

Title: Phiala Shanahan: MIT

Date: Nov 07, 2018 07:00 PM

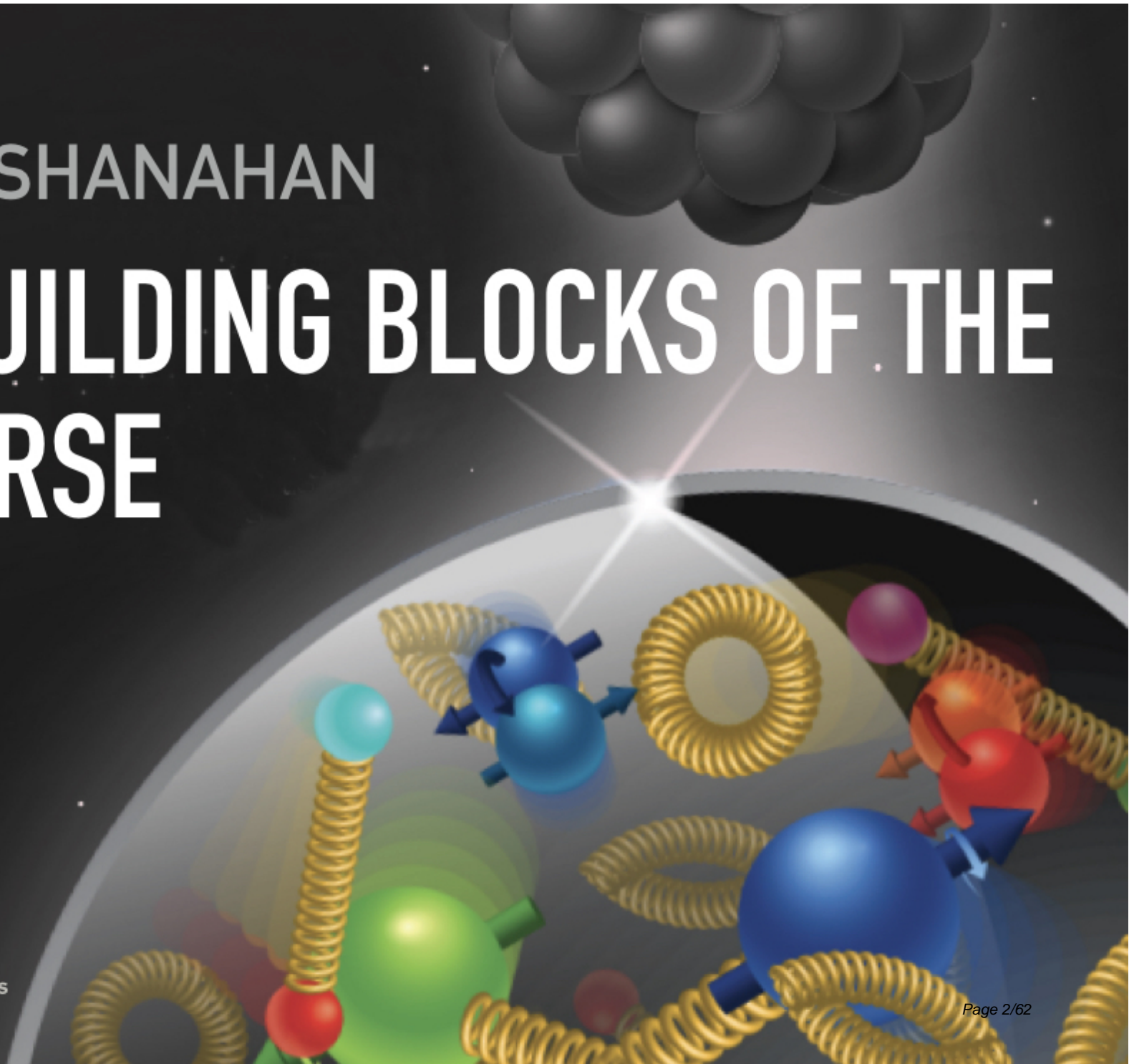
URL: <http://pirsa.org/18110071>

Abstract: <p>More than 99% of the visible matter in the universe is built from protons and neutrons and the nuclei that they form. This rich structure emerges dynamically from the complex interactions of quarks and gluons, the most elementary particles that have been discovered. Understanding how nuclear physics arises from the underlying quark and gluon dynamics is a computational challenge that pushes the capabilities of the world's largest supercomputers.</p>

<p>In her lecture, Dr. Shanahan will introduce the audience to the subatomic realm and describe what supercomputer calculations of quarks and gluons can reveal about the origins of mass, the primordial nuclear reactions that power the sun, and the nature of the elusive dark matter that permeates the universe.</p>

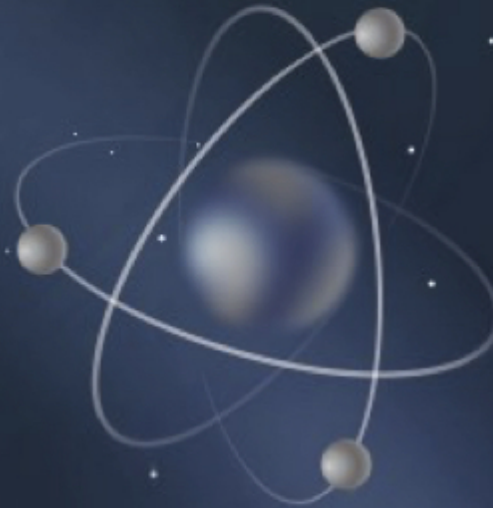
PHIALA SHANAHAN

THE BUILDING BLOCKS OF THE UNIVERSE





MATTER



ATOMS

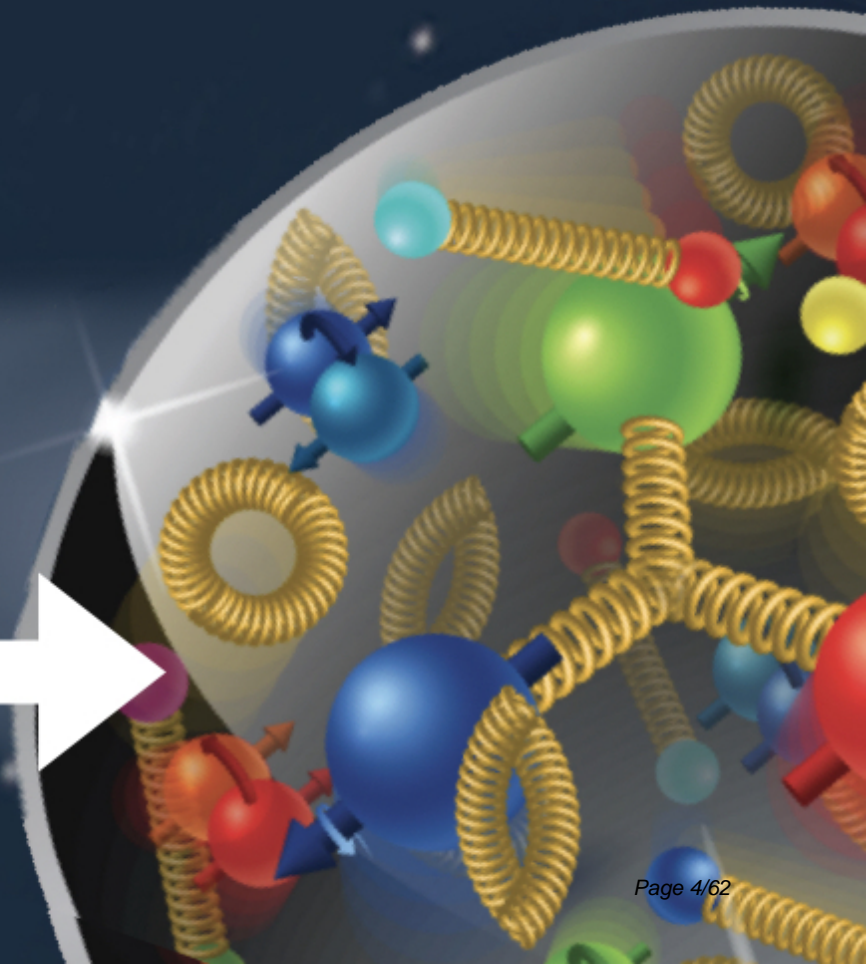
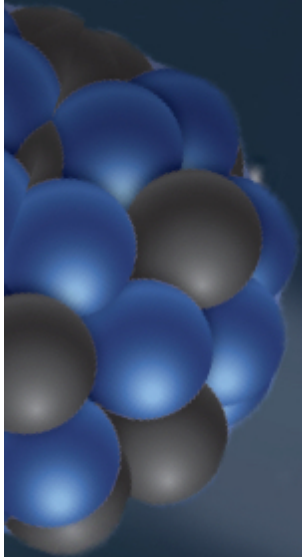
NUCLEI



NUCLEI

**PROTONS &
NEUTRONS**

**QUARKS, GLUONS
AND THE QUANTUM
VACUUM**



THE STANDARD MODEL OF ELEMENTARY PARTICLES



**17 FUNDAMENTAL
PARTICLES**

**STRONG FORCE
ELECTROMAGNETISM**

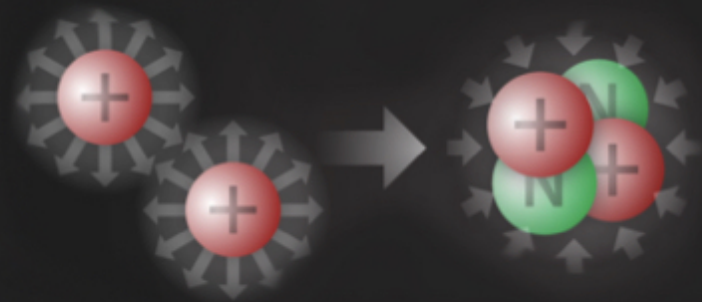
**WEAK FORCE
NO GRAVITY**

THE STANDARD MODEL OF ELEMENTARY PARTICLES

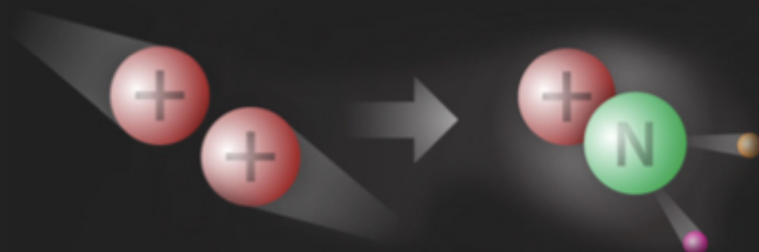
ELECTROMAGNETISM



STRONG FORCE

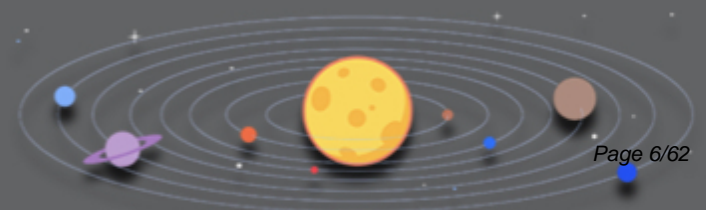


WEAK FORCE

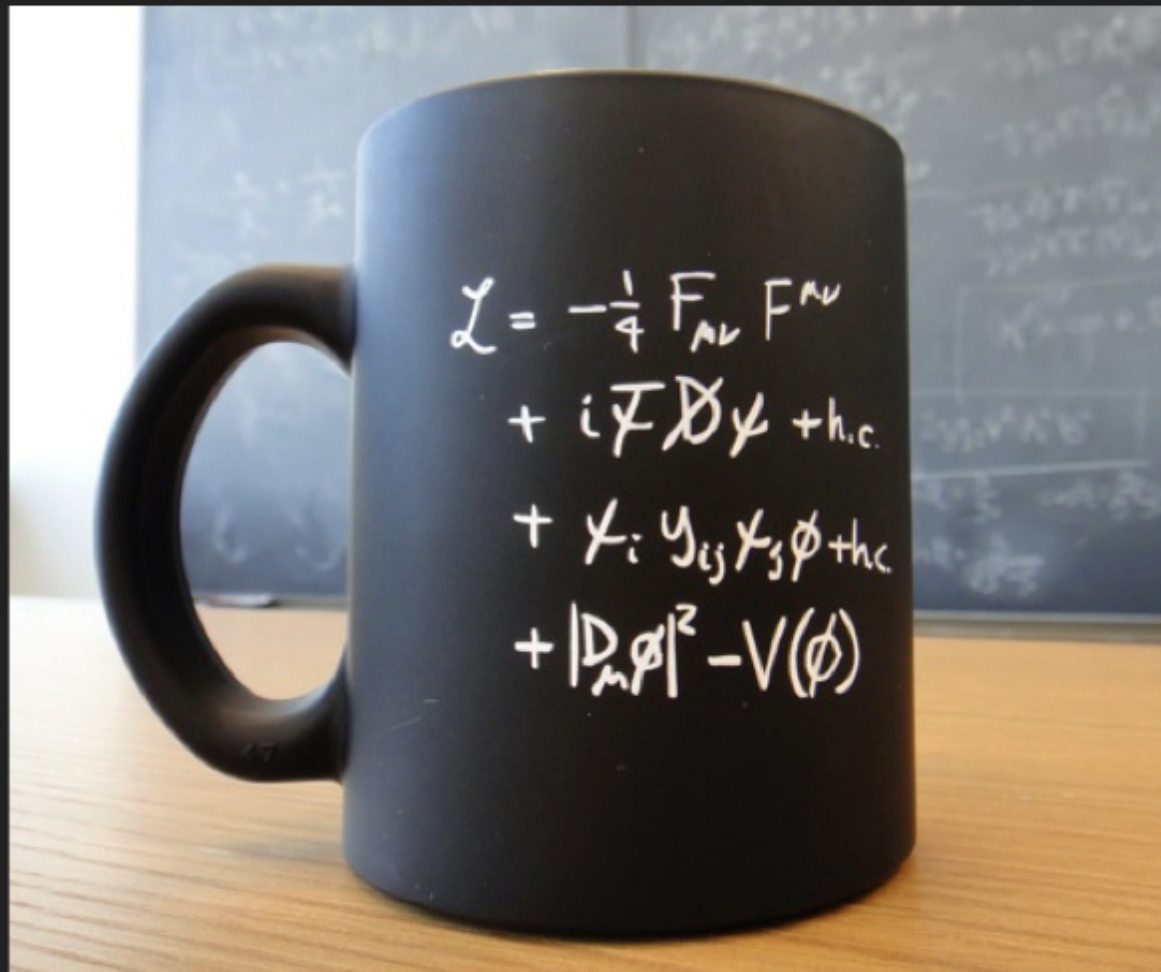


GENERAL RELATIVITY

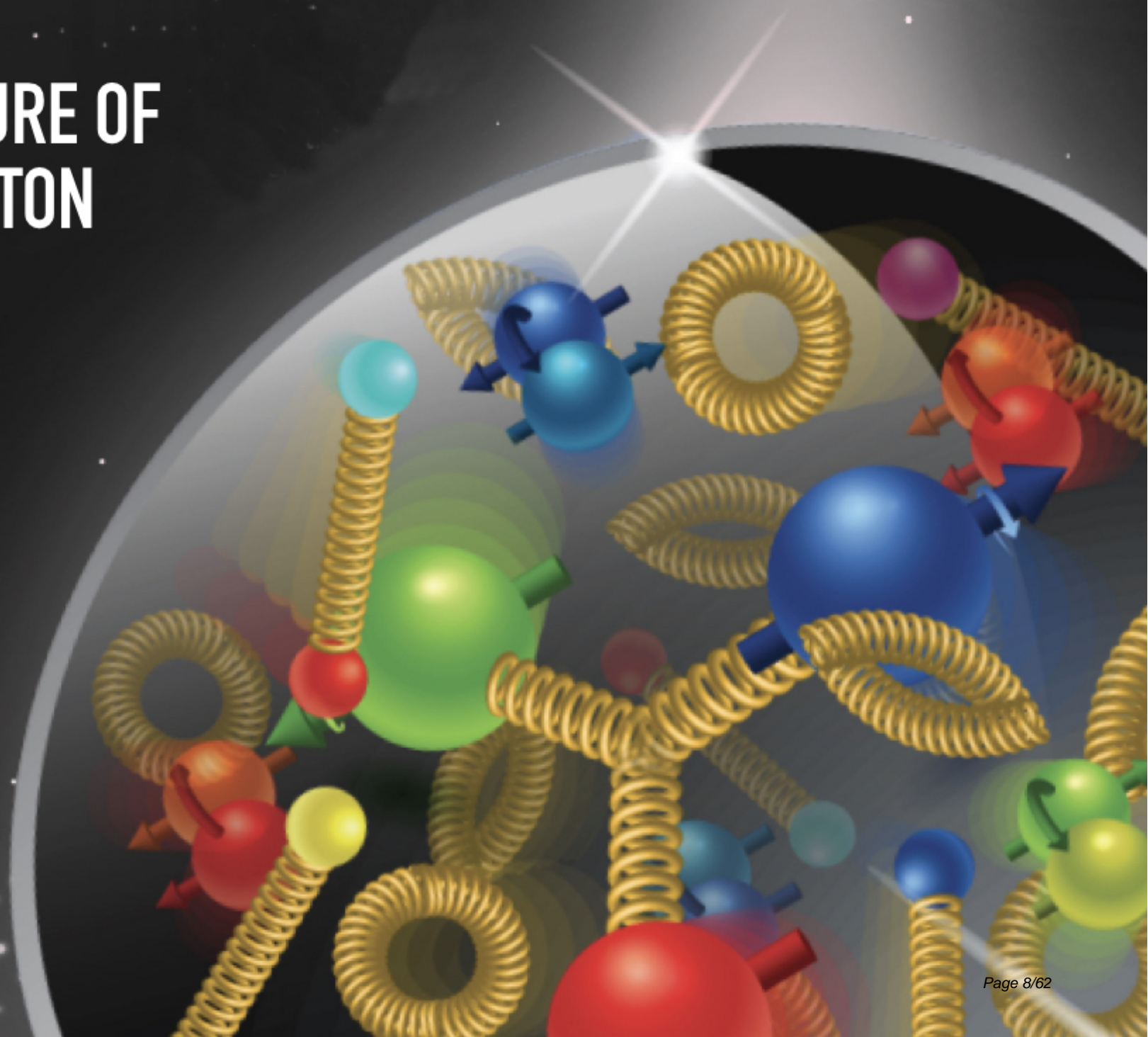
GRAVITY



THE STANDARD MODEL OF ELEMENTARY PARTICLES

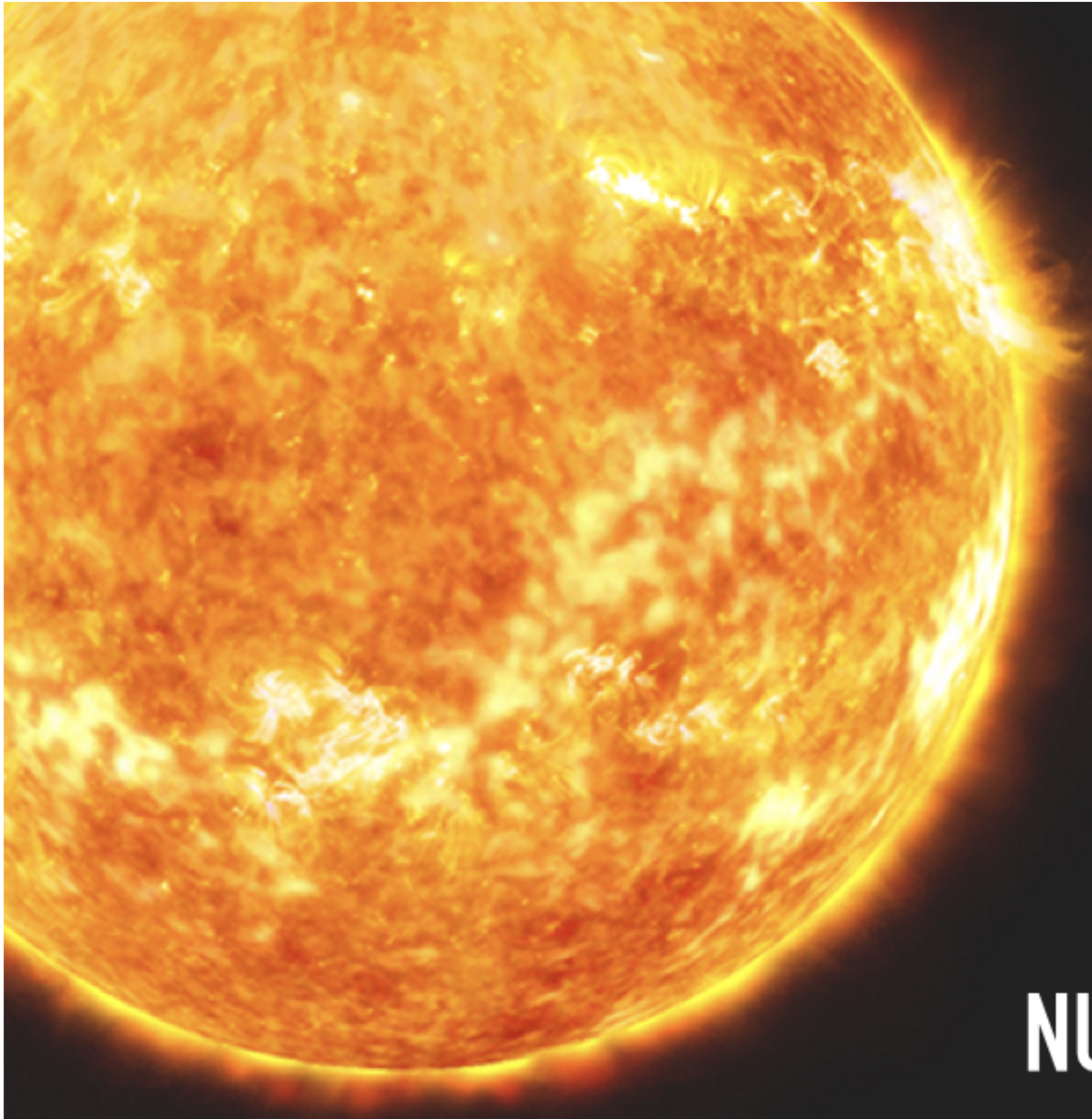


STRUCTURE OF THE PROTON



PERIODIC TABLE OF THE ELEMENTS

1 H Hydrogen 1.008																	2 He Helium 4.003																				
3 Li Lithium 6.941	4 Be Beryllium 9.012															5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180																
11 Na Sodium 22.990	12 Mg Magnesium 24.305															13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948																
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.798																				
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294																				
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018																				
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium unknown	114 Fl Flerovium [289]	115 Mc Moscovium unknown	116 Lv Livermorium [293]	117 Ts Tennessine unknown	118 Og Oganesson unknown																				
																		57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967					
																		89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]					
																		Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide										



NUCLEAR REACTIONS INSIDE THE SUN...

...AND IN REACTORS



DYNAMICS INSIDE NEUTRON STARS



STUDY THE STANDARD MODEL

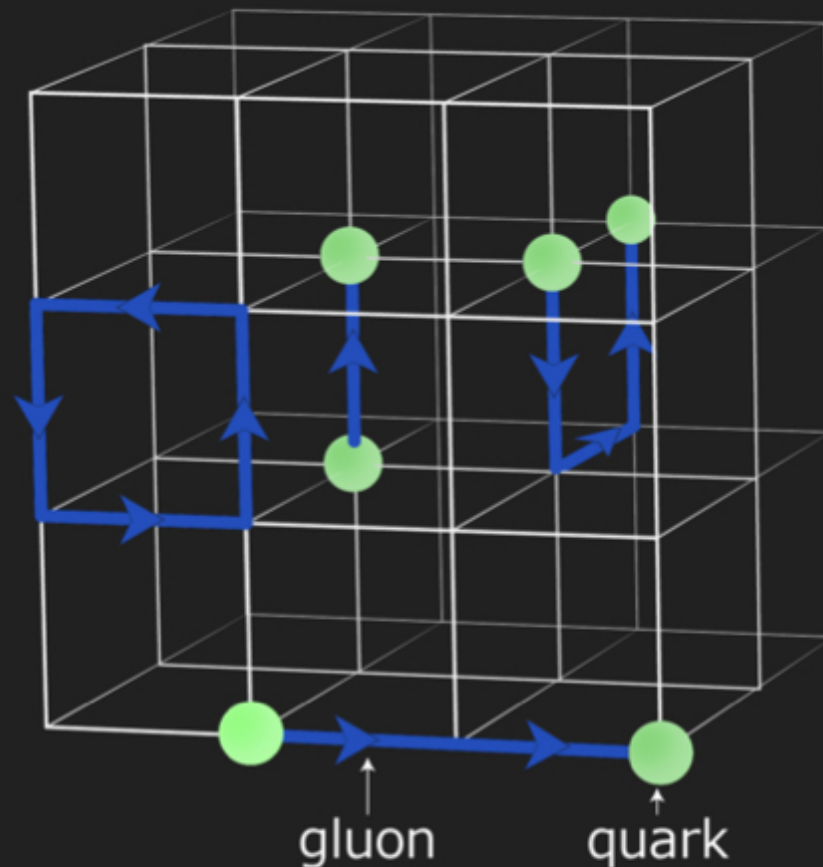
1

**UNDERSTAND HOW THE UNIVERSE
IS BUILT**

2

**FIND WHERE OUR
UNDERSTANDING BREAKS DOWN**

STANDARD MODEL CALCULATIONS ARE COMPUTATIONALLY DEMANDING



**CALCULATIONS I DISCUSS WOULD EACH TAKE
~10,000 YEARS ON YOUR DESKTOP COMPUTER**



USE THE MOST POWERFUL SUPERCOMPUTERS IN THE WORLD

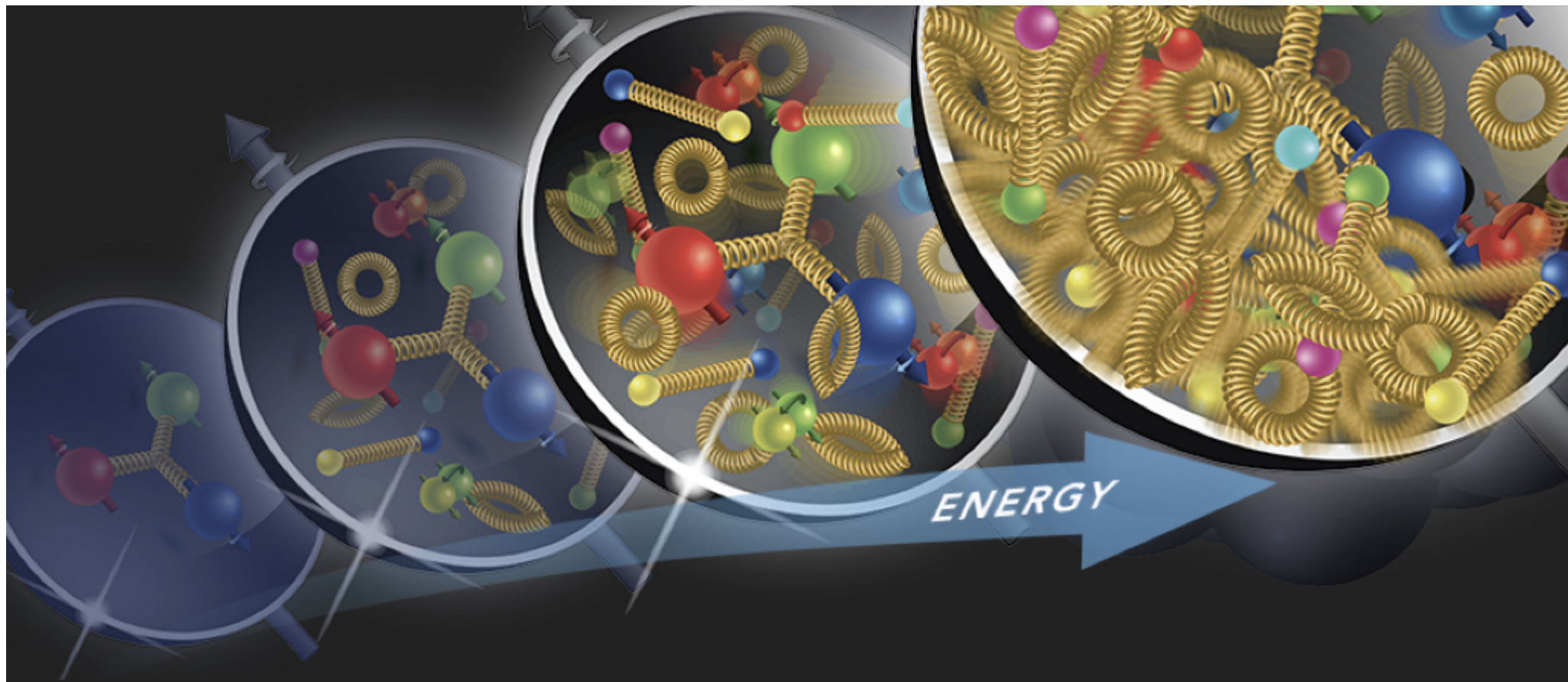


**IF EVERY PERSON ON EARTH COMPLETED ONE
CALCULATION PER SECOND, IT WOULD TAKE ONE YEAR TO
DO WHAT SUMMIT CAN DO IN ONE SECOND**



WHAT CAN WE LEARN ABOUT THE UNIVERSE?





PROTON STRUCTURE IS DYNAMICAL
HIGH ENERGY SCALES REVEAL MORE
QUARKS AND GLUONS

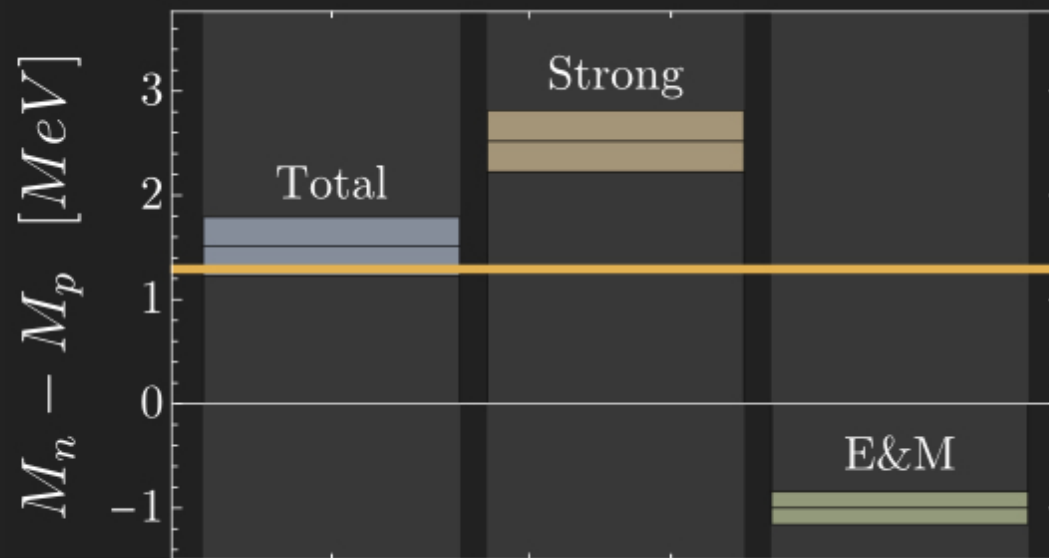
THE NEUTRON IS 0.1% HEAVIER THAN THE PROTON



ESSENTIAL FOR LIFE
AS WE KNOW IT

DELICATE BALANCE
OF STRONG AND
ELECTROMAGNETIC
INTERACTIONS

THE NEUTRON IS 0.1% HEAVIER THAN THE PROTON



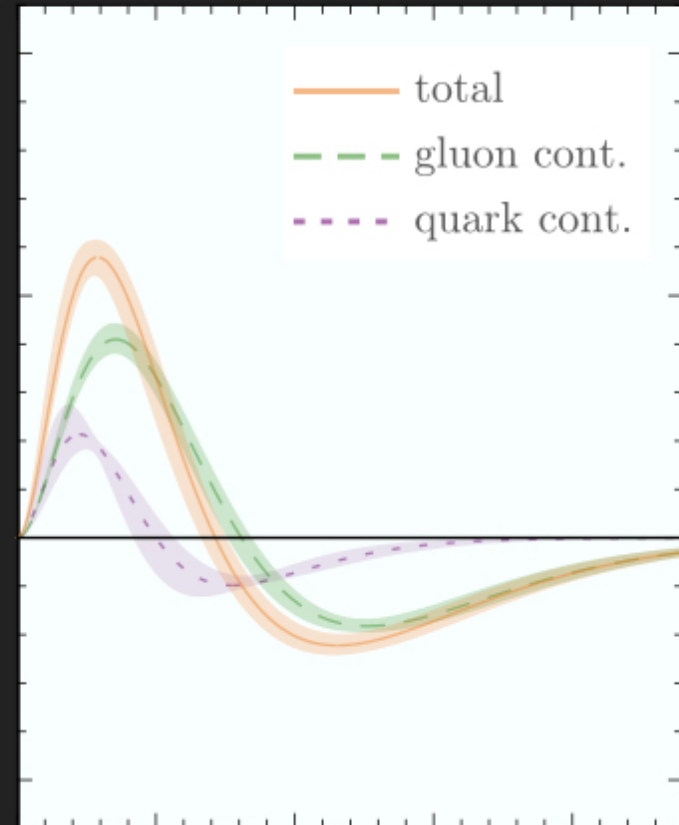
**ESSENTIAL FOR LIFE
AS WE KNOW IT**

**DELICATE BALANCE
OF STRONG AND
ELECTROMAGNETIC
INTERACTIONS**

PRESSURE INSIDE THE PROTON IS GREATER THAN INSIDE NEUTRON STARS

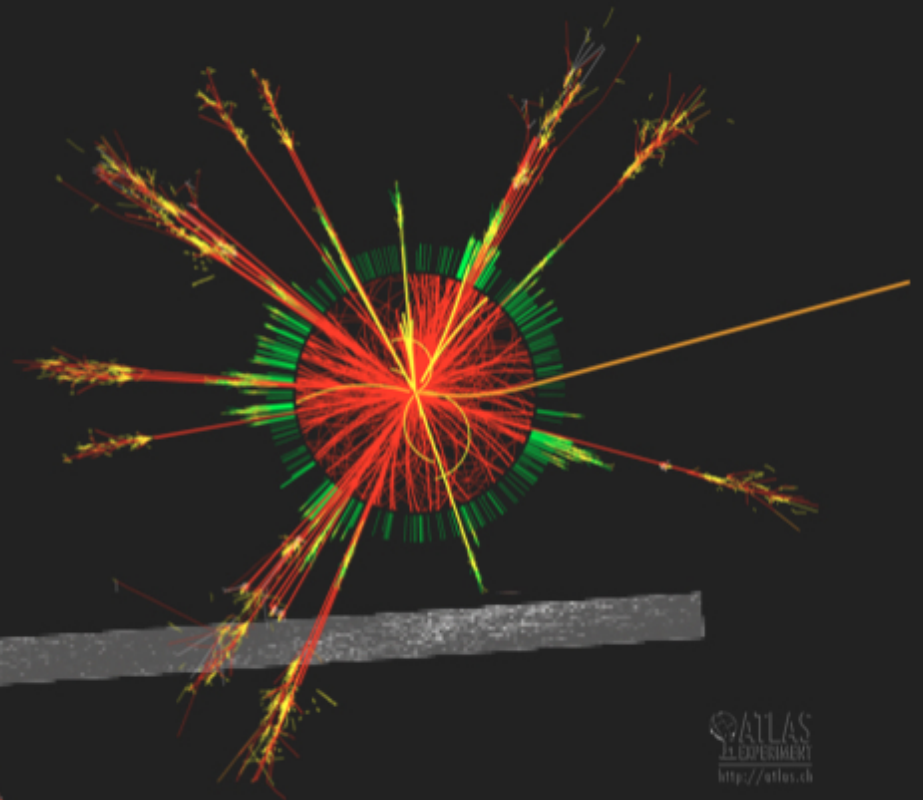


$(\text{DISTANCE})^2 \times \text{PRESSURE}$



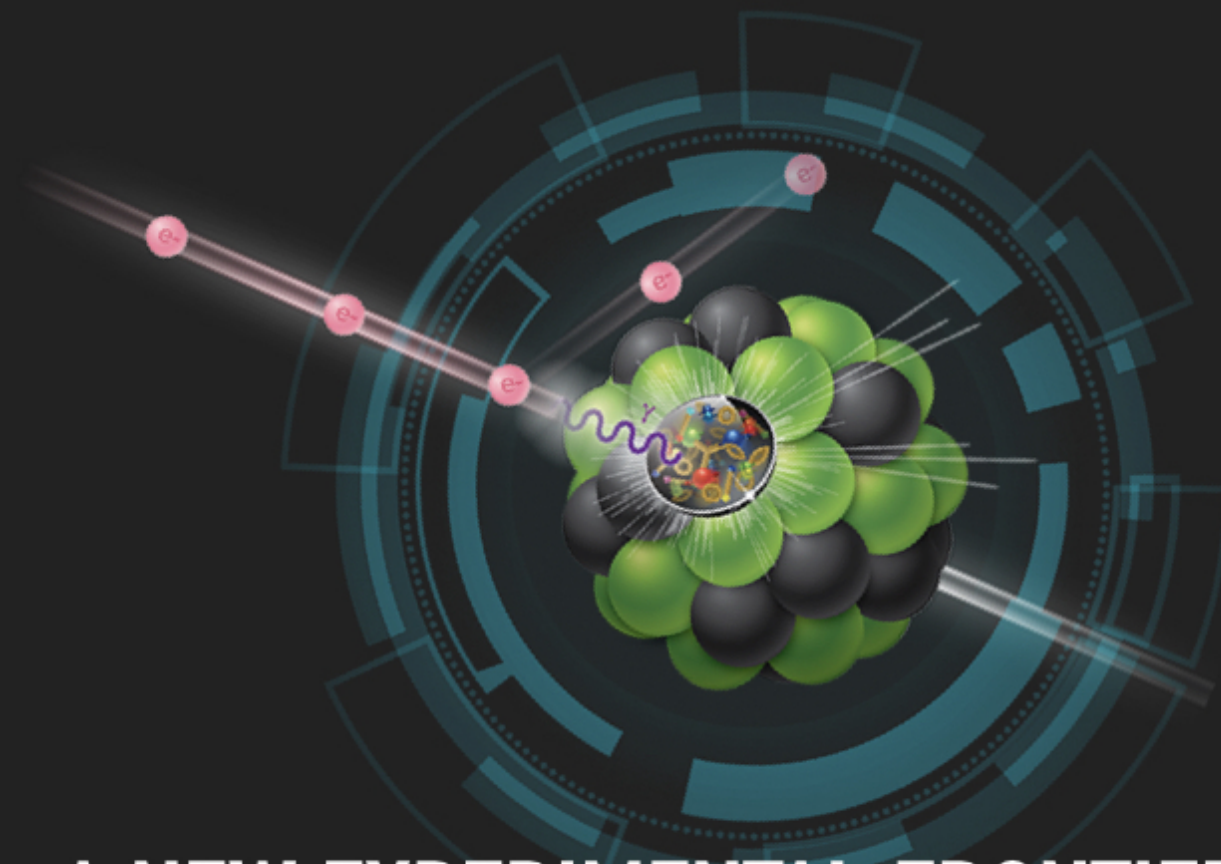
DISTANCE FROM CENTRE

THEORY COMPLIMENTS EXPERIMENT



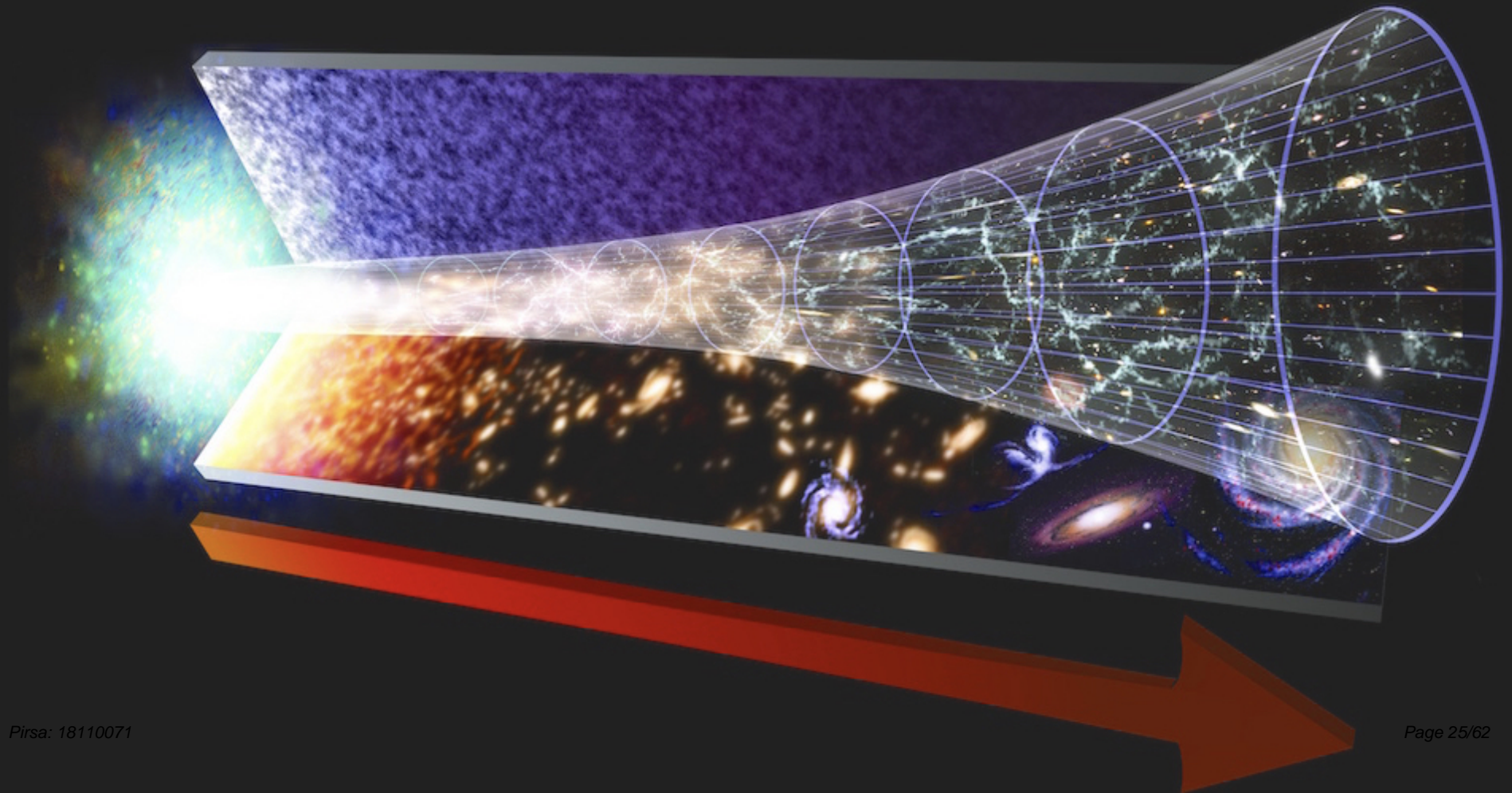
ATLAS
AN EXPERIMENT
<http://atlas.ch>

A FUTURE ELECTRON-ION COLLIDER 2025-2030

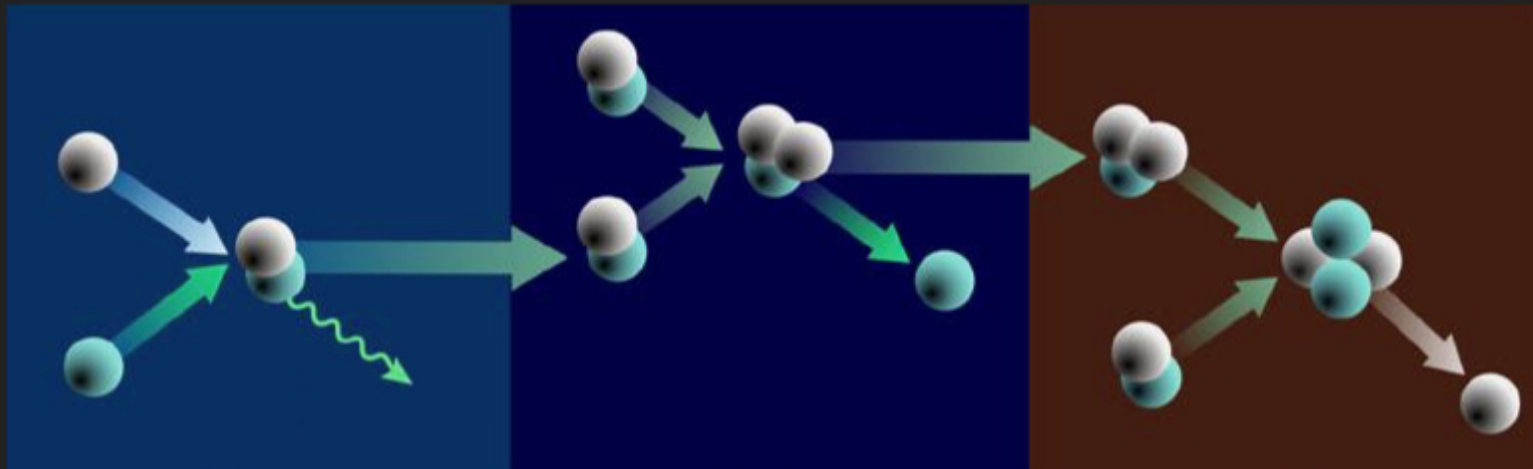


A NEW EXPERIMENTAL FRONTIER FOR STUDYING PROTON STRUCTURE

CREATING THE FIRST ELEMENTS AFTER THE BIG BANG

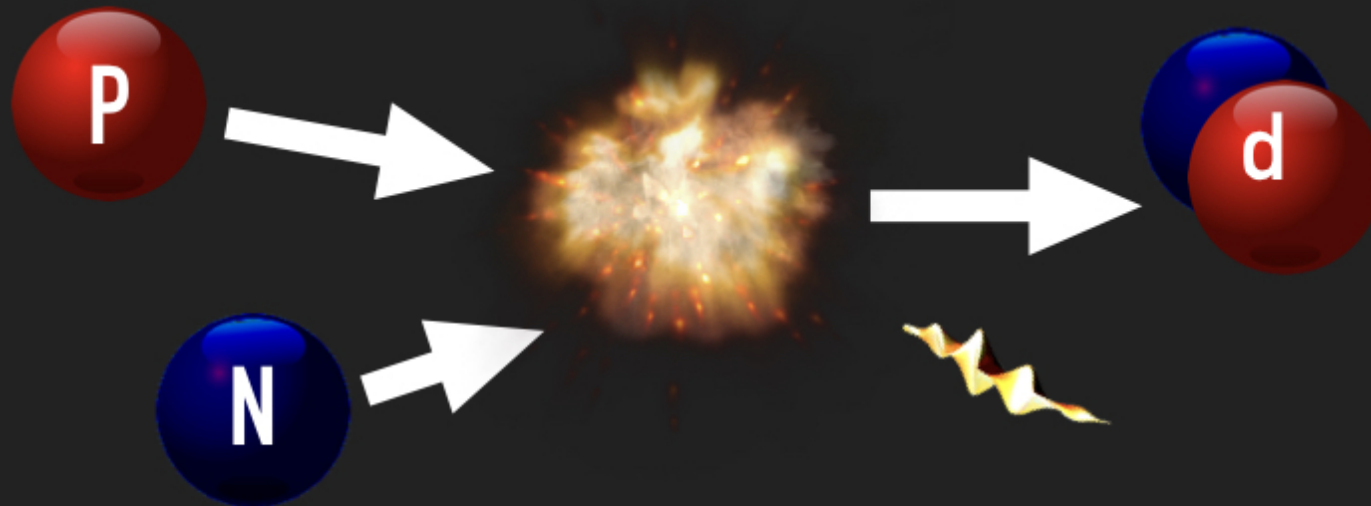


CREATING THE FIRST ELEMENTS AFTER THE BIG BANG



BIG BANG NUCLEOSYNTHESIS 10 SEC – 20 MIN AFTER BANG

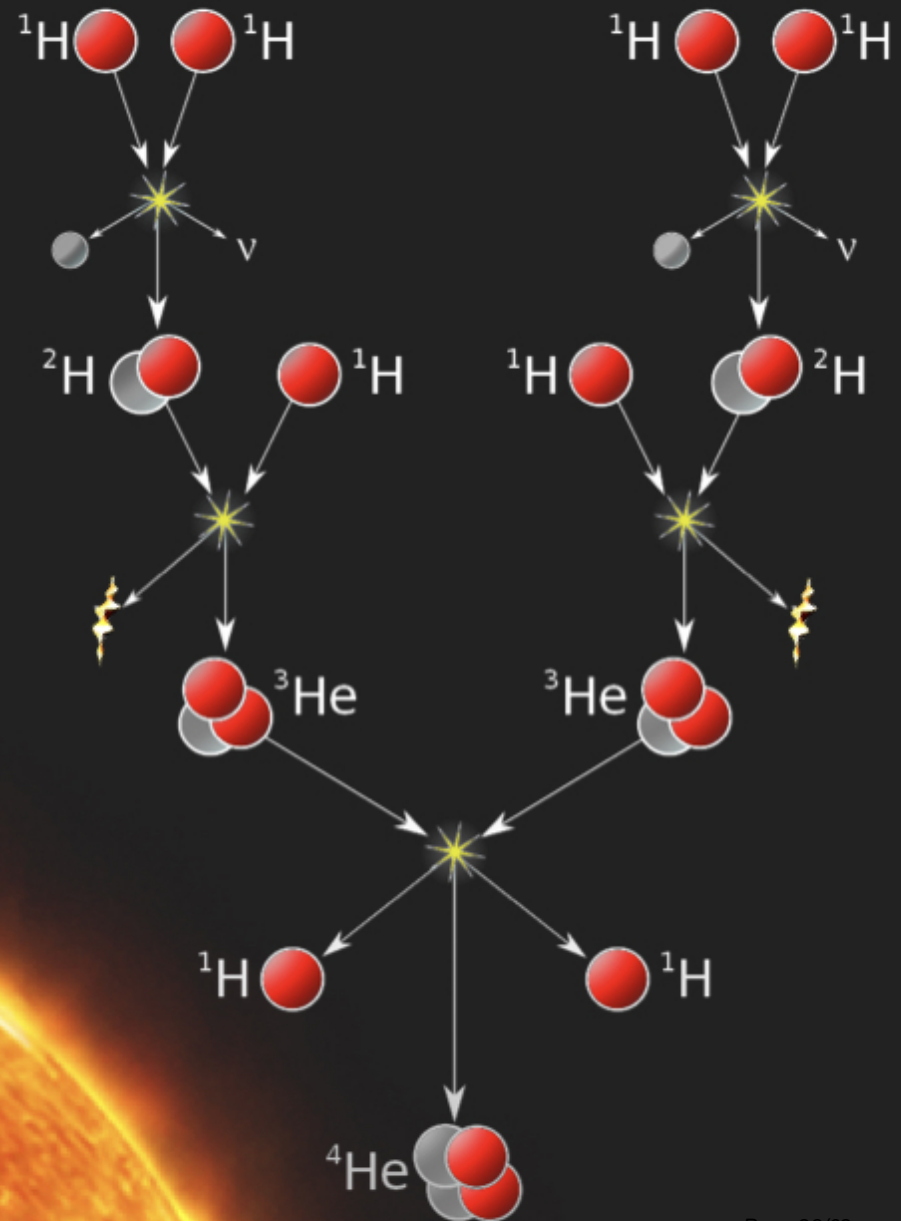
CREATING THE FIRST ELEMENTS AFTER THE BIG BANG



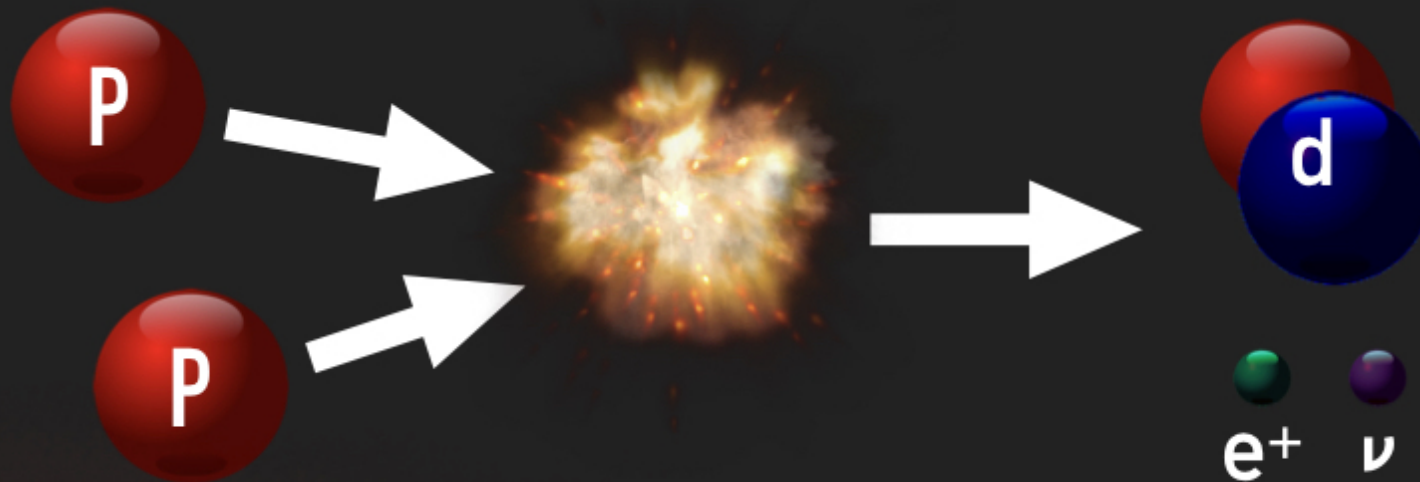
THE FIRST NUCLEAR REACTION



PROTON-PROTON FUSION CHAIN REACTION



POWERING THE SUN



ENTERING AN ERA OF UNDERSTANDING NUCLEAR PHYSICS FROM FUNDAMENTAL PARTICLES

THE STANDARD MODEL ISN'T EVERYTHING

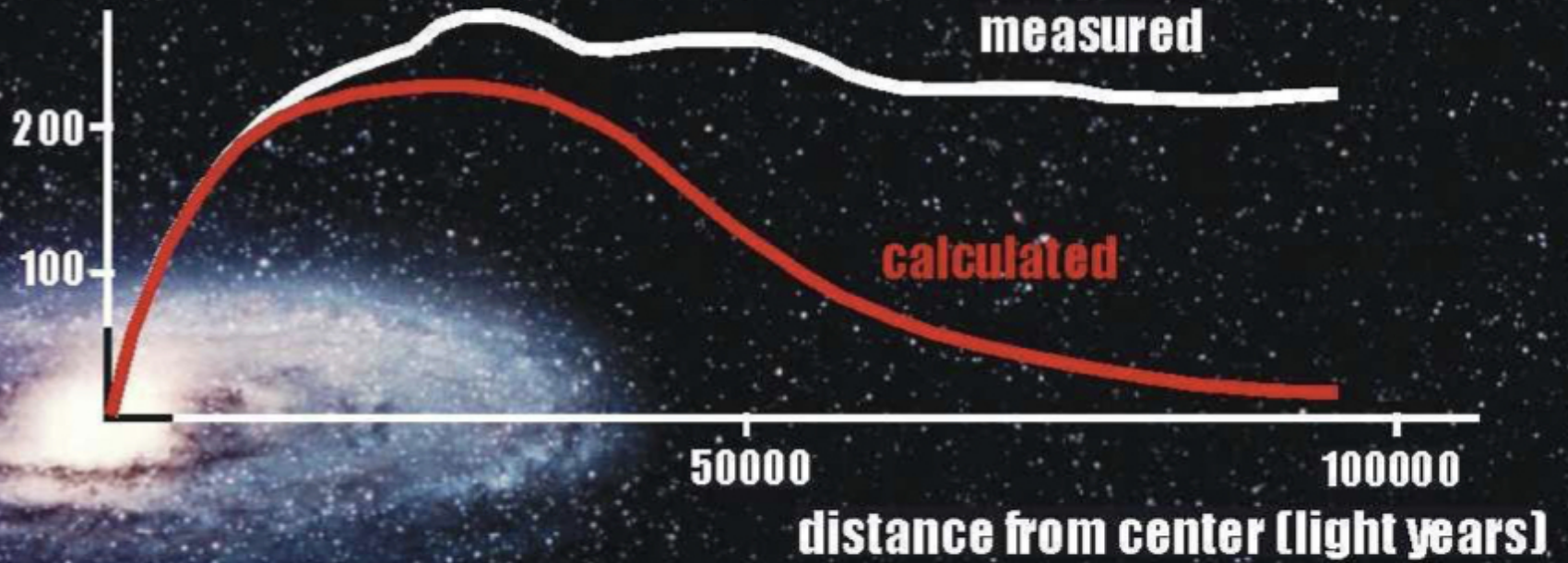


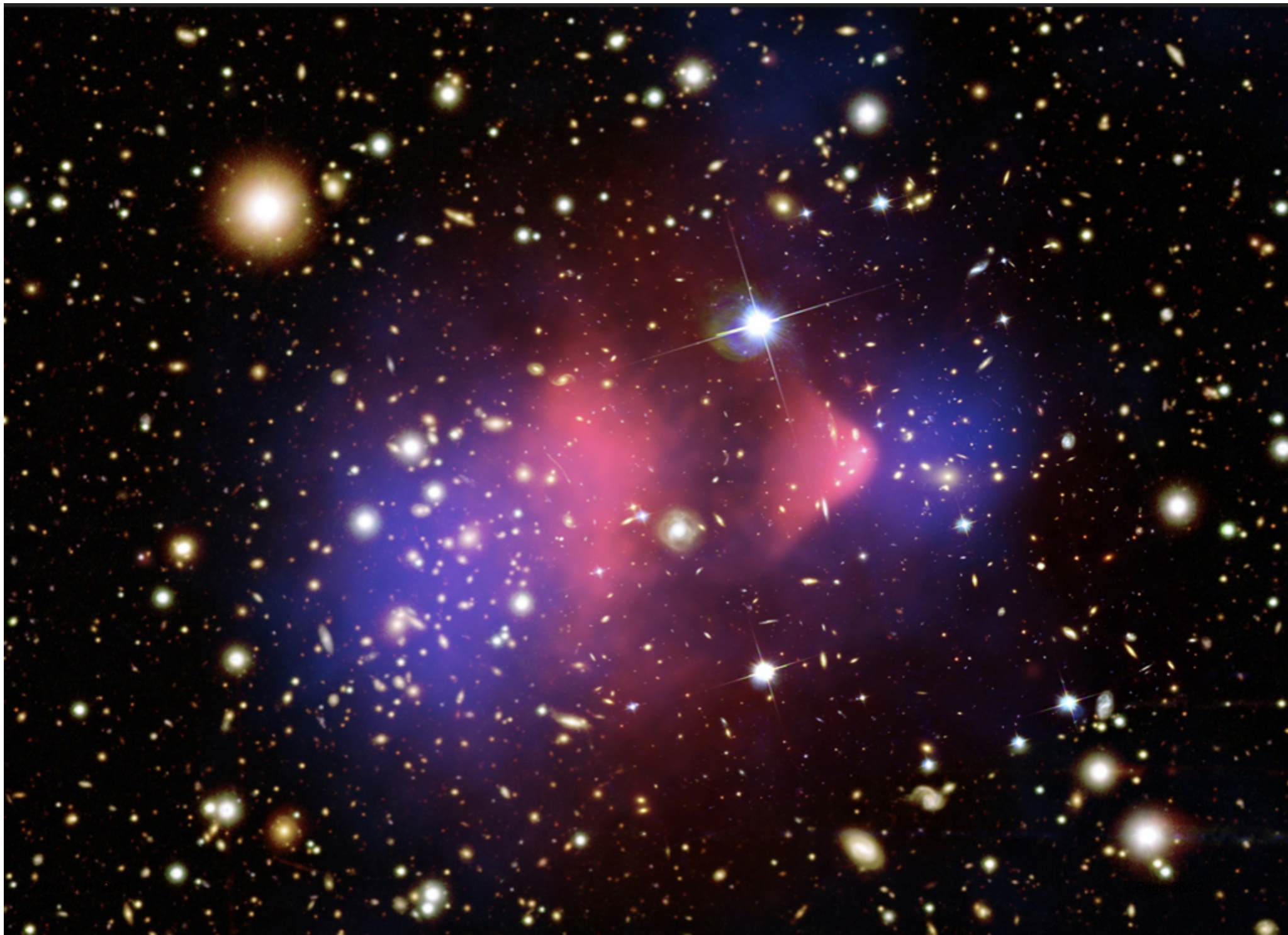
GRAVITY
NEUTRINO MASSES
MATTER—ANTIMATTER ASYMMETRY
DARK MATTER

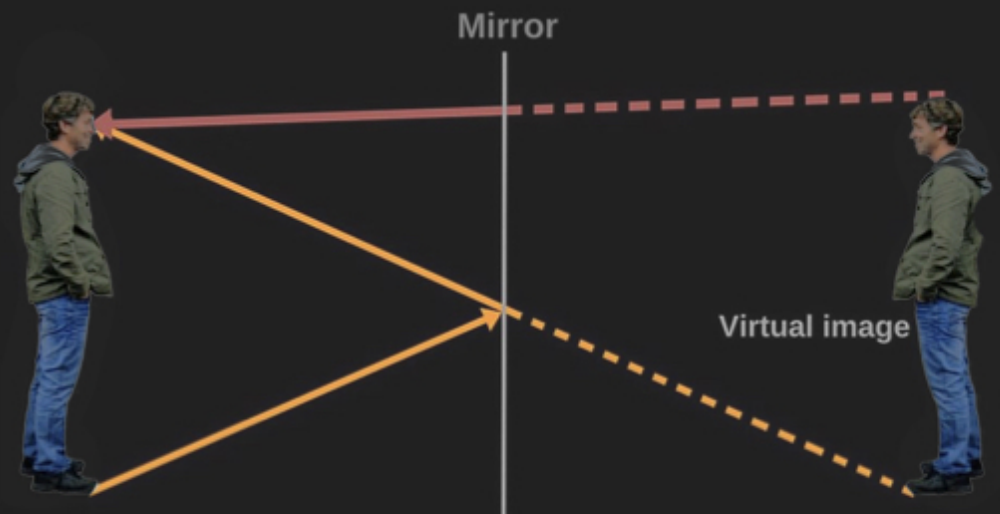
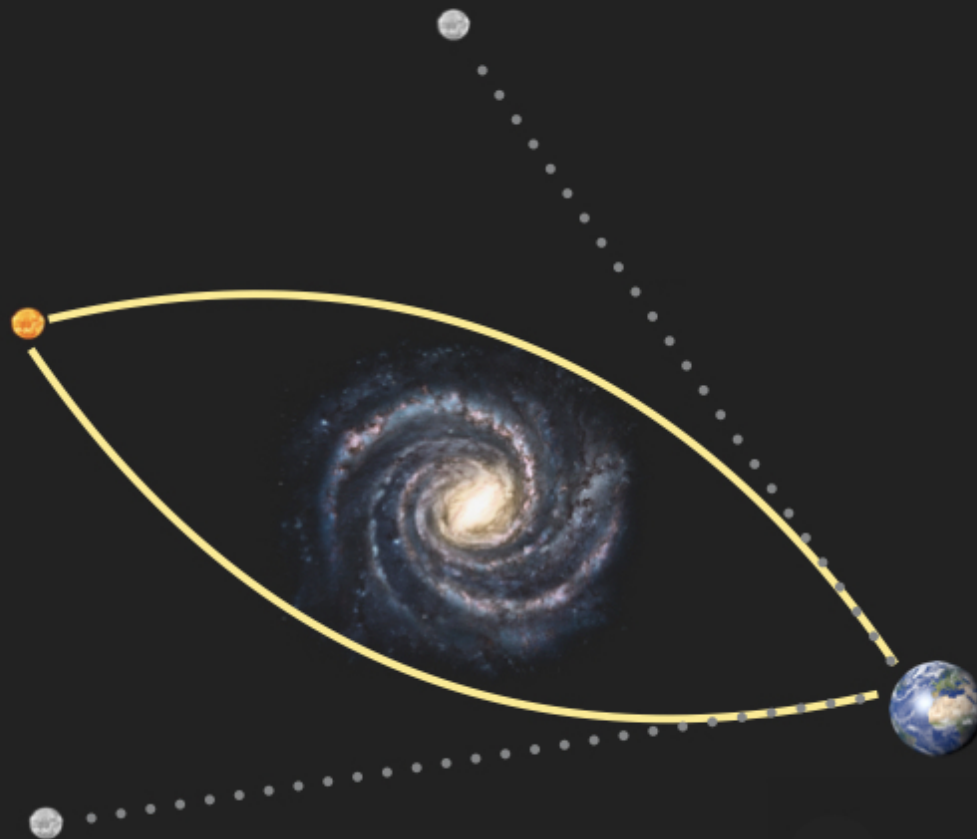
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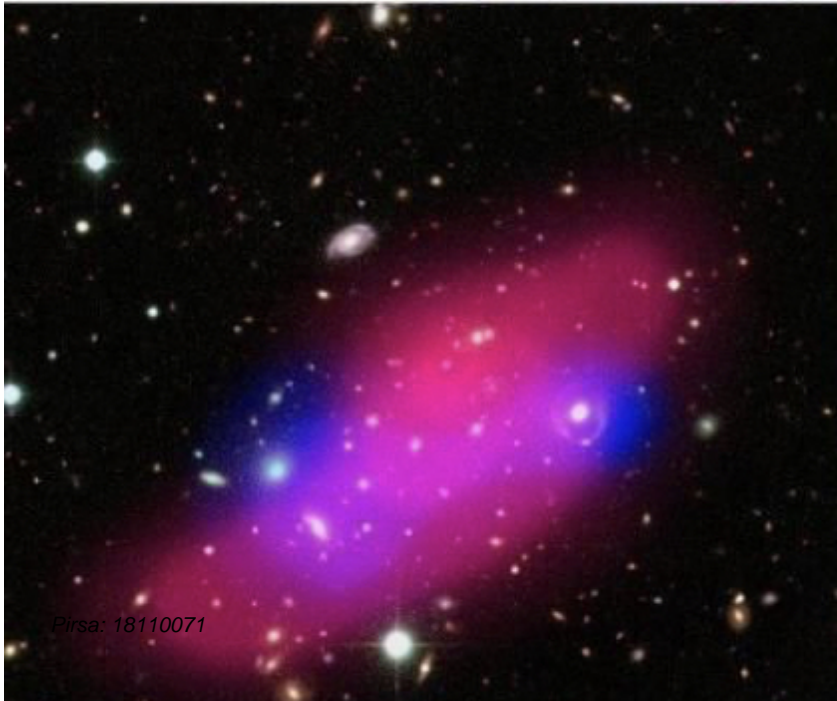
**rotational velocity
[km/s]**







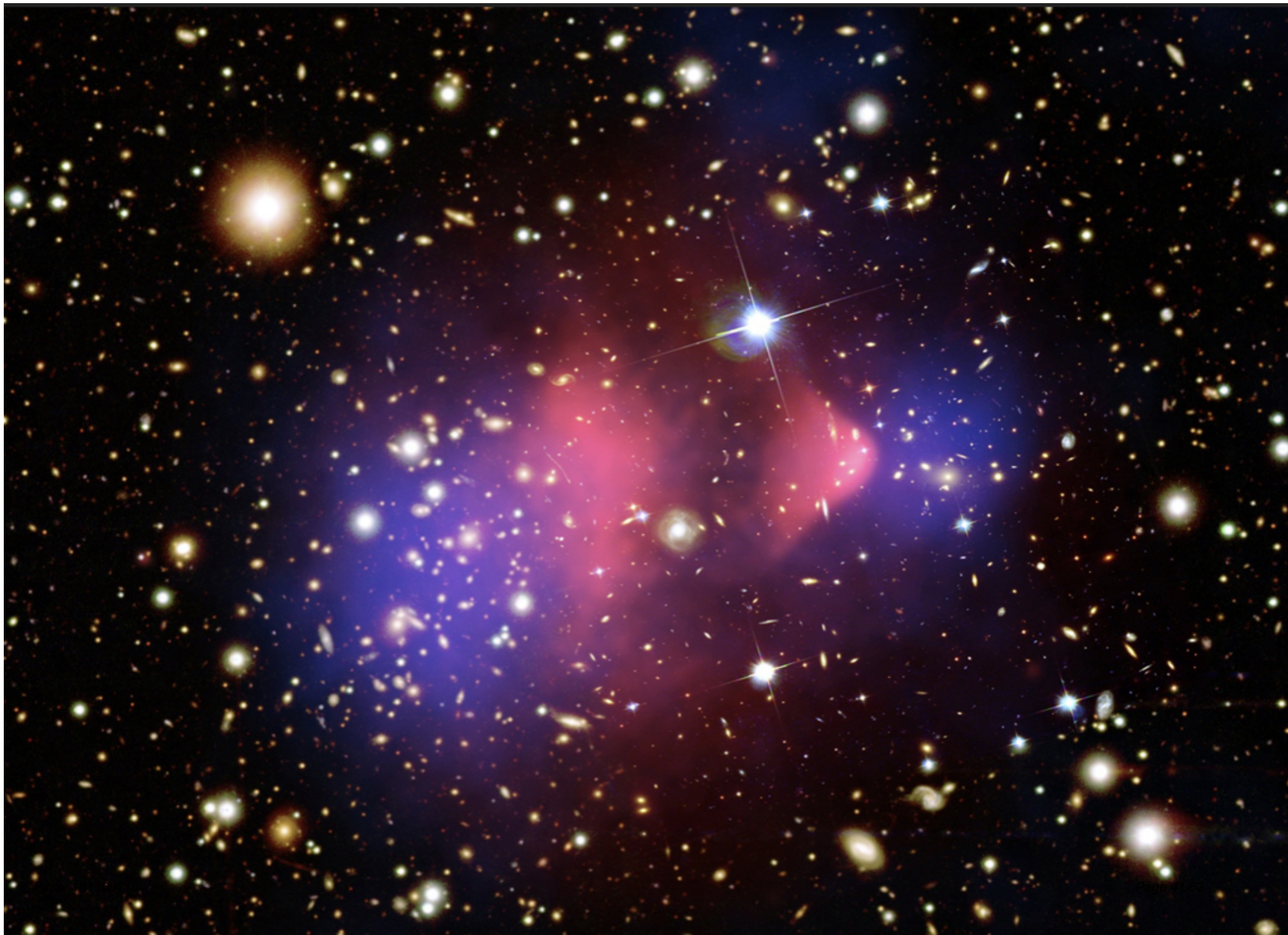


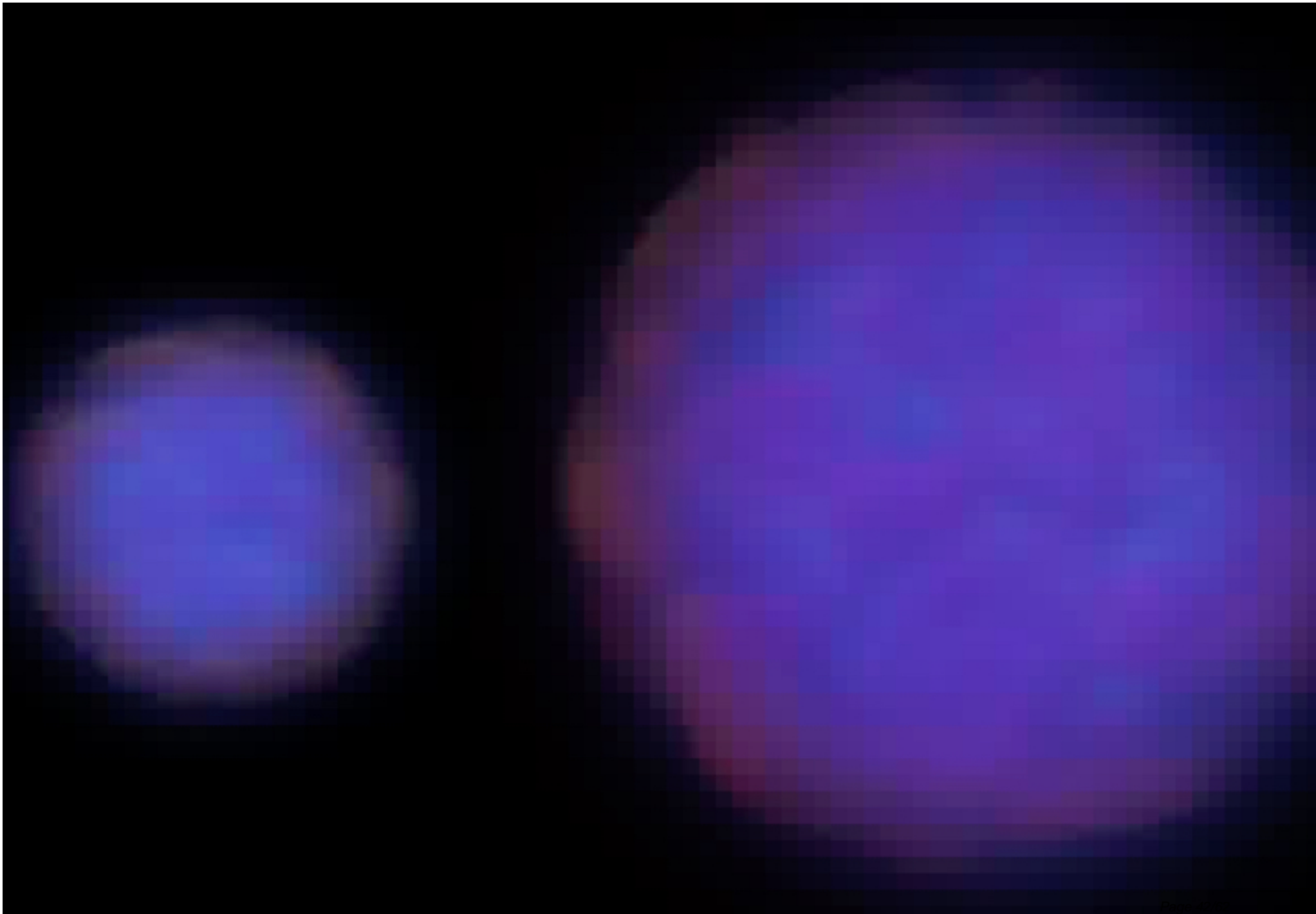


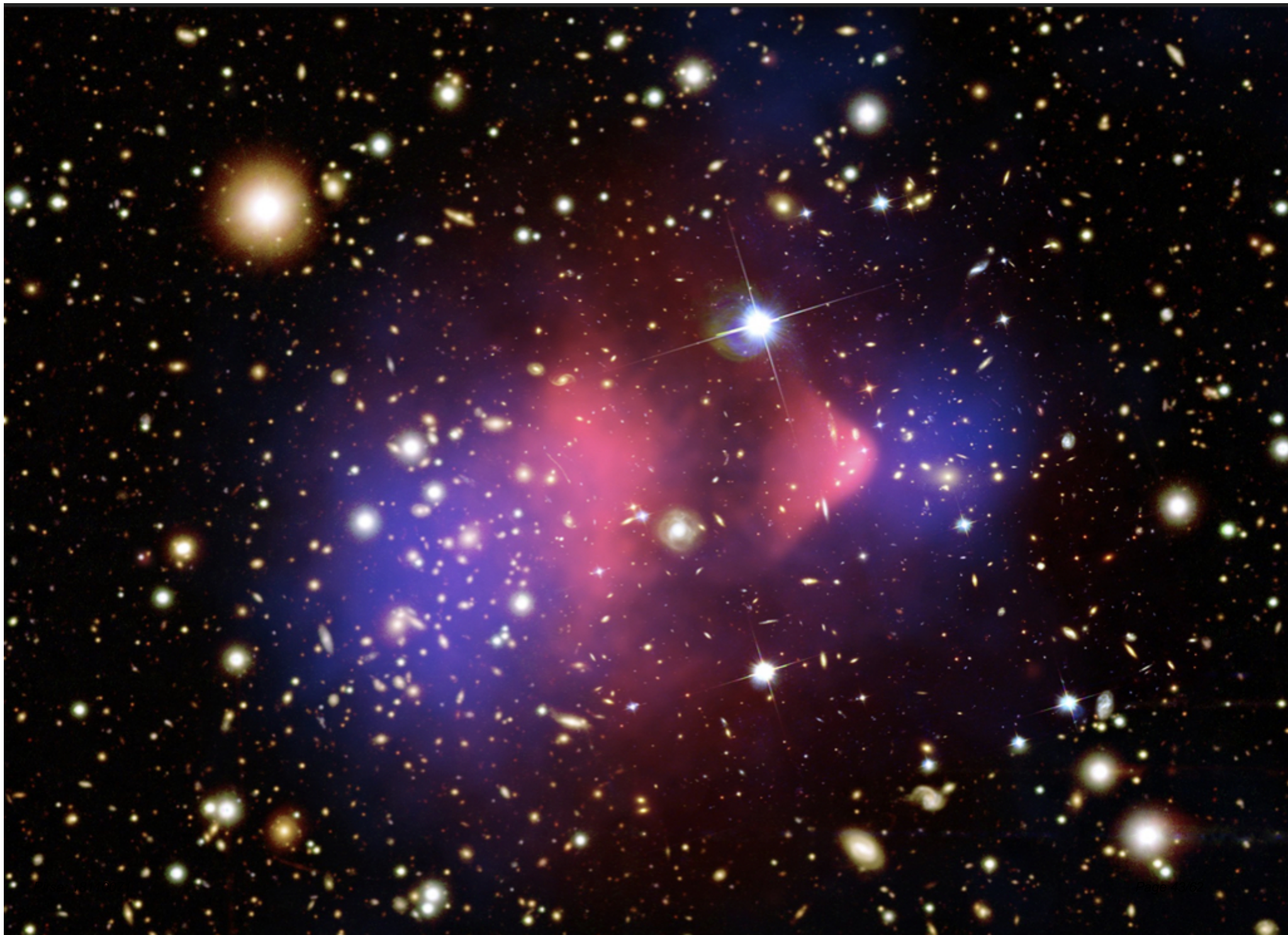
**WE DEDUCE
THE EXISTENCE OF
DARK MATTER**

**IT CAN'T BE SEEN,
BUT IT MUST BE
THERE**

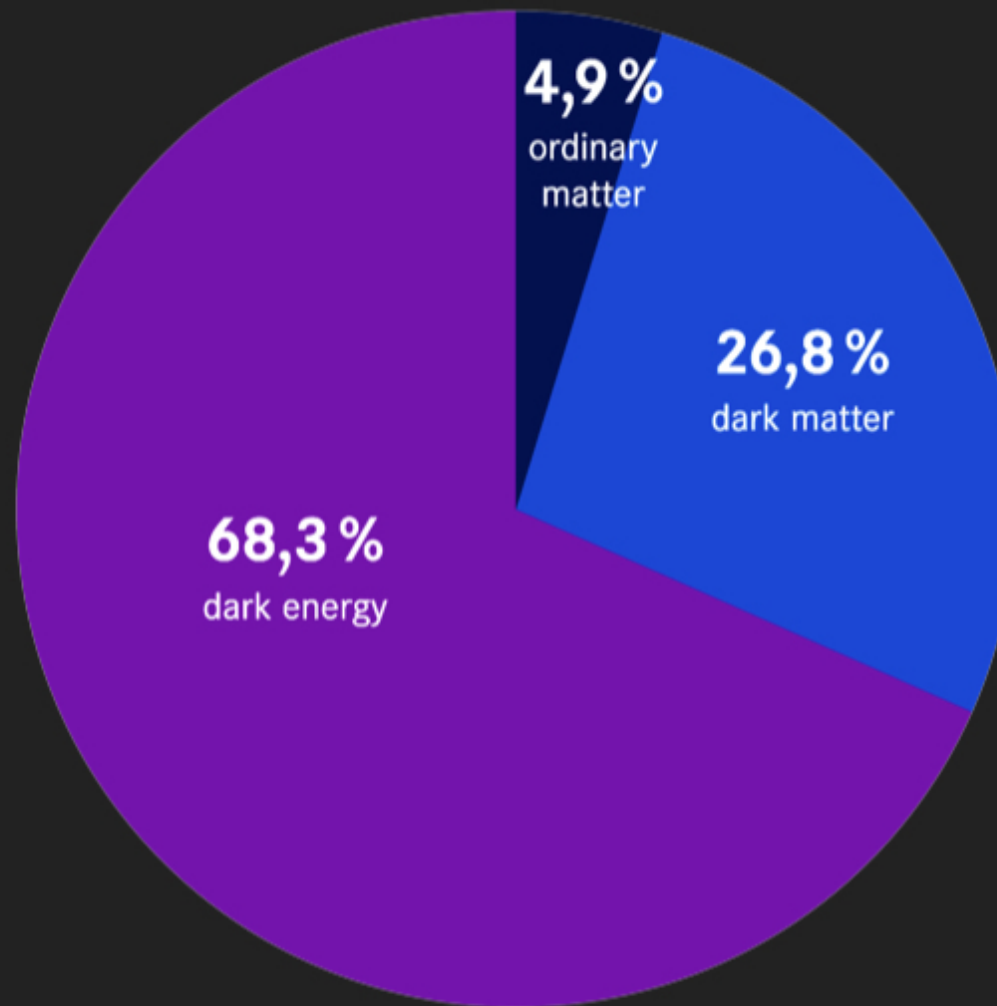








MOST OF THE MATTER IN THE UNIVERSE IS DARK



HOW DOES DARK MATTER INTERACT?

ELECTROMAGNETISM



STRONG FORCE



WEAK FORCE



GRAVITY



WE KNOW WHAT DARK MATTER IS NOT

NORMAL MATTER

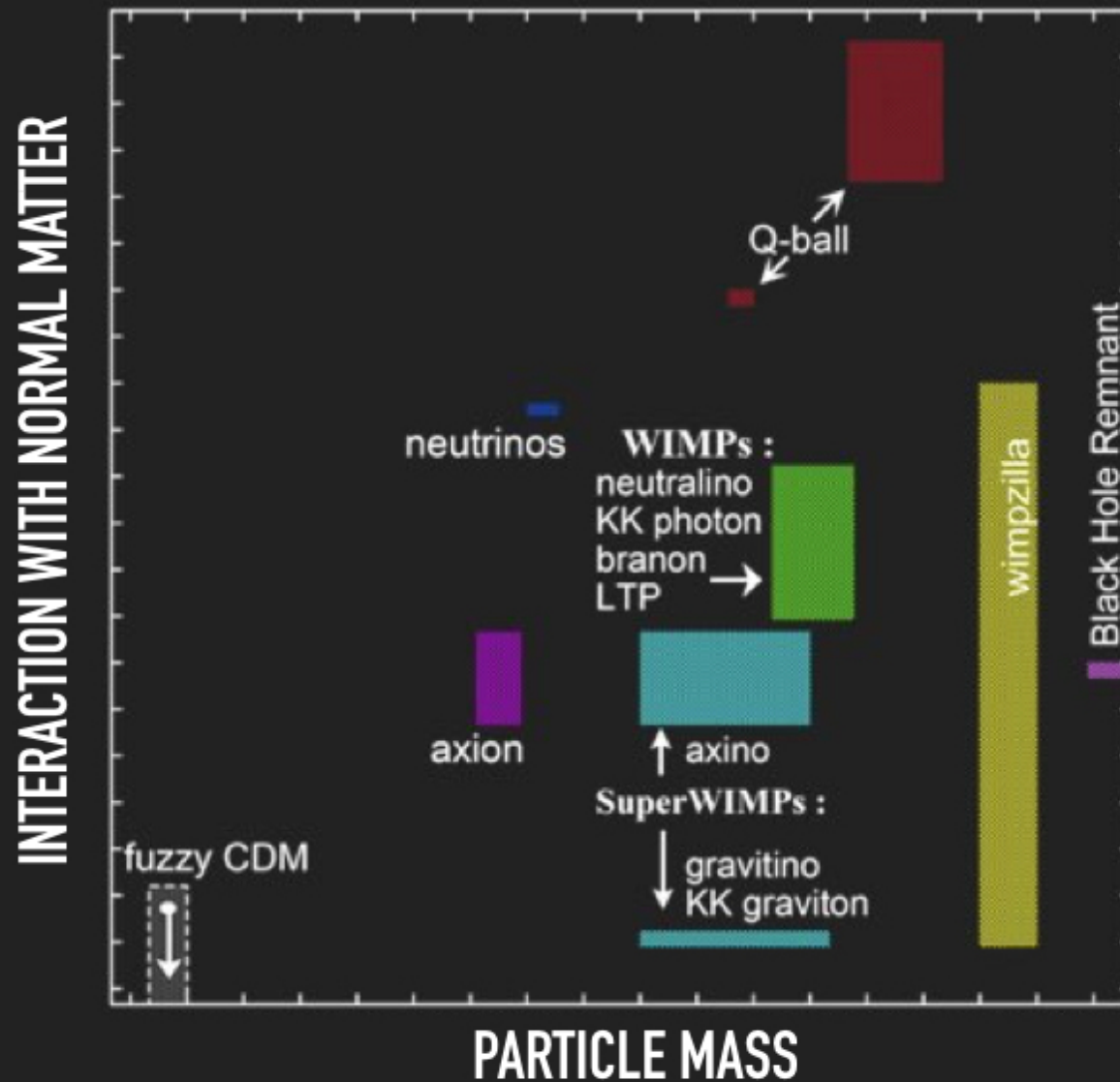
- ▶ STARS, PLANETS
- ▶ ANTIMATTER
- ▶ GALAXY-SIZED
BLACK HOLES



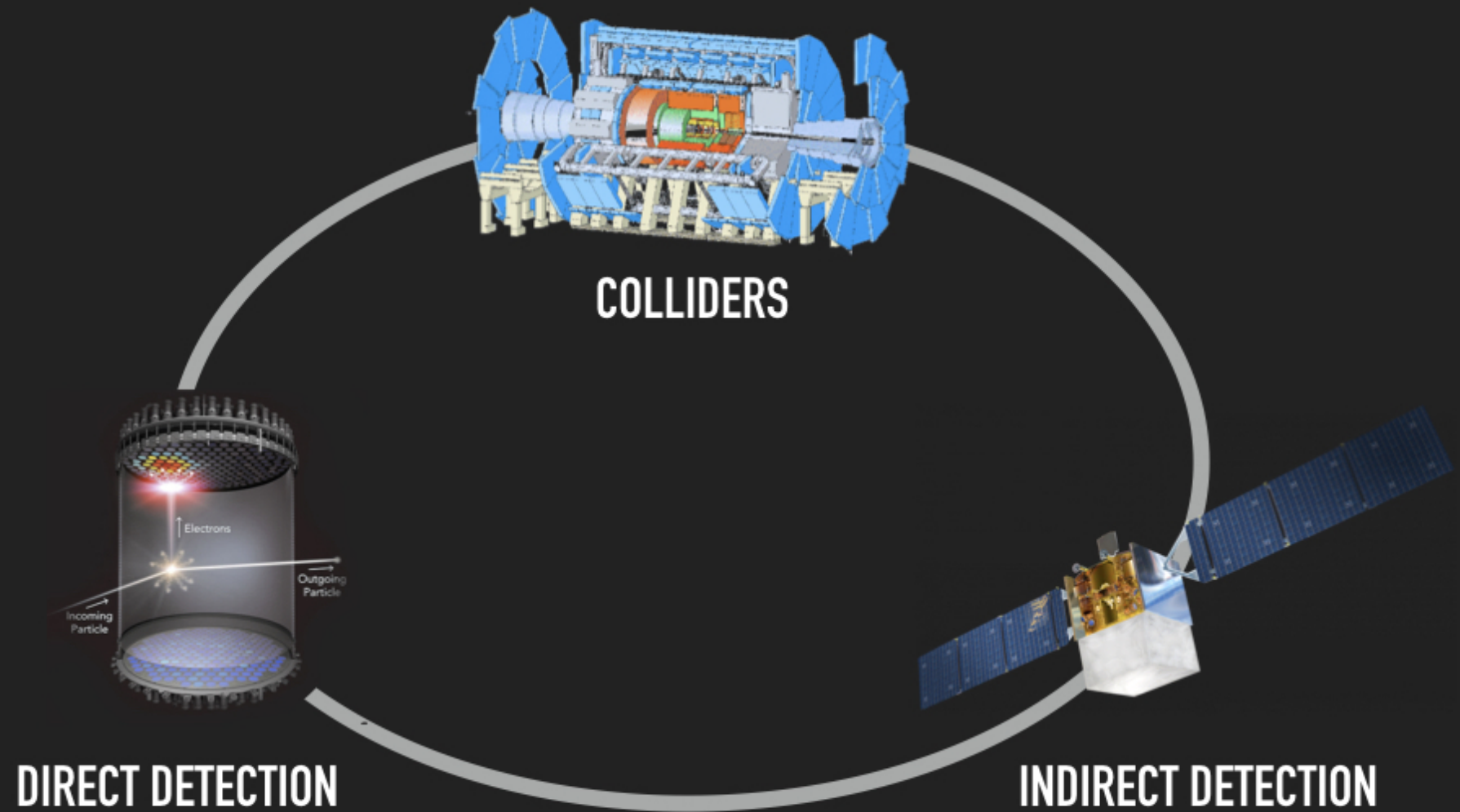
MANY POSSIBILITIES FOR DARK MATTER



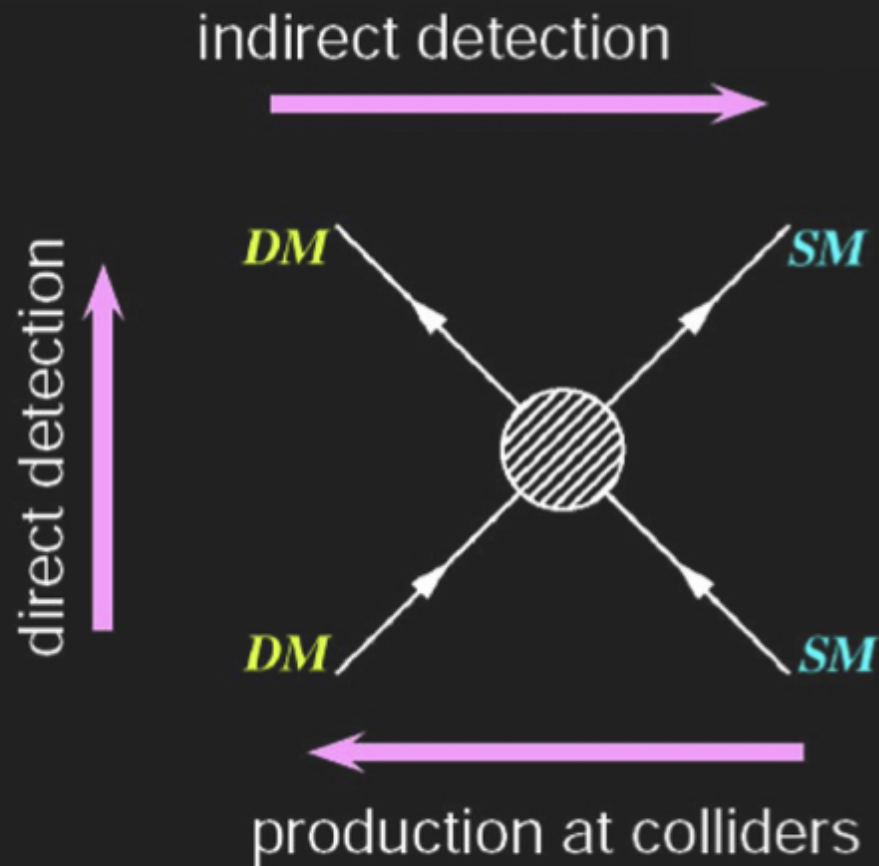
WITH DIFFERENT PREDICTED PROPERTIES



CONSTRAIN POSSIBLE DARK MATTER MODELS BY EXPERIMENT

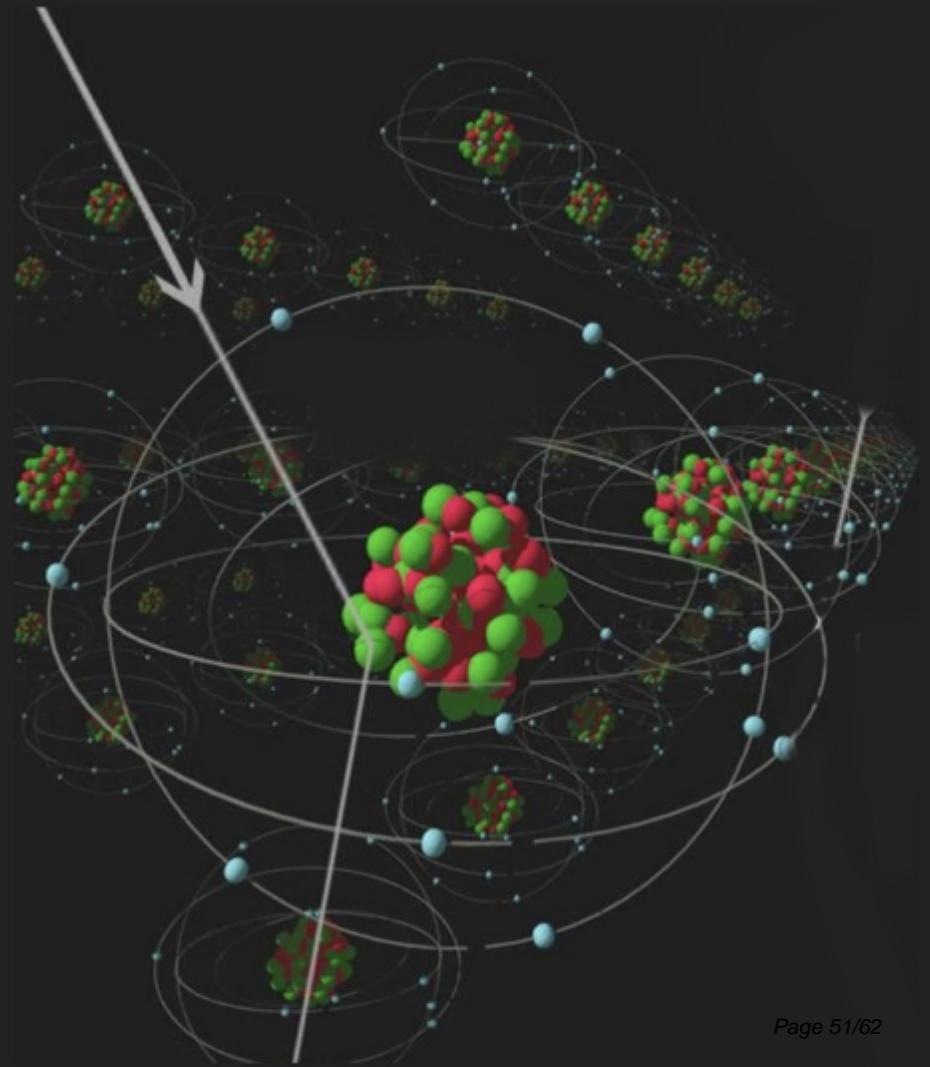


CONSTRAIN POSSIBLE DARK MATTER MODELS BY EXPERIMENT

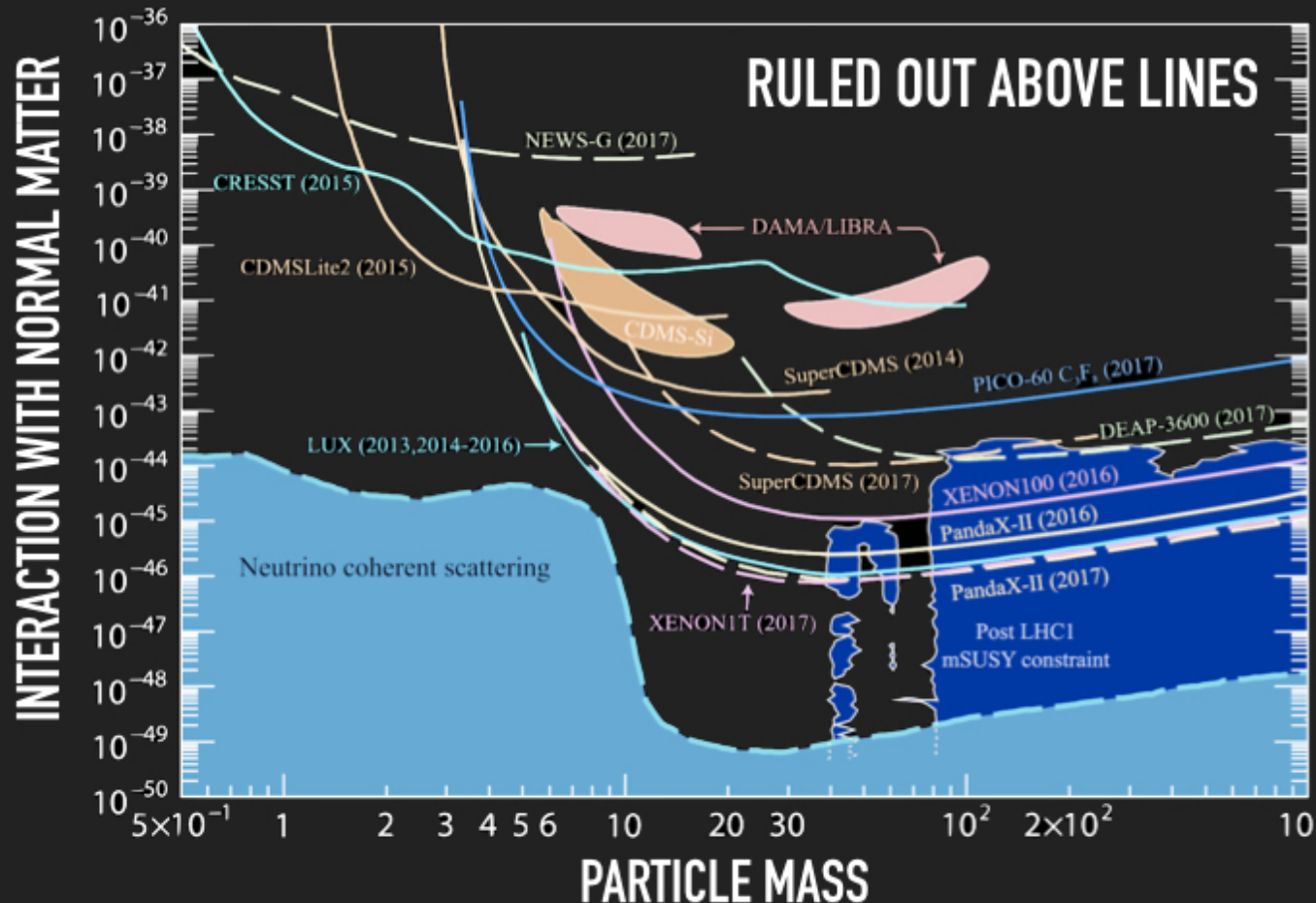


DIRECT SEARCHES FOR DARK MATTER

SEARCH FOR
WEAKLY
INTERACTING
MASSIVE
PARTICLES

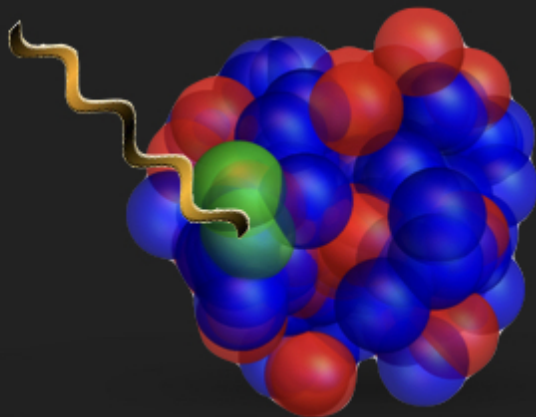
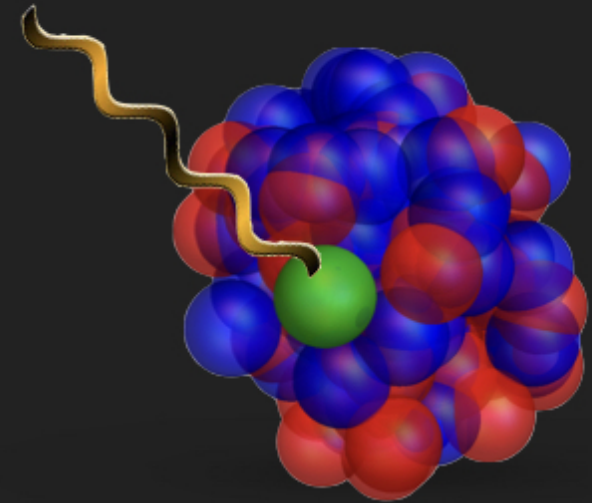


MANY LIMITS FROM EXISTING EXPERIMENTS



RELY ON THEORY CALCULATIONS OF DARK MATTER
INTERACTION WITH STANDARD MODEL

**ALL CONSTRAINTS ASSUME
DARK MATTER INTERACTS
WITH A SINGLE PROTON OR
NEUTRON IN THE NUCLEUS**



**NEW CALCULATIONS SHOW THAT
MULTI-BODY INTERACTIONS
ARE IMPORTANT**

**MANY PROBLEMS STILL
TOO EXPENSIVE
COMPUTATIONALLY**

STRUCTURE/INTERACTIONS OF LARGER NUCLEI FROM THE STANDARD MODEL

DARK MATTER INTERACTIONS WITH LARGER NUCLEI

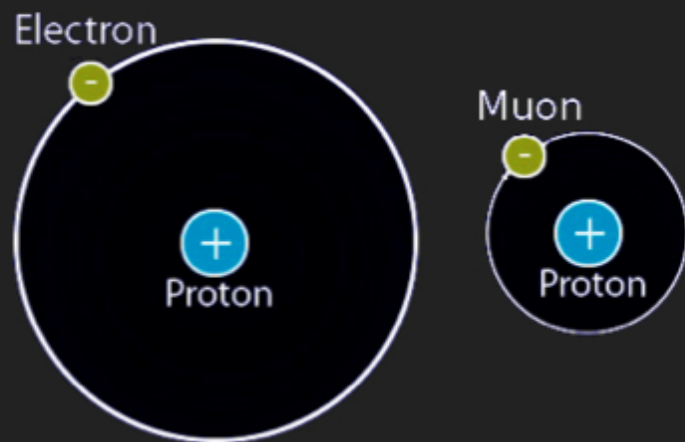
NEUTRINO-NUCLEUS SCATTERING

DOUBLE-BETA DECAY



... AND SIMPLER QUESTIONS

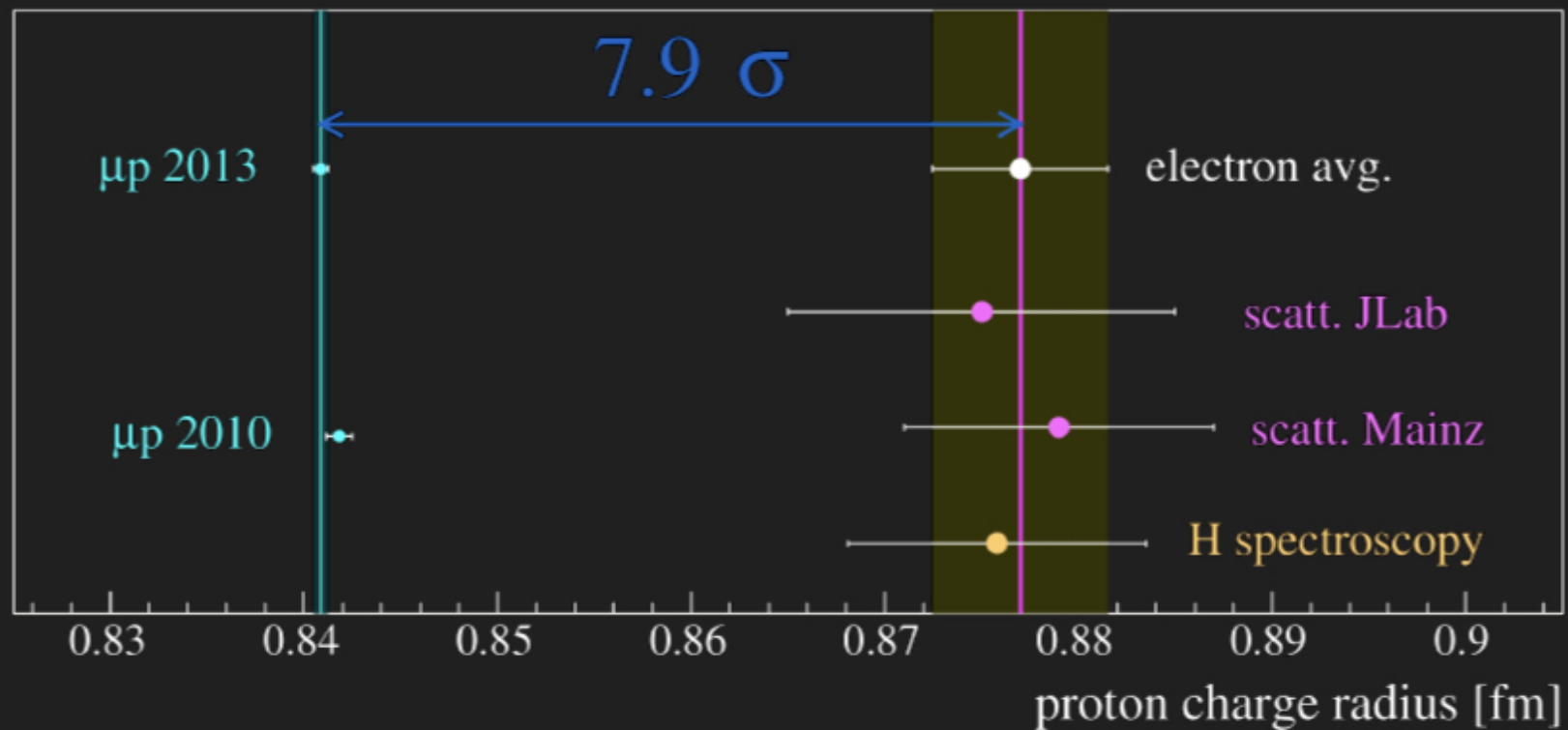
WHAT IS THE PROTON RADIUS?



CONFLICTING EXPERIMENTAL RESULTS

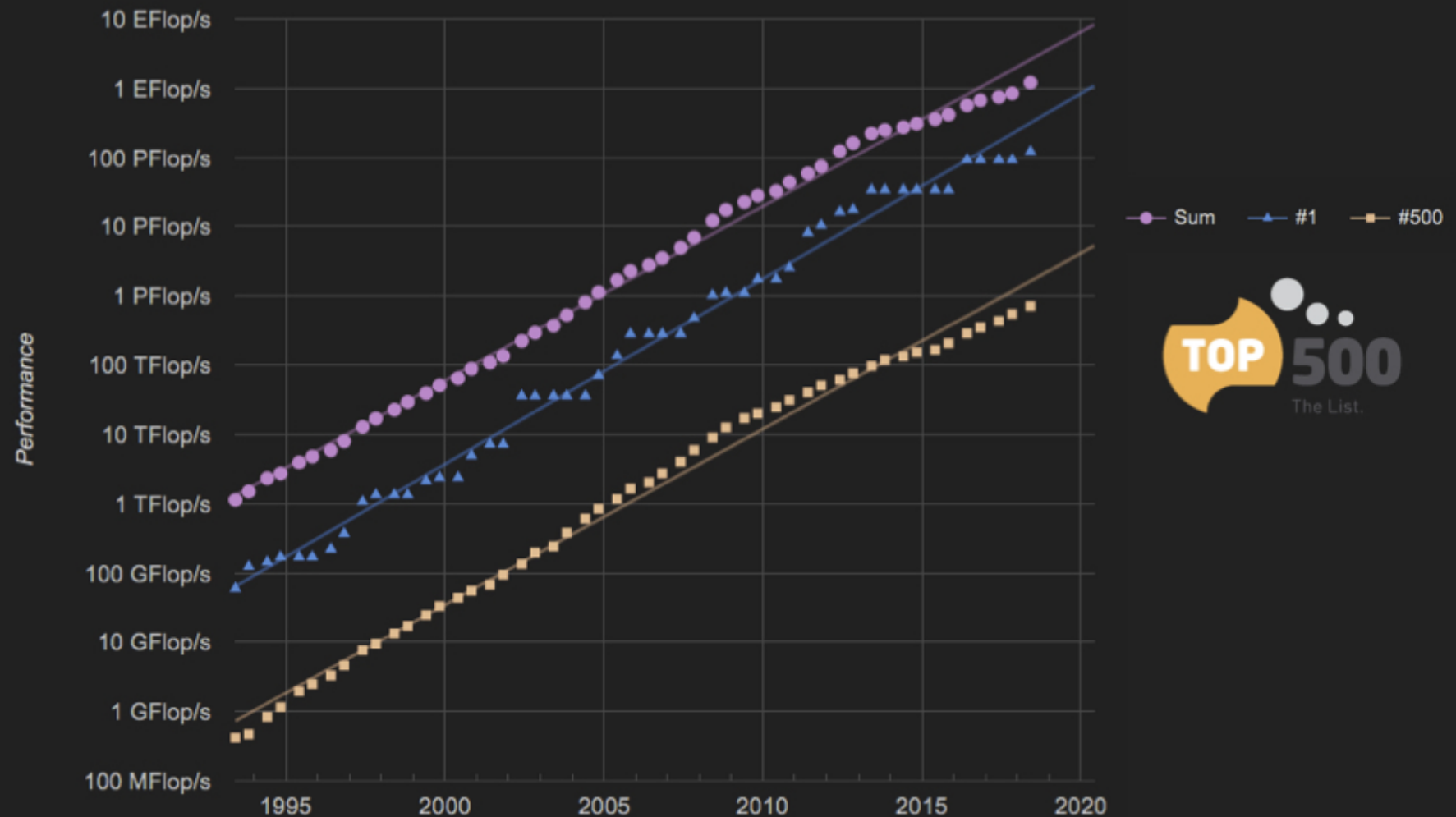


WHAT IS THE PROTON RADIUS?



**TOO COMPUTATIONALLY DEMANDING TO
CALCULATE AT REQUIRED PRECISION**

COMPUTERS IMPROVE QUICKLY – “MOORE’S LAW”



BUT NOT QUICKLY ENOUGH

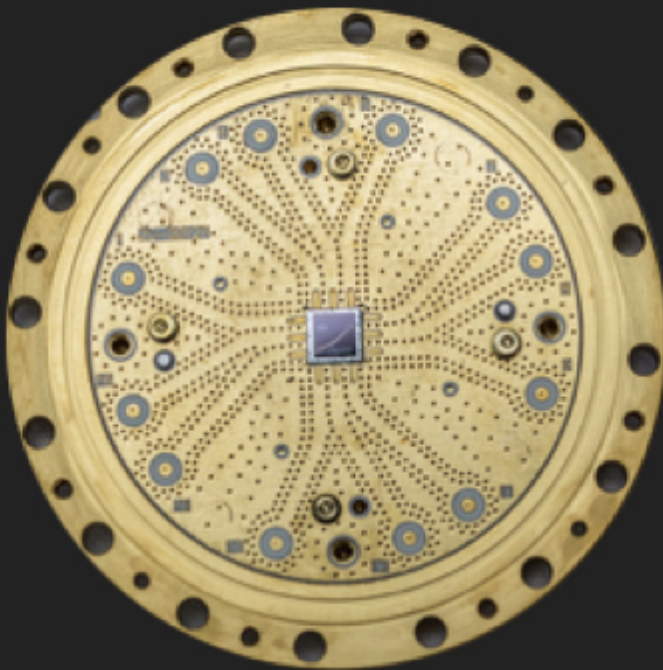
NEW ALGORITHMS FOR STANDARD MODEL CALCULATIONS

- ▶ SPARSE MATRIX
INVERSION
- ▶ NOISE OPTIMISATION
- ▶ MACHINE LEARNING
- ▶ ...



NEW COMPUTATIONAL PARADIGMS

QUANTUM COMPUTING



A CUSTOM COMPUTER DESIGNED FOR A SINGLE CALCULATION

FIELD **P**ROGRAMMABLE **G**ATE **A**rray

