NSAC Meeting
September 12 2024

Neutrinoless double beta decay: communicating the science

Vincenzo Cirigliano

INSTITUTE for NUCLEAR THEORY

U.S. DEPARTMENT OF ENERGY
Office of Science

UNIVERSITY of WASHINGTON

Outline

With invaluable input from:
J. Detwiler, G. Gratta, K. Heeger, D. Hertzog, Y. Kolomensky, K. Kumar, H. Murayama, J. Wilkerson, L. Winslow

- Part 1: Significance of $0\nu\beta\beta$ and discovery potential**

- Part 2: Communicating the science

** From the perspective of a theorist not directly involved in the experiments, but familiar with their development through NSAC service

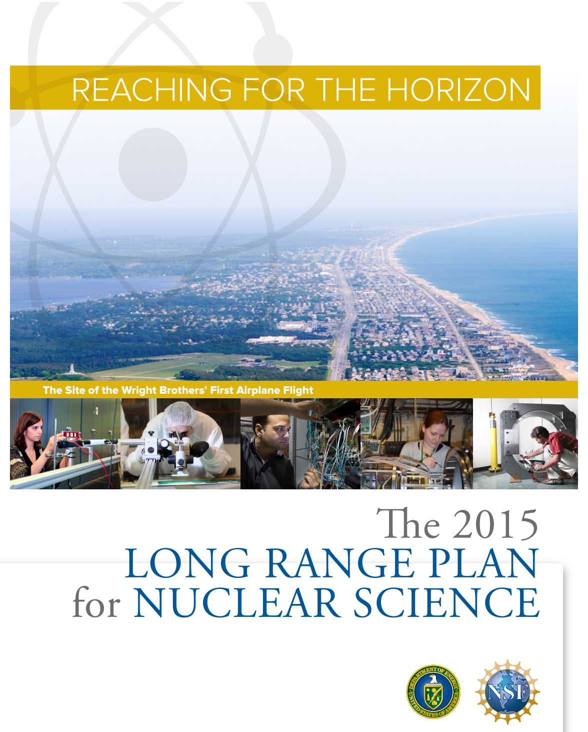
Part 1:
Significance and discovery potential of 0νββ decay

Prologue

- The US Nuclear Physics community has identified ton-scale neutrinoless double beta ($0\nu\beta\beta$) decay experiments as an outstanding scientific opportunity

- Longstanding priority that got stronger with time:
  - 2003 "Facilities for the Future of Science" report
  - High Priority recommendation in the 2004 APS multi-divisional (DNP/DPF/DAP/DPB) study "The Neutrino Matrix"
  - Mentioned in the 2007 LRP and featured as a major recommendation in the 2015 and 2023 NSAC Long Range Plans

2015



RECOMMENDATION II

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

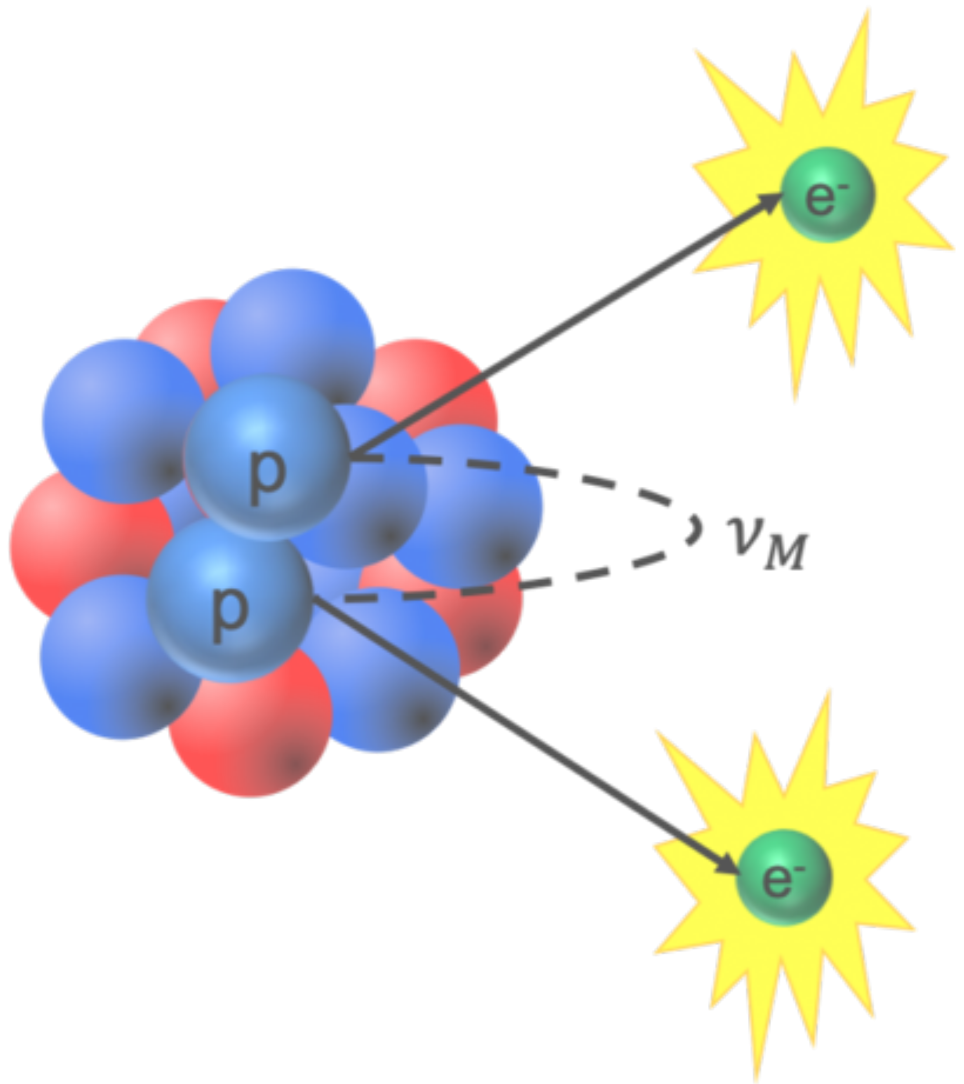
2023

RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

Neutrinoless double beta decay (0νββ)

The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics

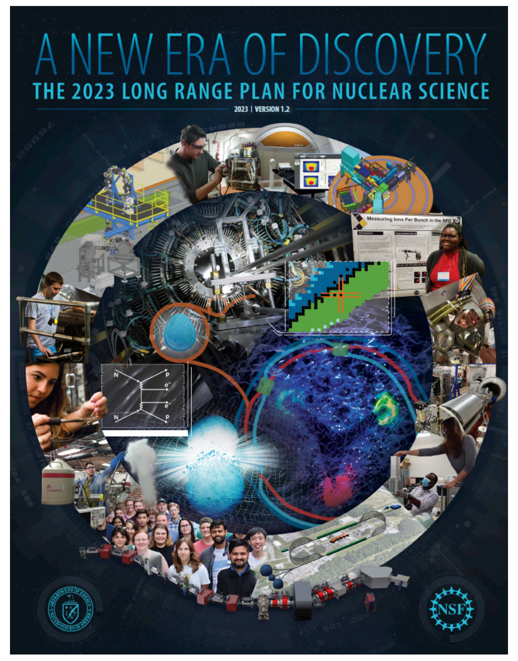


- The observation of 0νββ would reveal the quantum nature of the neutrino and dramatically transform our understanding of physics and the cosmos
  - Demonstrate matter creation (Lepton Number is not conserved)

    Point to an explanation of the matter-antimatter asymmetry in the cosmos
  - Demonstrate that the neutrino is its own anti-particle (Majorana particle)

    Point to a new means for the generation of mass

The highest priority for new experiment construction in Nuclear Science Advisory Committee's 2023 Long Range Plan for Nuclear Science



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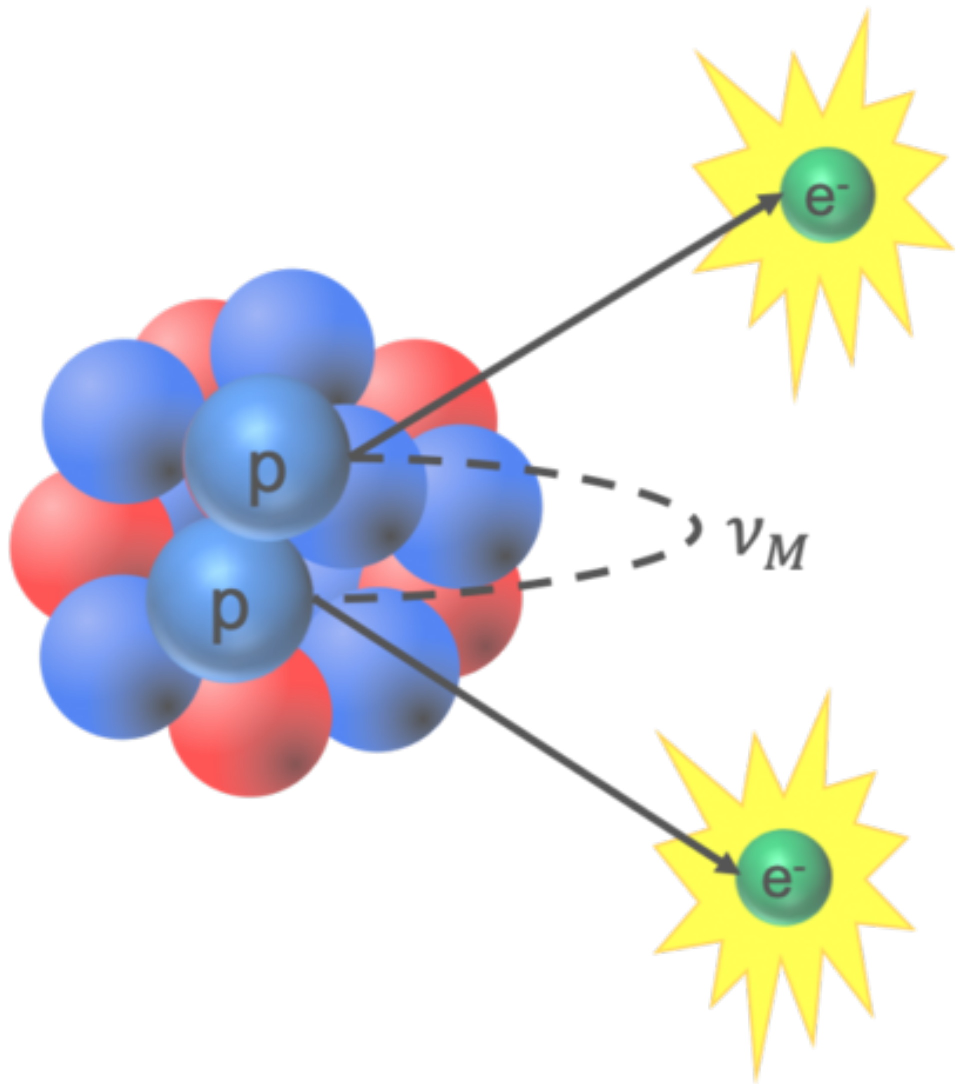

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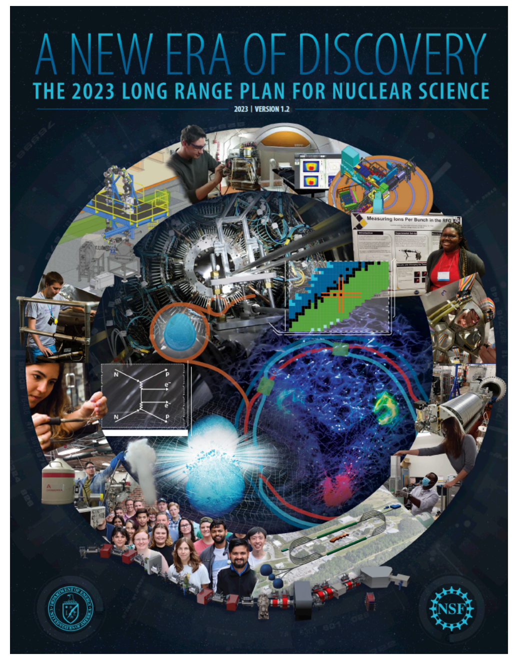

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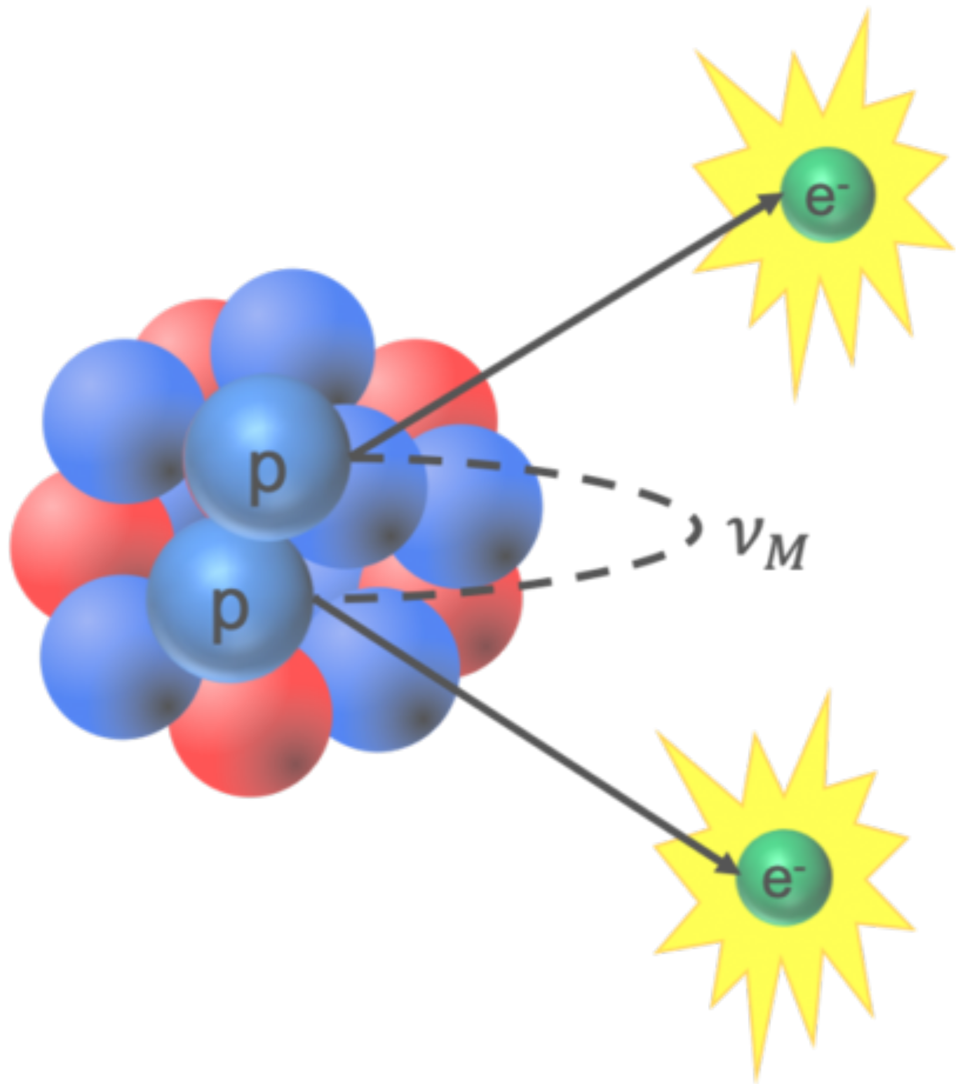

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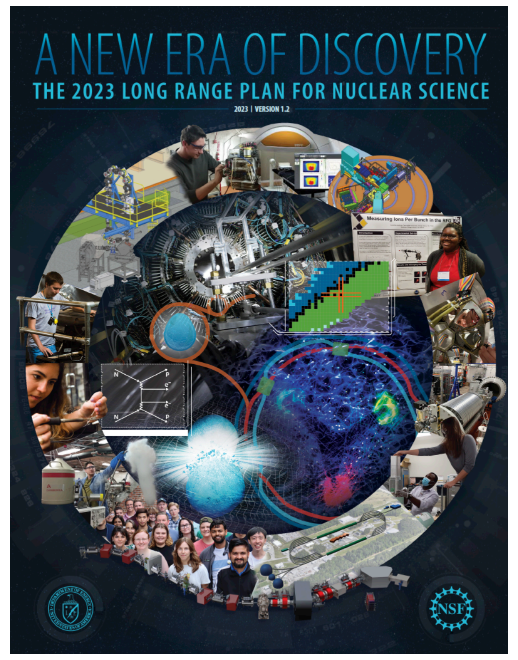
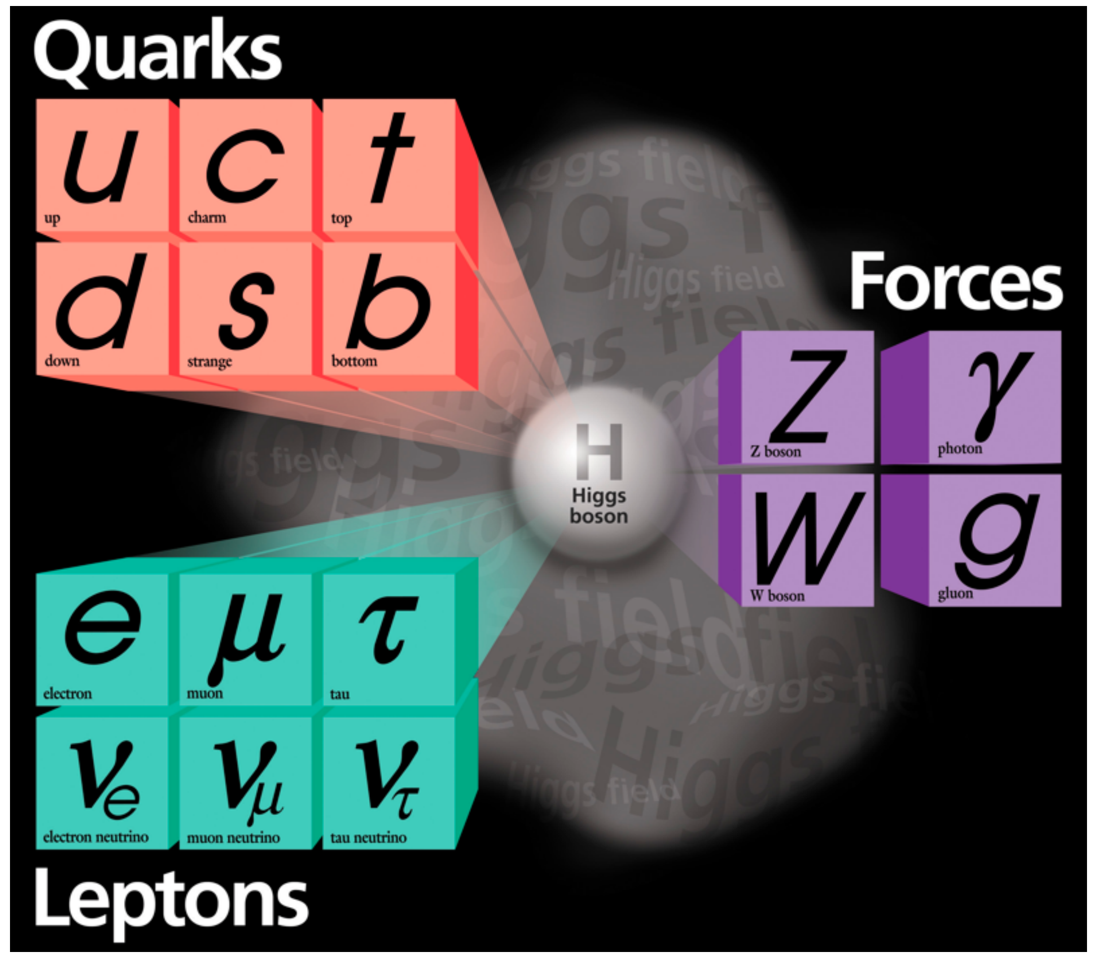
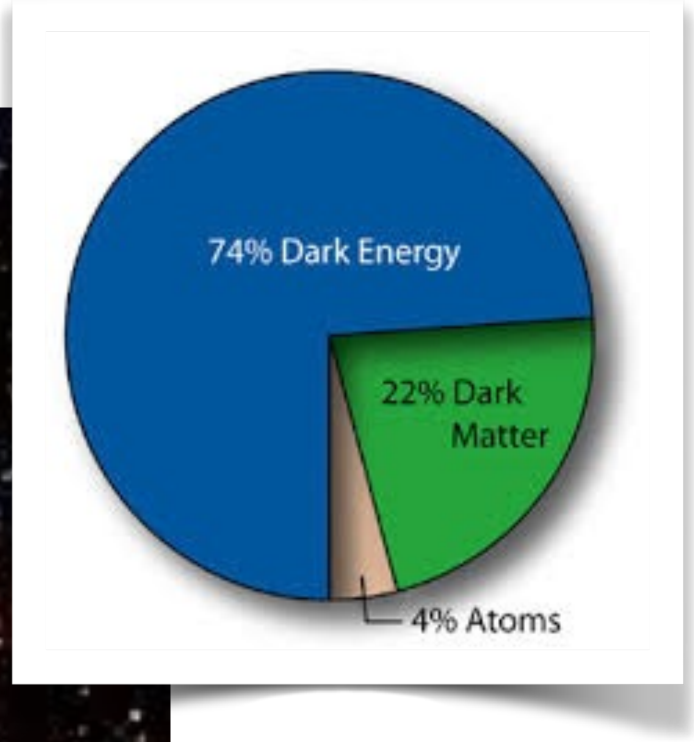


Context: open questions in subatomic physics

- The Standard Model encodes our knowledge of nature’s building blocks and interactions, but it is incomplete!



Credit: Fermilab



Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

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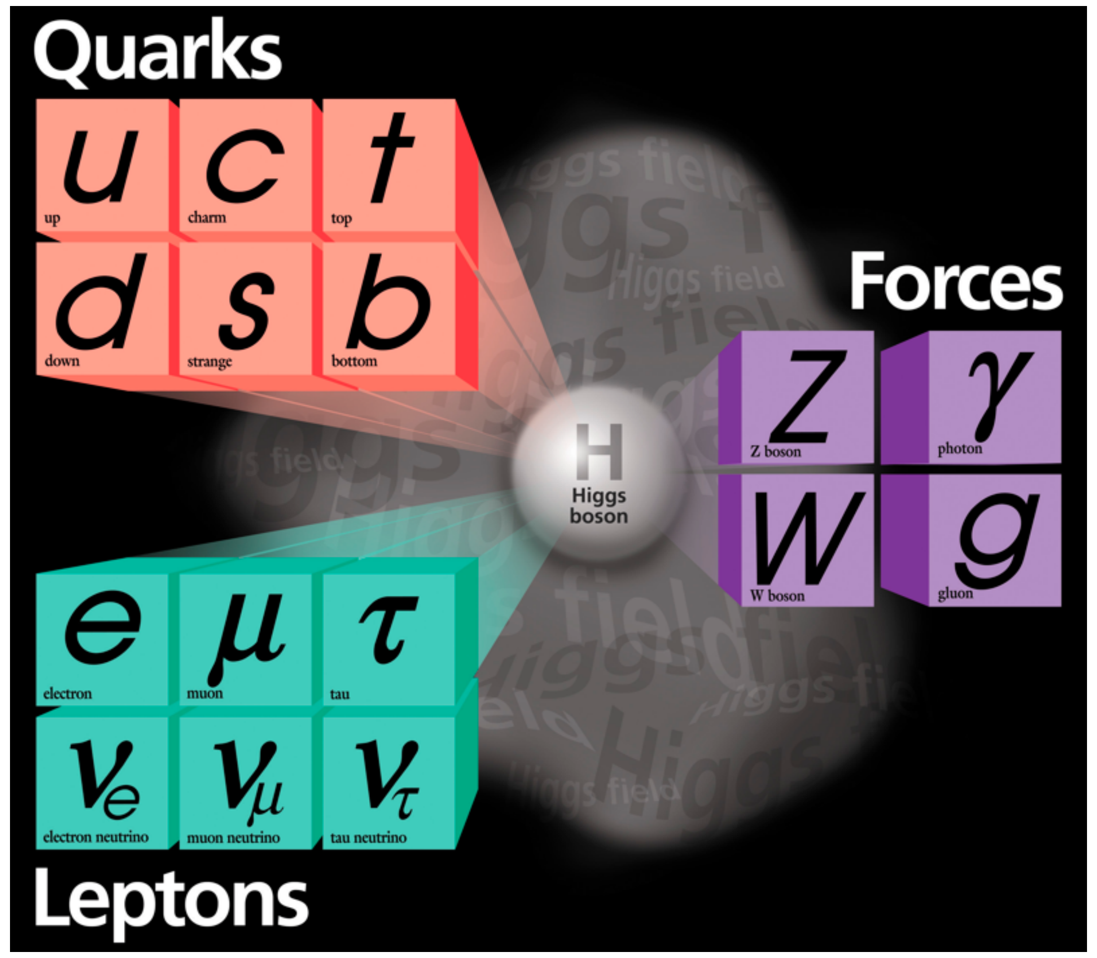

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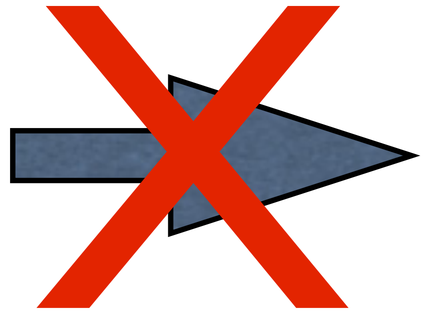

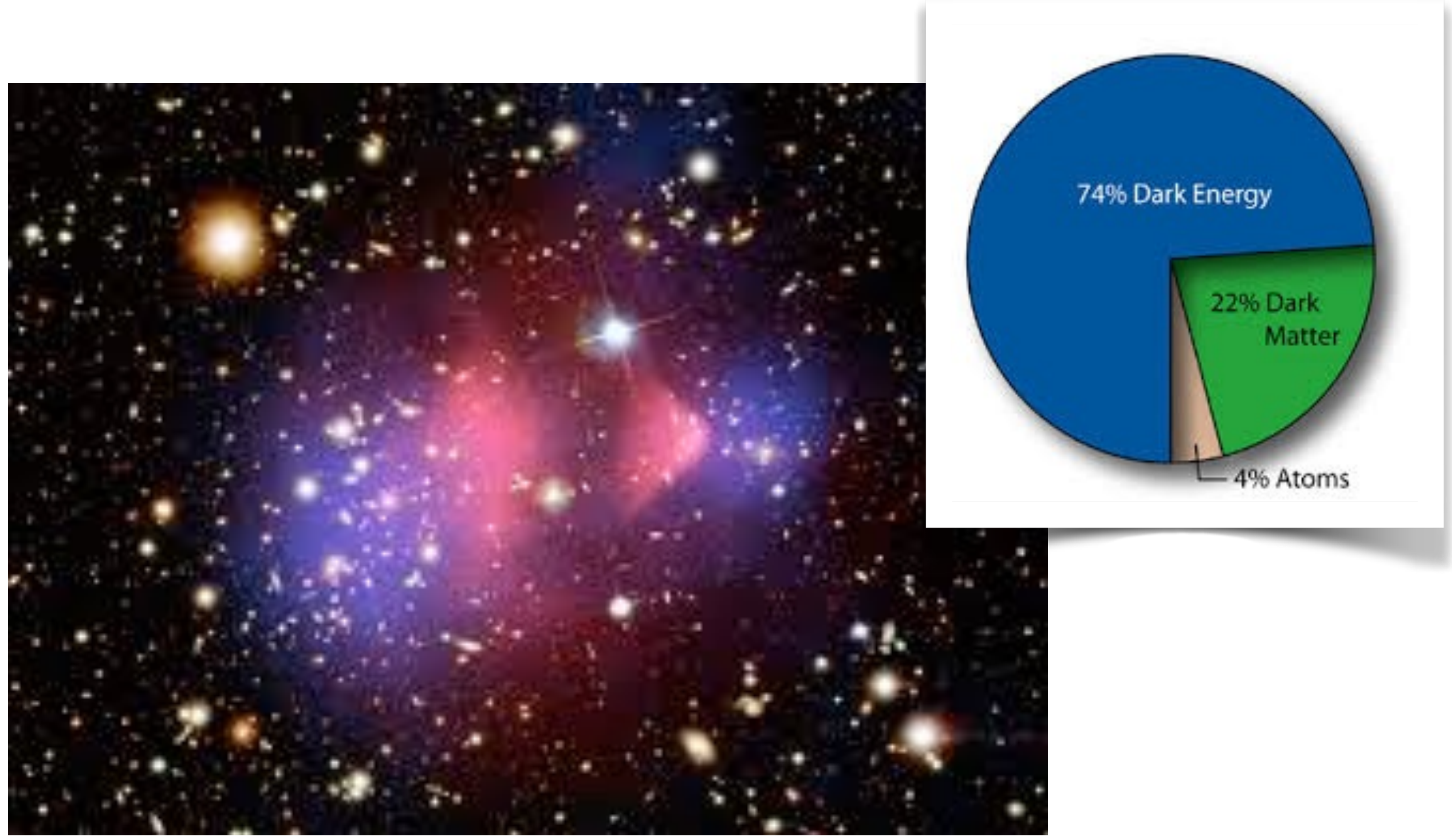

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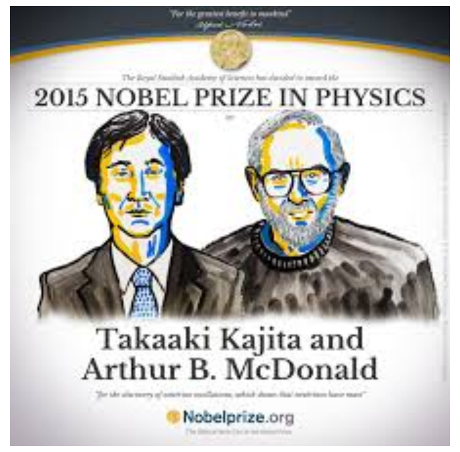
LAB What’s the origin and nature of the tiny neutrino mass? Dirac or Majorana (neutrino = anti-neutrino)?



Neutrino oscillations ⇒ neutrinos have mass

“…Neutrino masses clearly take us beyond the Standard Model…”
(S.Weinberg, 2018 SLAC Summer Institute)

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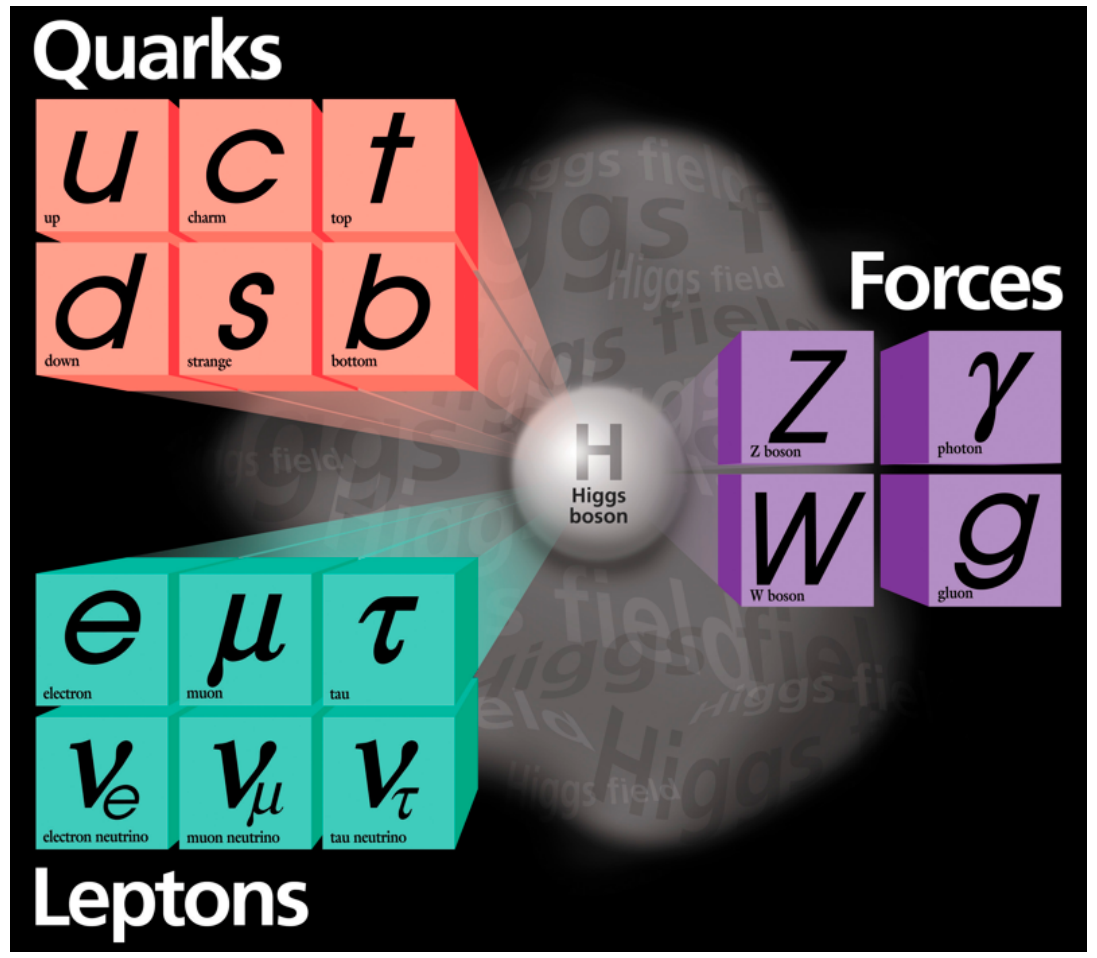

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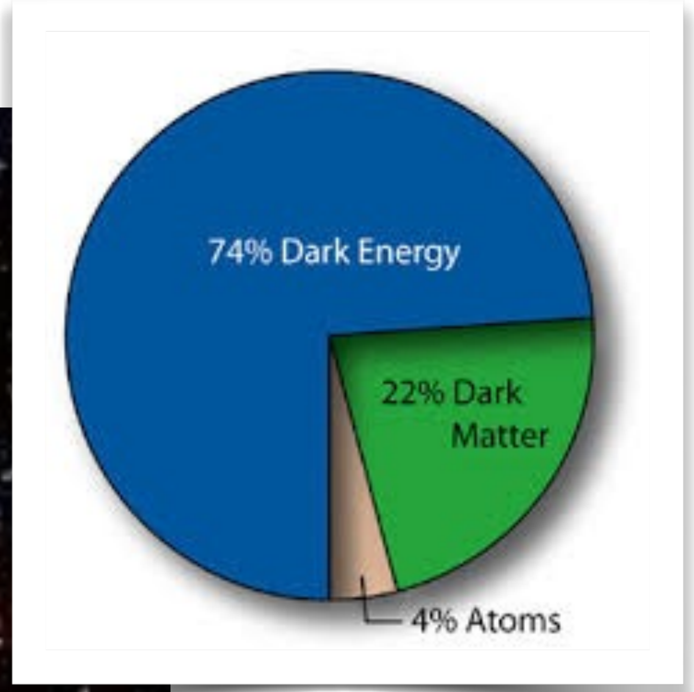

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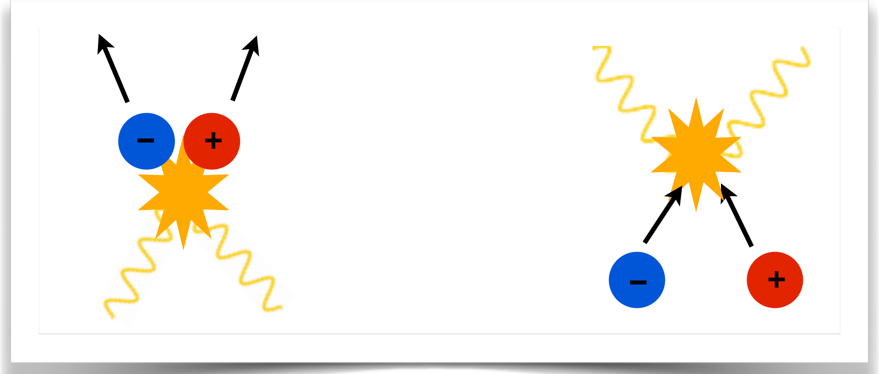
SKY Why is there more matter than antimatter in the universe? What is Dark Matter? What is Dark Energy?



Matter and antimatter particles are produced or annihilated in pairs, but we live in a universe made of *matter*!

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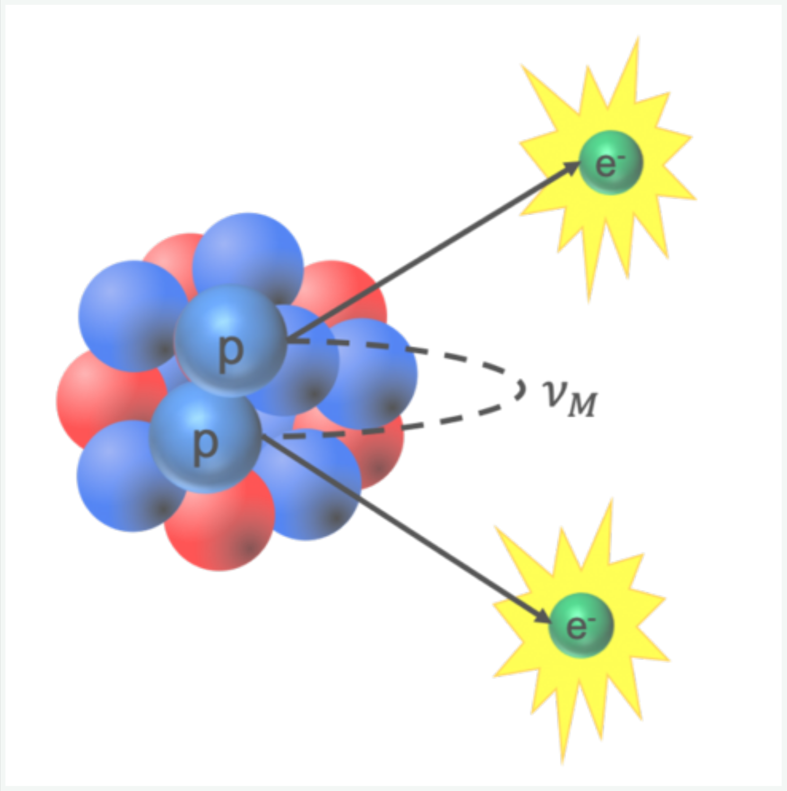

$0\nu\beta\beta$ decay plays a prominent role in the quest for new physics by addressing two major questions related to shortcomings of the Standard Model

LAB — What's the origin and nature of the tiny neutrino mass? Dirac or Majorana (neutrino = anti-neutrino)?

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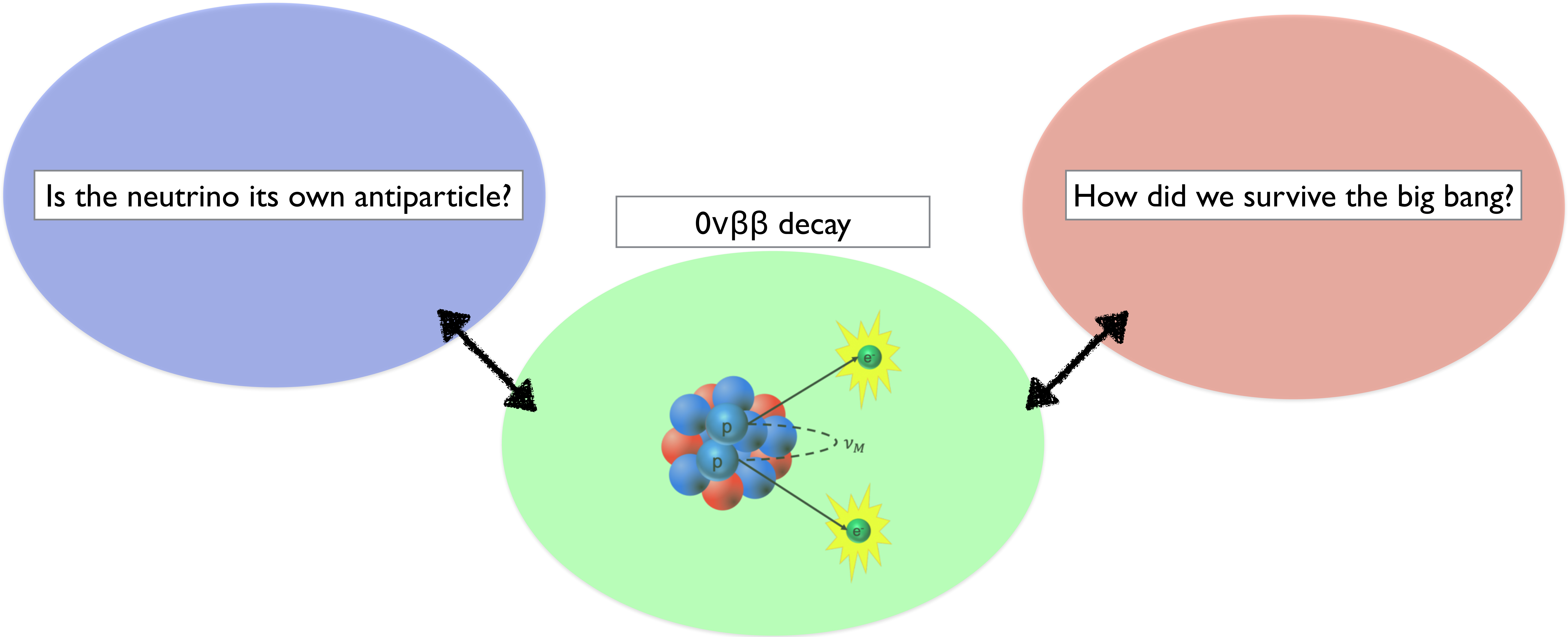
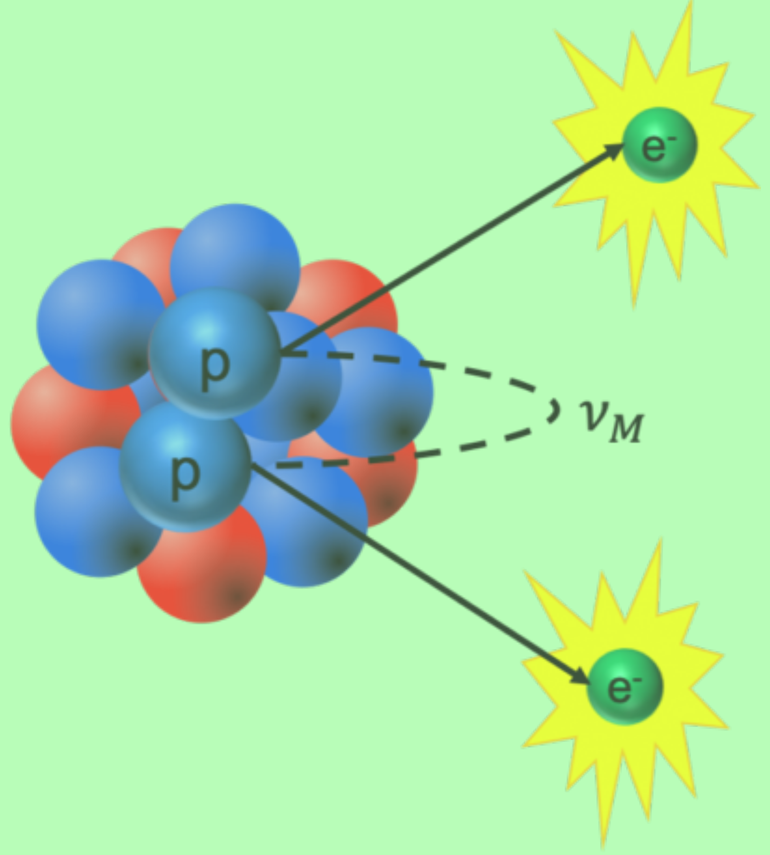
The significance of 0νββ decay



The significance of 0νββ decay

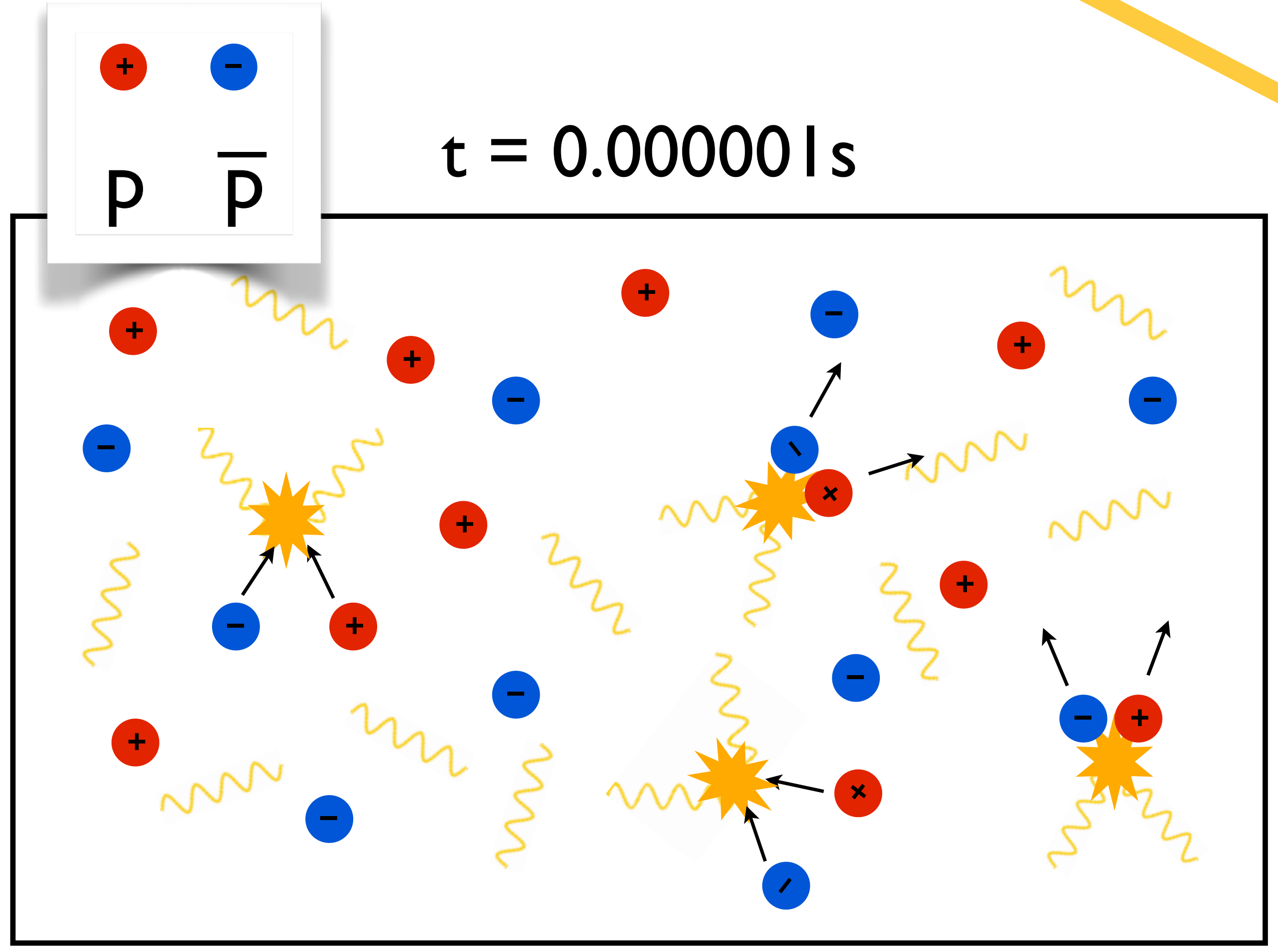
How did we survive the big bang?

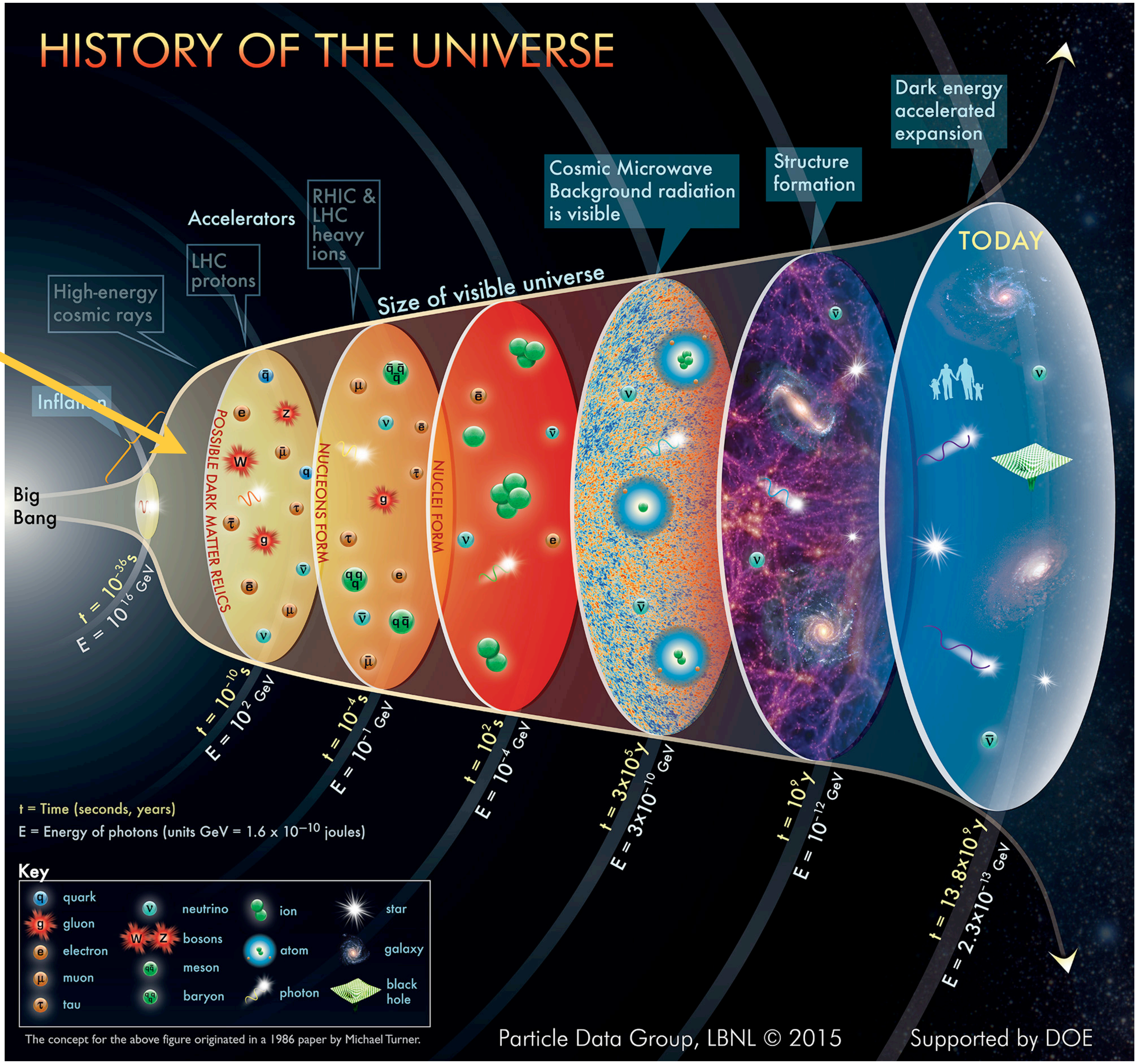
0νββ decay



What's the origin of matter in the universe?

Equal number of particles and antiparticles right after the big bang





As the universe expands and cools, particle-antiparticle annihilation takes over: end up with just radiation!

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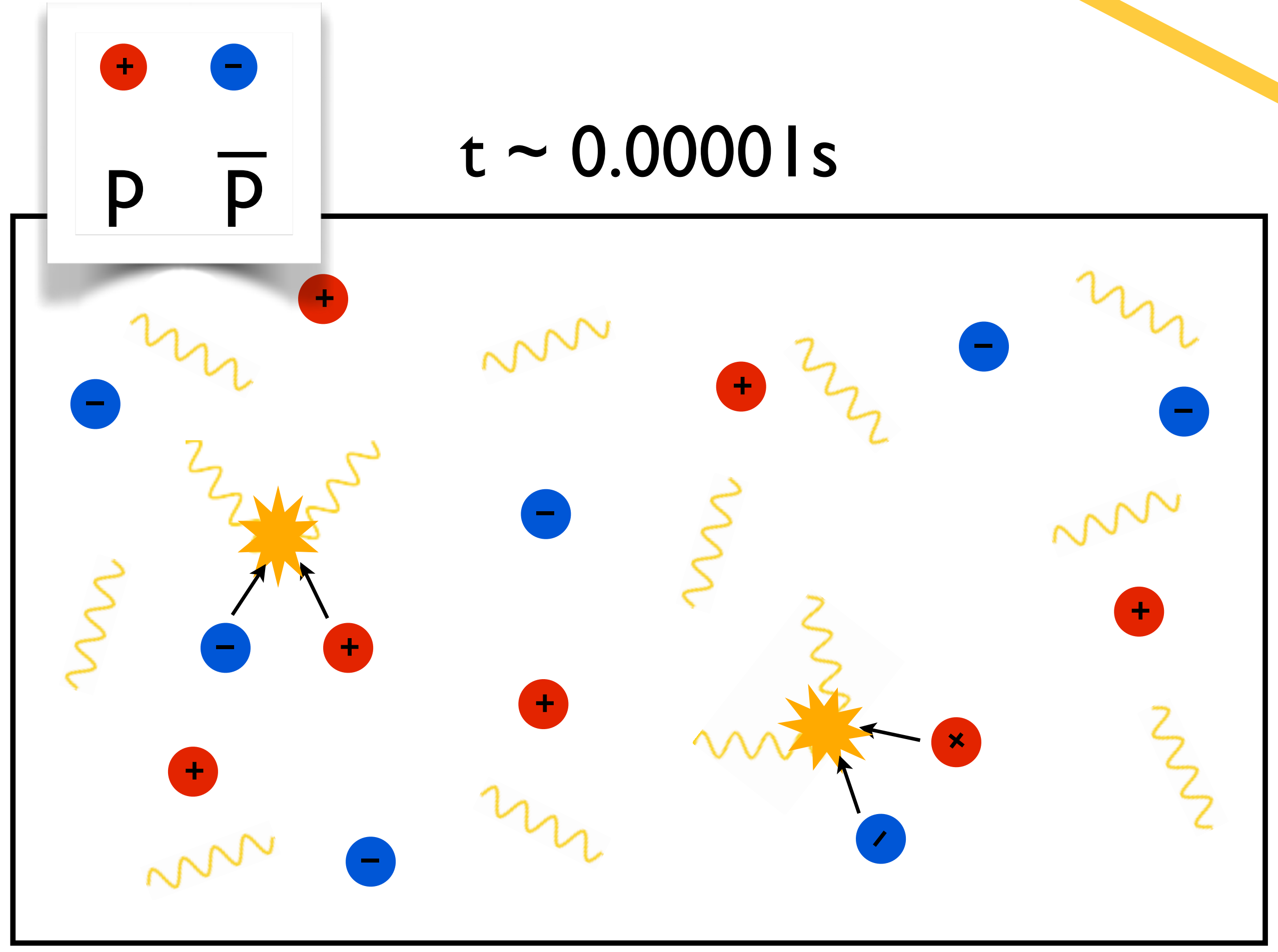

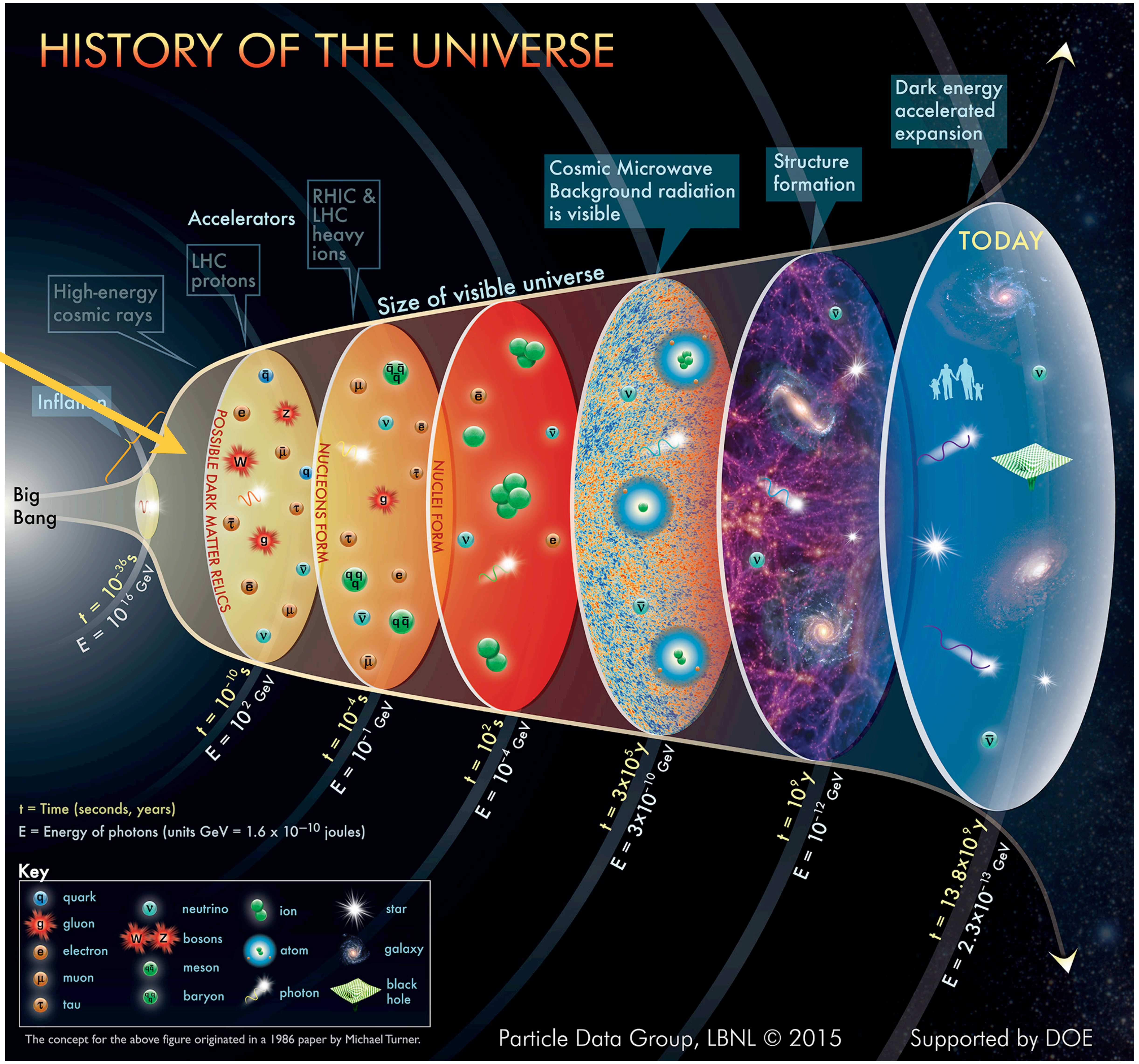

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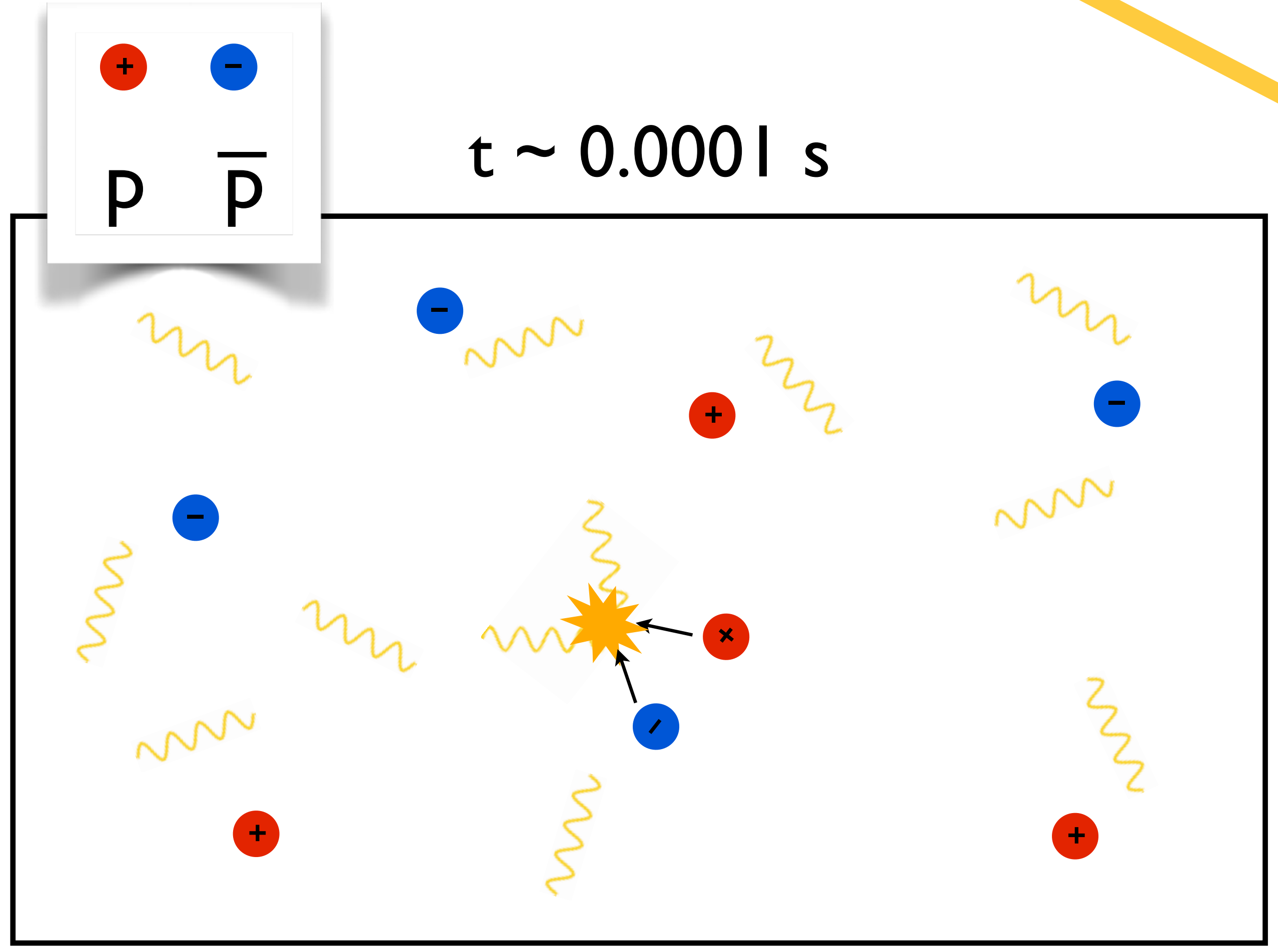

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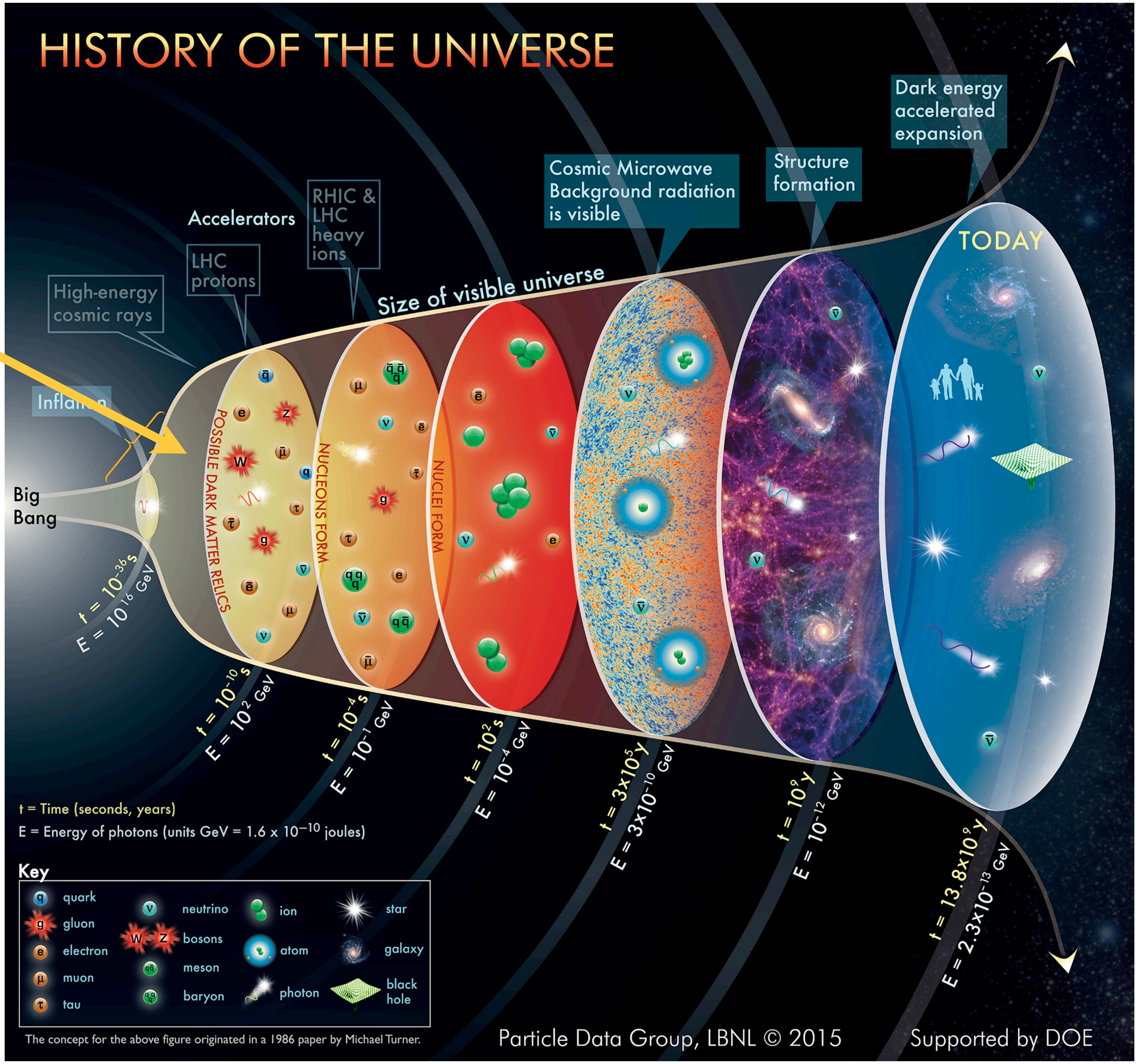

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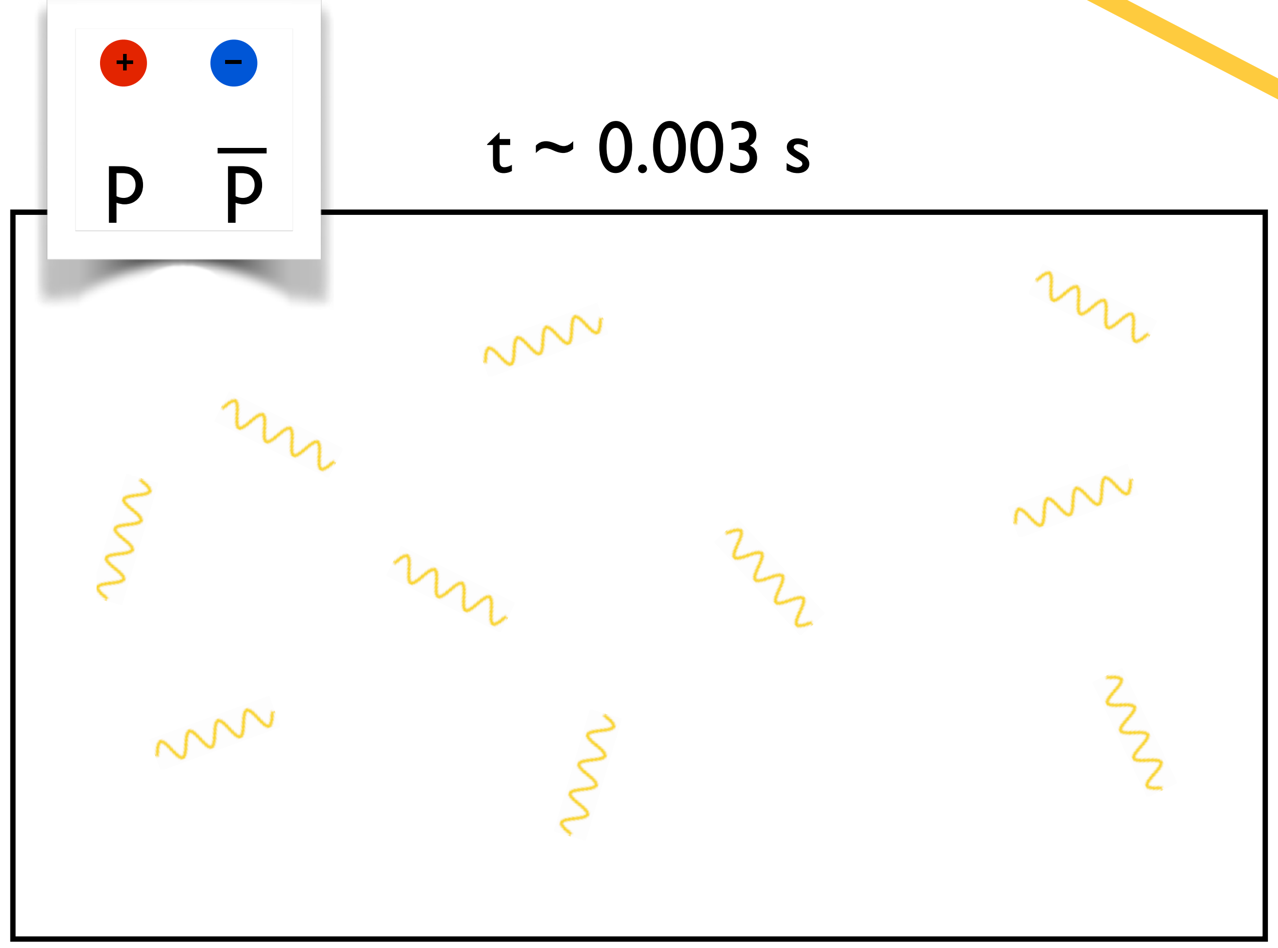
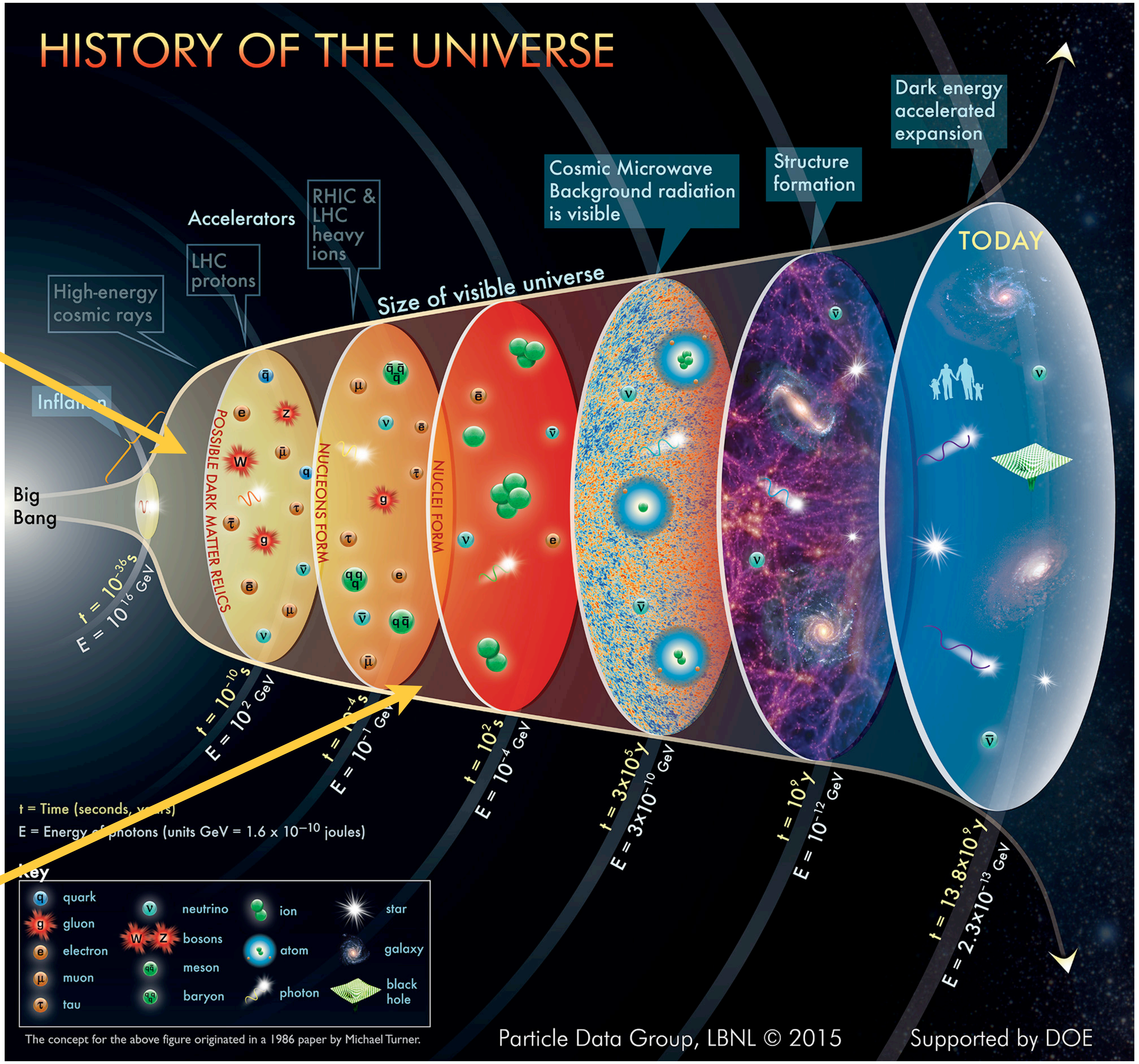


As the universe expands and cools, particle-antiparticle annihilation takes over: end up with just radiation!

$n_B/n_\gamma \;=\; n_{\bar{B}}/n_\gamma \;\sim\; 10^{-18}$



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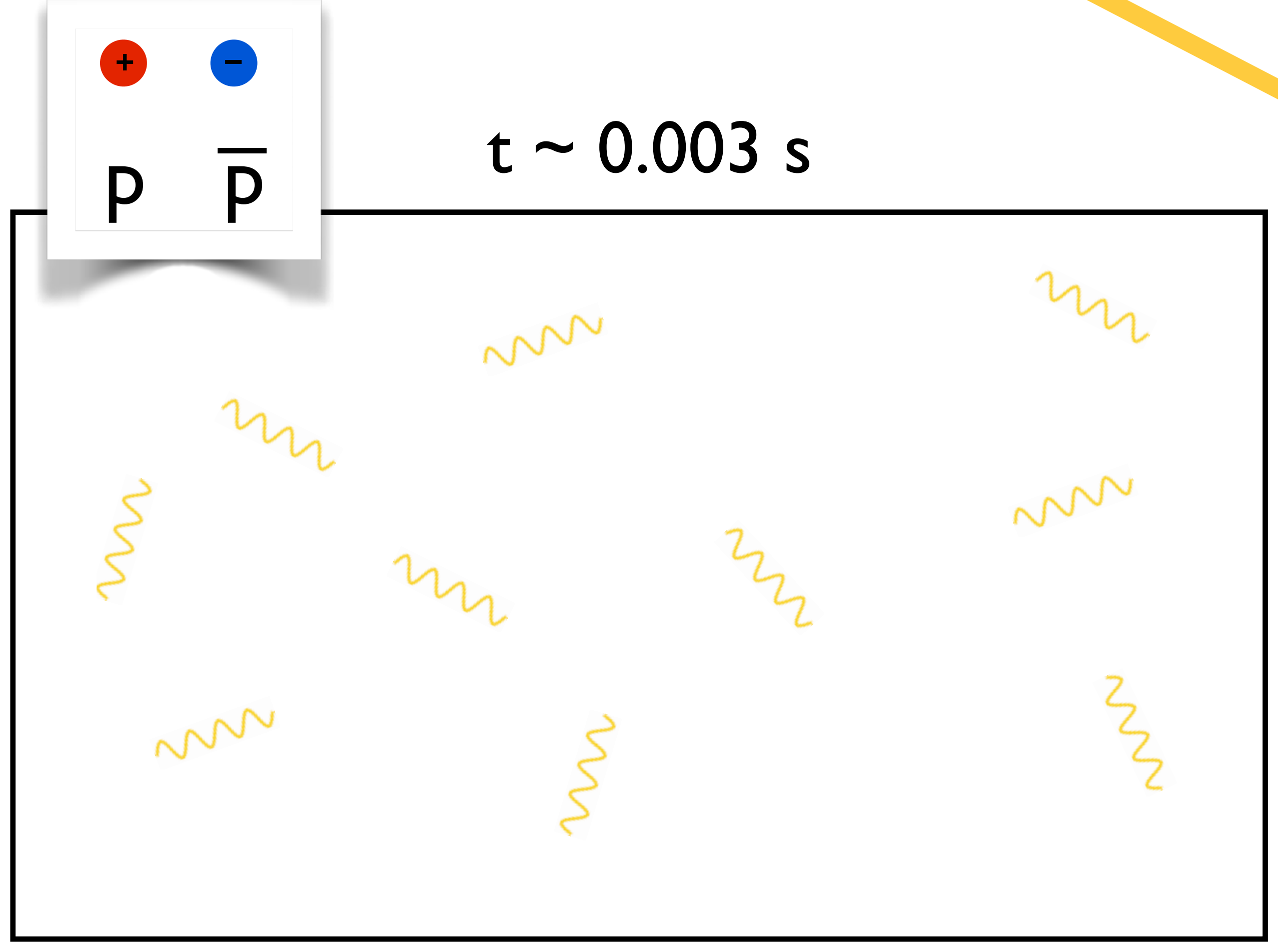

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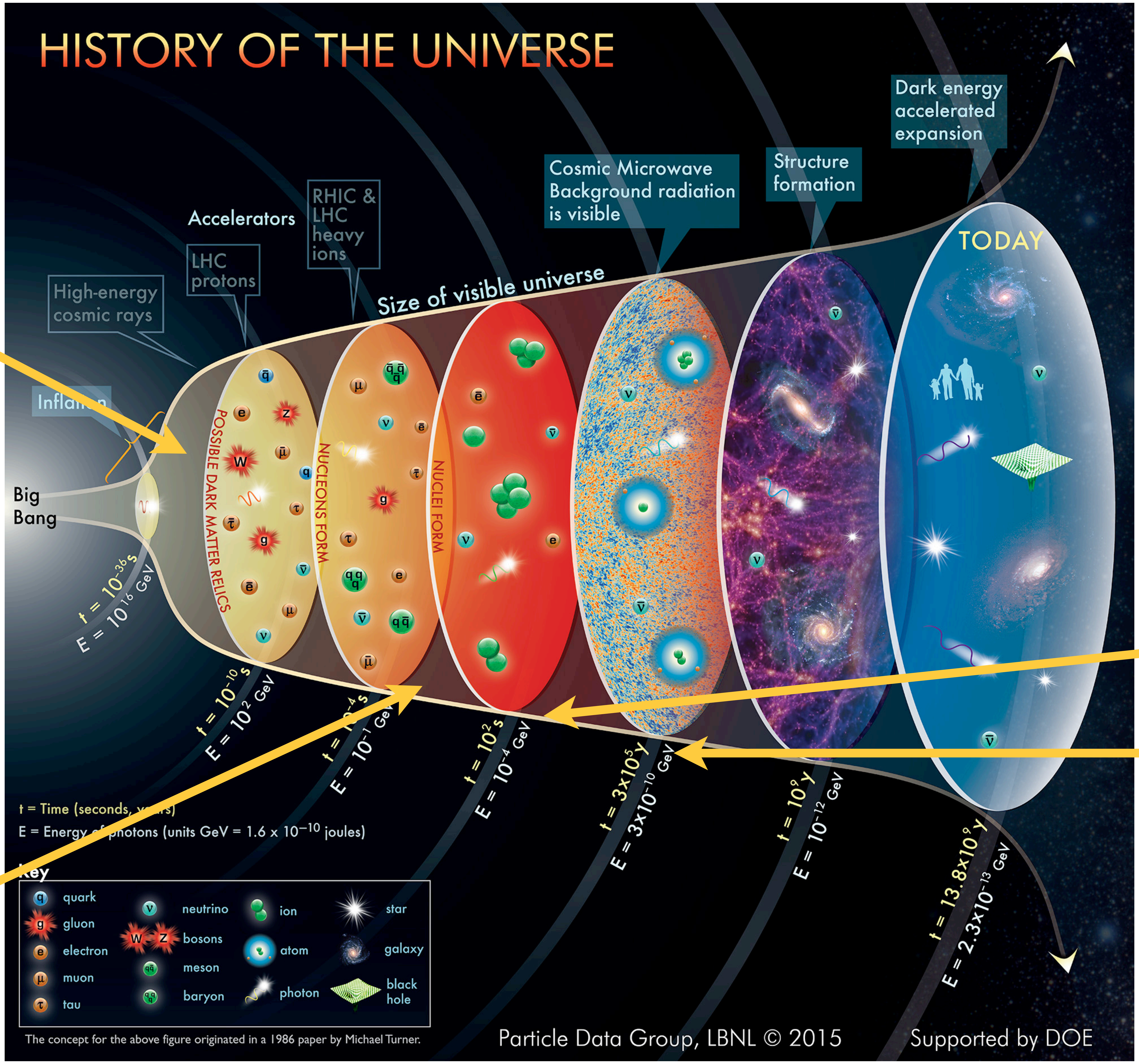

But our very existence and cosmological observations require a non-zero matter-antimatter asymmetry!

$\eta \equiv (n_B - n_{\bar{B}})/n_\gamma$

Big Bang Nucleosynthesis ($t \sim 3$ min) and the Cosmic Microwave Background ($t \sim 300{,}000$ yr) point to $\eta \sim 6 \times 10^{-10}$

What's the origin of matter in the universe?

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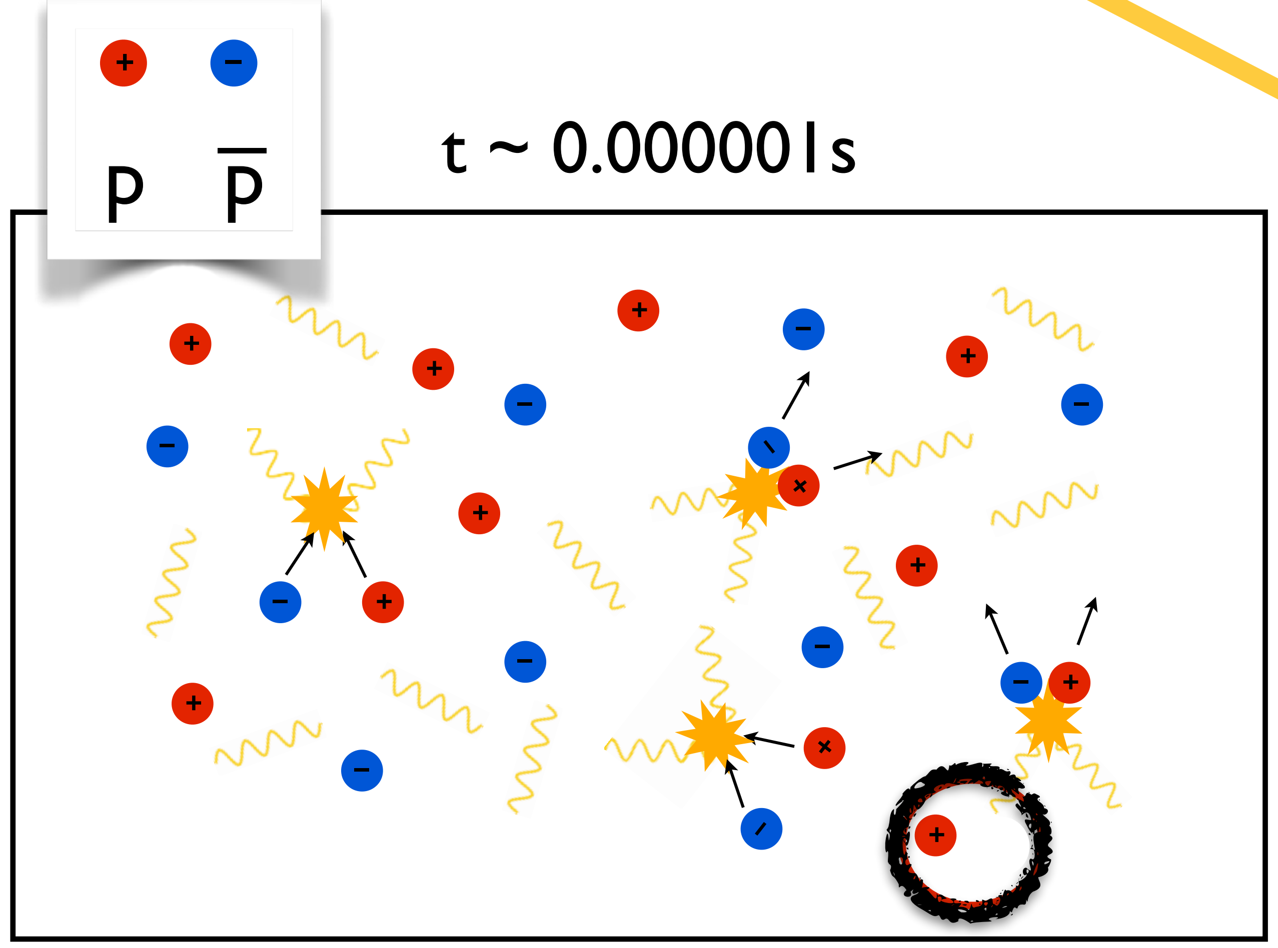
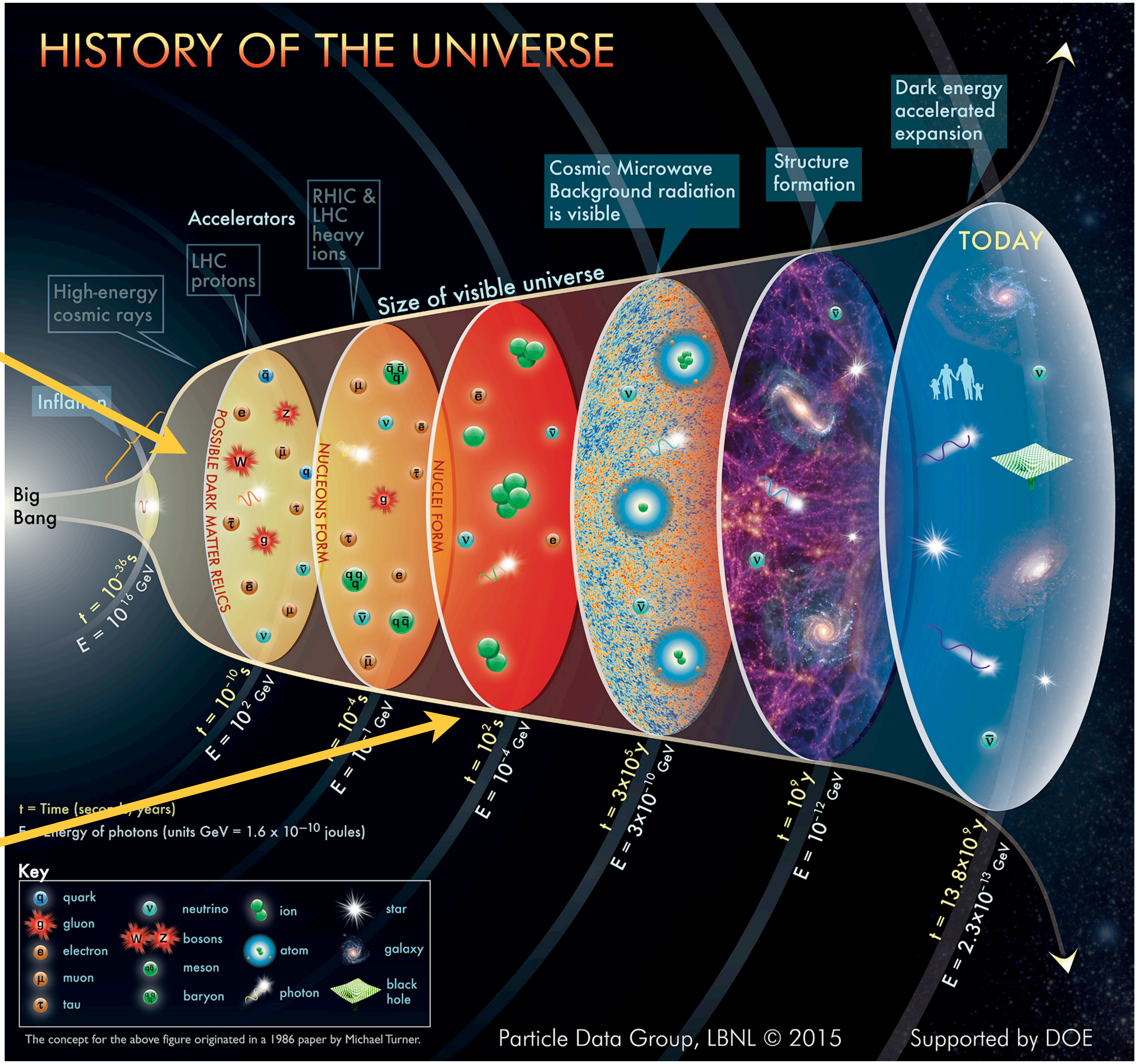
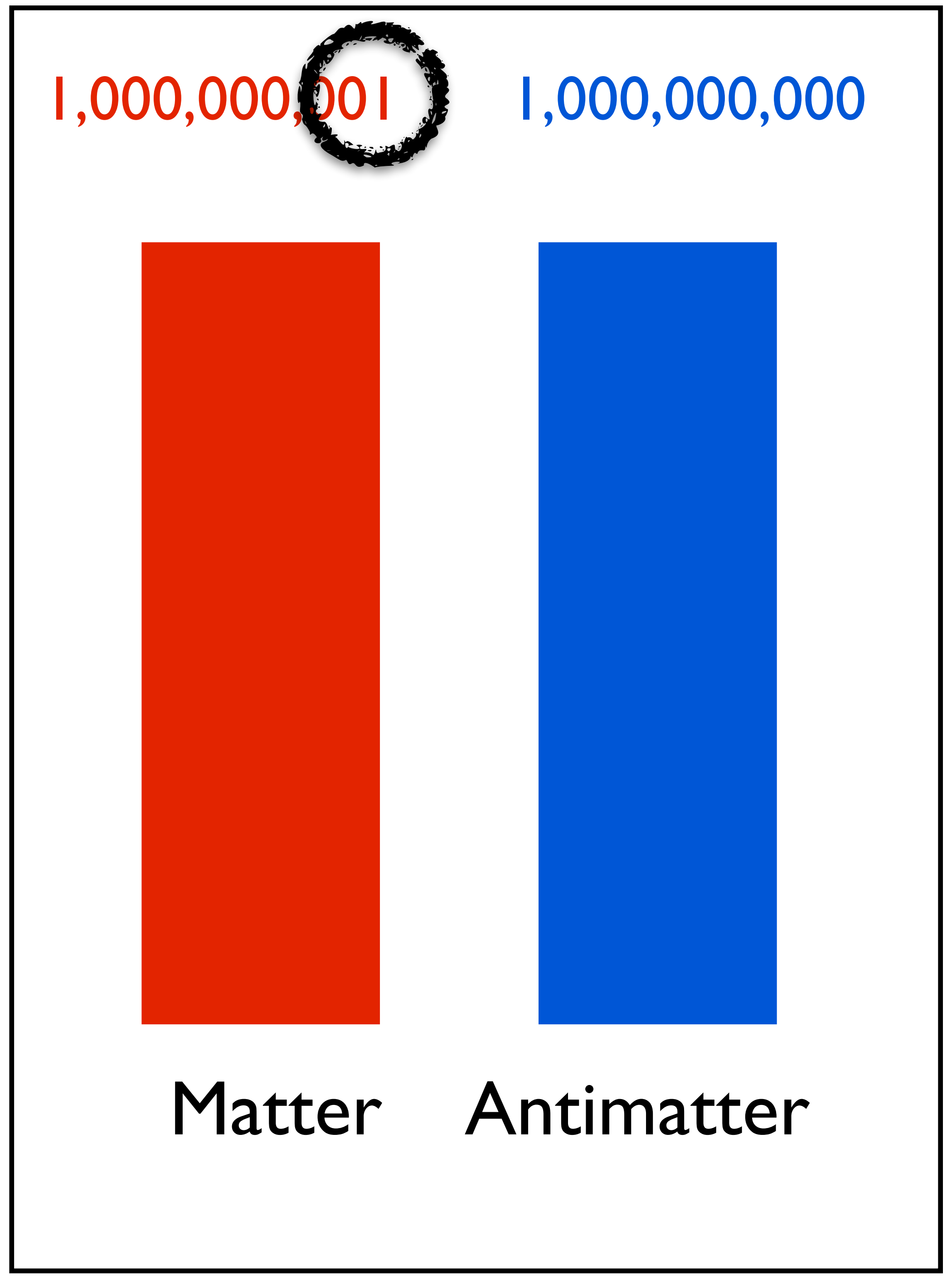
t ~ 0.000001s



To obtain O(1) protons per cubic meter today, early on need a tiny imbalance of + over −



Early universe



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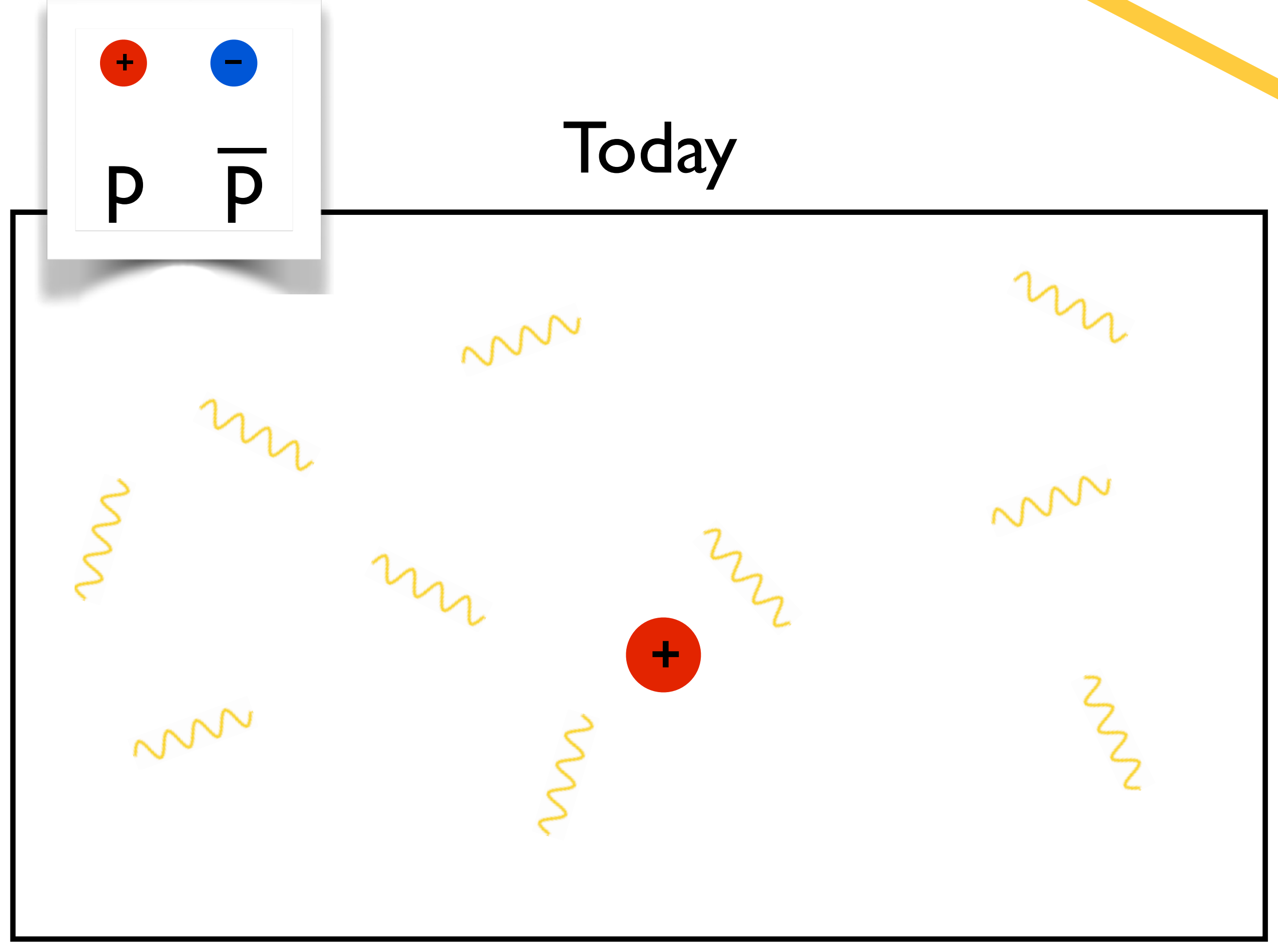

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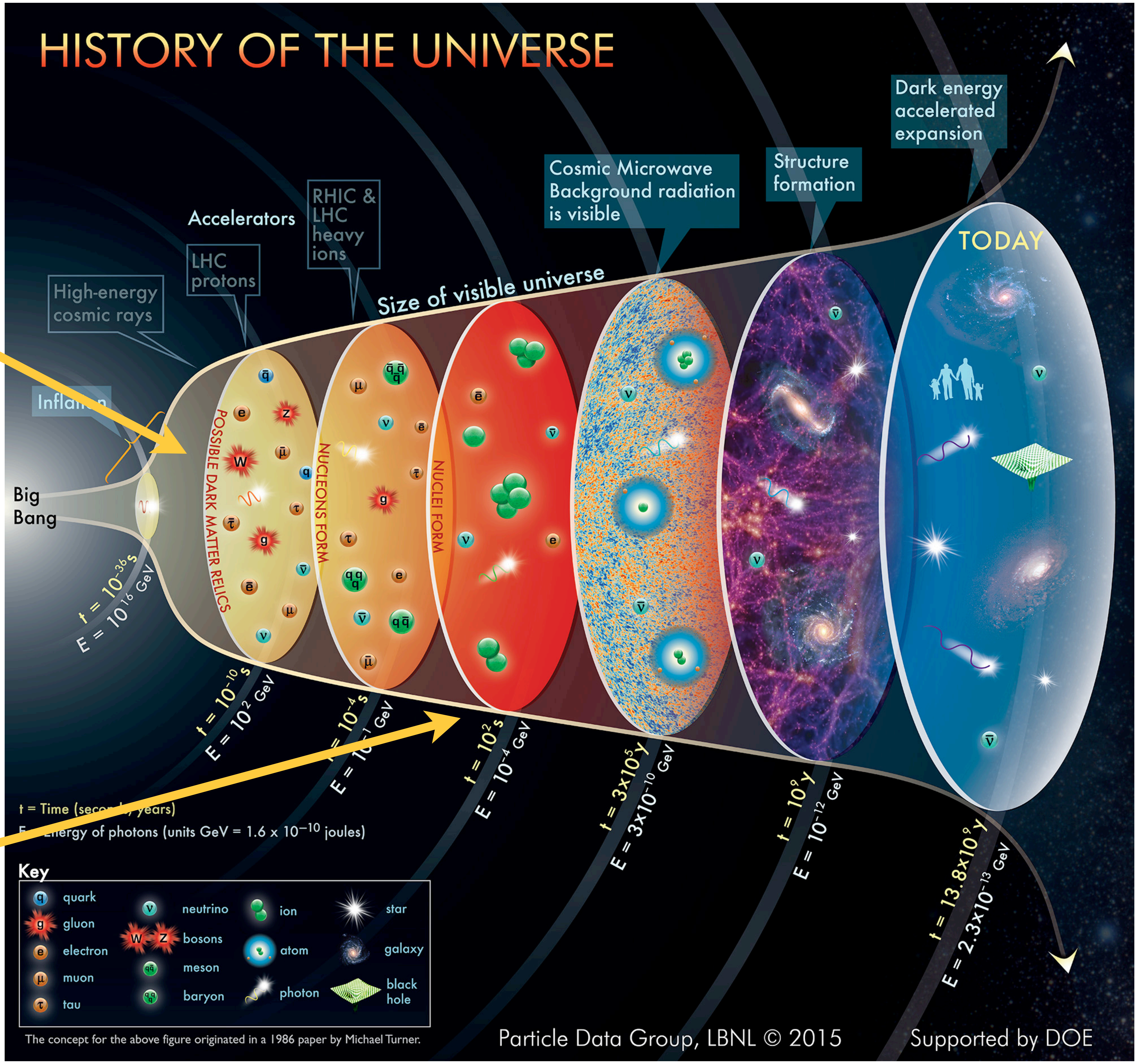

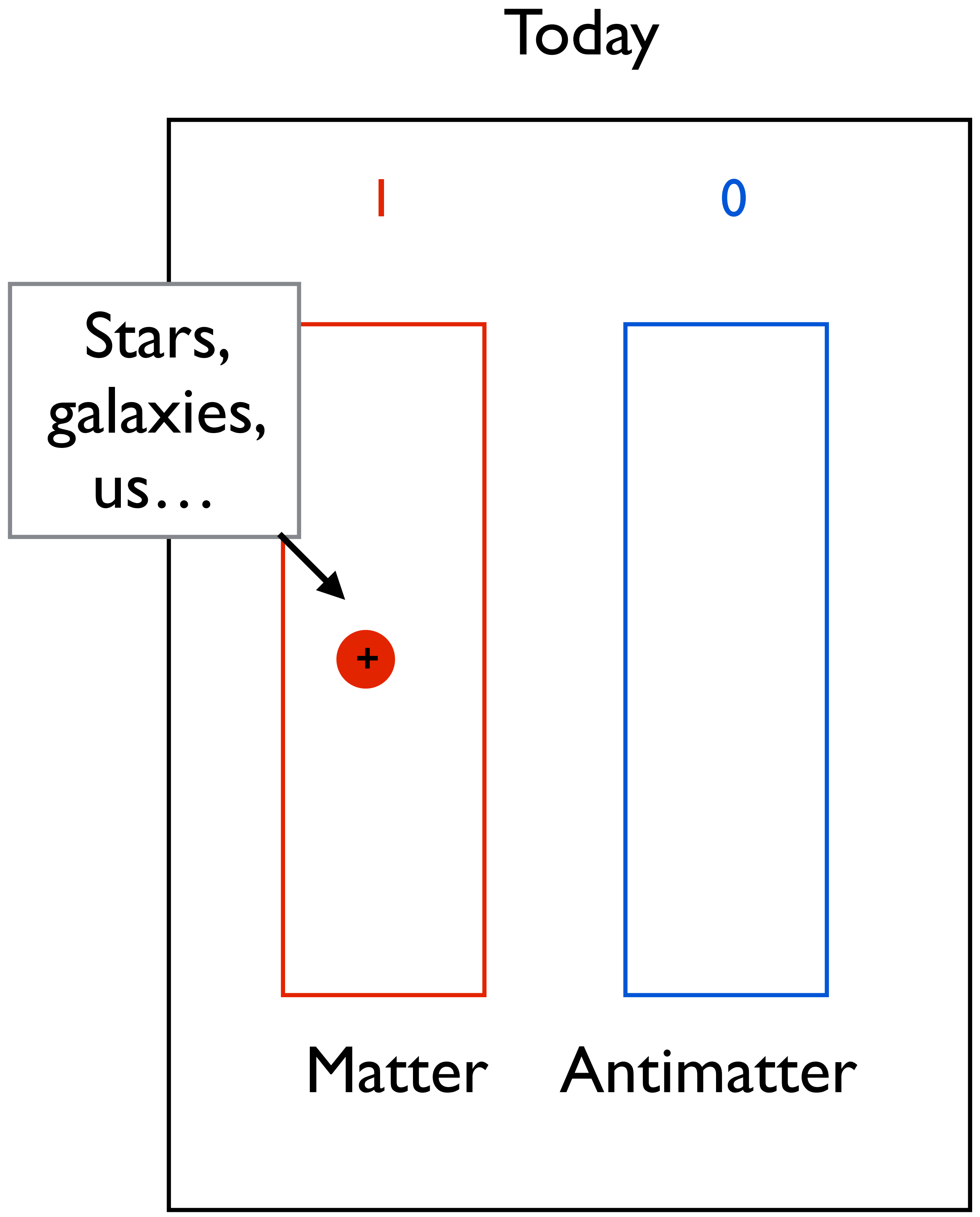

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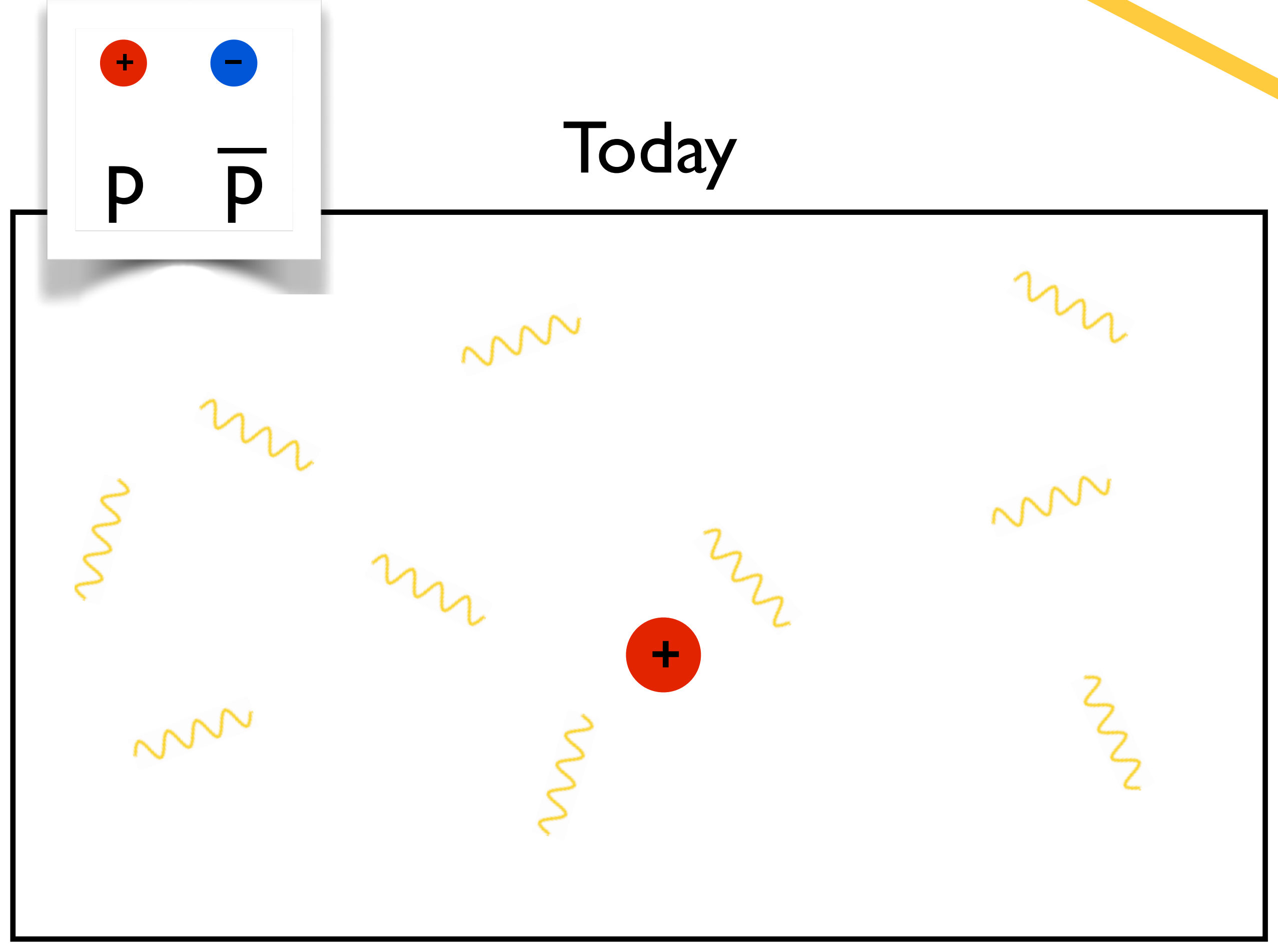
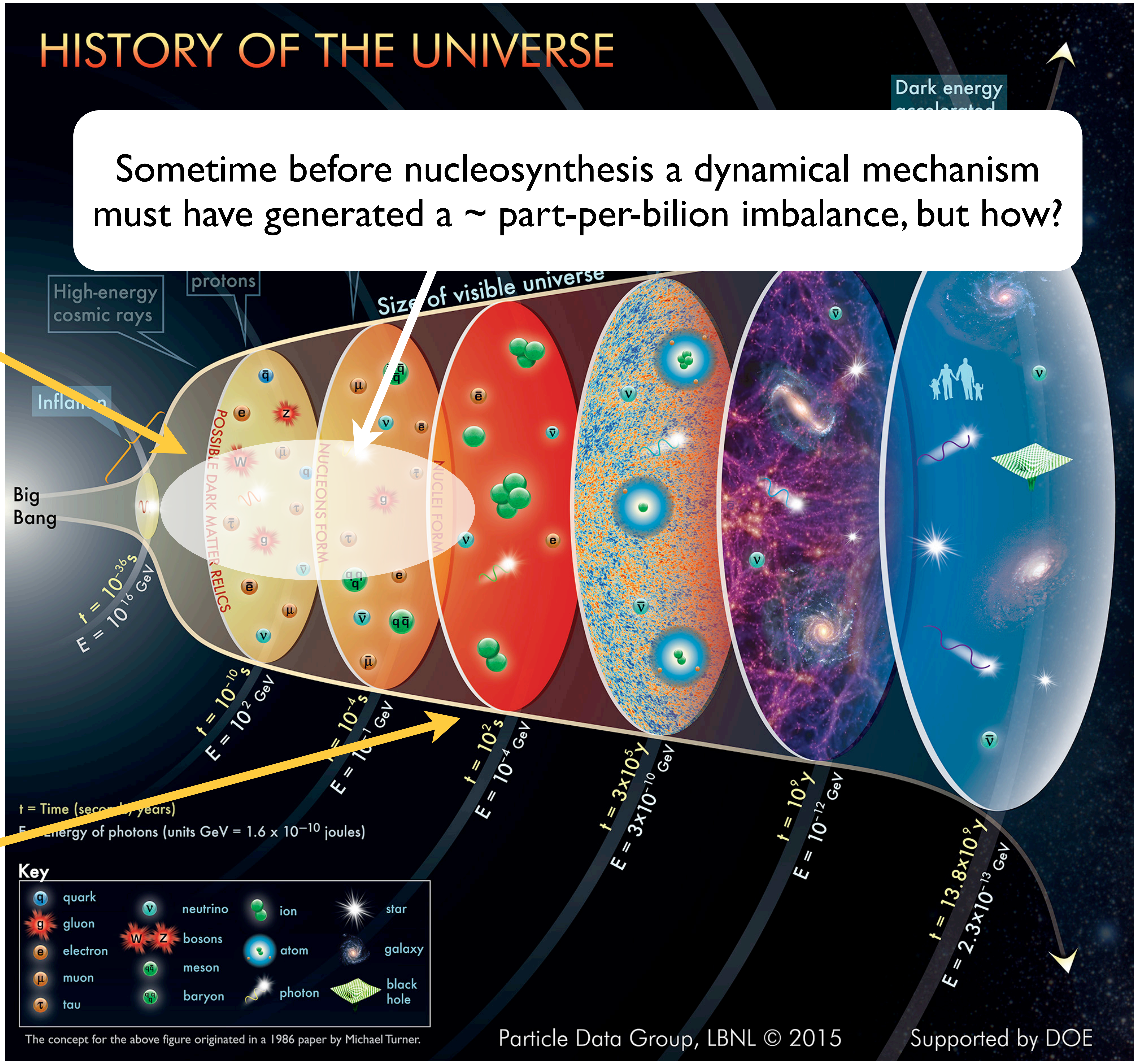


Sometime before nucleosynthesis a dynamical mechanism must have generated a ~ part-per-bilion imbalance, but how?



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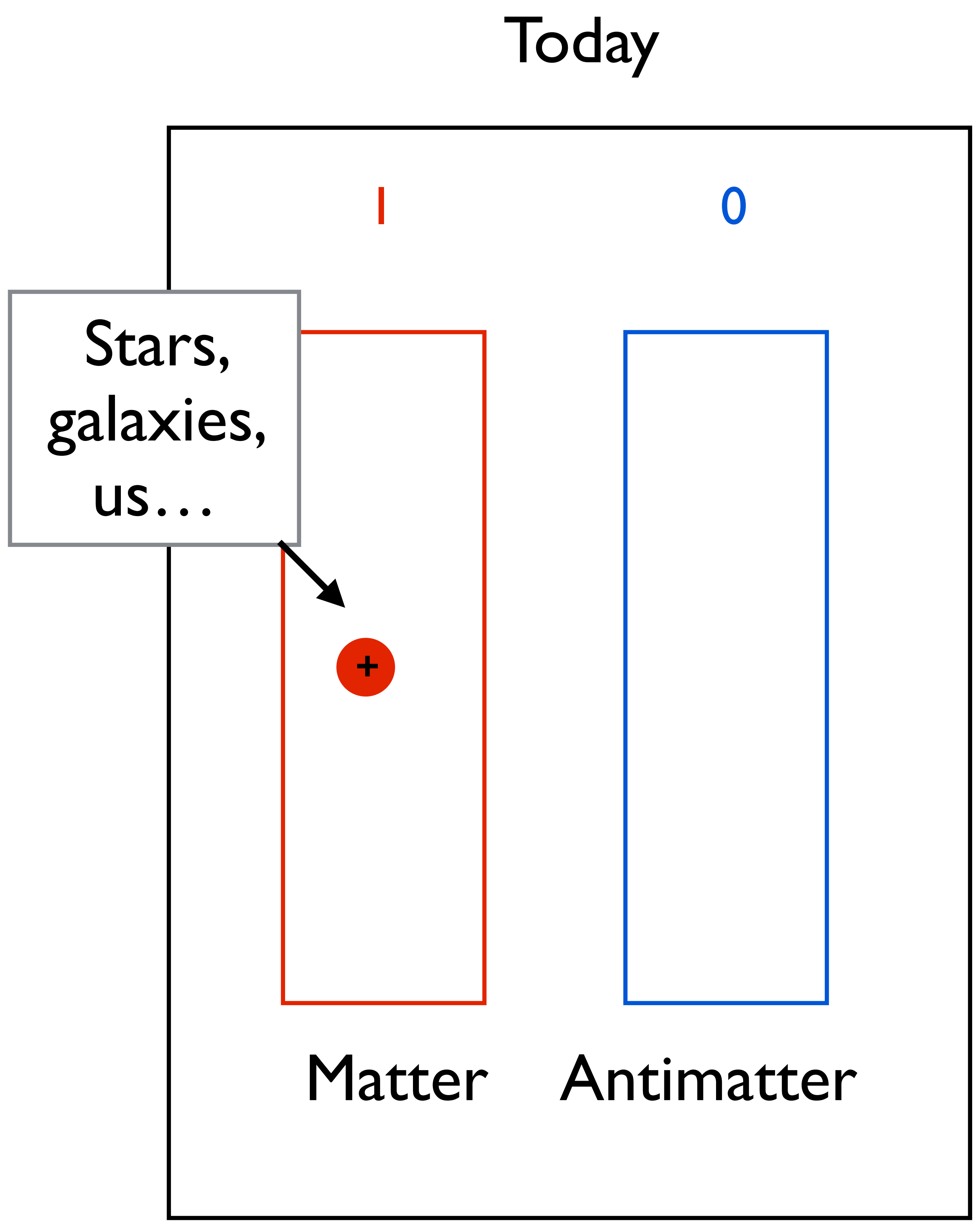

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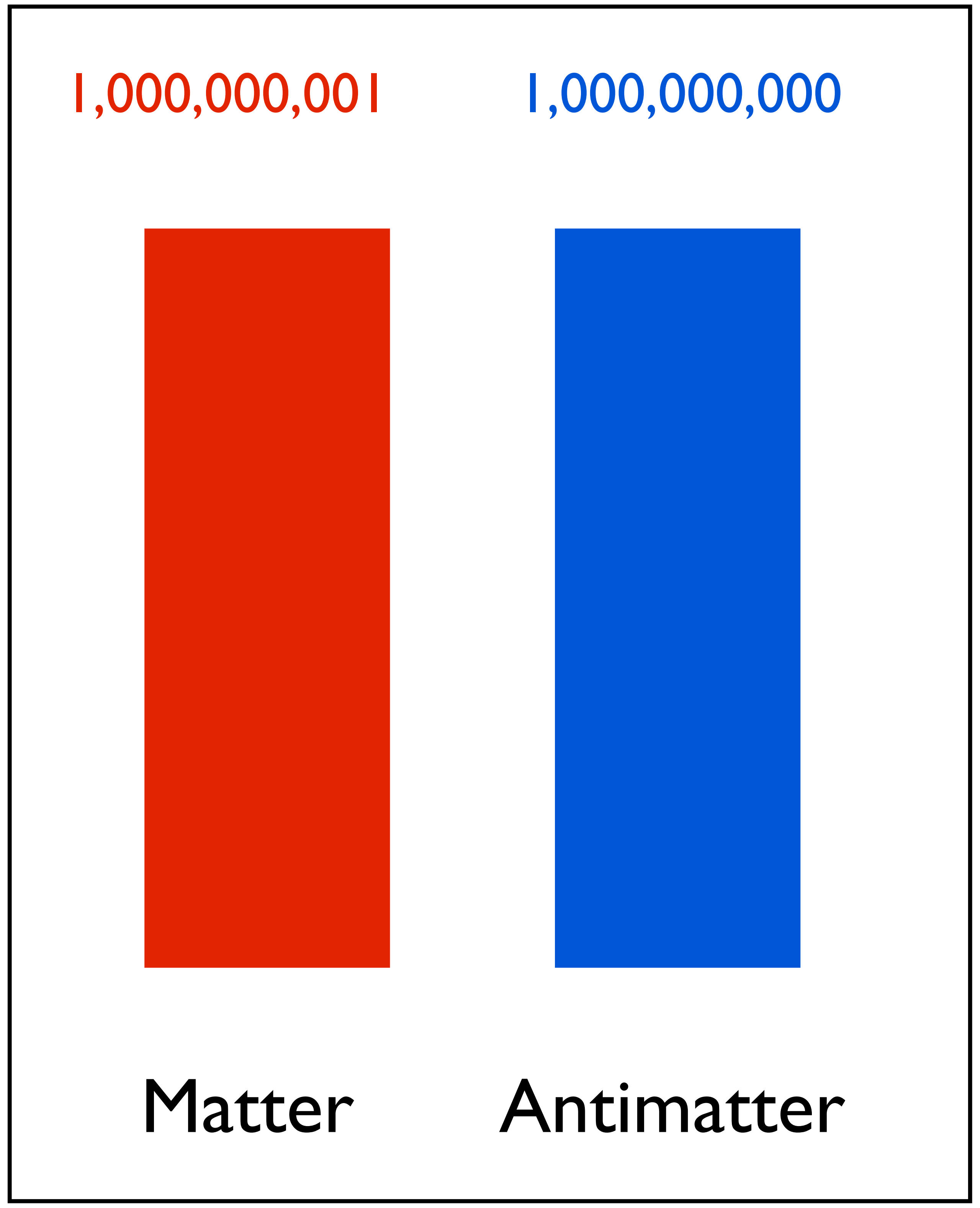
Ingredients for a lopsided universe

Andrei Sakharov, 1967



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#1. Processes that "create matter"

$A \rightarrow B$

# of particles − # of antiparticles is different in A and B

#2. "Asymmetrically" (faster than corresponding antimatter-creating process)

$A \rightarrow B \neq \bar{A} \rightarrow \bar{B}$

#3. "Irreversibly" (faster than matter annihilating inverse process)

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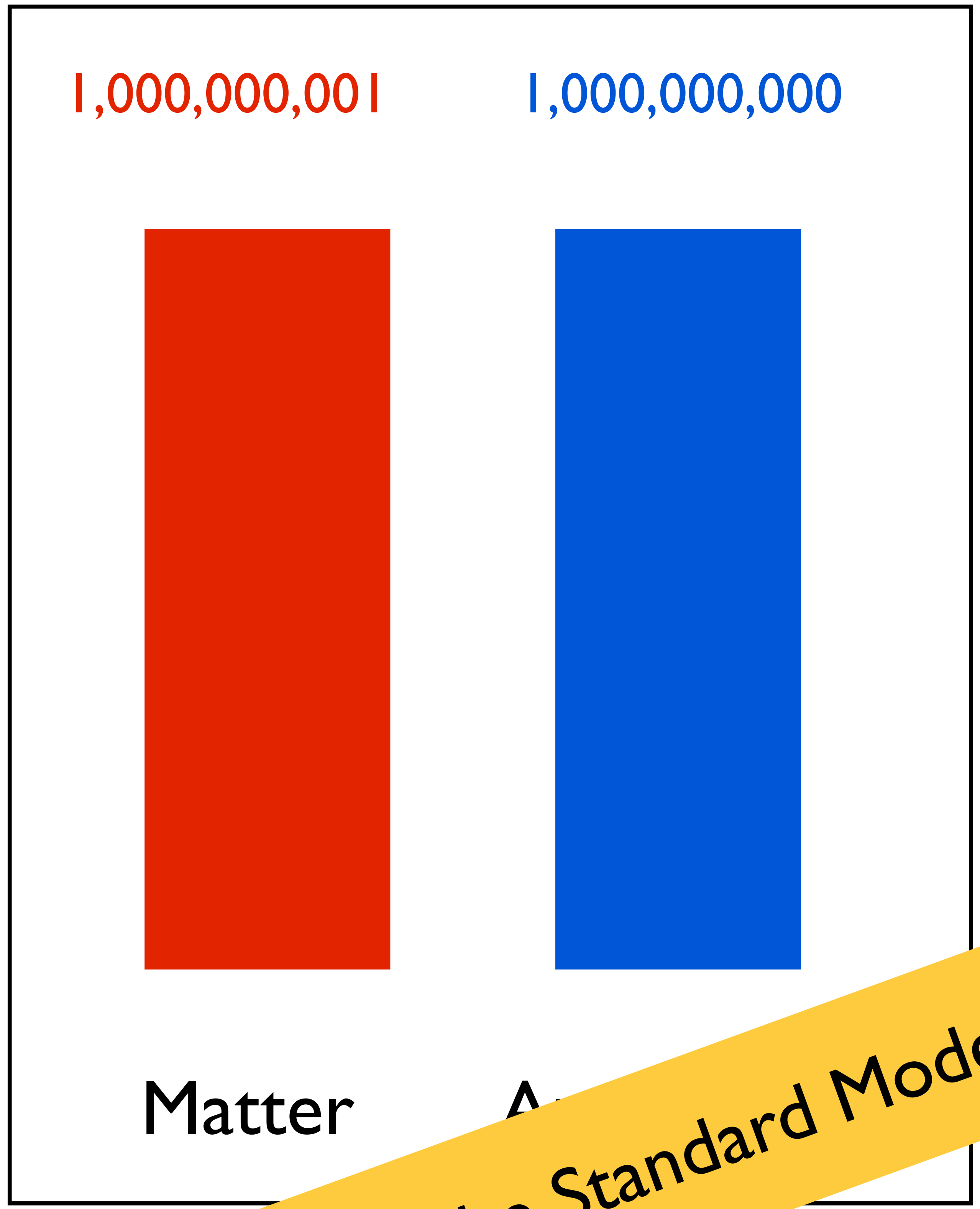

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# of particles − #

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A → B ≠ $\bar{A}$ → $\bar{B}$

#3. "Irreversibly" (faster than matter annihilating inverse process)

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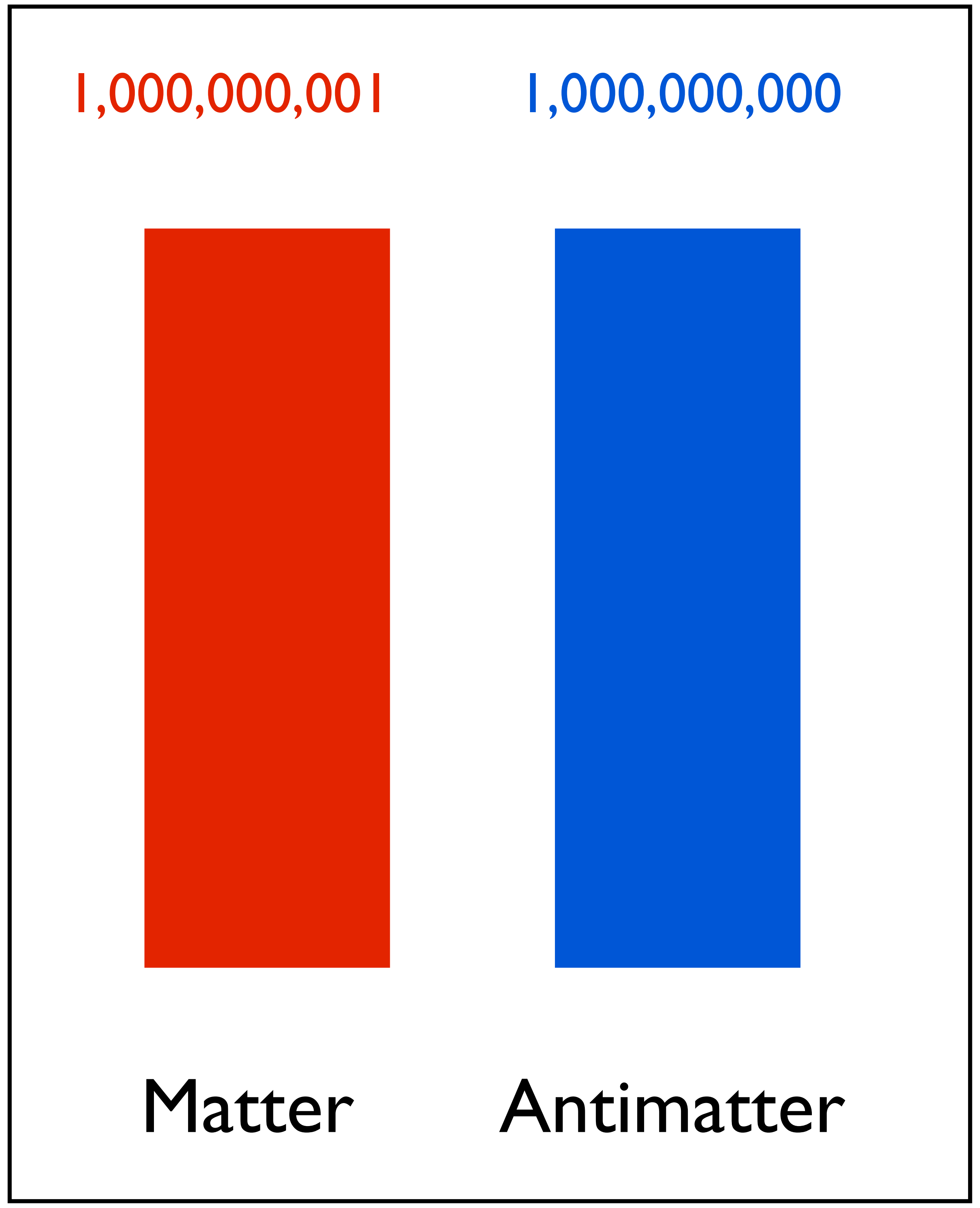
The Standard Model doesn't have all the ingredients to generate the asymmetry: need new physics!

How does 0νββ decay help?

Andrei Sakharov, 1967



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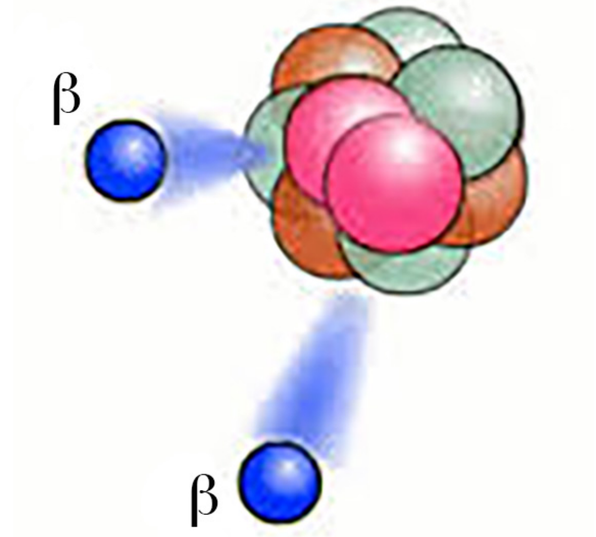
0νββ decay is a matter-creating process!



$$(N, Z) \rightarrow (N-2, Z+2) + e^- + e^-$$

Before: N + Z nucleons, no antiparticles

After: N + Z nucleons *plus two electrons*, no antiparticles

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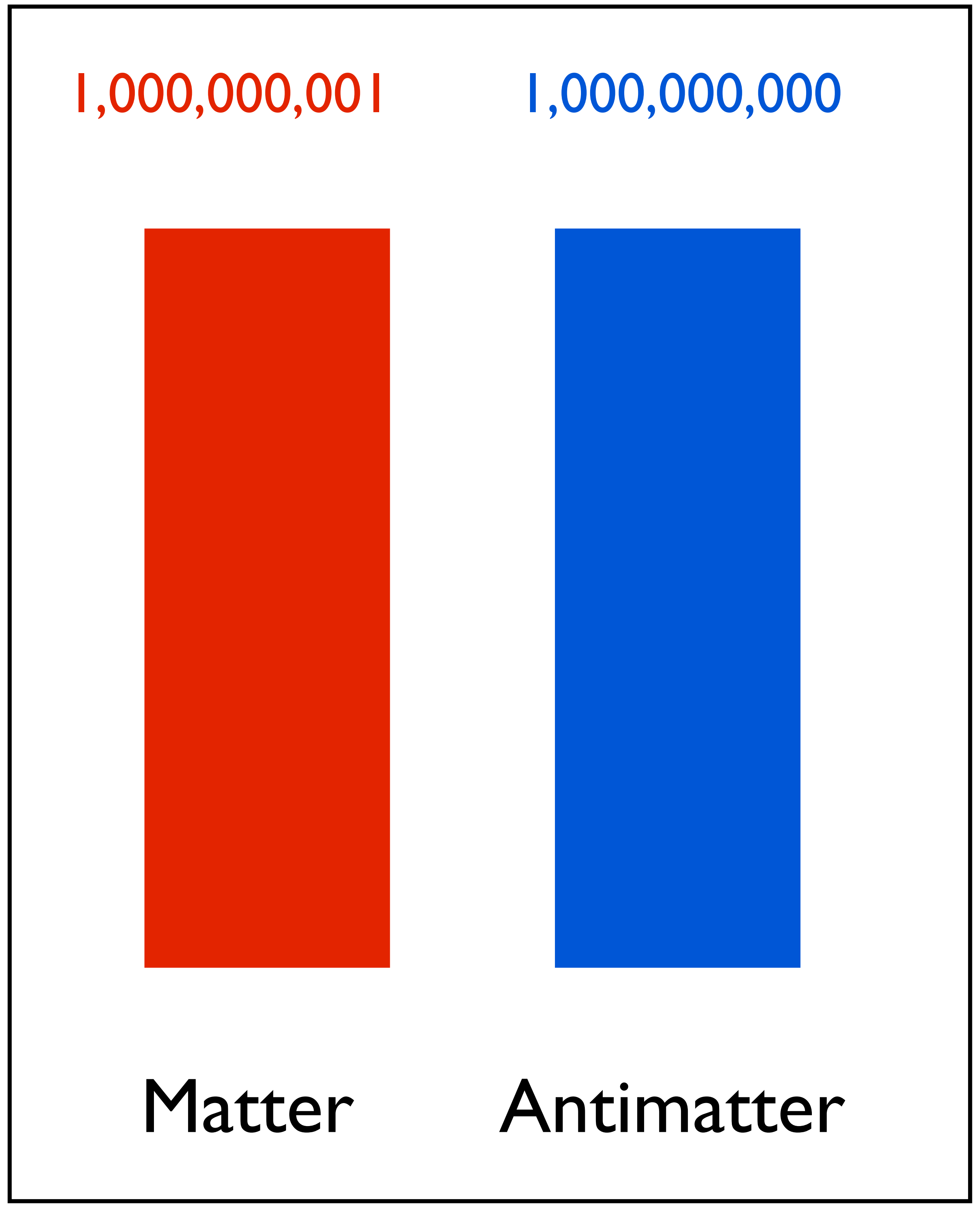

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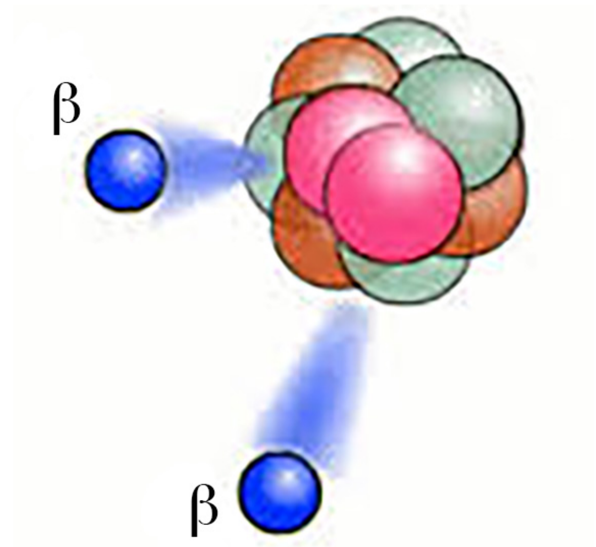

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This is deeply related to the Majorana nature:

neutrino = anti-neutrino

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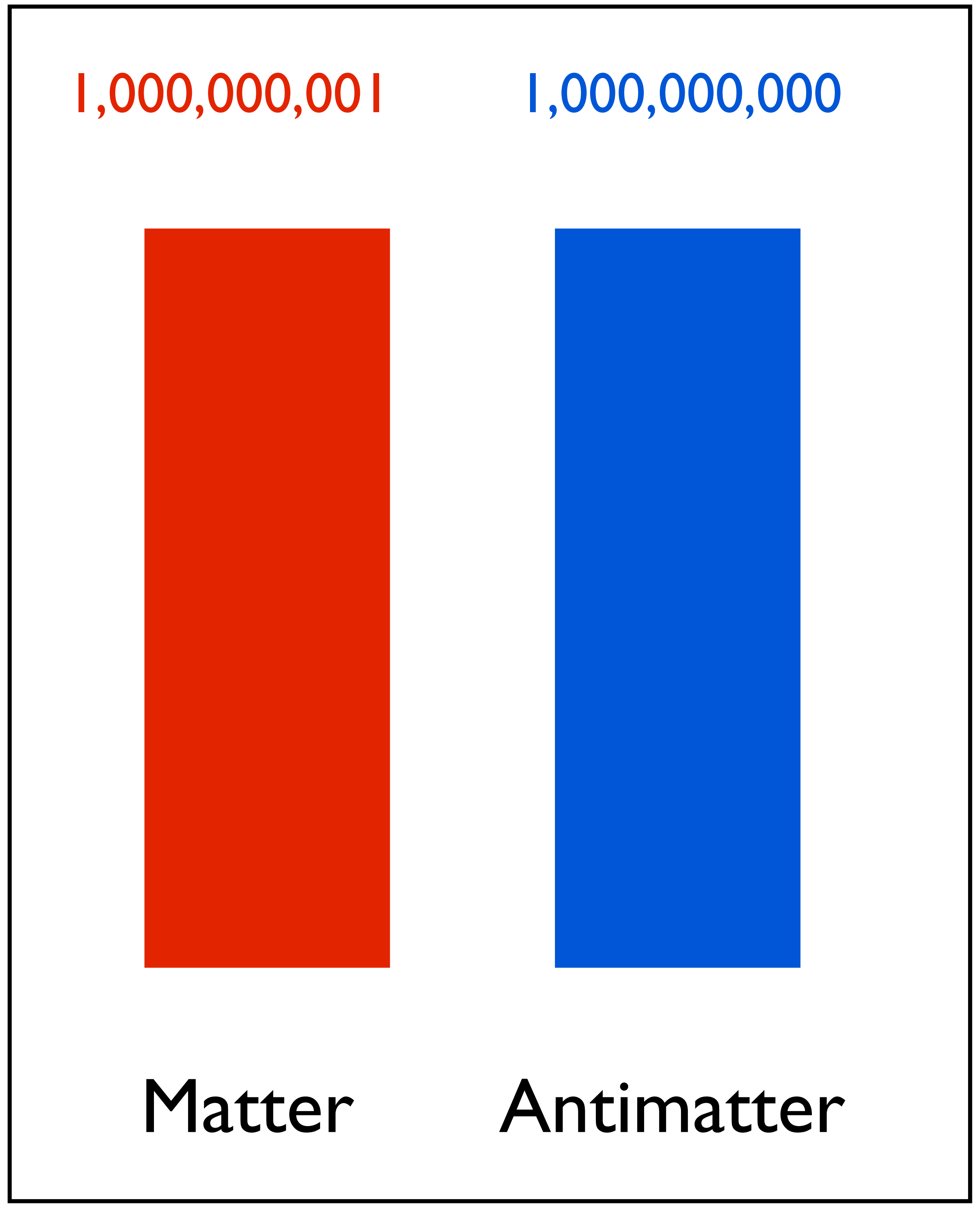

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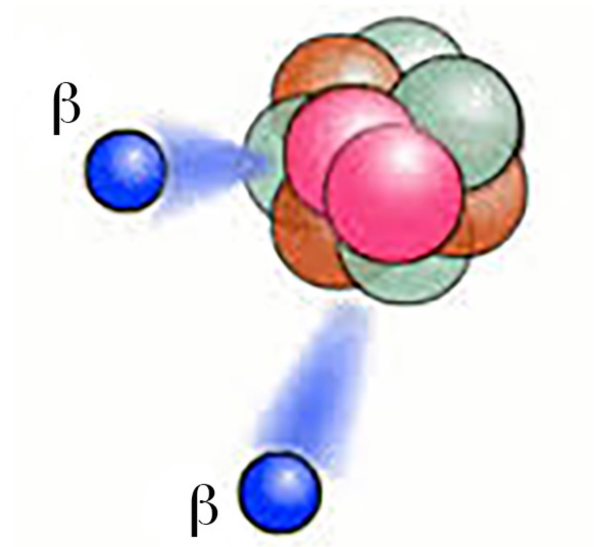

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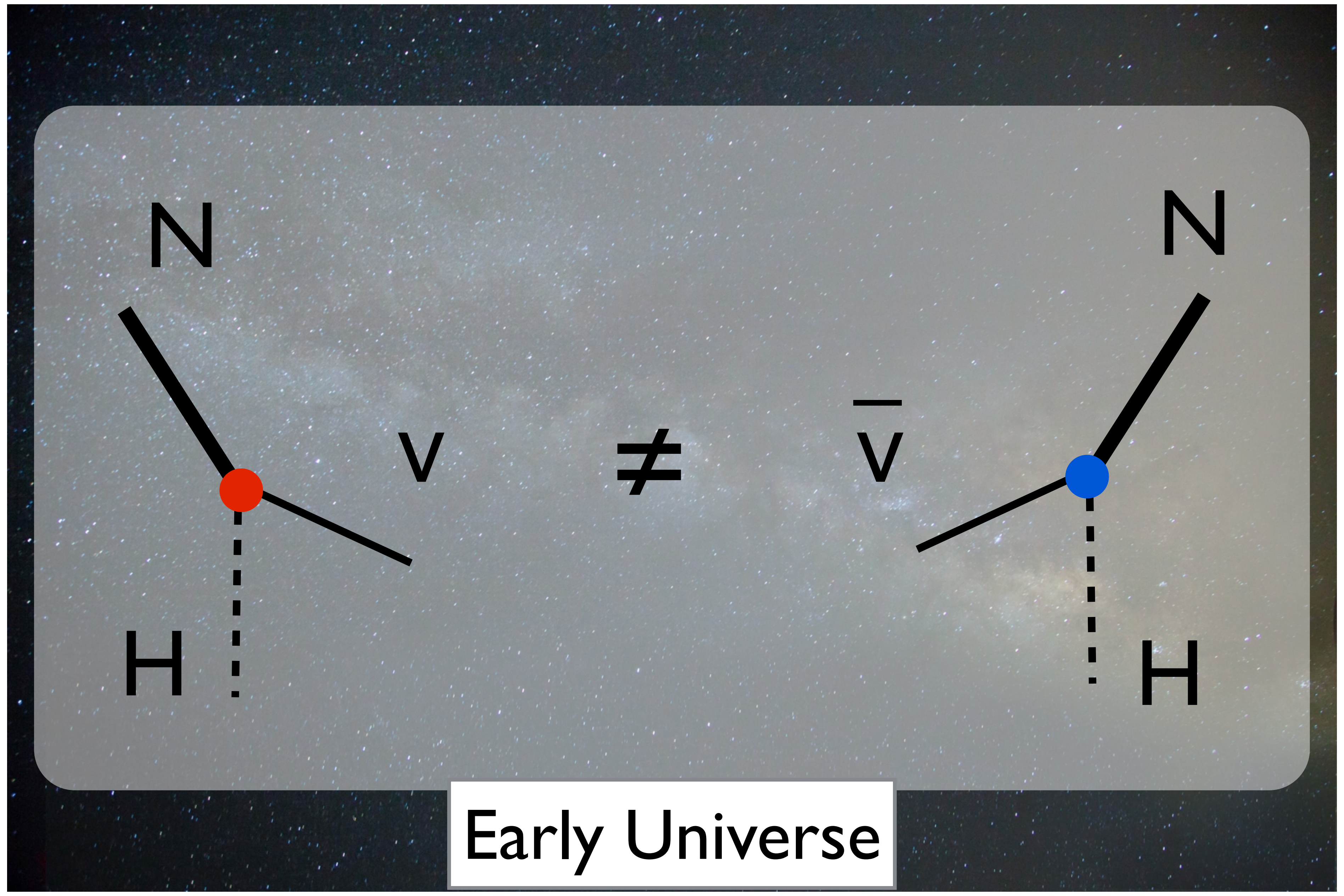
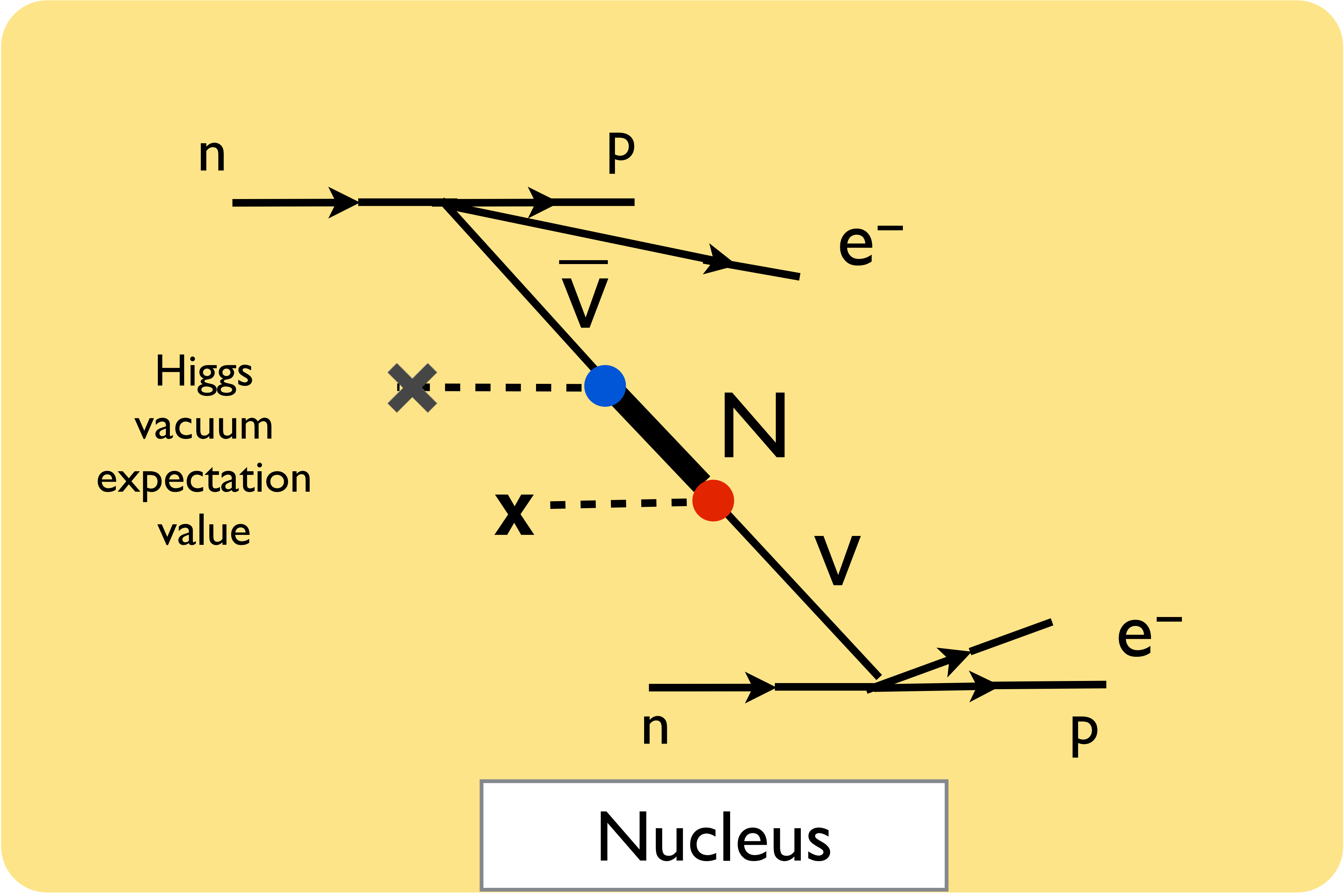
But there's more! The same physics could be responsible for both 0νββ decay and for generating the matter excess in the universe through the *leptogenesis mechanism*

Leptogenesis and 0νββ: a tantalizing connection

Fukugita-Yanagida 1987





Heavy siblings of the neutrinos (N) play key role in generating the matter-antimatter asymmetry by disintegrating into (anti)neutrinos and Higgs (H) particles

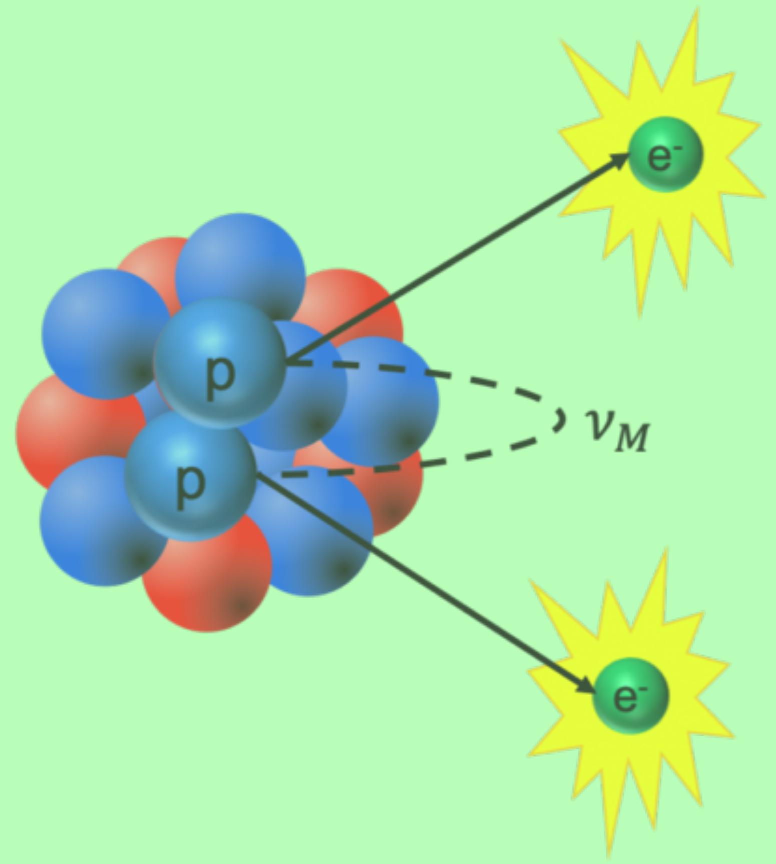
In 0νββ decay, through the lens of Quantum Mechanics, we probe within a nucleus the same interactions that operated in the early universe**

** An anti-neutrino scatters off the Higgs field vacuum expectation value (VEV) and becomes N, then N scatters off the Higgs VEV and becomes a neutrino

The significance of 0νββ decay

Is the neutrino its own antiparticle?

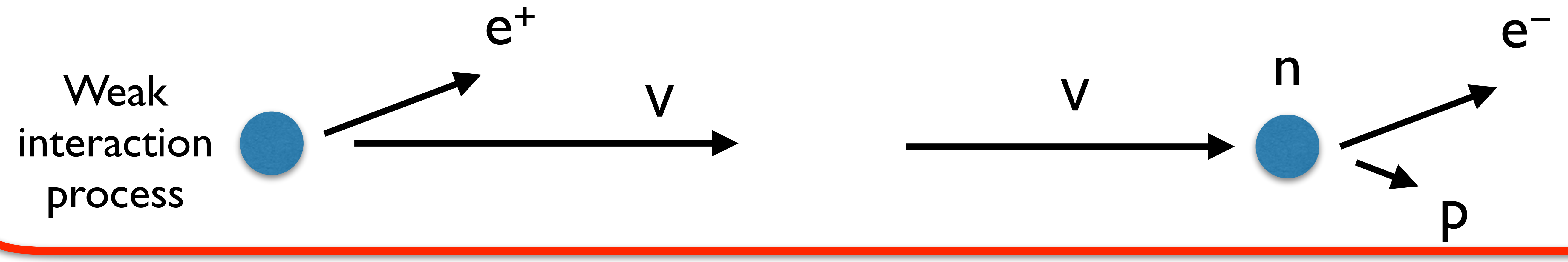
0νββ decay

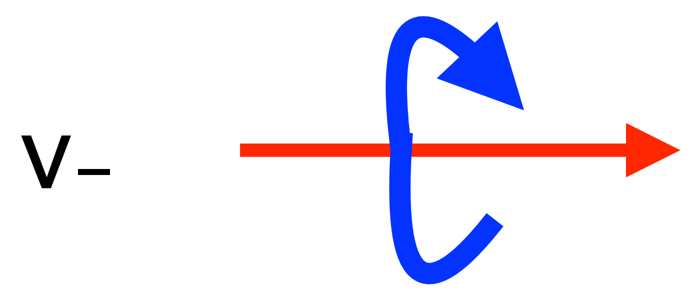


Are neutrinos their own antiparticles?

Neutrino (ν): emitted with e^+, when interacts with matter can transform into e^-

Left-handed: $\mathbf{s} \cdot \mathbf{p} = -1$





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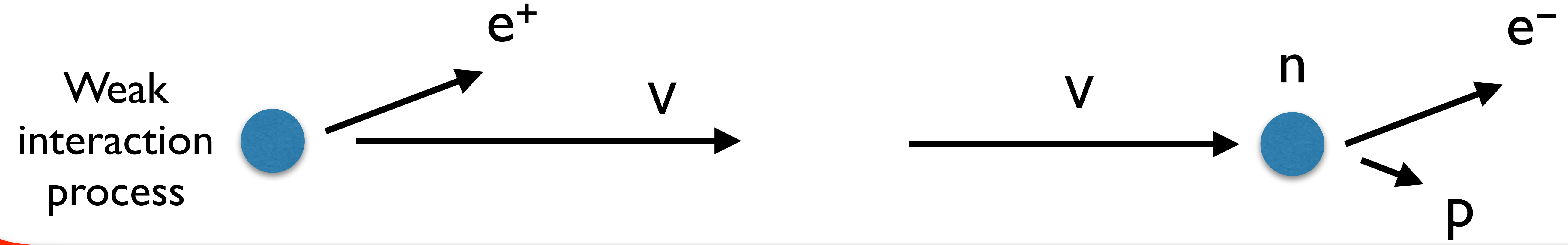

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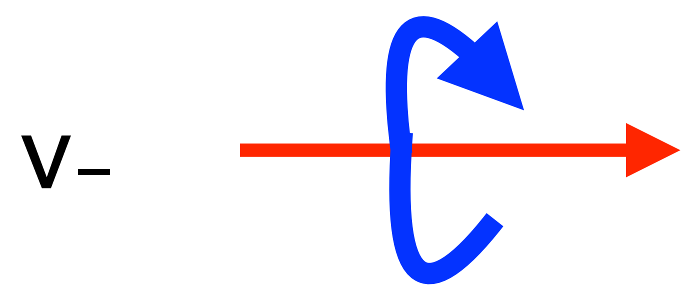
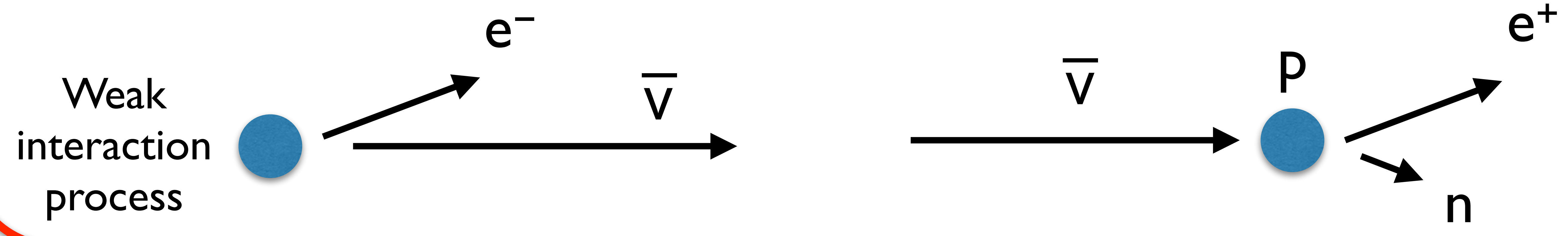
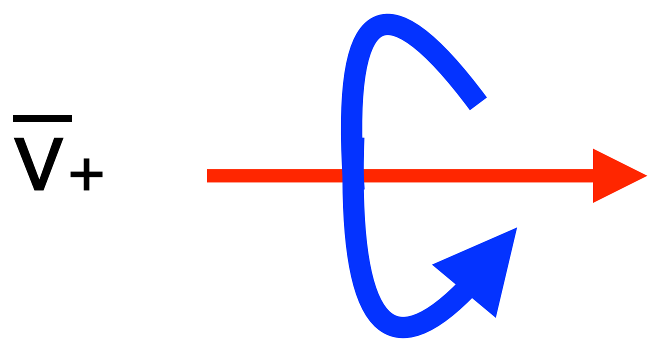


Anti-neutrino ($\bar{\nu}$): emitted with e^-, when interacts with matter can transform into e^+

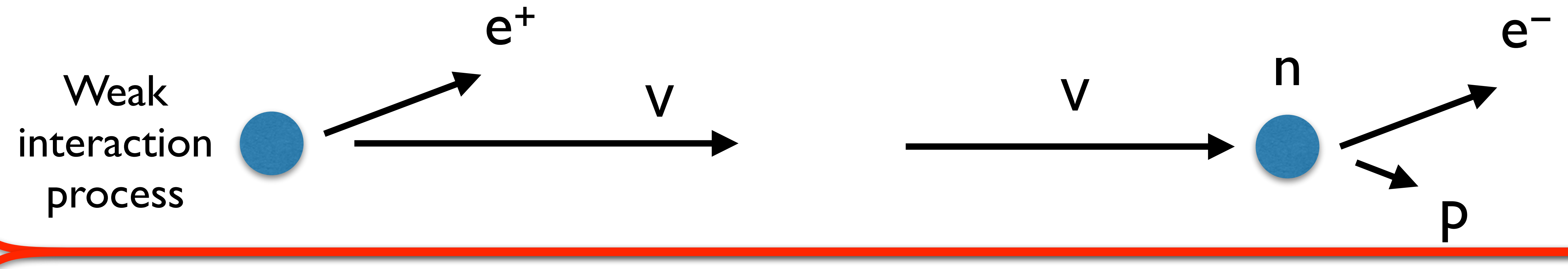


Right-handed: $\mathbf{S} \cdot \mathbf{p} = +1$



Are neutrinos their own antiparticles?

Neutrino (ν): emitted with e^+, when interacts with matter can transform into e^-



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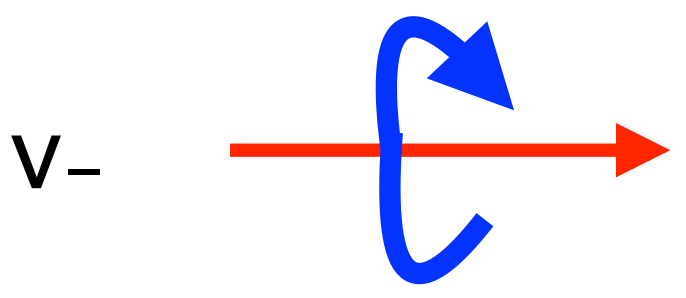
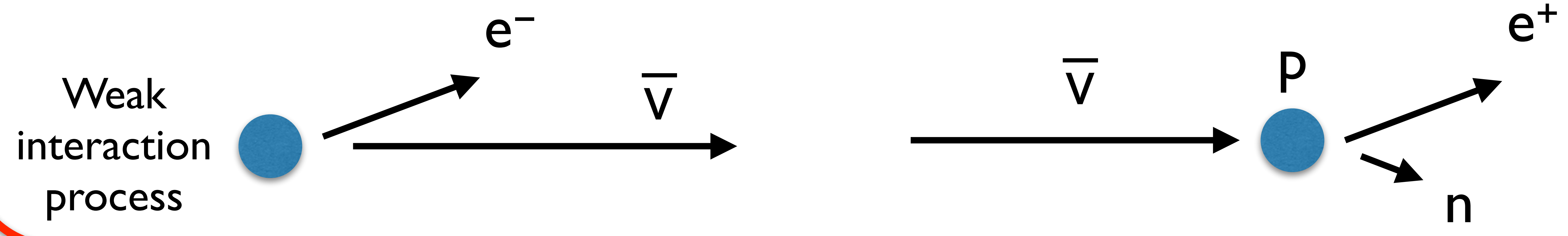


Anti-neutrino ($\bar{\nu}$): emitted with e^-, when interacts with matter can transform into e^+



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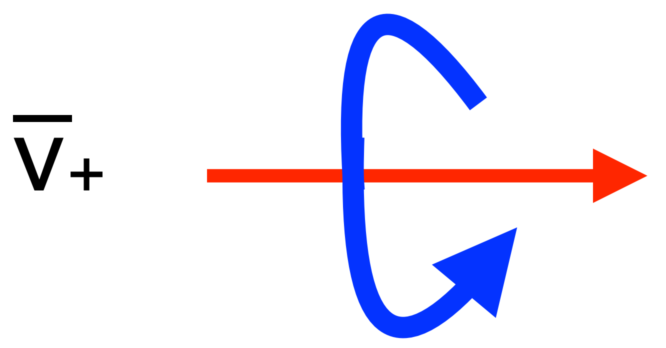


Are these two different spin states of the same particle?

No!

Dirac

Neutrino ≠ anti-neutrino
(similar to electron)

4 states:

$\nu_- \; \bar{\nu}_+ \qquad \nu_+ \; \bar{\nu}_-$

Participate in weak interactions

Yes!

Majorana

Neutrino = antineutrino

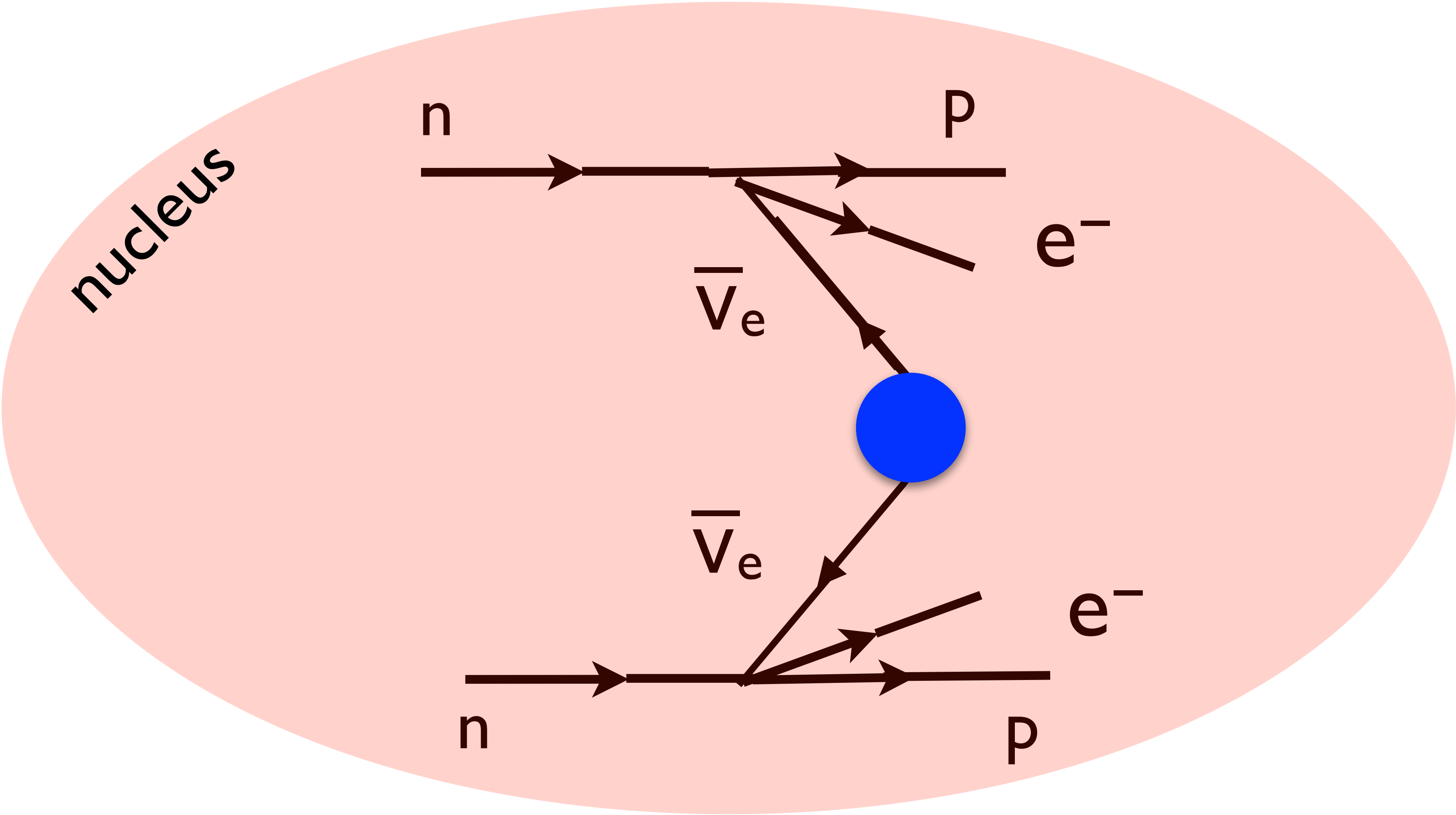
2 states: $\nu_- \; \nu_+$

A new type of spin=1/2 fermion!

0νββ decay is the arbiter

- If massive neutrinos are their own antiparticles, two *virtual* (anti)neutrinos can annihilate and mediate 0νββ decay

Quantum Mechanics
at work here!



Furry 1939

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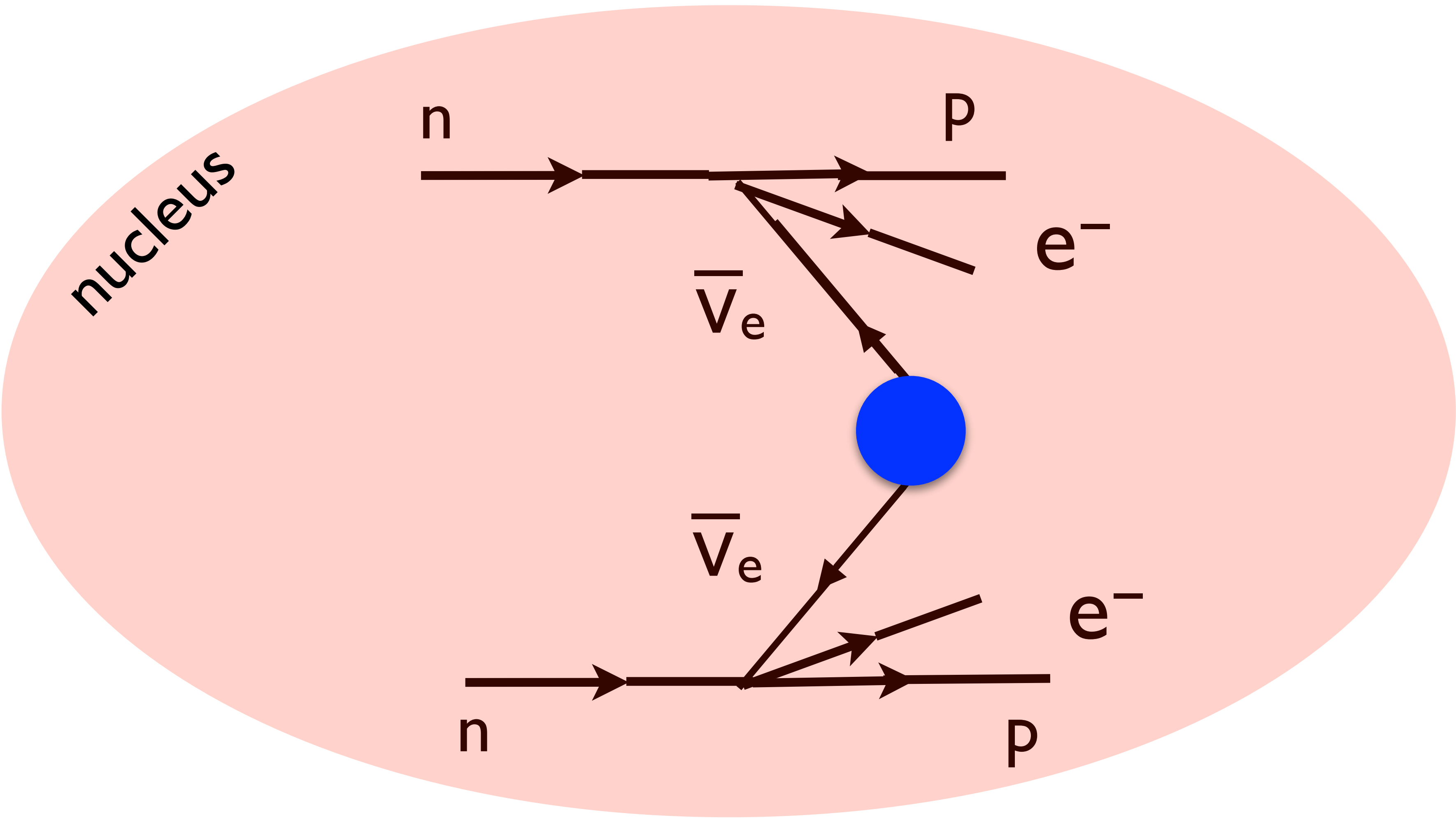
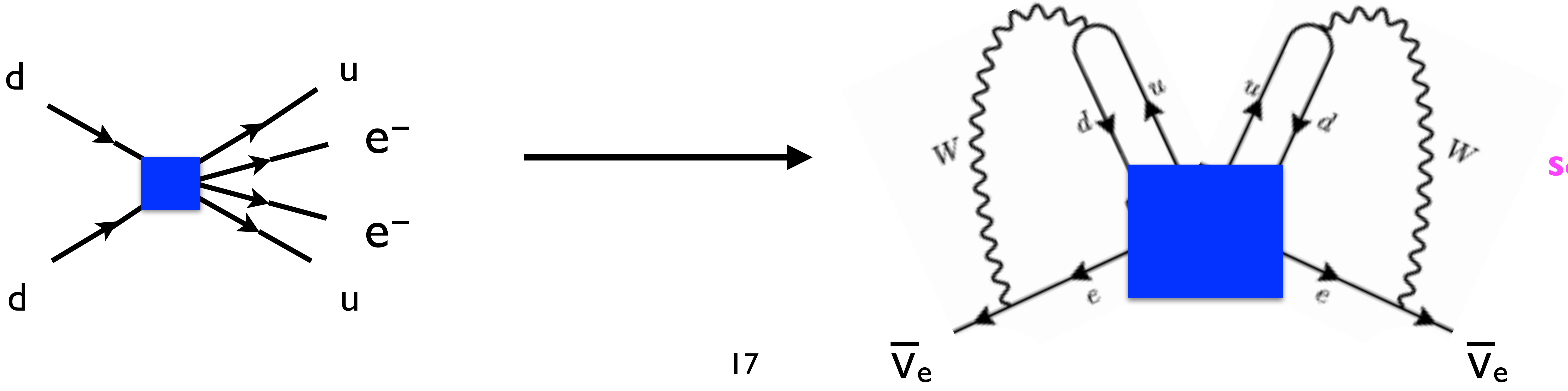


Furry 1939

- If 0νββ decay happens, through *quantum mechanical fluctuations two* $\bar{\nu}$ can annihilate each other ⇒ hallmark of Majorana ν!



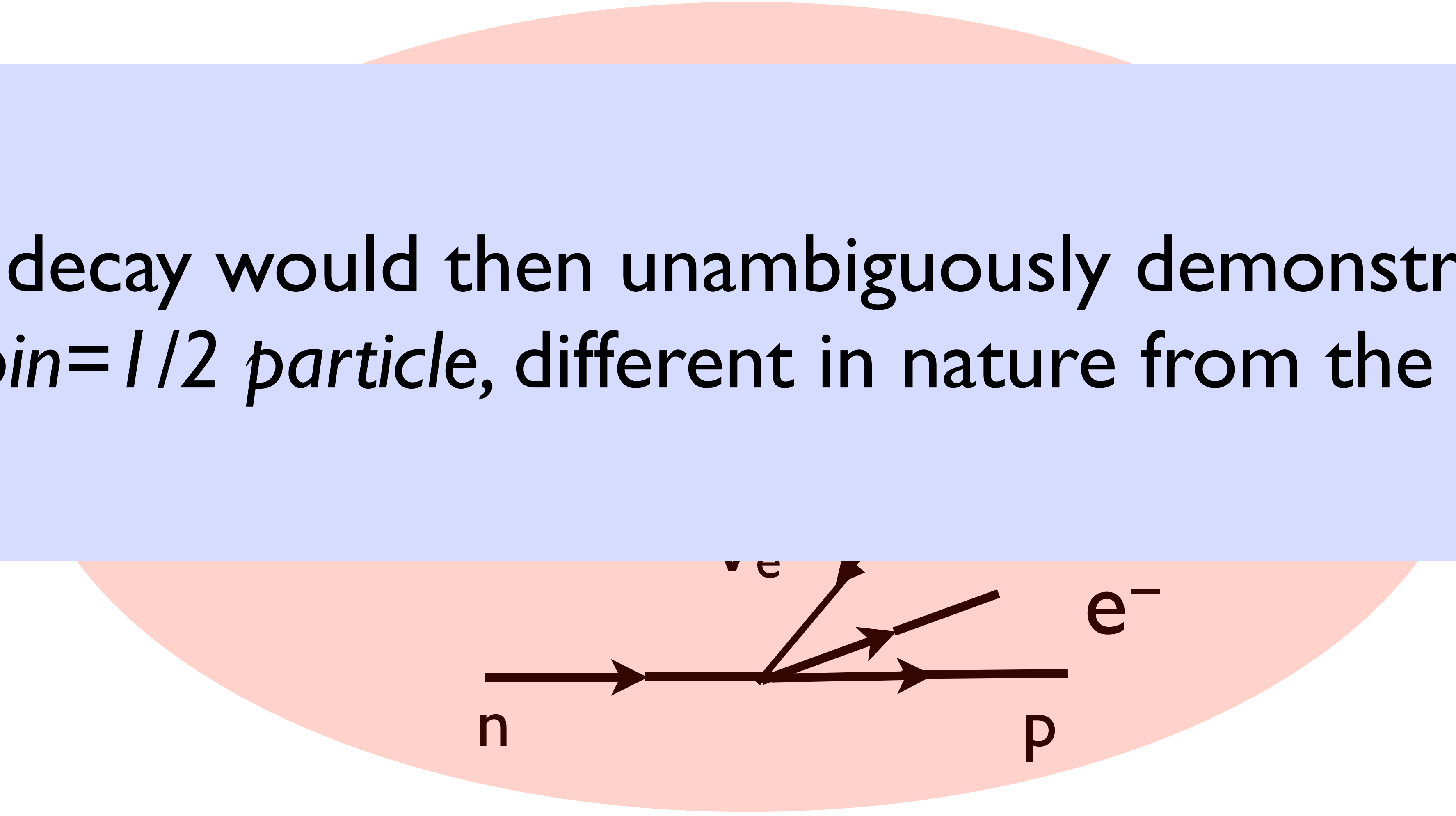
Schechter-Valle 1982

0νββ decay is the arbiter

- If massive neutrinos are their own antiparticles, two *virtual* (anti)neutrinos can annihilate and mediate 0νββ decay

Quant

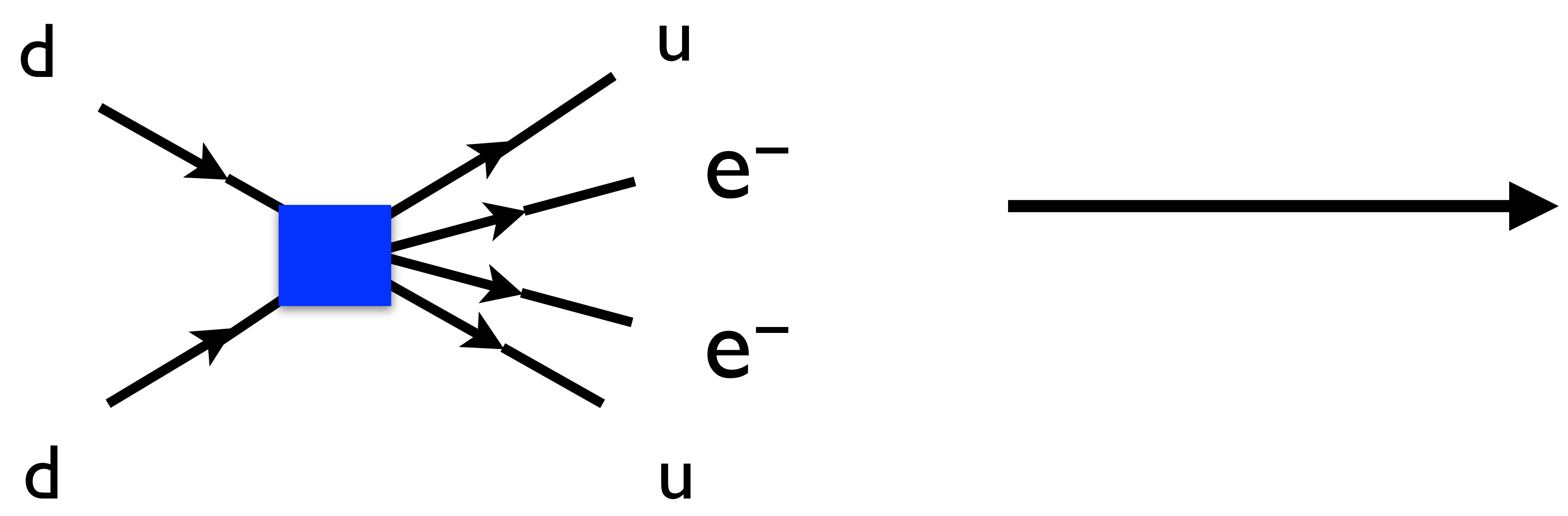
at

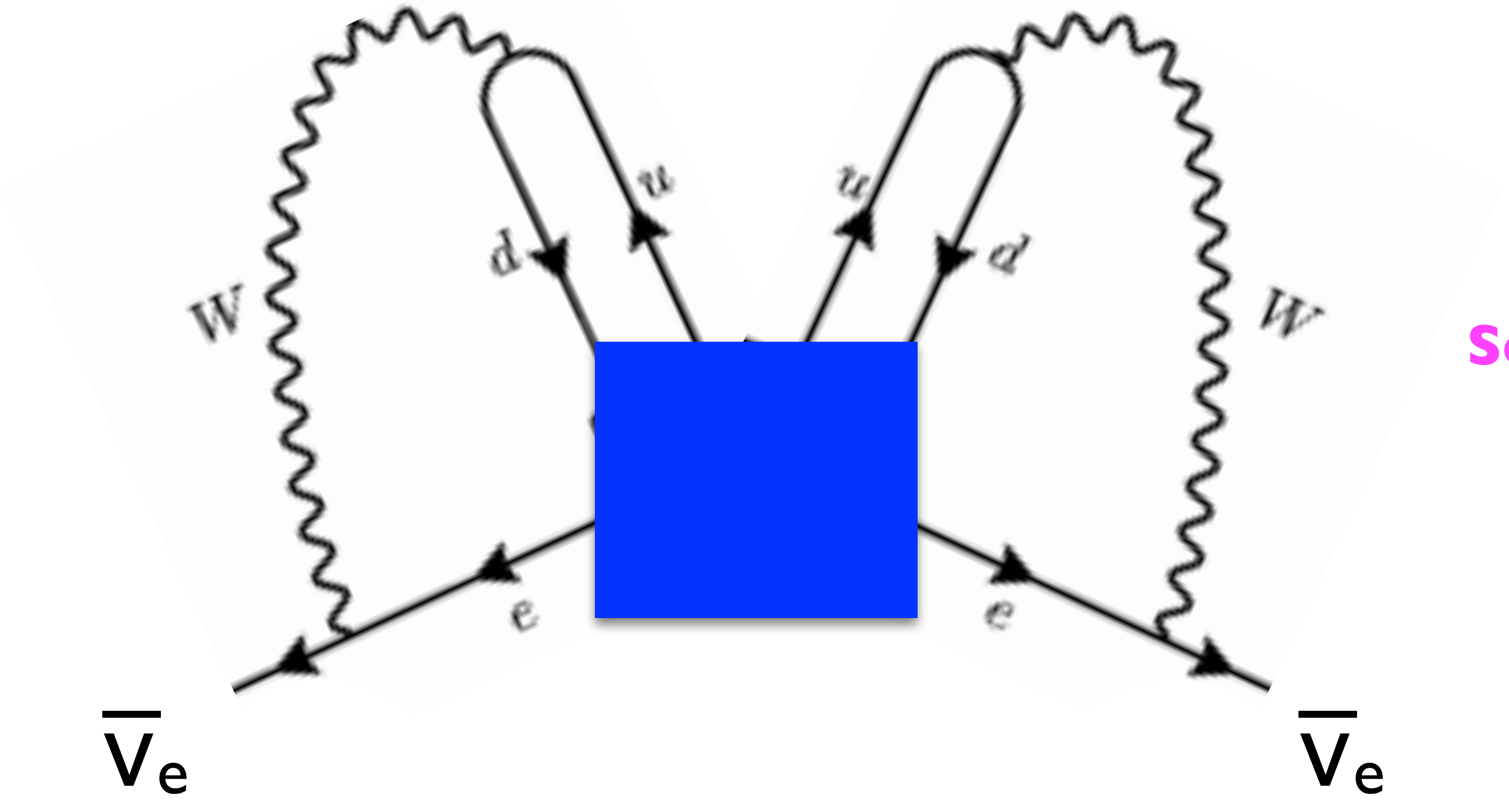


Observation of 0νββ decay would then unambiguously demonstrate that the neutrino is *a new type of spin=1/2 particle,* different in nature from the familiar electron

Furry 1939

- If 0νββ decay happens, through *quantum mechanical fluctuations two* $\bar{\nu}$ can annihilate each other ⇒ hallmark of Majorana ν!





Schechter-Valle 1982

0νββ decay: summary of significance

The neutrino and its mysteries

Demonstrate Majorana nature of massive neutrinos (neutrino=antineutrino)

0νββ decay

A ‘matter-creating’ nuclear process whose observation would have far reaching implications

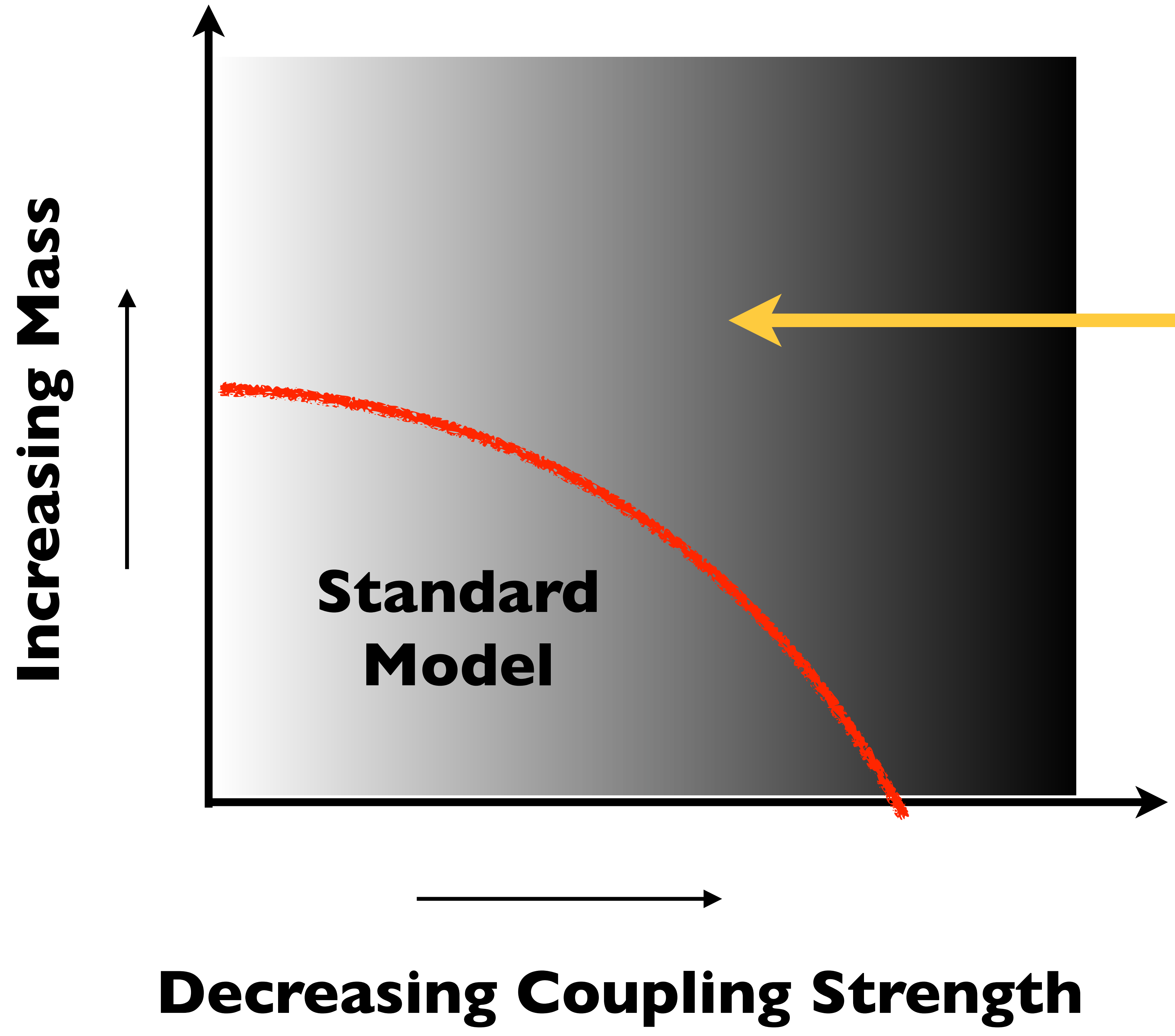
A cosmic mystery

Demonstrate that an excess of matter over antimatter can be created in an elementary process

Point to baryogengesis via leptogenesis

0νββ decay: broad discovery potential

- Ton-scale 0νββ searches [$T_{1/2}$ ~10^{28} yr, 10^{18} times the age of the universe!] can discover Lepton Number Violation from a broad variety of mechanisms that involve different mass scales and interaction strengths



Somewhere out here there must be new physics responsible for neutrino masses

If Lepton Number is not conserved (neutrinos are Majorana particles) this uncharted territory can be uniquely probed by 0νββ decay

0νββ decay: broad discovery potential

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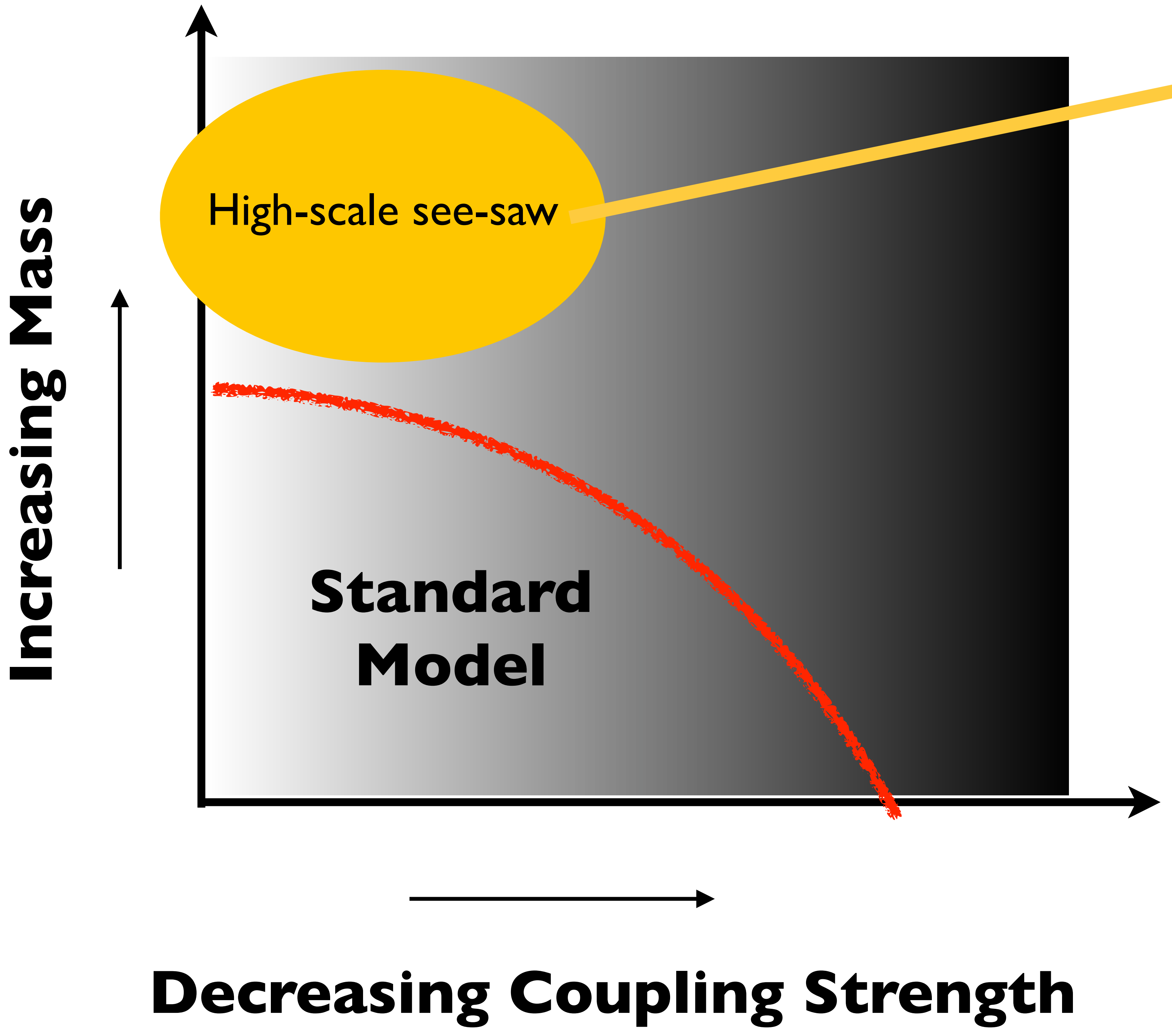
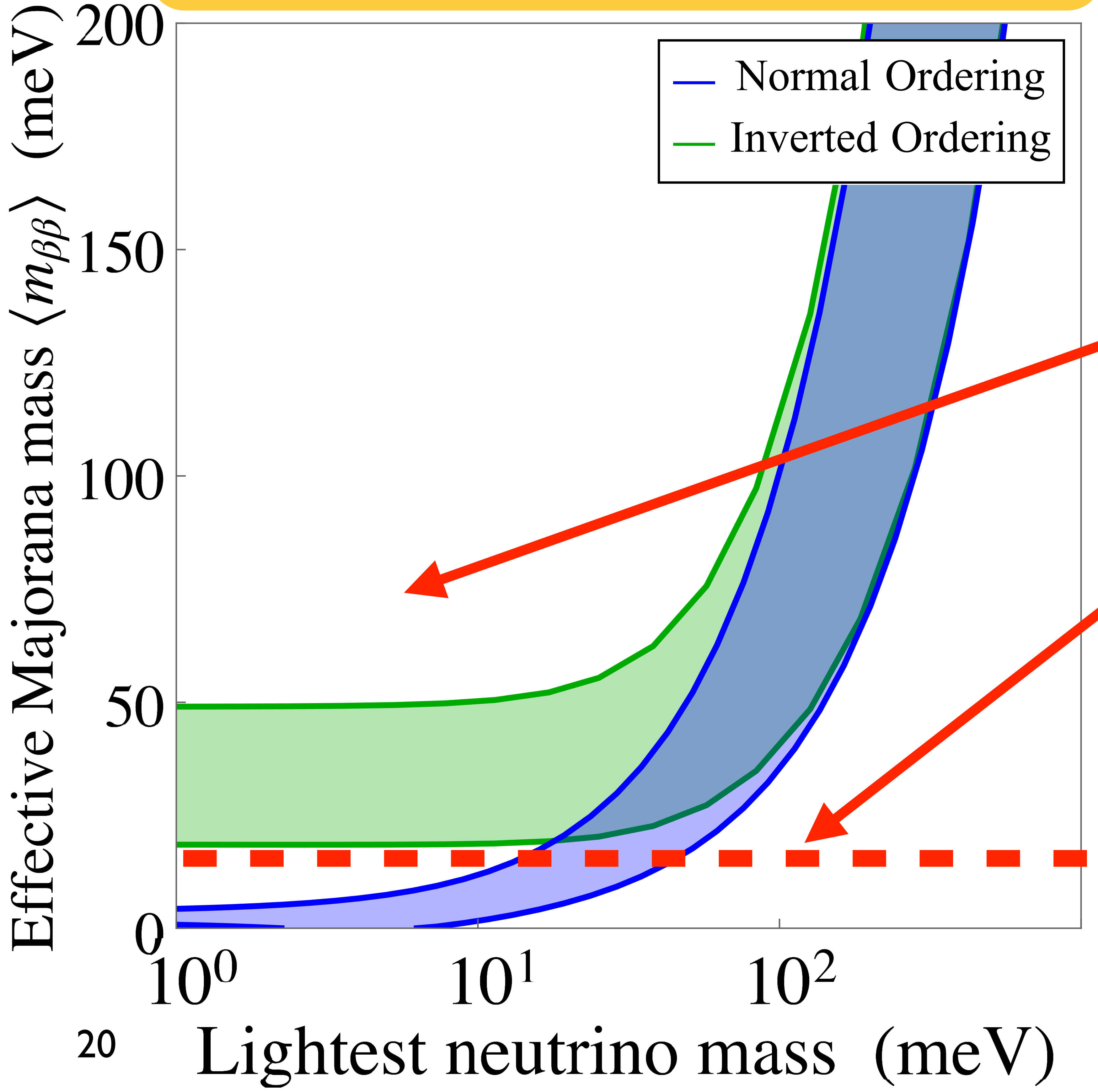
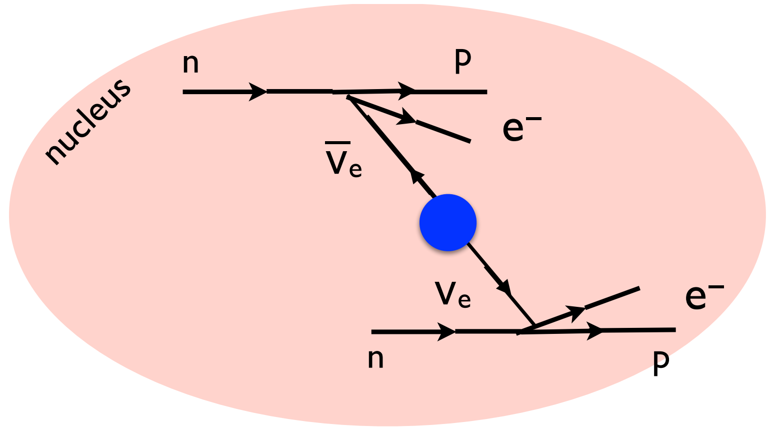


In high-scale models the half-life is related to neutrino mass parameters and concrete discovery targets exist





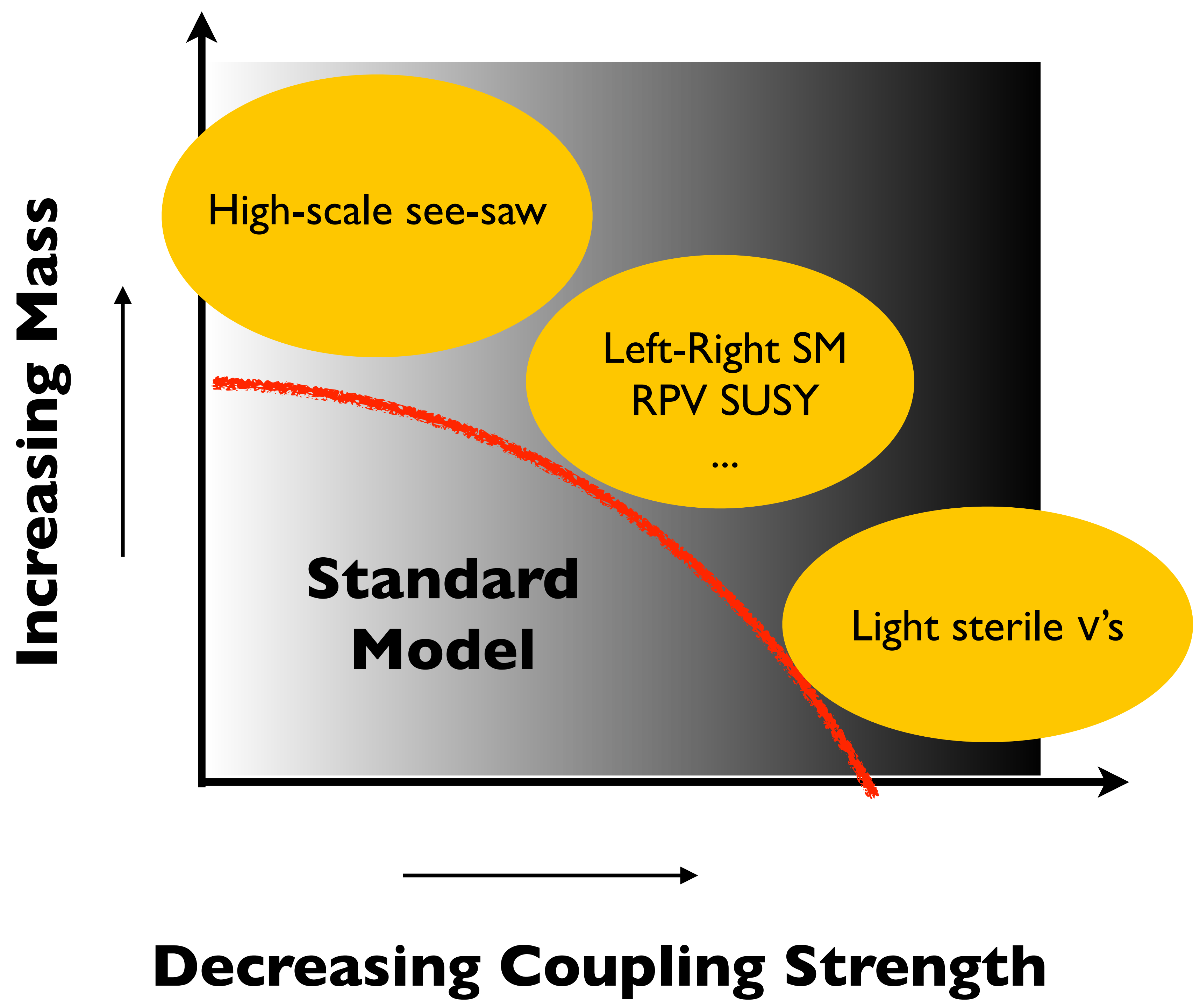
Current reach

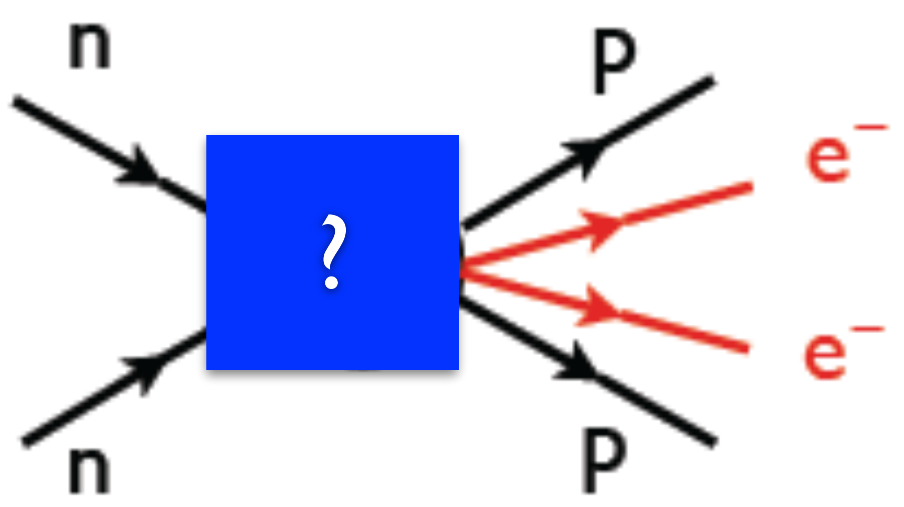
Goal for 'ton-scale' experiments is $m_{\beta\beta} \sim 18$ meV

Large discovery potential regardless of the mass ordering

0νββ decay: broad discovery potential

- Ton-scale 0νββ searches [$T_{1/2} \sim 10^{28}$ yr, 10^{18} times the age of the universe!] can discover Lepton Number Violation from a broad variety of mechanisms that involve different mass scales and interaction strengths

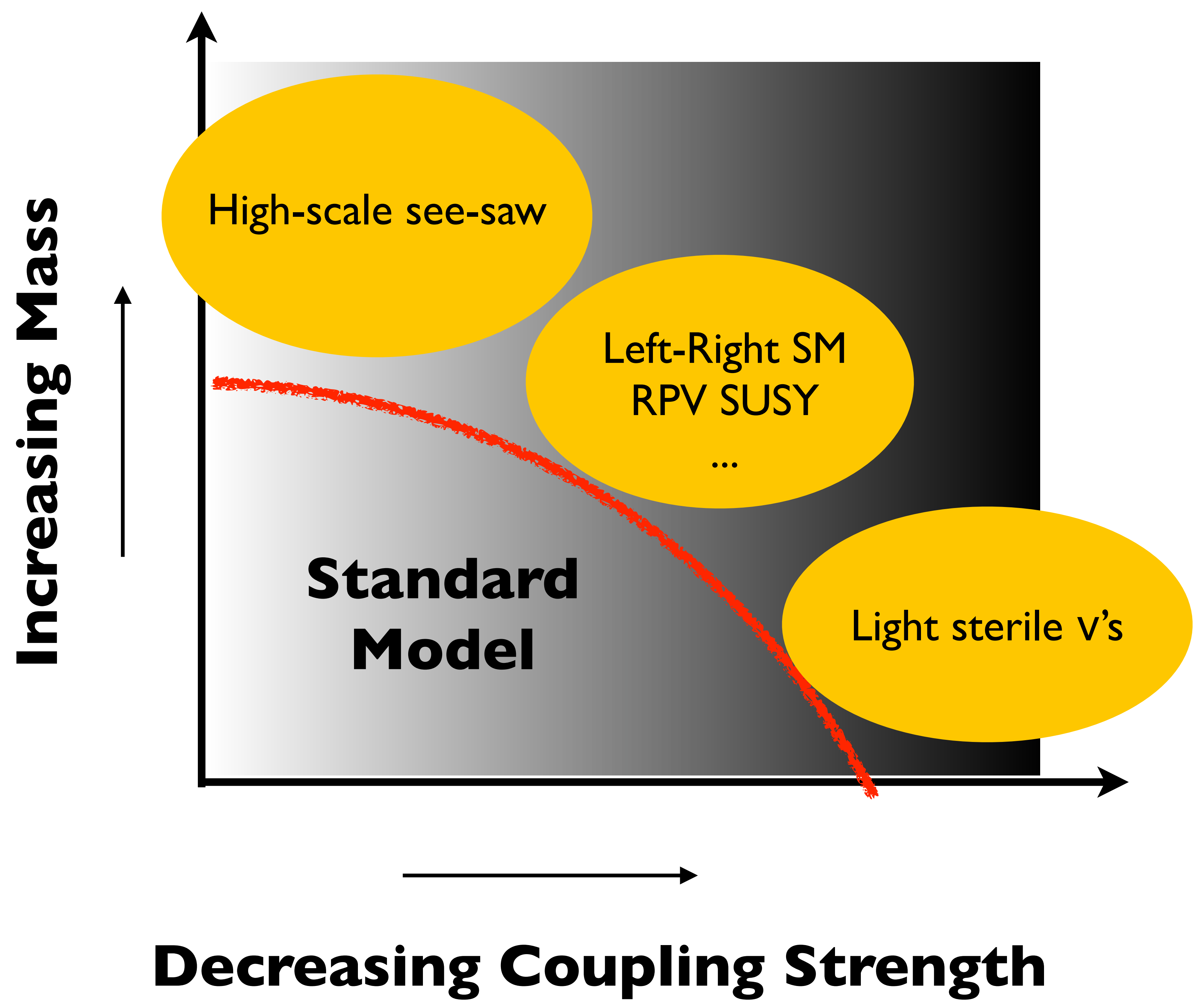


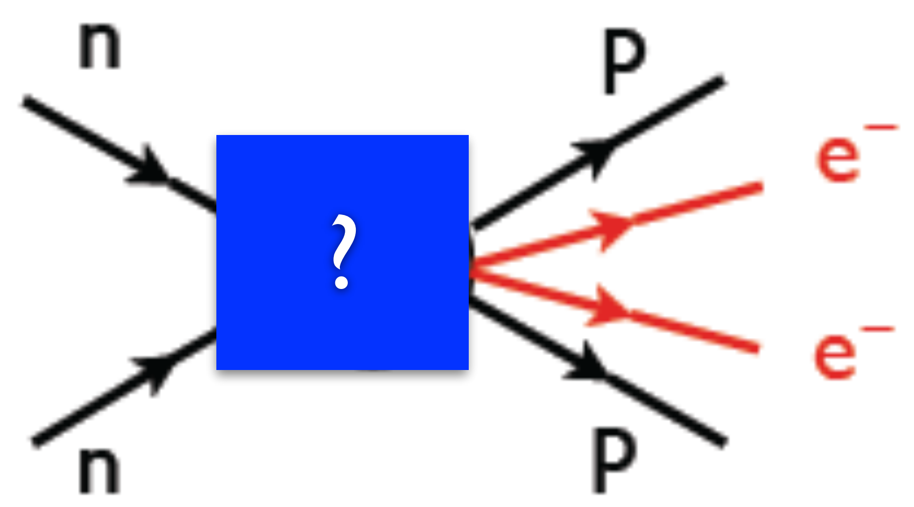


Many other new physics scenarios exist.
No single metric for discovery potential.
This is a "feature", not a "bug".

$0\nu\beta\beta$ decay: broad discovery potential

- Ton-scale $0\nu\beta\beta$ searches [$T_{1/2} \sim 10^{28}$ yr, 10^{18} times the age of the universe!] can discover Lepton Number Violation from a broad variety of mechanisms that involve different mass scales and interaction strengths





Many other new physics scenarios exist.
No single metric for discovery potential.
This is a "feature", not a "bug".

A corollary of this discussion:
Theoretical research is essential for understanding the underlying physics of any experimental signal

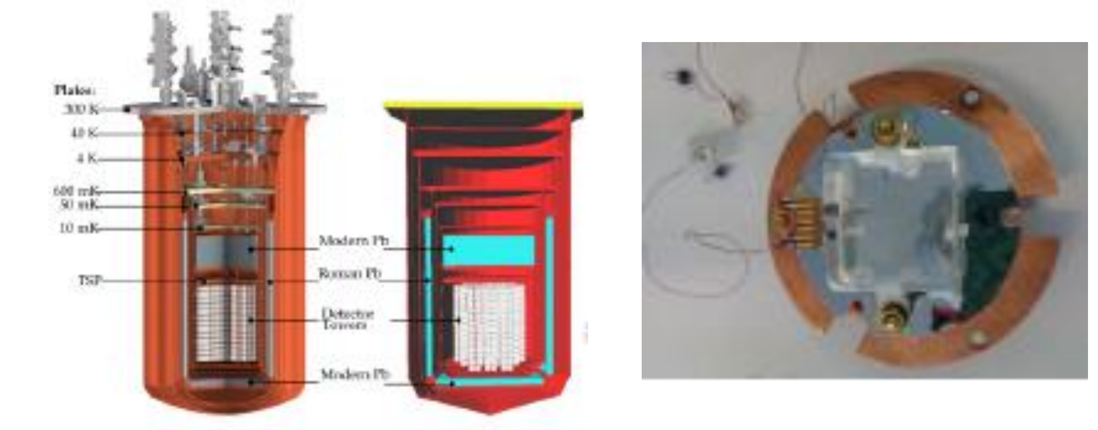
Example: NSF-funded theory hub

@NDB
Advancing Theory for Nuclear Double-Beta Decay
A Focused Research Hub in Theoretical Physics

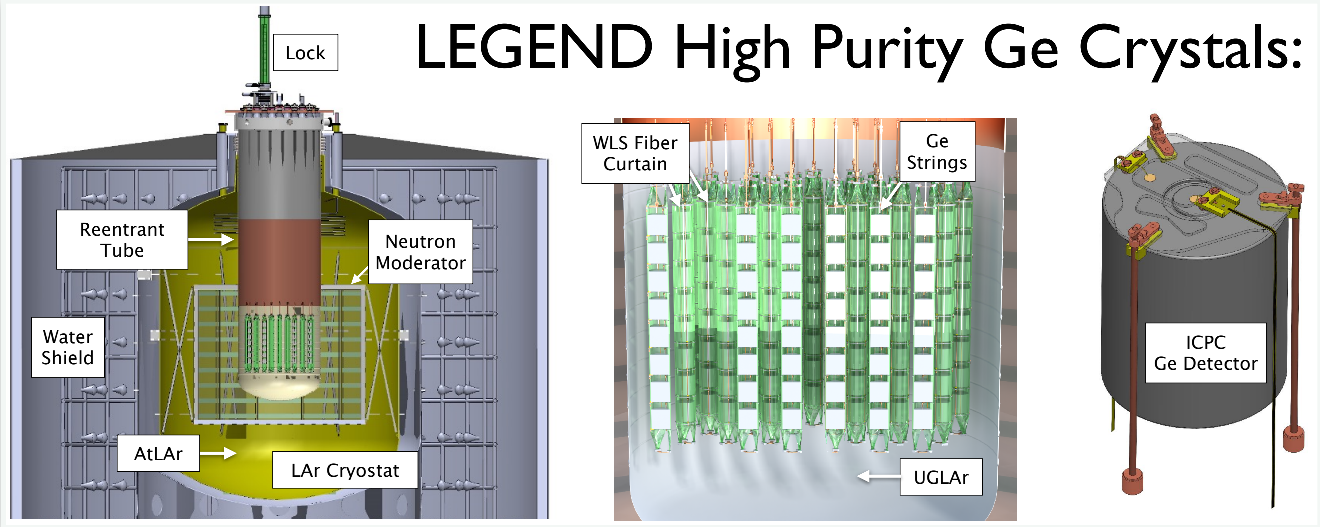
Experimental landscape and path forward

- Ongoing experiments and technology demonstrators have proven the principles required for successful $0\nu\beta\beta$ searches at the ton-scale
- The international ton-scale program consists of three experiments using three different isotopes and very different experimental technologies: CUPID (^{100}Mo), LEGEND-1000 (^{76}Ge), and nEXO (^{136}Xe). The three experiments have undergone a DOE portfolio review and are ready to start construction
- Multiple experiments with different isotopes, backgrounds, and detector systematics are needed to confirm a discovery. Long time frame for construction and operations calls for simultaneous deployment

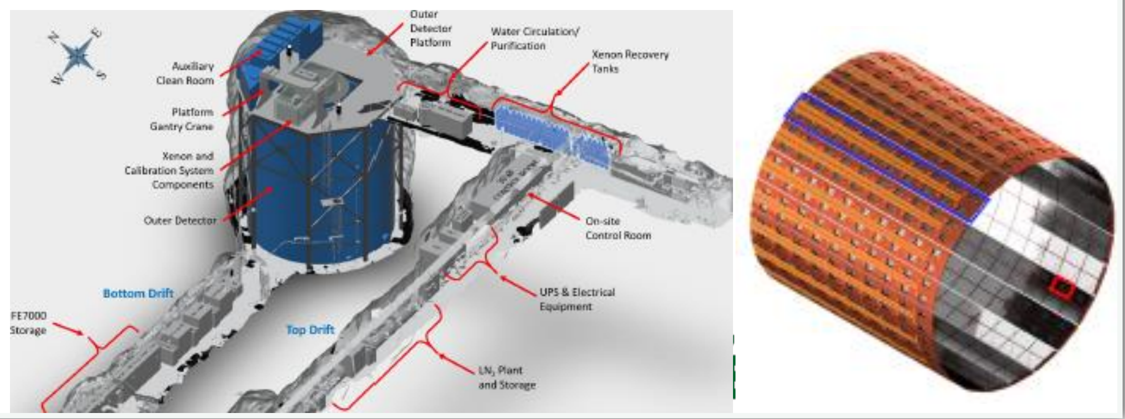
CUPID: Scintillating Crystal Bolometer



LEGEND High Purity Ge Crystals:



nEXO: Liquid Xe Time Projection Chamber



Capitalizing on investment, technology, and workforce developed over the years, the US is in the position to lead an international effort to address this exciting science

Part 2:
Communicating the science of
$0\nu\beta\beta$ decay

Switching hat

- I was also asked to seed a broader discussion on communicating the science of $0\nu\beta\beta$ decay
  - Reaching a broader audience: a (rough) script + vignettes
  - The infrastructure aspects: communication channels, resources, areas of improvement

Communicating 0νββ to any audience

- The science case for any audience could be built around the three key elements presented in Part I of the talk:

The neutrino and its mysteries:
Where does its mass come from?
Is the neutrino its own antiparticle?

A cosmic mystery:
how did we survive the big bang?

0νββ decay:
a ‘matter-creating’ nuclear process that sheds light on both these fundamental questions

Content should be tuned, but template works from a physics colloquium to a TED talk

A rough script (1)

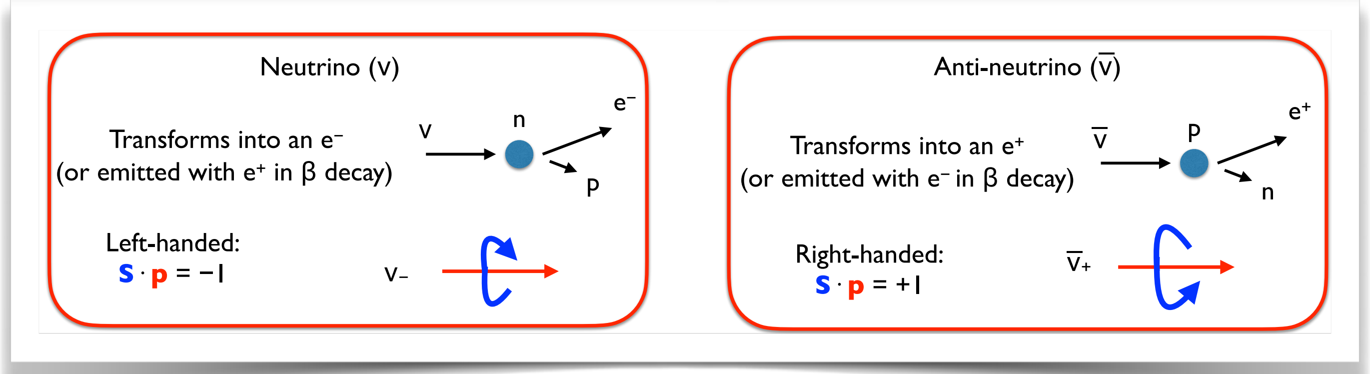
The neutrino and its mysteries

Most elusive of the known particles.
Neutrinos take us beyond the Standard Model.
Several properties still unknown.
In fact we don't know yet whether they are their own antiparticles!
While mysterious themselves, neutrinos may hold the key to unlock other mysteries in the universe, in particular the puzzle of the cosmic matter-antimatter asymmetry.

The script would contain these elements (connection to deep science questions) accompanied by better graphics and movies …

A cosmic mystery

Antimatter, pair-creation and pair annihilation.
Brief history of the universe.
'Movie' showing the great annihilation.
The necessity of baryogengesis,, i.e. the dynamical generation of the 1ppb matter-antimatter imbalance in the early universe.
Sakharov conditions.
How can neutrinos and $0\nu\beta\beta$ decay help?



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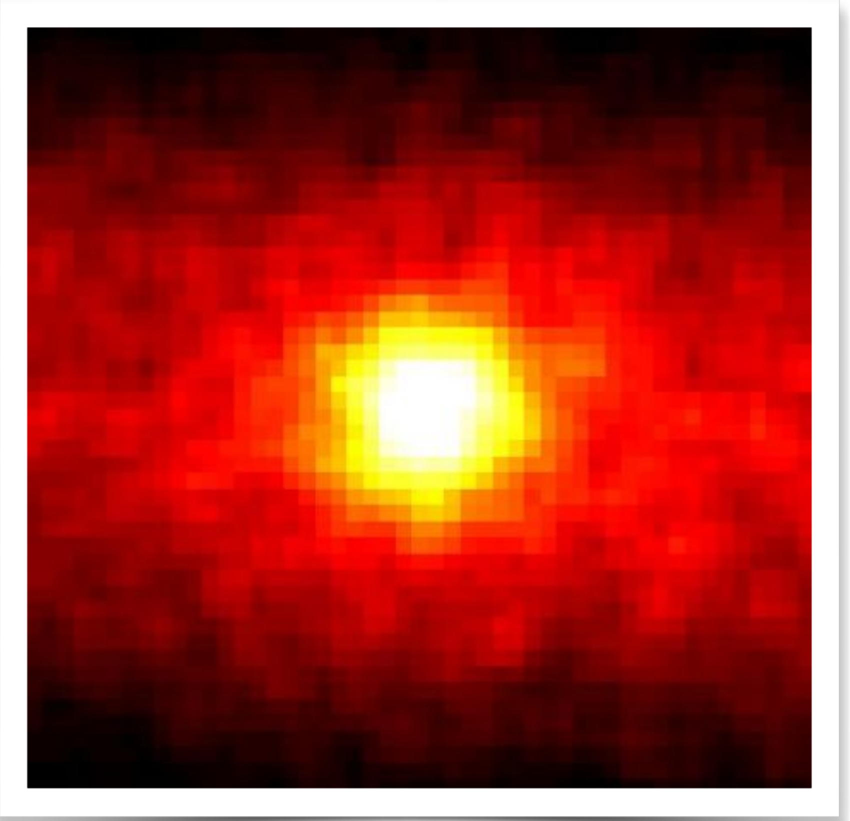
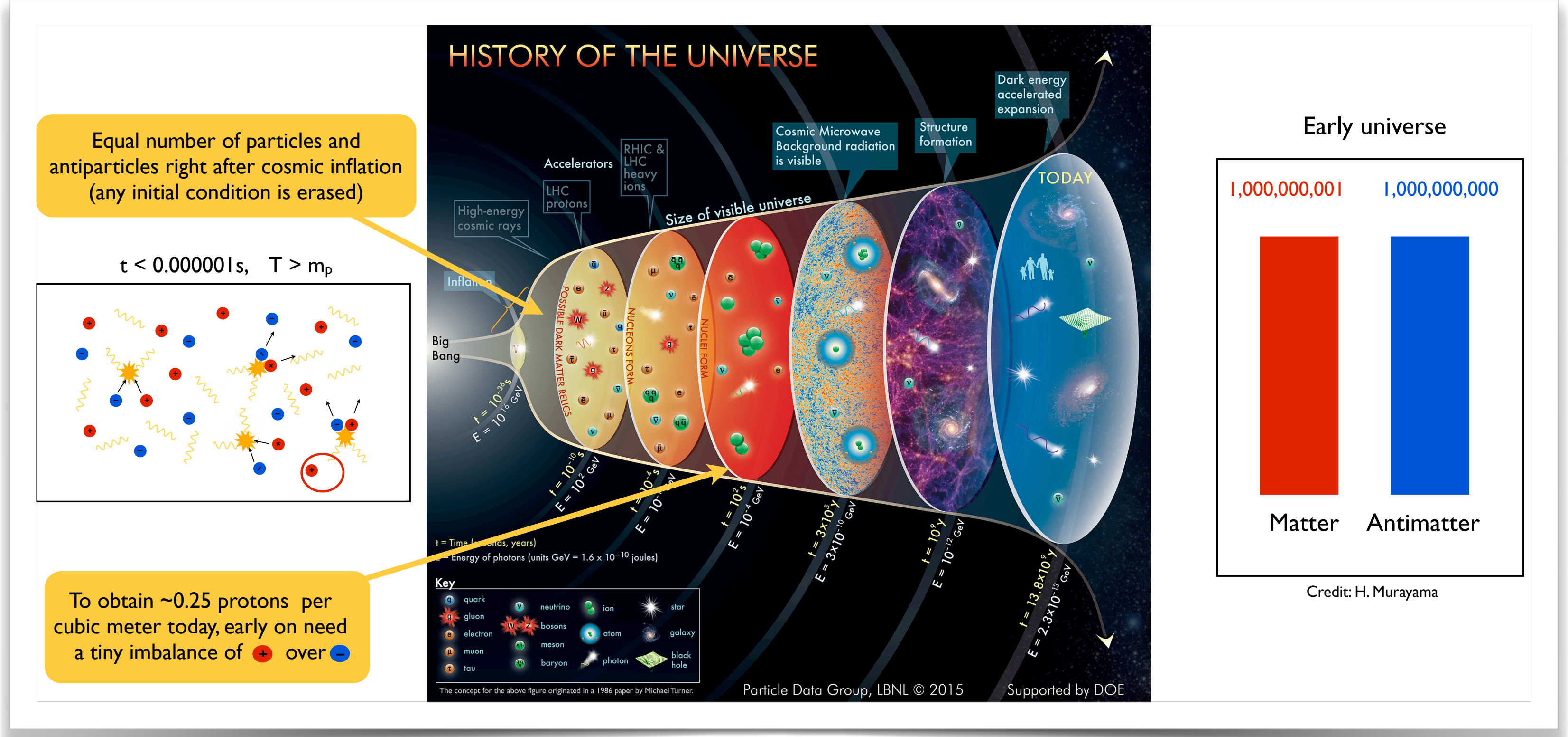
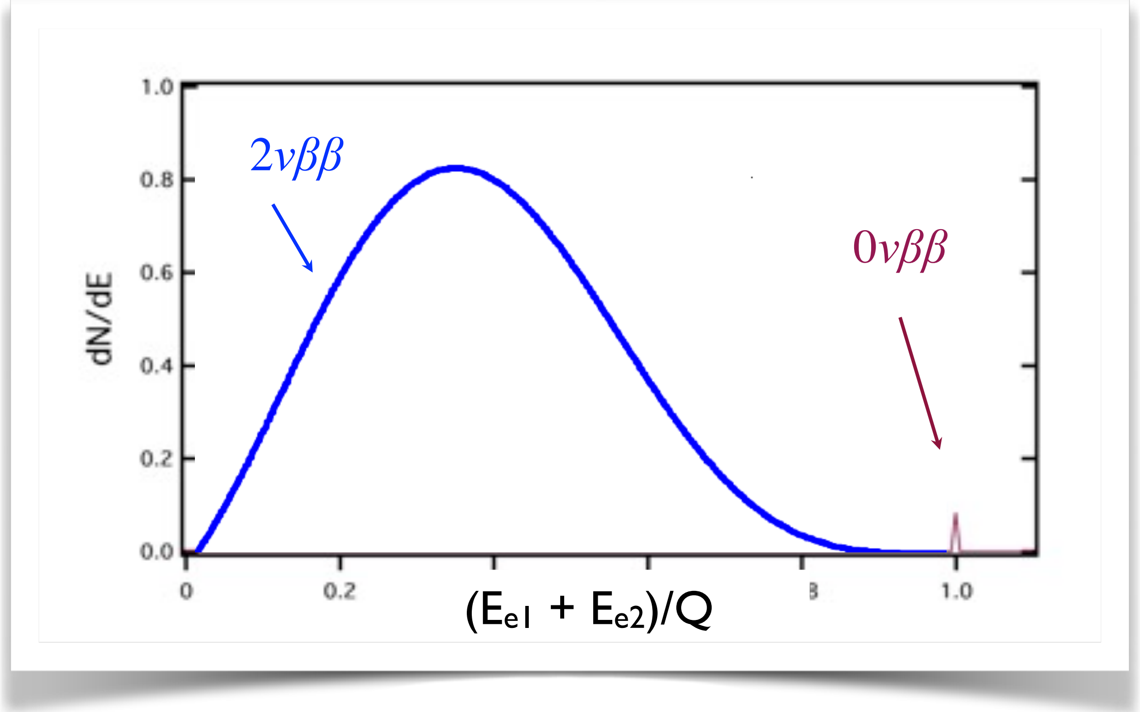


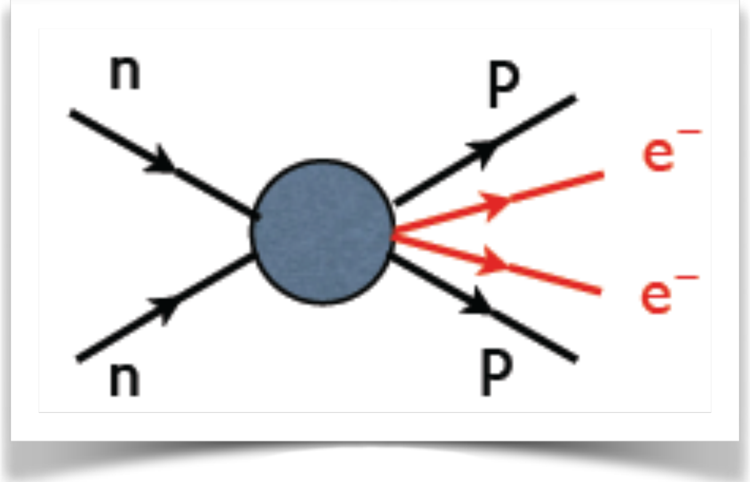
The sun in neutrino
(credit SuperK collaboration)

…



A rough script (2)

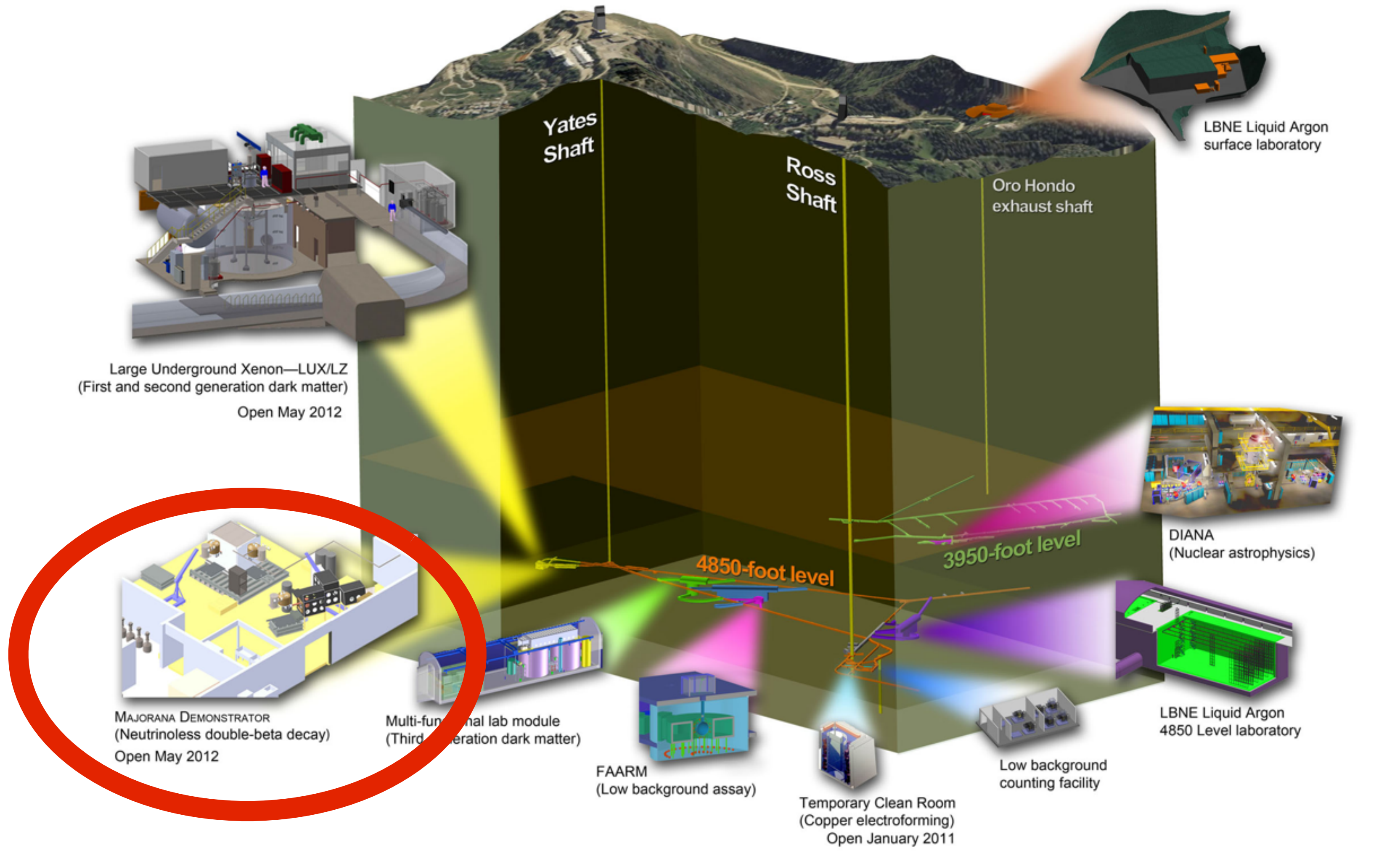




0νββ decay

What is it and how do we search for it.
To minimize backgrounds,
work done in underground laboratories.
Use ultra-pure materials.
Among quietest places in the universe.
New technologies, applicable elsewhere.
Societal impacts (workforce development,
national security, …).
…

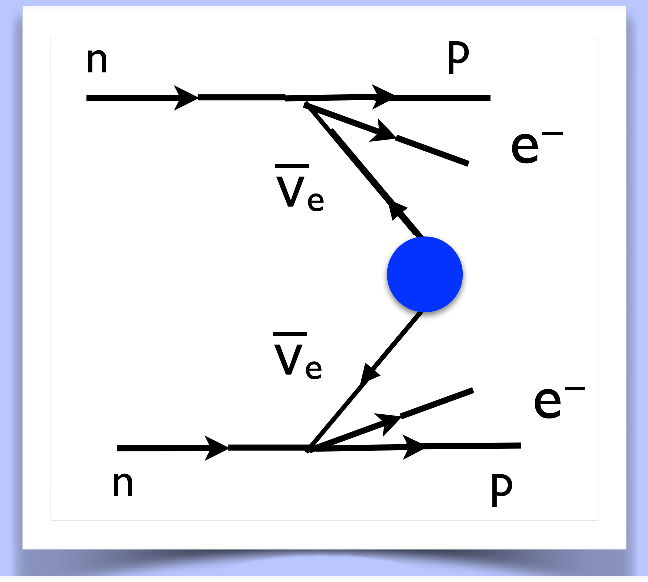
SURF (Sanford Underground Research Facility)

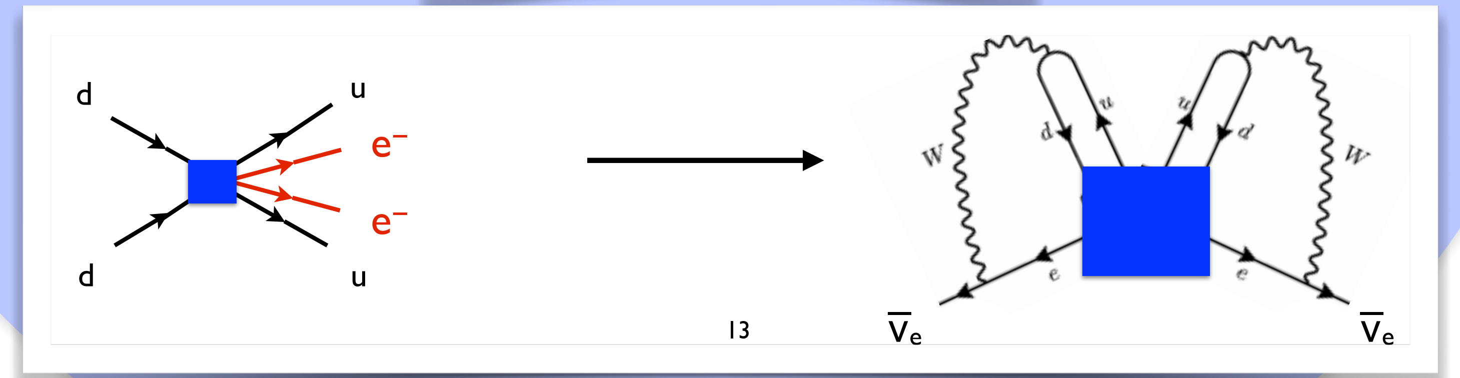


…and a component on how we look for 0νββ, decay, that includes the fascinating aspects of low-background science and articulates the societal impacts

A rough script (3)

The neutrino and its mysteries



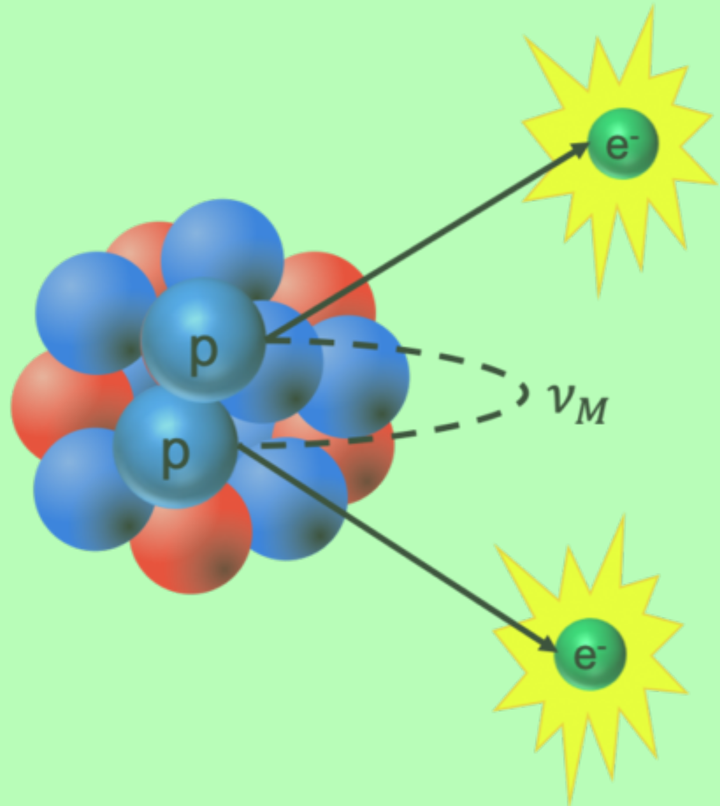


Neutrino = anti-neutrino ⇔ 0νββ occurs

Establish the nature of neutrinos

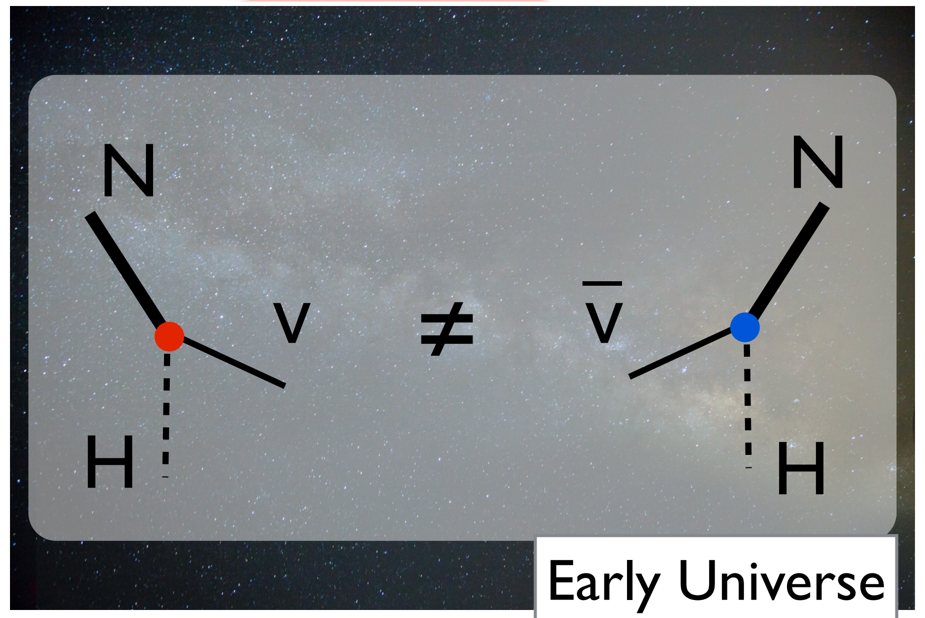
…and finally a component tying everything together: how 0νββ decay addresses the mysteries

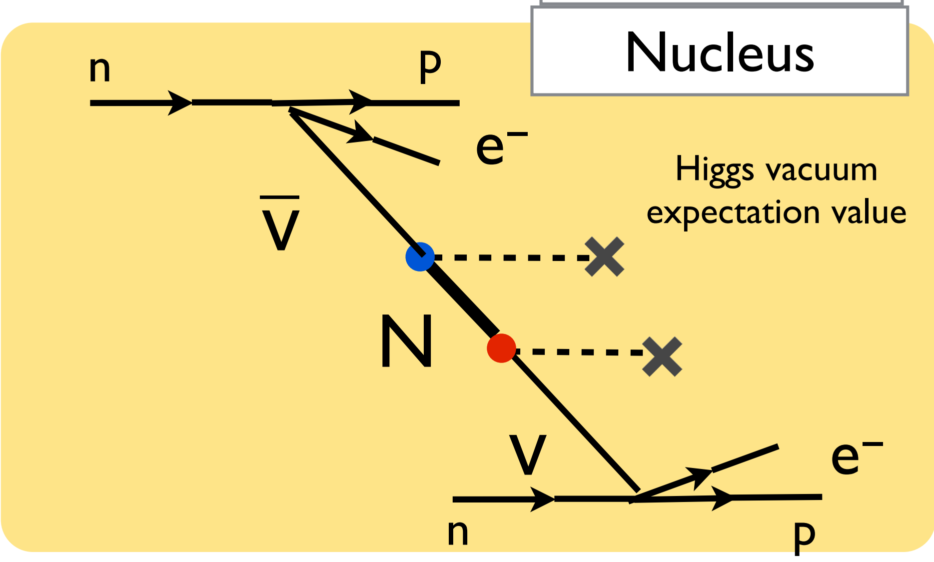
0νββ decay



A matter-creating process!

A cosmic mystery





Through the lens of Quantum Mechanics the nucleus lets us take a glimpse at what might have happened in the early universe!

Communicating $0\nu\beta\beta$: the infrastructure

Who's the audience? / Tools and issues	NP community & funding agencies	Funding agencies beyond NP, congressional staff	General public
Communication channels			
Resources			
Challenges and opportunities for improvements			

There is a compelling science case.
Clear societal benefits and broader impacts.
What infrastructure do we have to communicate them?

Communicating $0\nu\beta\beta$: the infrastructure

Who's the audience?

Tools and issues

NP community & funding agencies

Funding agencies beyond NP, congressional staff

General public

Communication channels

Resources

Challenges and opportunities for improvements

Well established channels, resources, and pipeline

- Conferences & workshops
- White papers
- NSAC Long Range Plan
- Capitol Hill Day
- …

- APS DNP, …
- NSAC, DNP Funding Committee
- LRP Town Halls, Snowmass meetings
- …

Communicating 0νββ: the infrastructure

Who's the audience?

Tools and issues

NP community & funding agencies

Funding agencies beyond NP, congressional staff

General public

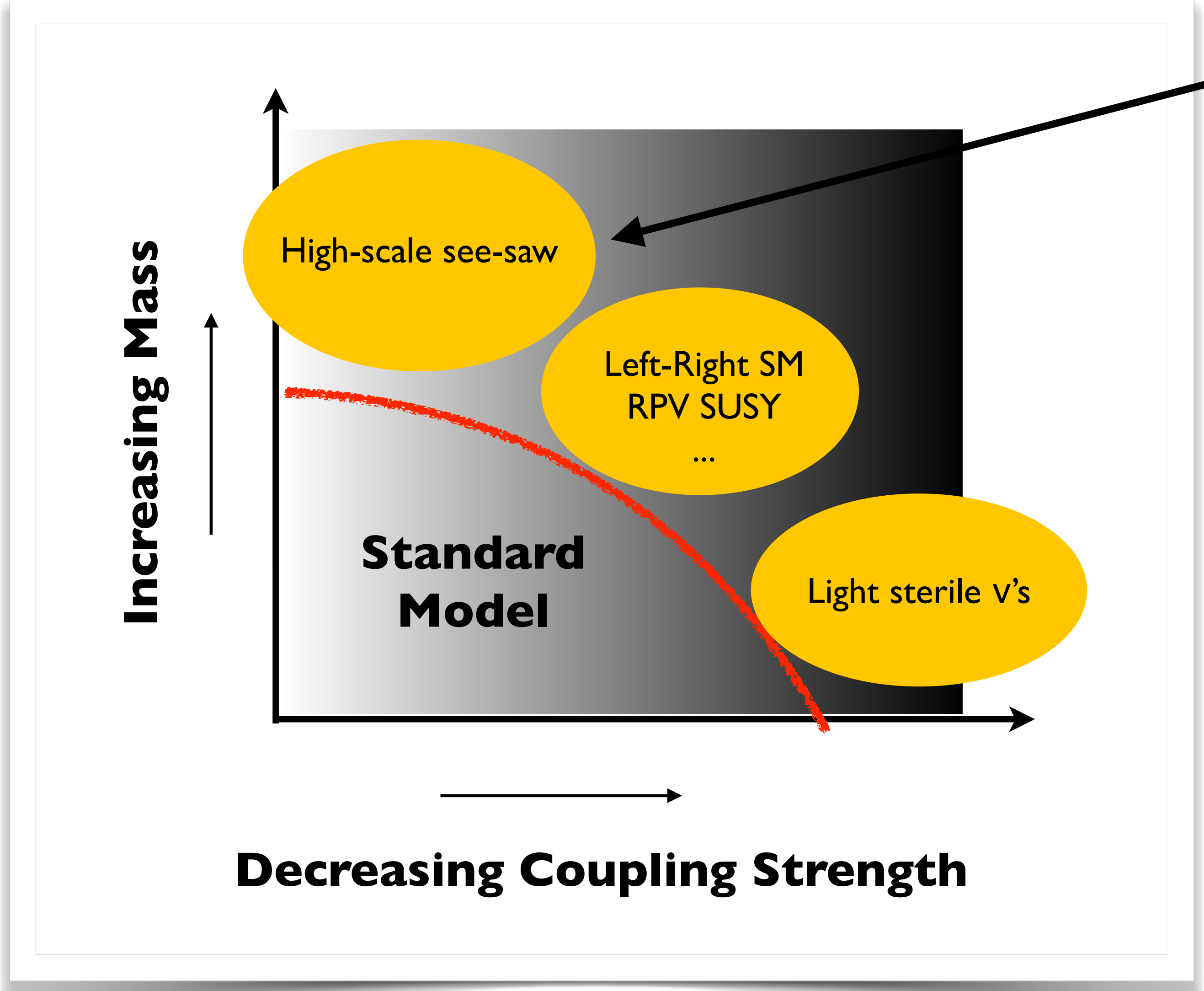
Communication channels

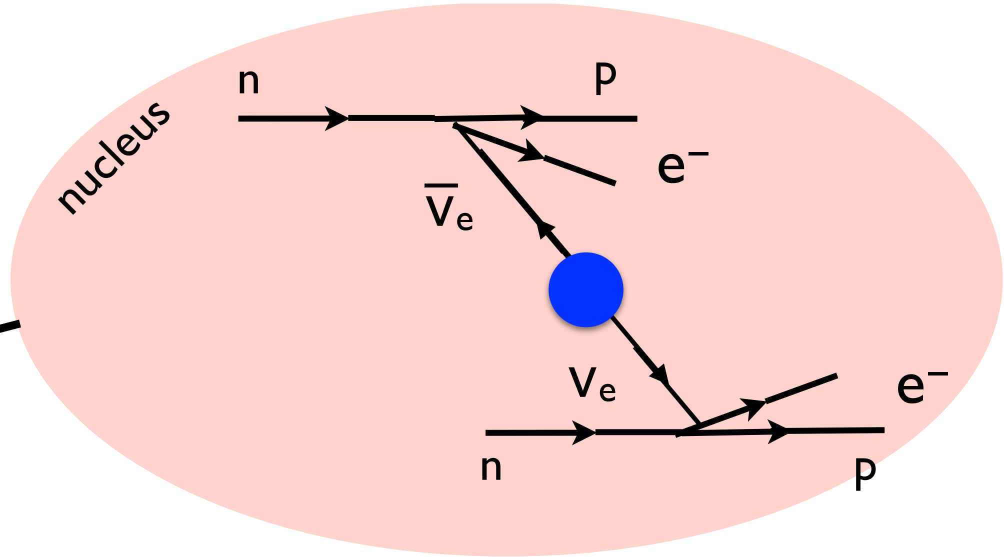
Resources

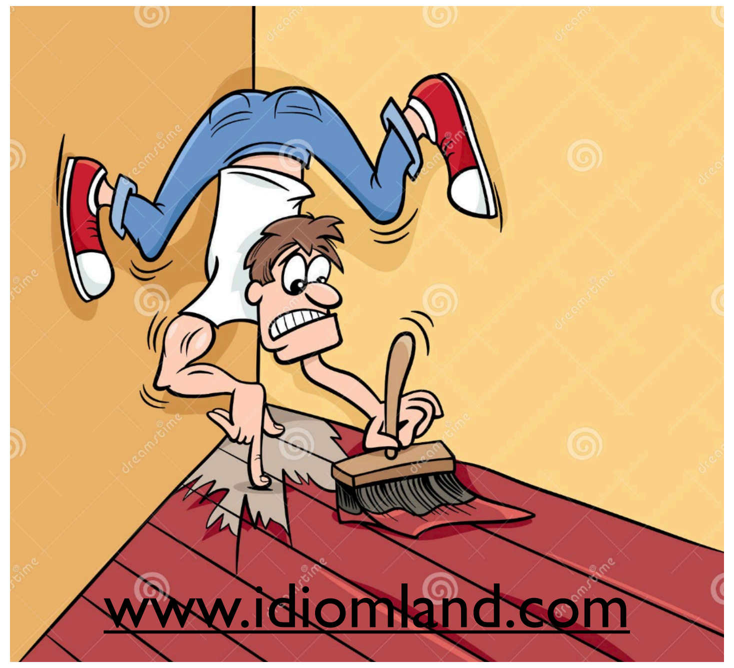
Challenges and opportunities for improvements

Area of improvement: communicate better the breadth of 0νββ experiments reach

- Tendency in the NP community to think about light neutrino exchange as **the only** mechanism for 0νββ decay







- While we *formulate the experimental goal in terms of reach in* $m_{\beta\beta}$, there is no 'standard mechanism' — we simply don't know what's the mechanism for neutrino mass and LNV
- This means the physics reach of 0νββ is larger than usually thought

Communicating 0νββ: the infrastructure

Who's the audience? / Tools and issues	NP community & funding agencies	Funding agencies beyond NP, congressional staff	General public

Would benefit from more coherent effort

Communication channels

- Public lectures: Typically successful, broad efforts, but not coordinated. We plan to survey the community to identify existing efforts as step towards future, more coherent outreach program
- YouTube videos: lots of (uncoordinated) material out there. *Some* stuff is excellent!
    - "The Matter Of Antimatter: Answering The Cosmic Riddle Of Existence" https://www.youtube.com/watch?v=qMMgsjnI1is (World Science Festival organization)
    - "An Ancient Roman Shipwreck May Explain the Universe" (Roman lead for CUORE) https://www.youtube.com/watch?v=o0A9M5wHBA4
    - neutrinos.fnal.gov/resources/videos/ ("Even bananas" and more…)
    - "Global benefits: the LBNF/DUNE Project" https://www.dunescience.org/ → https://www.youtube.com/watch?v=cBGXMYP8cq8
    - …

Resources

Challenges and opportunities for improvements

Communicating 0νββ: the infrastructure

Who's the audience? / Tools and issues	NP community & funding agencies	Funding agencies beyond NP, congressional staff	General public

Communication channels

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  - …

Part of Fermilab's efforts to promote neutrino projects: from science to societal impacts

Communicating $0\nu\beta\beta$: the infrastructure

Who's the audience? / Tools and issues	NP community & funding agencies	Funding agencies beyond NP, congressional staff	General public

Communication channels

Resources

Challenges and opportunities for improvements

Many resources exist, but not coordinated

- Websites of the $0\nu\beta\beta$ experimental collaborations
  - Good resources. Might benefit from having dedicated outreach subpages. This requires time, effort, and expertise in communication.
- National Laboratory / Universities communication offices
  - Generally good support, but the fact that there is no single national facility for $0\nu\beta\beta$ experiments has limited the community's voice
  - To be contrasted with the national NP facilities
    - https://www.bnl.gov/eic/
    - https://frib.msu.edu/
    - https://www.jlab.org/

Communicating 0νββ: the infrastructure

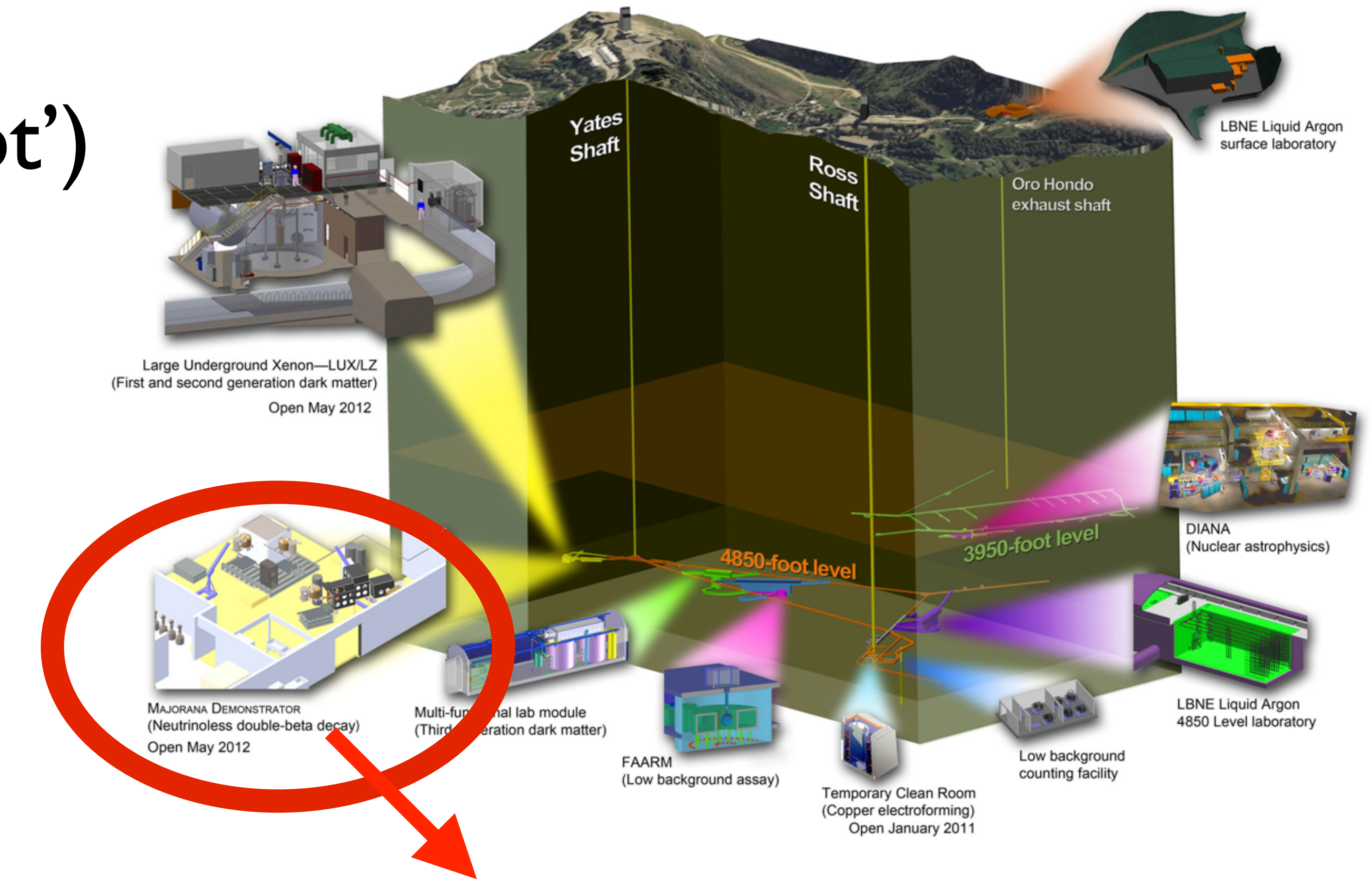
Who's the audience? / Tools and issues	NP community & funding agencies	Funding agencies beyond NP, congressional staff	General public

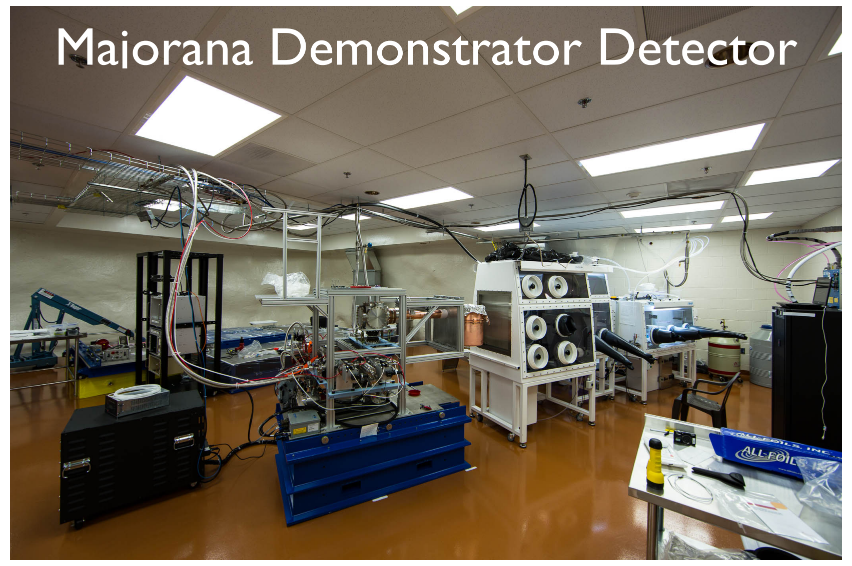
Communication channels

Resources

Challenges and opportunities for improvements

- An effective communication campaign will require professional support, use multiple media (brochures, videos, …) and emphasize multiple aspects of the 0νββ program (see 'script')
  - Connection of 0νββ decay to deep scientific questions & multi-disciplinary impact (Nuclear Physics, Particle Physics, Cosmology)
  - The 'cool factor' of low-background science: working in underground laboratories, ultra pure materials, connection to national security …
  - Positive societal impacts: technology spinoffs, train broad pool of talent, establish pipeline for workforce in basic science, national security, high tech jobs, …





Communicating 0νββ: the infrastructure

Who's the audience?

Tools and issues

NP community & funding agencies

Funding agencies beyond NP, congressional staff

General public

Communication channels

Resources

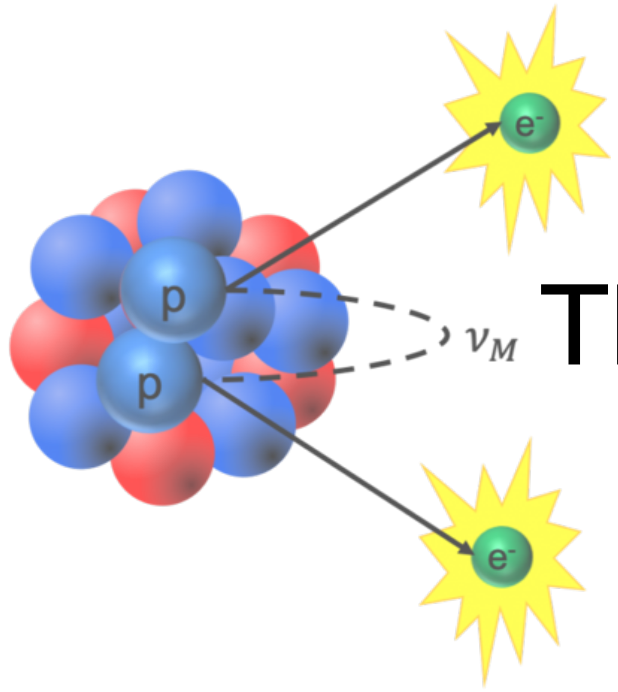
Challenges and opportunities for improvements

Path forward

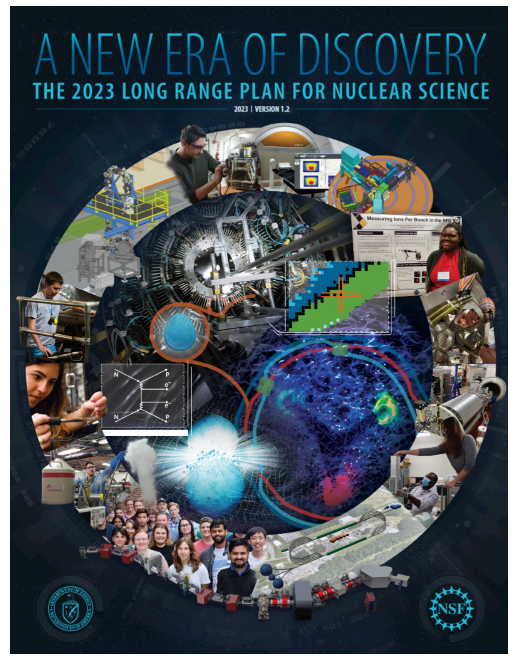
- The community is working towards a comprehensive and coherent communication plan
- Contribution of communication professionals will be essential
- Progress is slow in part because the 0νββ program is not represented by a single institution, but there exist pledges of support by multiple lead institutions
- What model?
  - Communication specialist(s) embedded in the experimental collaborations?
  - Task force within or across communication offices of the lead National Labs?
  - '0νββ unit' within a centralized Nuclear Physics communication center?
  - ….

Conclusion

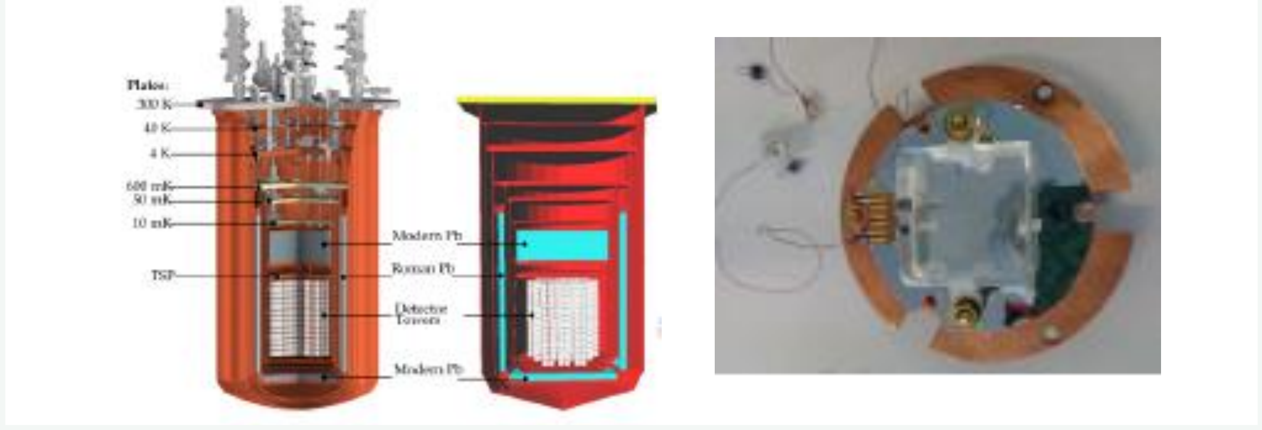
The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics



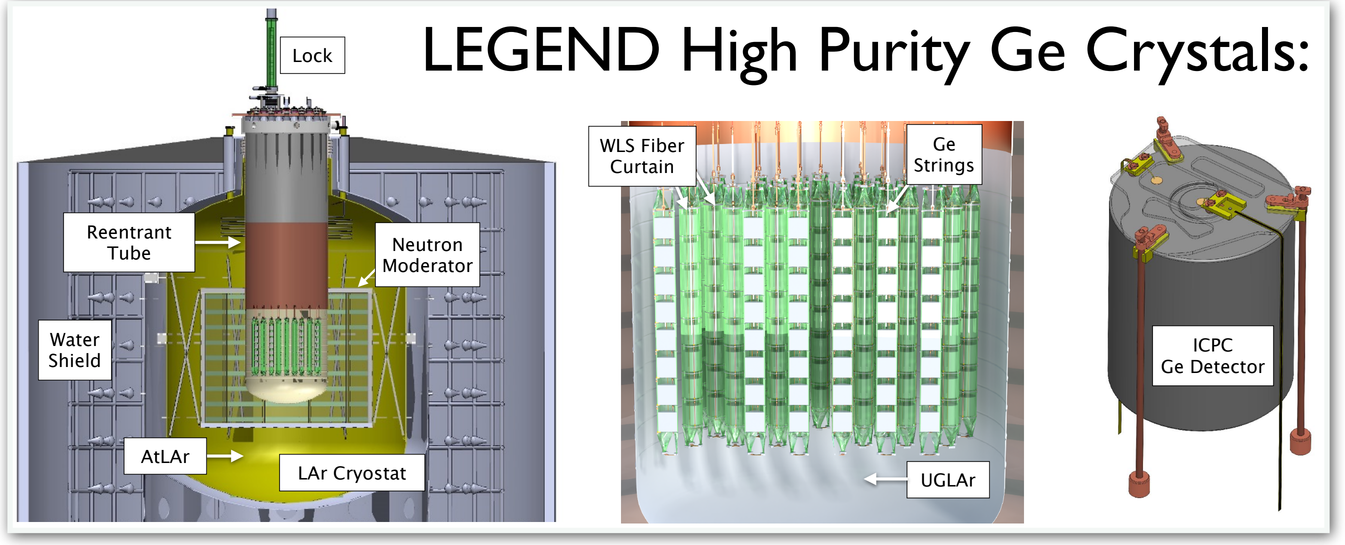
The highest priority for new experiment construction in Nuclear Science Advisory Committee's 2023 Long Range Plan for Nuclear Science



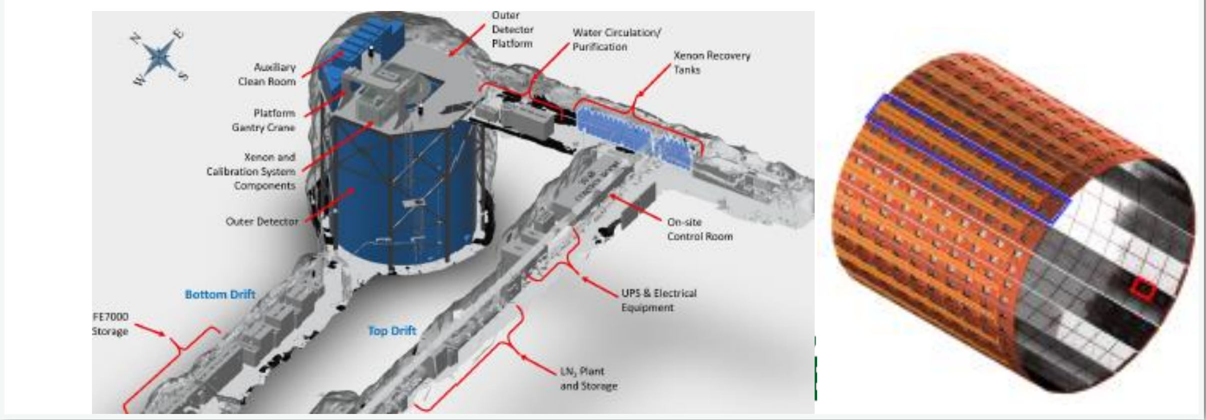
CUPID: Scintillating Crystal Bolometer



LEGEND High Purity Ge Crystals:



nEXO: Liquid Xe Time Projection Chamber



The international ton-scale experiments CUPID (^{100}Mo), LEGEND-1000 (^{76}Ge), and nEXO (^{136}Xe) are ready to start construction

This impactful science needs a comprehensive and coherent communication plan

Backup

Useful acronyms

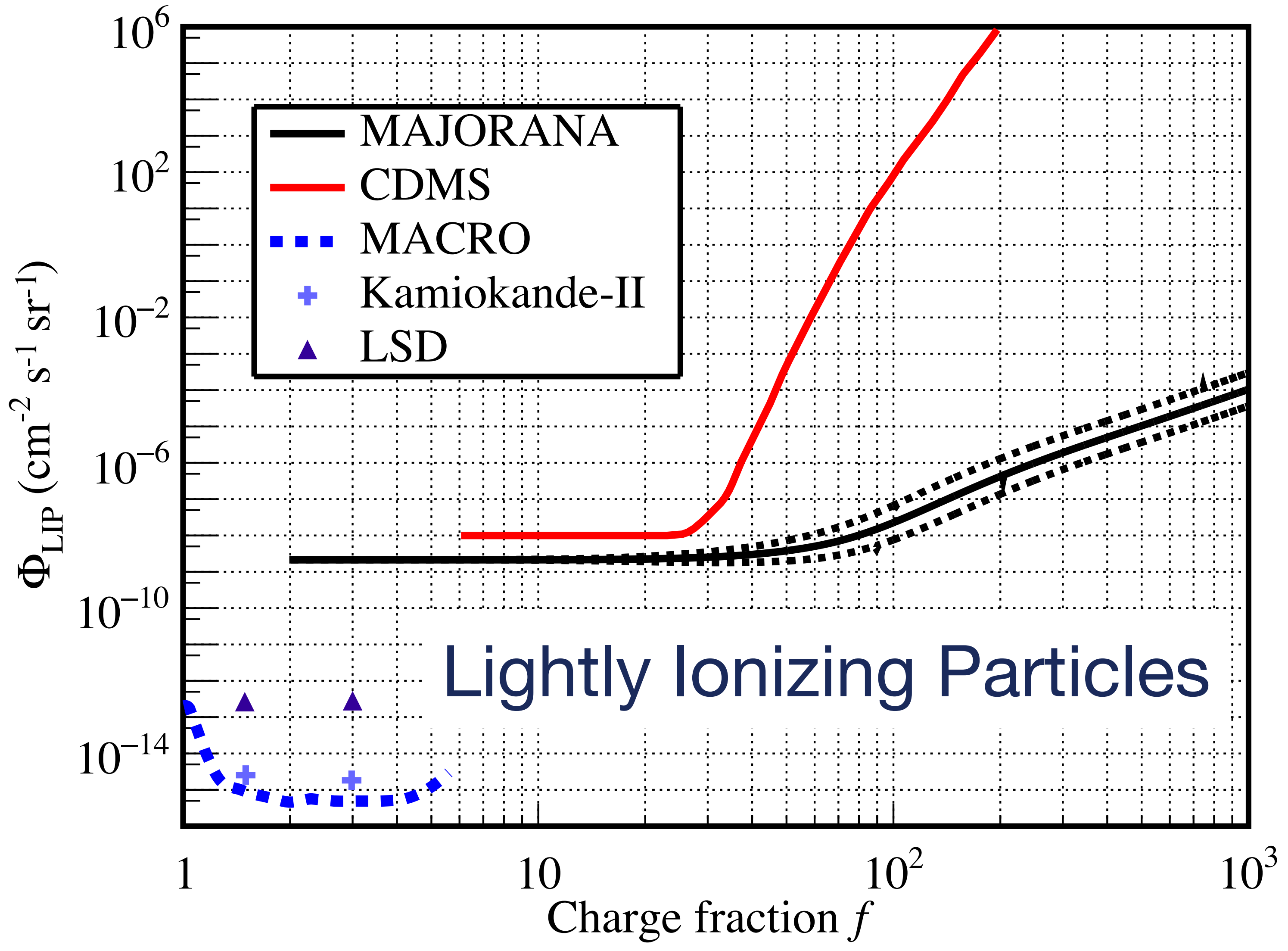
- B: Baryon Number = # of baryons - # of anti-baryons
- Baryon: bound state of 3 quarks (proton, neutron, …)
- BSM: Beyond the Standard Model
- BNV: Baryon Number Violation (Baryon Number is not conserved)
- C: Charge conjugation
- CP: Charge conjugation + Parity
- CPV: CP Violation
- EDM: Electric Dipole Moment
- L: Lepton Number = # of leptons - # of anti-leptons
- Leptons: electron, muon, tau and their corresponding neutrinos
- LNV: Lepton Number Violation (Lepton Number is not conserved)
- SM: Standard Model
- T: time-reversal

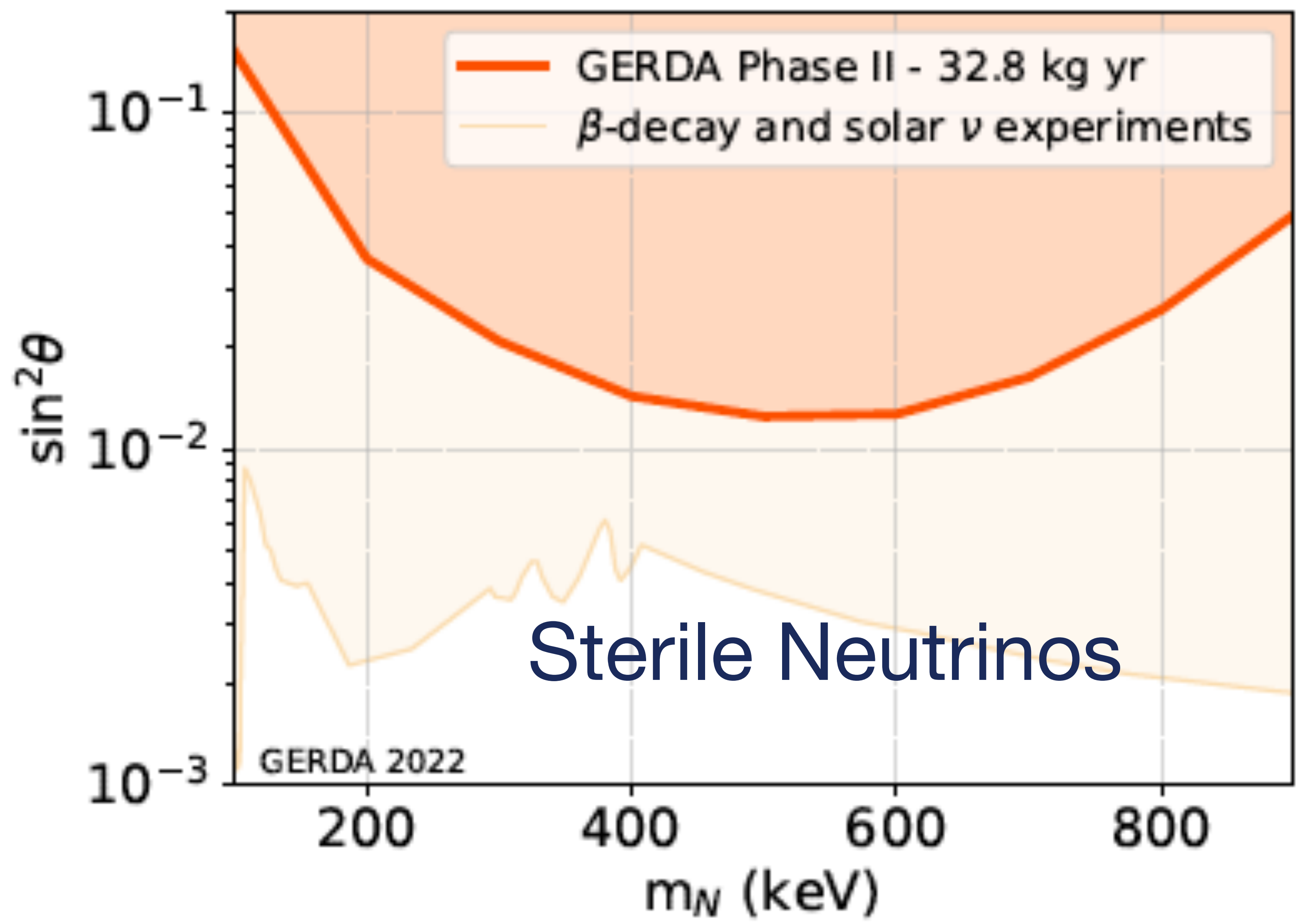
ββ Still Impactful Regardless of Other Results

Technique	Result	ββ Influence
Oscillations	Θ_{12} Measured	Would better define boundaries of IO/NO bands. That would be good for ββ.
Oscillations	Mass ordering determined	Inverted order with 3 ν's might become irrelevant. Even so, the NO branch still extends to high $m_{\beta\beta}$ values. LNV processes other than light ν aren't constrained by oscillations. Significance of IO exclusion still rather low.
LHC	Heavy ν or LR symmetry found	The result would be complementary to ββ. It would be an interesting test of the underlying physics if both techniques saw an effect.
Cosmology	Σm_ν constrained <100 meV	Cosmology does not discern Majorana/Dirac character. A 3ν NO scenario with Σ near its minimum would not constrain other potential LNV processes that might contribute to ββ. Importantly, laboratory measurements will help resolve tensions/degeneracies in cosmology.
Short Baseline Oscillation	Sterile ν discovered	If a 4^{th} ν is seen, it fits the Majorana ν paradigm, increasing ββ interest. The new ν might contribute to bb and significantly alter predicted $m_{\beta\beta}$ curves. The accessible sensitivity regions remain.
β decay	m_β measured	Would make the observation/non-observation of ββ even more exciting. Null ββ result might indicate Dirac ν.

Sensitivity to additional BSM Physics

Physics	Signature	Energy Range	Experiment
Bosonic dark matter (axionlike particle and dark photon)	Peak at DM mass	< 1 MeV	MAJORANA[72, 73], GERDA [74]
Sterile neutrino transition magnetic moment	Peak at 1/2 the sterile neutrino mass	< 1 MeV	MAJORANA [75]
Electron decay	Peak at 11.1 keV	~ 10 keV	MAJORANA [75]
Pauli exclusion principle violation	Peak at 10.6 keV	~ 10 keV	MAJORANA [72]
Solar axions	Peaked spectra, time-energy pattern	< 10 keV	MAJORANA[72, 76]
Majoron emission	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	GERDA [77, 78]
Exotic fermions	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	GERDA [78]
Lorentz violation	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	GERDA [78]
Exotic currents in $2\nu\beta\beta$ decay	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	(proposed) [79]
Time-dependent $2\nu\beta\beta$ decay rate	Modulation of $2\nu\beta\beta$ spectrum	$< Q_{\beta\beta}$	(proposed) [80]
Test of wave function collapse models	1/E X-ray radiation	< 100 keV	MAJORANA [81]
WIMP and related searches	Exponential excess, annual modulation	< 10 keV	CDEX [82]
Baryon decay	Timing coincidence	> 10 MeV	MAJORANA [83]
Fractionally charged cosmic-rays	Straight tracks	few keV	MAJORANA [84]
Fermionic dark matter	Nuclear recoil/deexcitation	$<$ few MeV	MAJORANA [73]
Inelastic boosted dark matter	Positron production	$<$ few MeV	(proposed) [85]
BSM physics in Ar	Features in Ar instrumentation spectrum	ECEC in ^{36}Ar	GERDA [86]





The case for multiple experiments

- Multiple & complementary approaches are the norm in big physics quests
  - UA1 and UA2 to find the W &. Z boson
  - LEP and SLC were built to study EW physics
  - ATLAS , CMS , LHCb @LHC
  - GW detectors: LIGO, VIRGO, ….

Discovering and studying the weak force mediators

Discovering the Higgs boson

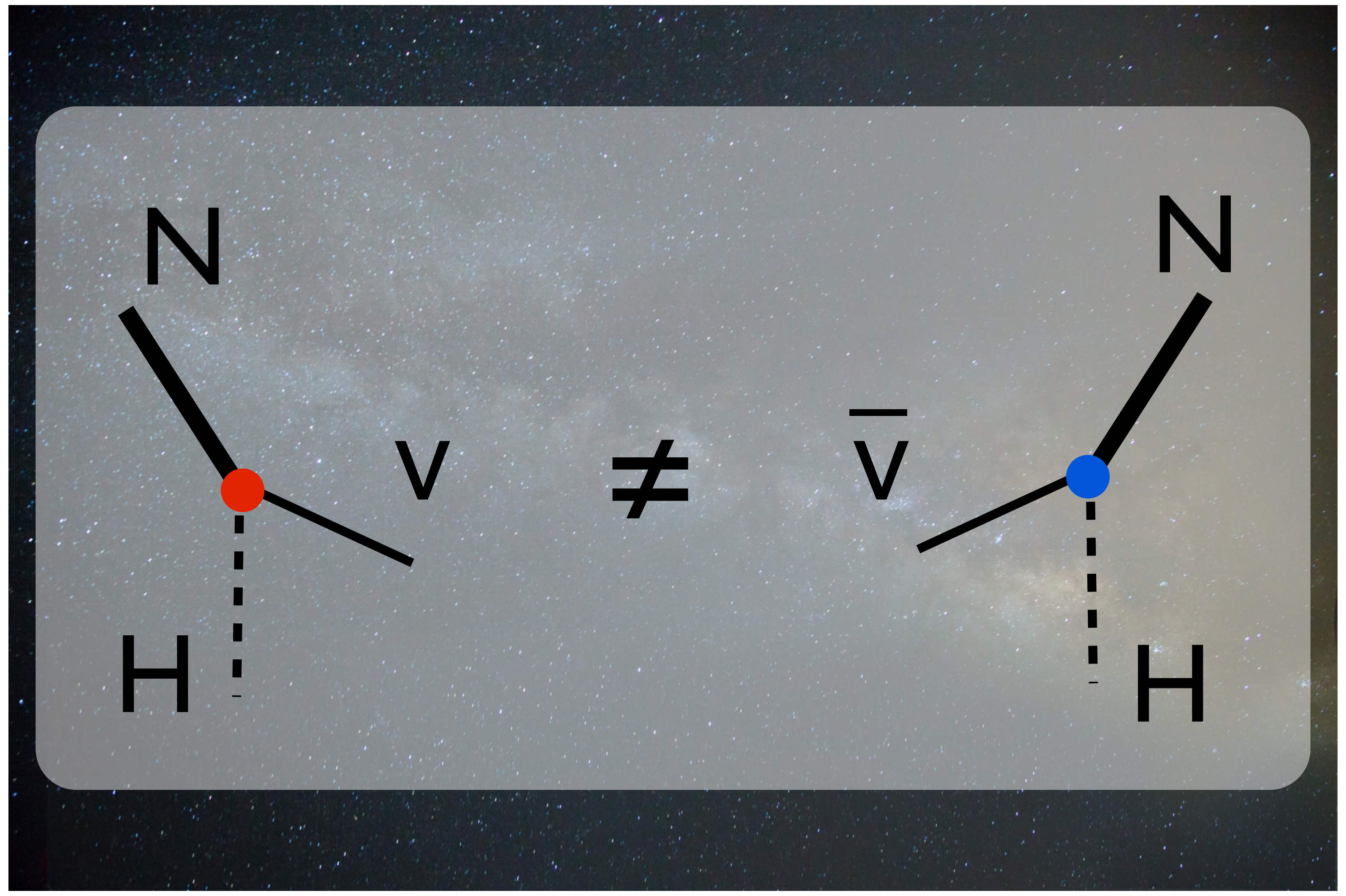
Discovering gravitational waves

- Discovery needs confirmation with significantly different backgrounds and detector uncertainties
- Long time frame for construction and operations calls for simultaneous deployment
- Observation in multiple isotopes is the first step towards unraveling underlying mechanism of LNV
- Stepping stone towards reaching "beyond inverse mass ordering", should that be needed

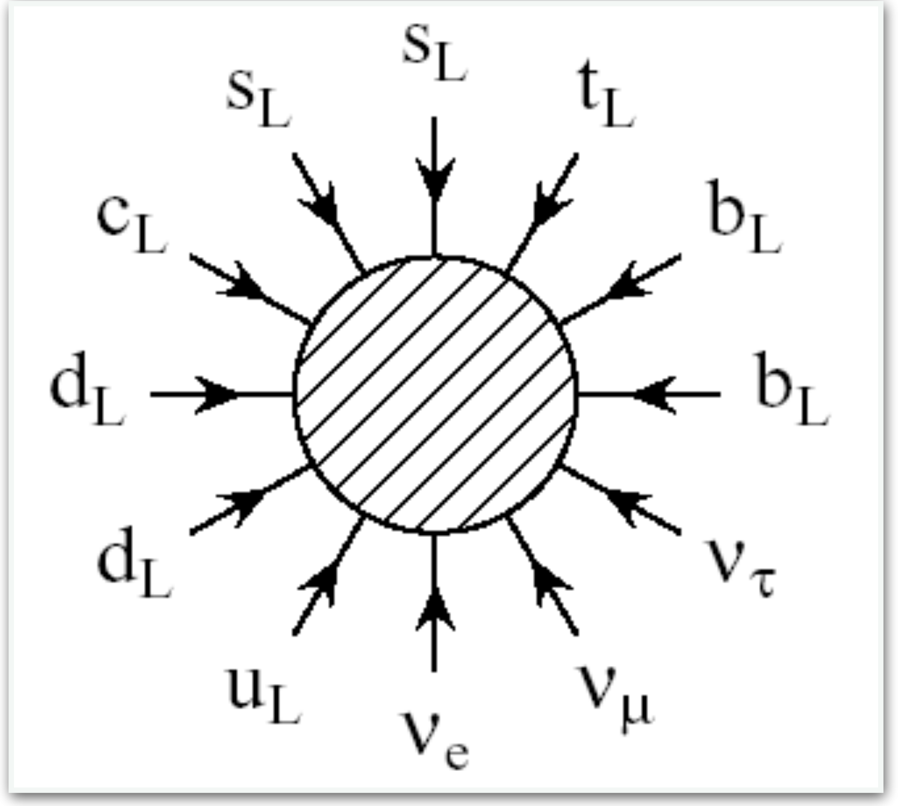
Leptogenesis

- Heavy siblings of the neutrinos are postulated. They help give neutrinos a mass, but do much more!
- Heavy neutrinos (N) disintegrate into (anti)neutrino and Higgs

Fukugita-Yanagida 1987



- Decays can create matter (ν or ν̄) [#1]
- At different rates [#2]
- Slowly compared to the expansion of the universe [#3]

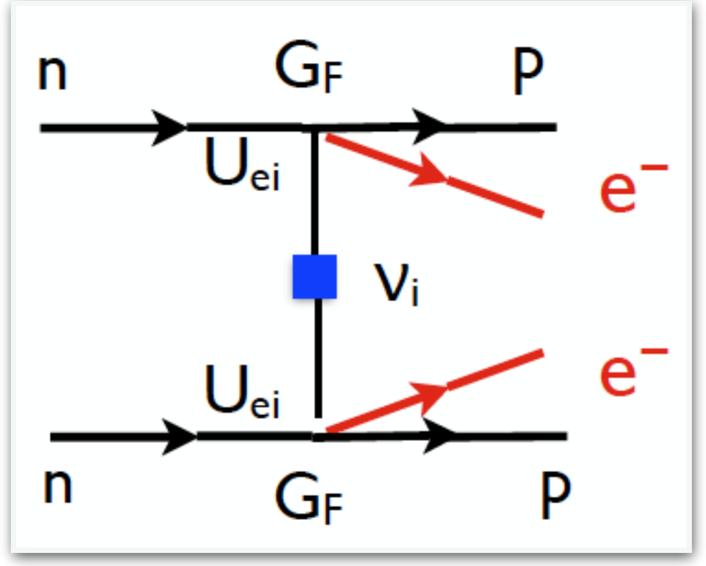


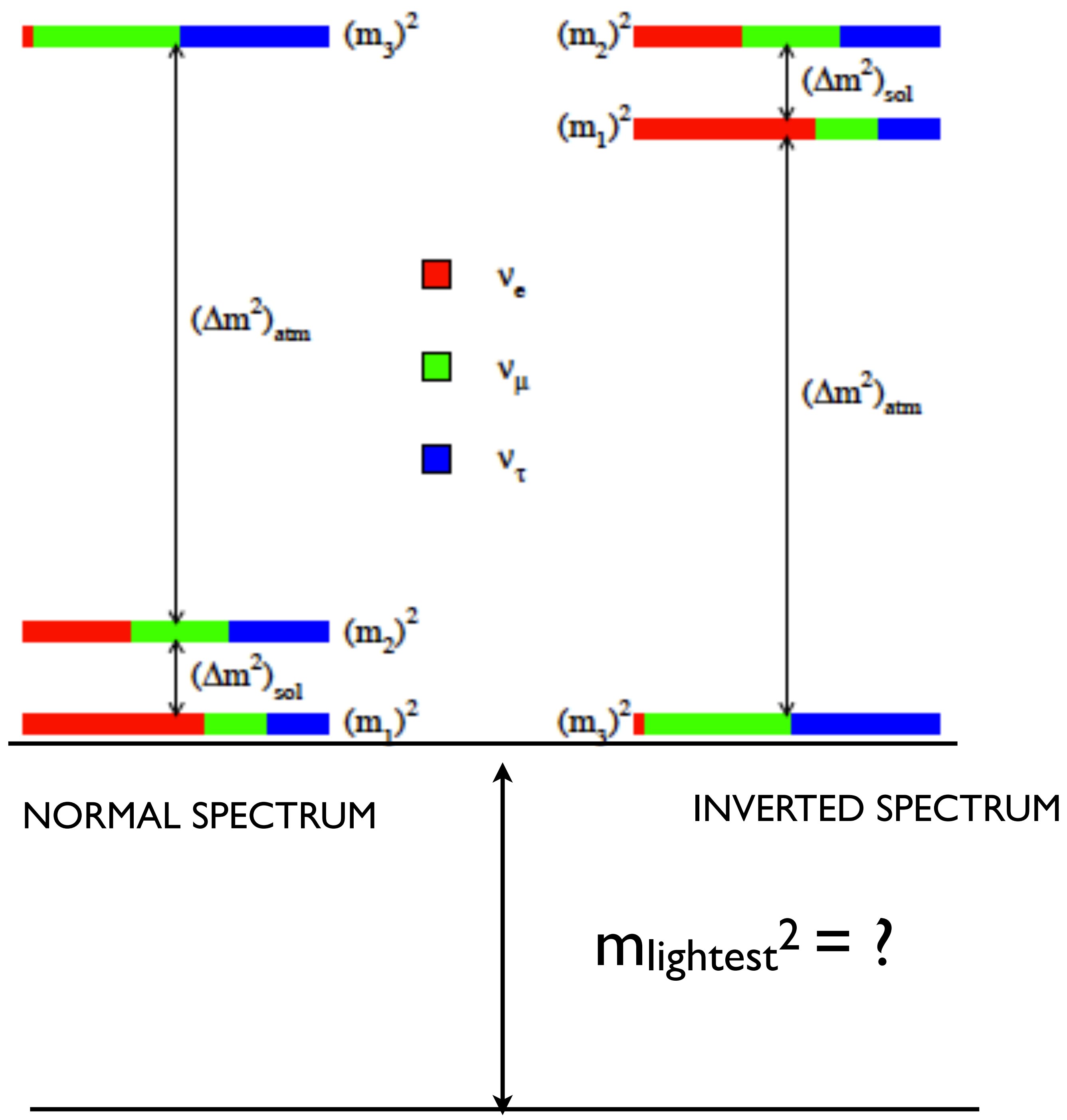
- The resulting neutrino imbalance is converted into quark imbalance by electroweak sphaleron processes [#1, Standard Model]

High-scale seesaw

- In this case 0νββ is a direct probe of ν mass parameters: $\Gamma \propto |M_{0\nu}|^2 \, (m_{\beta\beta})^2$

$$\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$





High-scale seesaw

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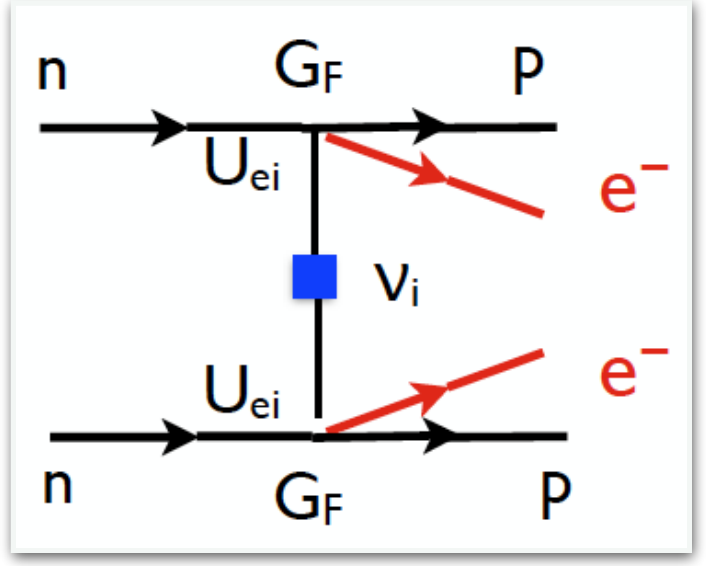
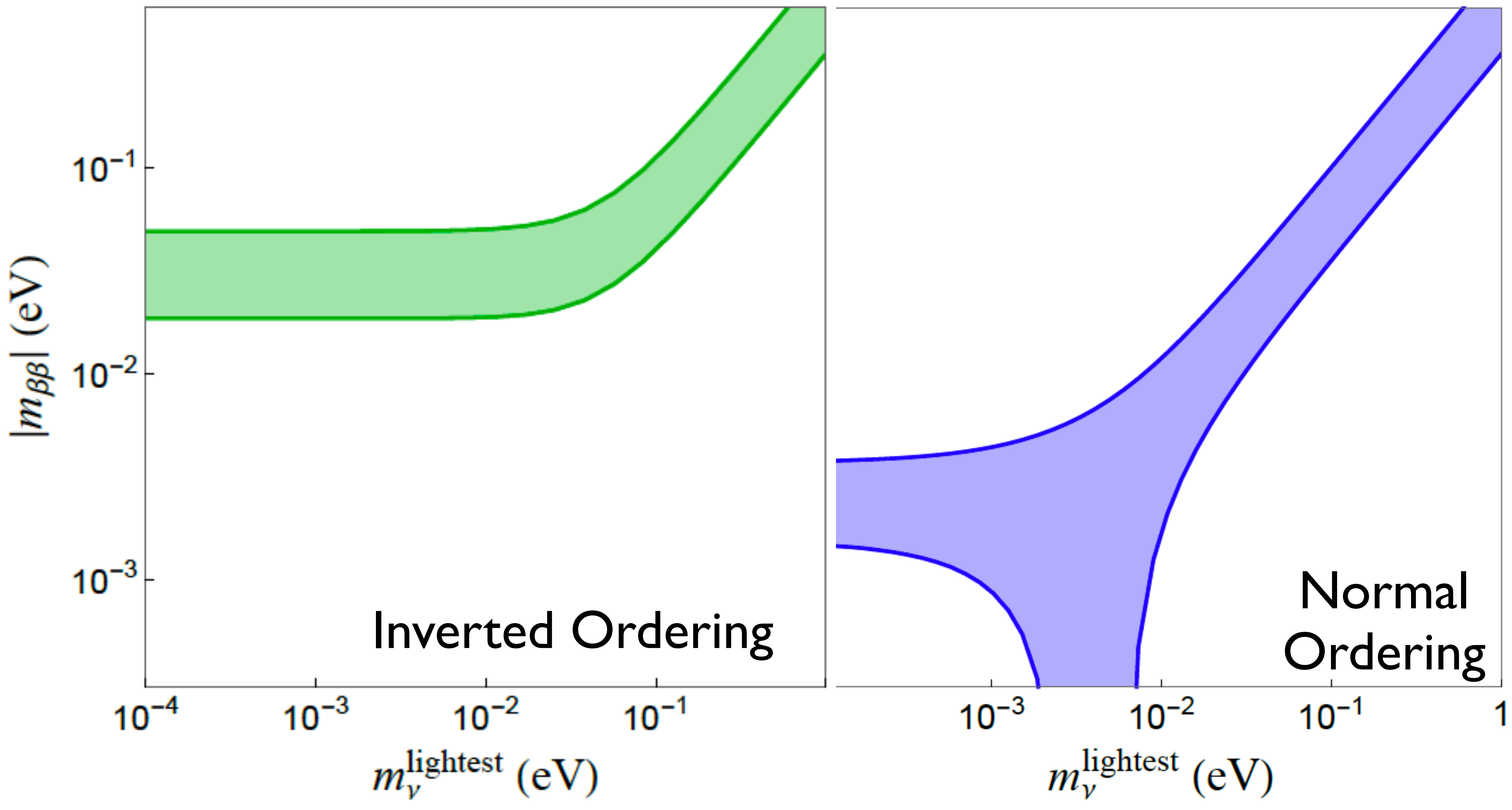


Bands: unknown Majorana phases



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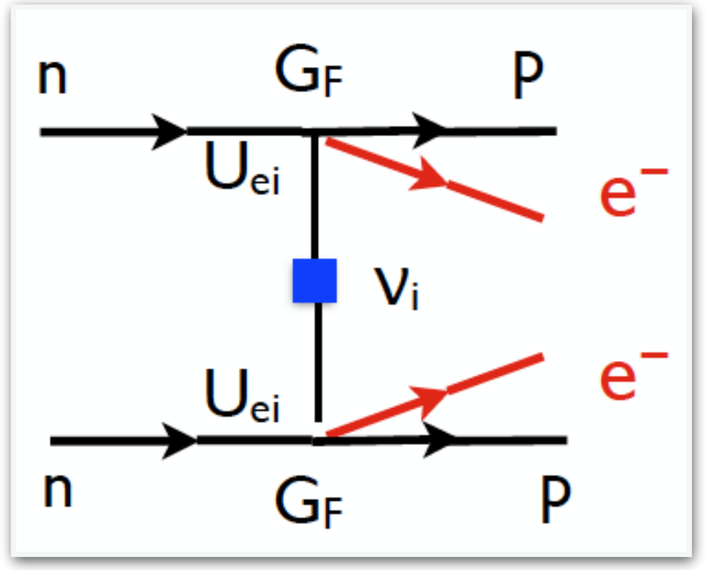

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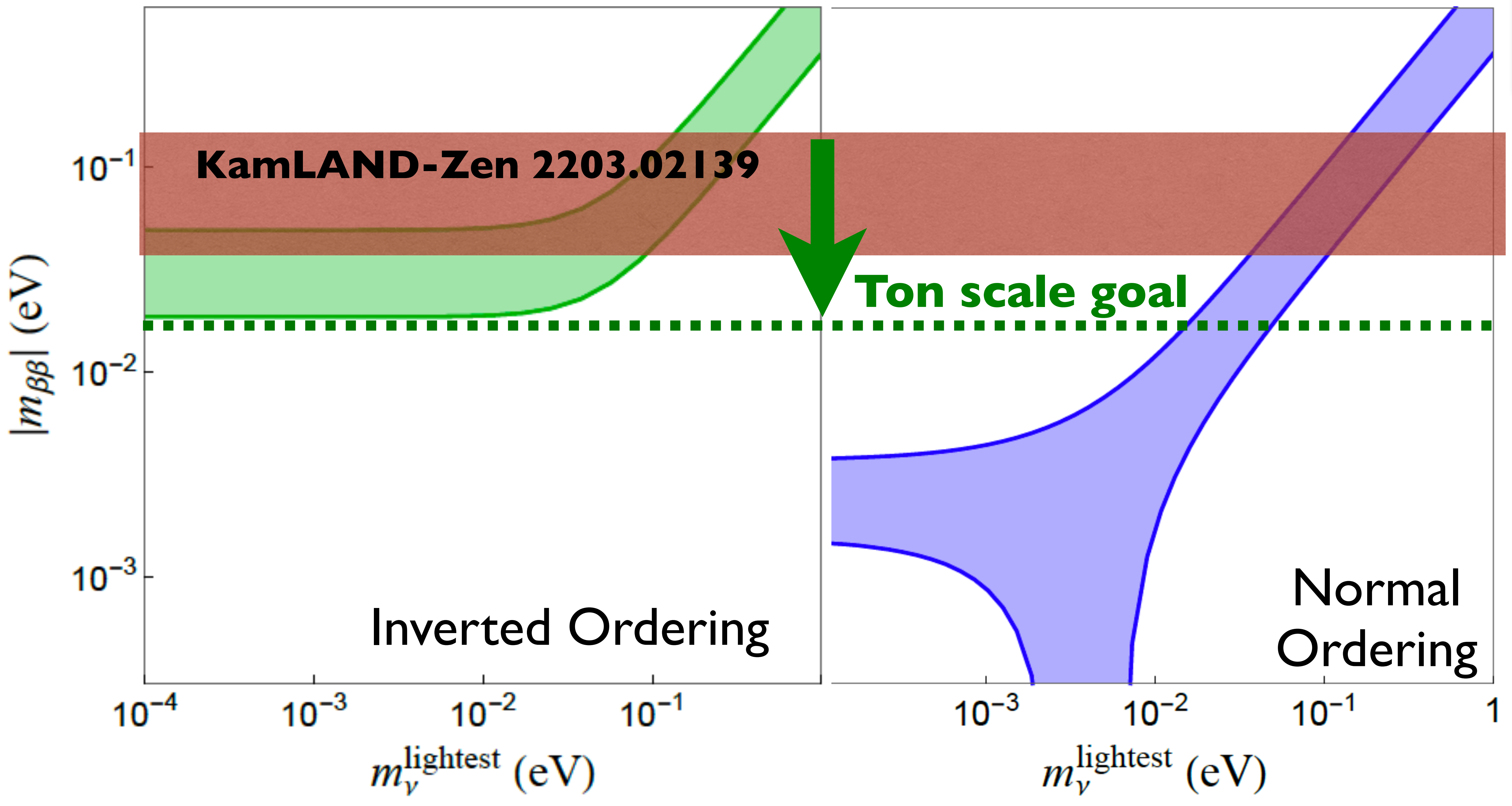
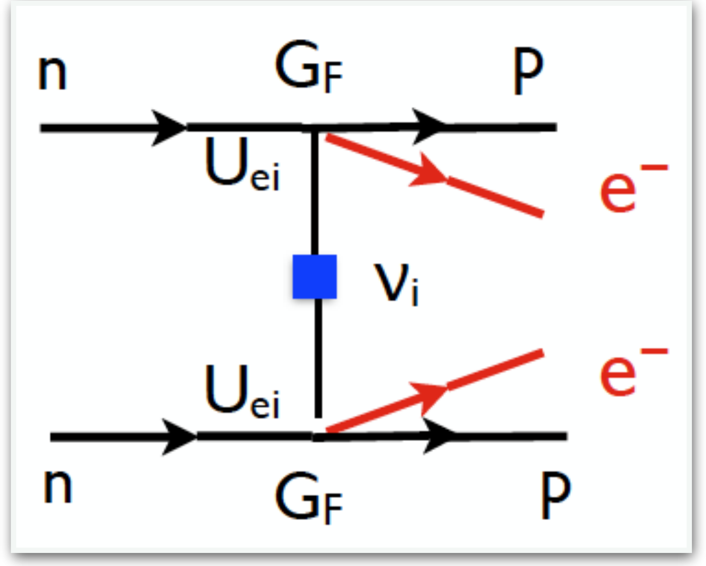


Discovery @ ton-scale *possible* for inverted ordering or $m_{lightest}$ > 50 meV for any ordering

High-scale seesaw

- In this case 0νββ is a direct probe of ν mass parameters: $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$



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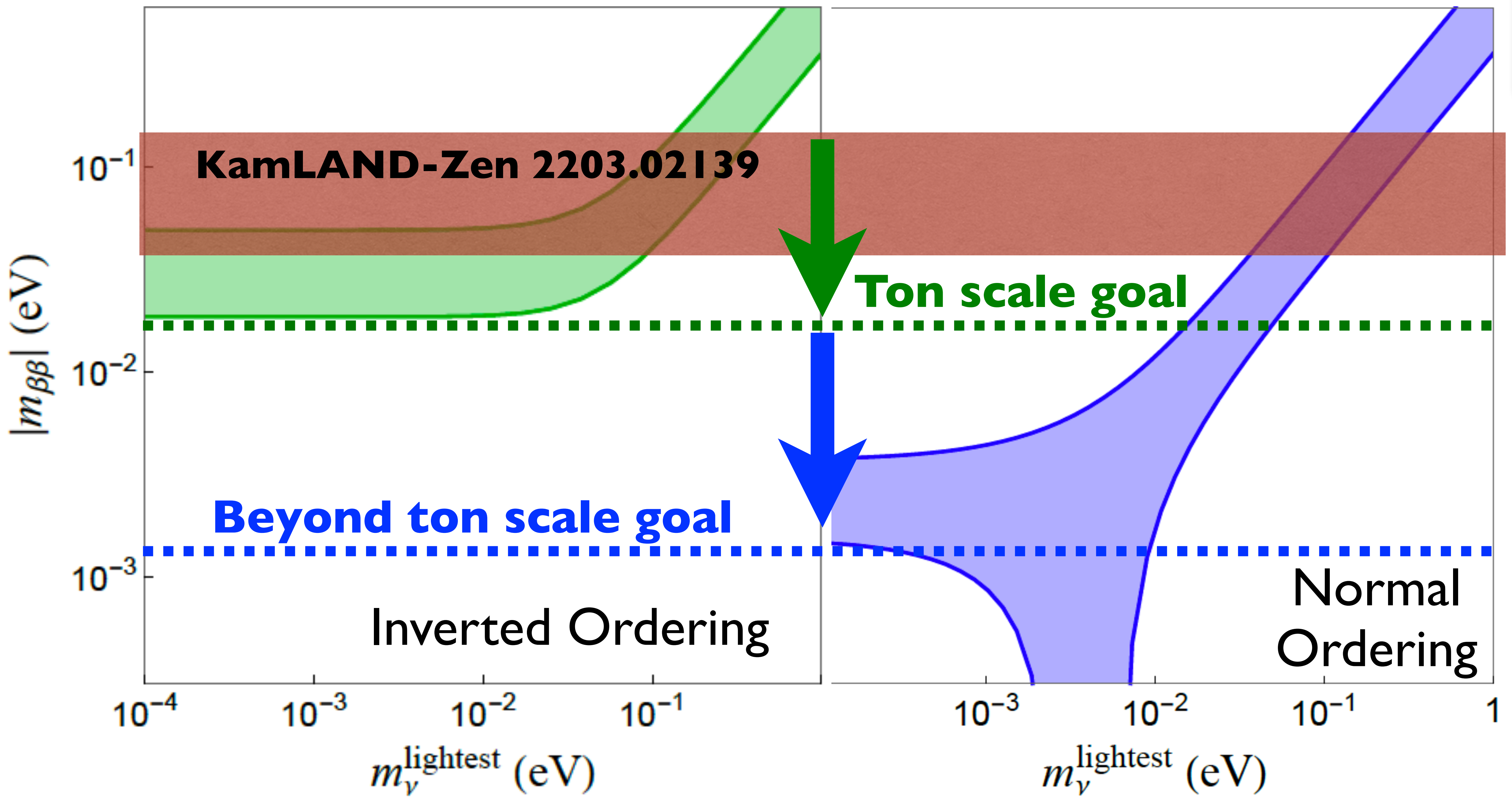

Communicating the science

Who's the audience? / Tools and issues	NP community & funding agencies	Funding agencies beyond NP, congressional staff	General public

Communication channels

Resources & Infrastructure

Challenges and opportunities for improvements

Acknowledge and communicate the complementarity of large experiments

- Many experiments aim to shed light on the mystery of the matter-antimatter asymmetry

  They probe different Sakharov conditions and different mechanisms

  - $0\nu\beta\beta$ decay (#1)
  - LBNF / DUNE: CP-violation in neutrino oscillations (#2)
  - Searches for permanent EDMs (#2)
  - Decays of B mesons: Belle-II, LHCb (#2)
  - LHC and future colliders (EW phase transition) (#3)

  Addressing big questions may require multiple, big endeavors