Fundamental Neutron Physics

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1. *Introduction to "Fundamental Neutron Physics"*

2. *Current (and near future) "high impact" research*

3. *Source Requirements for Fundamental Physics*

4. *Need for high flux beams*

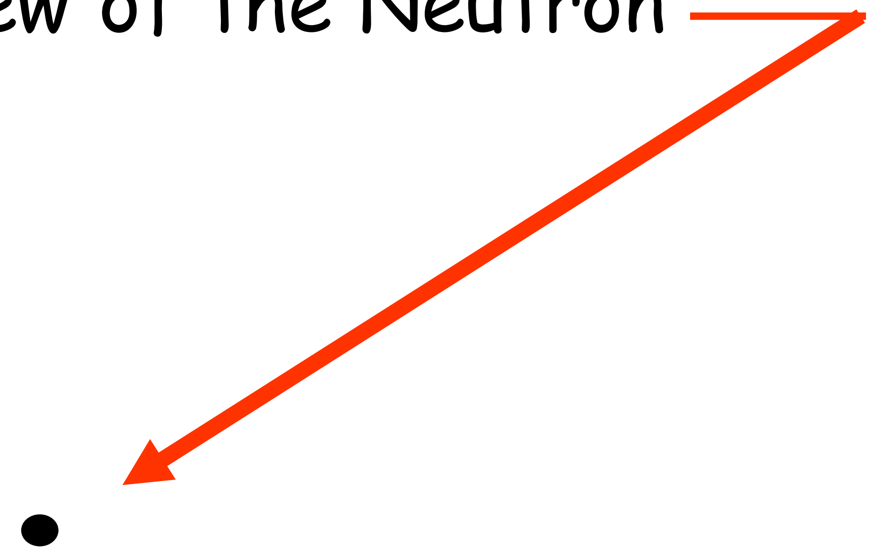
The neutron as a tool for scattering

Neutrons scatter from a nucleus as though it was a “hard sphere”
With a radius that is much smaller than the neutron wavelength.

At low energies, the coherent scattering of a neutron by a nucleus is pure s-wave and can be described by a <u>single number</u>, b_{coh} .

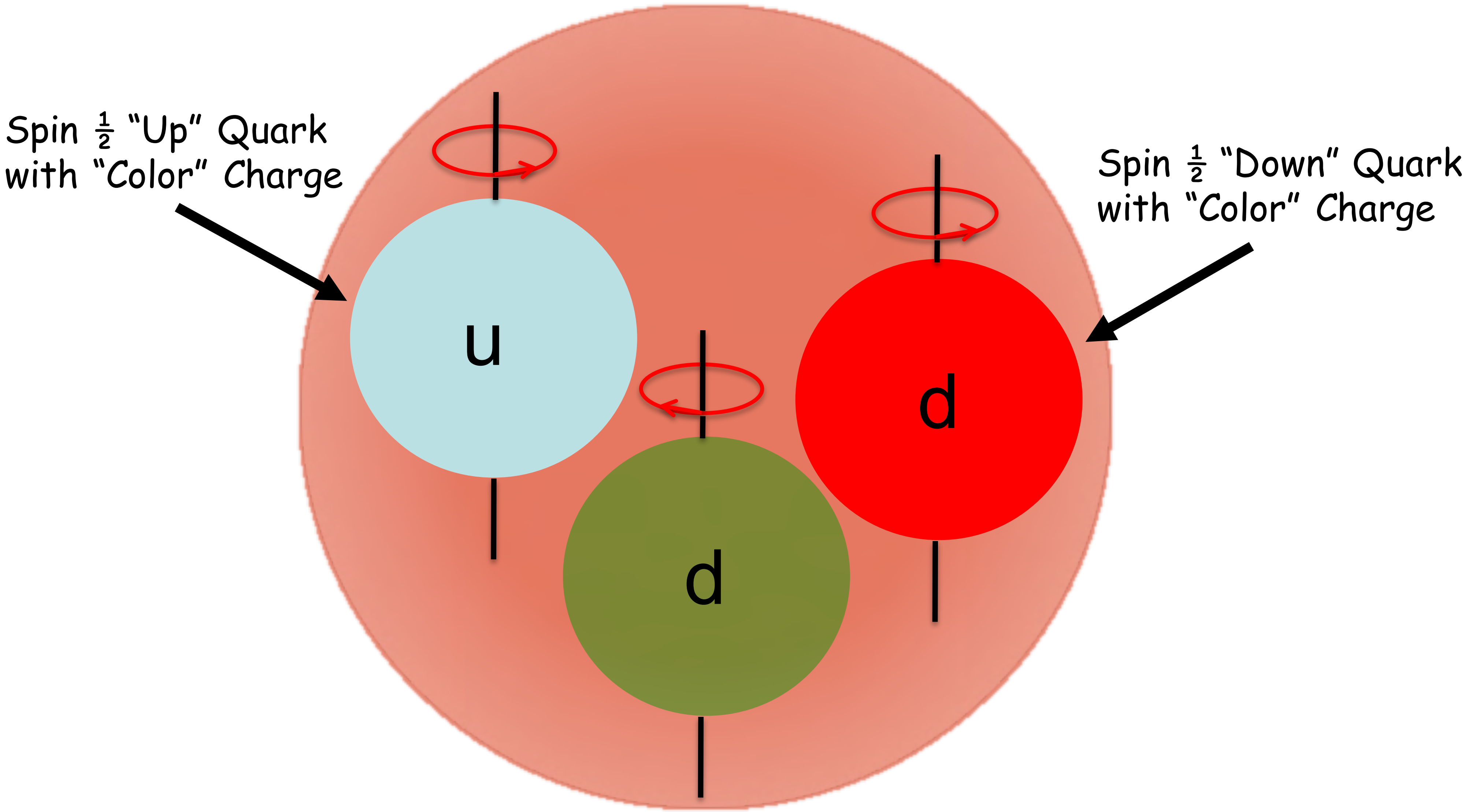
$$r = b_{coh} \ll \lambda_n$$

Dan Neumann's View of the Neutron

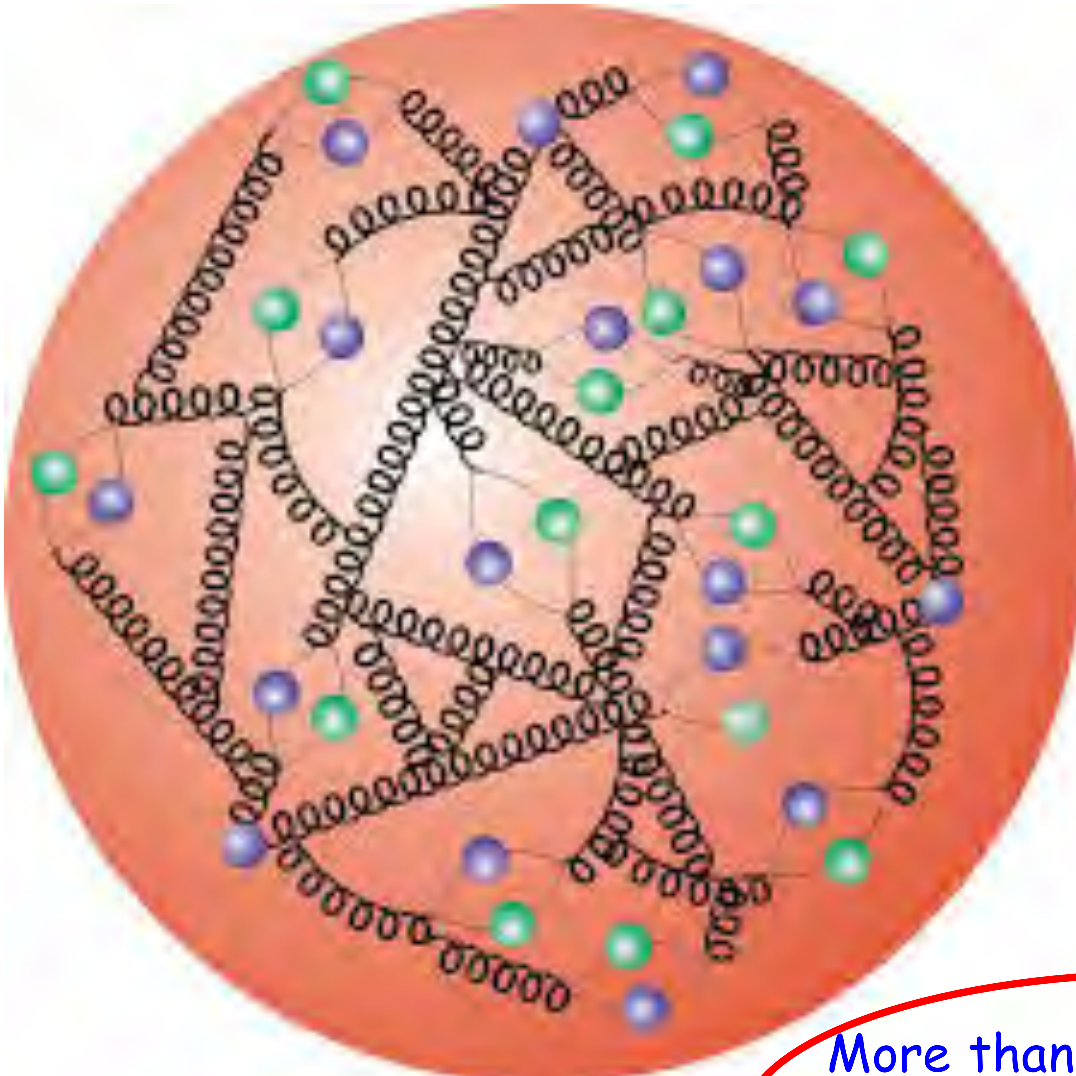


This simplicity makes the neutron
an excellent probe of condensed matter

The "Naive" Quark Model for the Neutron



The "Real" Neutron Structure is Very Complicated



A "Sea" of Gluons, "Strange" Quarks, Anti-Quarks,….

Image: DESY

More than 99% of the neutron mass comes from the self-energy of the gluon field

When examined closely, the neutron is a complicated object. It exhibits much of the complexity and phenomenological richness of nuclear and particle physics.

However, it is *MUCH SIMPLER* than an atomic nucleus.

For a particle physicist:

The neutron is complicated enough to be "interesting,"

but simple enough to be understandable.

Fundamental Neutron Physics Addresses "Big" Questions

Why does the universe contain only matter and no anti-matter?

Cosmic Matter-Antimatter Asymmetry

How were the chemical elements made during the first few minutes of the Big Bang?

Big Bang Nucleosynthesis

Why does the universe show a "preference" between left- and right-handedness?

Parity Violation

Can we observe phenomena that cannot be explained by the Standard Model of Particle Physics?

Dark Matter, New Interactions,…

A non-comprehensive "pot pouri" of Fundamental Neutron Physics investigation

- *Neutron interaction with the Earth's gravitational field*
- *Neutron's Weak coupling with nucleons*
- *Correlations in neutron decay*
- *Limits on neutron charge*
- *Determination of neutron magnetic moment*
- *Determination of neutron scattering lengths*
- *Limits on possible new short range interactions*
- *Search for neutron-anti neutron oscillations*
- *Search for a non-zero neutron electric dipole moment*
- *Determination of the free neutron lifetime*

A non-comprehensive “pot pouri” of Fundamental Neutron Physics investigation

- *Neutron interactio* **GRAVITY** *arth’s gravitational field*
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A non-comprehensive "pot pouri" of Fundamental Neutron Physics investigation

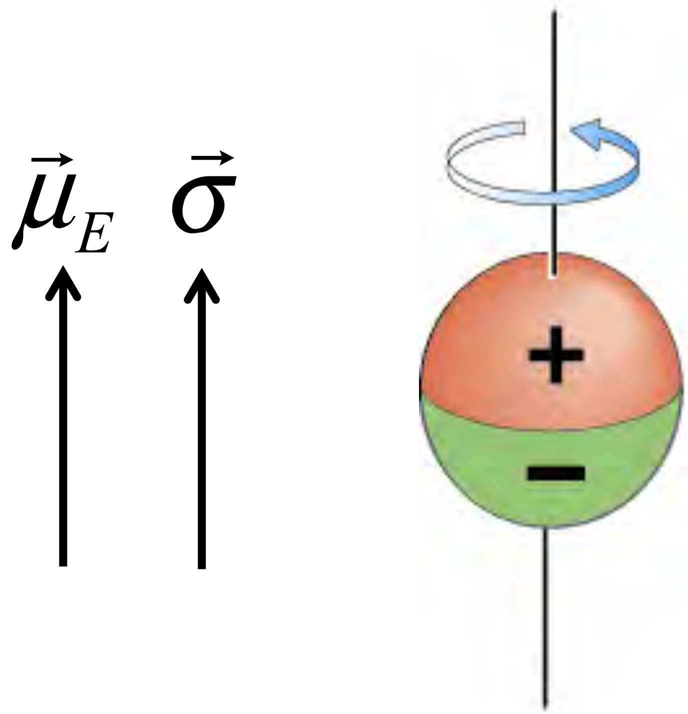
- *Neutron interaction with the Earth's gravitational field*

There are two experiments that have been among the highest priority in all of low energy particle physics for the last 40+ years. They continue to be the highest profile experiments in fundamental neutron physics and are likely to remain so for the foreseeable future.

- *Limits on possible new short range interactions*
- *Search for neutron-anti neutron oscillations*
- *Search for a non-zero neutron electric dipole moment*
- *Determination of the free neutron lifetime*

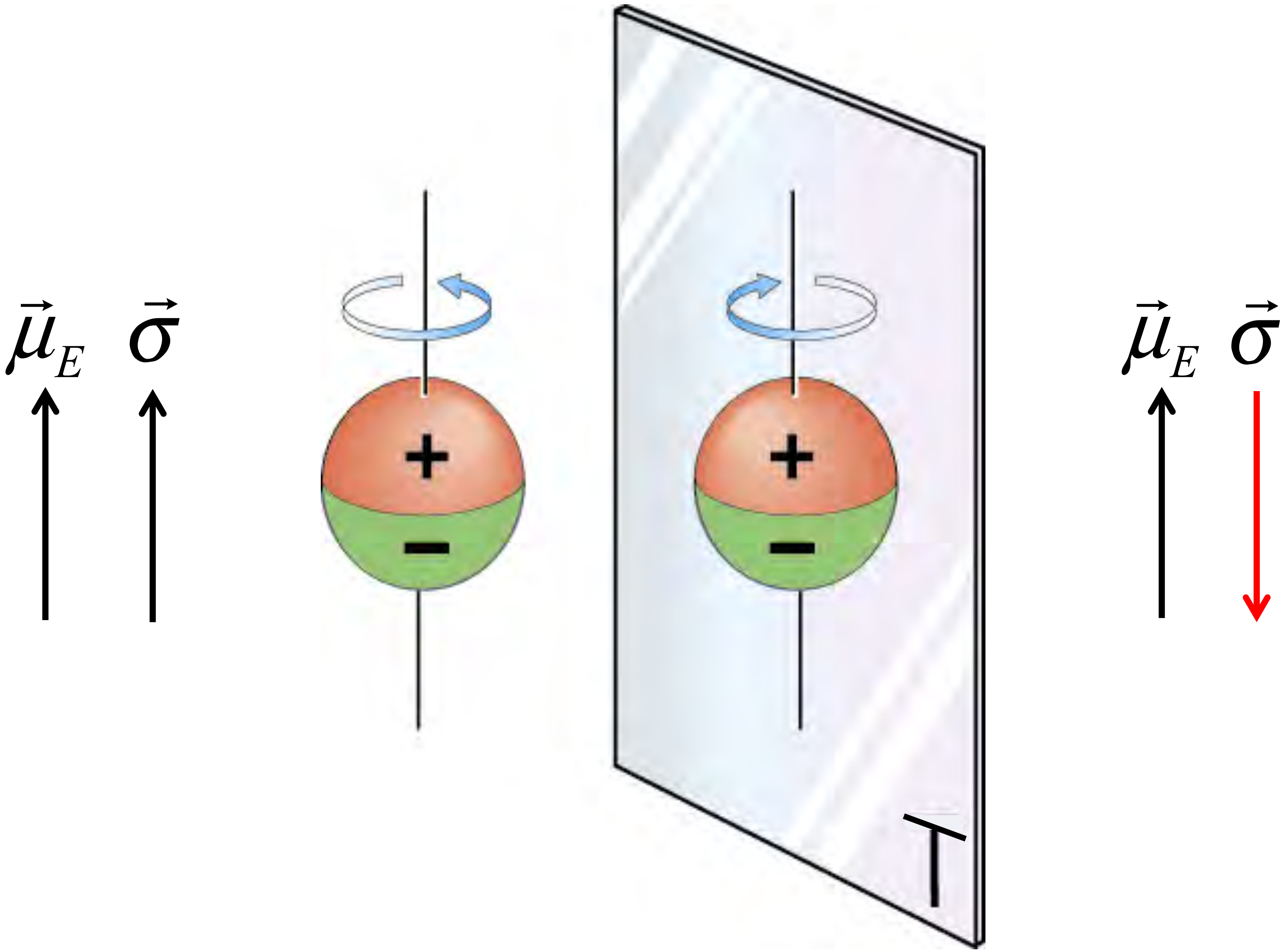
The Neutron Electric Dipole Moment

An Electric Dipole Moment for a Spin ½ Particle



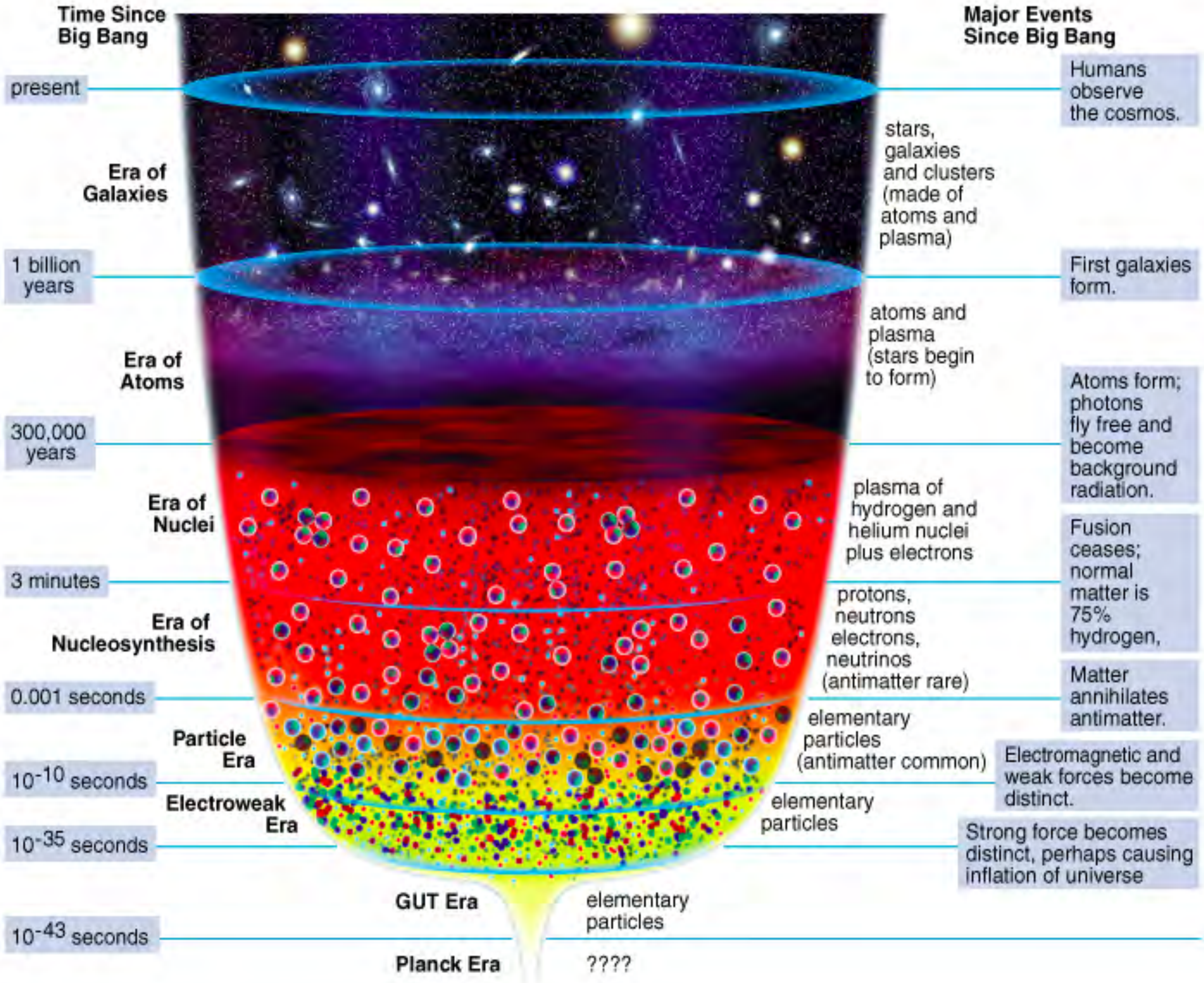
Quantum Mechanics requires that any dipole moment (electric or magnetic) be exactly parallel (or anti-parallel) with the spin of the particle

A Non-Zero Electric Dipole Moment Violates Time Reversal Non-Invariance



Disclaimer: This classical argument differs from the formal QM argument but yields the same result

Why is there MATTER, instead of NO MATTER?


Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
stars, galaxies and clusters (made of atoms and plasma)
Era of Galaxies
1 billion years
First galaxies form.
atoms and plasma (stars begin to form)
Era of Atoms
Atoms form; photons fly free and become background radiation.
300,000 years
plasma of hydrogen and helium nuclei plus electrons
Era of Nuclei
Fusion ceases; normal matter is 75% hydrogen,
3 minutes
protons, neutrons electrons, neutrinos (antimatter rare)
Era of Nucleosynthesis
0.001 seconds
Matter annihilates antimatter.
elementary particles (antimatter common)
Particle Era
10^{-10} seconds
Electromagnetic and weak forces become distinct.
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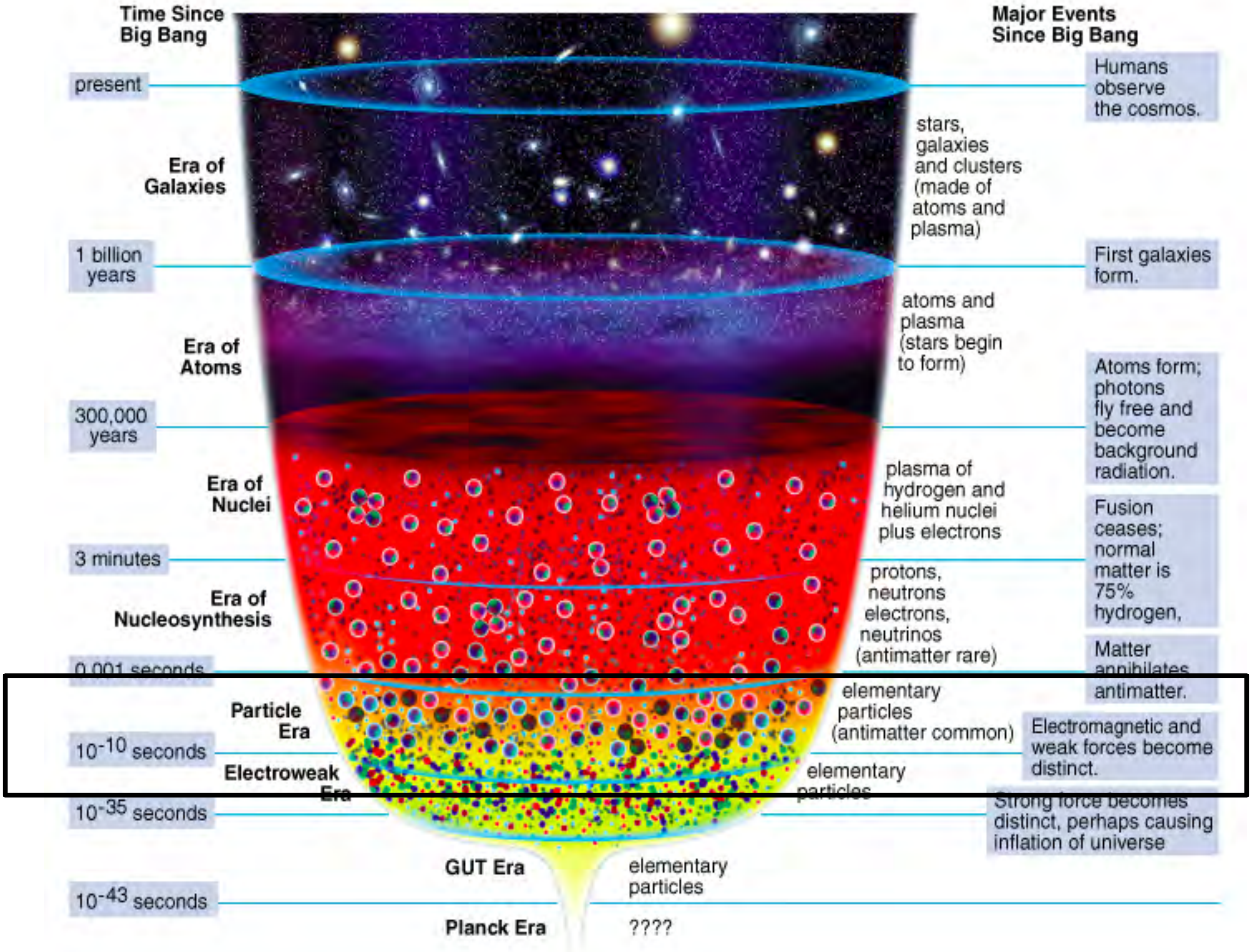
Strong force becomes distinct, perhaps causing inflation of universe
GUT Era
elementary particles
10^{-43} seconds
Planck Era
????



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Very early in the Big Bang there was no asymmetry

Just after Inflation, there were equal amounts of Matter and Antimatter.

If nothing else happened, all matter and antimatter would eventually annihilate leaving…

NOTHING!

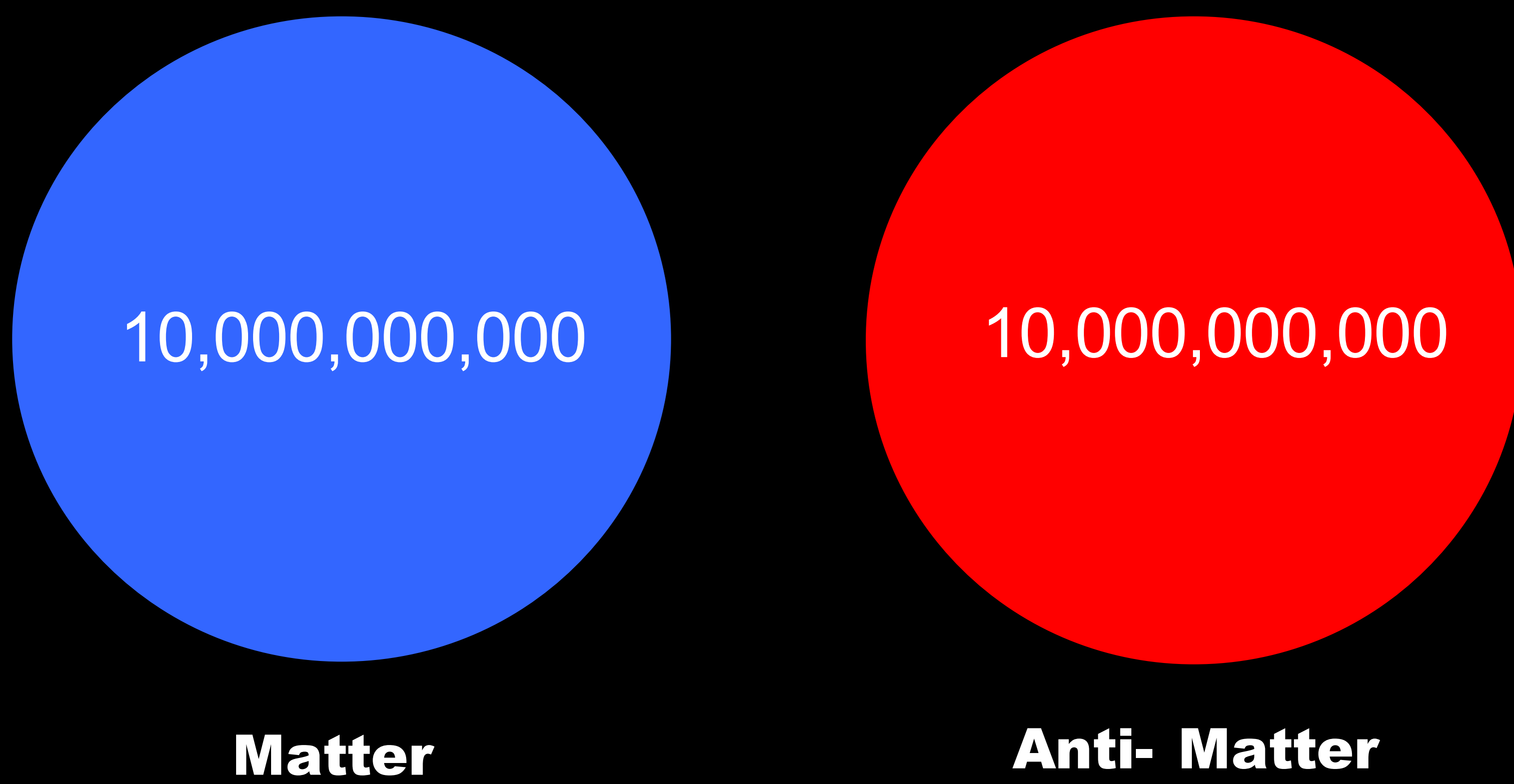
Now….there is complete asymmetry

Today, the Universe consists of matter and there is essentially NO anti-matter

This is the

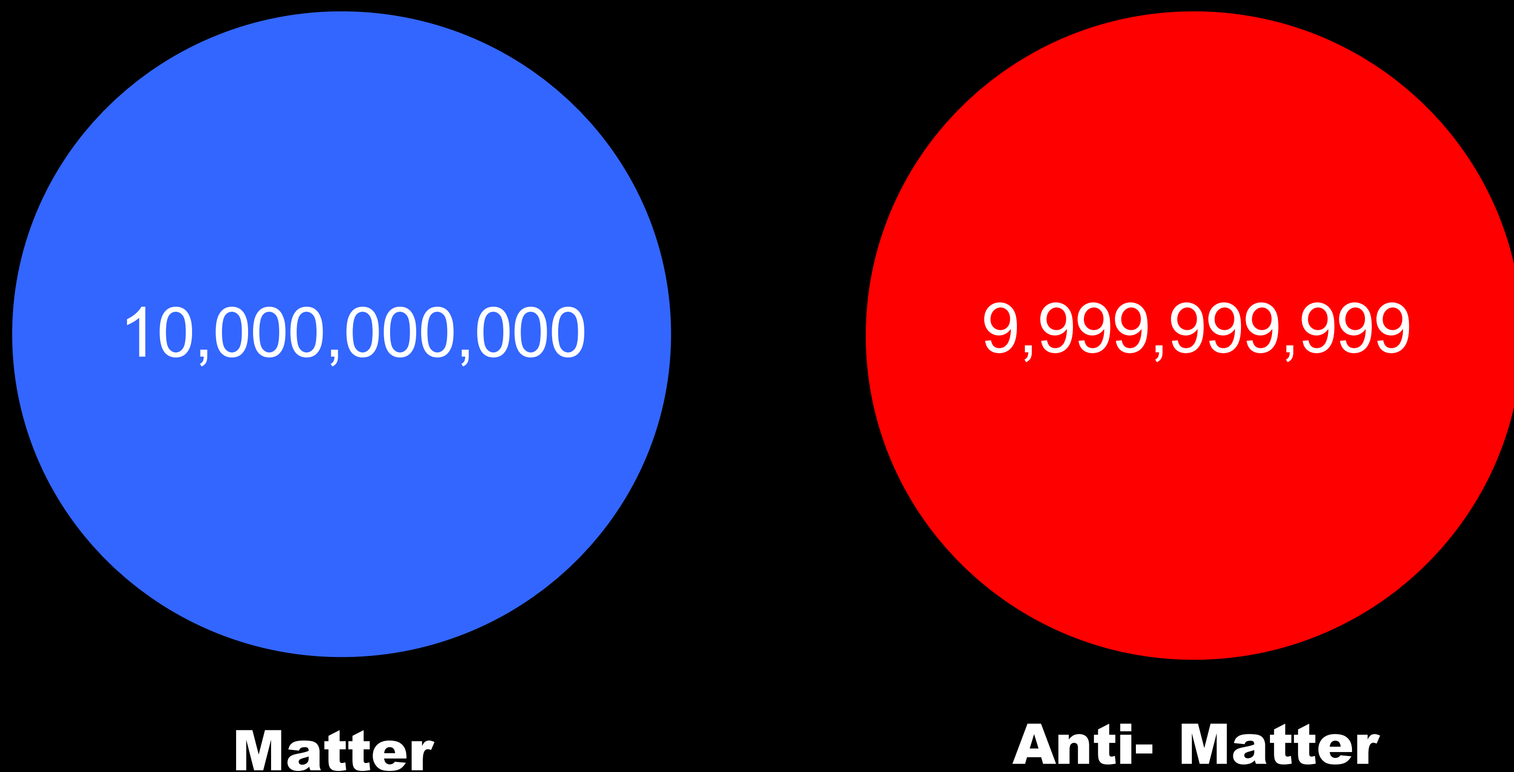
"Baryon Asymmetry Problem"

Matter and Antimatter Just After Inflation



after Hitoshi Murayama

Matter and Antimatter ~10^{-6} s later



after Hitoshi Murayama

Matter and Antimatter Now

1

Matter

Anti- Matter

after Hitoshi Murayama

Matter and Antimatter Now

That's us…and everything we can see

1

Matter

Anti- Matter

after Hitoshi Murayama

Generating a Matter-Antimatter Asymmetry

A. D. Sakharov, JETP Lett. 5, 24 (1967)

1. Very early in the Big Bang ($t<10^{-6}$ s), matter and antimatter (i.e. p & $\overline{p}$) were in thermal equilibrium ($T>>1$ GeV). There was exact balance between matter and antimatter.

2. At some point, there was a symmetry breaking process that led to a small imbalance between the number of Baryons and Anti-Baryons…i.e. a few more Baryons.

3. When the Universe cooled to below T~1GeV, All the anti-baryons annihilated leaving a few baryons and lots of high-energy annihilation photons.

4. The photons are still around! They have been highly red shifted by subsequent expansion and are now microwaves as the Cosmic Microwave Background (CMB).

In this scenario, the total "apparent" matter-antimatter asymmetry is really very tiny… given by ratio of Baryons to CMB photons:

$$\frac{n_{Baryon}}{n_{\gamma}} \approx 10^{-10}$$

Sakharov Process Requires Three Things

1. The process must violate Baryon Number Conservation
2. There must be a period of Non-Thermal Equilibrium
3. The process must violate Time Reversal Non-Invariance

A. Sakharov

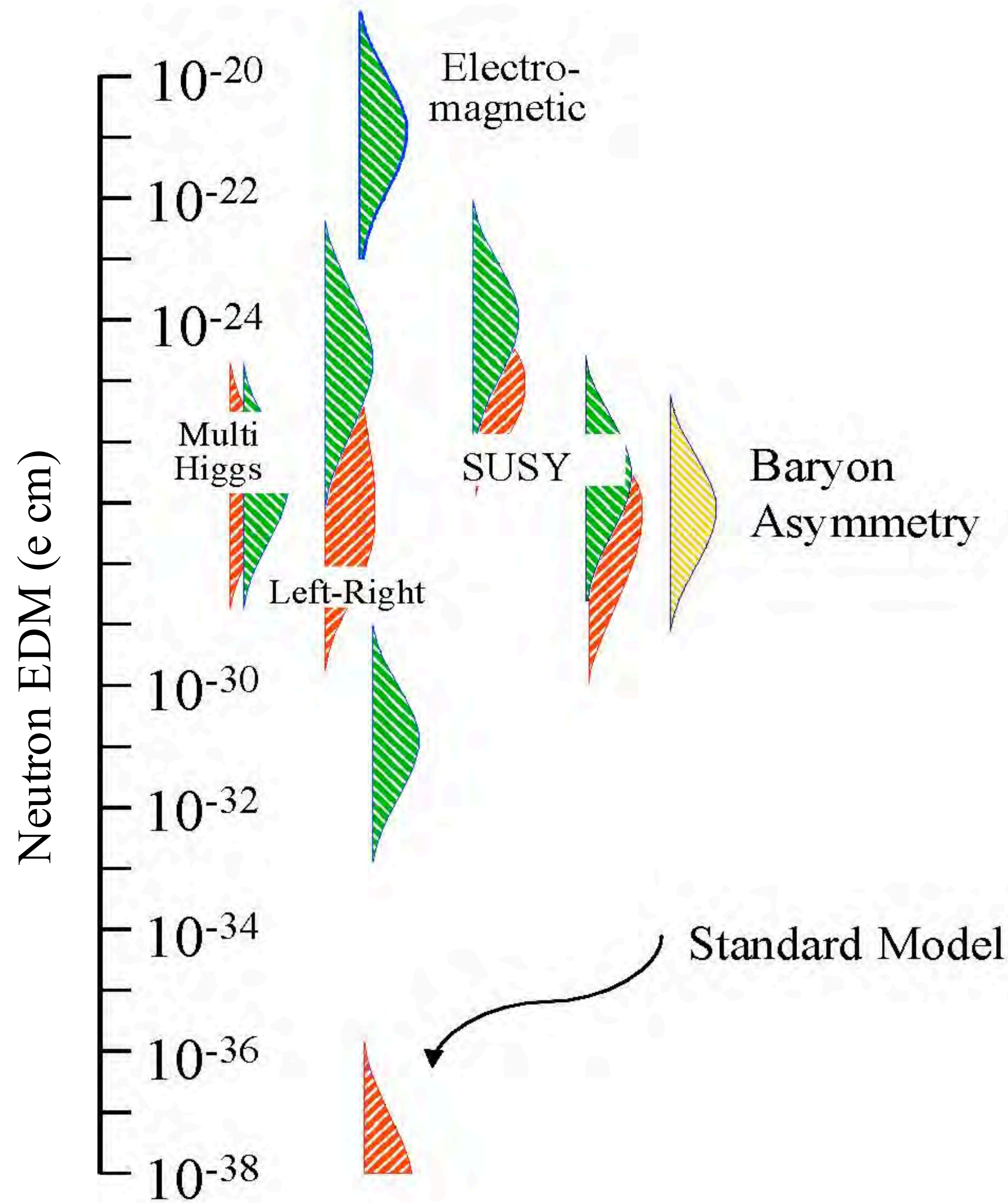
Question:

Can the T violation needed to generate the matter-antimatter asymmetry when the universe was 10^{-6}s old be related to an observable quantity today?

Many theories predict a non-zero neutron EDM

T-violation is allowed in the Standard Model.

However…it is not enough to explain the cosmic baryon asymmetry.



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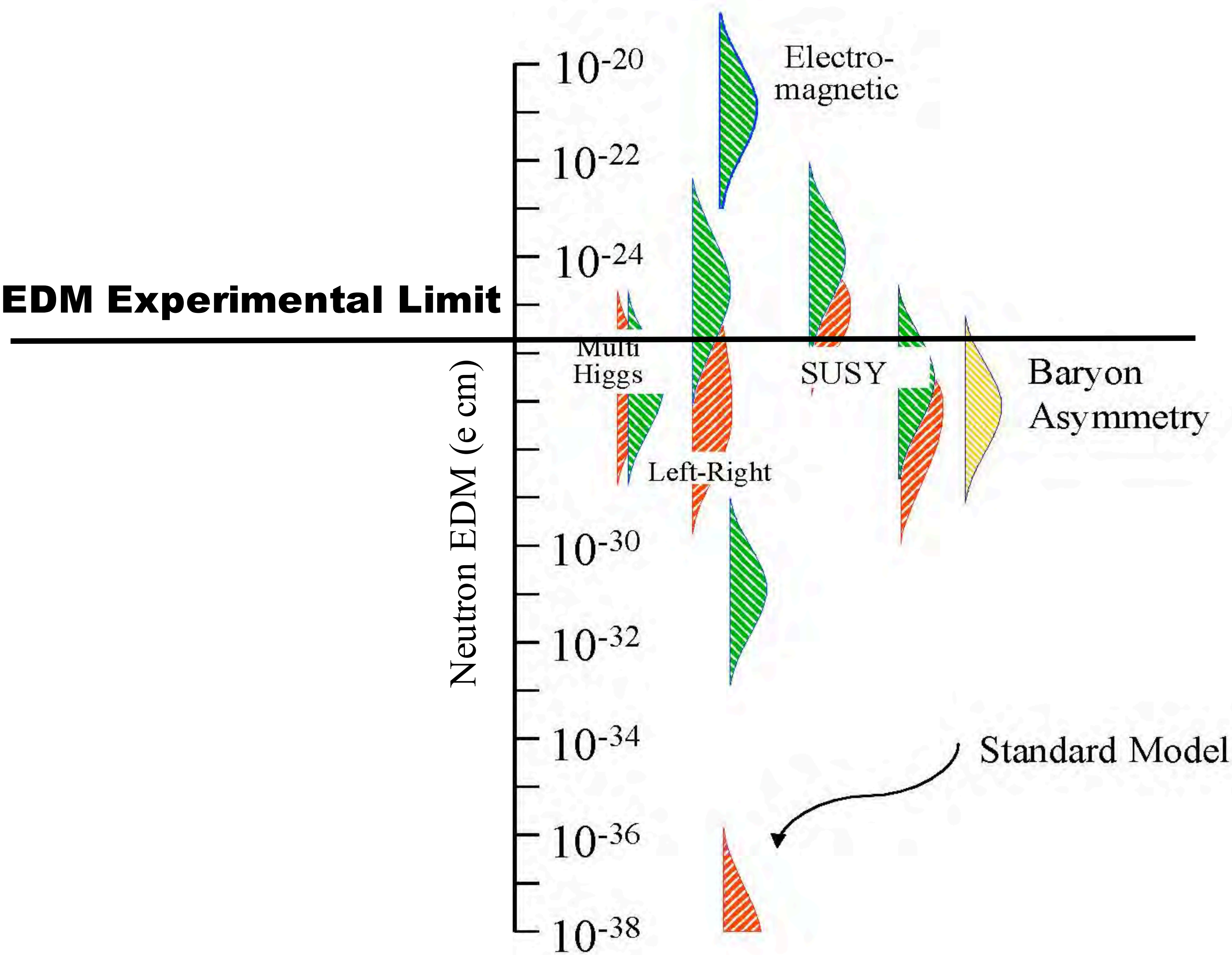
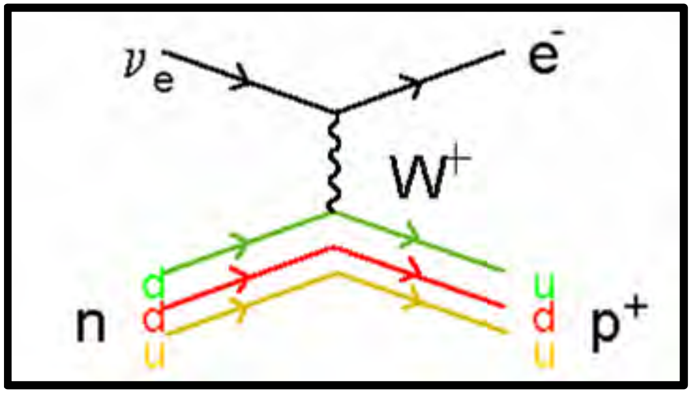
Current nEDM Experimental Limit



The Neutron Lifetime

Neutron decay is relevant to many other process



Primordial element formation $n + e^+ \longleftrightarrow p + \overline{\nu}_e$

$p + e^- \longleftrightarrow n + \nu_e$

$n \longrightarrow p + e^- + \overline{\nu}_e$

Solar cycle $p + p \longrightarrow {}^2H + e^+ + \nu_e$

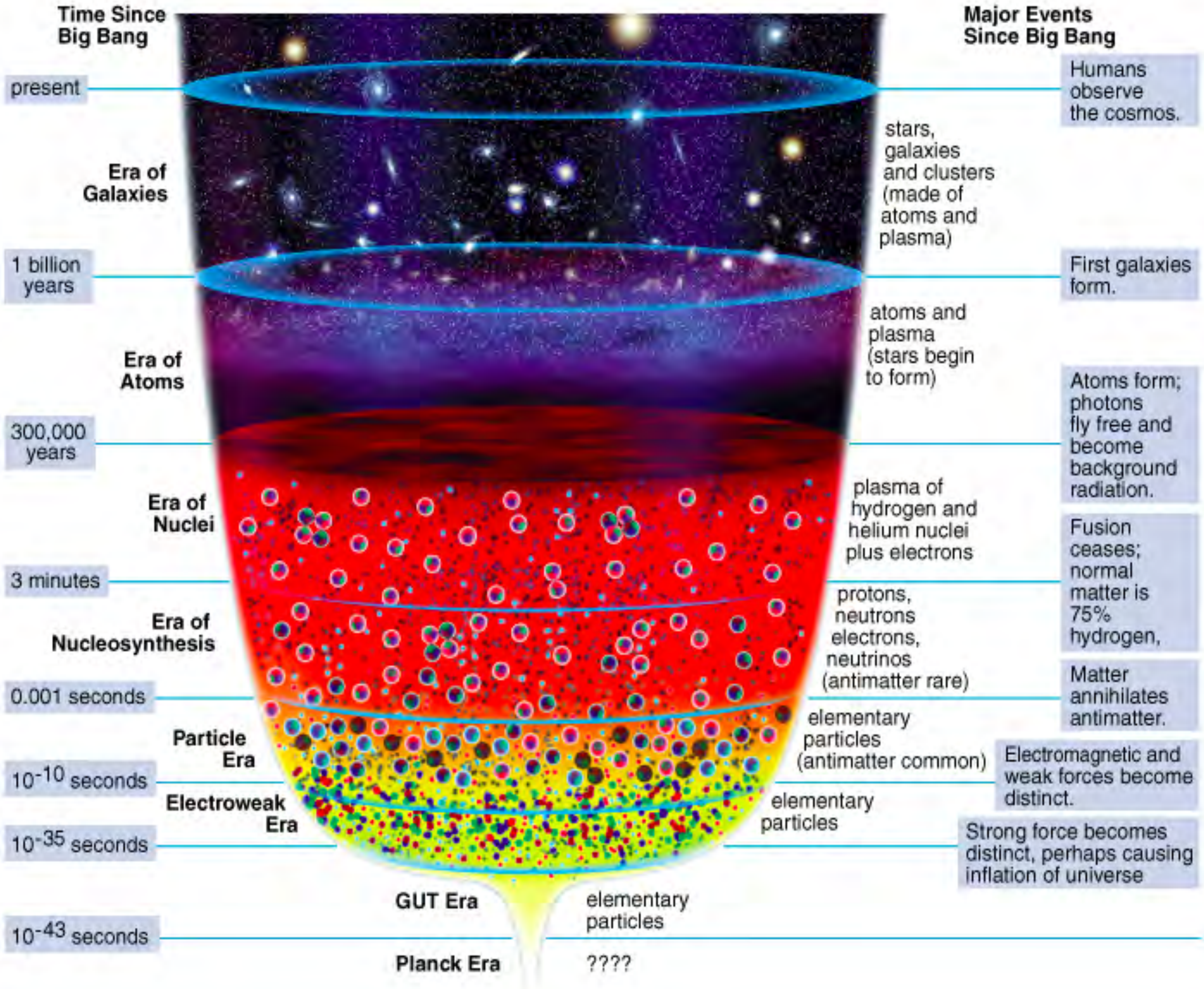
$p + p + e^- \longrightarrow {}^2H + \nu_e$ etc.

Neutron star formation $p + e^- \longrightarrow n + \nu_e$

Pion decay $\pi^- \longrightarrow \pi^0 + e^- + \overline{\nu}_e$

Neutrino detectors $\nu_e + p \longrightarrow e^+ + n$

After D. Dubbers



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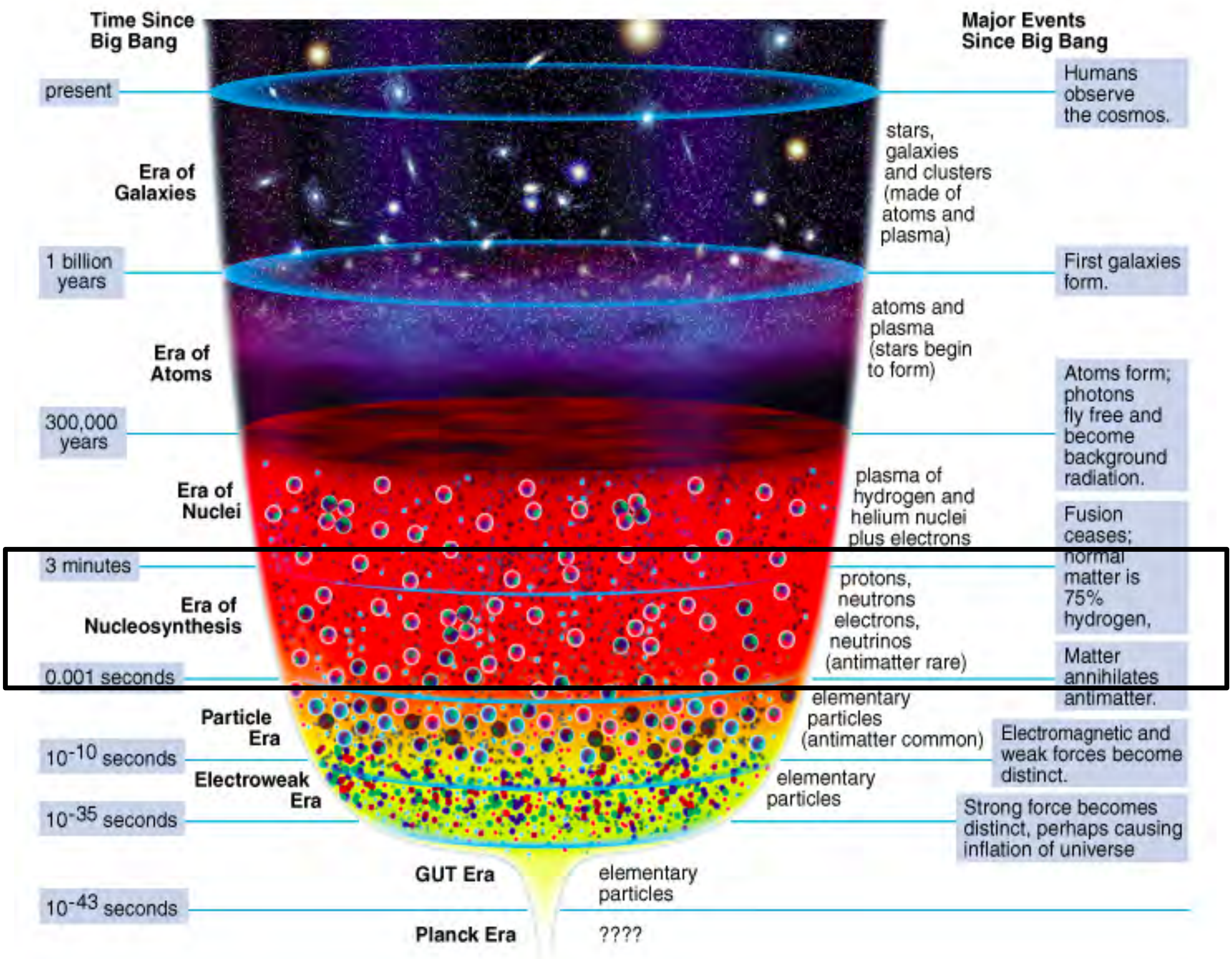

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The "Later" Big Bang

Time Since Big Bang	Temp	
0.01s	10^{11}K	Era of Nuclear Physics

At this temperature, only familiar "nuclear physics" particles are present, the density is well below nuclear densities, and only well understood processes are relevant.

Neutrons and Protons are in thermal equilibrium through the processes:

$$\nu_e + n \rightleftarrows p^+ + e^-$$

$$e^+ + n \rightleftarrows p^+ + \nu_e$$

$$\frac{N_n}{N_p} = e^{-(m_n - m_p)/kT}$$

The "Later" Big Bang

Time Since Big Bang	Temp	
1s	10^{10}K	Neutrino "Freeze Out"

Neutrino cross-sections are highly energy dependent and at this energy they become so small that neutrino scattering is insignificant. Thermal equilibrium between neutron and protons is no longer maintained.

$$\frac{N_n}{N_p} \approx 1/3$$

If nothing else happened ALL the neutrons would decay via

$$n \rightarrow p^+ + e^- + \bar{\nu}$$

and the universe would be end up with only protons (Hydrogen)

Big Bang Nucleosynthesis

Time Since Big Bang	Temp	
3 min	**10^9K**	**Nucleosynthesis Begins**

Nuclei are now stable against photo disassociation e.g.

$$n + p \rightarrow d + \gamma$$

and nuclei are quickly formed. The Universe is now ~87% protons & 13% neutrons

3½ min	**10^8K**	**Nucleosynthesis Ends**

Neutrons are all "used up" making ^{4}He and the Universe is now has ~75% H and ~25% He.

Important Reactions in Big Bang Nucleosynthesis

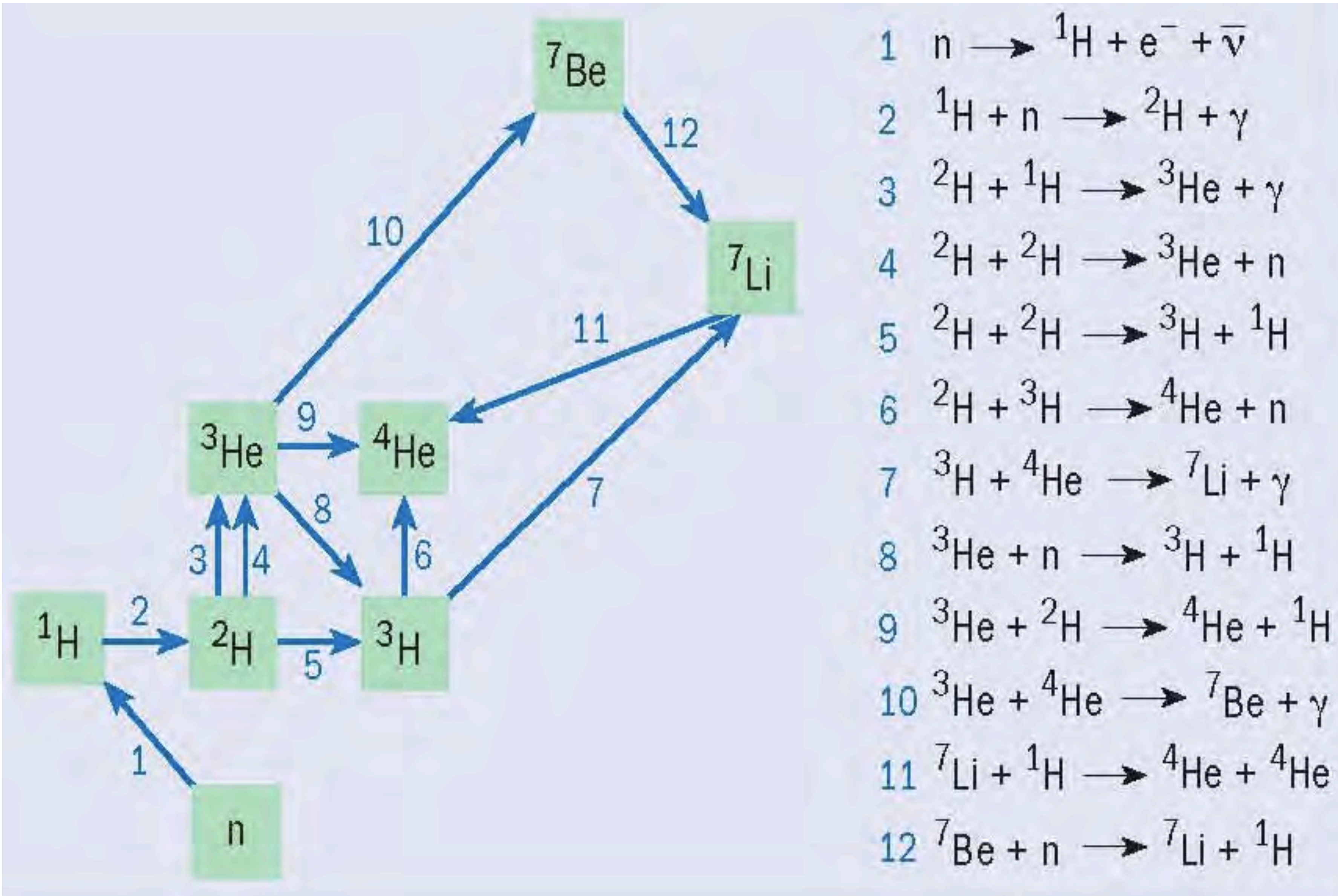
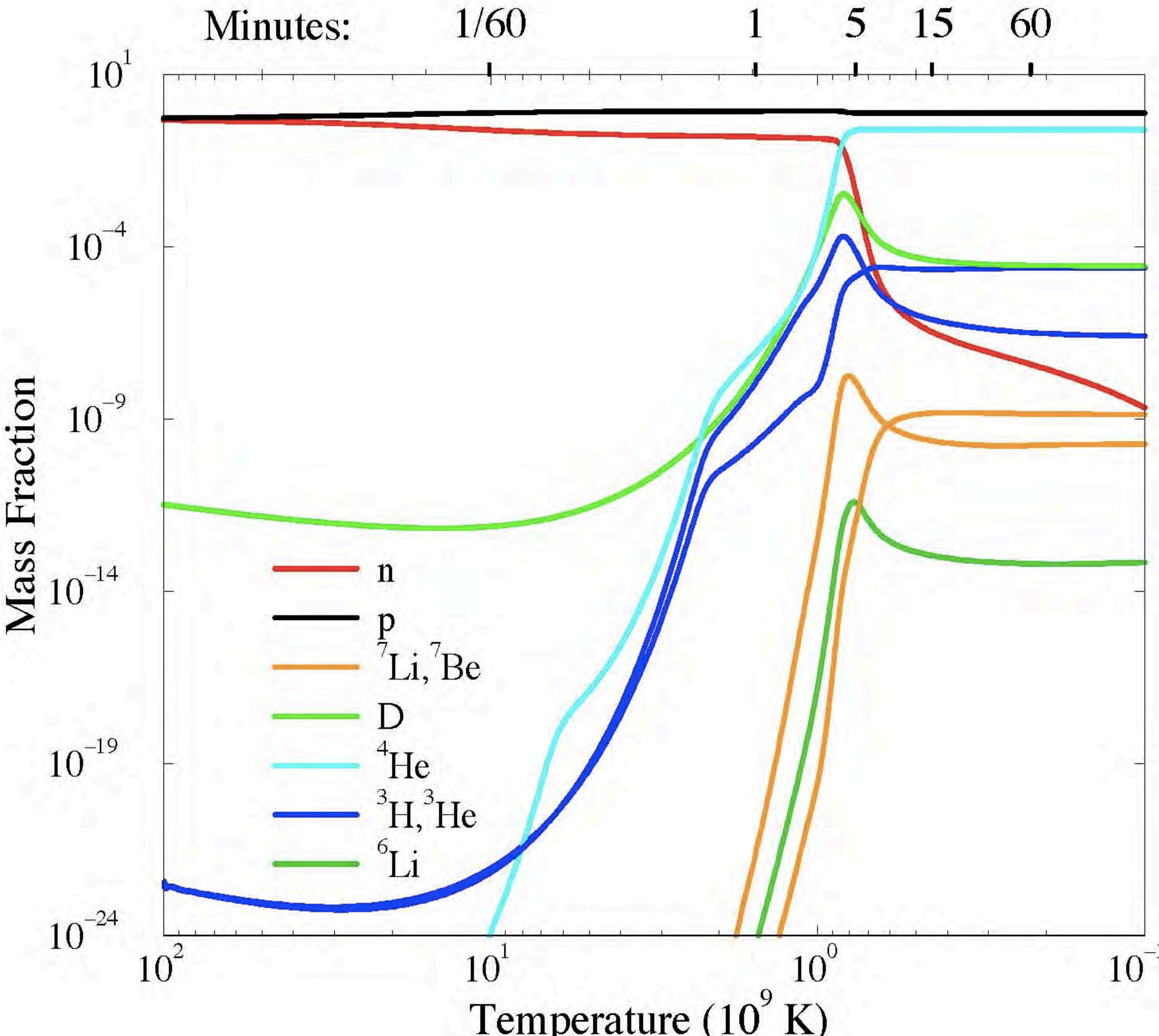


Image courtesy Ken Nollet



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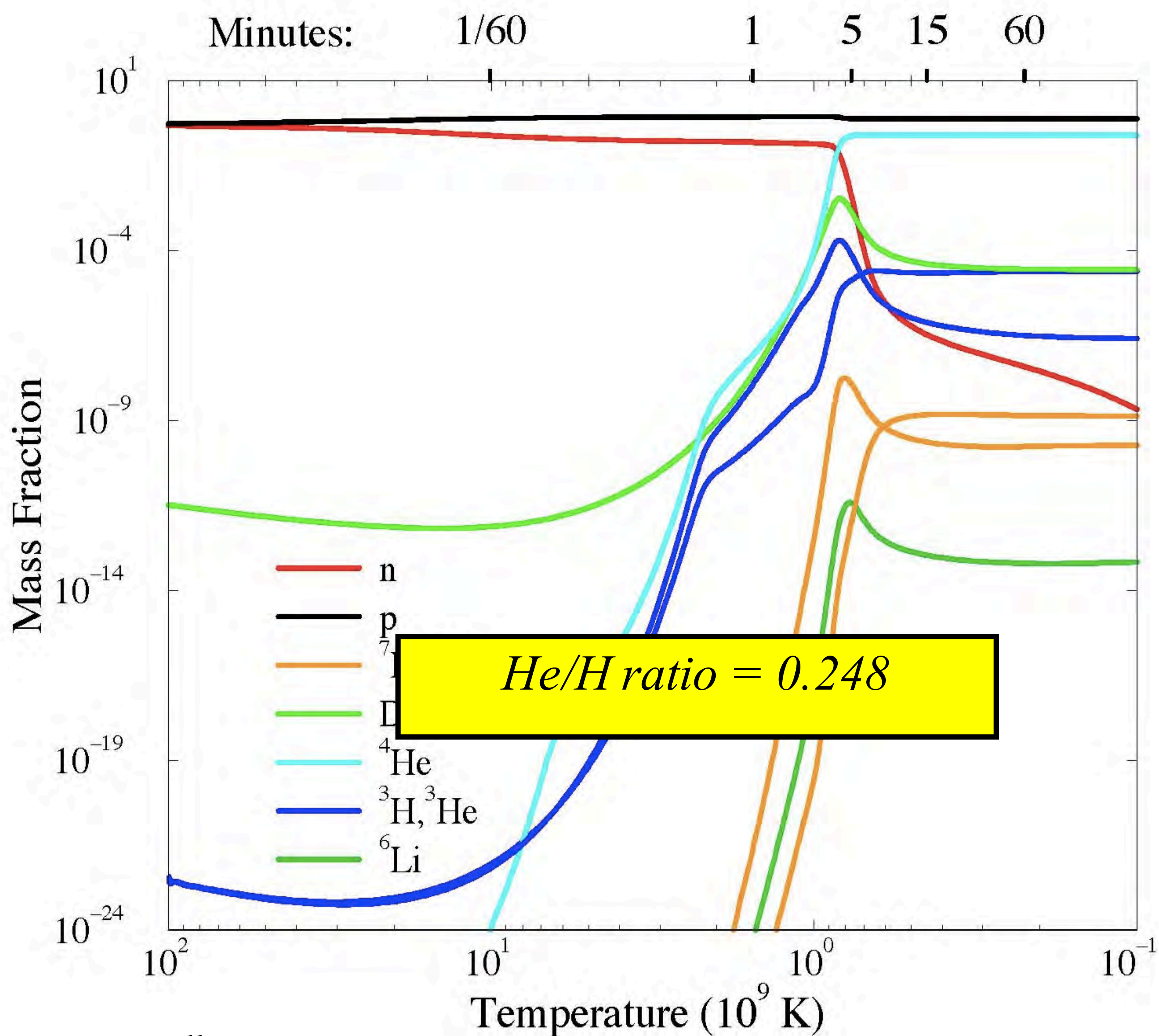

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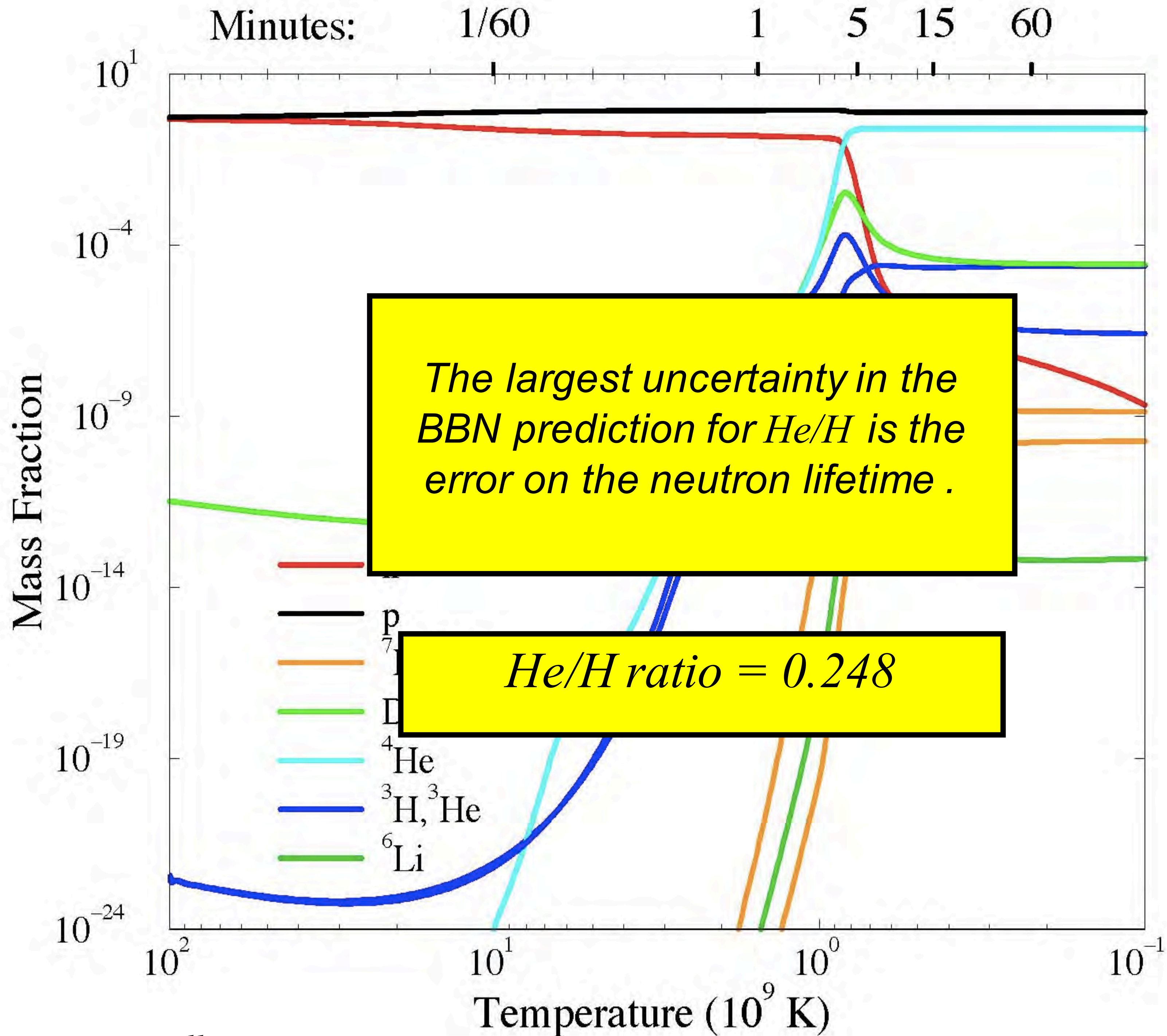


The largest uncertainty in the BBN prediction for He/H is the error on the neutron lifetime .

He/H ratio = 0.248

Image courtesy Ken Nollet

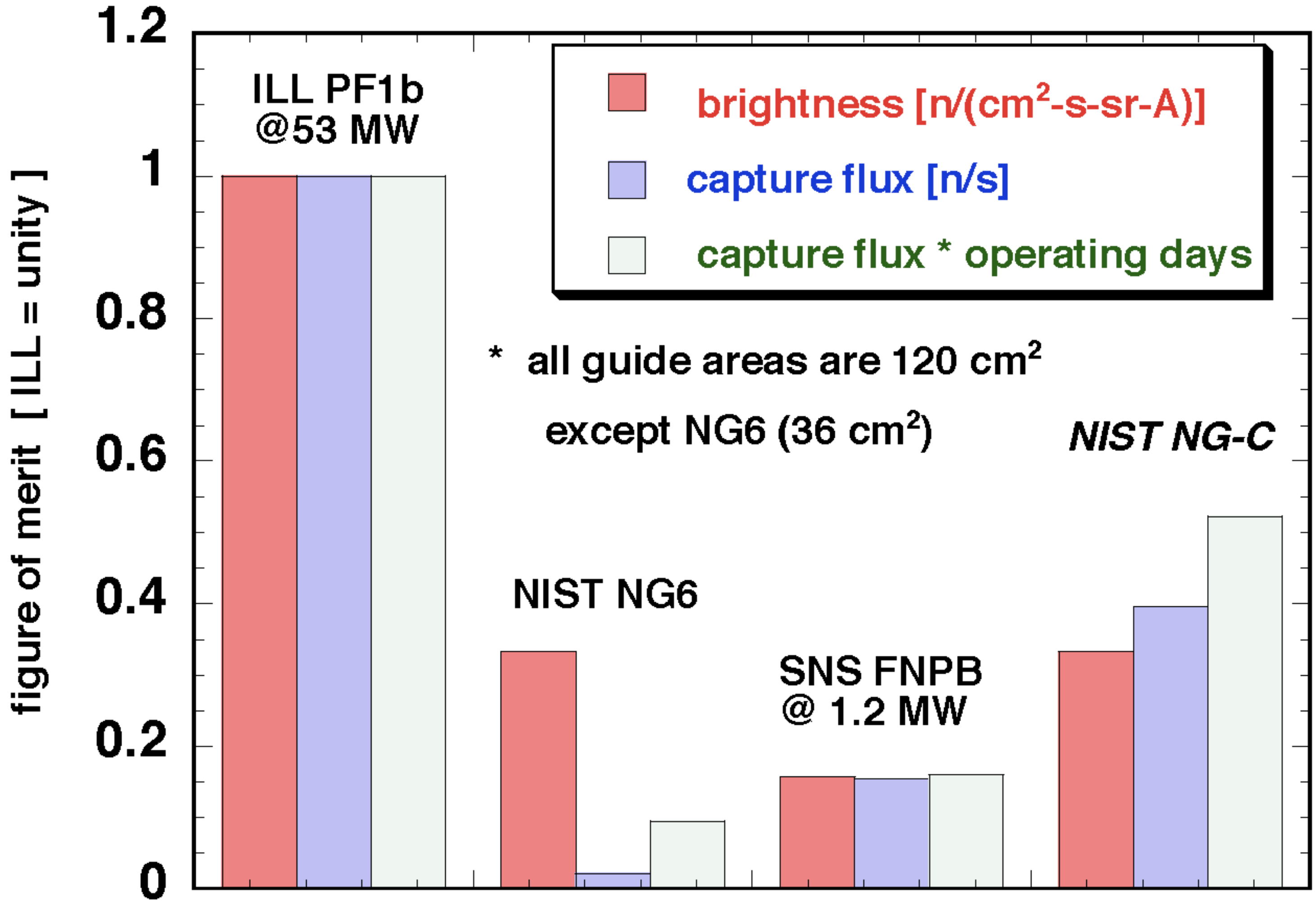
Source Requirements for Fundamental Neutron Physics

- *Most modern experiments are truly count rate limited and require the highest possible total flux (n/s). Brightness (n/cm^2/s) is usually of secondary importance.*

- *A vibrant fundamental neutron physics research effort requires access to BOTH cold and ultracold neutrons*

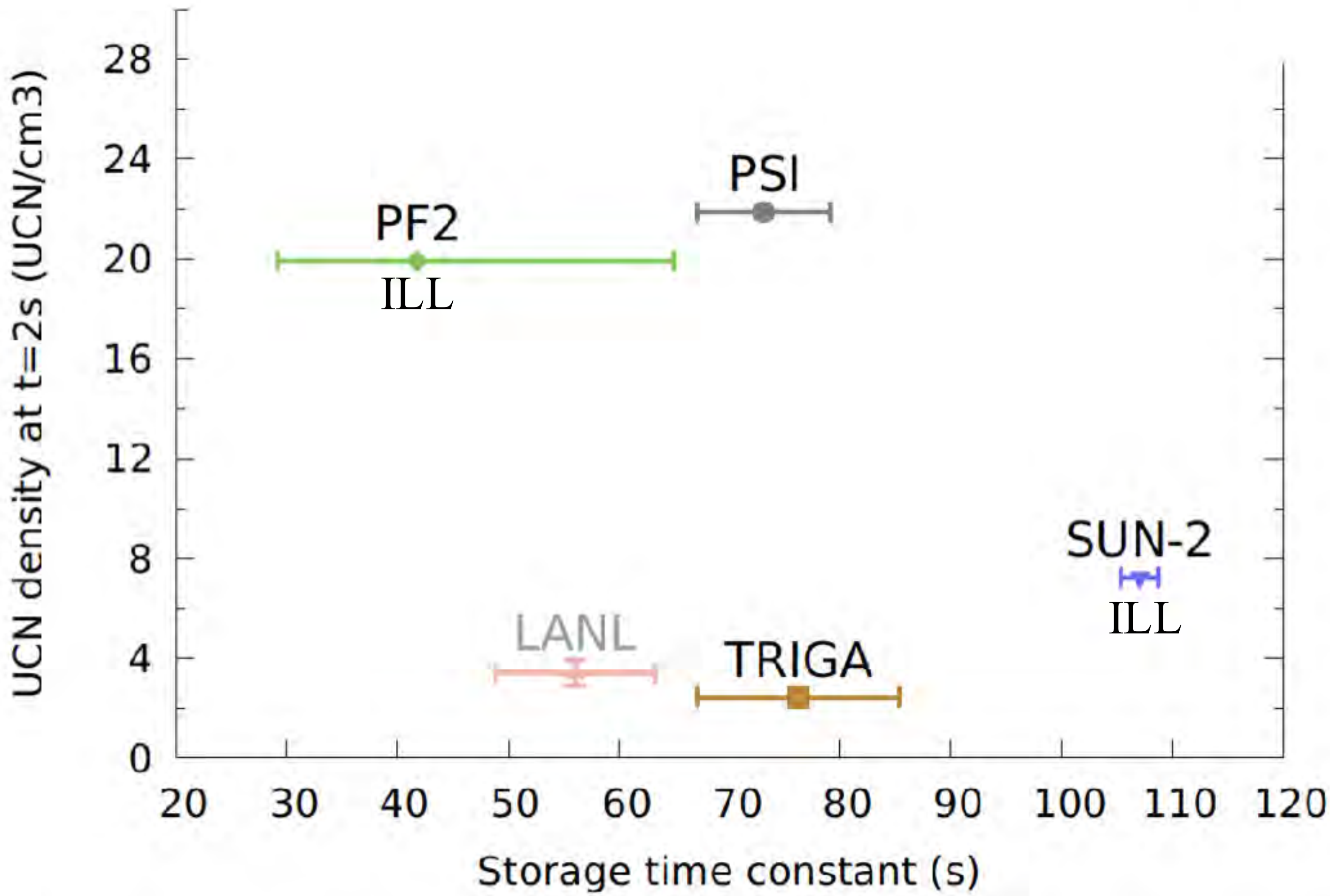
- *Most modern require extended access (months/year) to a neutron source for a single measurement. Each measurement is akin to the development, construction, commissioning, and operation of a totally new neutron scattering spectrometer. Experiments must be done sequentially and the number of beamlines is a serious constraint.*

Comparison of Cold Neutron Beams Available for Fundamental Neutron Physics



Source: T. Gentile, Source brightness & operating day – NSAC Subcommittee on Fundamental Physics with Neutrons report, 8/03, *(http://science.energy.gov/np/nsac/reports)*

Comparison of Spallation and Reactor Ultracold Neutron Production



Source: Comparison of ultra cold neutron sources for fundamental physics measurements, *G. Bison, et.al., submitted to PRC, 26/10/2016*

Some Thoughts on Availability of High Flux Reactors for Fundamental Neutron Physics

- *Fundamental neutron physics is not the primary motivation for the availability of high flux beam reactors, but for the past 40+ years it has been an important component of neutron beam research at such facilities. It is reasonable to assume that this will continue.*

- *A vibrant fundamental neutron physics research effort requires access to BOTH cold and ultracold neutrons*

- *While spallation sources appear poised to eclipse the performance of high flux reactors for the production of ultracold neutrons, reactors are likely to remain unsurpassed for cold neutron experiments.*

Afterthought - Neutrinos

High flux reactors are extremely BRIGHT sources of relatively low energy (10’s of MeV) neutrinos.

From time to time such sources have been used for “short baseline” neutrino oscillation experiments (e.g. PROSPECT now at HFIR).

n.b. Electrical power reactors with GW power’s have MUCH higher total neutrino production rates and have been the sources of choice for most, (longer baseline) neutrino oscillation experiments.