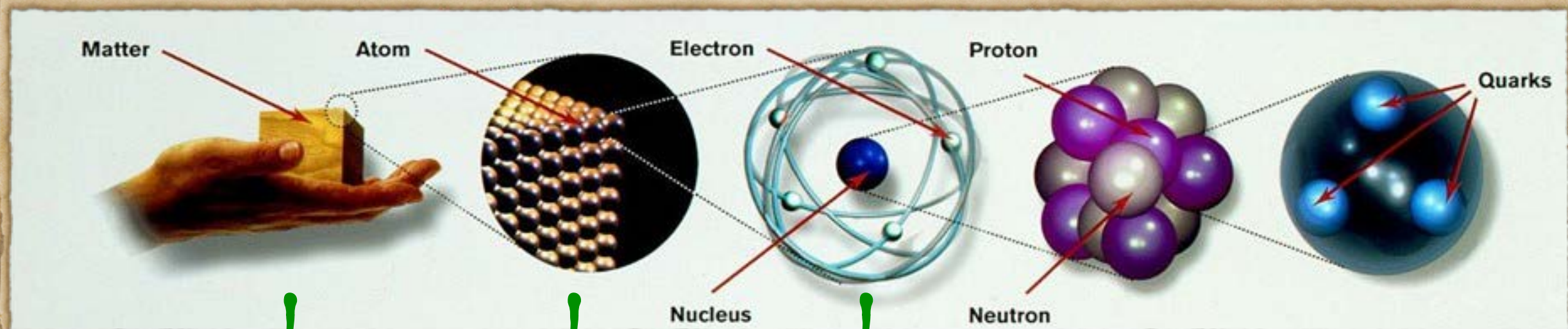
Nucleus

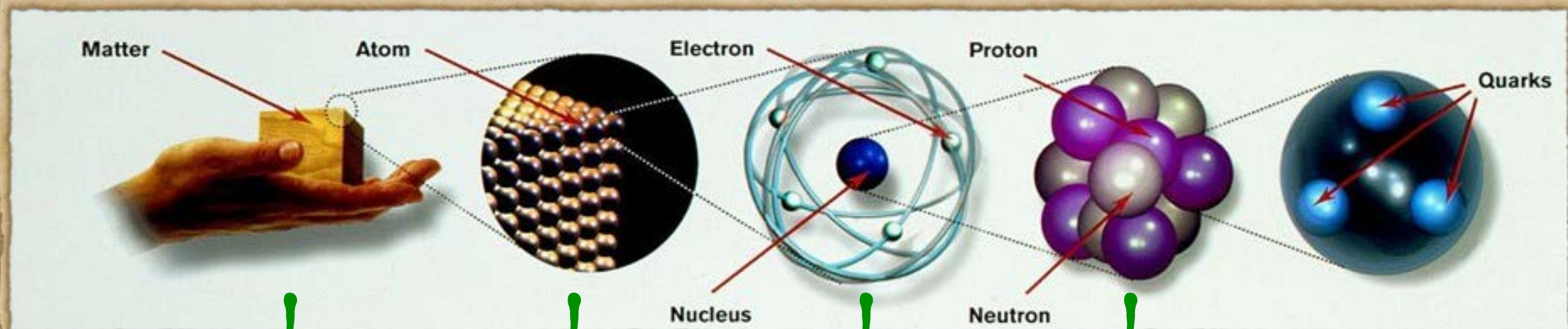
Neutron



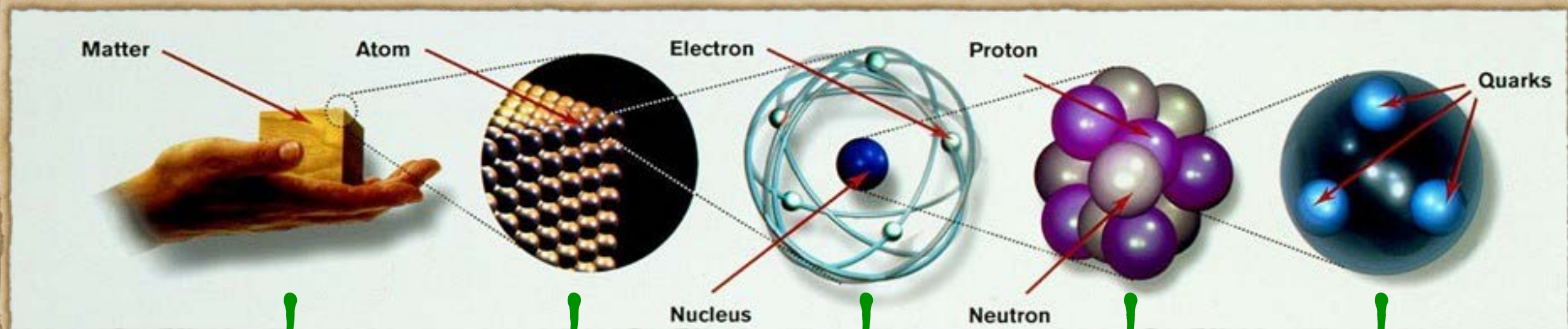








Credit: CERN



Credit: CERN



Credit: CERN

Big machines
reach high energy
By accelerating protons
(of femtometer size)
and use them to search
for tiny particles

2

Big Machines

Particle Colliders

Particle Colliders

Accelerate: increase the energy of their particles

Particle Colliders

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Collide: smash two particles on each other
to release extreme energy

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Detect: observe the creation of (new) particles

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Detect: observe the creation of (new) particles

Understand: analyse the results, to
deeply probe the mysteries of Life

Particle Colliders

Accelerate: increase the energy of their particles

Collide: smash two particles on each other
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Detect: observe the creation of (new) particles

~~**Understand:** analyse the results, to
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Particle Colliders

Accelerate: increase the energy of their particles

Collide: smash two particles on each other
to release extreme energy

Detect: observe the creation of (new) particles

~~**Understand:** analyse the results, to
deeply probe the mysteries of Life~~

→ Humans, not machines (though this is changing...)

Particle Colliders

Prime example: the **Large Hadron Collider**

Particle Colliders

Prime example: the **Large Hadron Collider**



26.659 km

9593 magnets

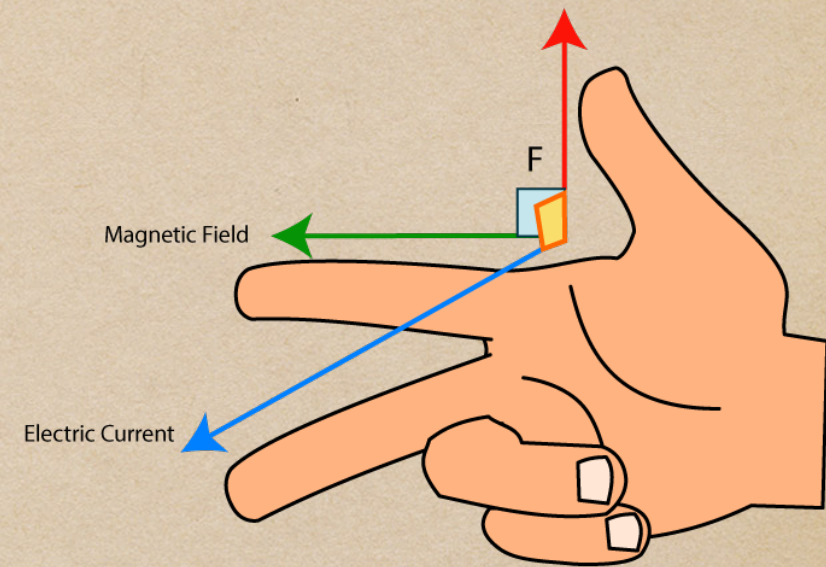
1~2 **billion** collisions / s

Accelerators

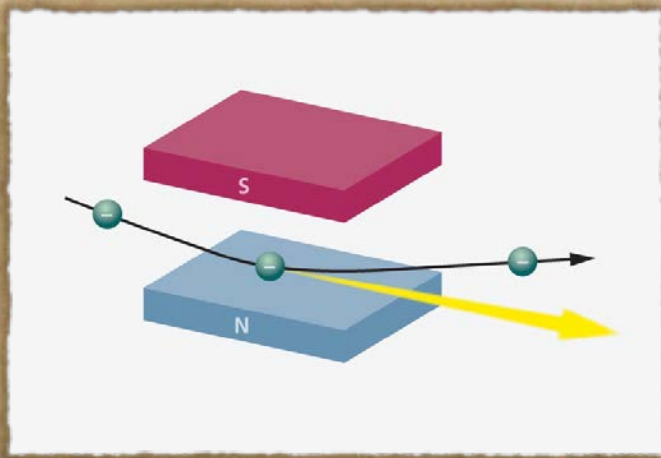
Magnets?

Accelerators

Magnets?

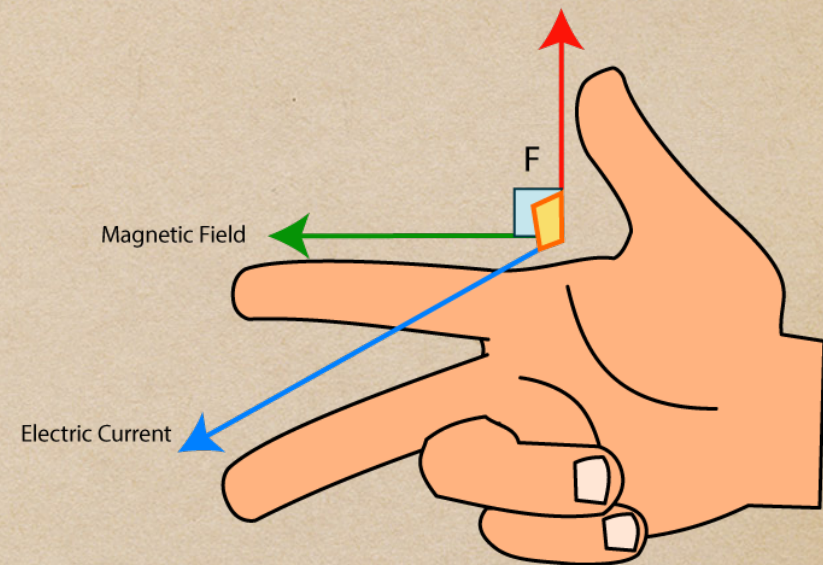


Lorentz force is *perpendicular*

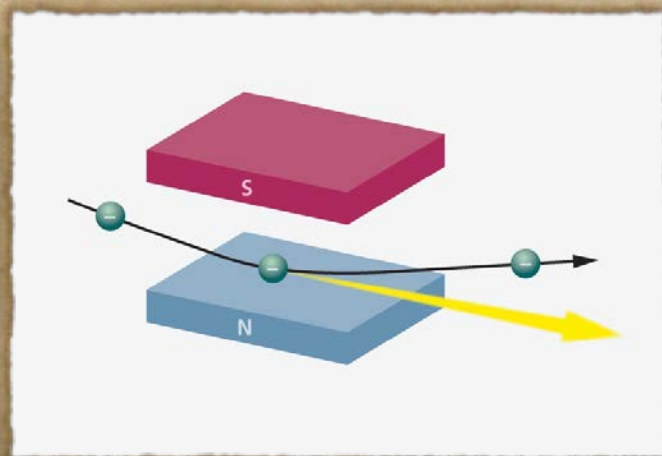


Accelerators

Magnets?



Lorentz force is *perpendicular*



Effect of magnet is in 'wrong' direction

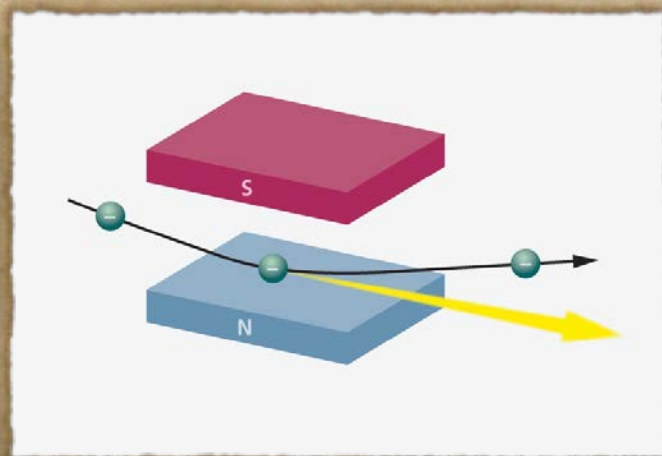
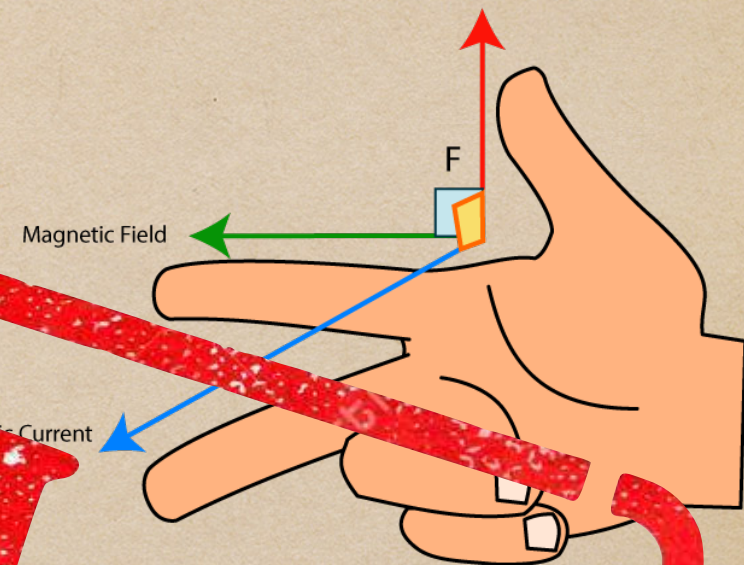
Like pushing a swing from the side



Accelerators

Magnets?

Lorentz force is perpendicular



Effect of magnet is in 'wrong' direction

Like pushing a swing from the side



Accelerators

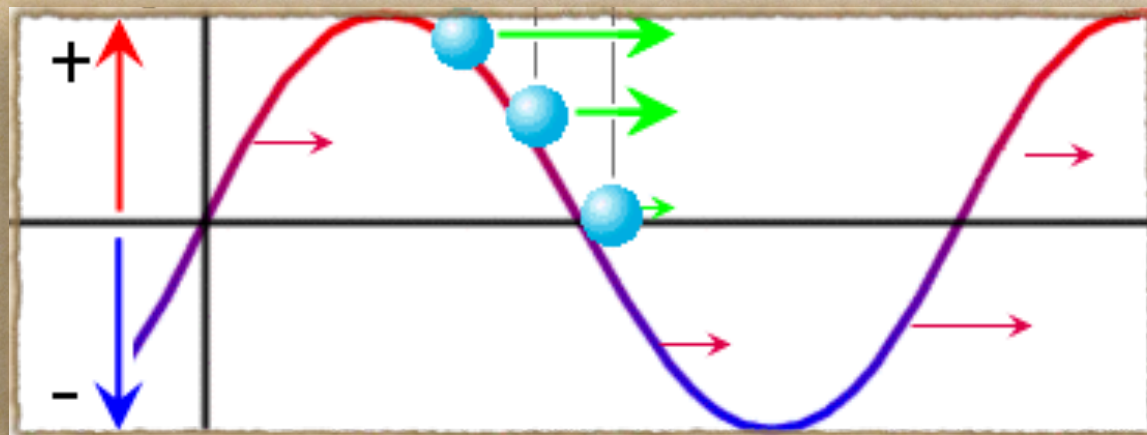
Accelerators

Electric field

Accelerators

Electric field

Force is *longitudinal*

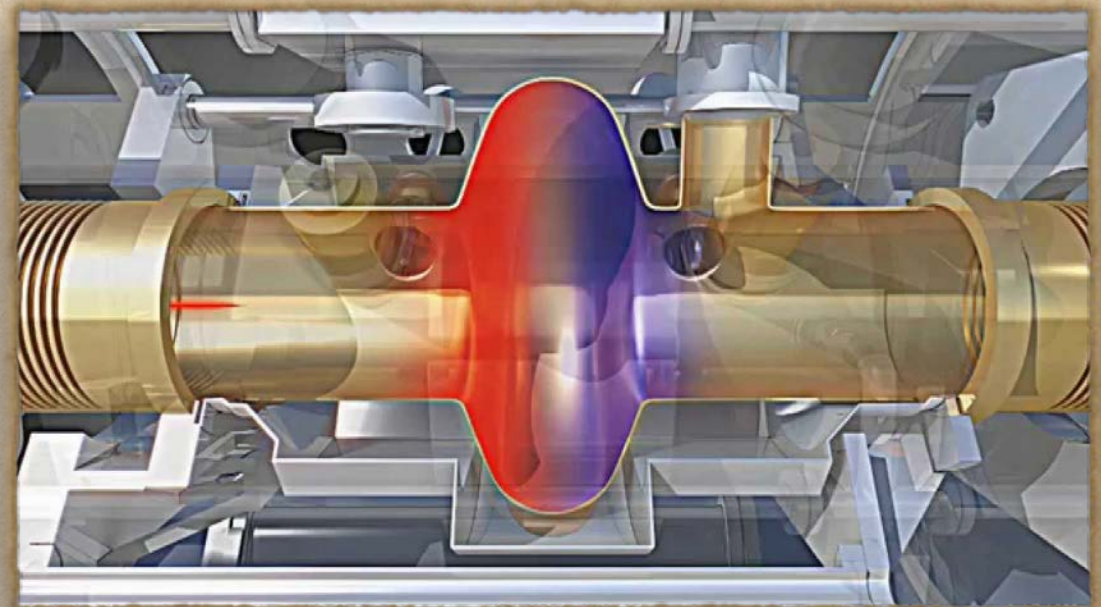


Credit: JLAB

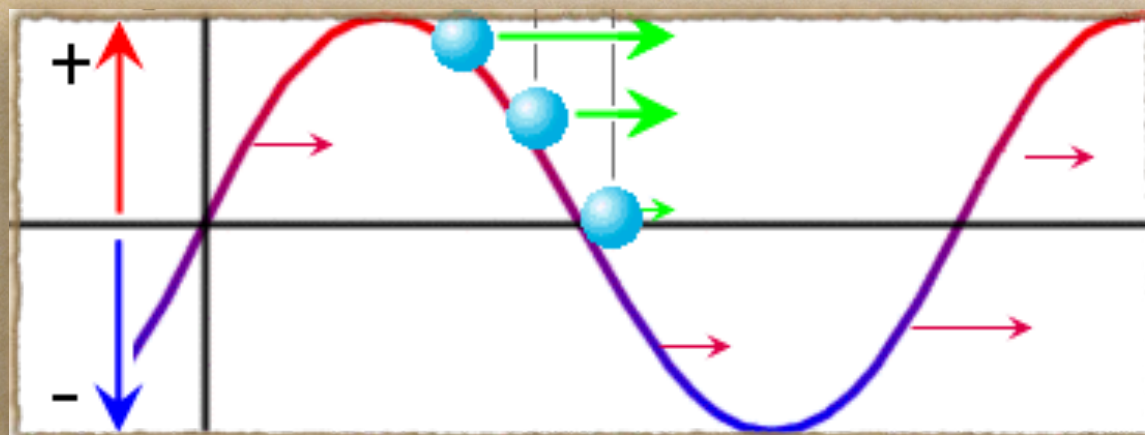
Accelerators

Electric field: cavities

Force is longitudinal



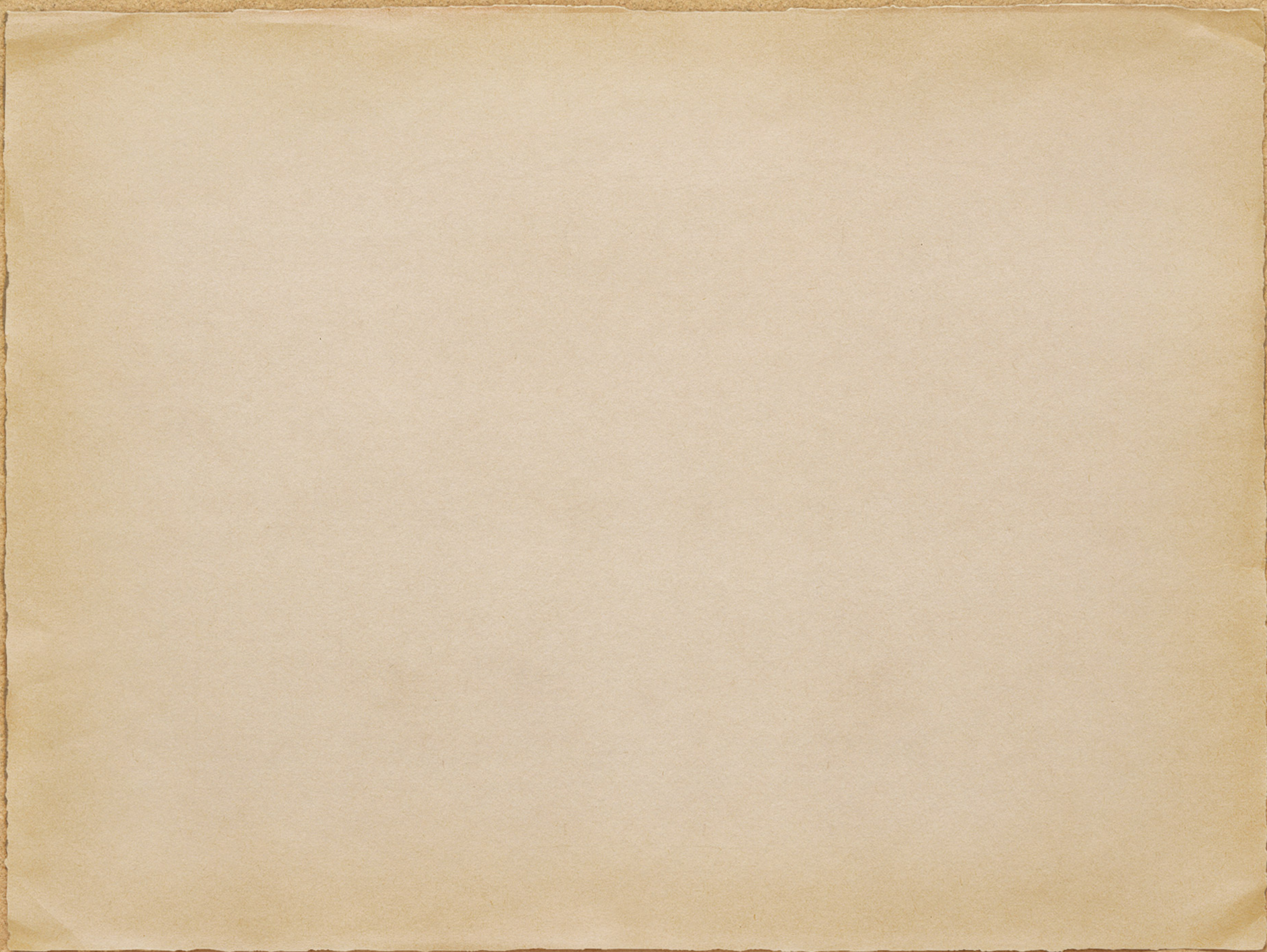
Credit: CERN



Credit: JLAB

Field should be positive at right moment

Correct timing is crucial



But..

But..

But..

But..

LHC has 9600 magnets!

But..

But..

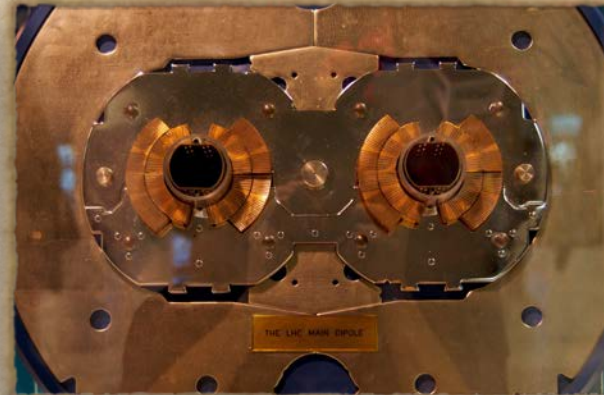
LHC has 9600 magnets!

Then.. why?

Magnets

Magnets

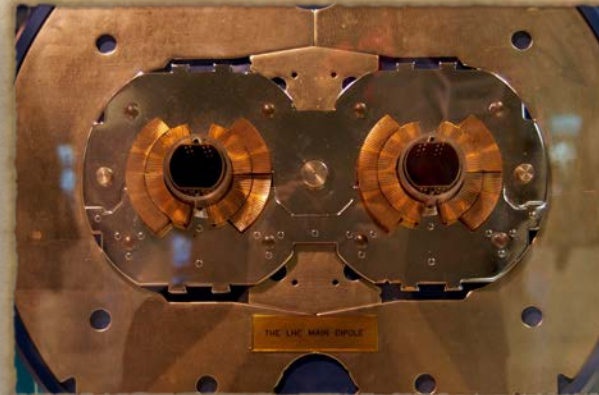
dipole:
bending



Credit: CERN

Magnets

dipole:
bending



Credit: CERN

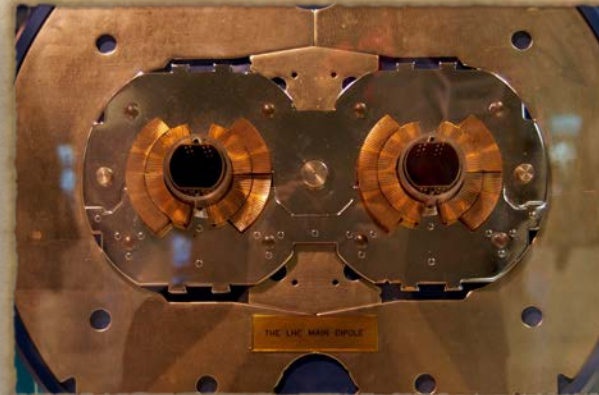
quadrupole:
focussing



Credit: CERN

Magnets

dipole:
bending



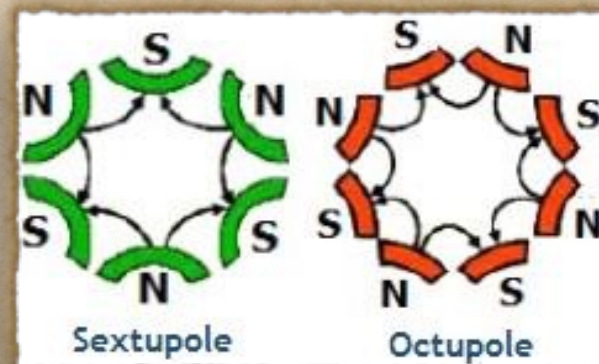
Credit: CERN

quadrupole:
focussing

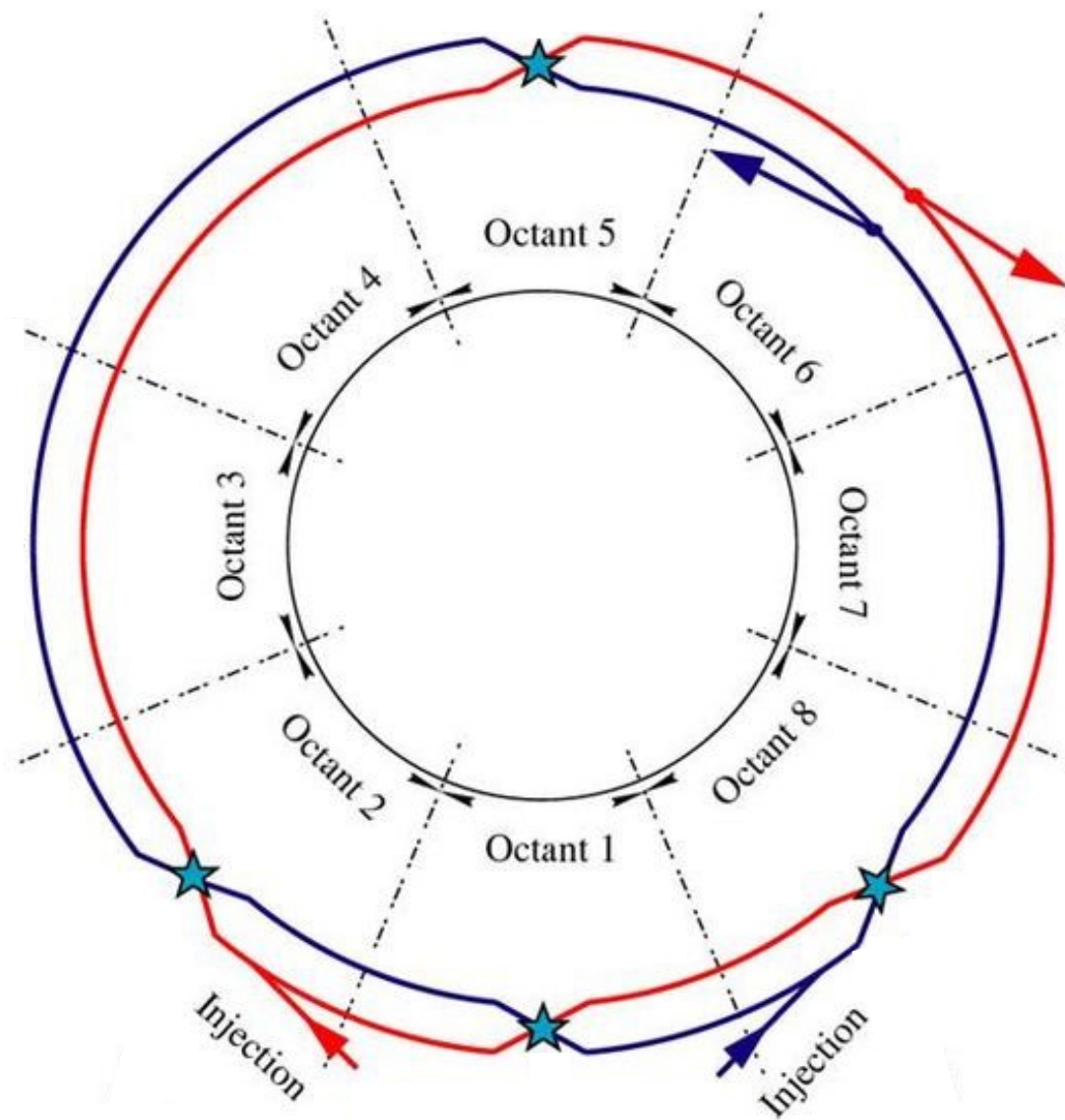


Credit: CERN

higher orders:
other stuff

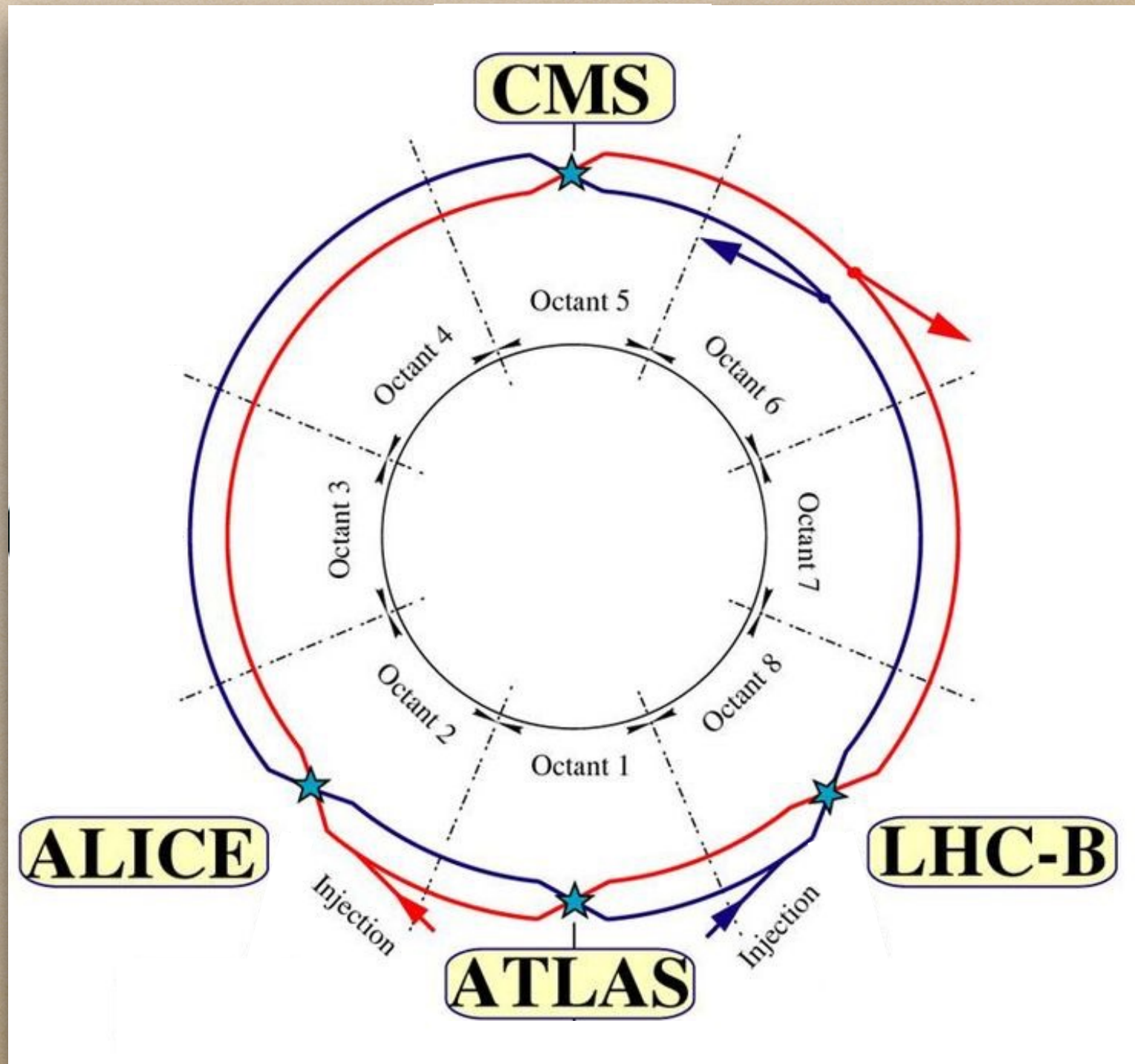


The Large Hadron Collider



The Large Hadron Collider

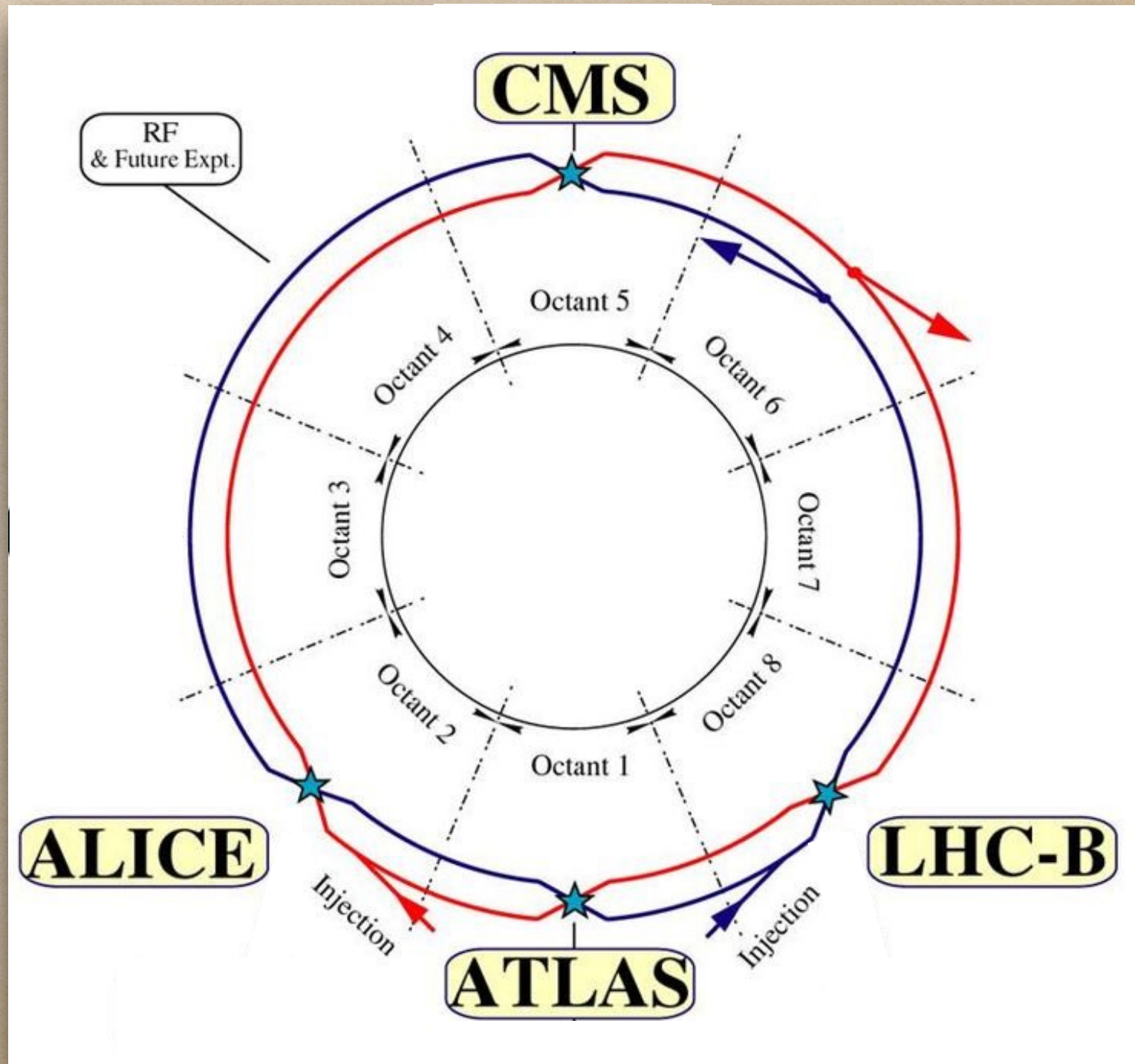
Detectors



The Large Hadron Collider

Detectors

Acceleration

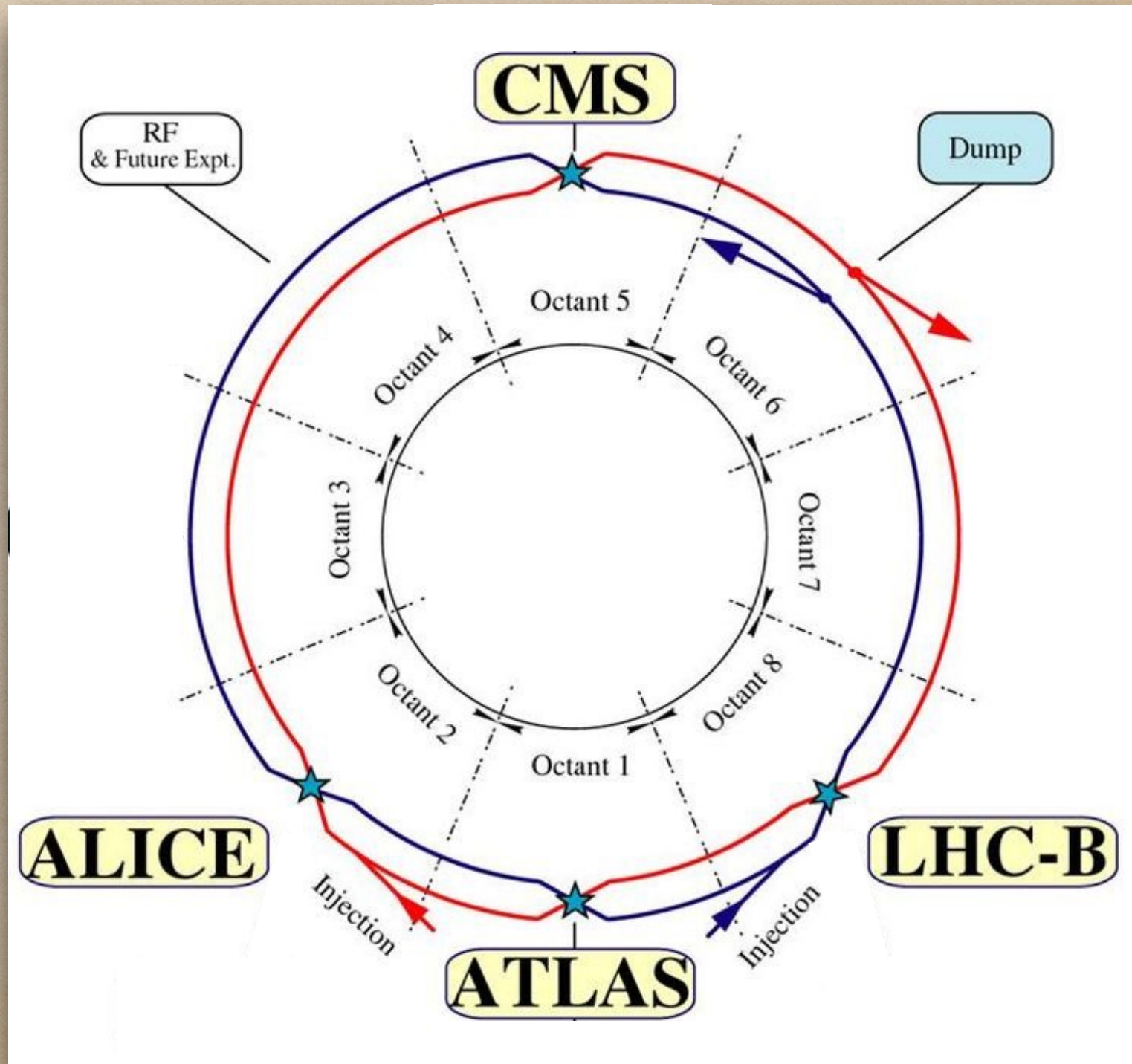


The Large Hadron Collider

Detectors

Acceleration

Beam dump



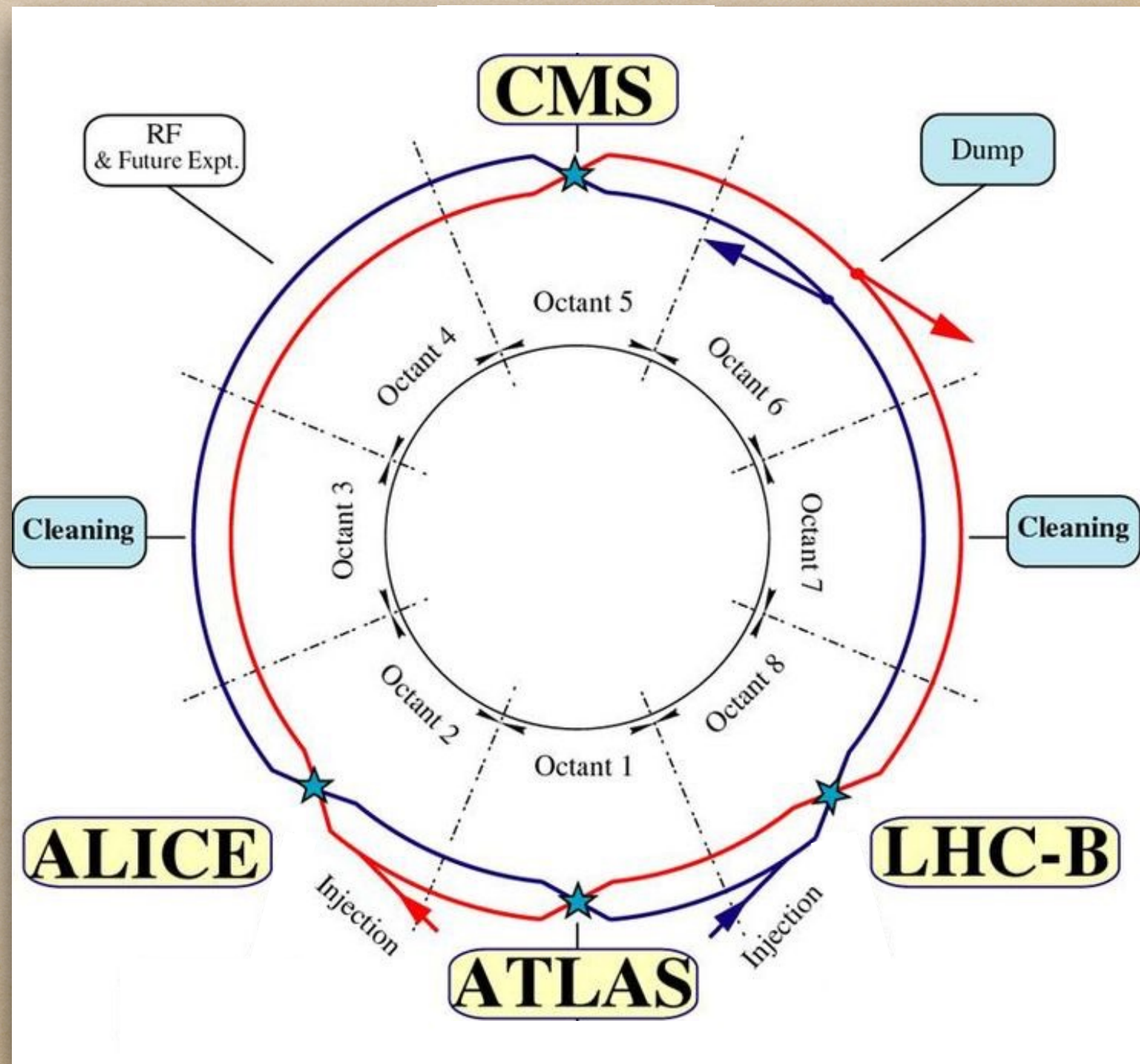
The Large Hadron Collider

Detectors

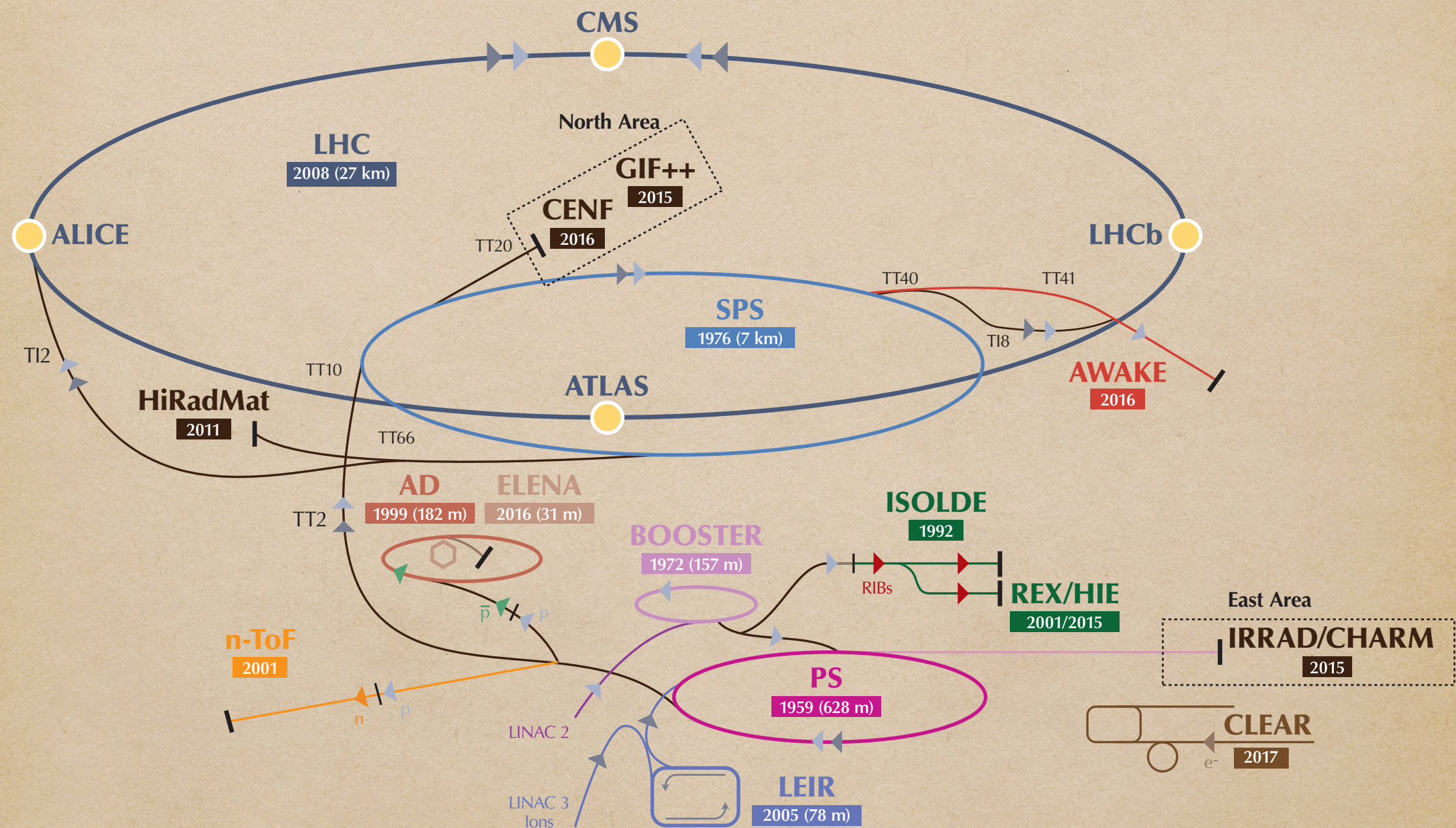
Acceleration

Beam dump

Beam cleaning



The Accelerator Complex



Detectors

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}$) $\sim 1\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000\text{A}$

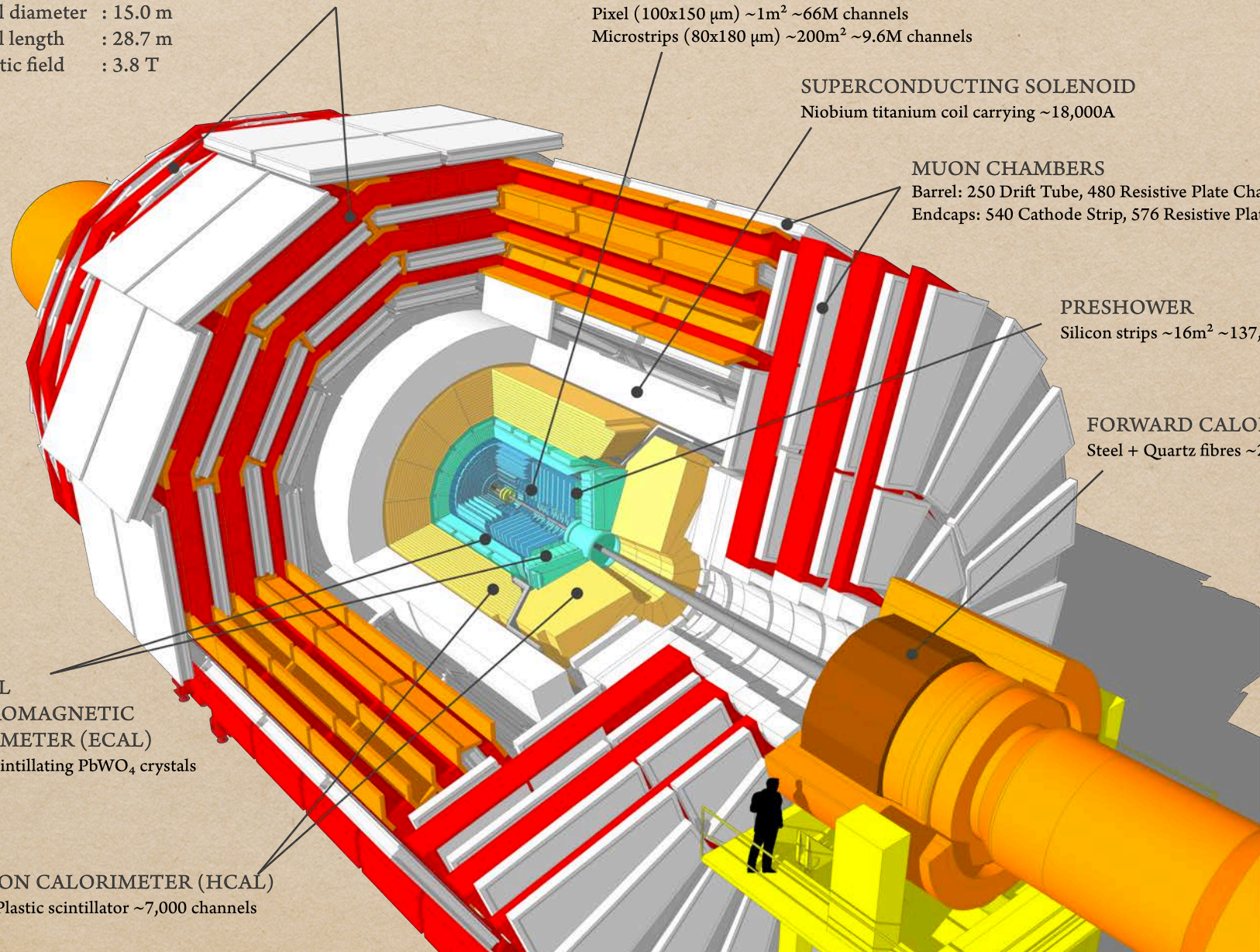
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

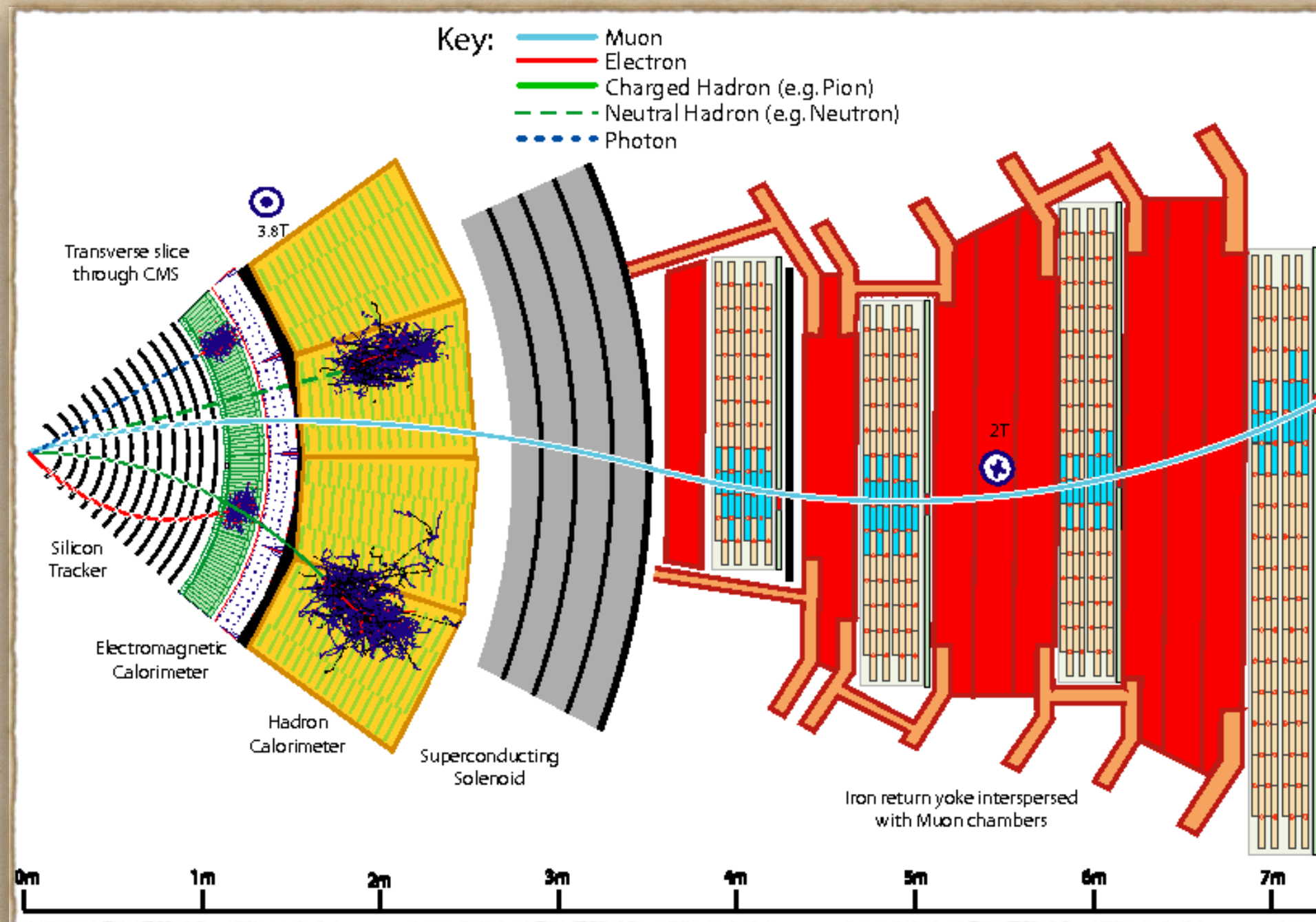
FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels



Detectors



3

Tiny particles



**What are we
made of?**



**What are we
made of?**

**What is the universe
made of?**



**What are we
made of?**

**What is the universe
made of?**

**Why does everything
just “work”?**



**What are we
made of?**

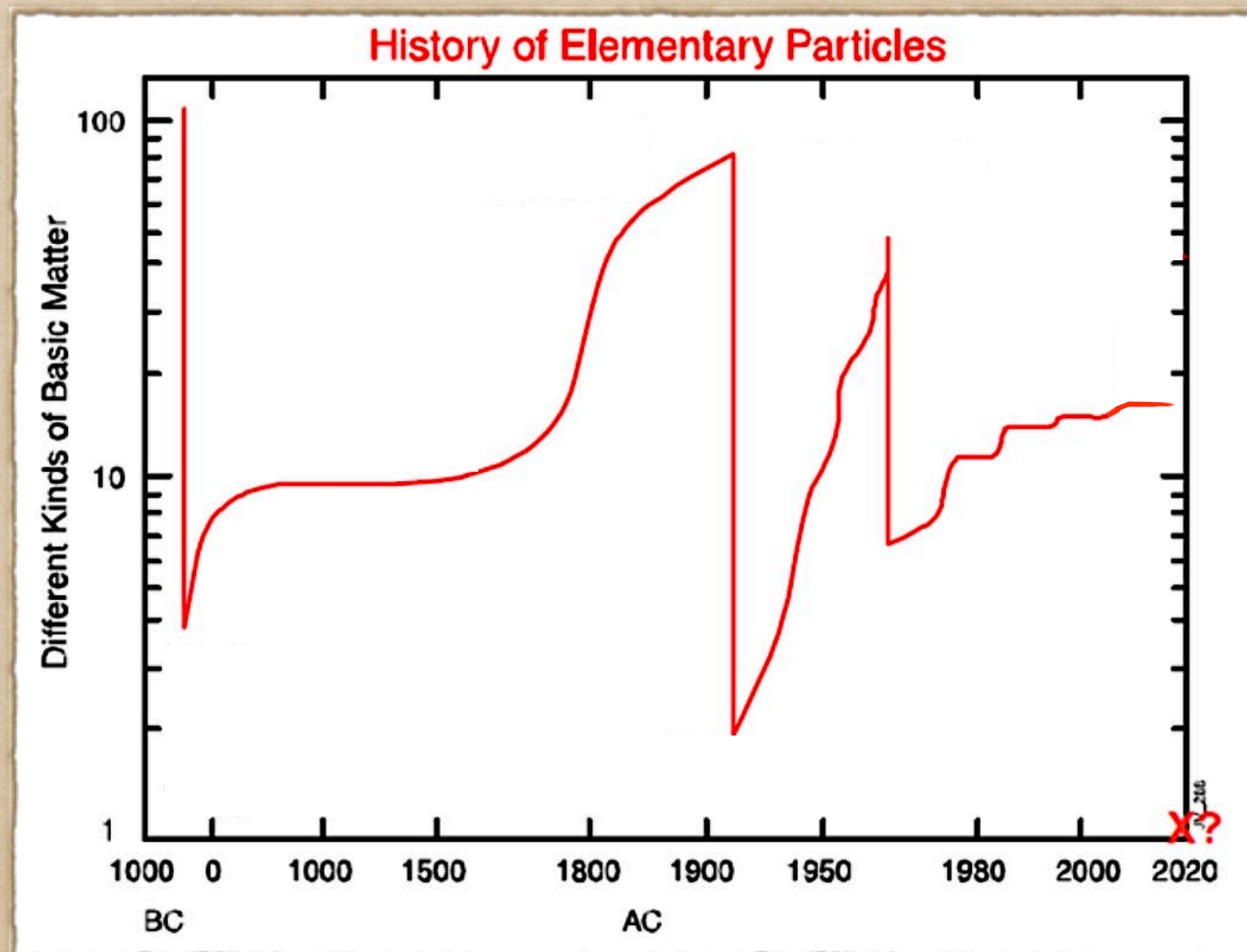
**What is the universe
made of?**

**Why does everything
just “work”?**

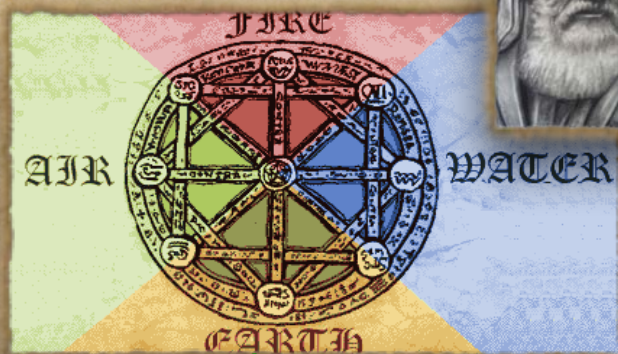
... ?



Basic Bricks of the Universe

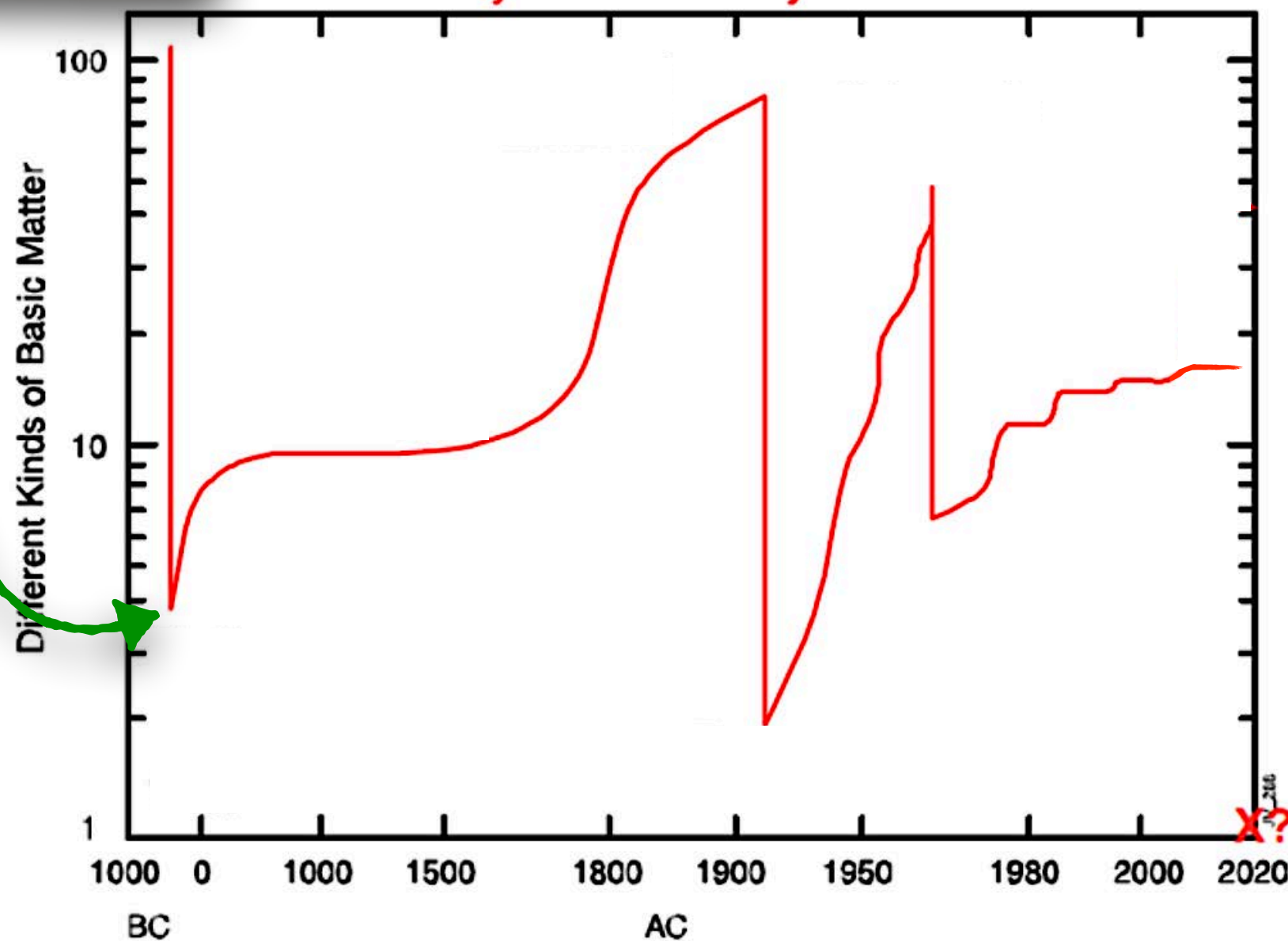


Credit: <http://arxiv.org/abs/1311.1769>

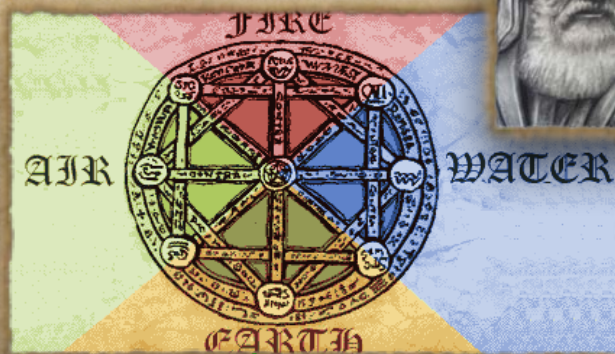


Bricks of the Universe

History of Elementary Particles

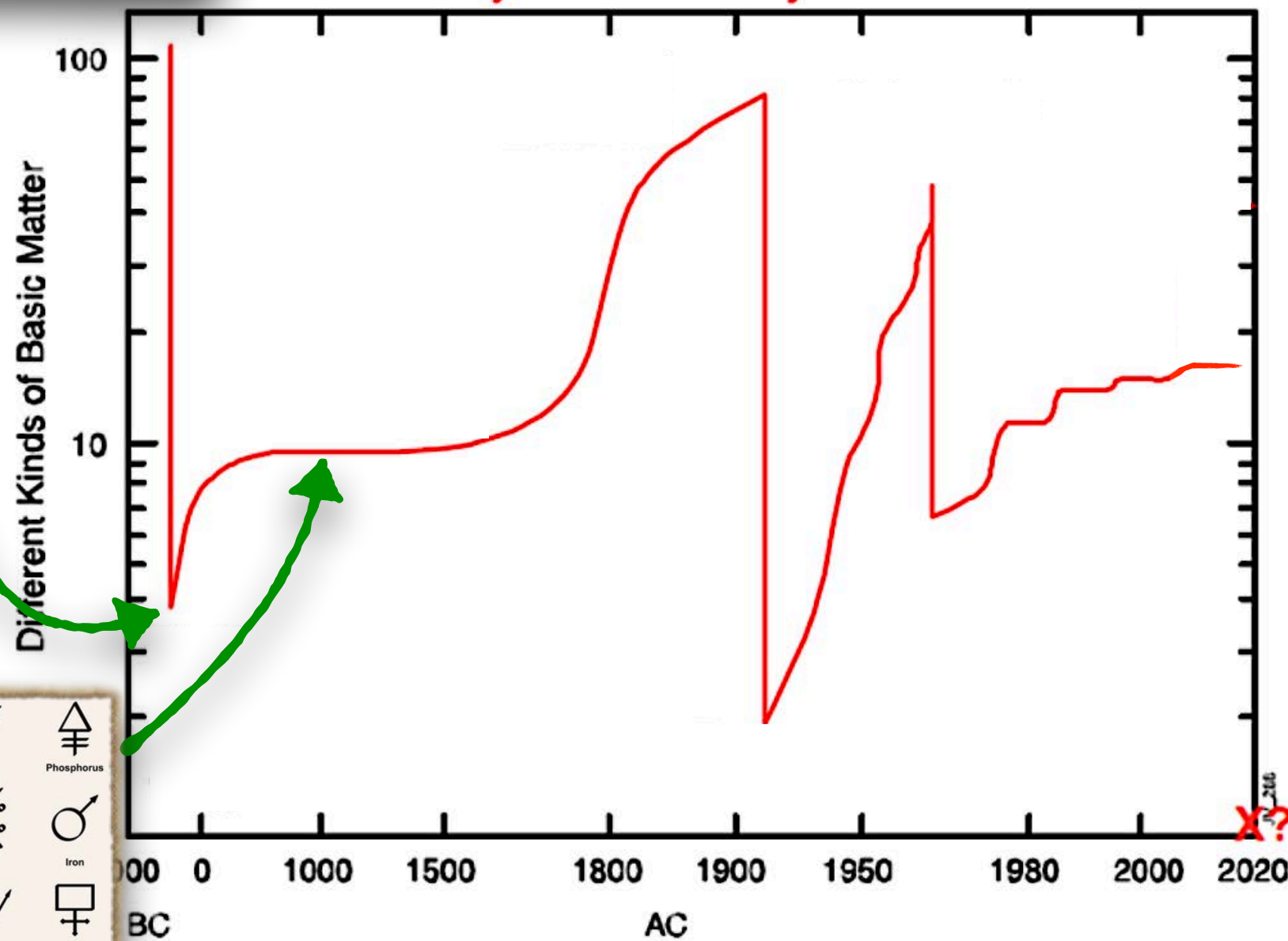


Credit: <http://arxiv.org/abs/1311.1769>



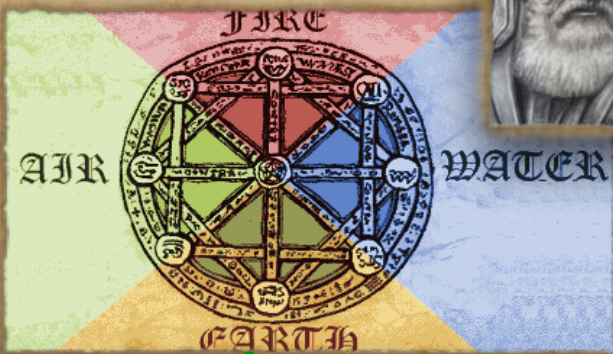
Bricks of the Universe

History of Elementary Particles



			
Antimony	Bismuth	Gold	Phosphorus
			
Lead	Mercury	Copper	Iron
			
Sulfur	Tin	Silver	Potassium carbonate
			
Zinc	Platinum	Magnesium	Arsenic

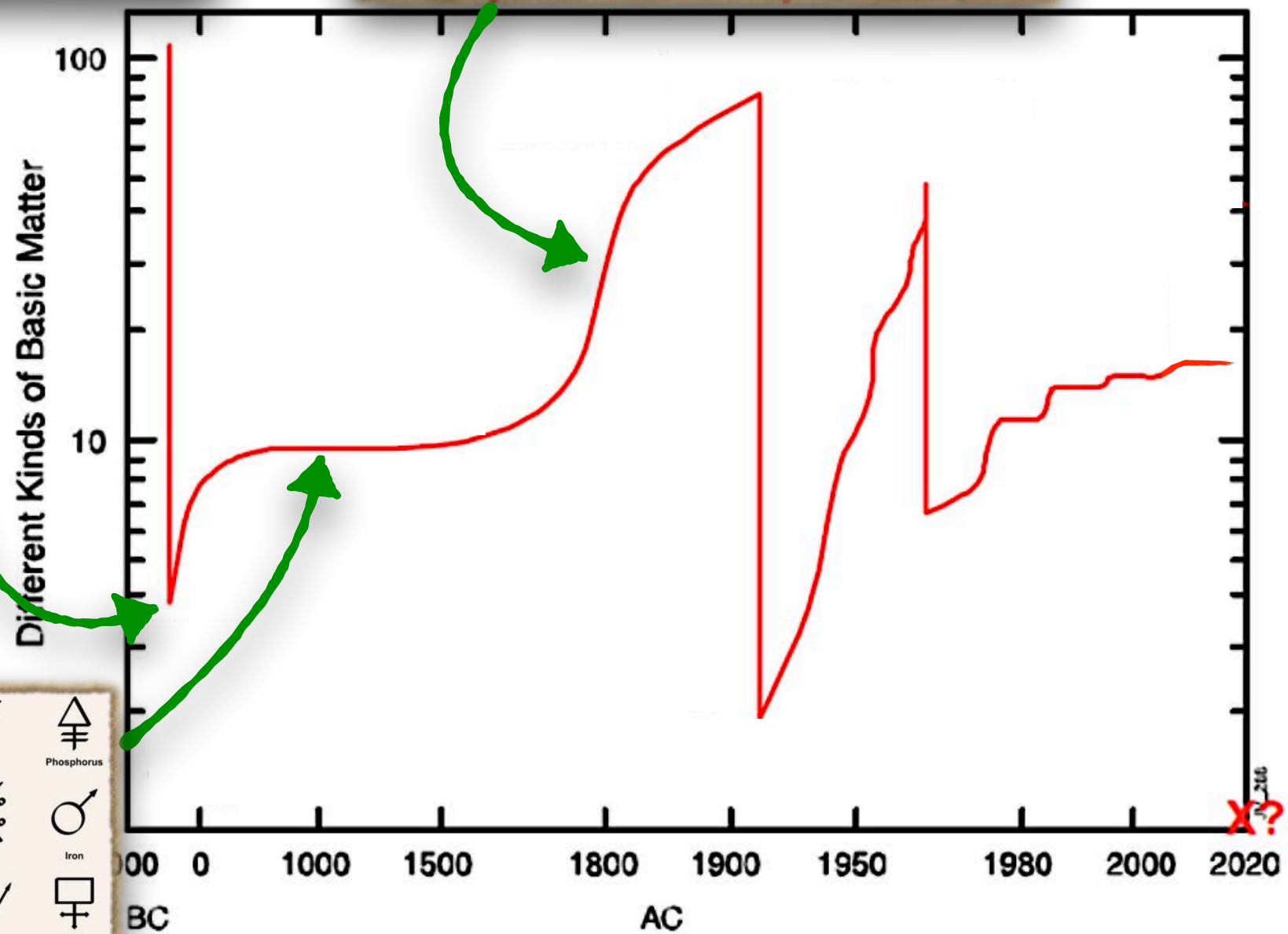
Credit: <http://arxiv.org/abs/1311.1769>



period	group	1	2											13	14	15	16	17	18
1	1	1	2																2
		H																	He
2		3	4											5	6	7	8	9	10
		Li	Be											B	C	N	O	F	Ne
3		11	12											13	14	15	16	17	18
		Na	Mg											Al	Si	P	S	Cl	Ar
4		19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
		K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5		37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
		Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6		55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
		Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7		87	88	89	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
		Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

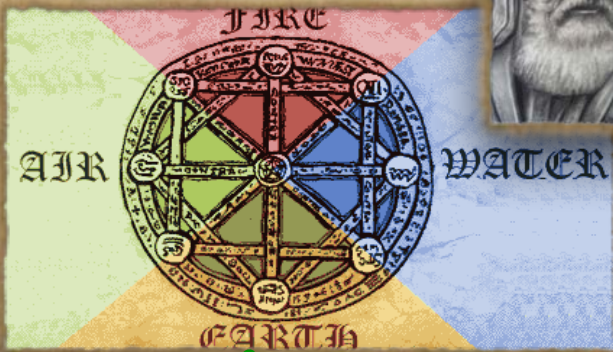

lanthanoid series	6	58	59	60	61	62	63	64	65	66	67	68	69	70	71
		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
actinoid series	7	90	91	92	93	94	95	96	97	98	99	100	101	102	103
		Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

niverse



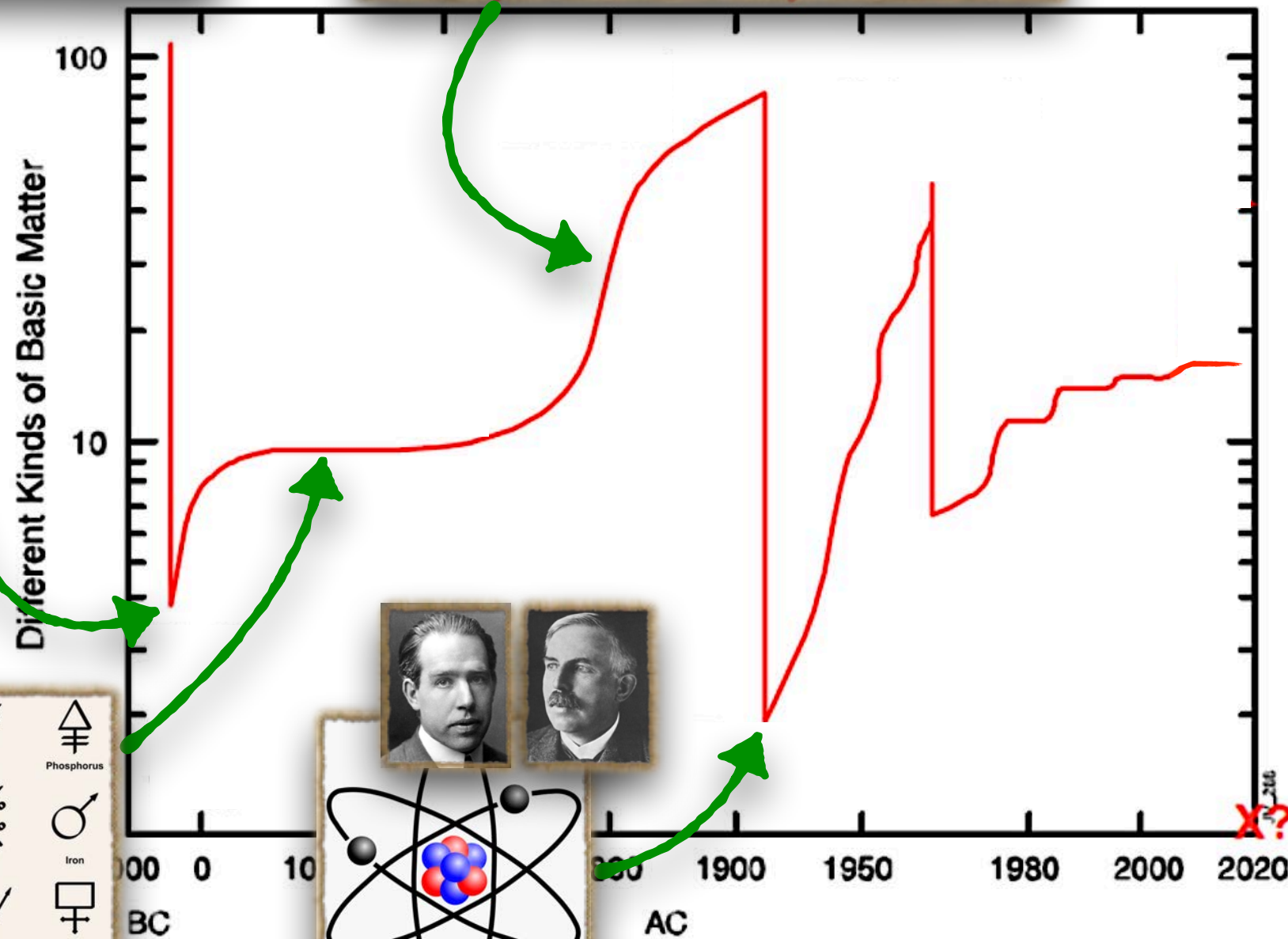
Antimony	Bismuth	Gold	Phosphorus
Lead	Mercury	Copper	Iron
Sulfur	Tin	Silver	Potassium carbon
Zinc	Platinum	Magnesium	Arsenic

Credit: <http://arxiv.org/abs/1311.1769>

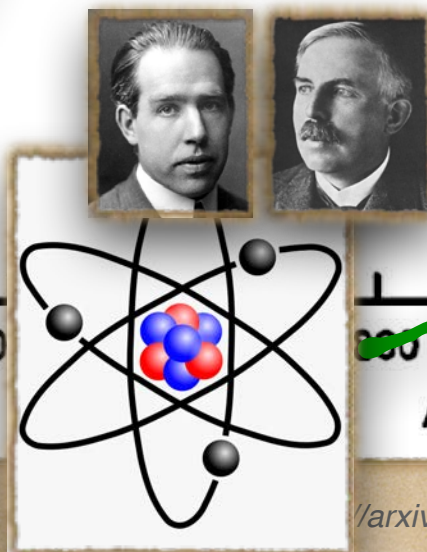



group																18	
1																2	
1	2											13	14	15	16	17	18
1	2											13	14	15	16	17	18
3	4											5	6	7	8	9	10
3	4											5	6	7	8	9	10
11	12											13	14	15	16	17	18
11	12											13	14	15	16	17	18
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
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55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
87	88	89	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
87	88	89	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
lanthanoid series 6																71	
lanthanoid series 6																71	
actinoid series 7																103	
actinoid series 7																103	

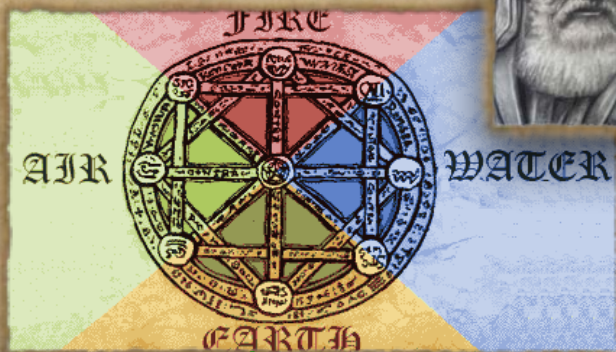
niverse



Antimony	Bismuth	Gold	Phosphorus
Lead	Mercury	Copper	Iron
Sulfur	Tin	Silver	Potassium
Zinc	Platinum	Magnesium	Arsenic



[/arxiv.org/abs/1311.1769](https://arxiv.org/abs/1311.1769)



group

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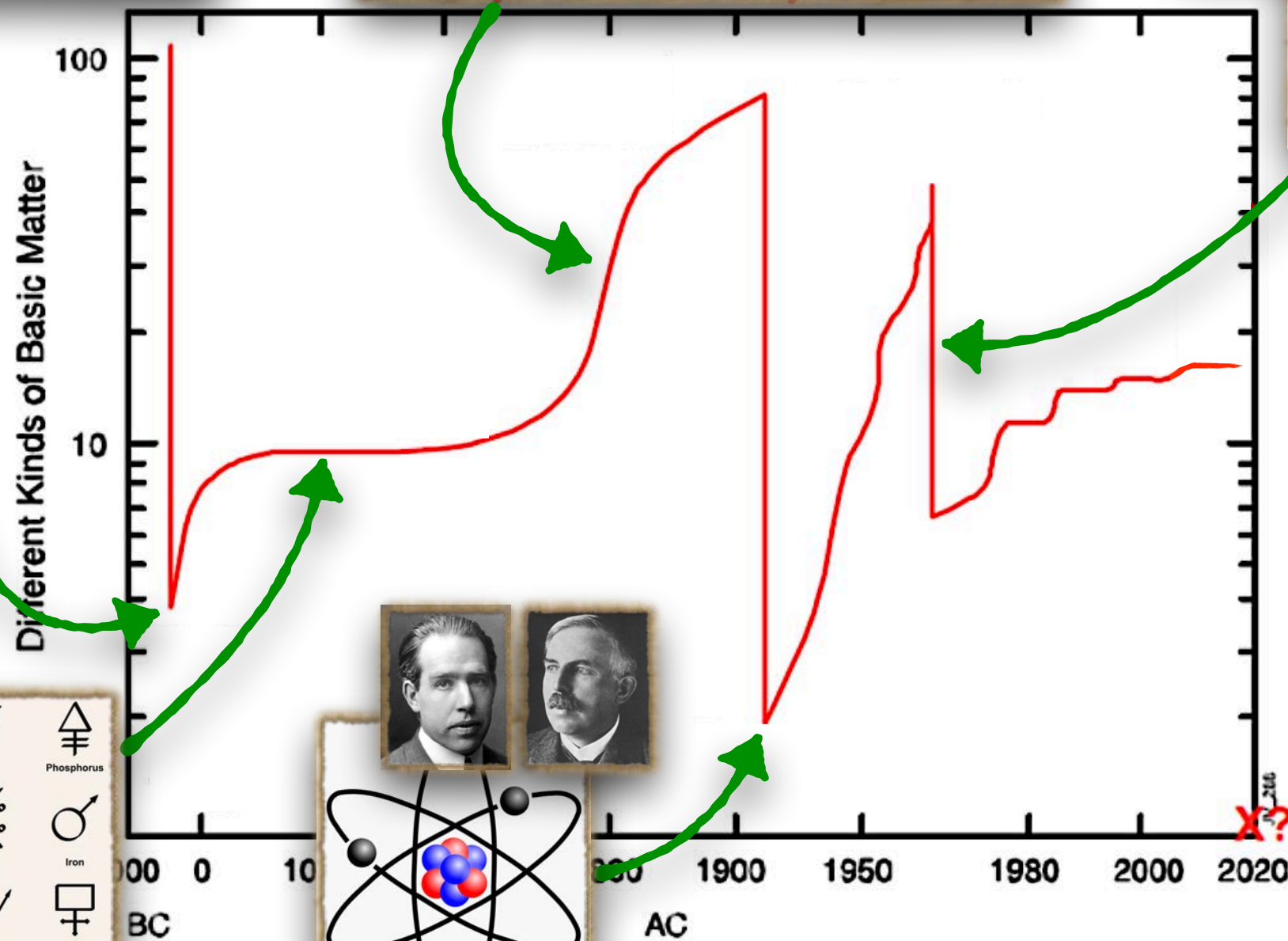
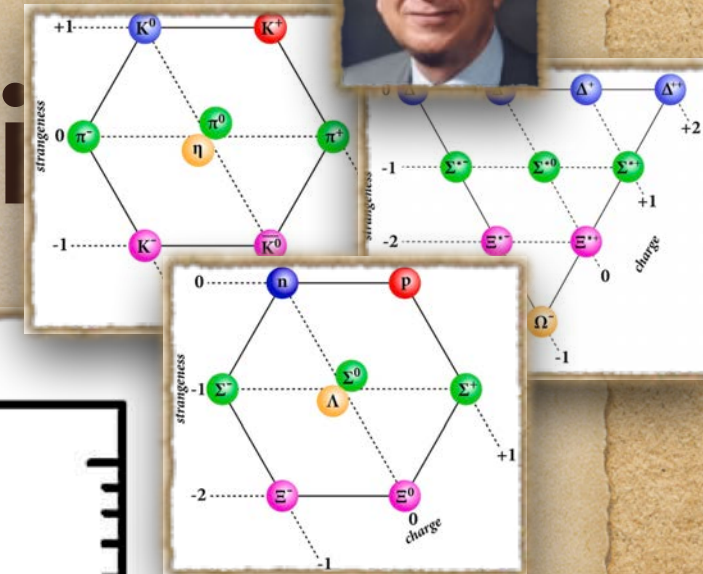
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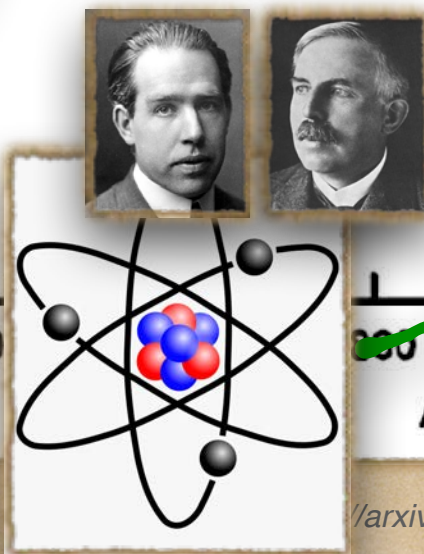
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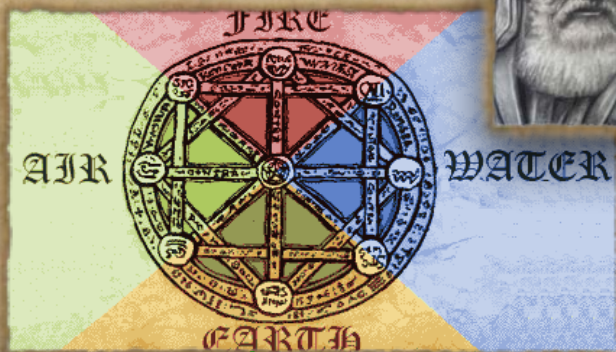
15



Antimony	Bismuth	Gold	Phosphorus
Lead	Mercury	Copper	Iron
Sulfur	Tin	Silver	Potassium
Zinc	Platinum	Magnesium	Arsenic



[/arxiv.org/abs/1311.1769](https://arxiv.org/abs/1311.1769)



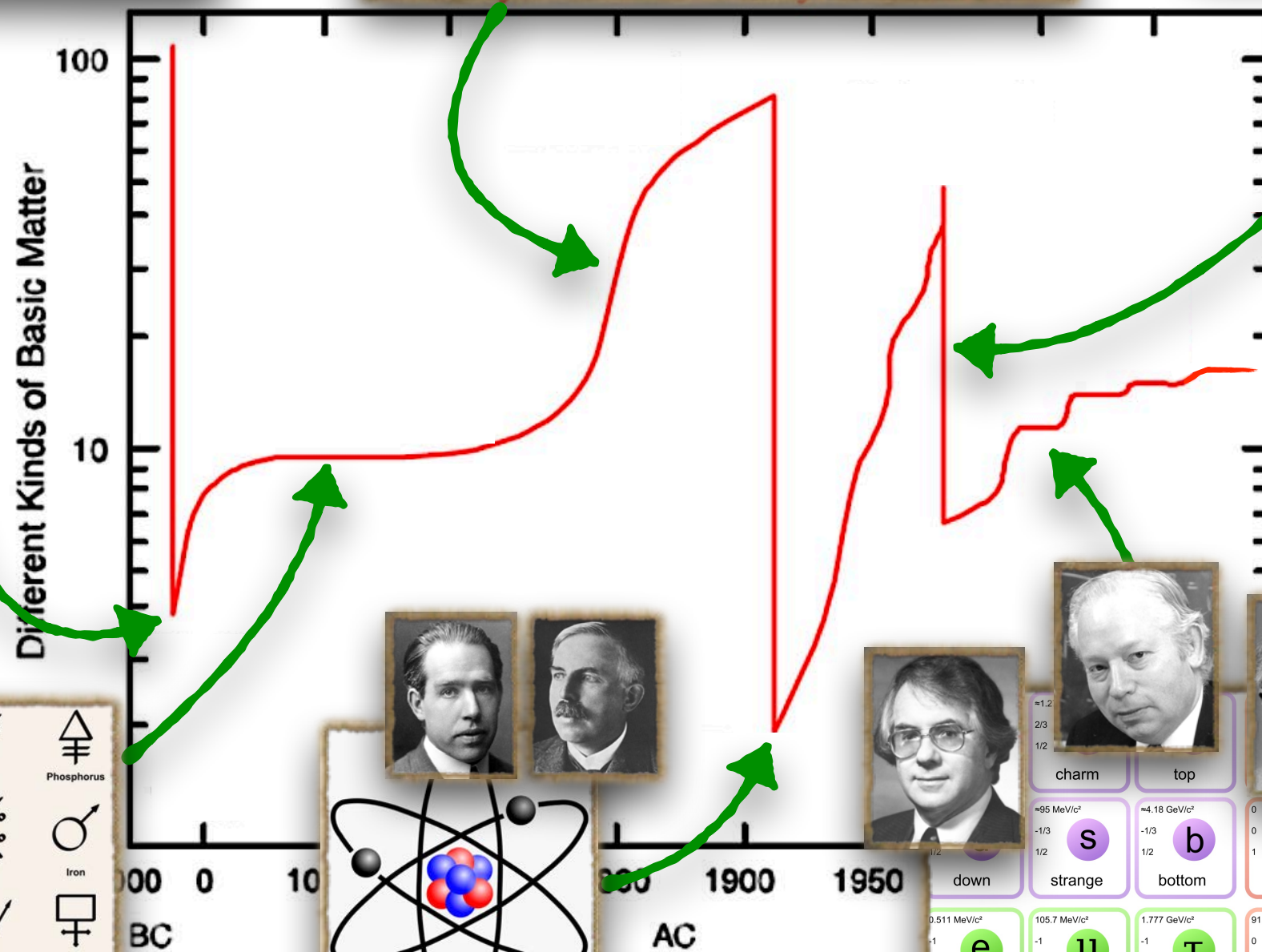
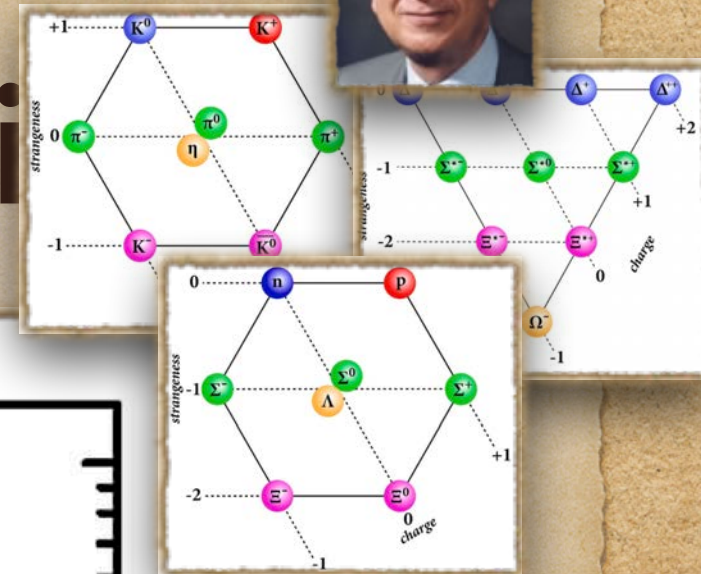
Portrait of Dmitri Mendeleev

group	1	2											13	14	15	16	17	18
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

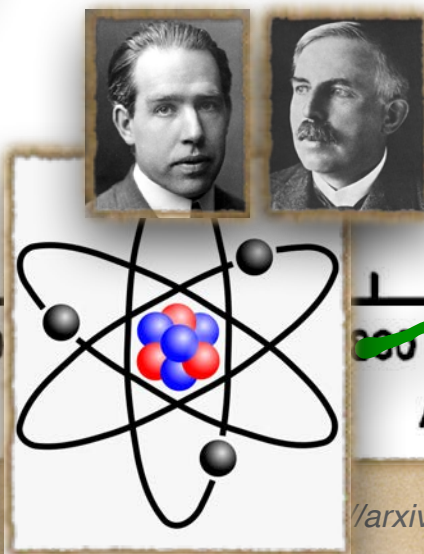
lanthanoid series 6: Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu

actinoid series 7: Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr

ni



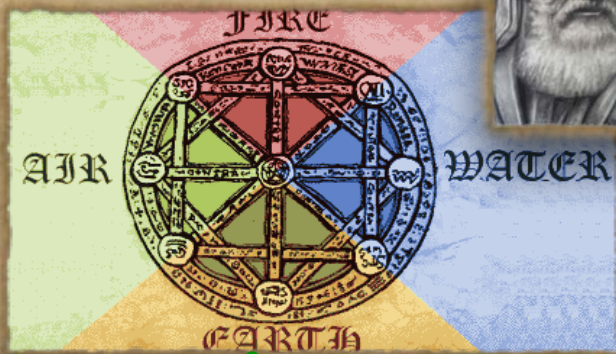
Antimony	Bismuth	Gold	Phosphorus
Lead	Mercury	Copper	Iron
Sulfur	Tin	Silver	Potassium carbonate
Zinc	Platinum	Magnesium	Arsenic



[/arxiv.org/abs/1311.1769](https://arxiv.org/abs/1311.1769)



charm	top	photon
strange	bottom	Z boson
electron	muon	tau
electron neutrino	muon neutrino	tau neutrino
		W boson



group																		18							
period	1																	2							
	1	H																	He						
	2	Li	Be																	B	C	N	O	F	Ne
	3	Na	Mg																	Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr							
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe							
6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn							
7	Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og							

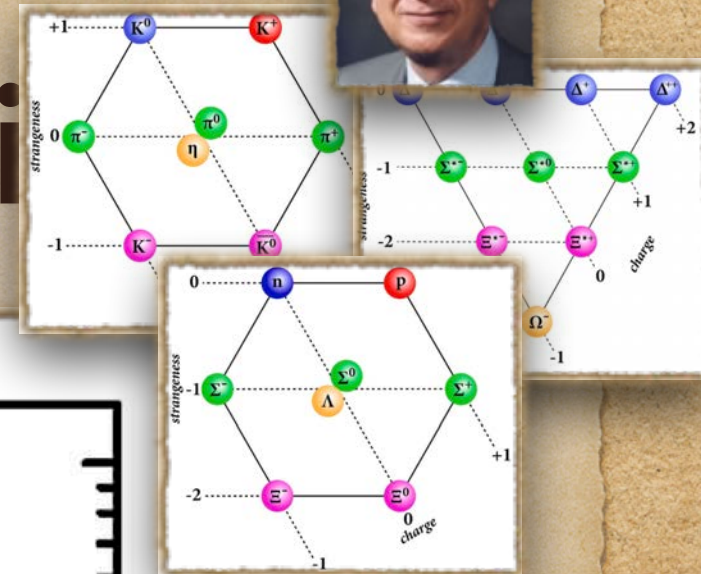
lanthanoid series

58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

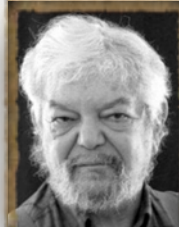
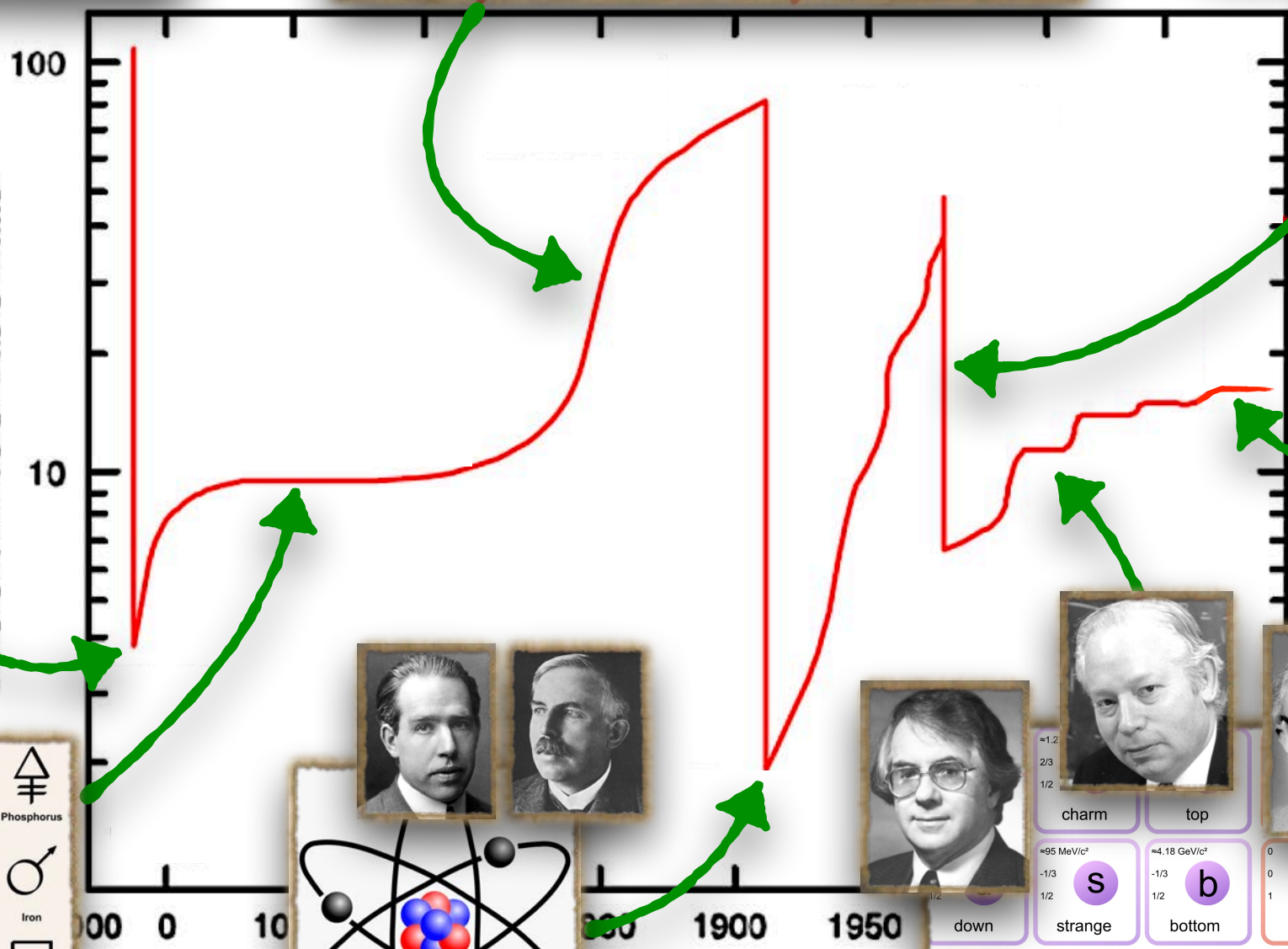
actinoid series

90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

ni



Different Kinds of Basic Matter




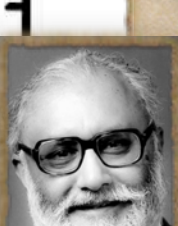
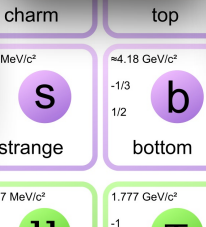
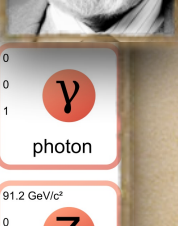

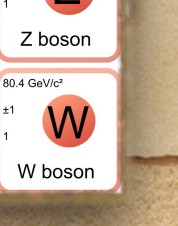


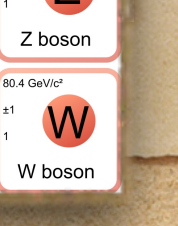

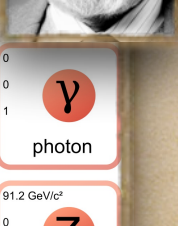

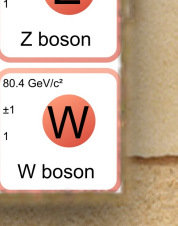

V/c^2
H
Higgs boson



			
Antimony	Bismuth	Gold	Phosphorus
			
Lead	Mercury	Copper	Iron
			
Sulfur	Tin	Silver	Potassium
			
Zinc	Platinum	Magnesium	Arsenic



AC
1900 1950
[/arxiv.org/abs/1311.1769](https://arxiv.org/abs/1311.1769)

	
charm	top
	
s	b
strange	bottom
	
e	muon
electron	muon
	
electron neutrino	muon neutrino
	
tau	tau neutrino
	
photon	Z boson
	
W boson	W boson

17

particles



group	1	2														16	17	18
1	H	He																
2			3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
3	Li	Be	B	C	N	O	F	Ne										
4	Na	Mg	Al	Si	P	S	Cl	Ar										
5	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
6	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
7	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
8	Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og



V/c^2
H
Higgs boson



Antimony	Bismuth	Gold	Phosphorus
Lead	Mercury	Copper	Iron
Sulfur	Tin	Silver	Potassium
Zinc	Platinum	Magnesium	Arsenic



charm	top
down	strange
electron	muon
electron neutrino	muon neutrino
tau	tau neutrino
photon	Z boson
W boson	W boson

The Standard Model

QUARKS	<div><div>mass → $\approx 2.3 \text{ MeV}/c^2$</div><div>charge → $2/3$</div><div>spin → $1/2$</div><div><div>u</div><div>up</div></div></div>	<div><div>mass → $\approx 1.275 \text{ GeV}/c^2$</div><div>charge → $2/3$</div><div>spin → $1/2$</div><div><div>c</div><div>charm</div></div></div>	<div><div>mass → $\approx 173.07 \text{ GeV}/c^2$</div><div>charge → $2/3$</div><div>spin → $1/2$</div><div><div>t</div><div>top</div></div></div>	<div><div>0</div><div>0</div><div>1</div><div><div>g</div><div>gluon</div></div></div>	<div><div>mass → $\approx 126 \text{ GeV}/c^2$</div><div>0</div><div>0</div><div><div>H</div><div>Higgs boson</div></div></div>
	<div><div>mass → $\approx 4.8 \text{ MeV}/c^2$</div><div>$-1/3$</div><div>$1/2$</div><div><div>d</div><div>down</div></div></div>	<div><div>mass → $\approx 95 \text{ MeV}/c^2$</div><div>$-1/3$</div><div>$1/2$</div><div><div>s</div><div>strange</div></div></div>	<div><div>mass → $\approx 4.18 \text{ GeV}/c^2$</div><div>$-1/3$</div><div>$1/2$</div><div><div>b</div><div>bottom</div></div></div>	<div><div>0</div><div>0</div><div>1</div><div><div>γ</div><div>photon</div></div></div>	
	<div><div>mass → $0.511 \text{ MeV}/c^2$</div><div>-1</div><div>$1/2$</div><div><div>e</div><div>electron</div></div></div>	<div><div>mass → $105.7 \text{ MeV}/c^2$</div><div>-1</div><div>$1/2$</div><div><div>μ</div><div>muon</div></div></div>	<div><div>mass → $1.777 \text{ GeV}/c^2$</div><div>-1</div><div>$1/2$</div><div><div>τ</div><div>tau</div></div></div>	<div><div>mass → $91.2 \text{ GeV}/c^2$</div><div>0</div><div>1</div><div><div>Z</div><div>Z boson</div></div></div>	GAUGE BOSONS
	<div><div>mass → $< 2.2 \text{ eV}/c^2$</div><div>0</div><div>$1/2$</div><div><div>ν_e</div><div>electron neutrino</div></div></div>	<div><div>mass → $< 0.17 \text{ MeV}/c^2$</div><div>0</div><div>$1/2$</div><div><div>ν_μ</div><div>muon neutrino</div></div></div>	<div><div>mass → $< 15.5 \text{ MeV}/c^2$</div><div>0</div><div>$1/2$</div><div><div>ν_τ</div><div>tau neutrino</div></div></div>	<div><div>mass → $80.4 \text{ GeV}/c^2$</div><div>±1</div><div>1</div><div><div>W</div><div>W boson</div></div></div>	
	LEPTONS				

4

High Energy

High Energy Physics

THERE ARE FOUR
FUNDAMENTAL FORCES
BETWEEN PARTICLES:
(1) *GRAVITY*, WHICH
OBEYS THIS INVERSE
SQUARE LAW:

$$F_{\text{gravity}} = G \frac{m_1 m_2}{d^2}$$



OK...

(2) *ELECTROMAGNETISM*,
WHICH OBEYS THIS
INVERSE-SQUARE LAW:

$$F_{\text{static}} = k_e \frac{q_1 q_2}{d^2}$$

AND ALSO
MAXWELL'S
EQUATIONS



ALSO WHAT?

(3) THE *STRONG NUCLEAR
FORCE*, WHICH OBEYS, UH...

...WELL, UMM...

...IT HOLDS PROTONS AND
NEUTRONS TOGETHER.



I SEE.

IT'S STRONG.

AND (4) THE *WEAK FORCE*. IT
[MUMBLE MUMBLE] RADIOACTIVE
DECAY [MUMBLE MUMBLE]

THAT'S NOT A SENTENCE.
YOU JUST SAID 'RADIO—
—AND THOSE ARE THE
FOUR FUNDAMENTAL
FORCES!



How do we do it?

How do we do it?

Black Box Mechanism:

we know what we put in

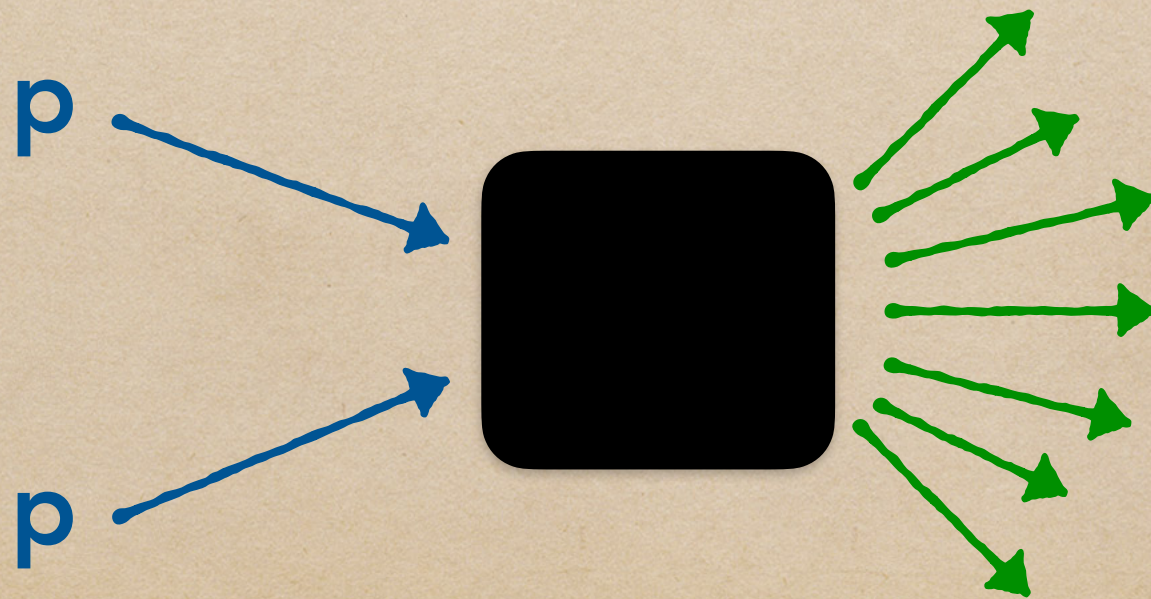
we measure what comes out

use statistics to deduce what happened in between

How do we do it?

Black Box Mechanism:

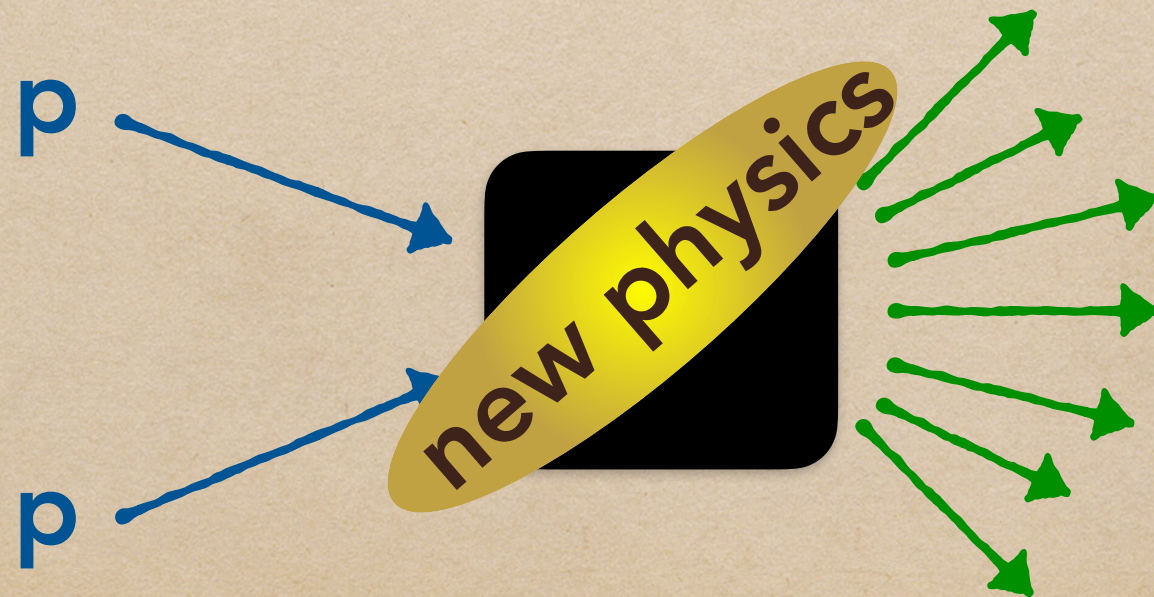
we know what we put in
we measure what comes out
use statistics to deduce what happened in between



How do we do it?

Black Box Mechanism:

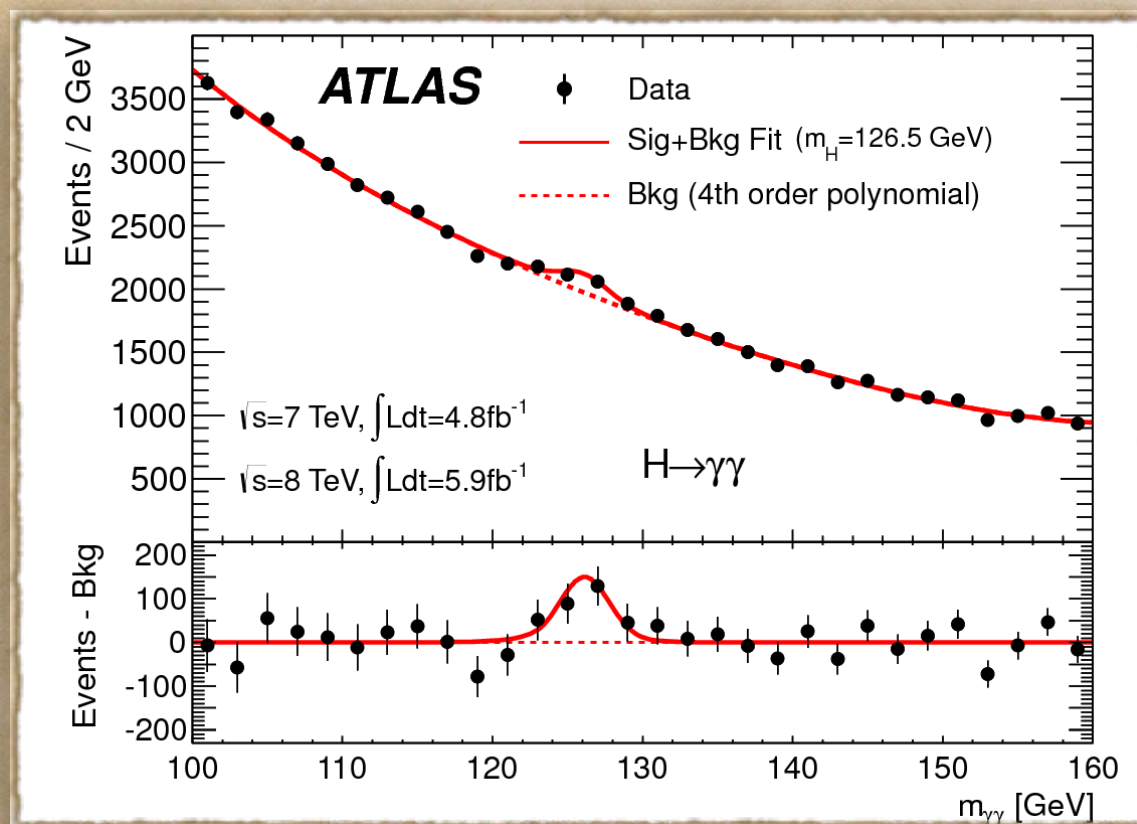
we know what we put in
we measure what comes out
use statistics to deduce what happened in between



Statistics!

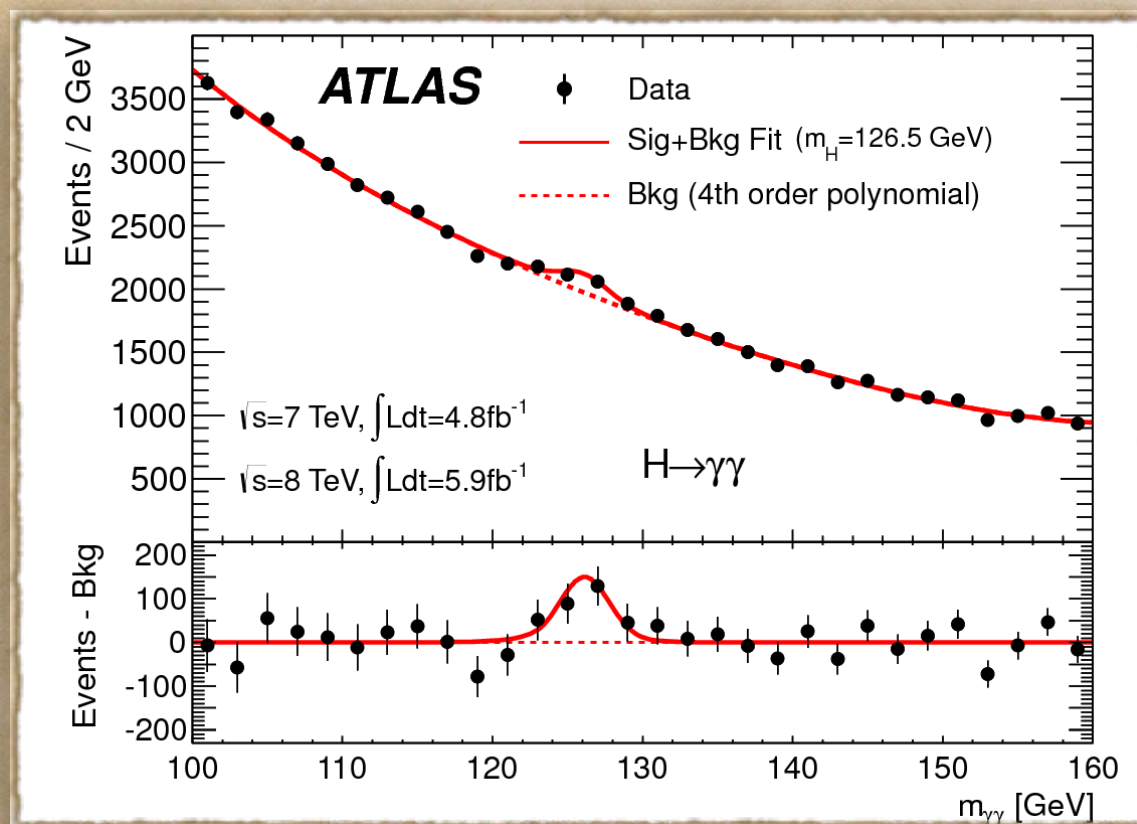
Statistics!

Higgs found!

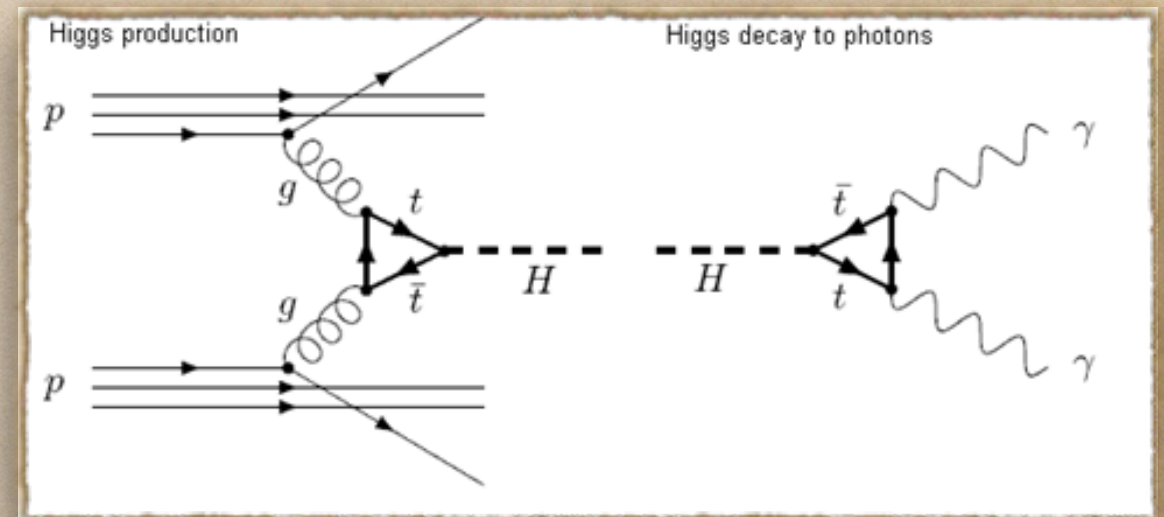


Statistics!

Higgs found!

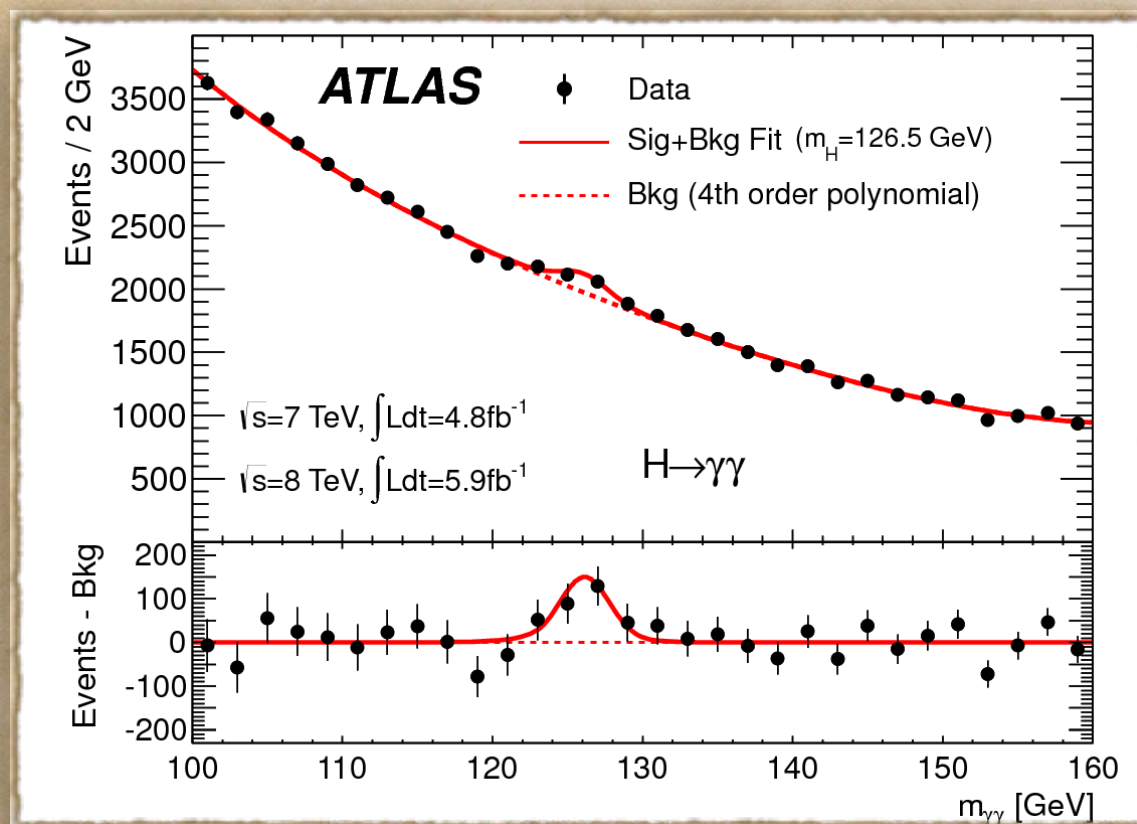


Example process

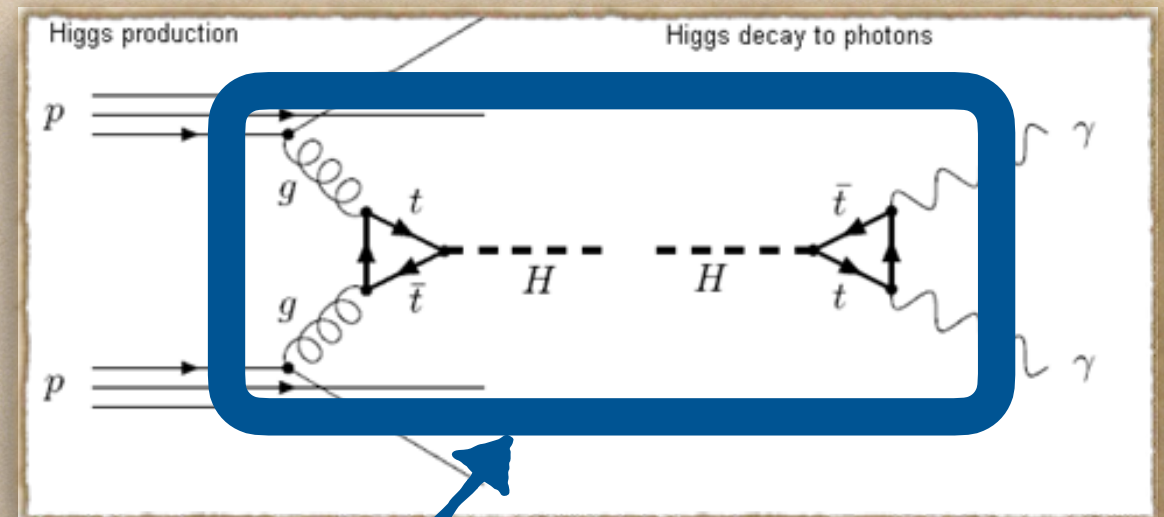


Statistics!

Higgs found!



Example process

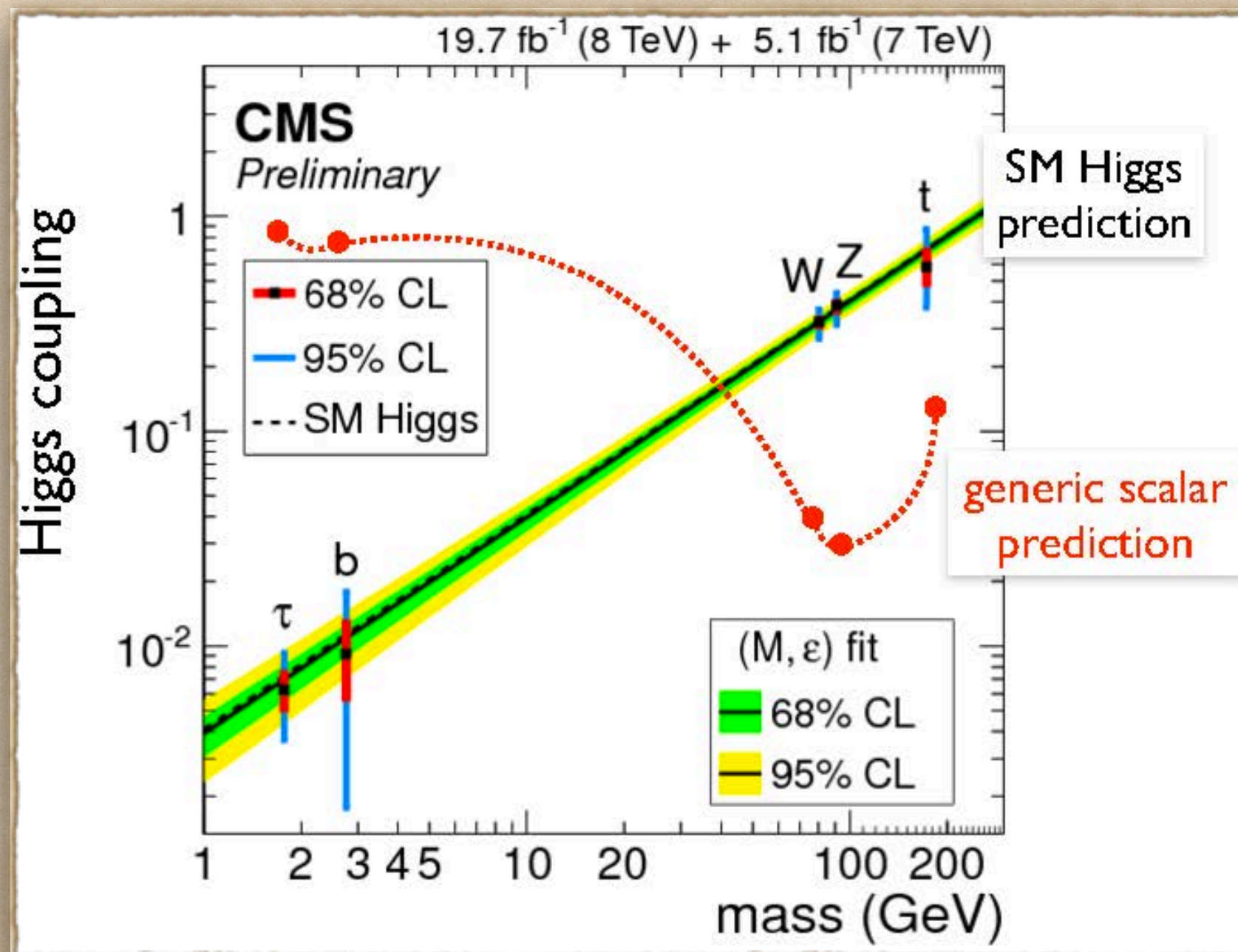


Black box:

Can be everything; we don't know (Higgs, photon, gluon,)

Use **statistics** and **probability** to peek into process

It walks like a Higgs...



Inside the Black Box

Feynman diagrams

Inside the Black Box

Feynman diagrams

Notations

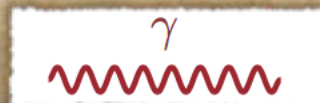
quark, lepton



antiquark, antilepton



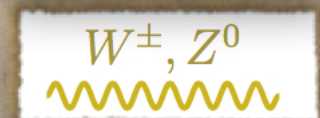
photon



gluon



weak boson



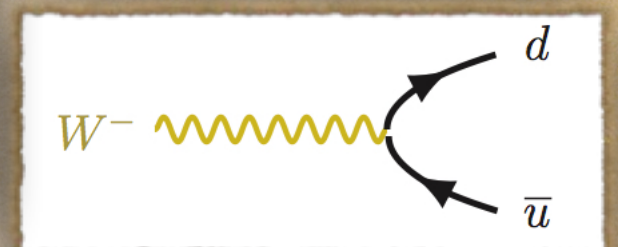
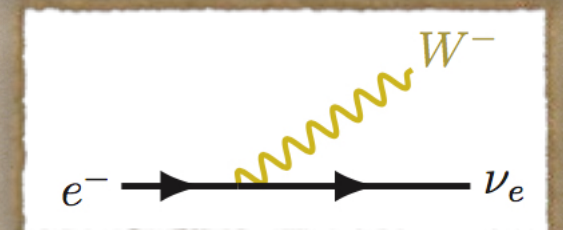
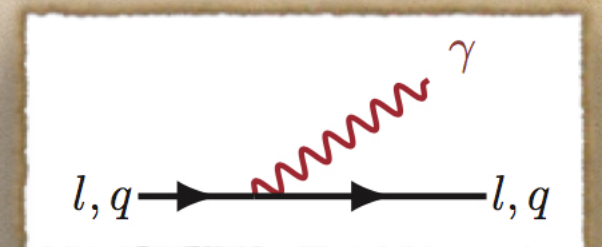
Inside the Black Box

Feynman diagrams

Notations

quark, lepton	
antiquark, antilepton	
photon	
gluon	
weak boson	

Interactions



5

The Future

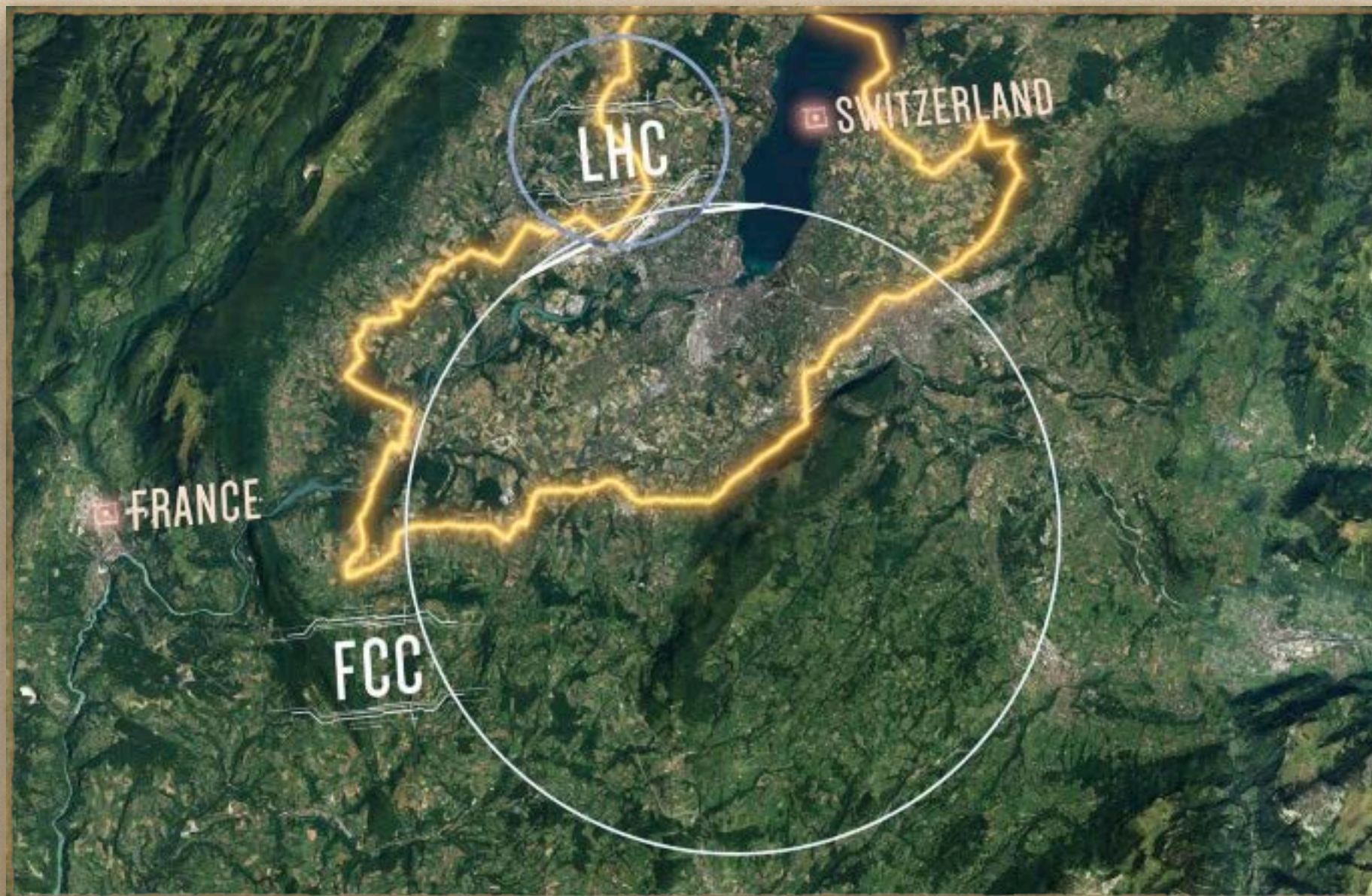
Expanding the search...

Expanding the search...

Bigger, larger, better

Expanding the search...

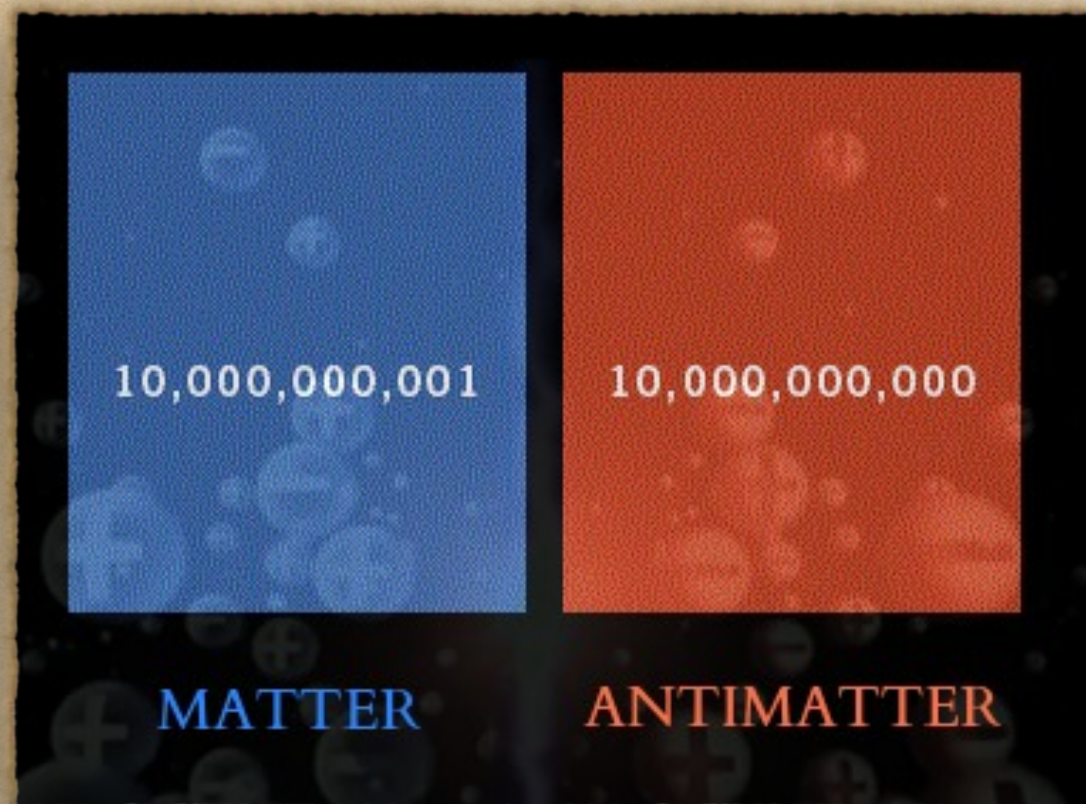
Bigger, larger, better



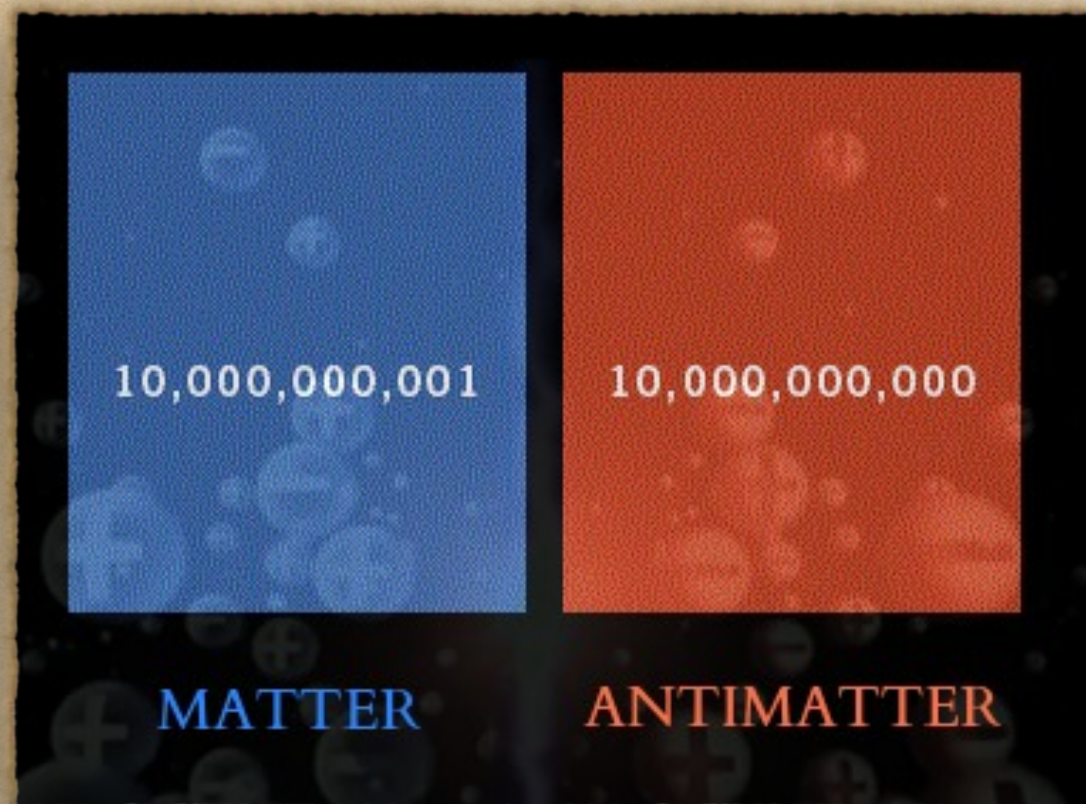
(Anti)Matter Asymmetry



(Anti)Matter Asymmetry



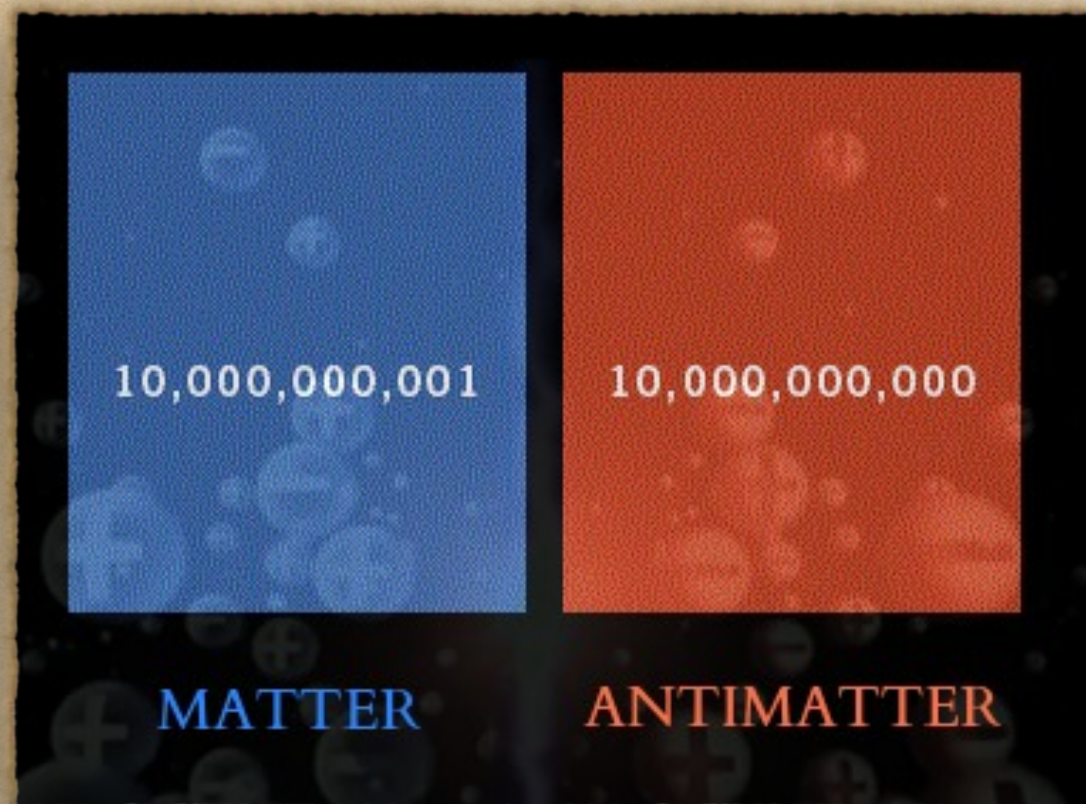
(Anti)Matter Asymmetry



Hidden somewhere far?



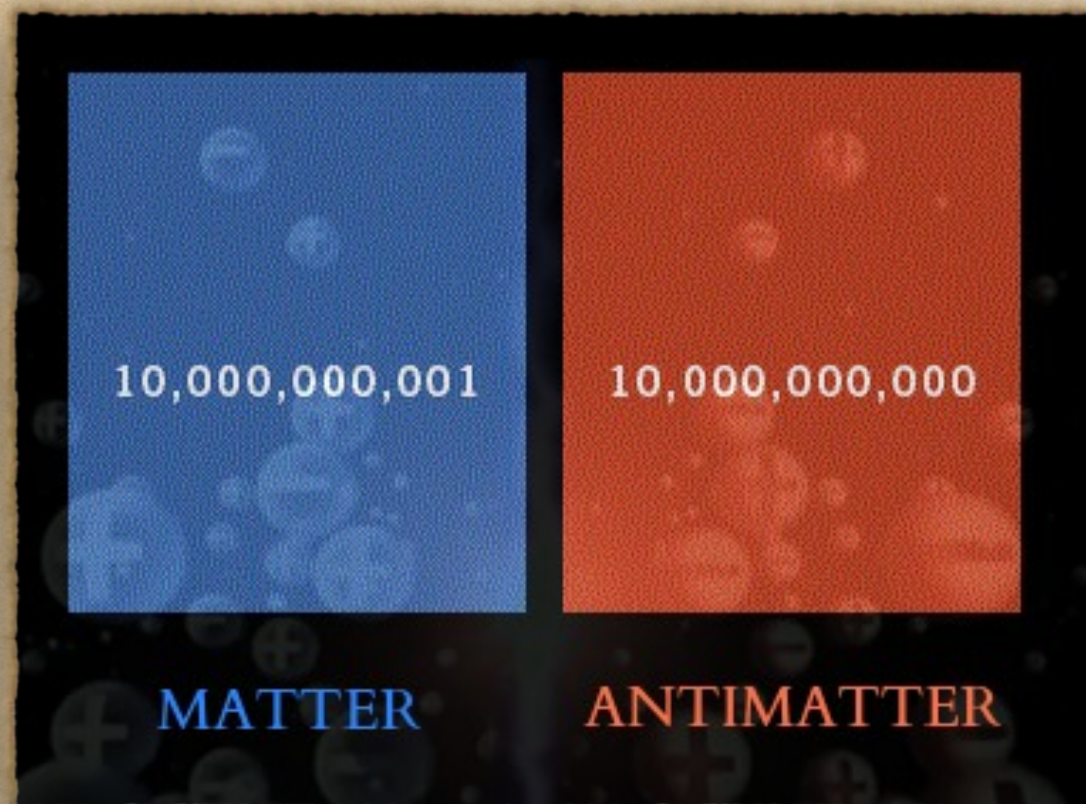
(Anti)Matter Asymmetry



Hidden somewhere far?

Created asymmetrically?

(Anti)Matter Asymmetry

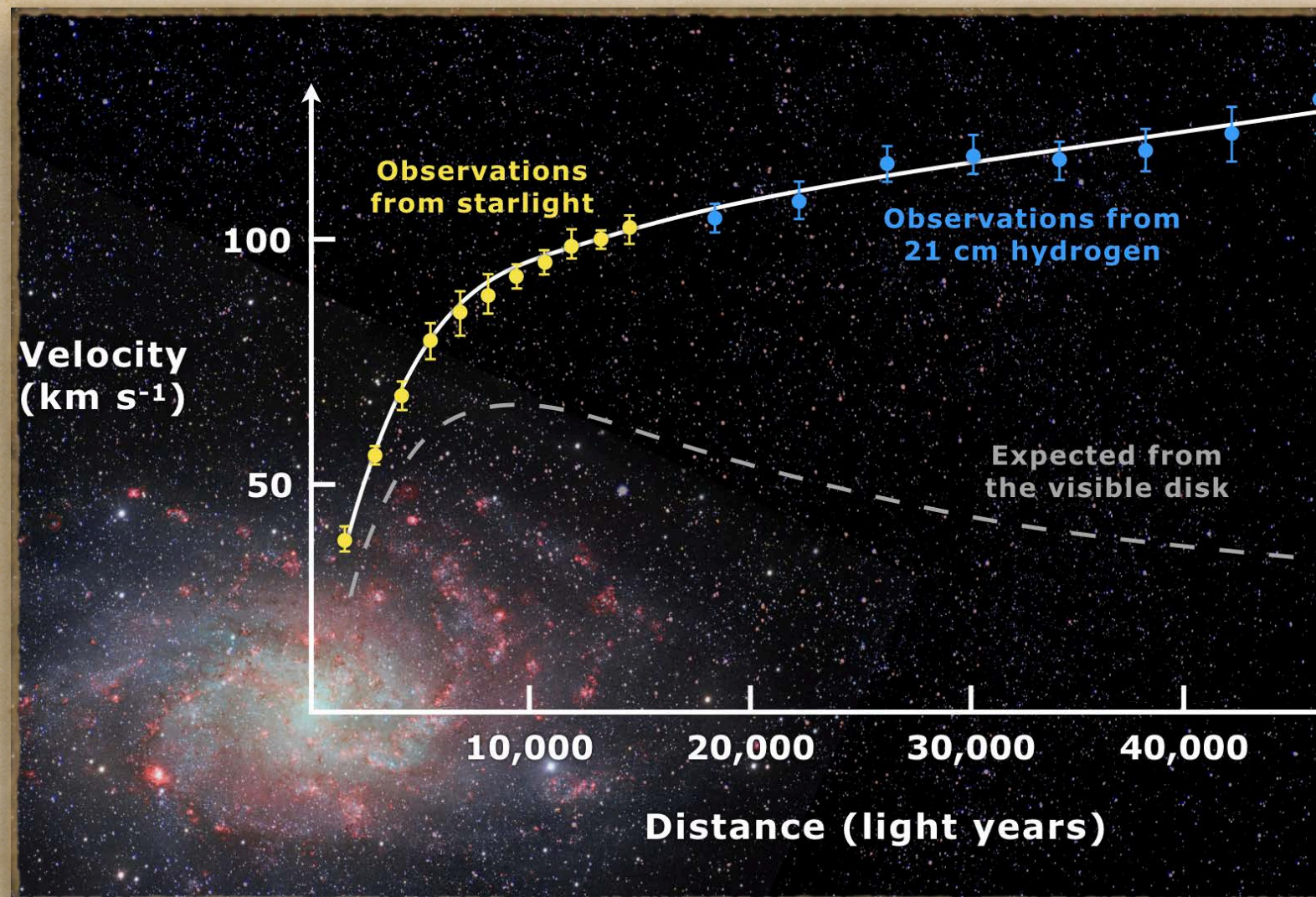


Hidden somewhere far?

Created asymmetrically?

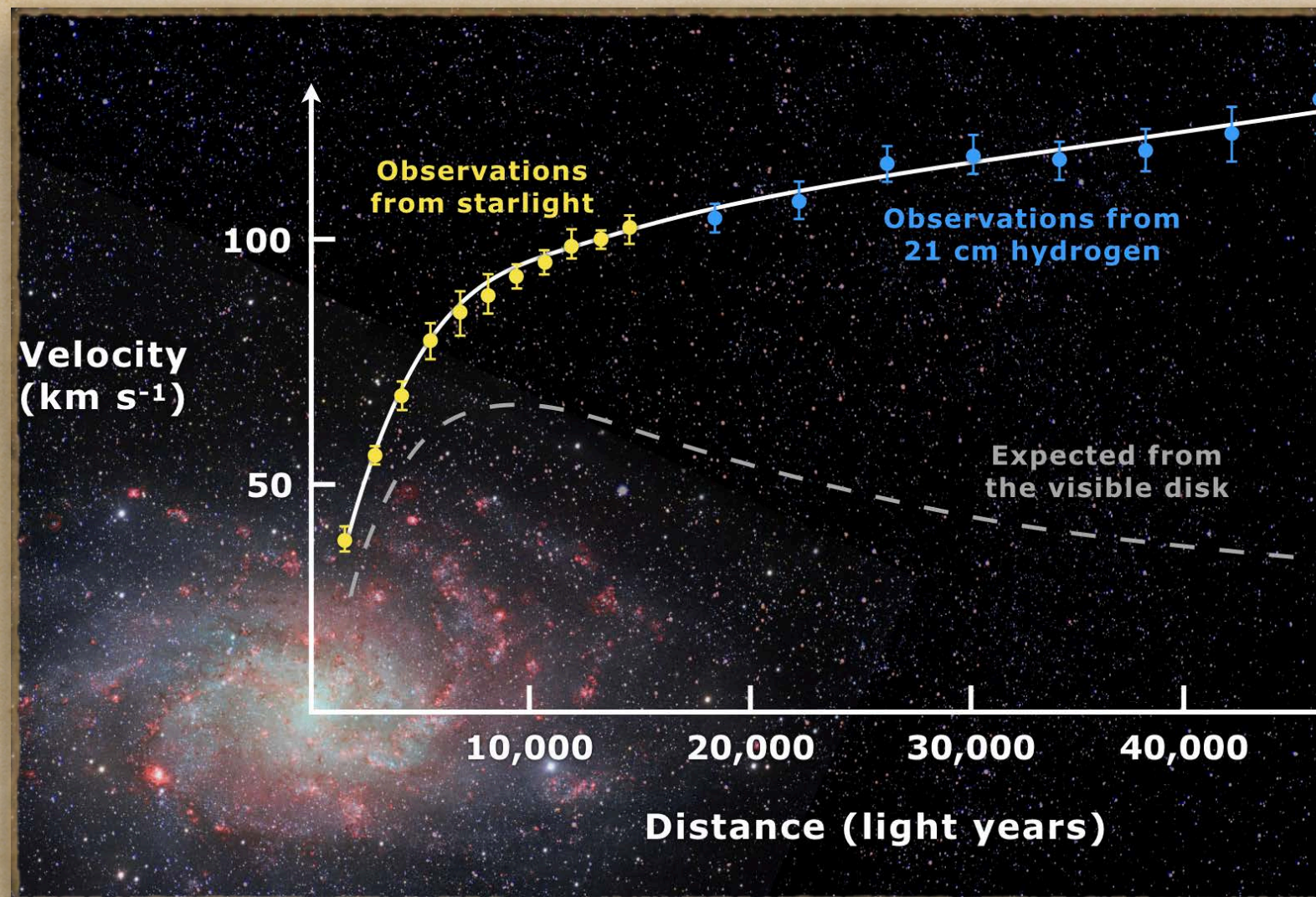
Asymmetric decay?

Dark Matter

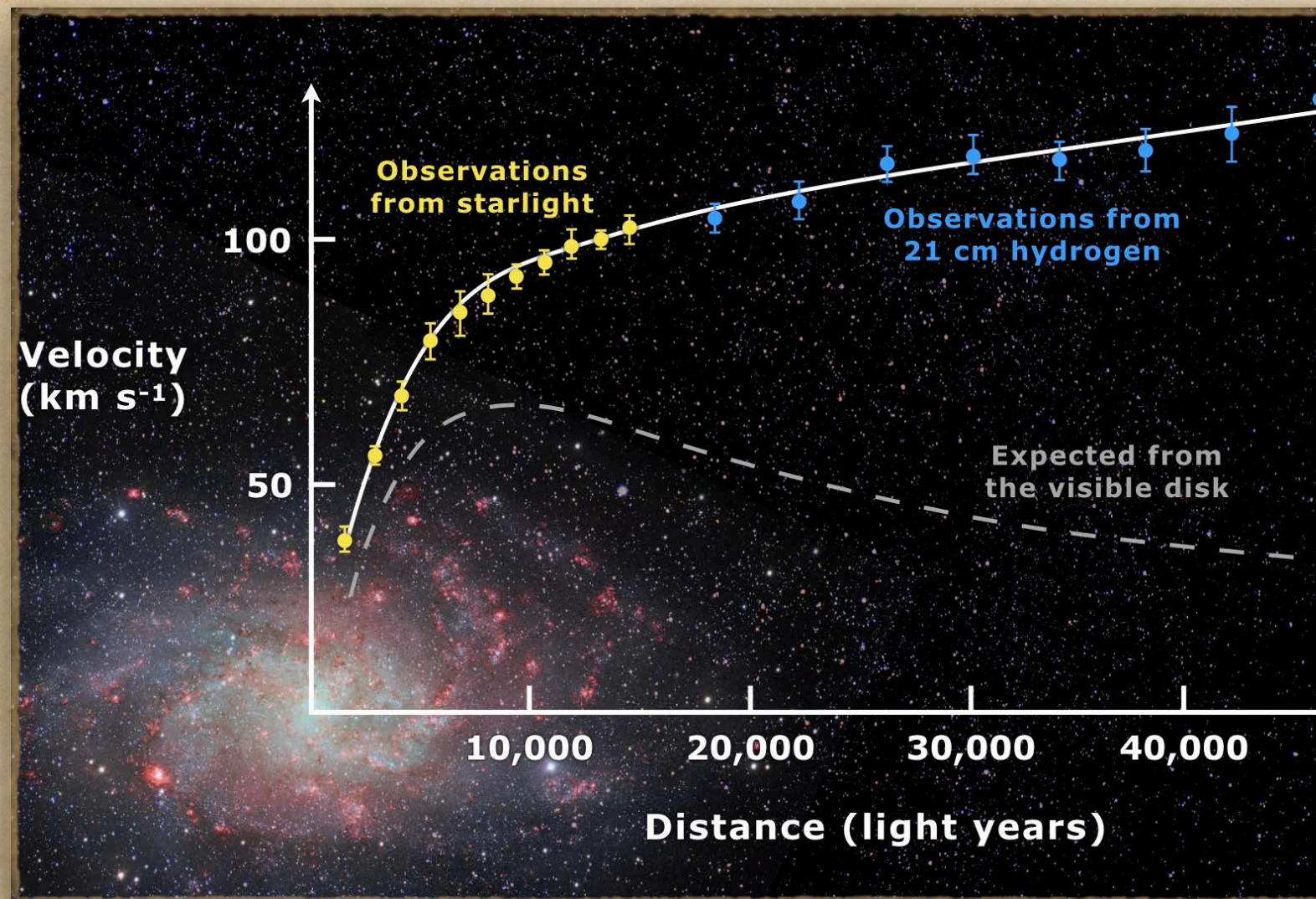


Dark Matter

Black holes?



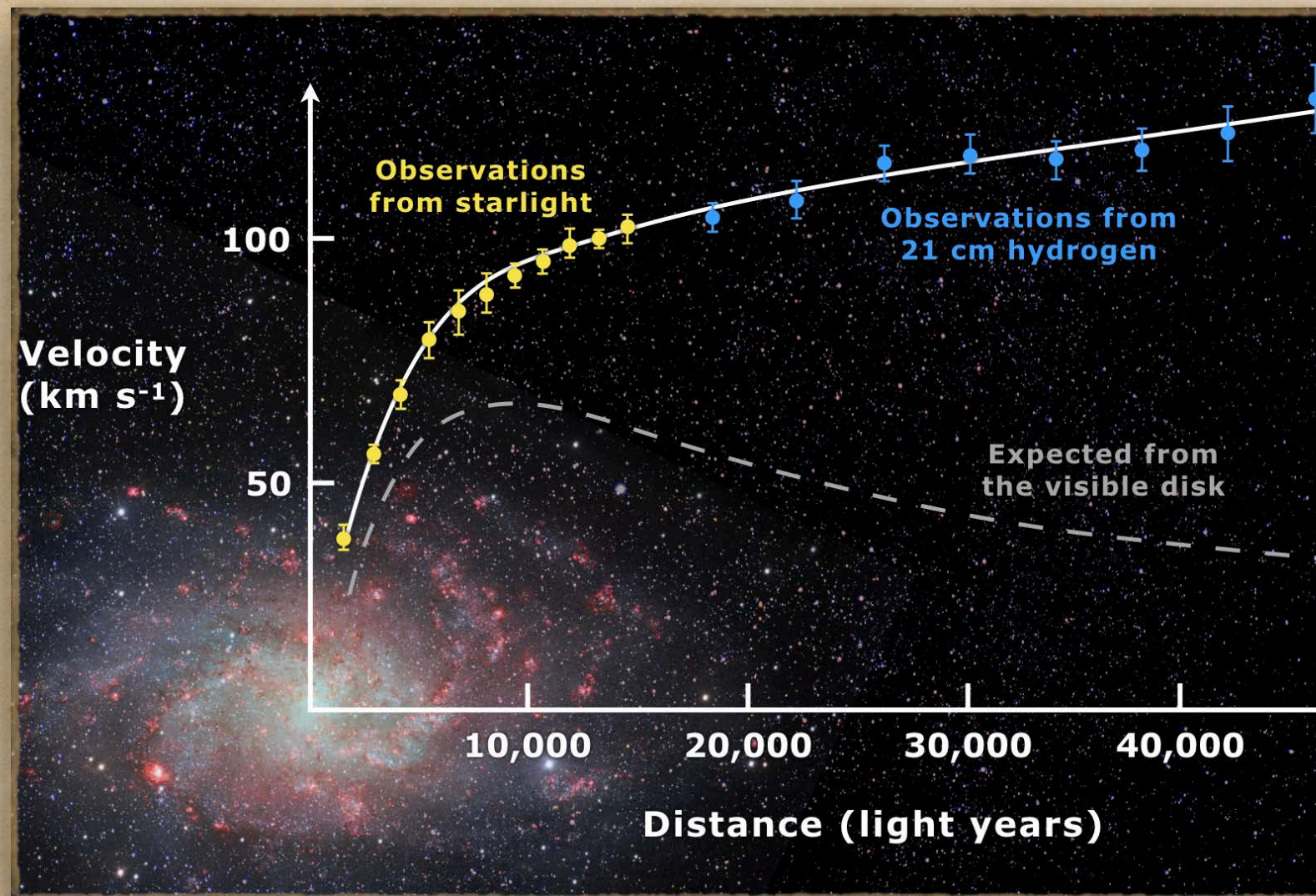
Dark Matter



Black holes?

WIMPs?

Dark Matter

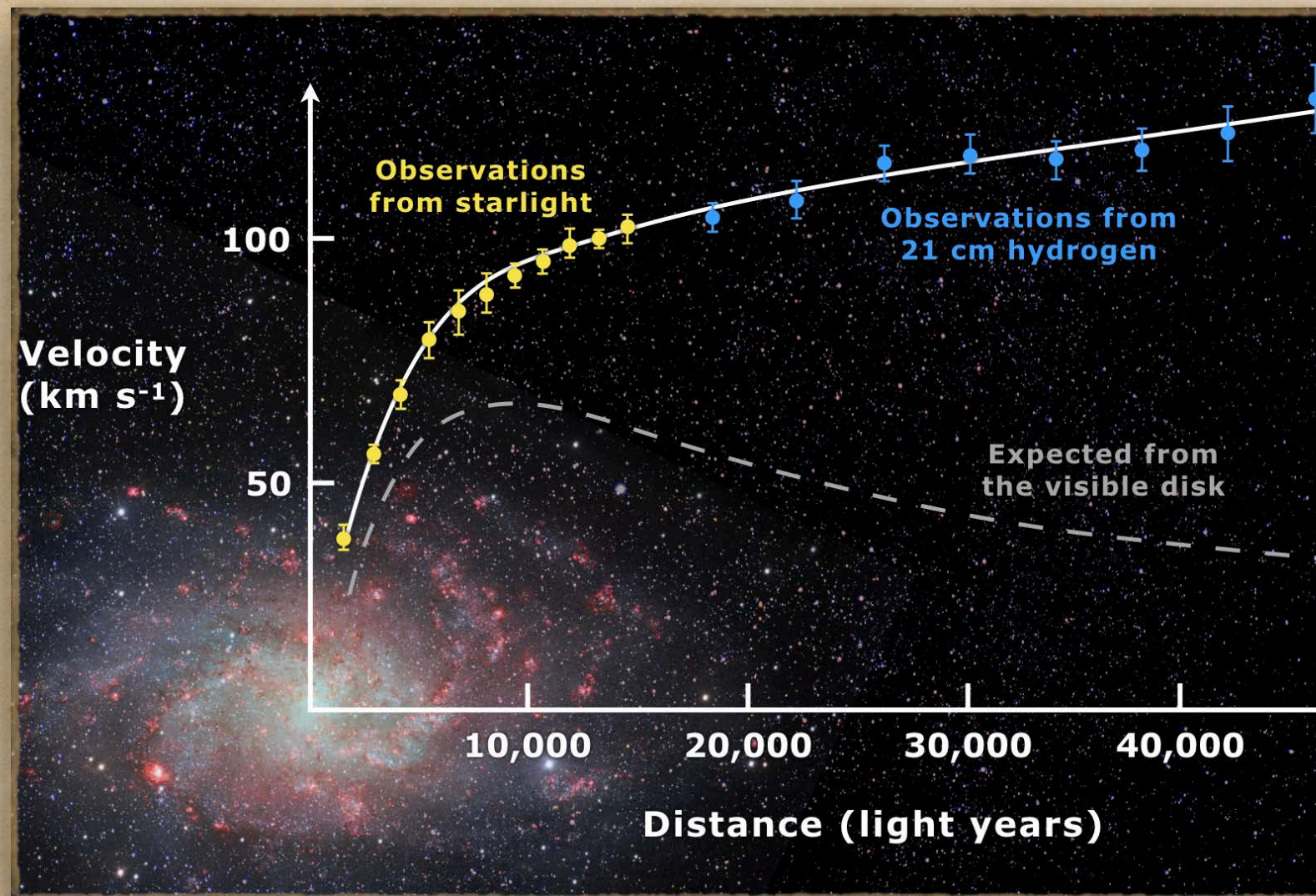


Black holes?

WIMPs?

Sterile neutrinos?

Dark Matter



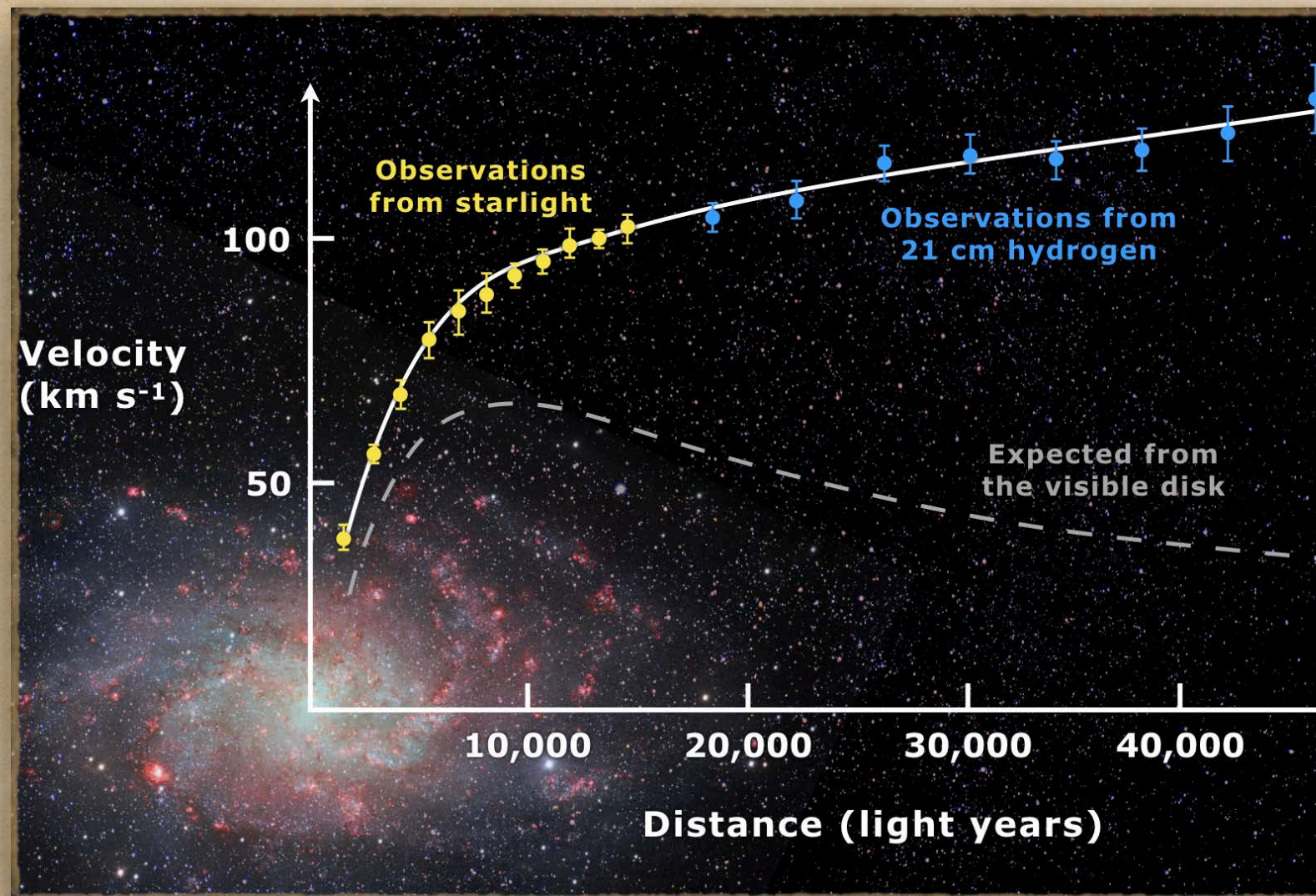
Black holes?

WIMPs?

Sterile neutrinos?

Gravity behaves different at large scales?

Dark Matter



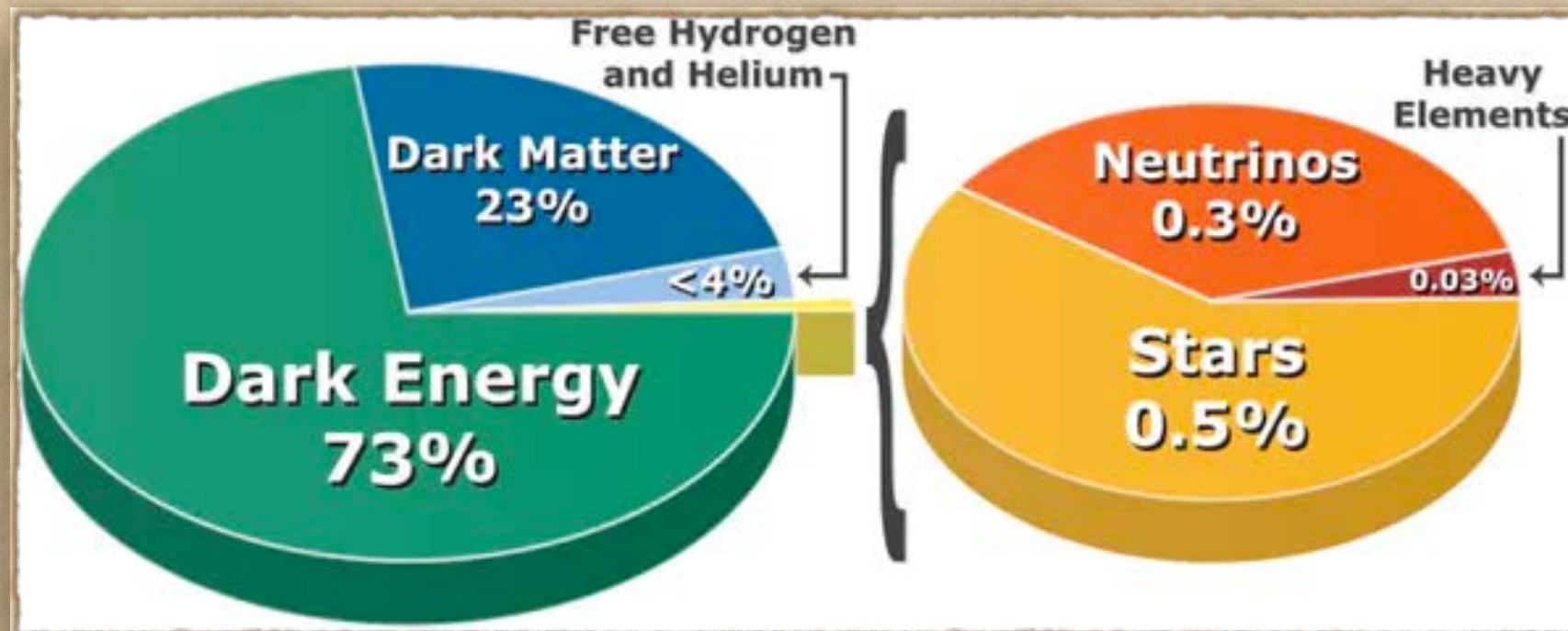
~~Black holes?~~

WIMPs?

Sterile neutrinos?

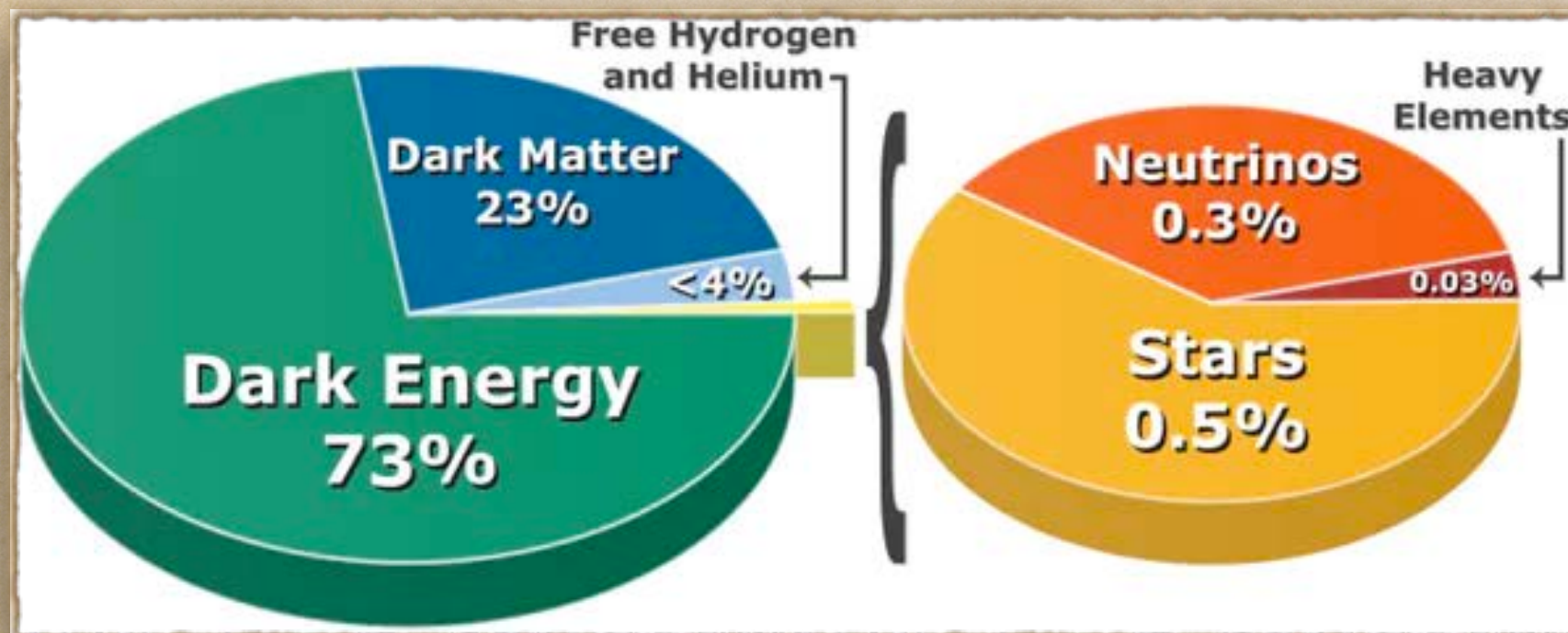
Gravity behaves different at large scales?

Dark Energy



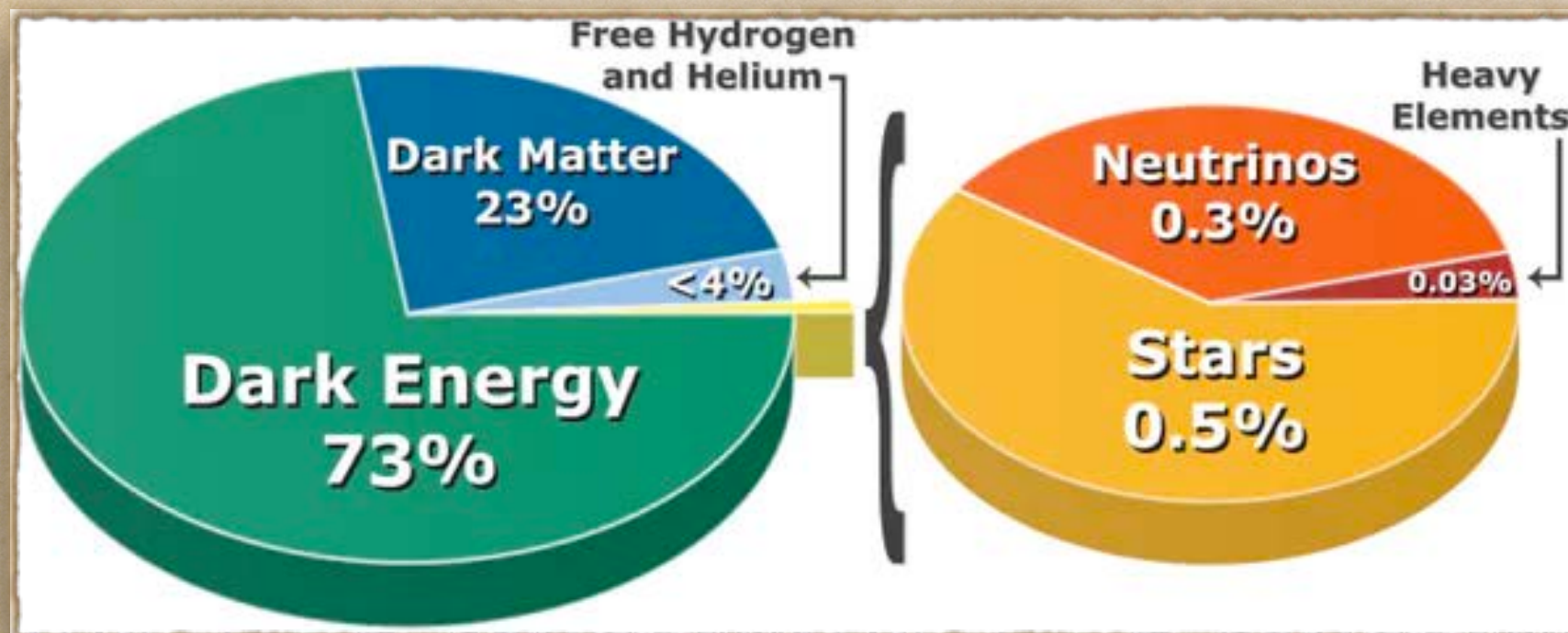
Dark Energy

Variable energy field?



Dark Energy

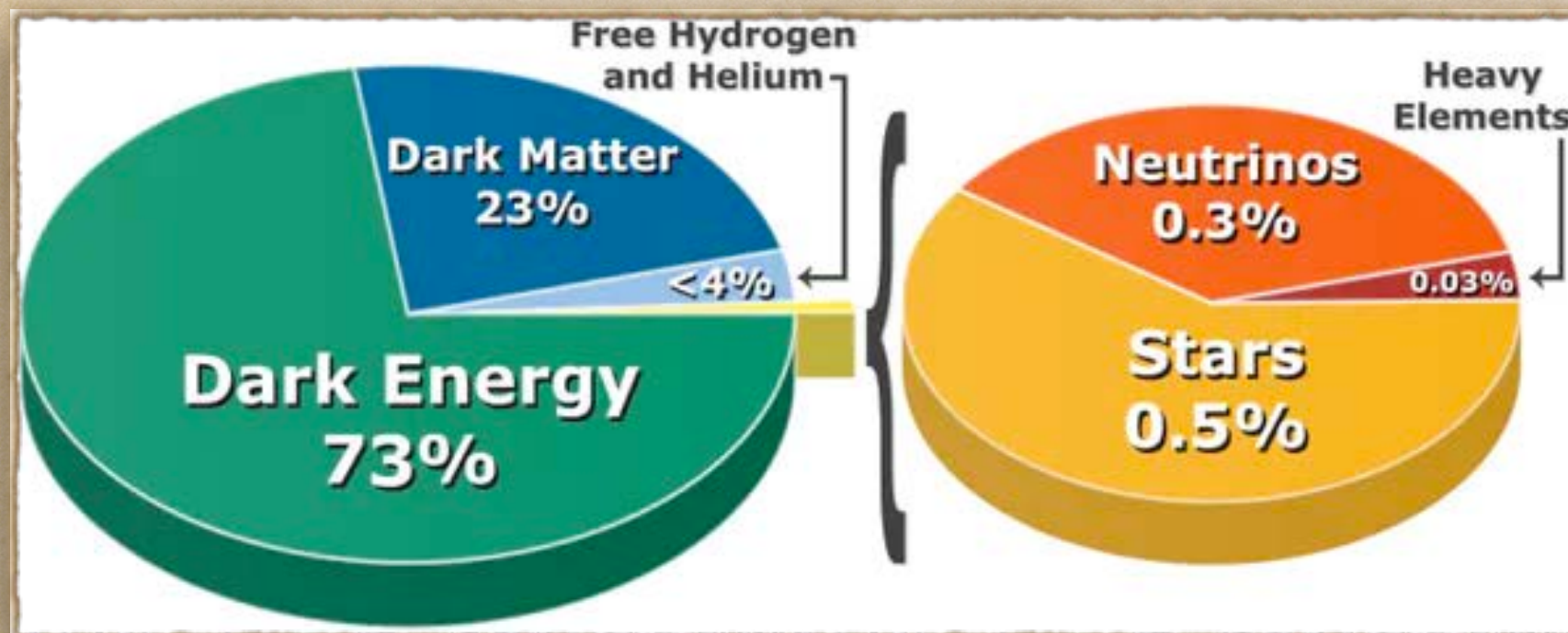
Variable energy field?



Fundamental property of space?

Dark Energy

Variable energy field?

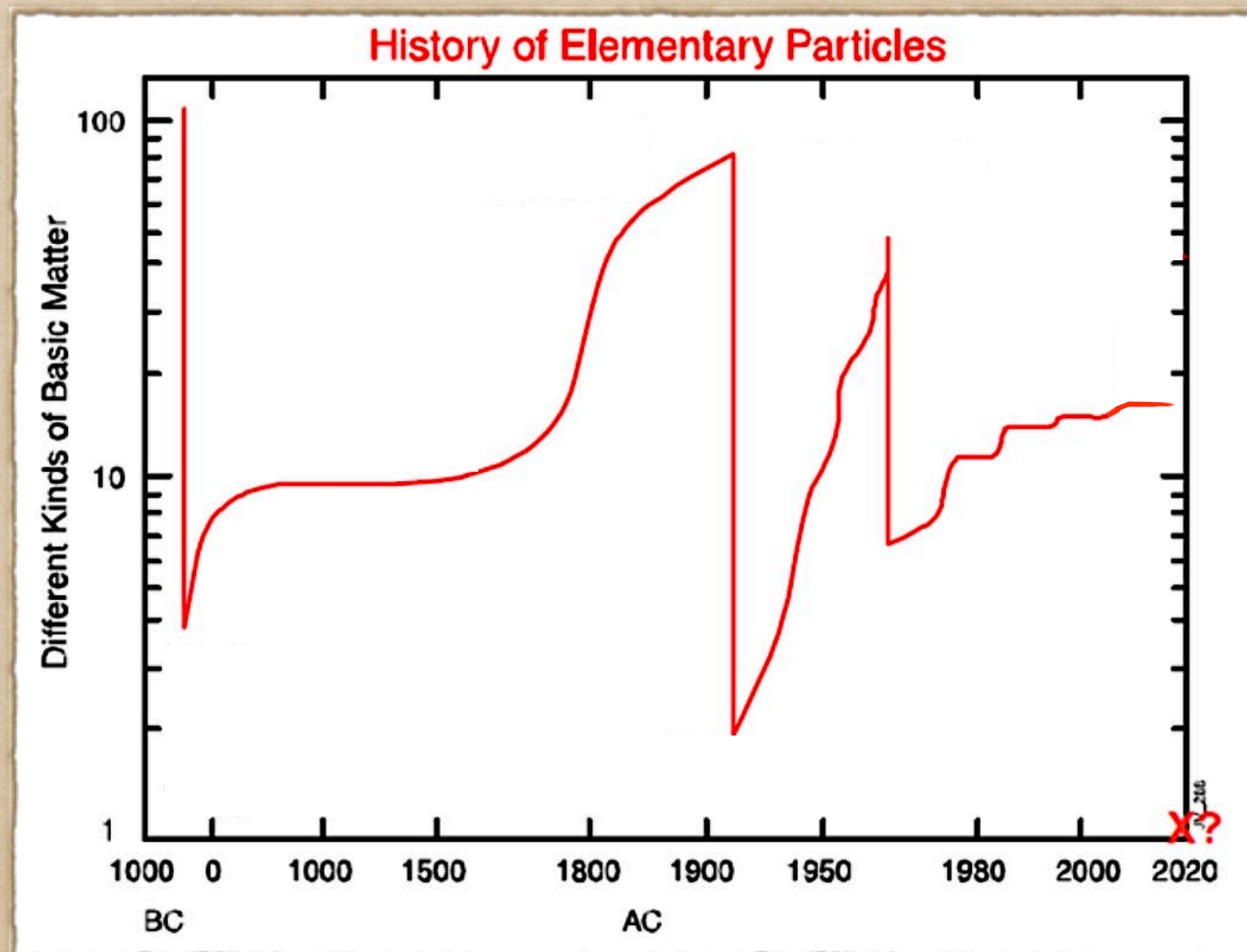


Fundamental property of space?

Gravity behaves different at large scales?

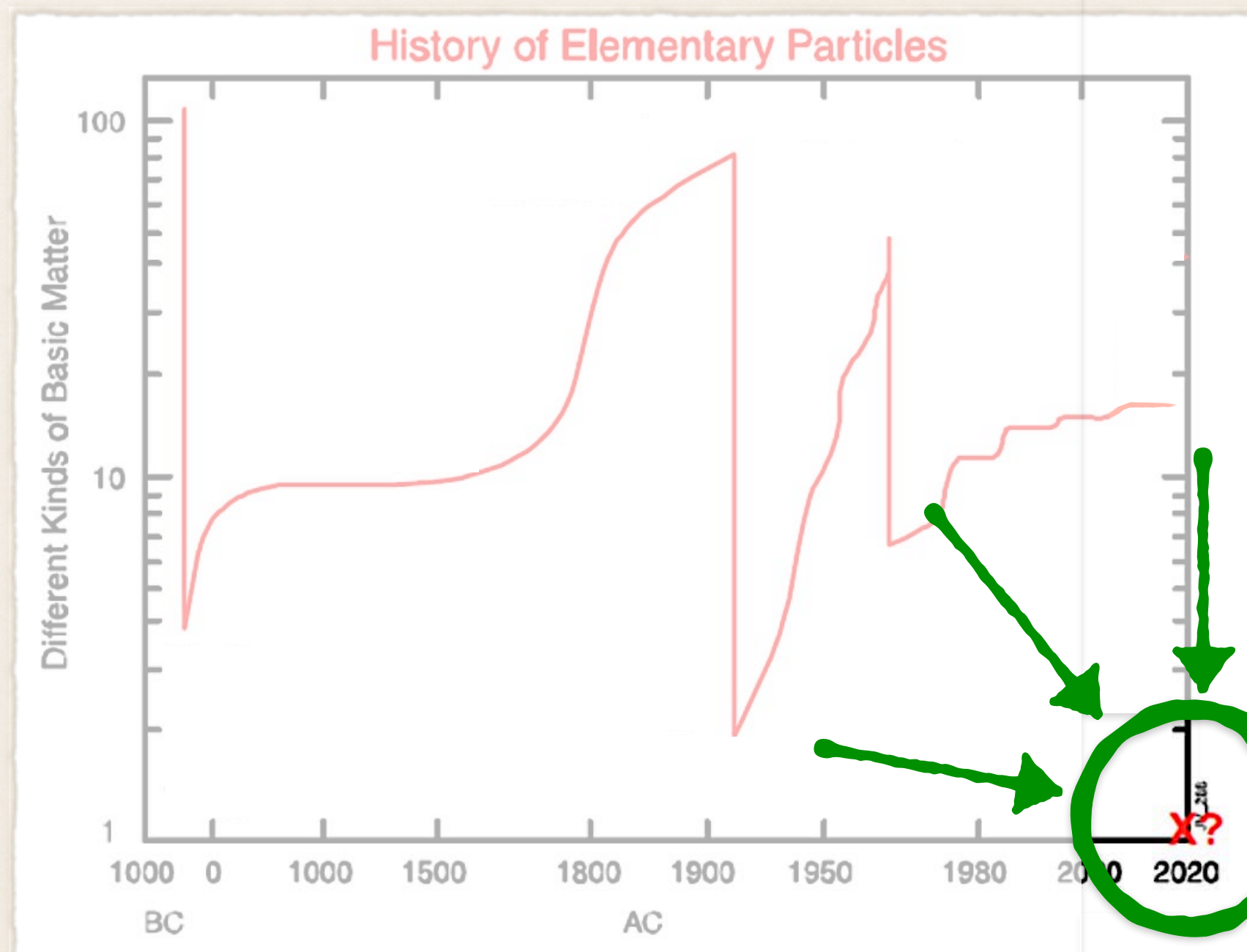
One more thing..

Basic Bricks of the Universe



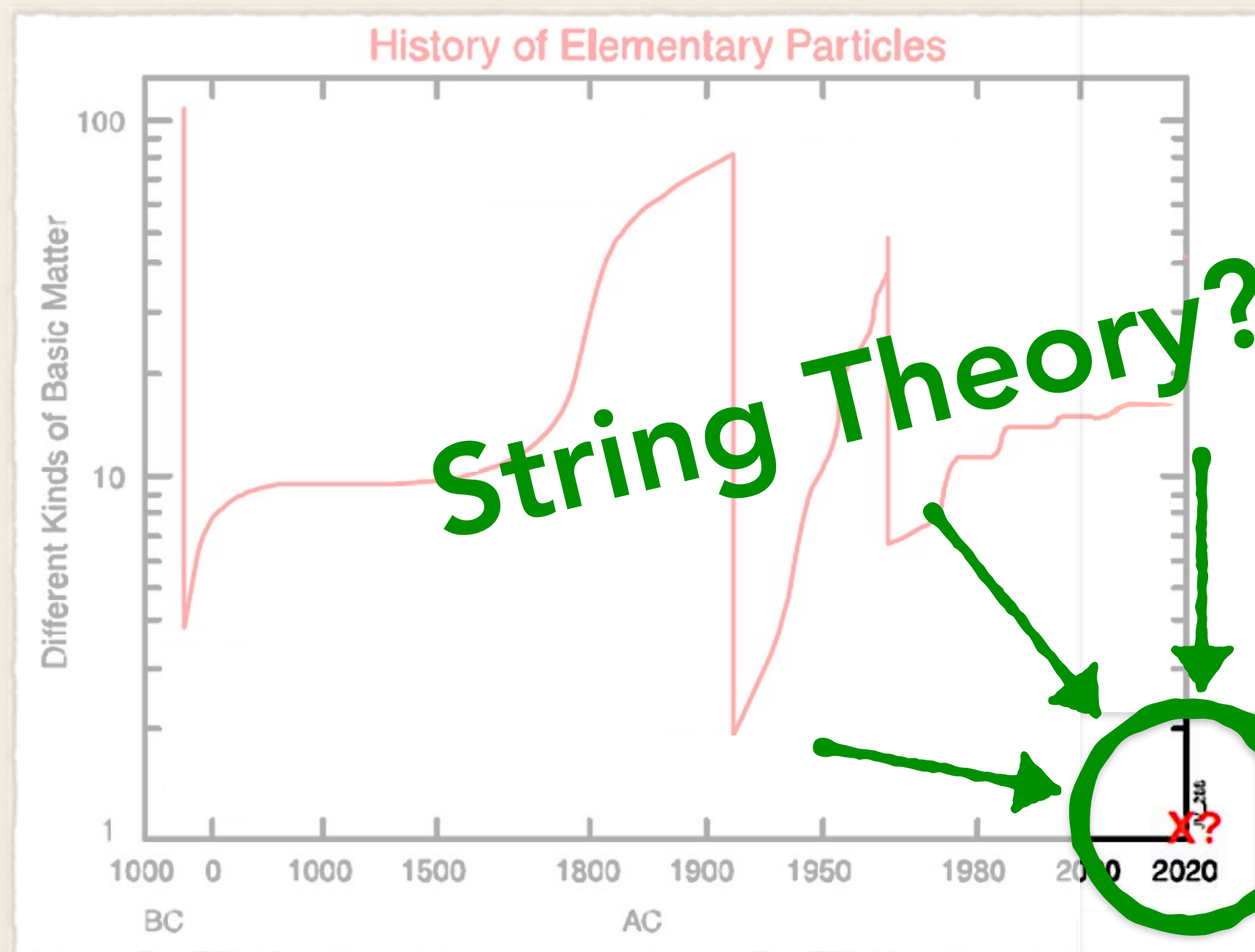
Credit: <http://arxiv.org/abs/1311.1769>

Basic Bricks of the Universe



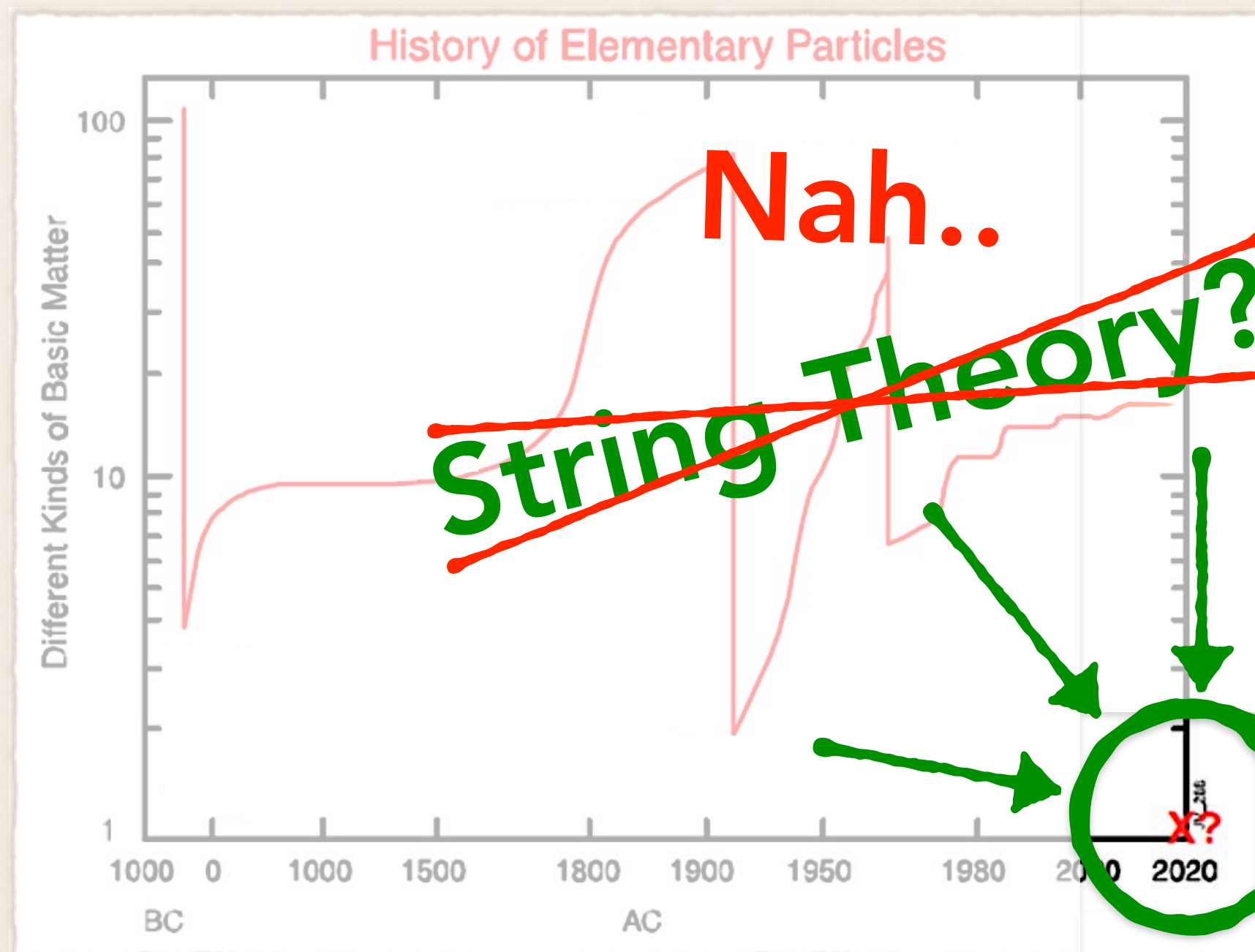
Credit: <http://arxiv.org/abs/1311.1769>

Basic Bricks of the Universe



Credit: <http://arxiv.org/abs/1311.1769>

Basic Bricks of the Universe



Credit: <http://arxiv.org/abs/1311.1769>

These are open questions
left to be explored...

Thank you for your attention

Questions?

=> frederikvanderveken@gmail.com