Title: Phiala Shanahan: MIT

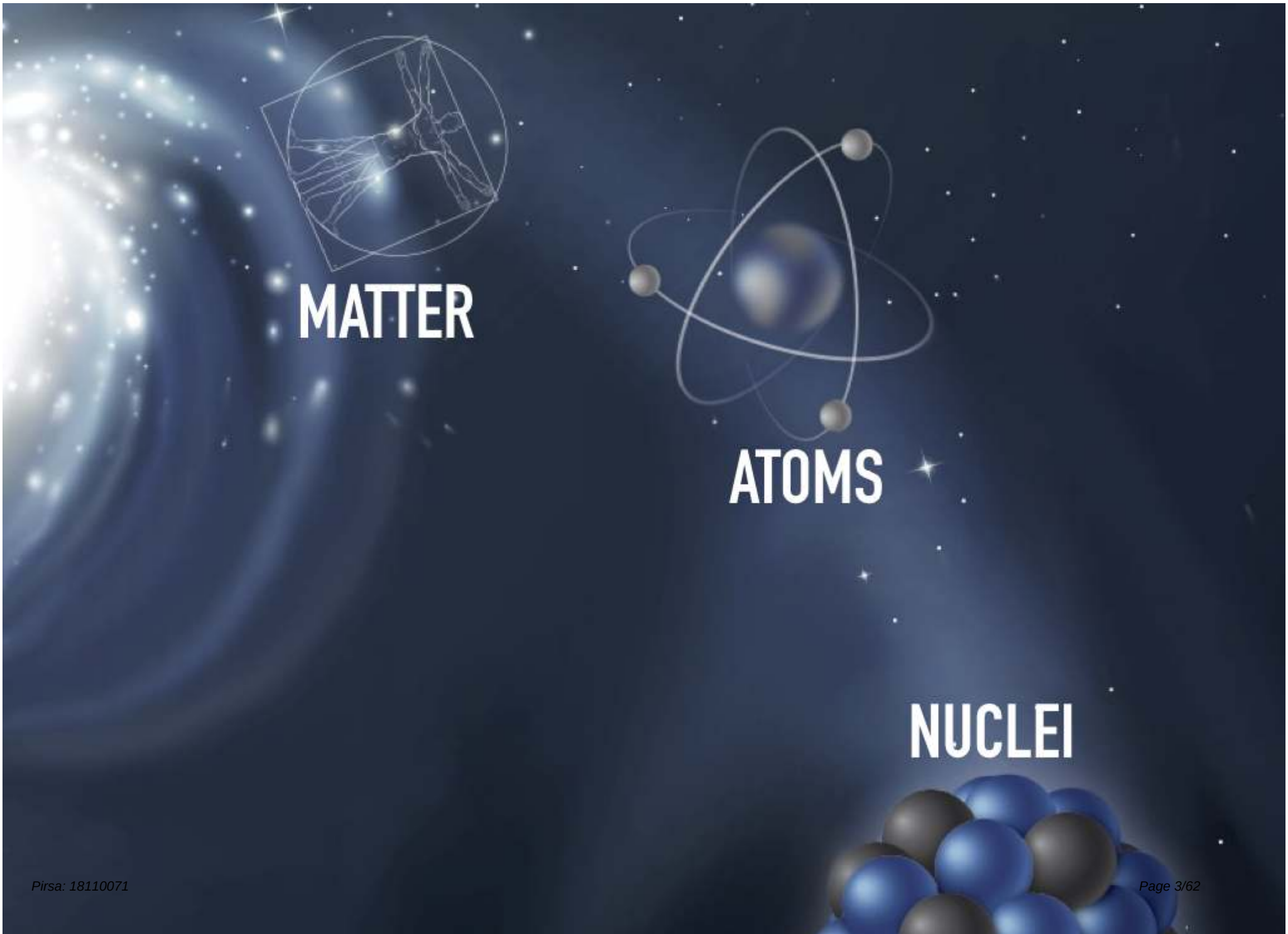
Date: Nov 07, 2018 07:00 PM

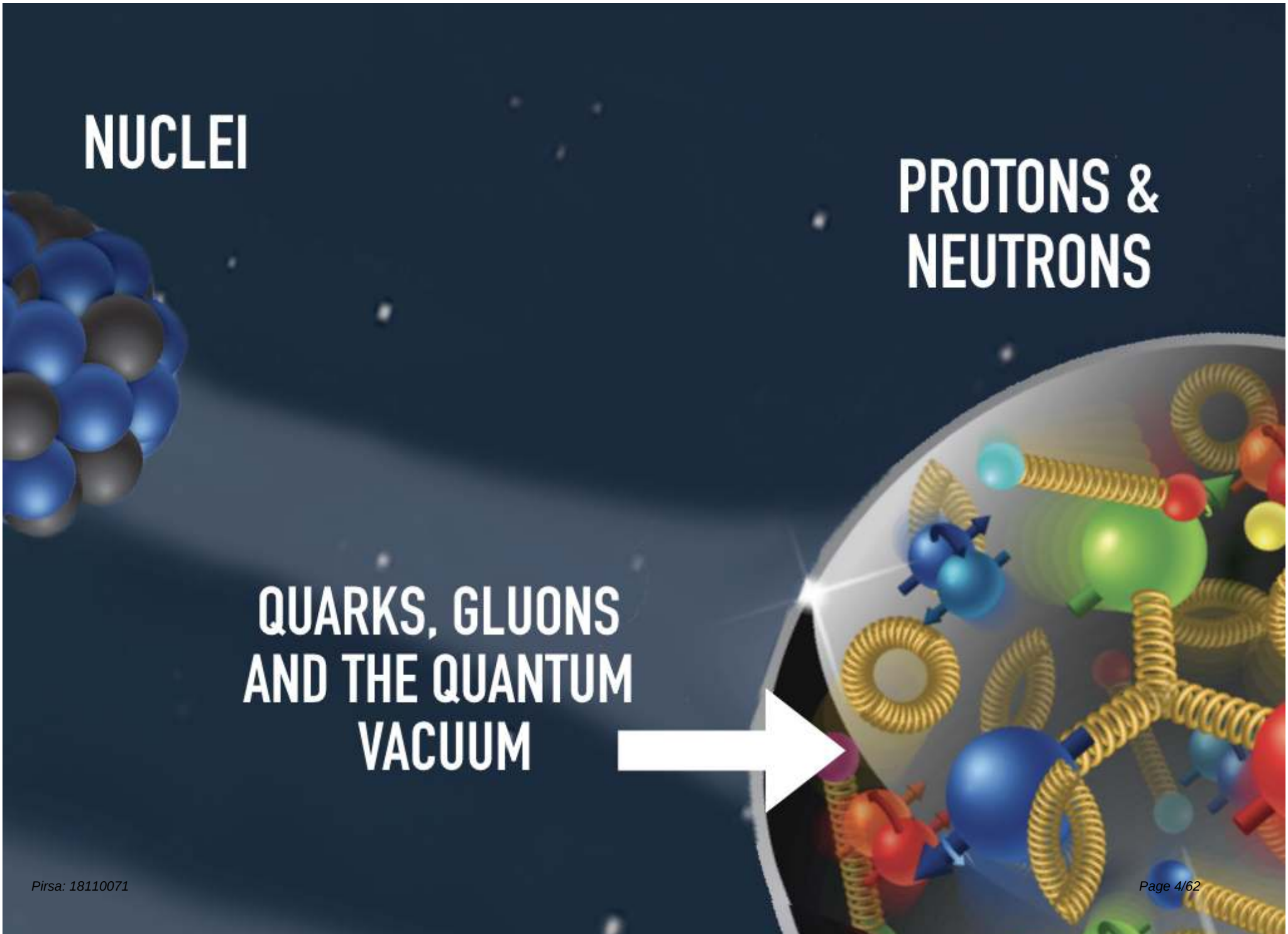
URL: http://pirsa.org/18110071

Abstract: 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 worldâ€™s largest supercomputers.

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.

PHIALA SHANAHAN
THE BUILDING BLOCKS OF THE UNIVERSE
Massachusetts Institute of Technology


MATTER
ATOMS
NUCLEI


NUCLEI
PROTONS &
NEUTRONS
QUARKS, GLUONS
AND THE QUANTUM
VACUUM

THE STANDARD MODEL OF ELEMENTARY PARTICLES

17 FUNDAMENTAL PARTICLES

STRONG FORCE

ELECTROMAGNETISM

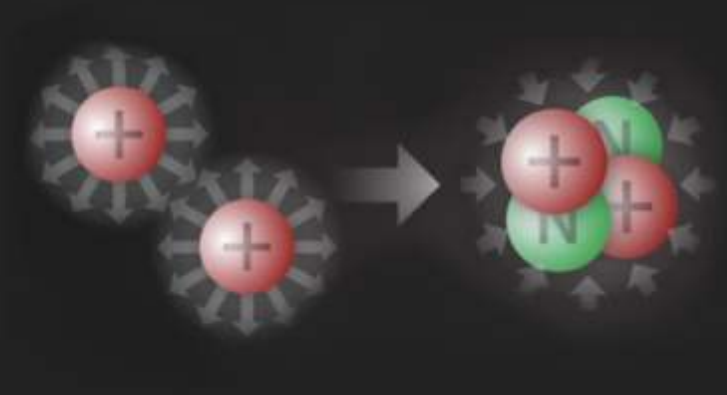
WEAK FORCE

NO GRAVITY

THE STANDARD MODEL OF ELEMENTARY PARTICLES

ELECTROMAGNETISM

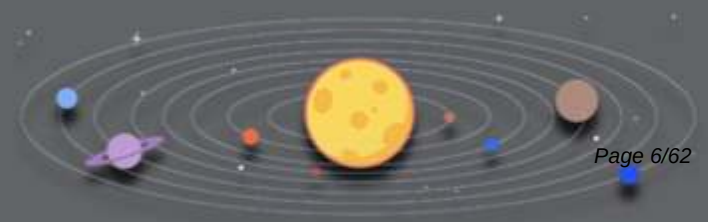
STRONG FORCE



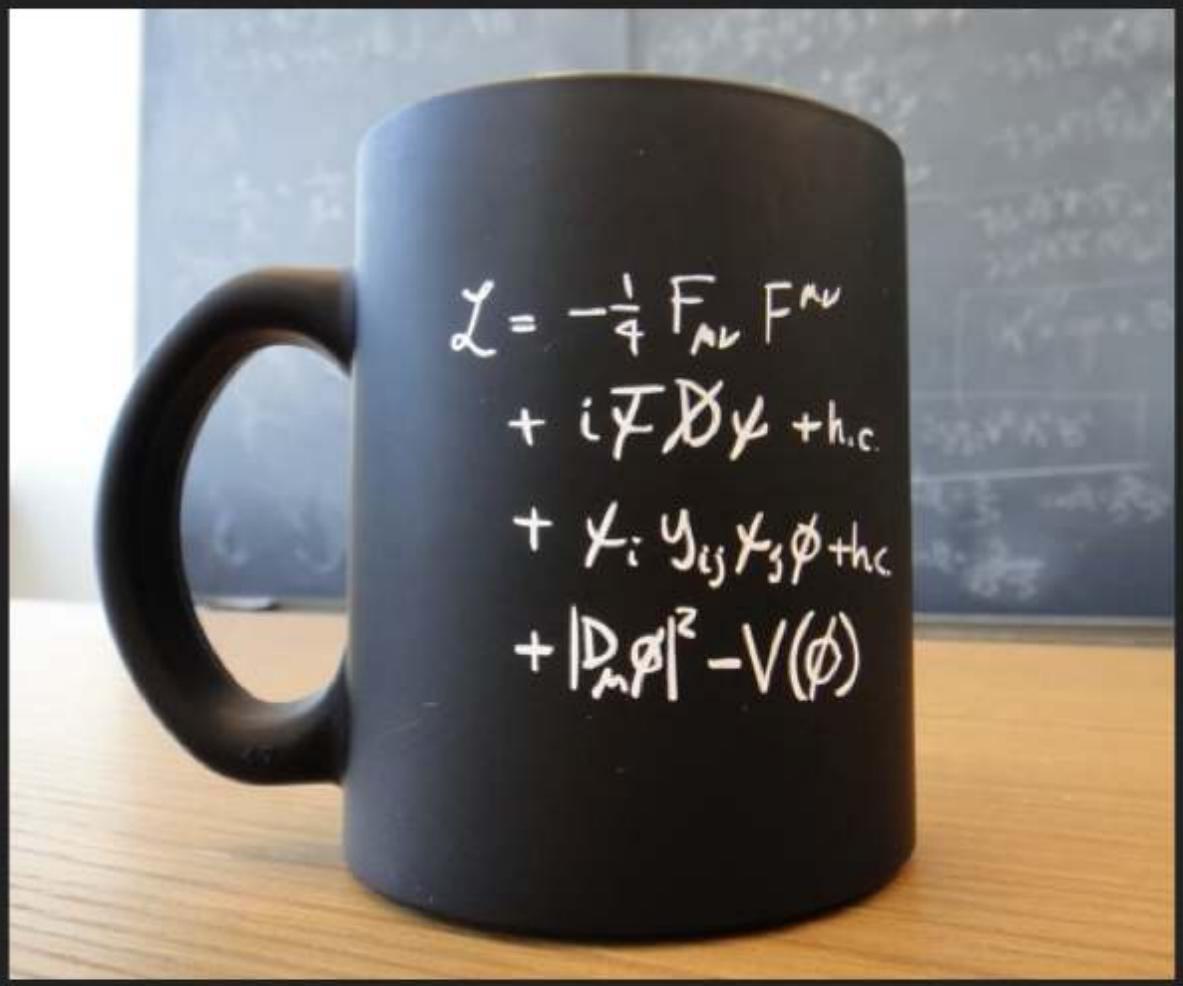
WEAK FORCE

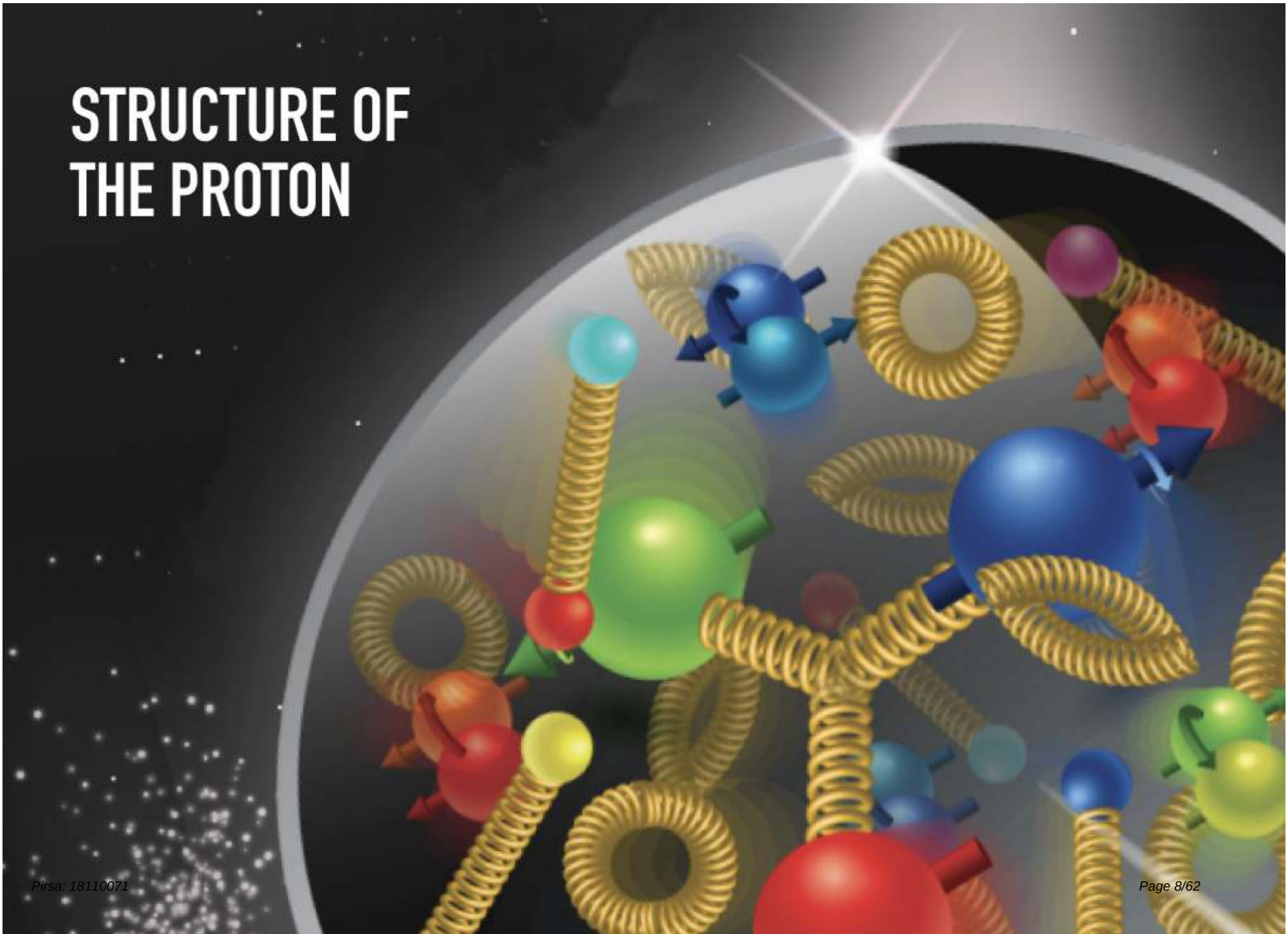
GENERAL RELATIVITY

GRAVITY

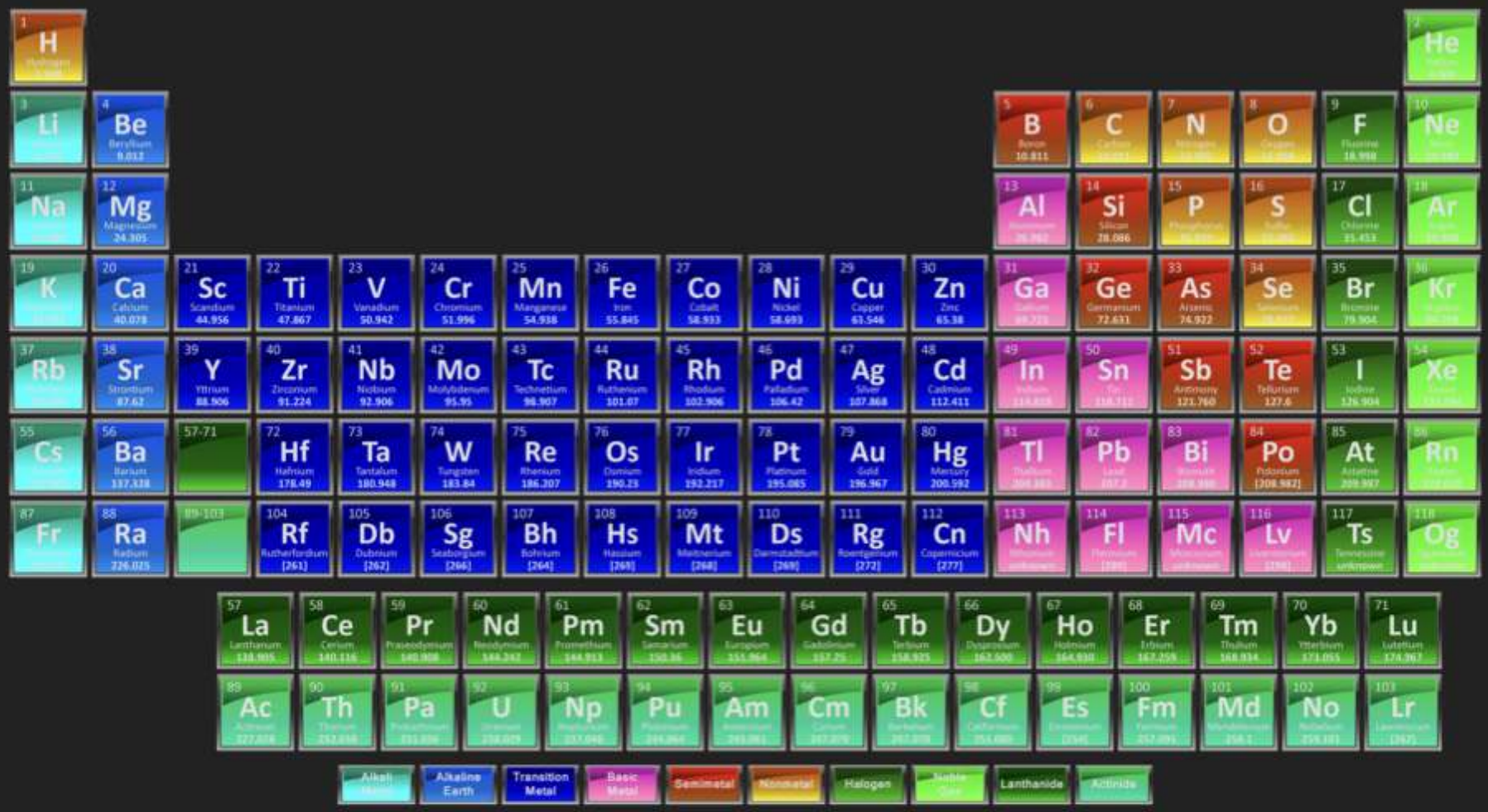


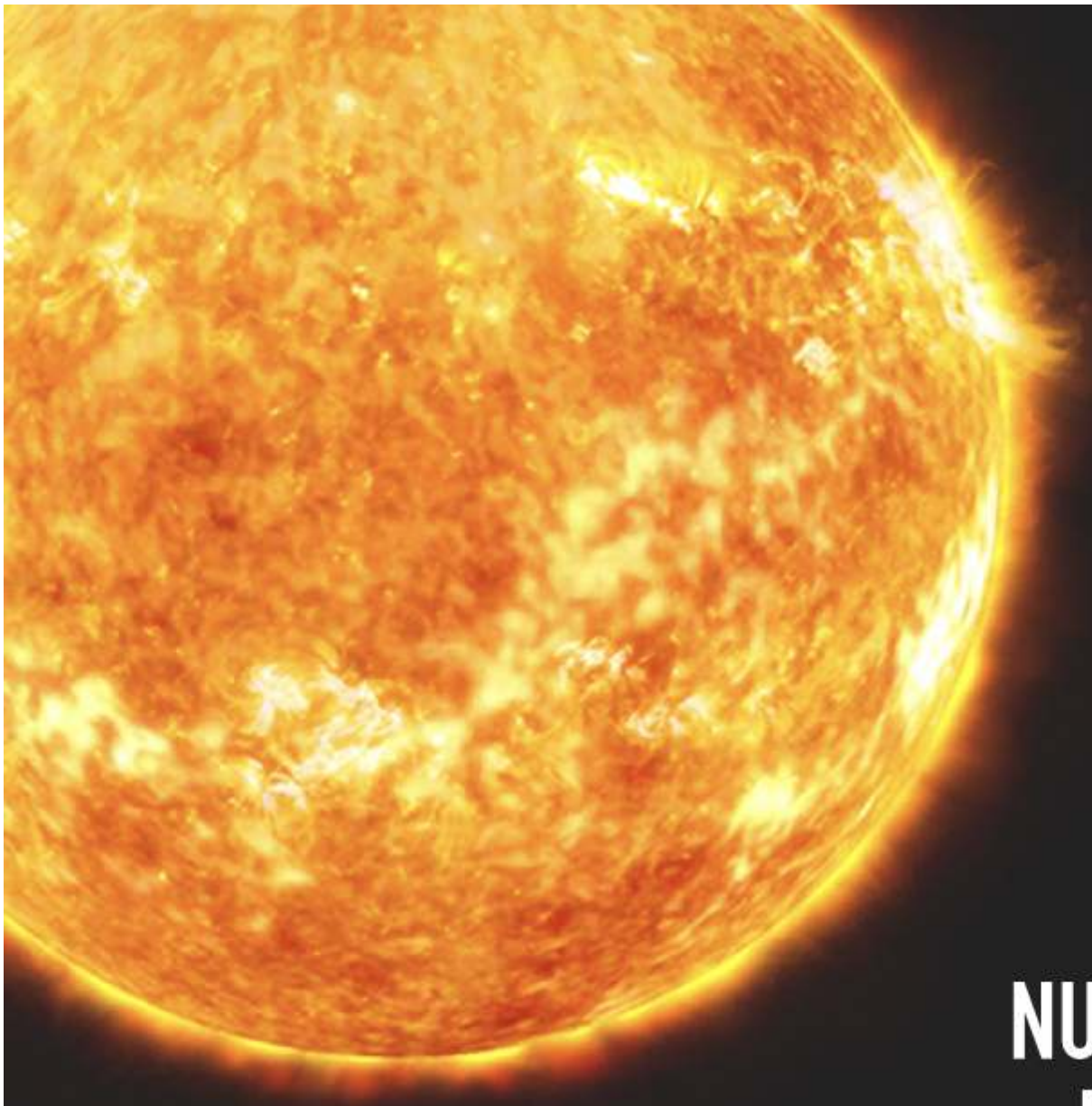
THE STANDARD MODEL OF ELEMENTARY PARTICLES




STRUCTURE OF
THE PROTON

PERIODIC TABLE OF THE ELEMENTS

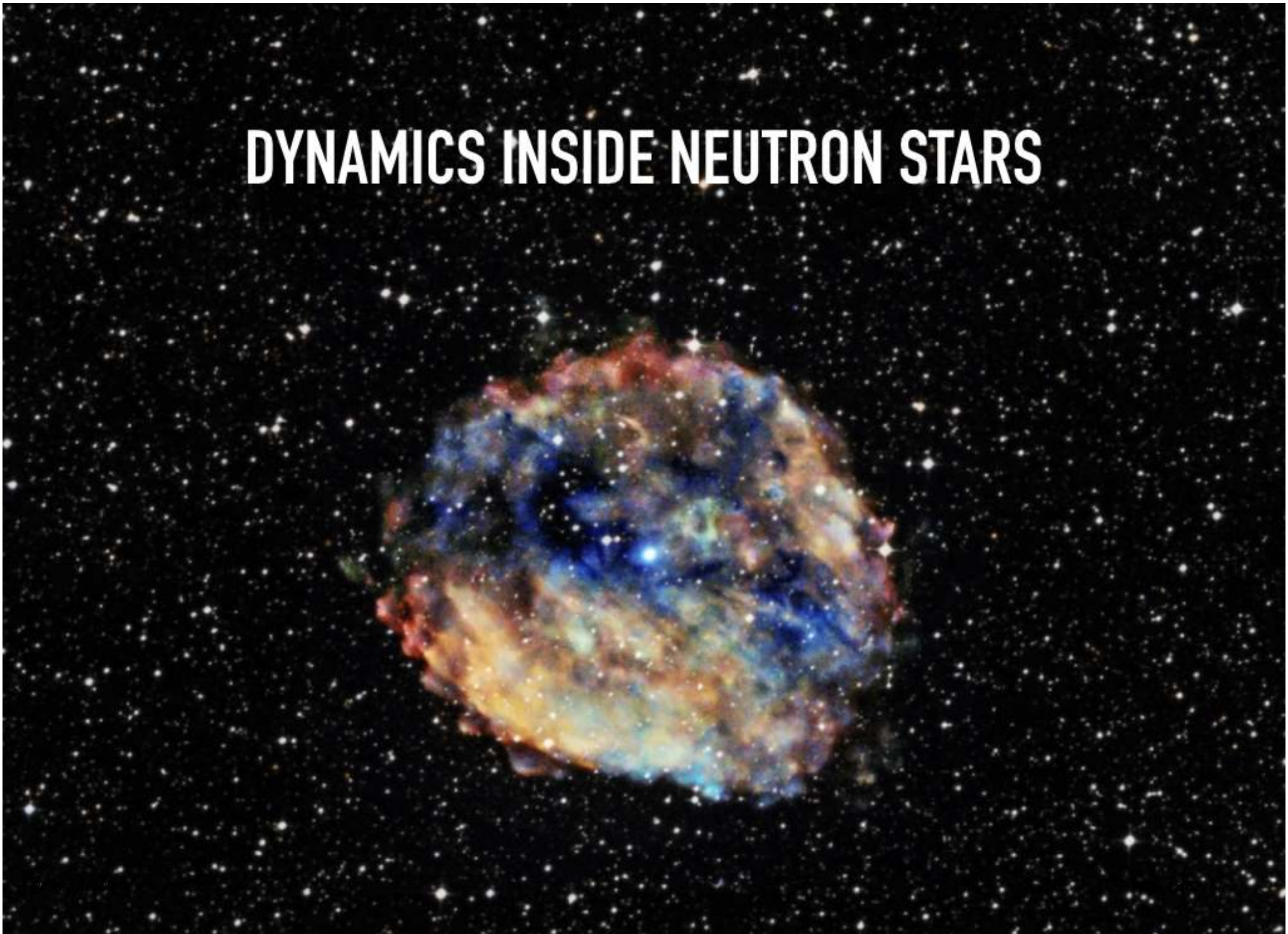




NUCLEAR REACTIONS INSIDE THE SUN...

...AND IN REACTORS

DYNAMICS INSIDE NEUTRON STARS

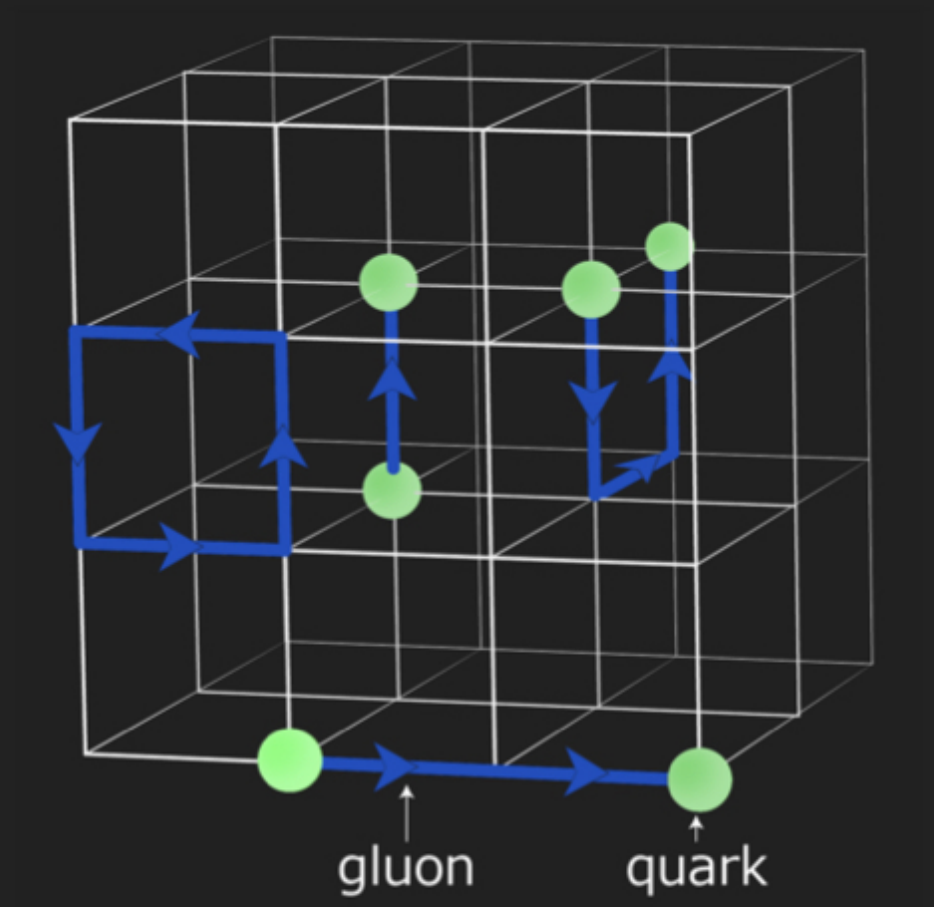


STUDY THE STANDARD MODEL

1 UNDERSTAND HOW THE UNIVERSE IS BUILT

2 FIND WHERE OUR UNDERSTANDING BREAKS DOWN

STANDARD MODEL CALCULATIONS ARE COMPUTATIONALLY DEMANDING

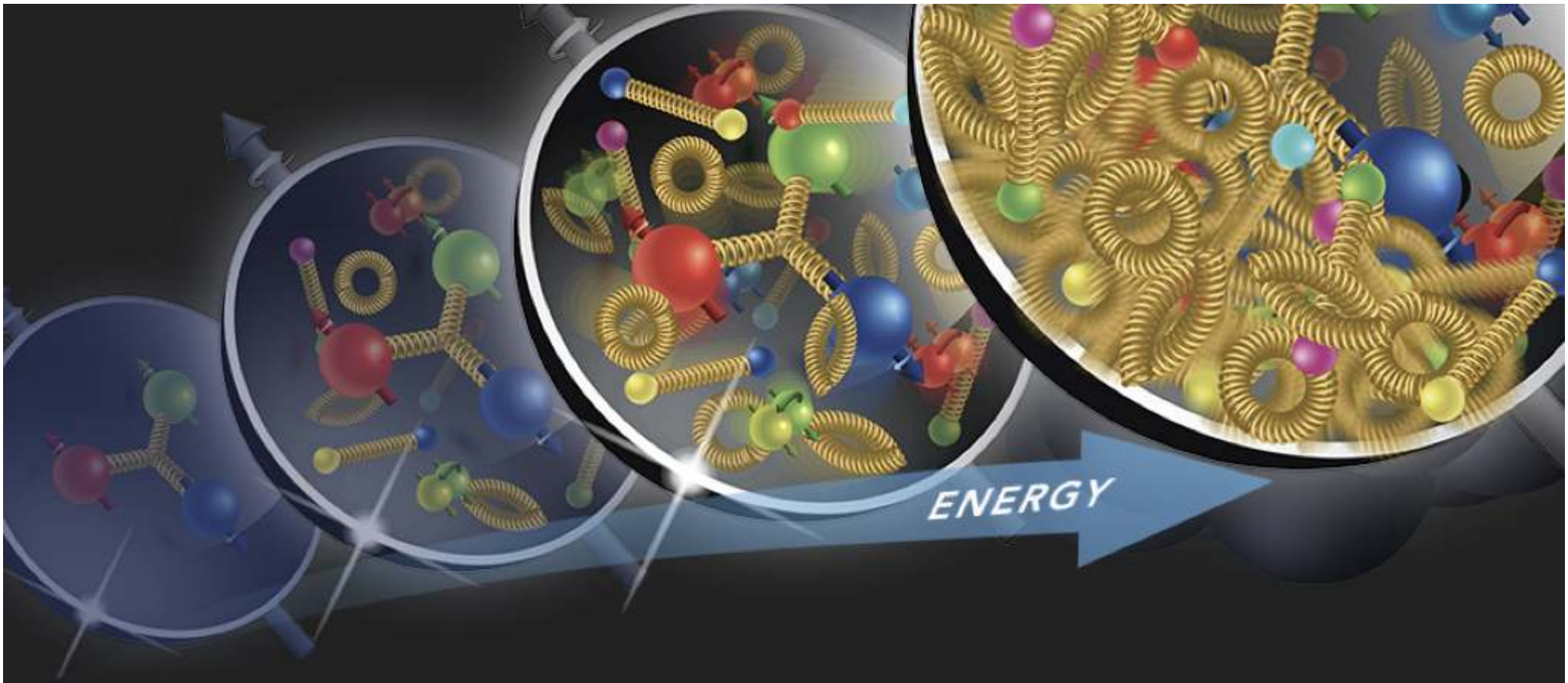


CALCULATIONS I DISCUSS WOULD EACH TAKE ~10,000 YEARS ON YOUR DESKTOP COMPUTER

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

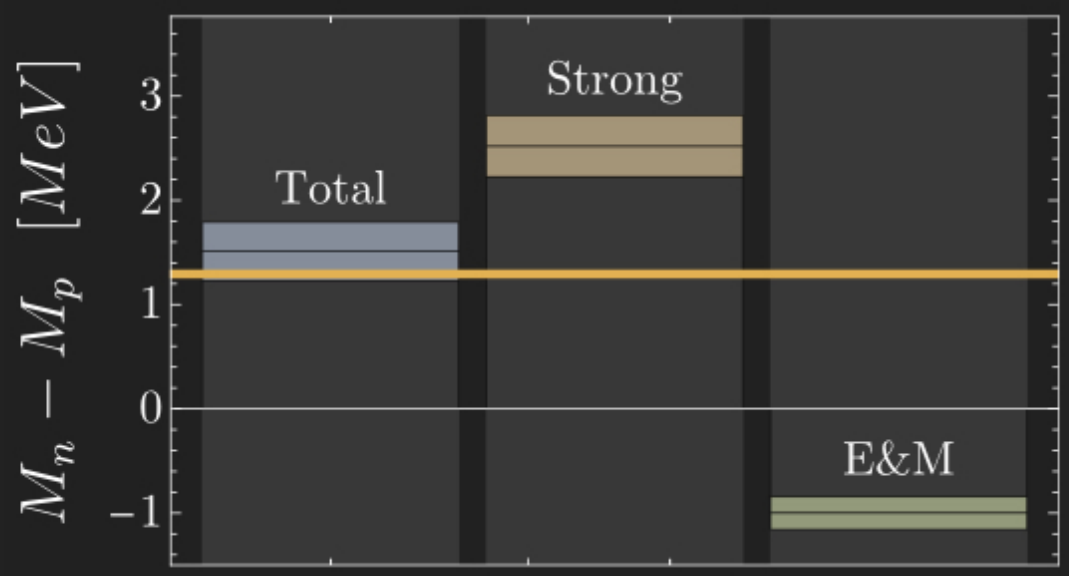
THE NEUTRON IS 0.1% HEAVIER THAN THE PROTON

ESSENTIAL FOR LIFE AS WE KNOW IT

DELICATE BALANCE OF STRONG AND ELECTROMAGNETIC INTERACTIONS

Borsanyi et al. Science, 347 (2015)

THE NEUTRON IS 0.1% HEAVIER THAN THE PROTON

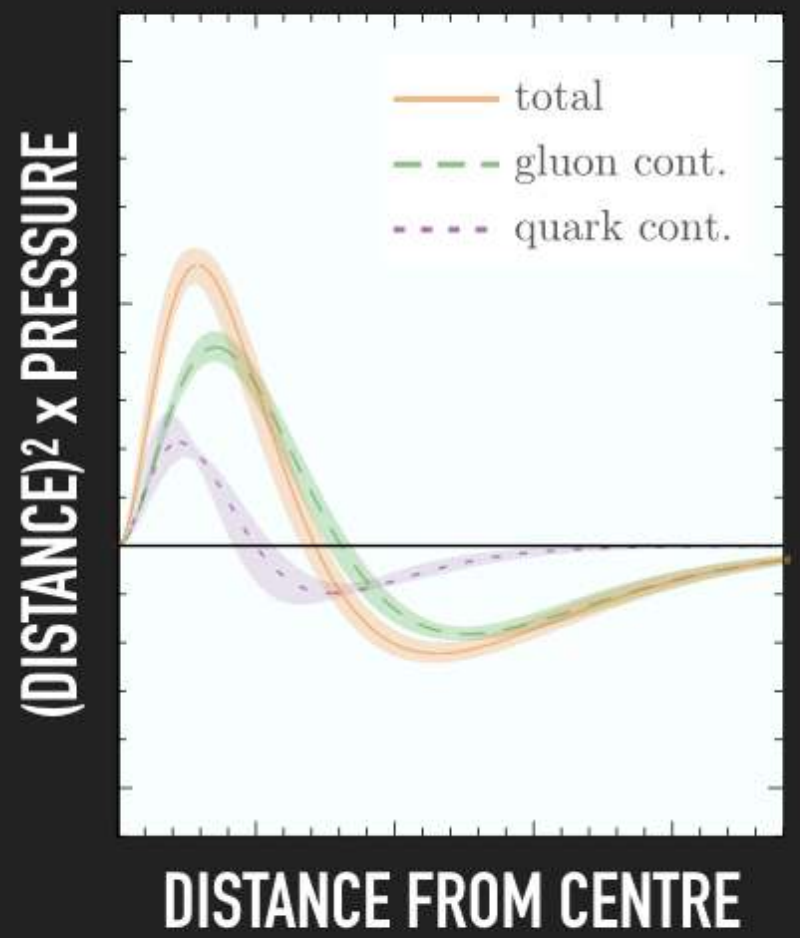


ESSENTIAL FOR LIFE AS WE KNOW IT

DELICATE BALANCE OF STRONG AND ELECTROMAGNETIC INTERACTIONS

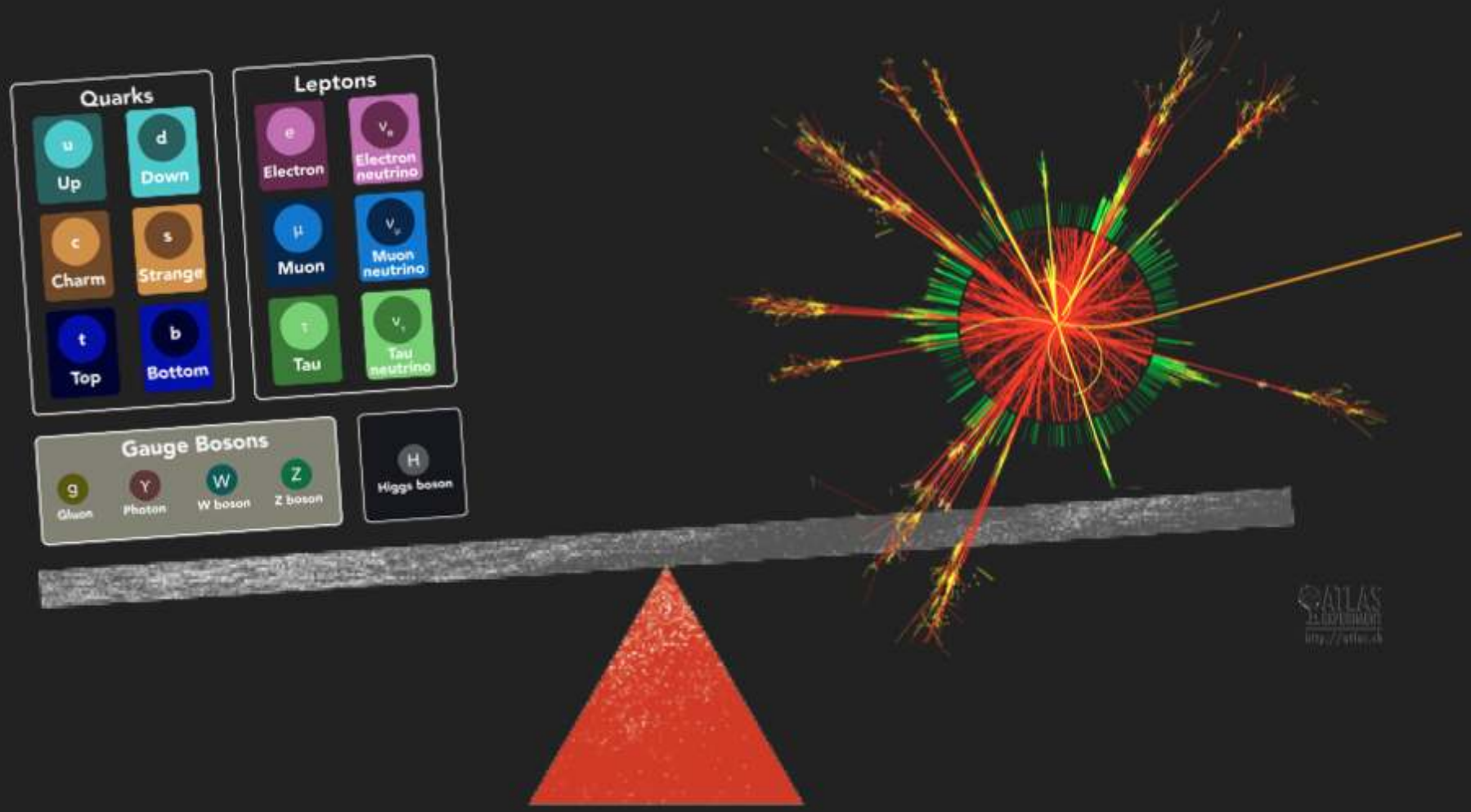
Borsanyi et al. Science, 347 (2015)

PRESSURE INSIDE THE PROTON IS GREATER THAN INSIDE NEUTRON STARS

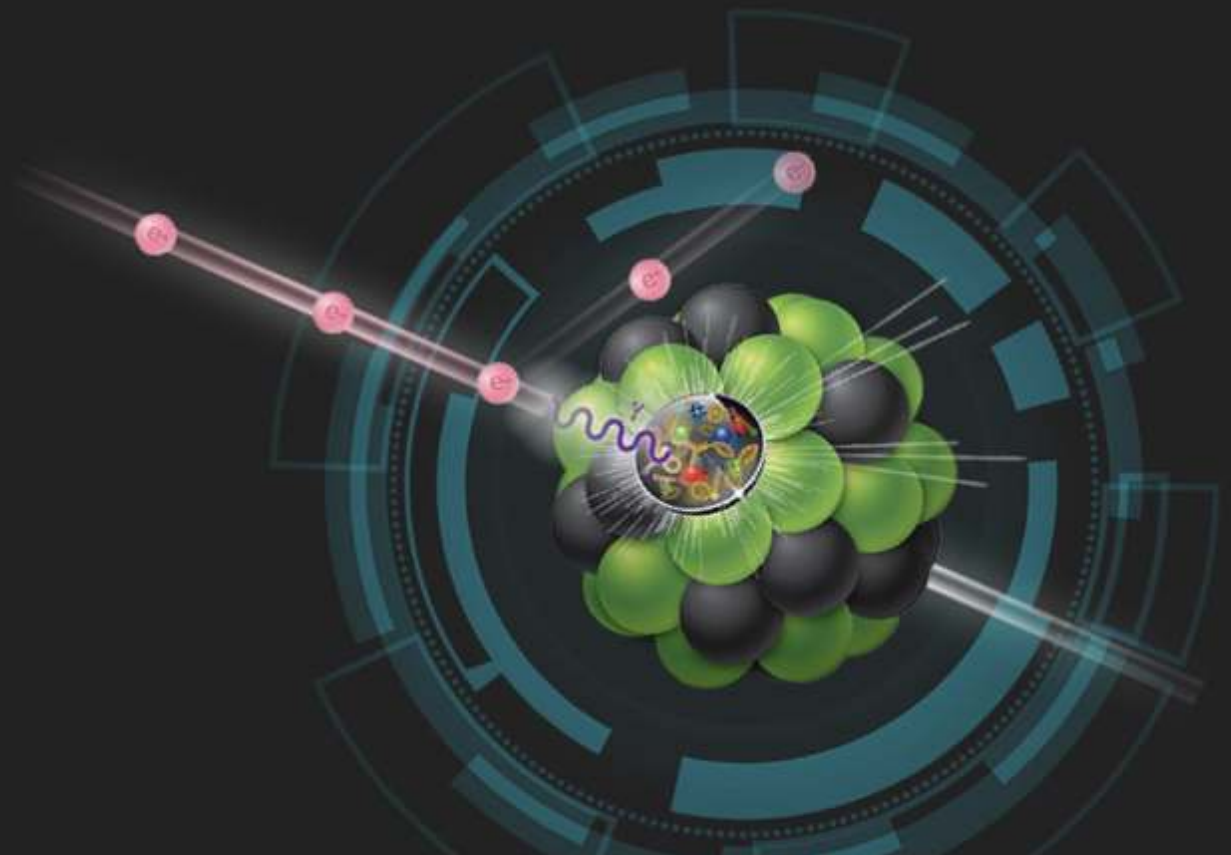


Shanahan & Detmold, arXiv:1810.07589

THEORY COMPLIMENTS EXPERIMENT



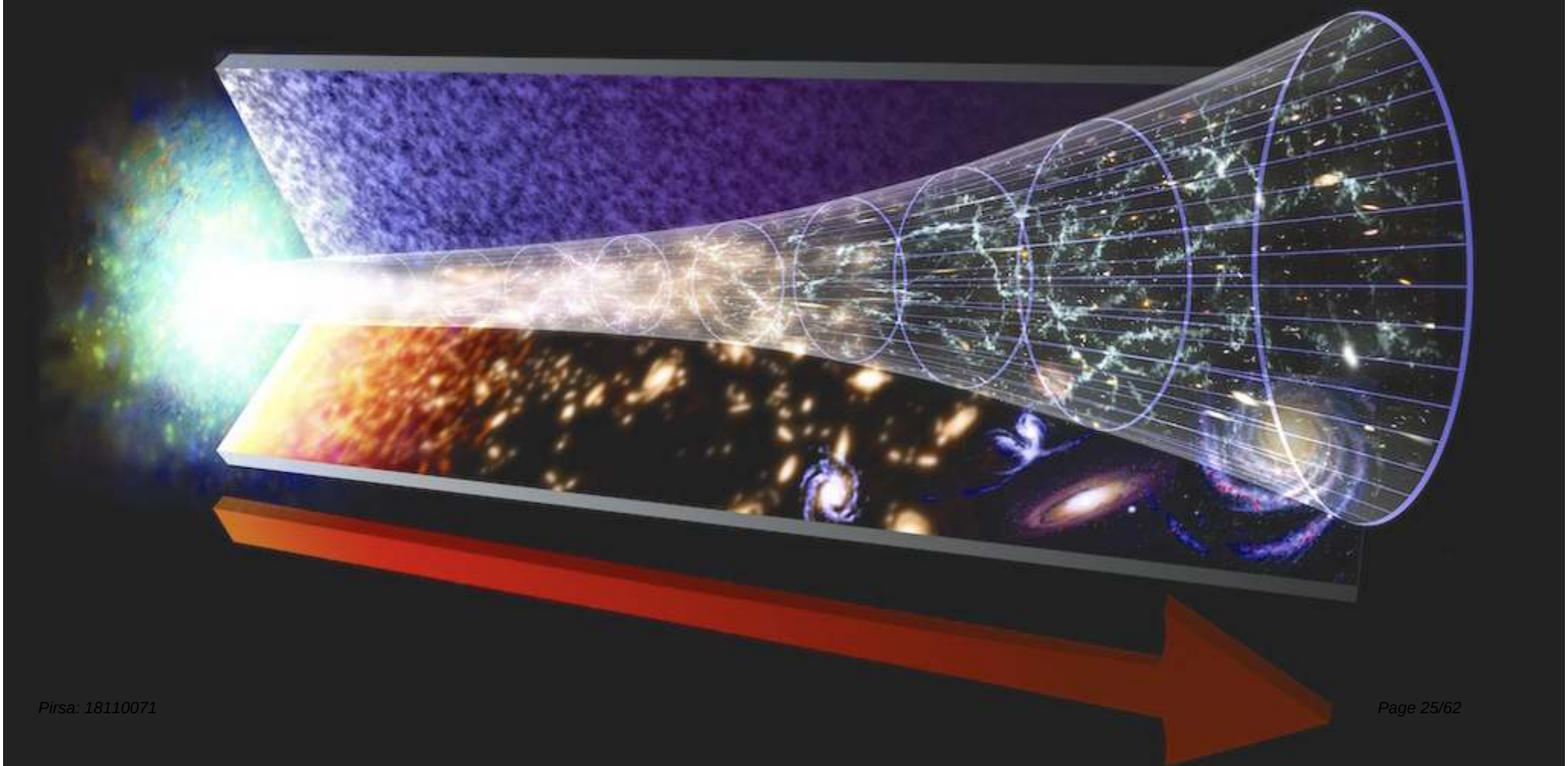
A FUTURE ELECTRON-ION COLLIDER 2025-2030



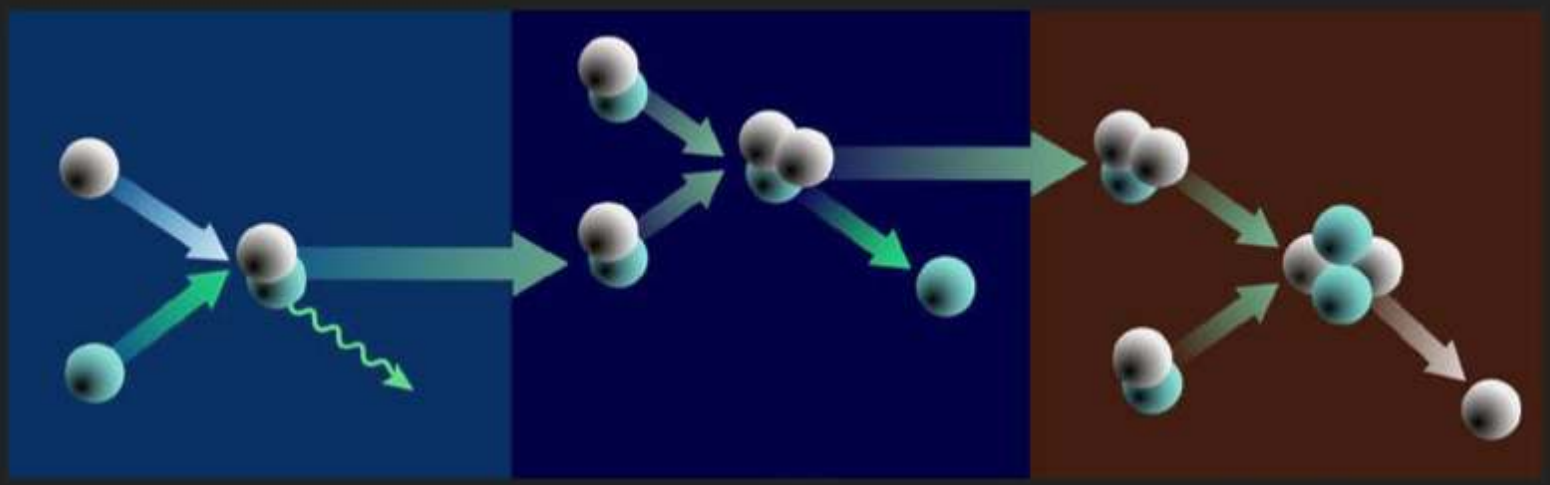
A NEW EXPERIMENTAL FRONTIER FOR STUDYING PROTON STRUCTURE

https://www.bnl.gov/eic/

CREATING THE FIRST ELEMENTS AFTER THE BIG BANG

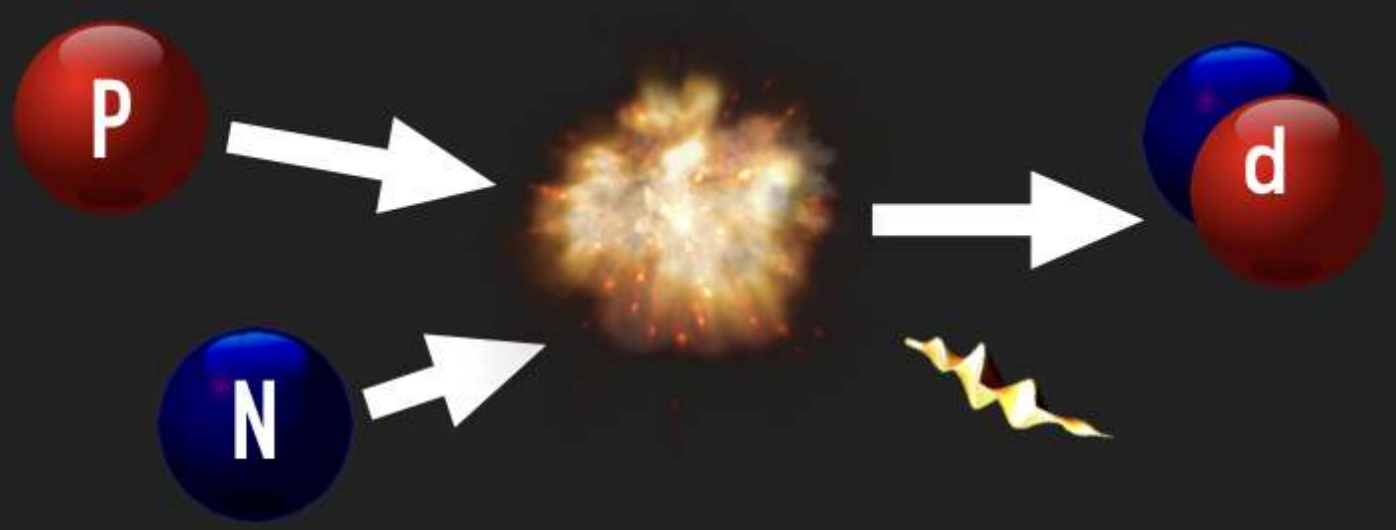


CREATING THE FIRST ELEMENTS AFTER THE BIG BANG



BIG BANG NUCLEOSYNTHESIS
10 SEC – 20 MIN AFTER BANG

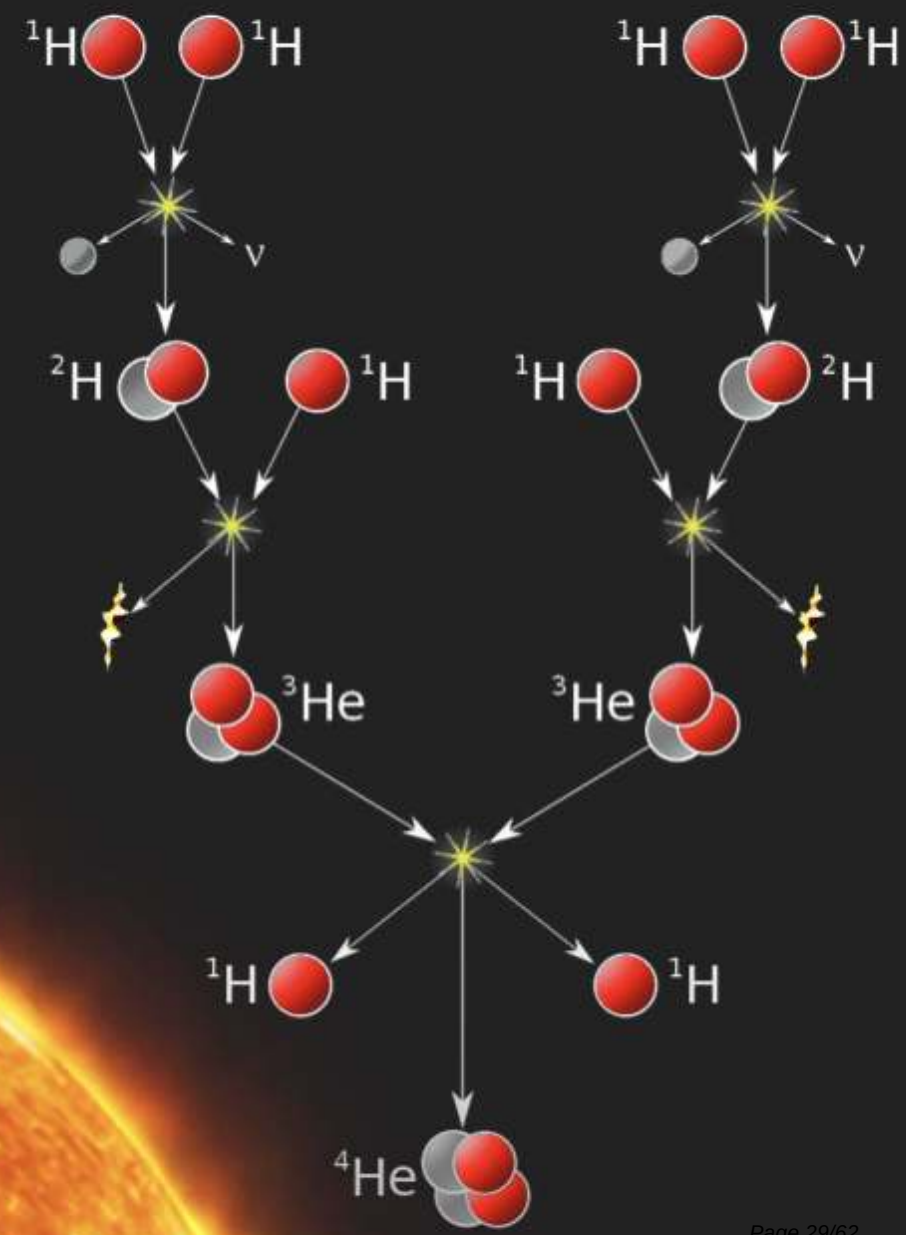
CREATING THE FIRST ELEMENTS AFTER THE BIG BANG



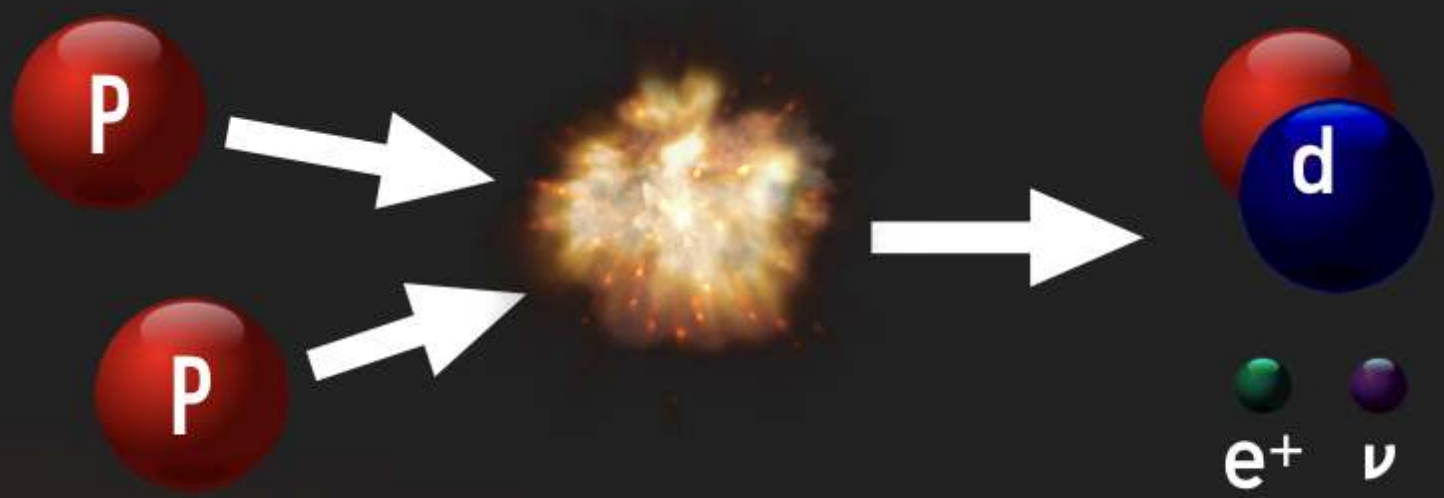
THE FIRST NUCLEAR REACTION

Beane et al. PRL 115, 132001 (2015)

PROTON–PROTON FUSION CHAIN REACTION



POWERING THE SUN



Savage et al, PRL 119, 062002 (2017)

ENTERING AN ERA OF UNDERSTANDING NUCLEAR PHYSICS FROM FUNDAMENTAL PARTICLES

THE STANDARD MODEL
ISN'T EVERYTHING

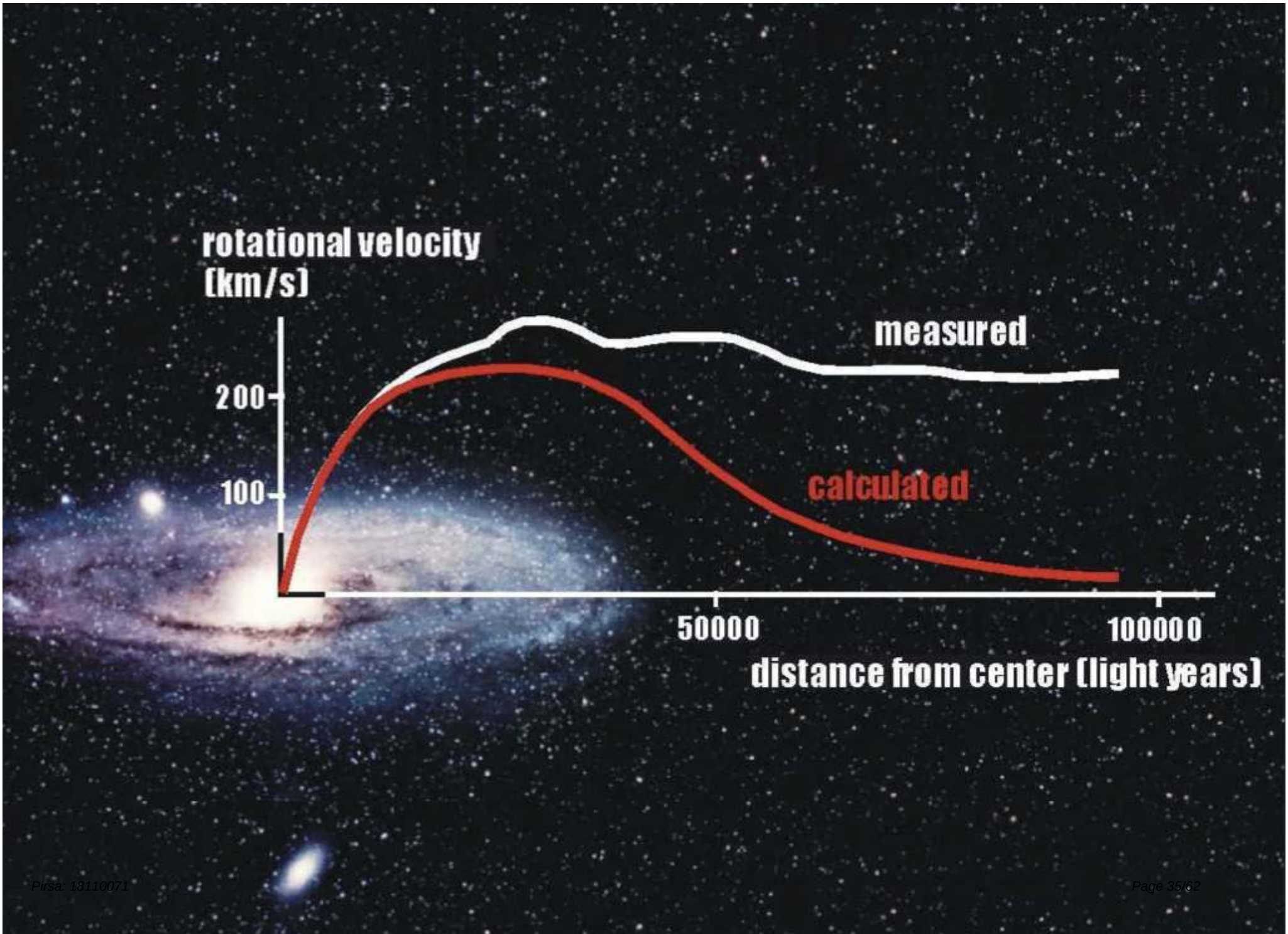
GRAVITY

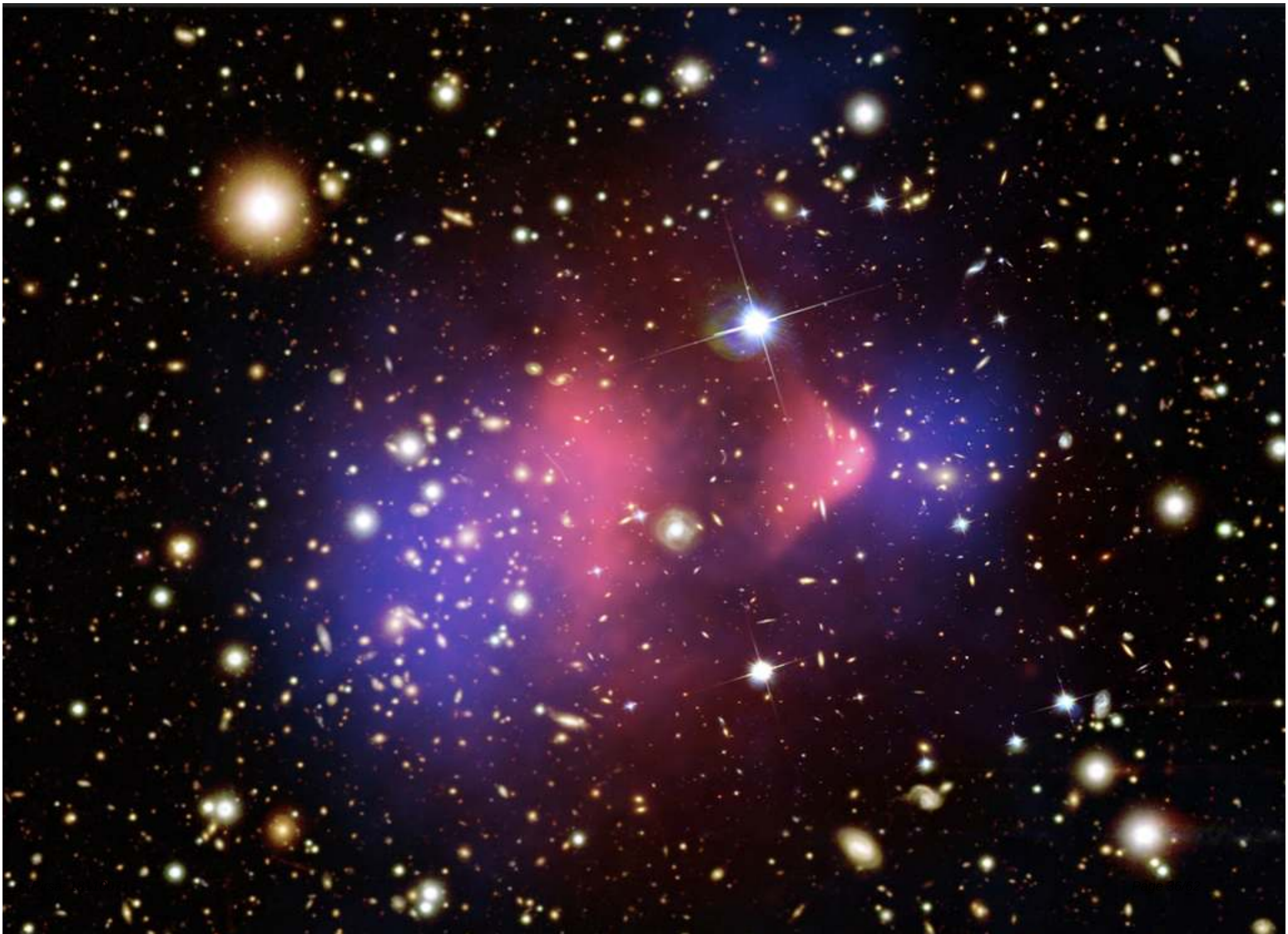
NEUTRINO MASSES

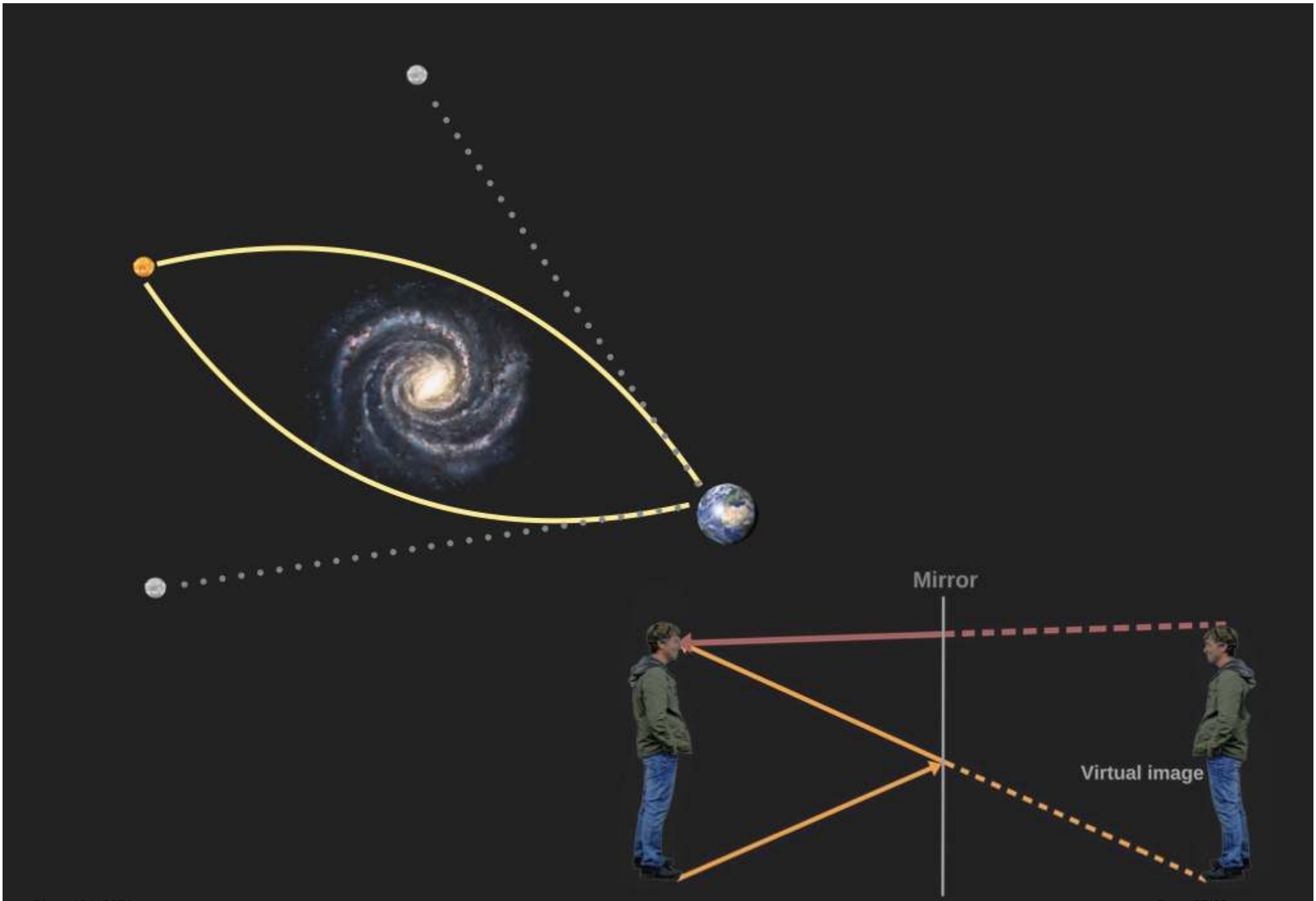
MATTER–ANTIMATTER ASYMMETRY

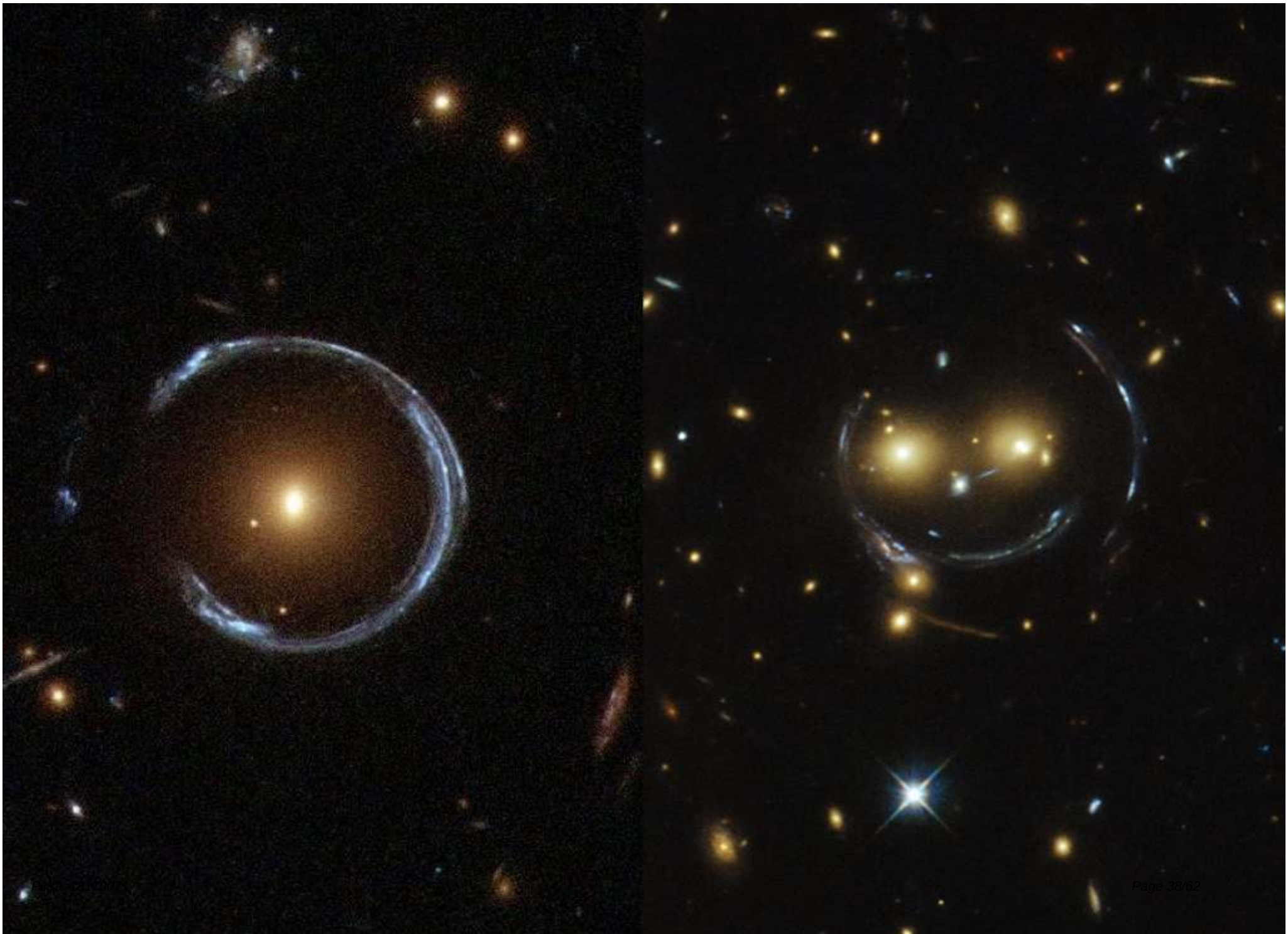
DARK MATTER

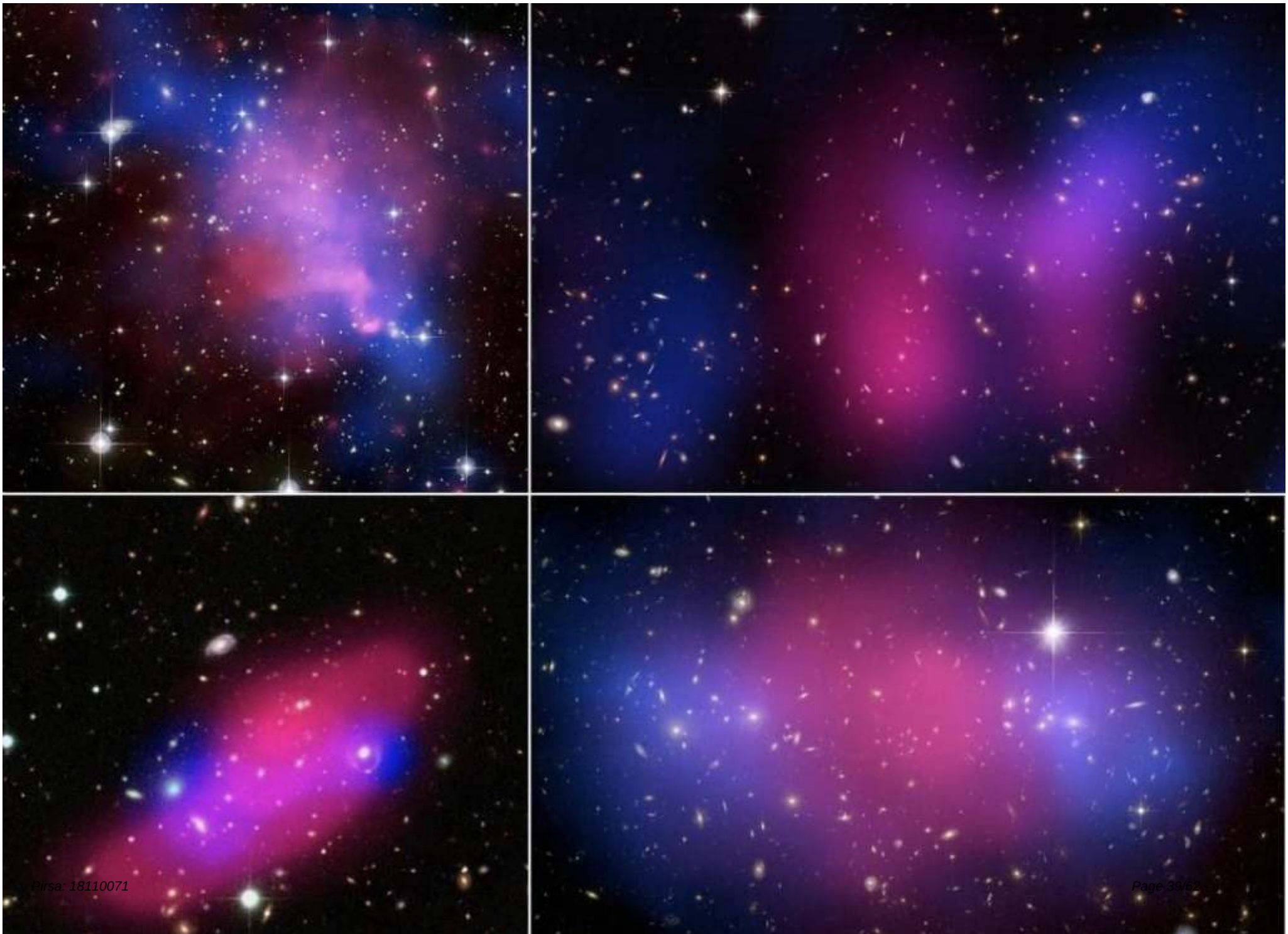
⋮


rotational velocity
[km/s]
200
100
measured
calculated
50000
100000
distance from center [light years]



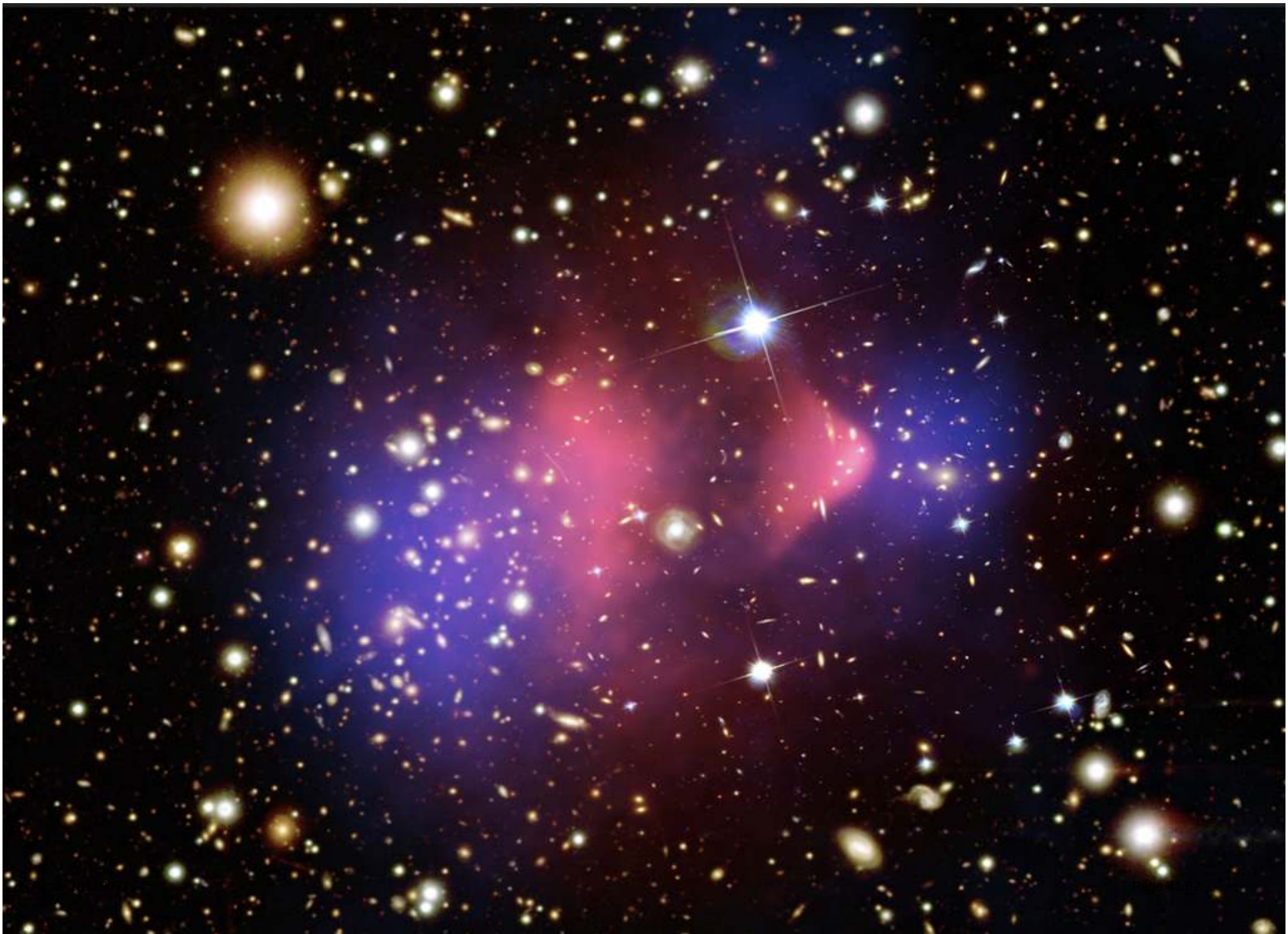

Mirror
Virtual image

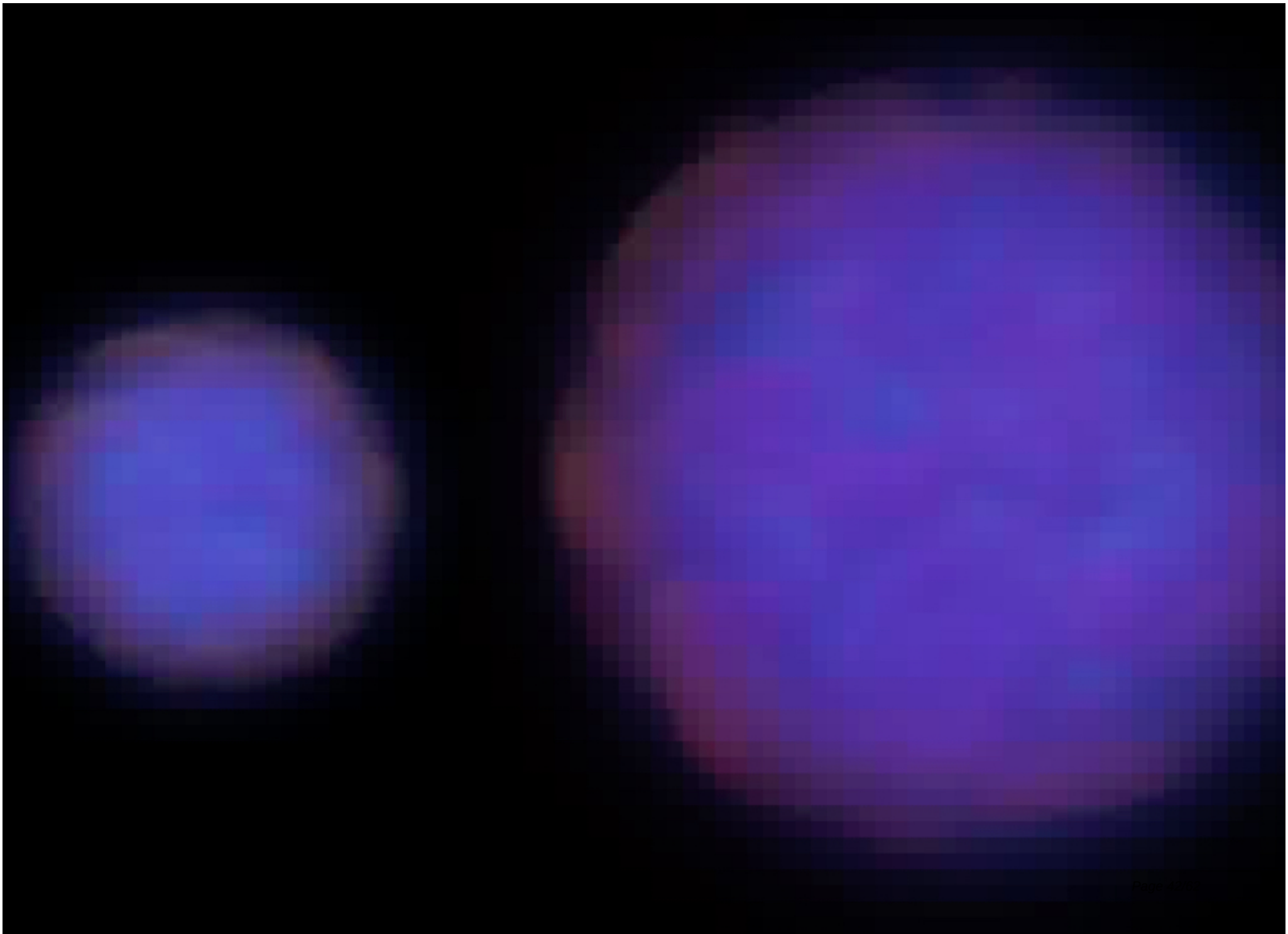


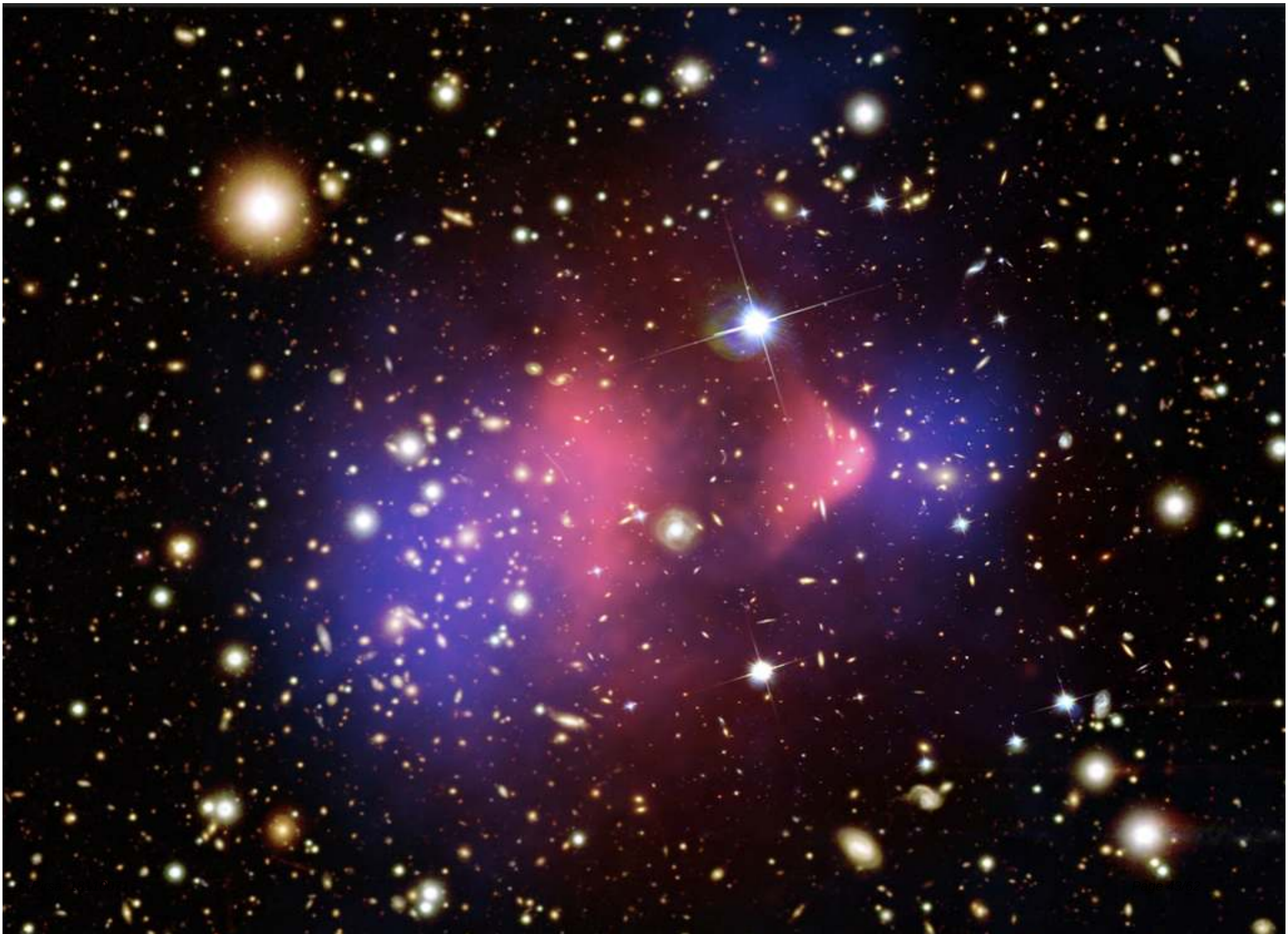


WE DEDUCE
THE EXISTENCE OF
DARK MATTER

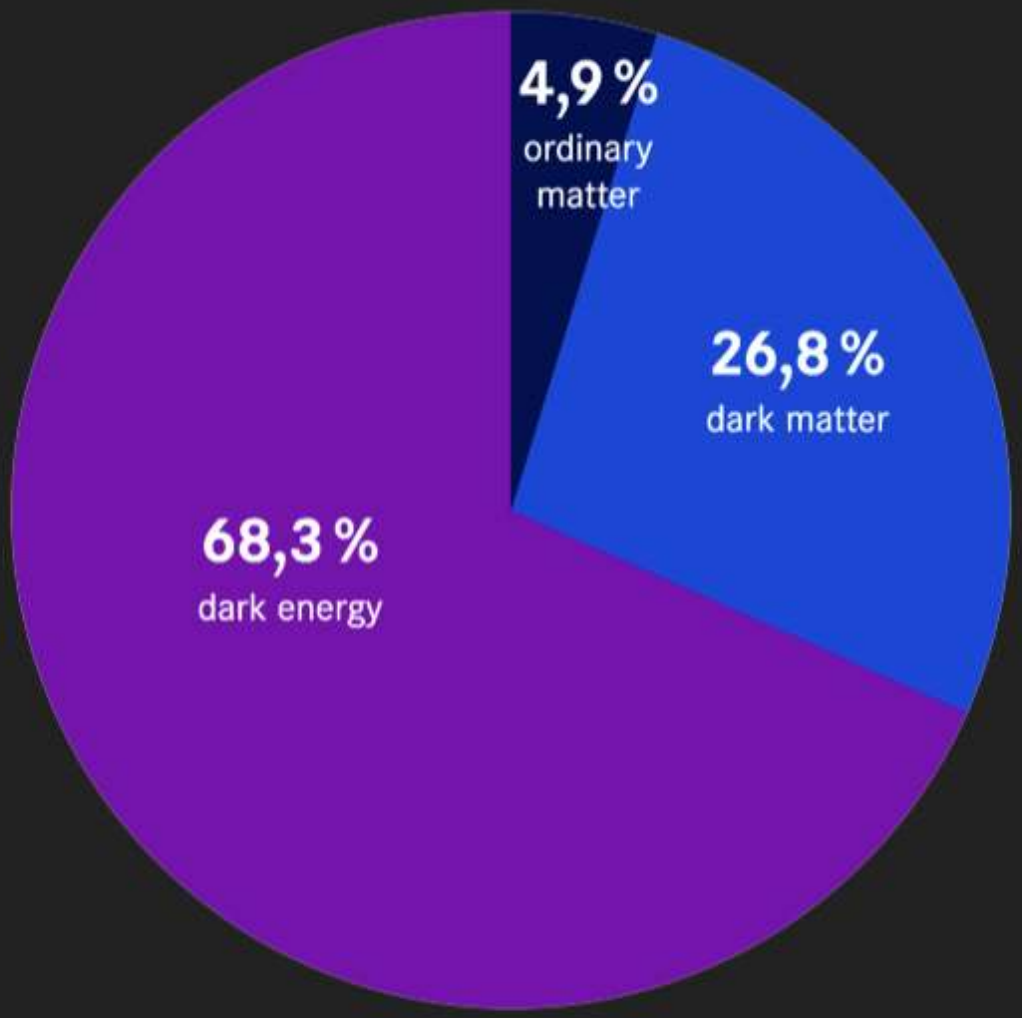
IT CAN'T BE SEEN,
BUT IT MUST BE
THERE







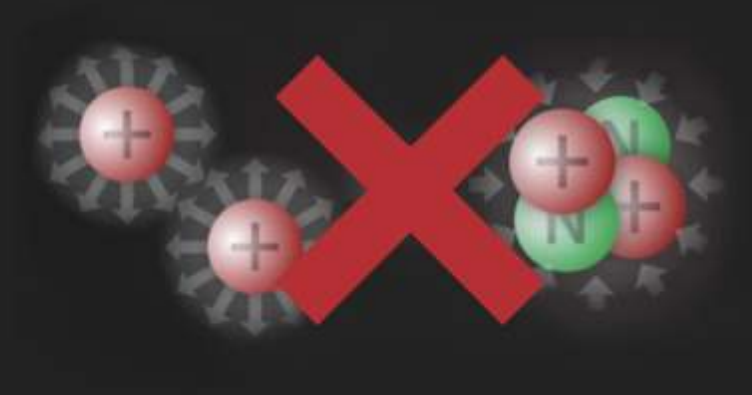
MOST OF THE MATTER IN THE UNIVERSE IS DARK



HOW DOES DARK MATTER INTERACT?

ELECTROMAGNETISM

STRONG FORCE



WEAK FORCE

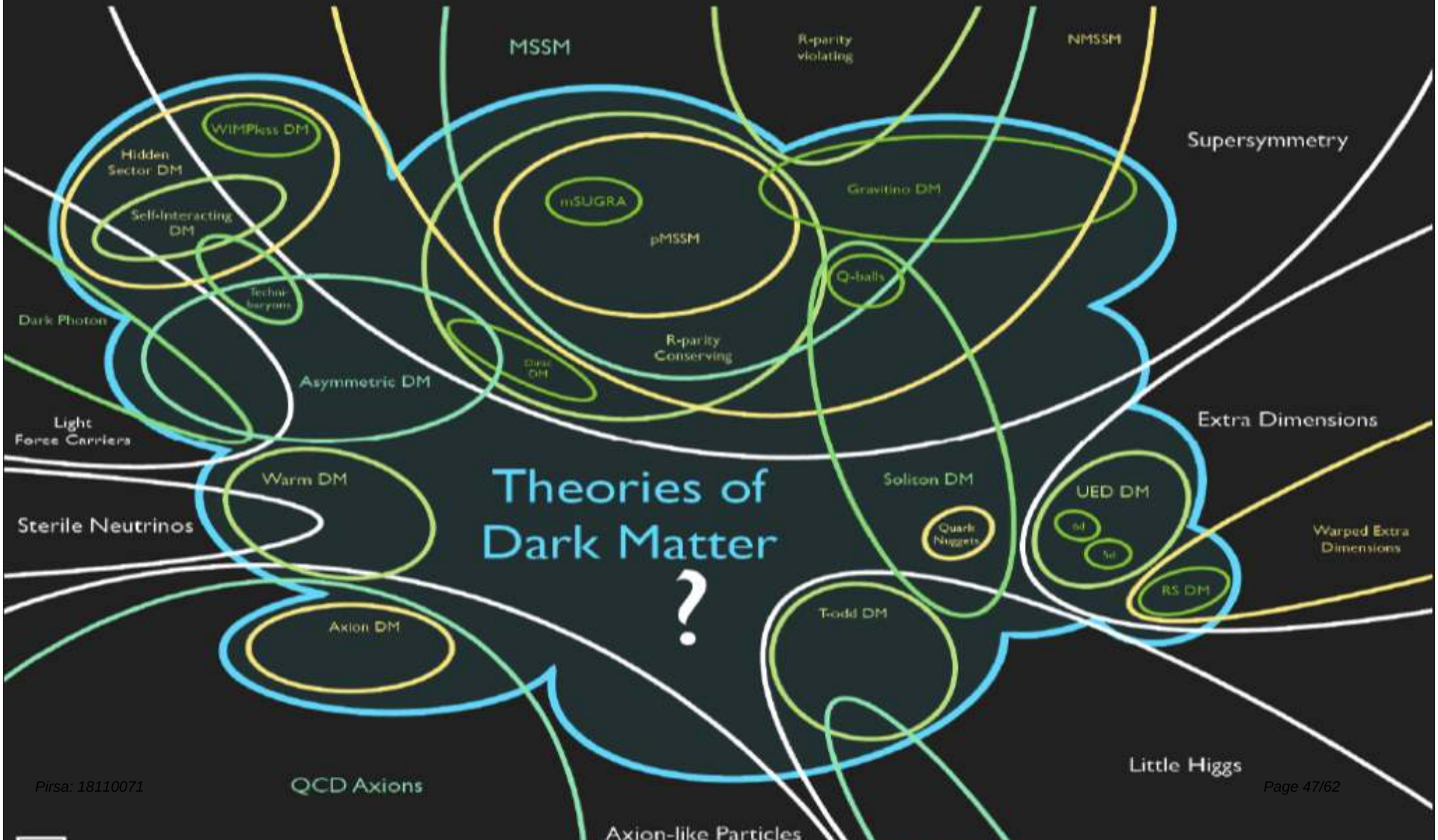
GRAVITY

WE KNOW WHAT DARK MATTER IS NOT

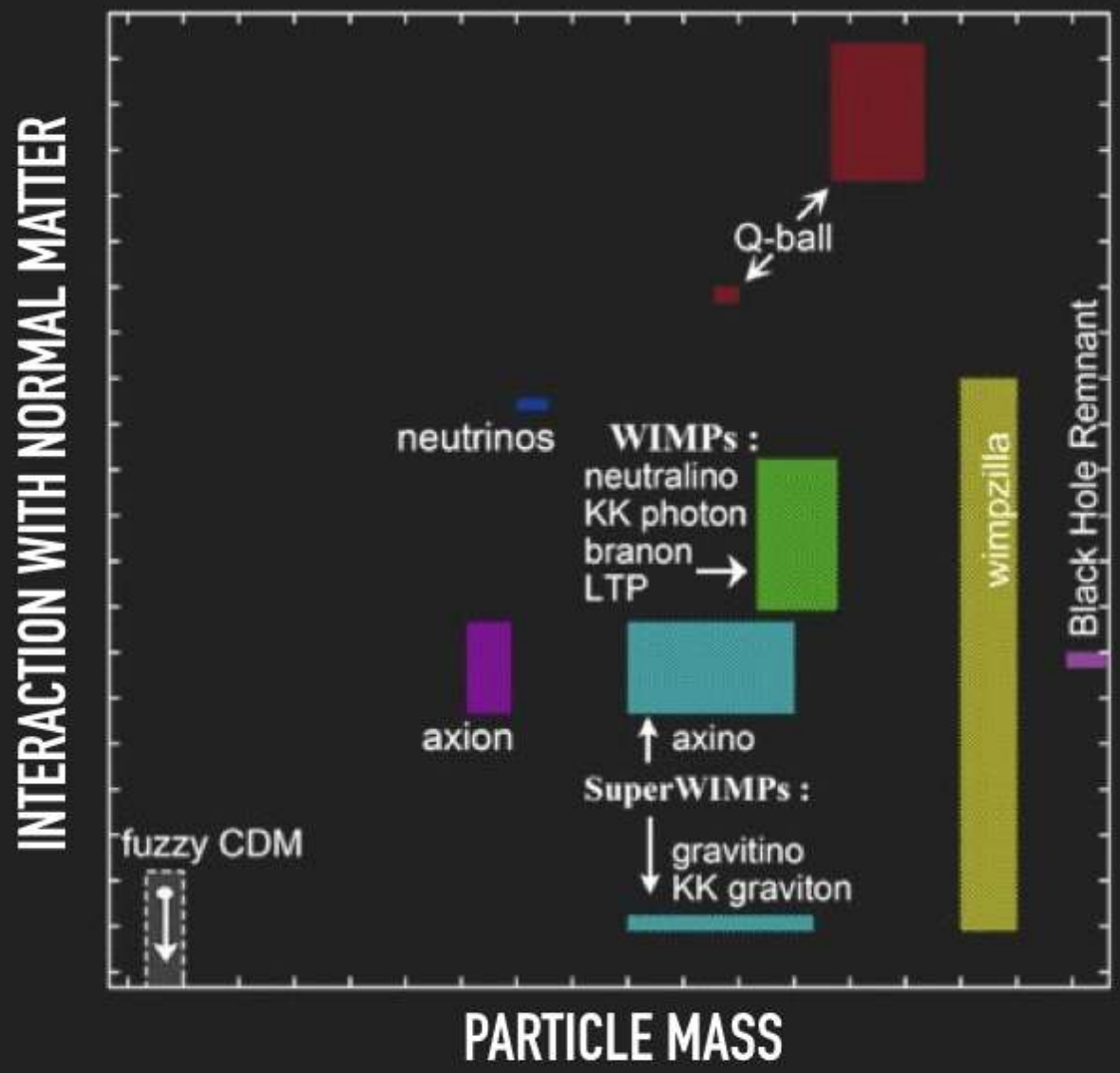
NORMAL MATTER

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

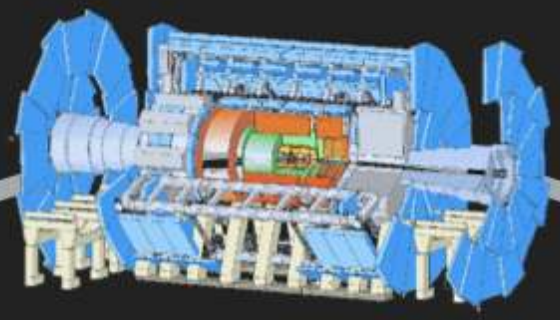
MANY POSSIBILITIES FOR DARK MATTER



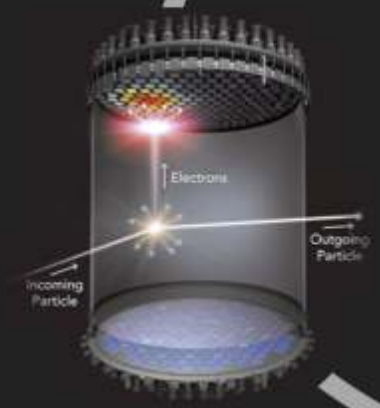
WITH DIFFERENT PREDICTED PROPERTIES



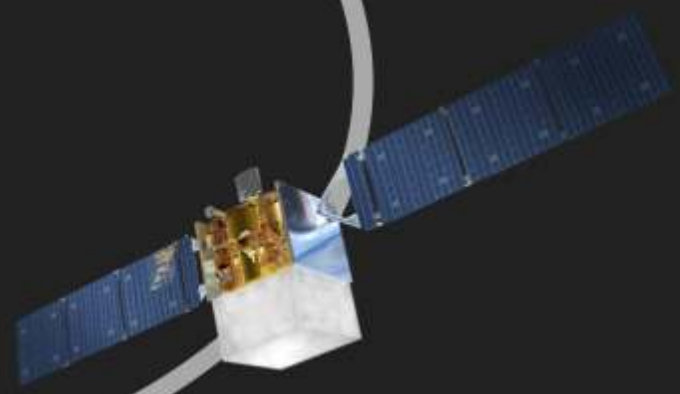
CONSTRAIN POSSIBLE DARK MATTER MODELS BY EXPERIMENT



COLLIDERS

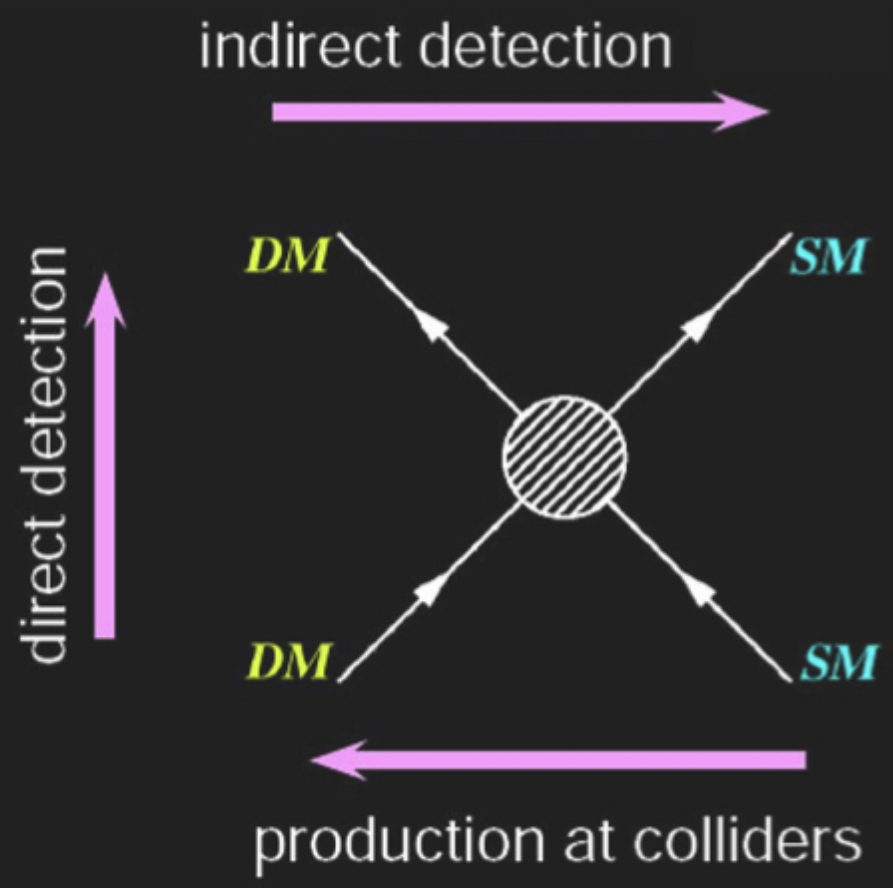


DIRECT DETECTION



INDIRECT DETECTION

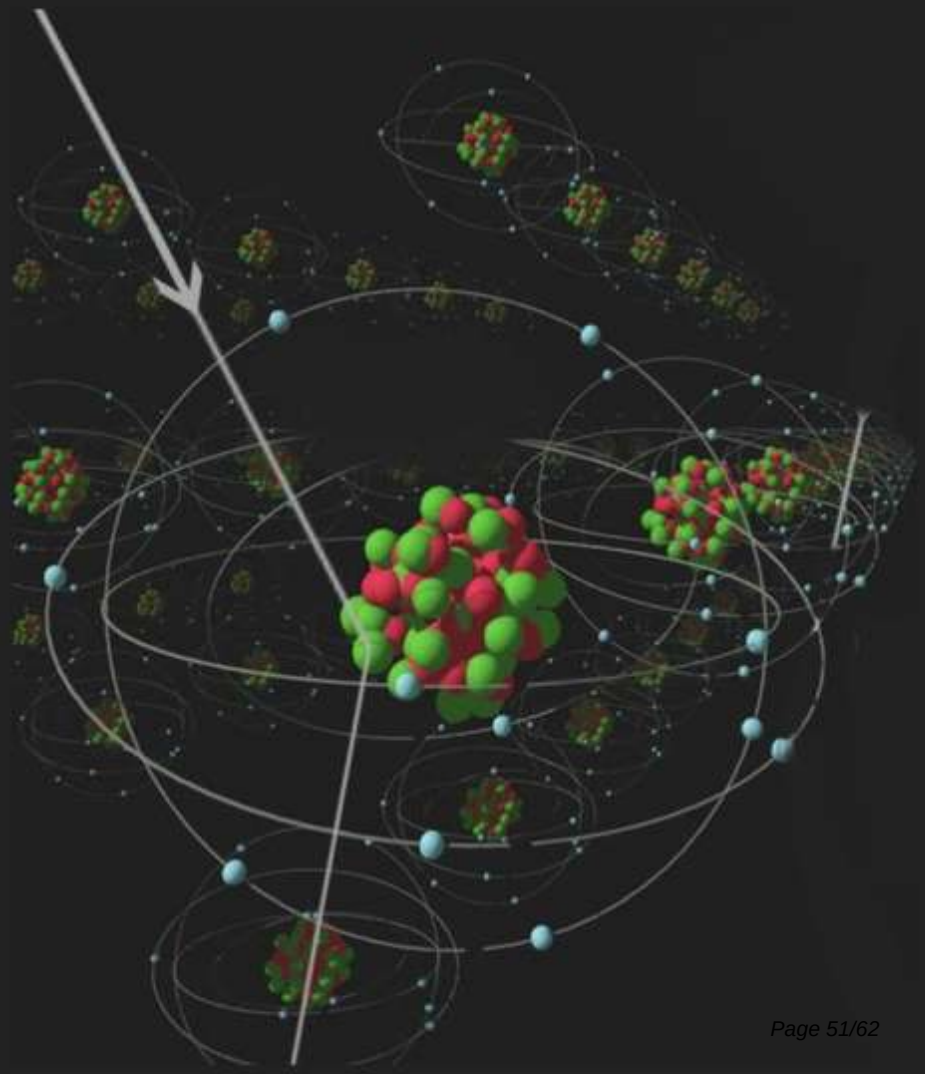
CONSTRAIN POSSIBLE DARK MATTER MODELS BY EXPERIMENT



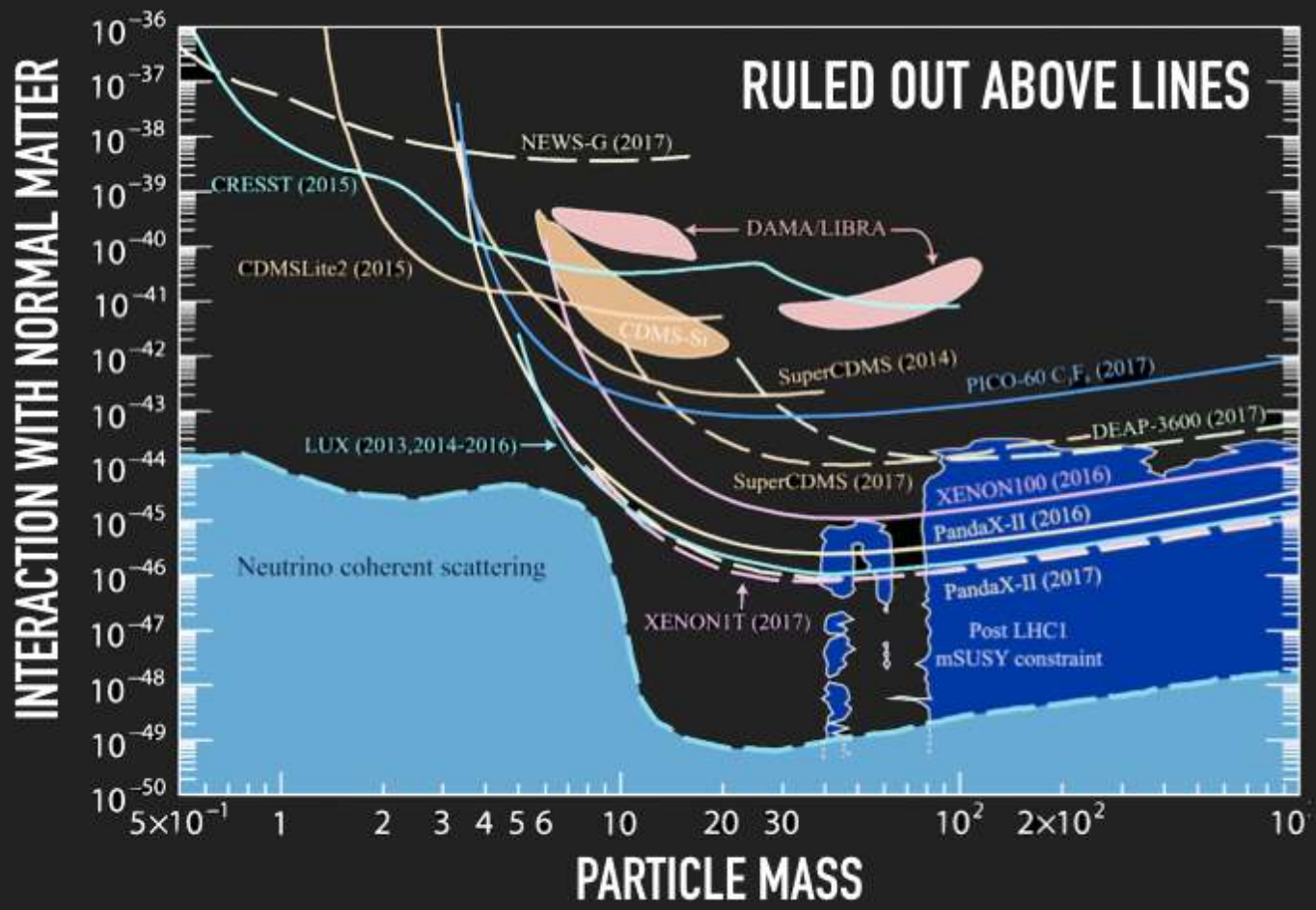
DIRECT SEARCHES FOR DARK MATTER

SEARCH FOR

WEAKLY
INTERACTING
MASSIVE
PARTICLES

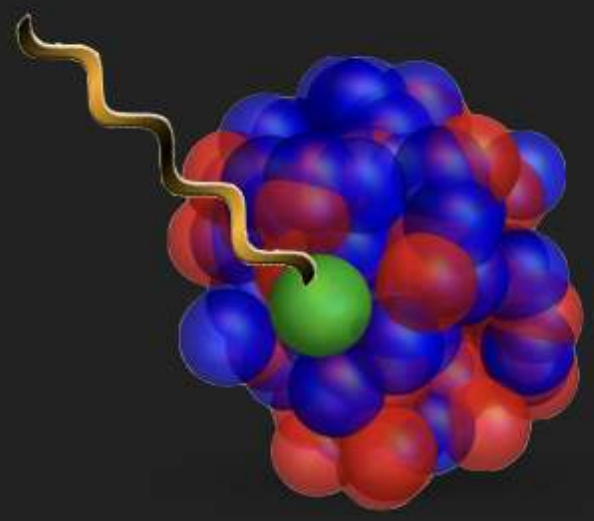


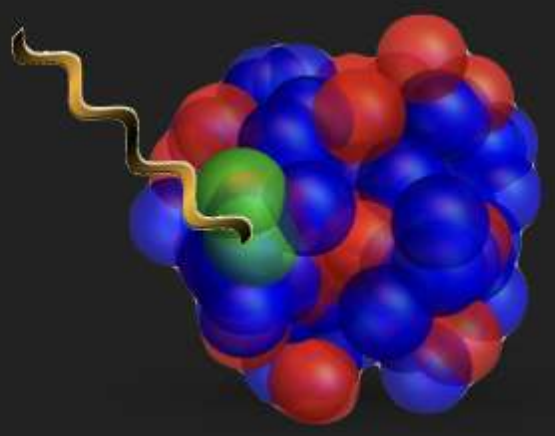
MANY LIMITS FROM EXISTING EXPERIMENTS



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

Chang et al, PRL 120, 152002 (2018)

MANY PROBLEMS STILL TOO EXPENSIVE COMPUTATIONALLY

STRUCTURE/INTERACTIONS OF LARGER NUCLEI FROM THE STANDARD MODEL

DARK MATTER INTERACTIONS WITH LARGER NUCLEI

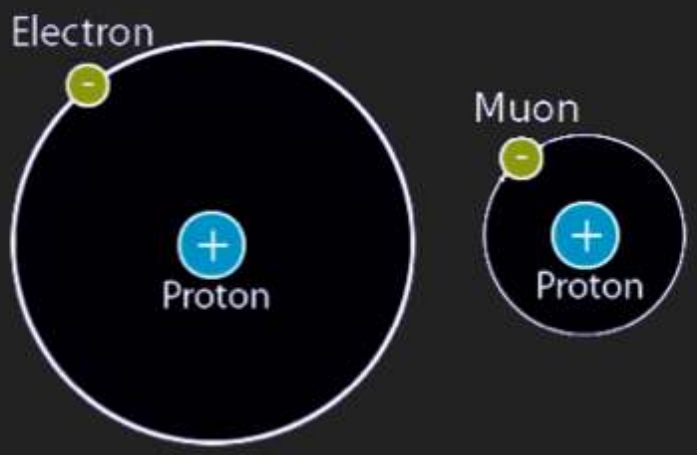
NEUTRINO-NUCLEUS SCATTERING

DOUBLE-BETA DECAY

⋮

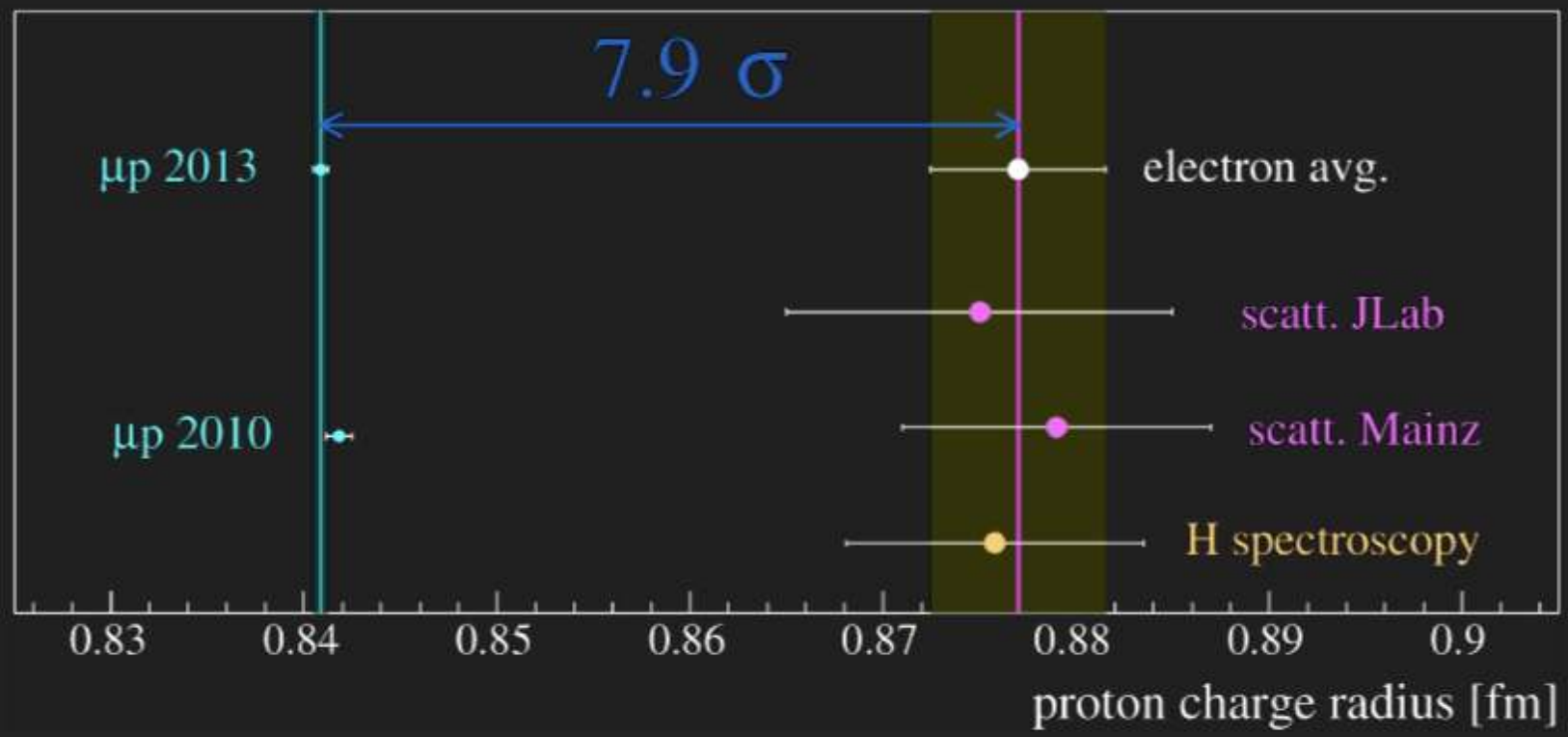
. . . AND SIMPLER QUESTIONS

WHAT IS THE PROTON RADIUS?



CONFLICTING EXPERIMENTAL RESULTS

WHAT IS THE PROTON RADIUS?



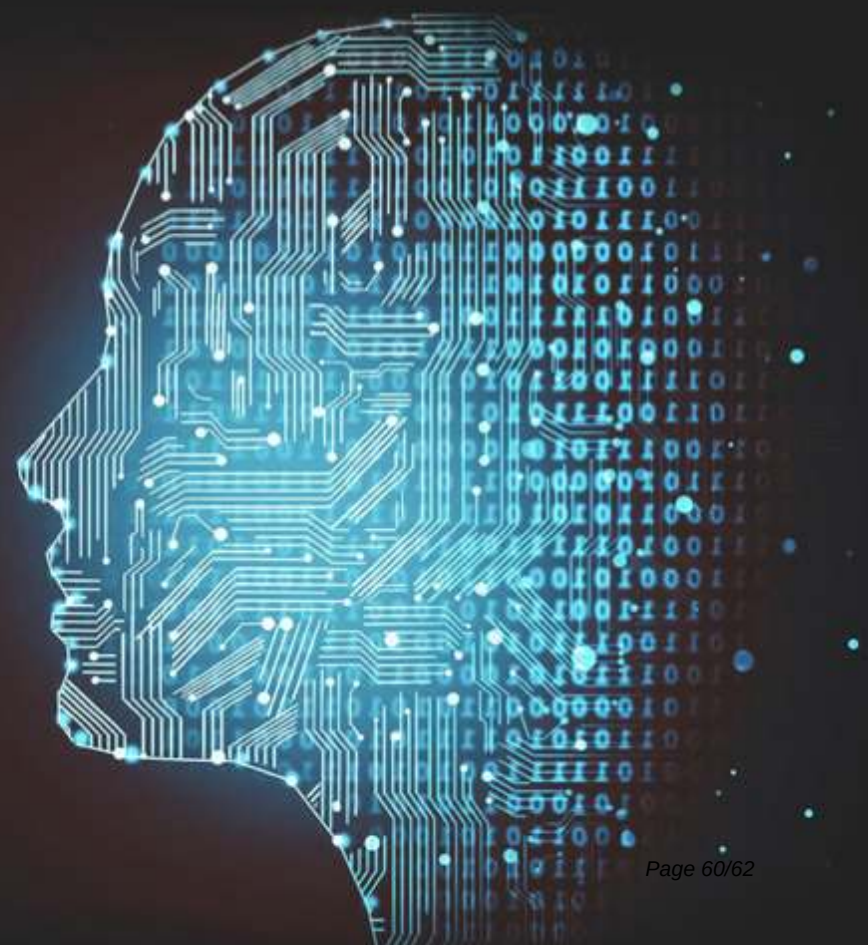
TOO COMPUTATIONALLY DEMANDING TO CALCULATE AT REQUIRED PRECISION

COMPUTERS IMPROVE QUICKLY – "MOORE'S LAW"

BUT NOT QUICKLY ENOUGH

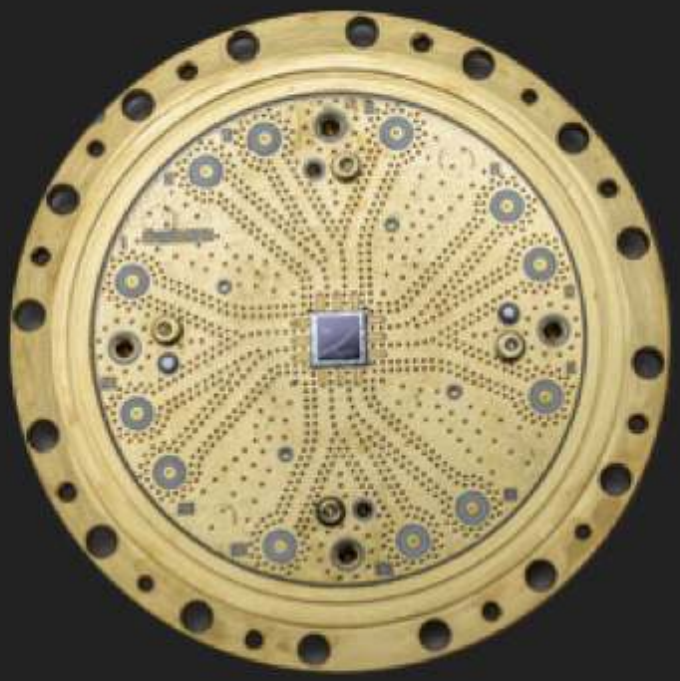
NEW ALGORITHMS FOR STANDARD MODEL CALCULATIONS

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

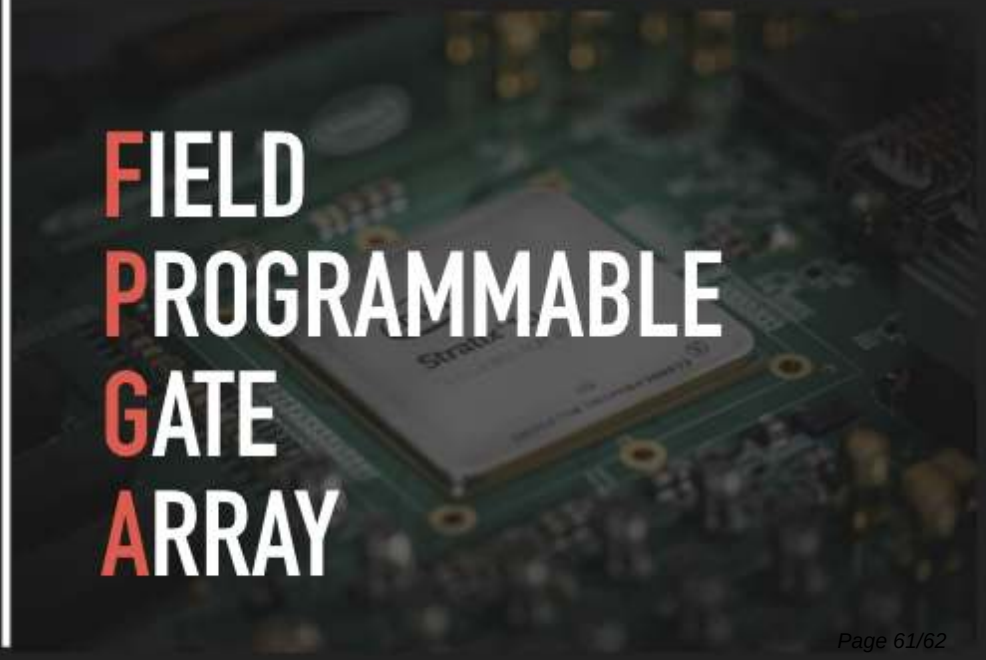


NEW COMPUTATIONAL PARADIGMS

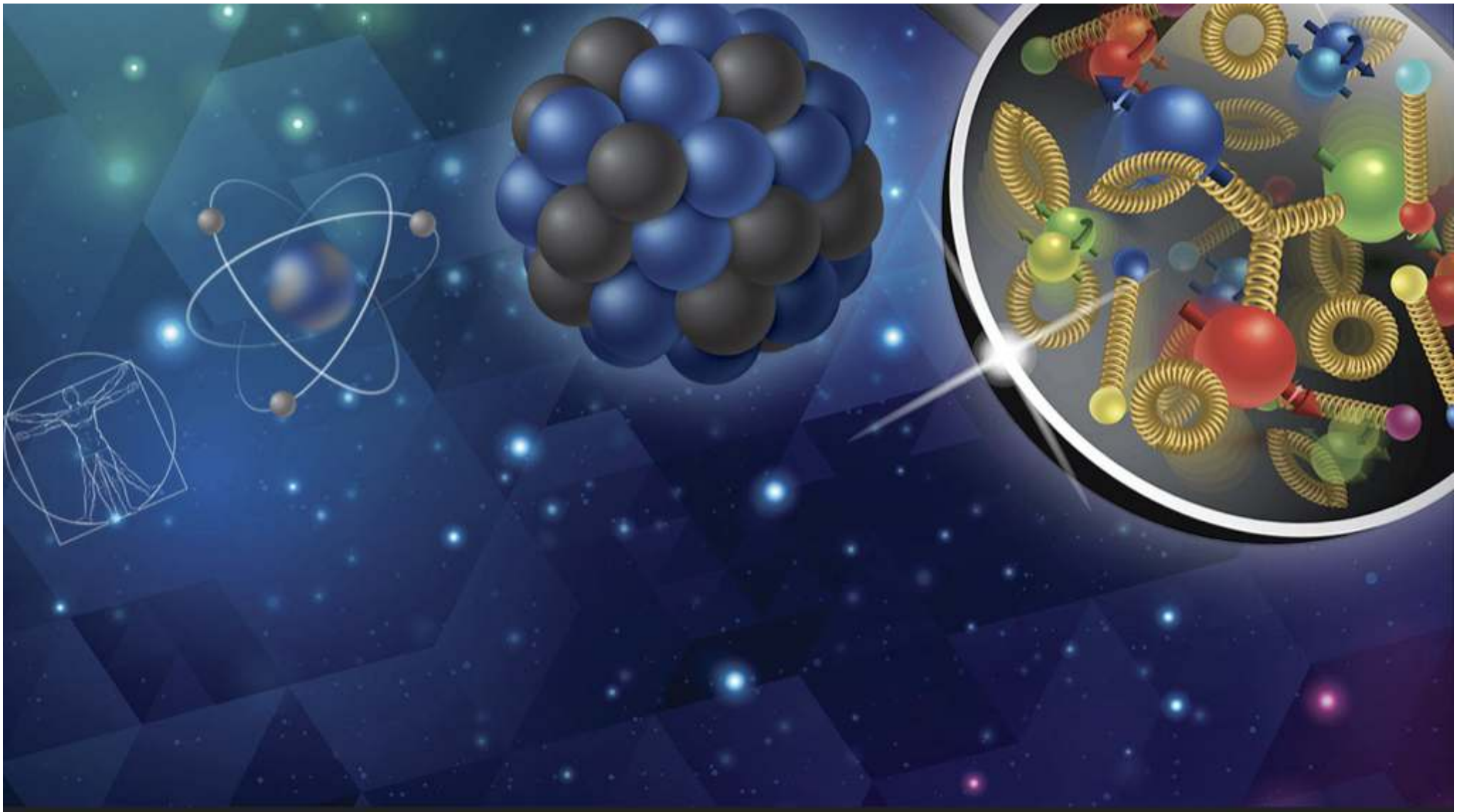
QUANTUM COMPUTING



A CUSTOM COMPUTER DESIGNED FOR A SINGLE CALCULATION



FIELD
PROGRAMMABLE
GATE
ARRAY



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