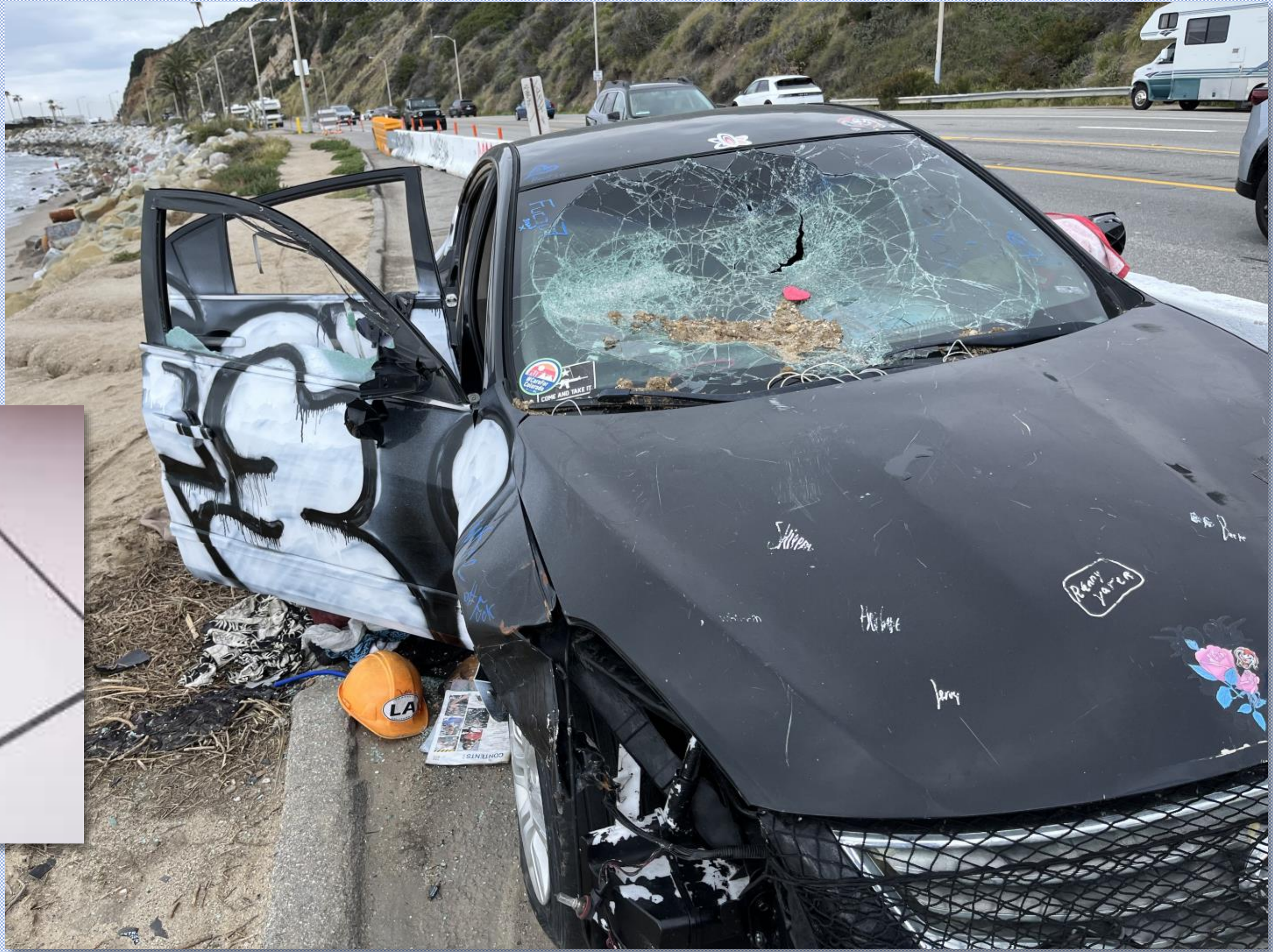
Dark Matter and Dark Energy Today

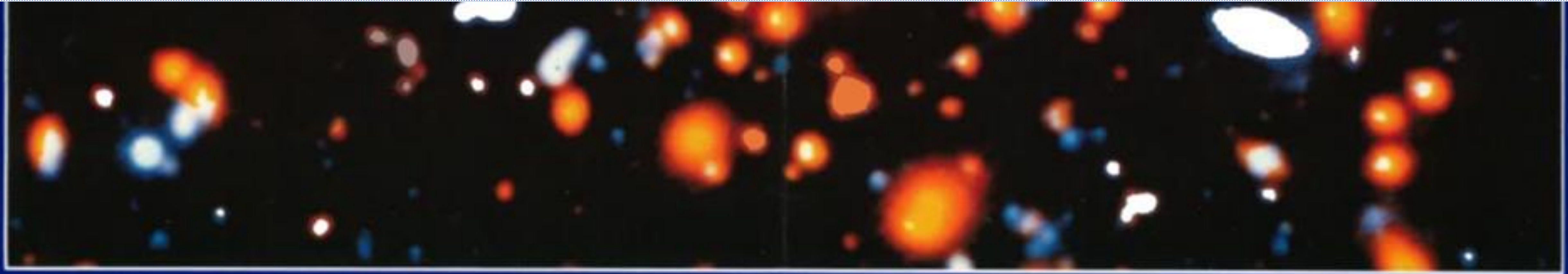
UCLA Dark Matter 2023

1 April 2023

Michael S. Turner
UCLA and UChicago

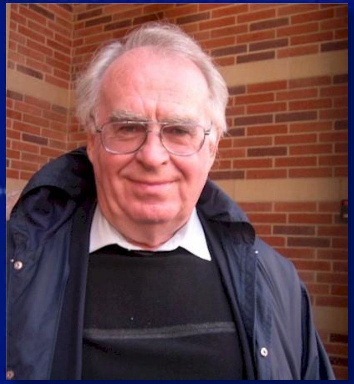
My "air" bnb in Malibu





February 16-18, 1994

BayView Plaza Holiday Inn, Santa Monica



Critique of the Sources of Dark Matter in the Universe

IOC

J. Bahcall (IAS)
E. Becklin (UCLA)
D. Cline (UCLA)
F. Halzen (Univ. Wisc.)
W. Haxton (Univ. Wash.)
R. Peccei (UCLA)
N. Reay (Kansas St. Univ.)
B. Sadoulet (UCB)
P. F. Smith (RAL)
M. Spiro (Saclay)
F. Stecker (NASA/GSFC)
M. Turner (FNAL/Univ. Chicago)
E. Wright (UCLA)

LOC

M. Atac
E. Becklin
D. Cline
G. Gelmini
I. McLean
Th. Müller
R. Peccei
E. Wright

TOPICS

CANDIDATES

- SUSY Particles
- Axions
- Black Holes/MACHOS
- Mixed Dark Matter Models
- Massive Neutrinos
- Dark Baryons

SEARCHES

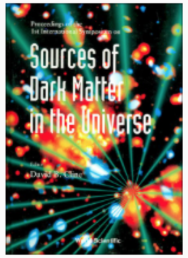
- Direct
- Indirect
- At Accelerators

CONSTRAINTS

- Electroweak Parameters
- Astrophysics
- Cosmological
- COBE/Large Scale Structure

World Scientific
Connecting Great Minds

Subject | Journals | Books | Major Reference Works | Resources For Partners | Open Access | Abo



Sources of Dark Matter in the Universe

Proceedings of the 1st International Symposium

1st International Symposium, Bel Air, California, 16 – 18 February 1994

https://doi.org/10.1142/2627 | February 1995

Pages: 332

Edited By: David B Cline (*UCLA*)

ISBN: 978-981-4549-7 (ebook)

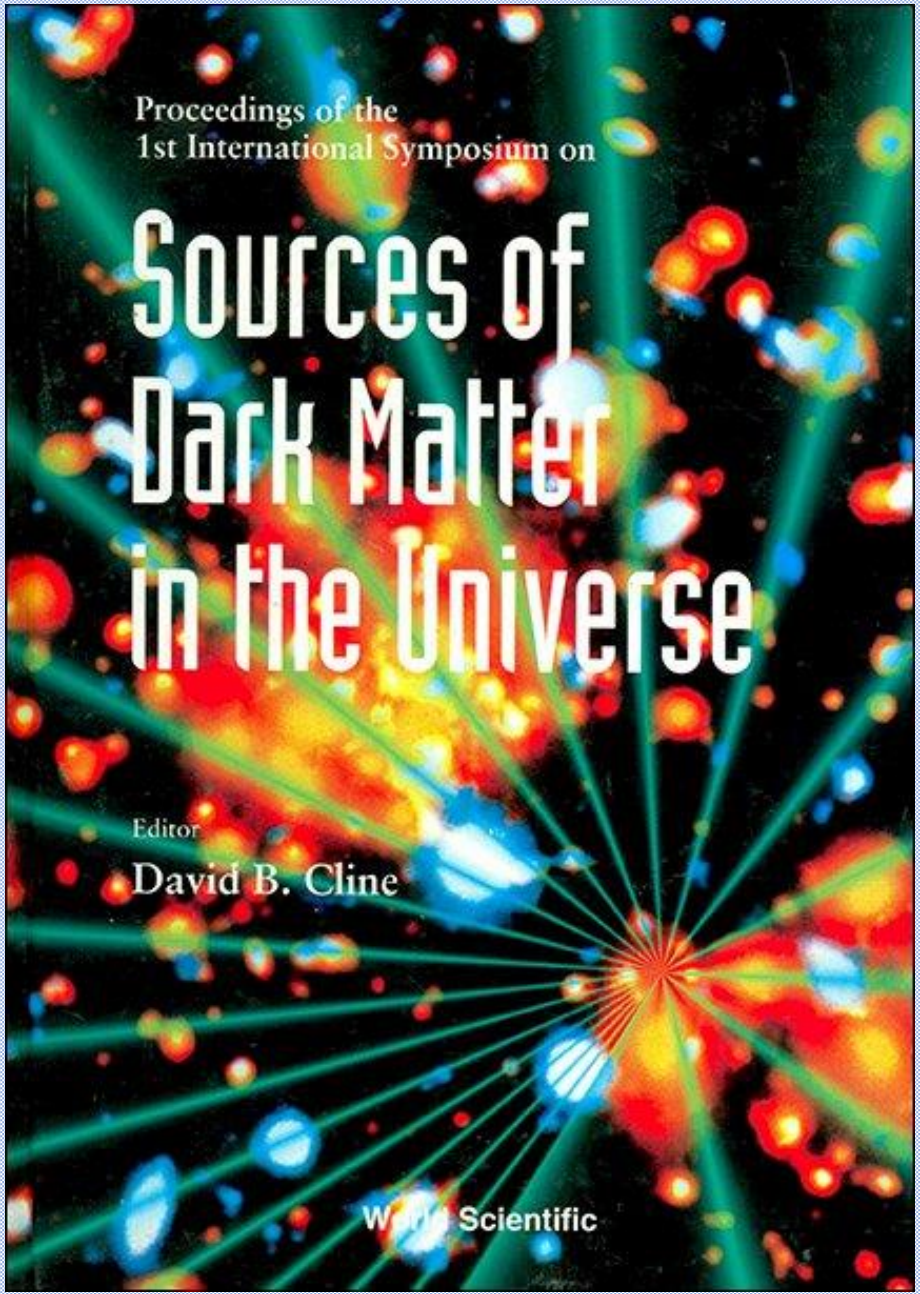
For institutional ebook ISBN: 9

View Full Book | Tools | Share

Recommend to Library

Description | Chapters

Contents:



My talk: “The case for particle dark matter”

14^{th} UCLA DM meeting (2 year cadence)

- First, 1994 in Santa Monica (Bel Air). "Critique of the Sources of Dark Matter in the Universe."
- Moved to Marina del Rey (aka Venice Heights) for a few symposia
- 1998: Announcement of the accelerating Universe
- 2000: Now, the International Symposium on Sources and Detection of Dark Matter and Dark Energy in the Universe.

…

- 2016: at UCLA (first without David Cline)
- 2018: at UCLA

Covid break

- 2023: UCLA Dark Matter is back, better than ever! Amazing meeting

The Dark Matter and Dark Energy questions as articulated, circa 1994 to 201x

- Dark Matter: What is the constituent of dark matter?
  - Light neutrino
  - WIMP/neutralino
  - Axion

- Dark Energy (1998 –): What is the nature of dark energy?
  - Vacuum energy ($w = -1$ and $w_a = 0$)
  - Quintessence
  - Modified gravity

1994: the evidence for nonbaryonic DM

THE ASTROPHYSICAL JOURNAL, **281**:493–511, 1984 June 15

PRIMORDIAL NUCLEOSYNTHESIS: A CRITICAL COMPARISON OF THEORY AND OBSERVATION

J. YANG,[1,2] M. S. TURNER,[2,3] G. STEIGMAN,[4] D. N. SCHRAMM,[2,3] AND K. A. OLIVE[3]
Received 1983 August 25; accepted 1983 December 20

ABSTRACT

Primordial nucleosynthesis is reexamined in the context of a detailed comparison of theory and observation. A new argument is presented to show how the observed abundances of D and ^{3}He can be used to derive a *lower* bound to the nucleon density. In concert with the previously known upper bound from D alone, we define a conservative ("safe bet") range for the nucleon-to-photon ratio: $\eta = (3\text{–}10) \times 10^{-10}$. New observations of ^{7}Li are consistent with the abundances of D and ^{3}He and help us to define a reasonable ("best bet") range: $\eta = (4\text{–}7) \times 10^{-10}$. In either of these ranges the predicted and observed abundances of D, ^{3}He, and ^{7}Li are all in concordance. The upper bounds correspond to $\Omega_N \leq 0.14\text{–}0.19$, and we conclude that nucleons fail to close the universe by at least a factor of 5–7. We review the recent observational data on ^{4}He and conclude that there is complete consistency between the predicted abundance of ^{4}He and those of the other light elements. In particular, for the standard model ($N_\nu = 3$, $10.4 \leq \tau_{1/2} \leq 10.8$ minutes) we find that $Y_p \leq 0.25$ for $\eta \lesssim 7 \times 10^{-10}$. We predict a lower bound to the ^{4}He mass fraction of $Y_p \geq 0.24$ if $N_\nu \geq 3$ and $\tau_{1/2} \geq 10.4$ minutes. If ν_τ is not light (i.e., $m \gtrsim 1$ MeV), $N_\nu \geq 2$, and Y_p can be as low as 0.226; if Y_p is unambiguously determined to be less than this value, the standard model will be in trouble. Only one additional light, two-component neutrino species ($N_\nu = 4$) is marginally permitted: for $N_\nu = 4$, $\tau_{1/2} \geq 10.4$ minutes, and $\eta \geq 3 \times 10^{-10}$, $Y_p \geq 0.253$.

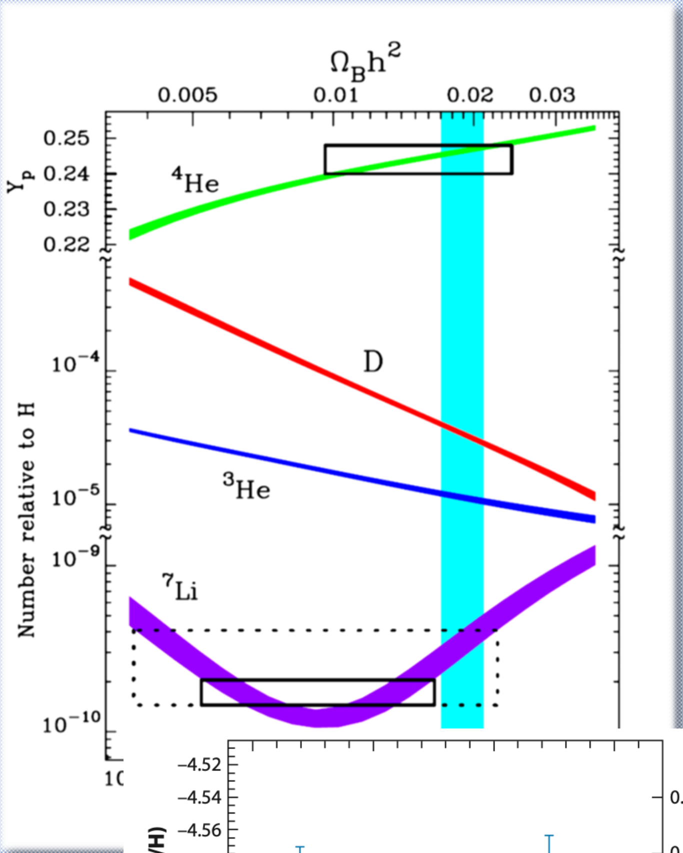
Subject headings: cosmology — early universe — nucleosynthesis

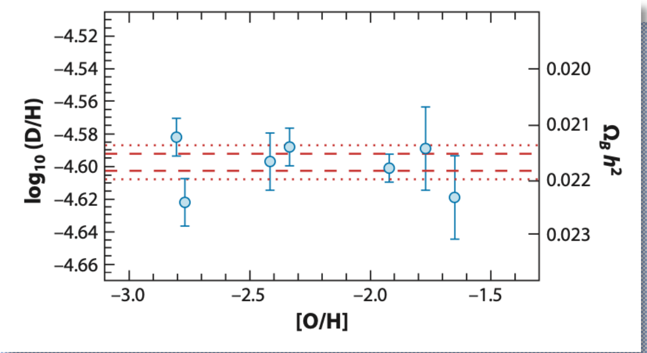
BBN (D, D + ^{3}He):
$\Omega_B h^2 = 0.015$ to 0.025
→ $\Omega_B < 0.1$
vs.
Mass-to-light ratios and peculiar velocities:
$\Omega_M > 0.1$ to 0.2
NB. Inflation: $\Omega_0 = 1.0$
$H_0 = 100h$ km/s/Mpc

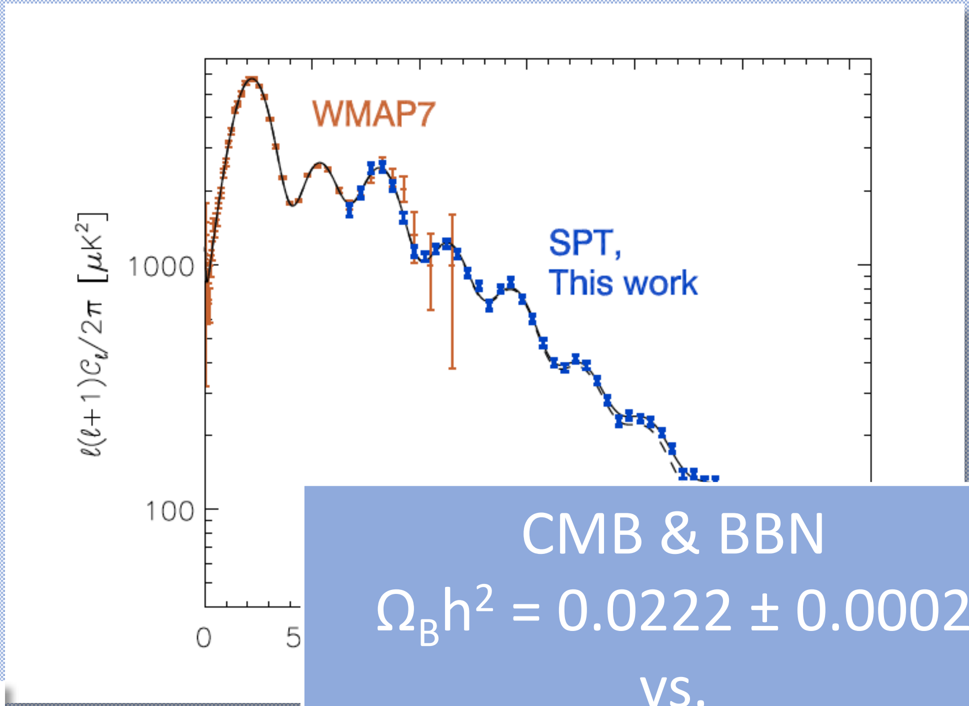
2023: Dark Matter Centerstage

- Dark matter is a portal to a world of new particles and forces and how they fit together
- Dark matter is a window to the earliest moments of the Universe
  - Highest temperature, thermal history, epoch of inflation, …
- Dark matter shapes cosmic structures and is critical to the detailed understanding of the story of stars, galaxies and us
- Dark matter and atomic matter have similar mass densities; why? What else?
- Dark matter has inspired (and borrowed from) new detector technologies
  - Smaller detectors: $n \; \alpha \; 1/m$
  - Smaller energies and momenta: $p, E \; \alpha \; m$
  - High occupancy ($m \ll eV$) $\rightarrow$ coherent effects!

Today: airtight evidence for nonbaryonic DM (or a big problem)







CMB & BBN

$\Omega_B h^2 = 0.0222 \pm 0.0002$

vs.

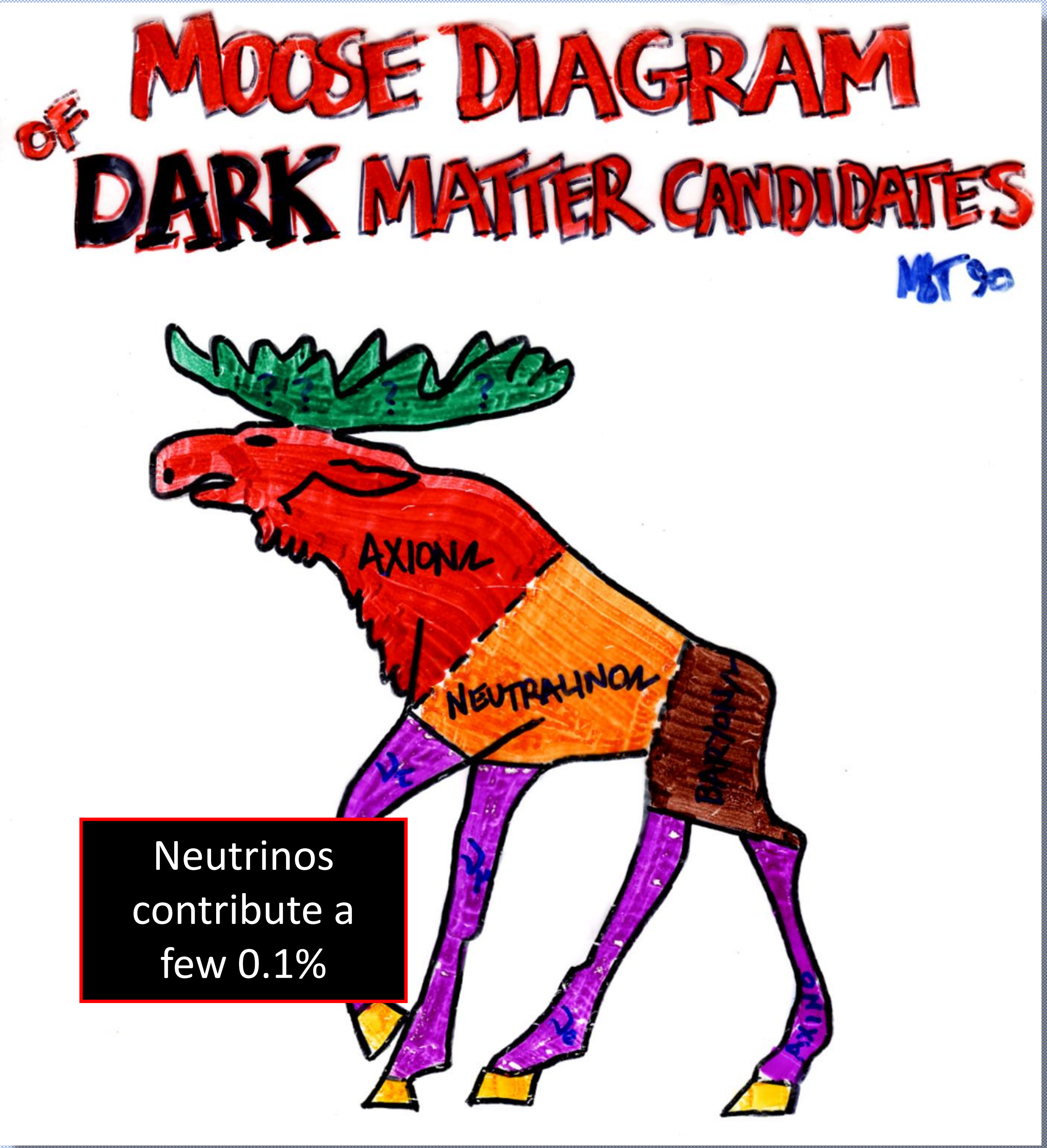
CMB/SDSS/DES/BOSS

$\Omega_M h^2 = 0.143 \pm 0.001$

> 50σ discrepancy

Full Court Press!!
- Produce at LHC
- Detect particles in our halo
- Detect annihilation products

But where is the WIMP?



Neutrinos contribute a few 0.1%

… and don't forget the ones who brought you to the big dance

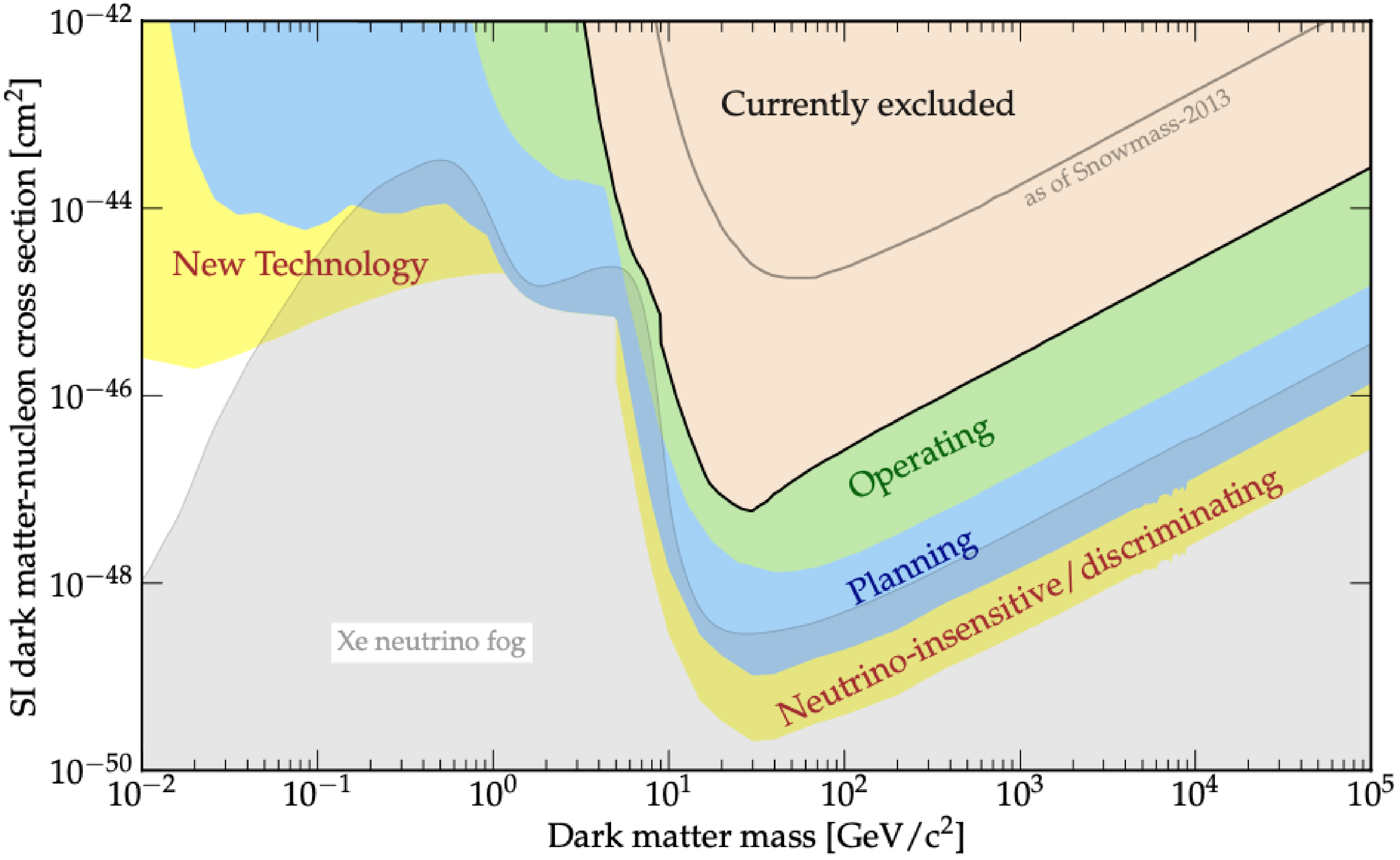


Figure 5-18. *Combined Spin-independent dark-matter nucleon scattering cross section space. Current 90% c.l. constraints are shaded beige, while the reach of currently operating experiments are shown in green (LZ, XENONnT, PandaX-4T, SuperCDMS SNOLAB, SBC). Future experiments are shown in blue (SuperCDMS, DarkSide-20k, DarkSide-LowMass, SBC, XLZD, ARGO) and yellow (Snowball and Planned× 5). The neutrino fog for a xenon target is shaded light grey. From Ref. [97].*

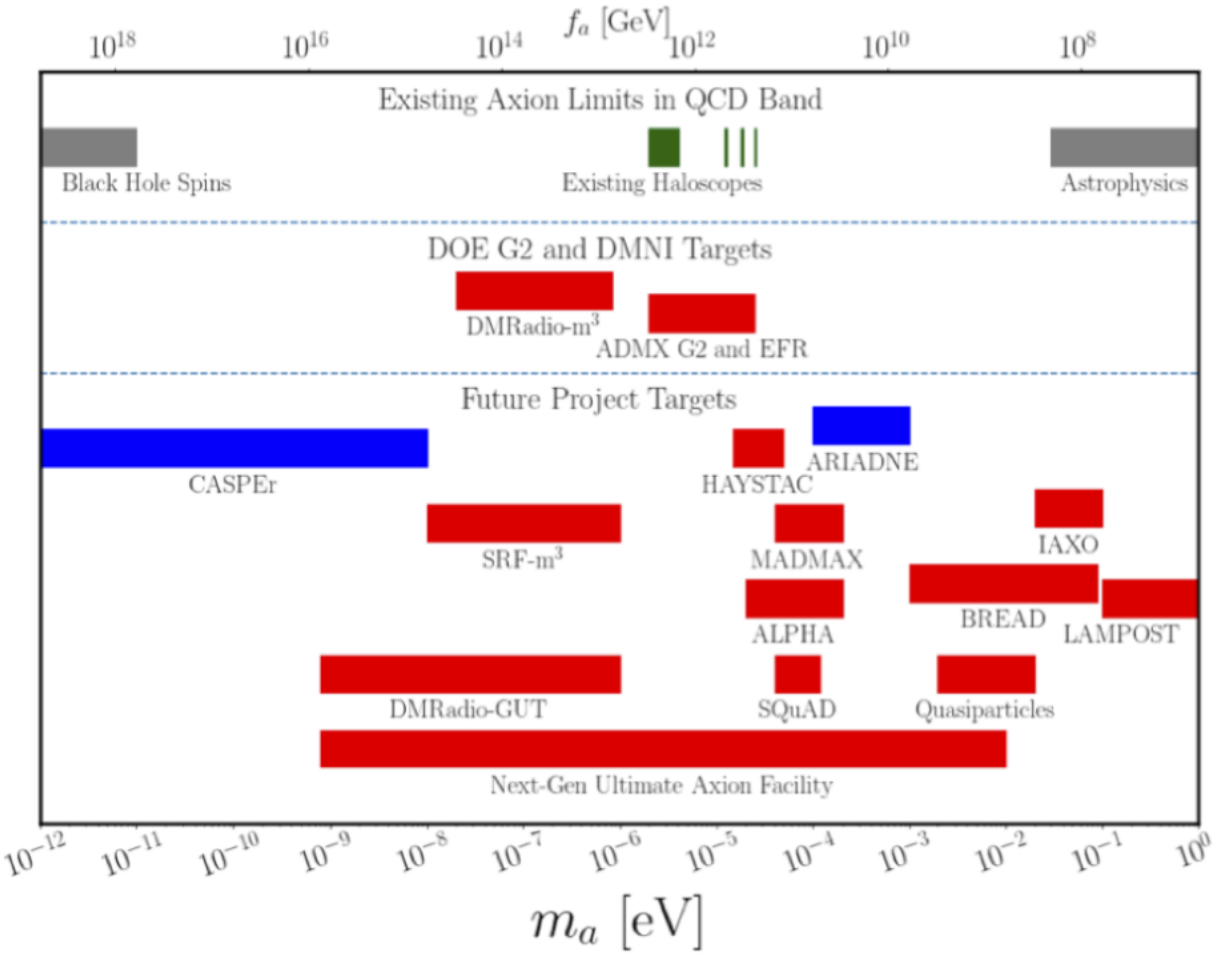
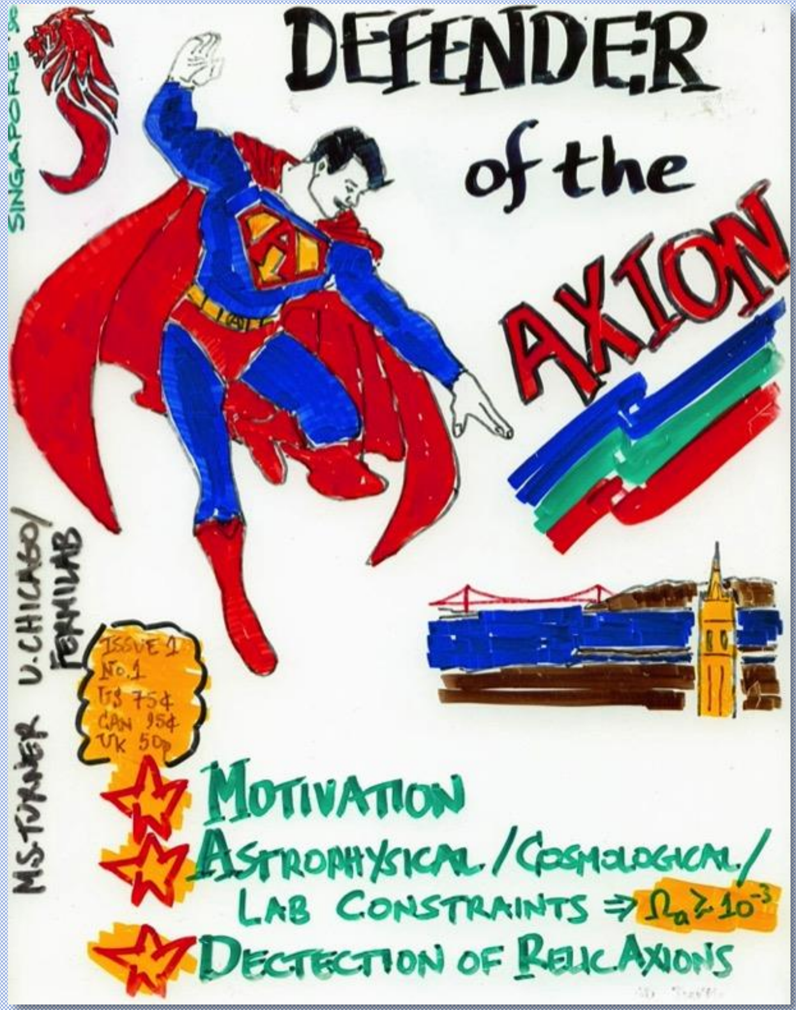
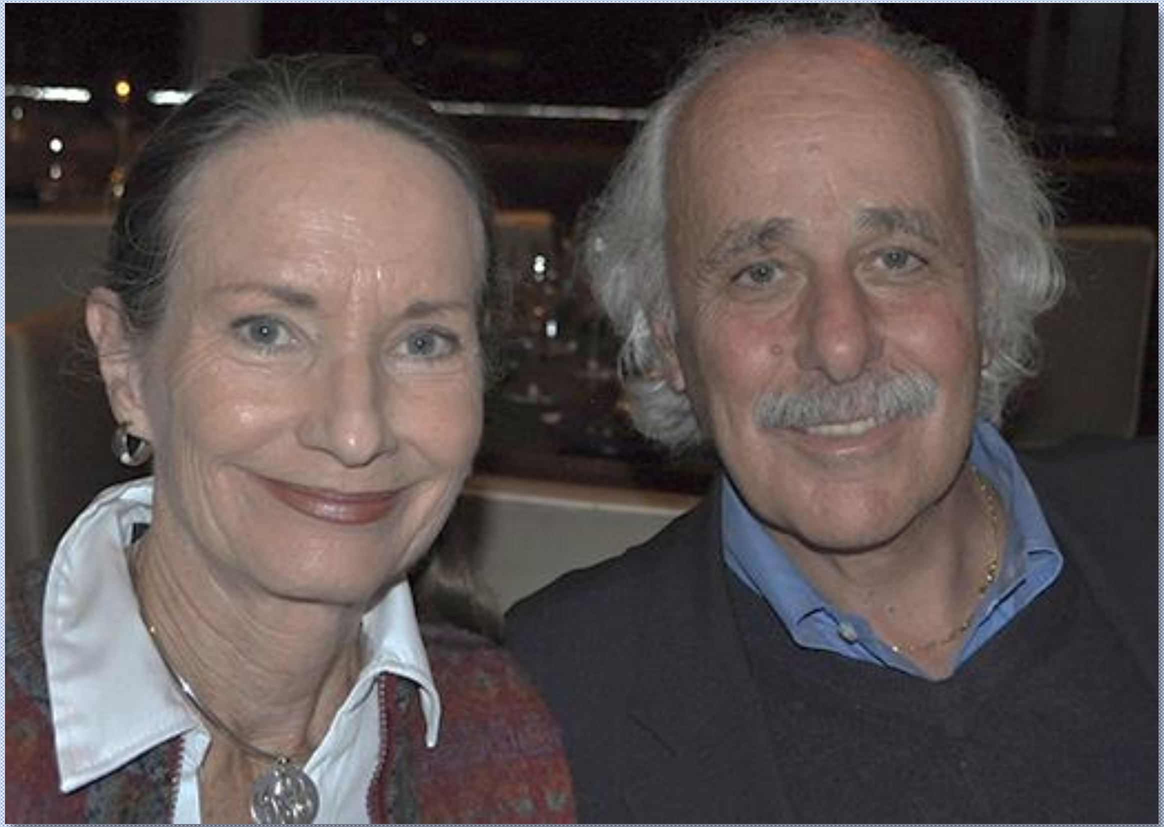


Figure 5-13. *A high priority target is the QCD axion which solves the strong CP problem as well as the origin of the dark matter. The QCD axion model makes testable predictions for the interaction strengths as a function of mass, providing useful benchmarks. This plot shows a suite of ongoing and future experiments which will test the QCD model by providing broad coverage of axion mass regions at the predicted coupling strengths to photons (red) and gluons (blue). From the CF2 report [2].*





Zeno (Roberto Peccei) and his Lady Jos

at UCLA from 1989 to 2020: Distinguished scholar, Chair, Dean and Vice Chancellor for Research

https://www.pa.ucla.edu/peccei-memorial.php

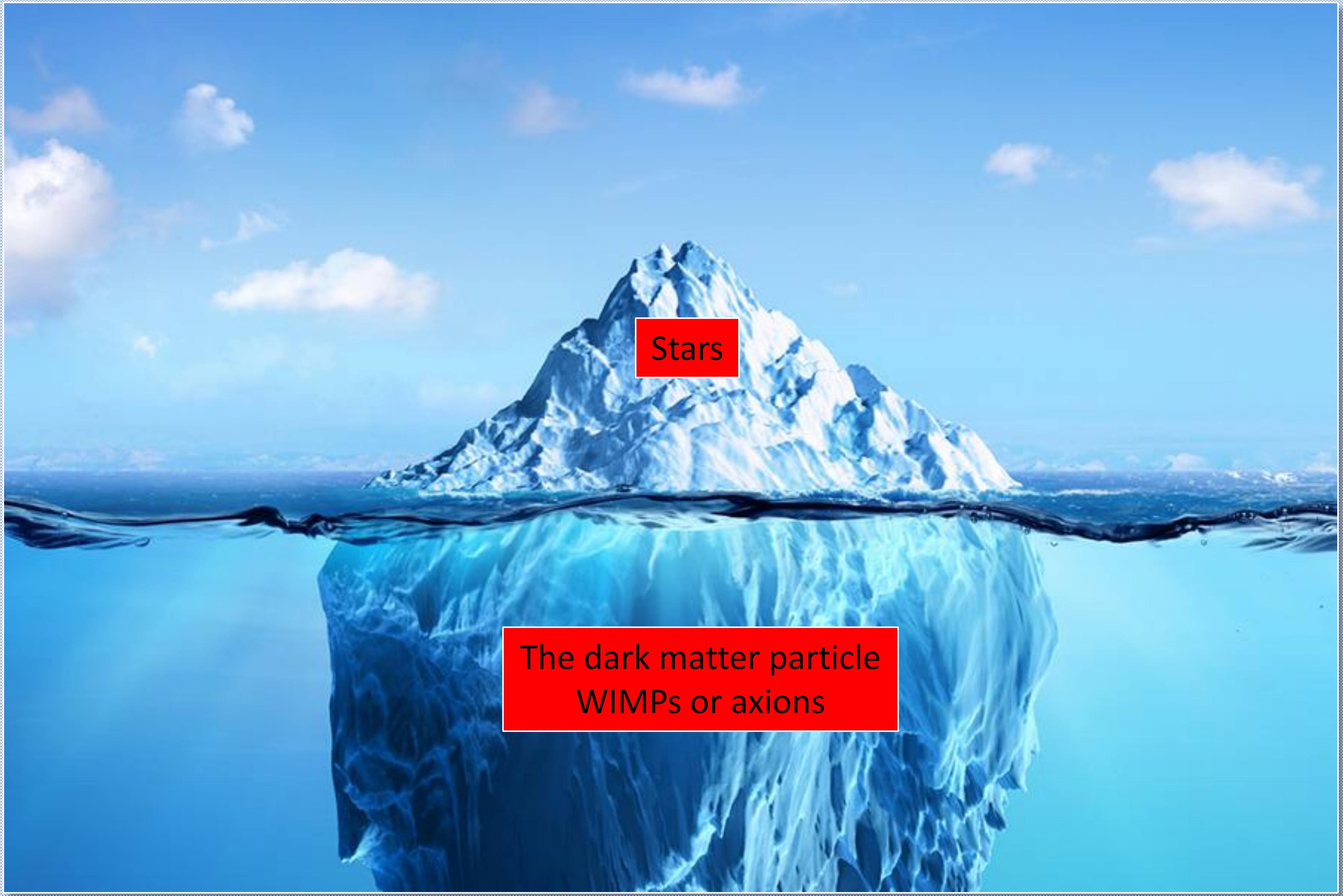
Grandparents of the axion:

Roberto and Helen Quinn

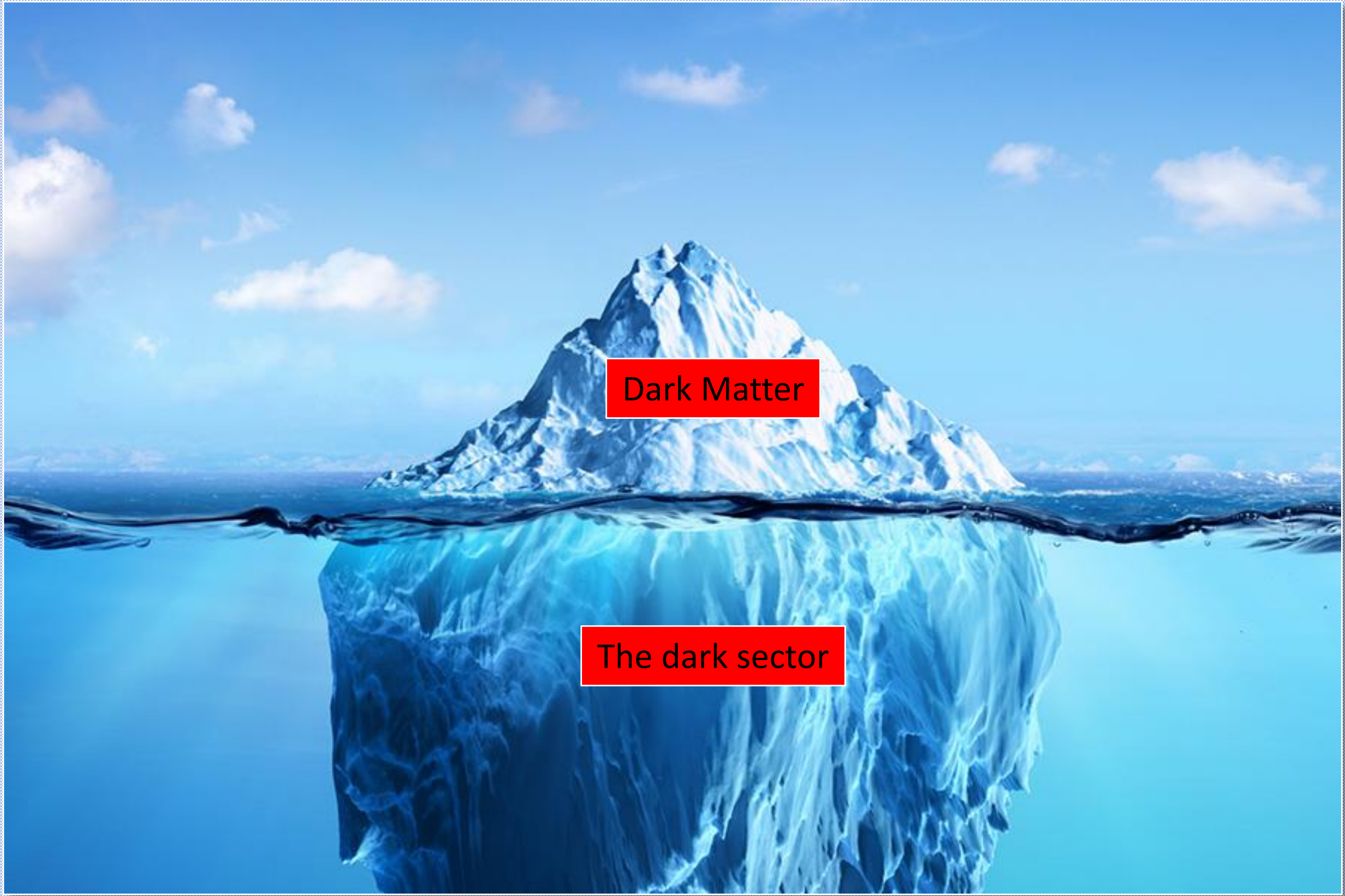
They made it all possible!

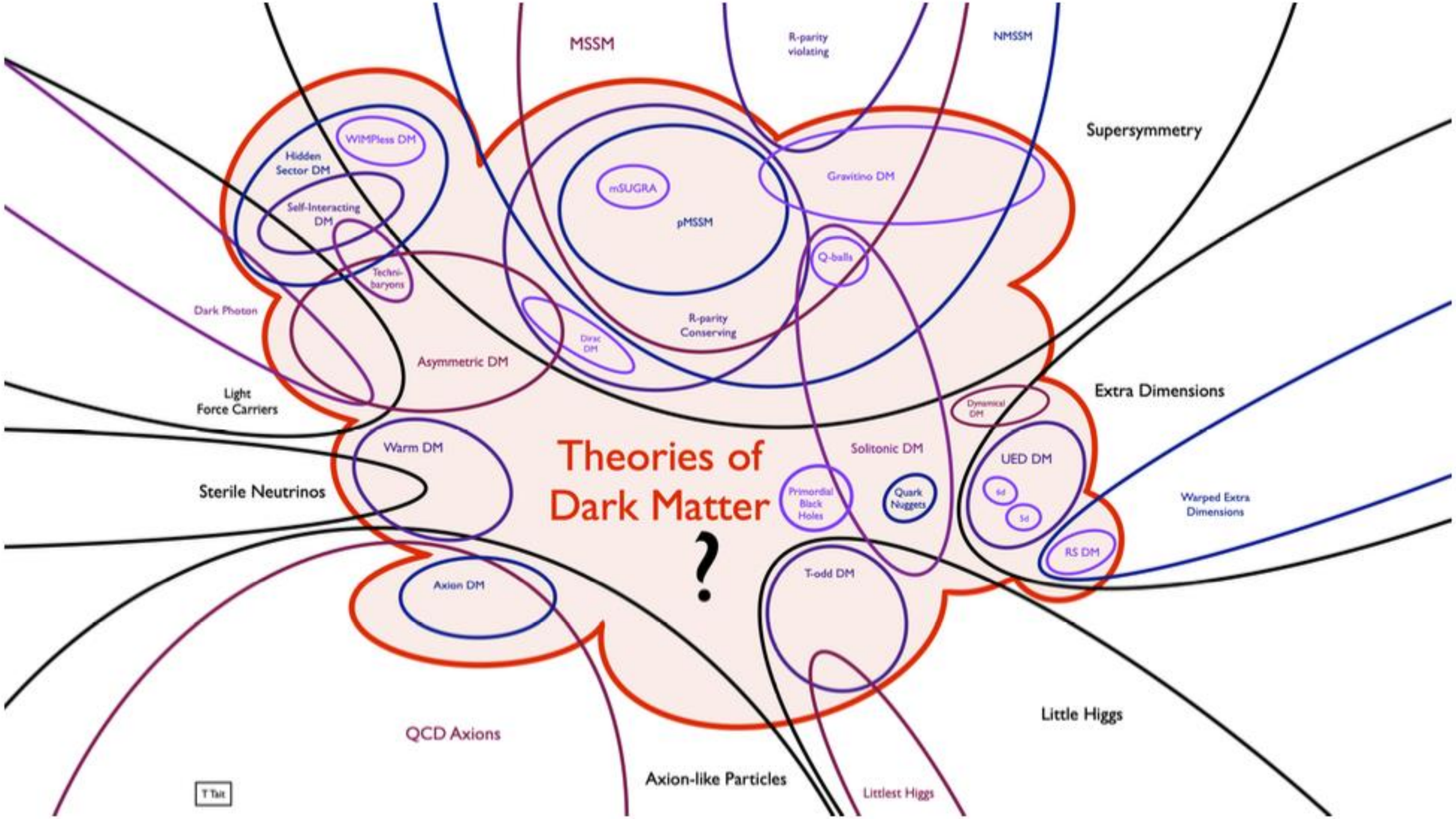
Frank Wilczek: Roberto made the world a better place while he was with us. He exuded warmth, enthusiasm, and generosity. His contributions to the substance of science and to its community live on.

Dark Matter: this?



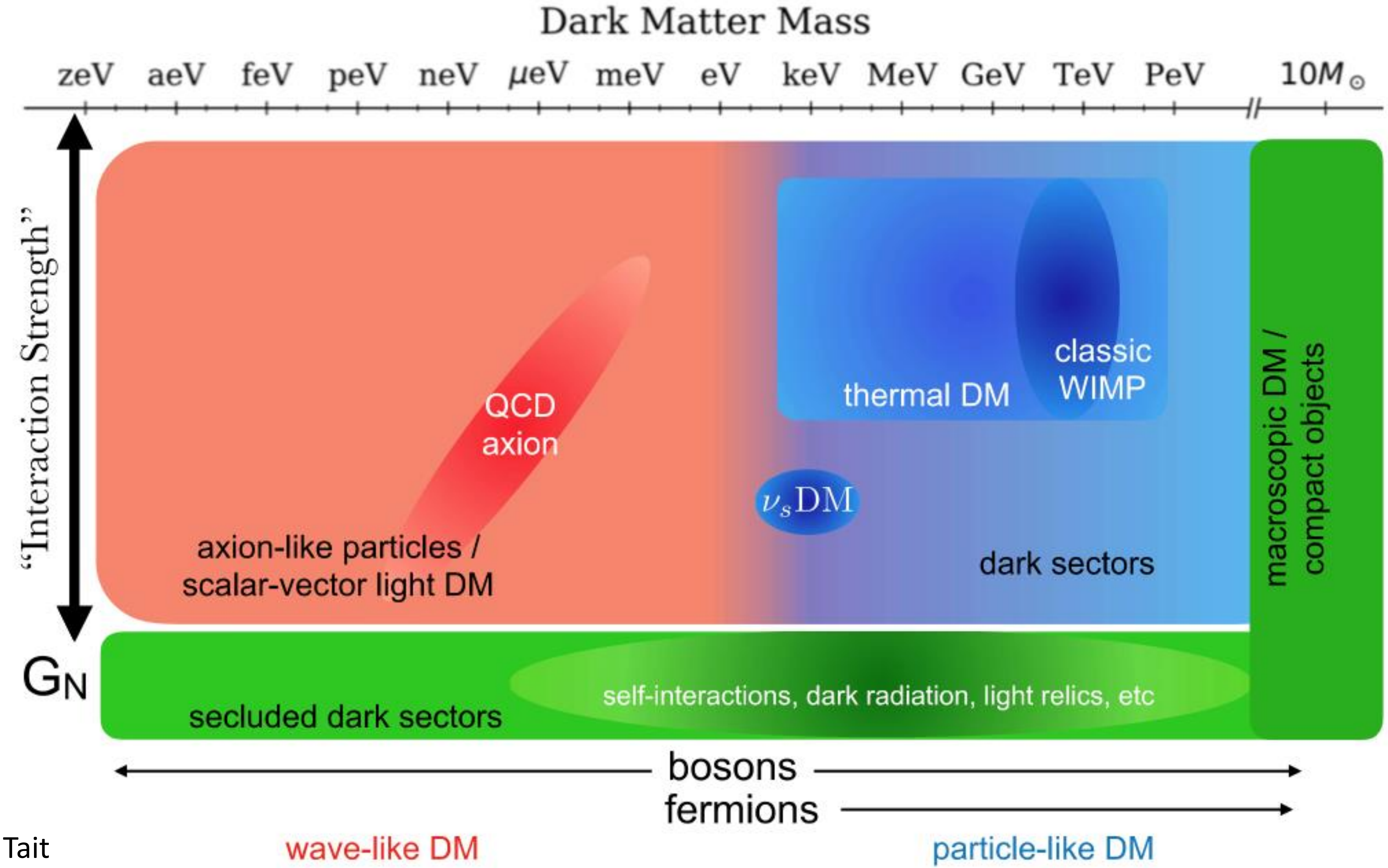
Dark Matter: or that?





Tait

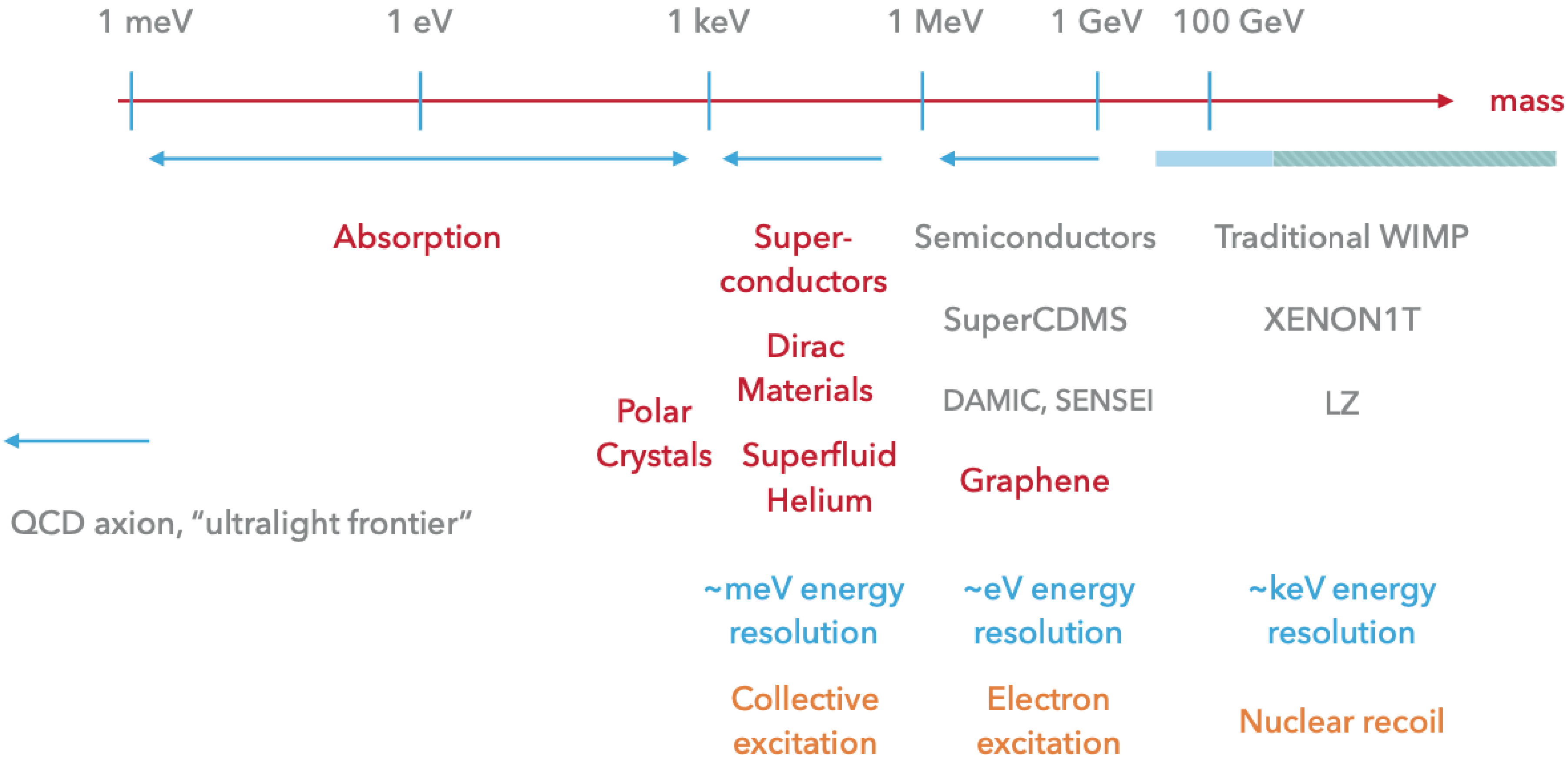
Figure 5-10. *Venn diagram of dark matter models, showing relationships between different ideas for the fundamental nature of dark matter.*


Dark Matter Mass
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 10$M_\odot$
"Interaction Strength"
G_N
QCD axion
axion-like particles / scalar-vector light DM
thermal DM
classic WIMP
ν_sDM
dark sectors
macroscopic DM / compact objects
self-interactions, dark radiation, light relics, etc
secluded dark sectors
bosons
fermions
wave-like DM
particle-like DM

Tait

LOOKING BEYOND BILLIARD BALLS

- Experimental Panorama



Zurek

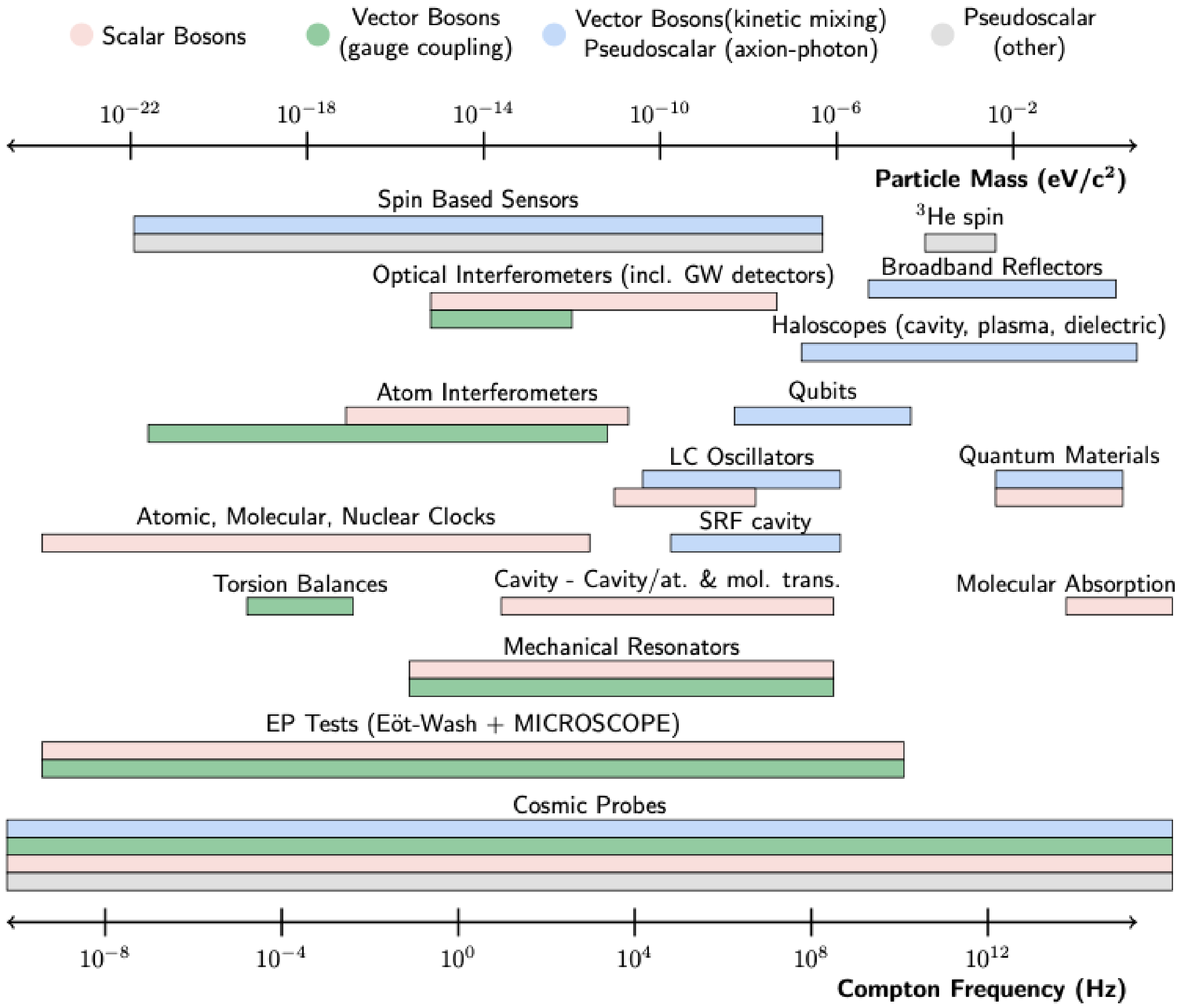
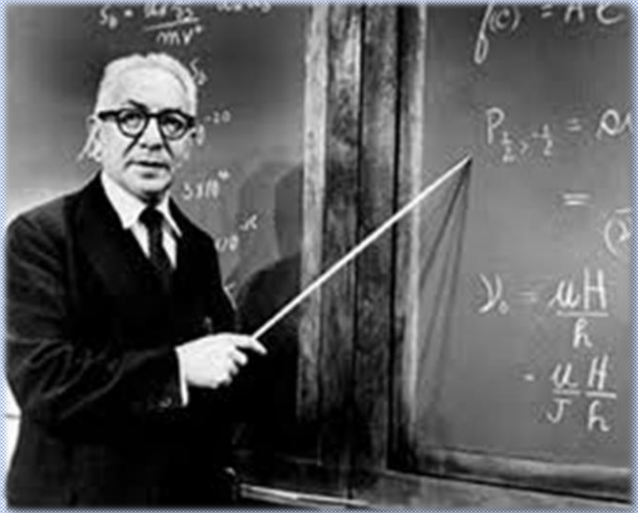


Figure 5-12. *Waves of ultra-light bosonic dark matter can be probed through a range of experimental and observational approaches including cavity experiments, quantum sensing technologies, AMO techniques, and cosmic probes. Assembled from the CF2 and CF3 reports [2, 3].*

A complicated Universe

- Atoms : Democritus to 1964
- + photons: 1964
- + neutrinos (e, μ): 1967
- + exotic dark matter: 1981
- + CDM: 1983/4
- + massive neutrinos: 1998
- + dark energy: 1998
- + τ neutrino: 2000
- Done? Not likely!
- Why is $\Omega_{CDM}/\Omega_B \approx 5$?



I.I. Rabi
Who ordered that?

How much room for more:

- UR: ~$0.2\rho_{CMB}$
- NR: ~$0.1\rho_{crit}$
- Other leftovers: ??

Modern Physics Letters A, Vol. 2, No. 1 (1987) 1–7

WHY SHOULD BARYONS AND EXOTIC RELIC PARTICLES HAVE COMPARABLE DENSITIES?

MICHAEL S. TURNER
NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

and

Departments of Physics and Astronomy and Astrophysics, Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA

and

BERNARD J. CARR
School of Mathematical Sciences, Queen Mary College, Mile End Road, London E1 4NS, England

Received 23 December 1986

Observations suggest that the mass density of the Universe is dominated, not by ordinary matter, but by exotic particles which are a relic of the Big Bang. In this case, a new dimensionless cosmological ratio arises, the ratio of the mass density in ordinary matter to that in exotic matter, whose value is about 0.1. *A priori*, it might seem remarkable that this ratio should be so close to unity. However, we point out that, for many exotic dark matter candidates, the ratio is related to the fundamental scales of particle physics. A value of order unity arises naturally provided rather simple relationships exist between these scales. If the exotic particles are of a kind whose relic abundance is determined by annihilations (e.g., the photino or a heavy neutrino), then the required relationship is already satisfied for independent, cosmological reasons.

Dimensionless numbers play a crucial role in physics and in cosmology[1] and attempts to explain them often lead to important insights. The cosmological significance of the primordial mass fractions of the light elements, of the baryon and lepton number to entropy ratios, and of the neutrino to photon temperature ratio are well-known and appreciated. In addition, there are certain dimensionless combinations of physical

- Combinations of fundamental constants?
- Similar asymmetries and masses?
- Accident?
- cf. Milgrom's Law (DM "kicks in" at a = cH_0) or CMB energy vs. stellar free energy

Precision Cosmology!

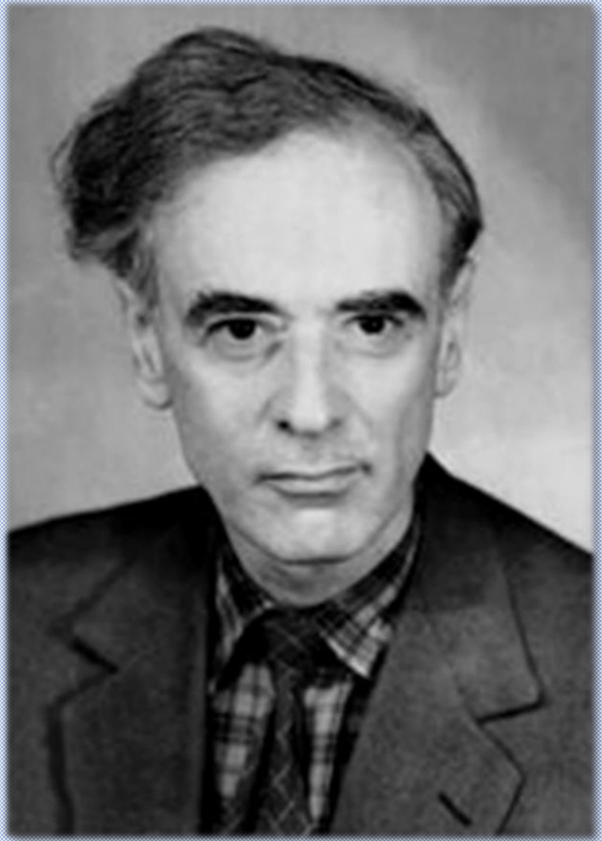
Precision Cosmology is Hard

Accurate Cosmology is even Harder!

Powerful tool
Team sport: theorists, builders and analysts

H_0 again!

Landau on Cosmologists



Often in Error,
Never in Doubt!

A word from your sponsor:

Annu. Rev. Nucl. Part. Sci. **72**, 1-35 (2022)

ANNUAL REVIEWS

Annual Review of Nuclear and Particle Science

The Road to Precision Cosmology

Michael S. Turner[1,2]

[1]Kavli Institute for Cosmological Physics, University of Chicago, Chicago, Illinois, USA; email: mturner@uchicago.edu

[2]The Kavli Foundation, Los Angeles, California

Annu. Rev. Nucl. Part. Sci. 2022. 72:1–35

First published as a Review in Advance on June 9, 2022

The *Annual Review of Nuclear and Particle Science* is online at nucl.annualreviews.org

https://doi.org/10.1146/annurev-nucl-111119-041046

Keywords

cosmic microwave background, cosmology, dark energy, dark matter, early Universe, inflation, particle cosmology, Lambda CDM

Abstract

In the past 50 years, cosmology has gone from a field known for the errors being in the exponents to a precision science. The transformation—powered by ideas, technology, a paradigm shift, and culture change—has revolutionized our understanding of the Universe, with the Lambda cold dark matter (ΛCDM) paradigm as its crowning achievement. I chronicle the journey of precision cosmology and finish with thoughts about the next cosmological paradigm.

Precision cosmology – once an oxymoron – with its large, high quality datasets is now probing dark matter and dark energy in unprecedented ways

2023: Cosmic Acceleration

- When and why is gravity repulsive?
- How are inflation and today's accelerated expansion related?
- Are there other epochs of cosmic acceleration?
- What does cosmic acceleration tell us about the destiny *and origin* of the Universe?
- What is nothing and how much does it weigh?
- Signatures beyond the expansion rate
- NB: dark energy is merely the cause of the current epoch of cosmic acceleration

Names matter: from Dark Energy to Cosmic Acceleration

1998

The Third Stromlo Symposium: The Galactic Halo
ASP Conference Series, Vol. 165, 1999
B. K. Gibson, T. S. Axelrod and M. E. Putman (eds.)

Dark Matter and Dark Energy in the Universe

Michael S. Turner[1]

Departments of Astronomy & Astrophysics and of Physics, Enrico Fermi Institute, University of Chicago

Abstract.

For the first time, we have a plausible, complete accounting of matter and energy in the Universe. Expressed a fraction of the critical density it goes like this: neutrinos, between 0.3% and 15%; stars, 0.5%; baryons (total), 5%; matter (total), 40%; smooth, dark energy, 60%; adding up to the critical density (summarized in Fig. 1). This accounting is consistent with the inflationary prediction of a flat Universe and defines three dark-matter problems: Where are the dark baryons? What is the non-baryonic dark matter? What is the nature of the dark energy? The leading candidate for the (optically) dark baryons is diffuse hot gas; the leading candidates for the nonbaryonic dark matter are slowly moving elementary particles left over from the earliest moments (cold dark matter), such as axions or neutralinos; the leading candidates for the dark energy involve fundamental physics and include a cosmological constant (vacuum energy), a rolling scalar field (quintessence), and light, frustrated topological defects.

Dark Energy and the Accelerating Universe

Joshua A. Frieman,[1,2] Michael S. Turner,[2] and Dragan Huterer[3]

[1]Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, Illinois 60510; email: frieman@fnal.gov

[2]Kavli Institute for Cosmological Physics, The University of Chicago, Chicago, Illinois 60637; email: mturner@uchicago.edu

[3]Department of Physics, University of Michigan, Ann Arbor, Michigan 48109; email: huterer@umich.edu

Key Words

cosmological constant, cosmology, galaxy clusters, large-scale structure, supernovae, weak gravitational lensing

Abstract

Ten years ago, the discovery that the expansion of the universe is accelerating put in place the last major building block of the present cosmological model, in which the universe is composed of 4% baryons, 20% dark matter, and 76% dark energy. At the same time, it posed one of the most profound mysteries in all of science, with deep connections to both astrophysics and particle physics. Cosmic acceleration could arise from the repulsive gravity of dark energy—for example, the quantum energy of the vacuum—or it may signal that general relativity (GR) breaks down on cosmological scales and must be replaced. We review the present observational evidence for cosmic acceleration and what it has revealed about dark energy, discuss the various theoretical ideas that have been proposed to explain acceleration, and describe the key observational probes that will shed light on this enigma in the coming years.

Inner Space and Outer Space are connected in deep and profound ways

You cannot understand one without understanding the other

Dark Matter and Dark Energy are the poster children of that connection