MAYORANA International School
Modica
June 19-25 2025

# Neutrinoless double beta decay and Lepton Number Violation - I

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Office of Science

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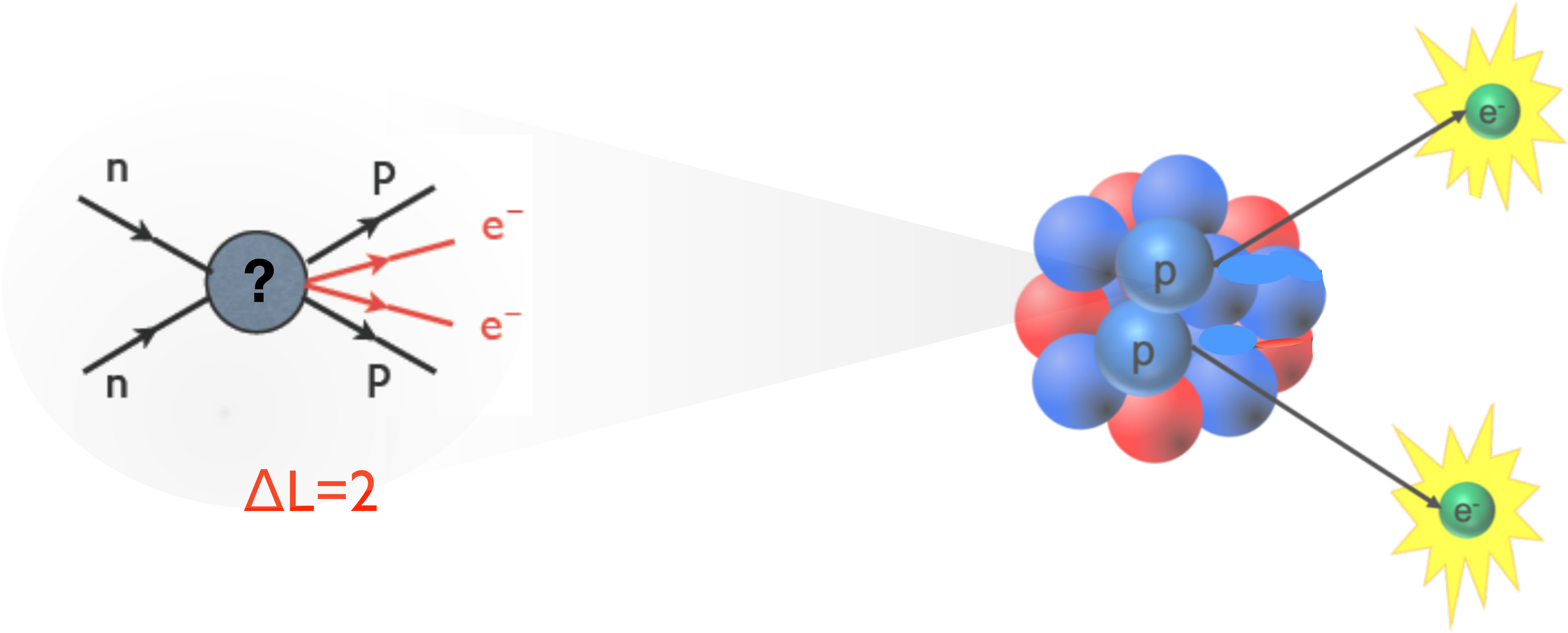
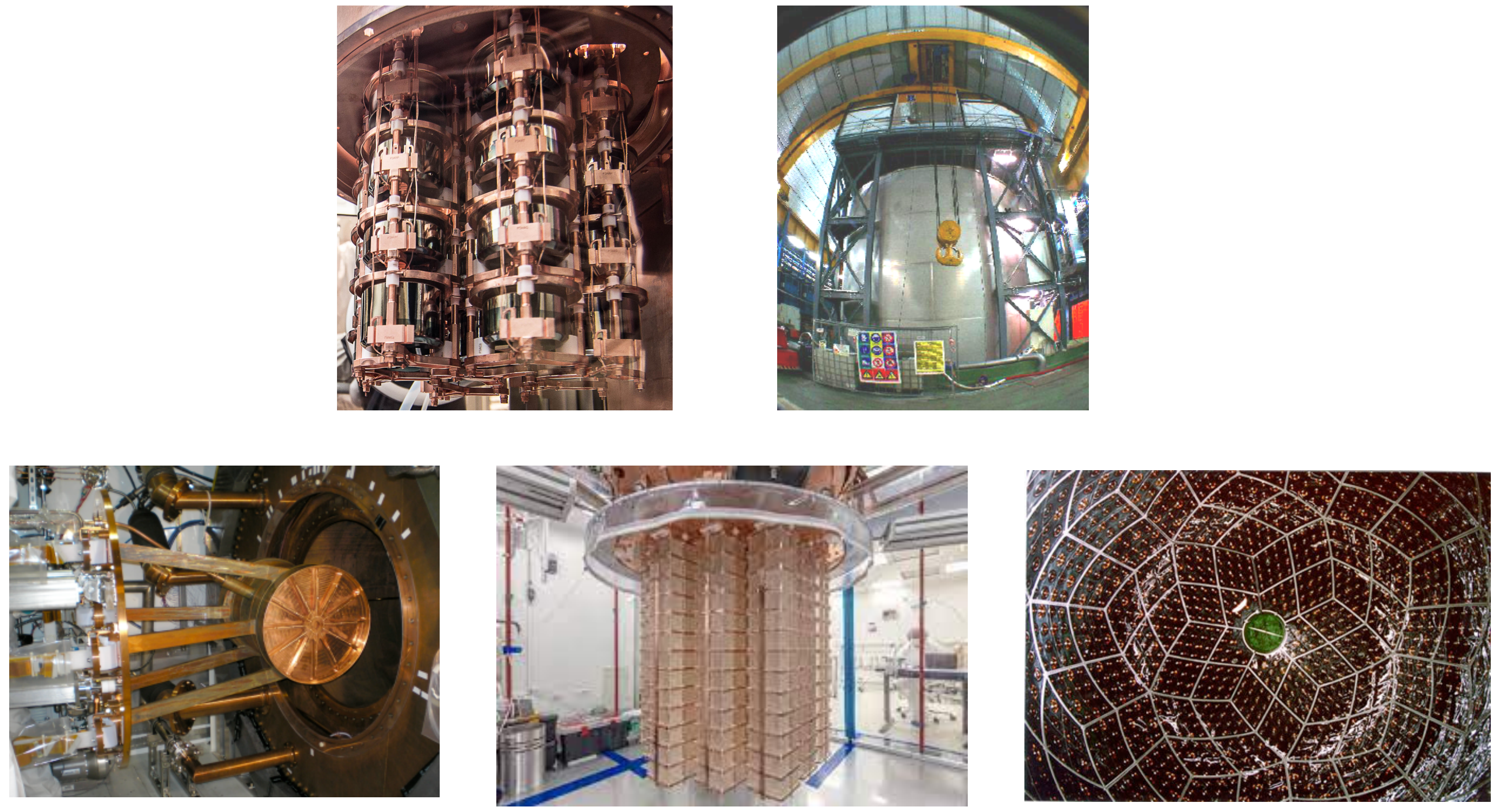
# Goal of these lectures

Introduction to neutrinoless double beta decay ($0\nu\beta\beta$),

its significance (nature of neutrino mass & baryon asymmetry),

and the discovery potential of current experimental searches



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

# Plan for the lectures

- Significance of neutrinoless double beta decay & connection to big questions
    - Origin and nature of neutrino mass
    - The baryon asymmetry of the universe
    - Discovery potential of $0\nu\beta\beta$ — overview
- *End-to-end* Effective Field Theory for Lepton Number Violation (LNV) and $0\nu\beta\beta$
    - $0\nu\beta\beta$ from high-scale see-saw (LNV @ dim 5 = 3 light $\nu$ exchange mechanism)
    - $0\nu\beta\beta$ from (multi)TeV-scale dynamics (LNV @ dim 7, 9, …)
    - $0\nu\beta\beta$ from sterile neutrinos
- Conclusions and outlook

1st lecture 45'

2nd lecture 45'

3rd lecture 90'

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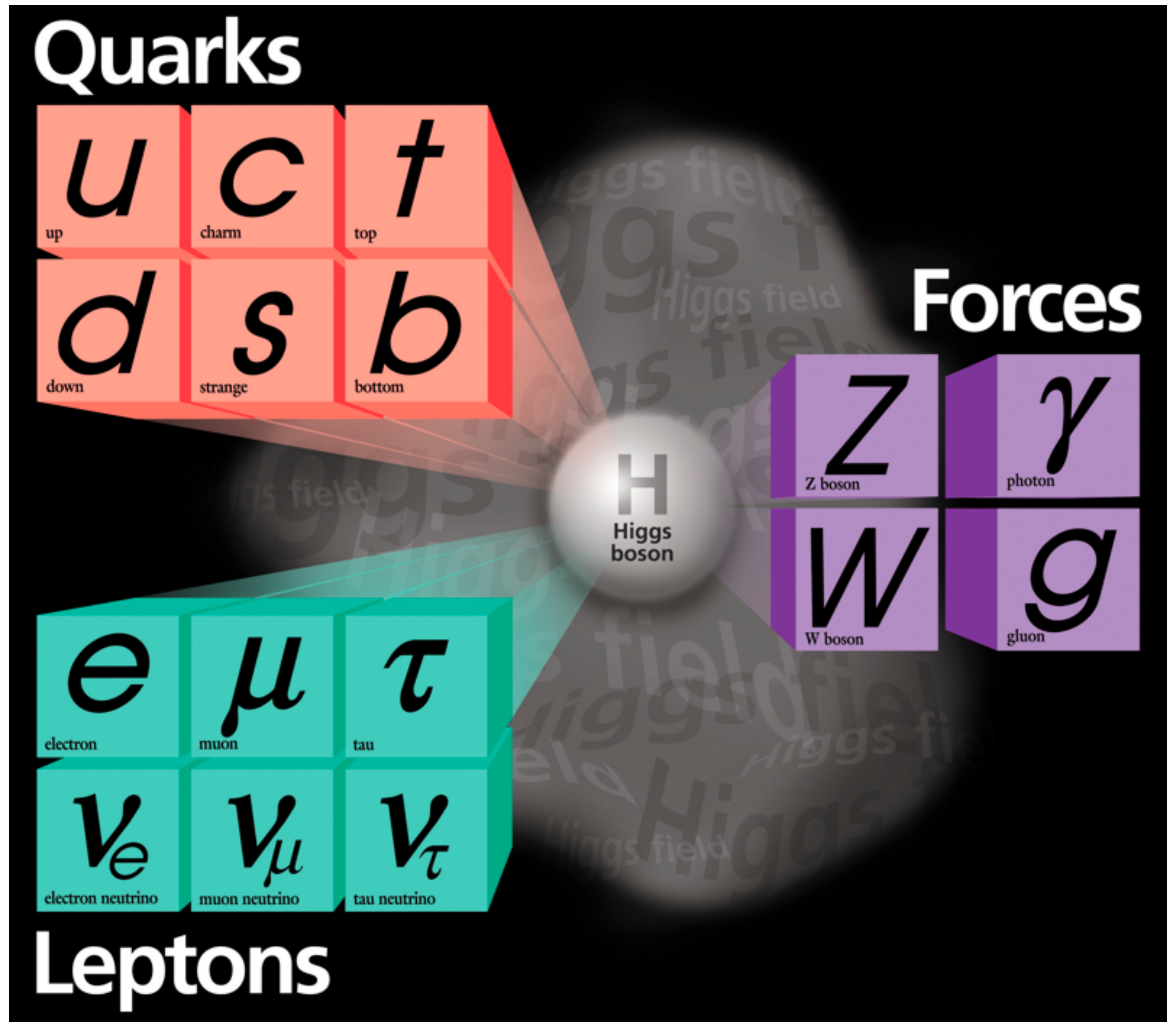
3[rd] lecture 90'

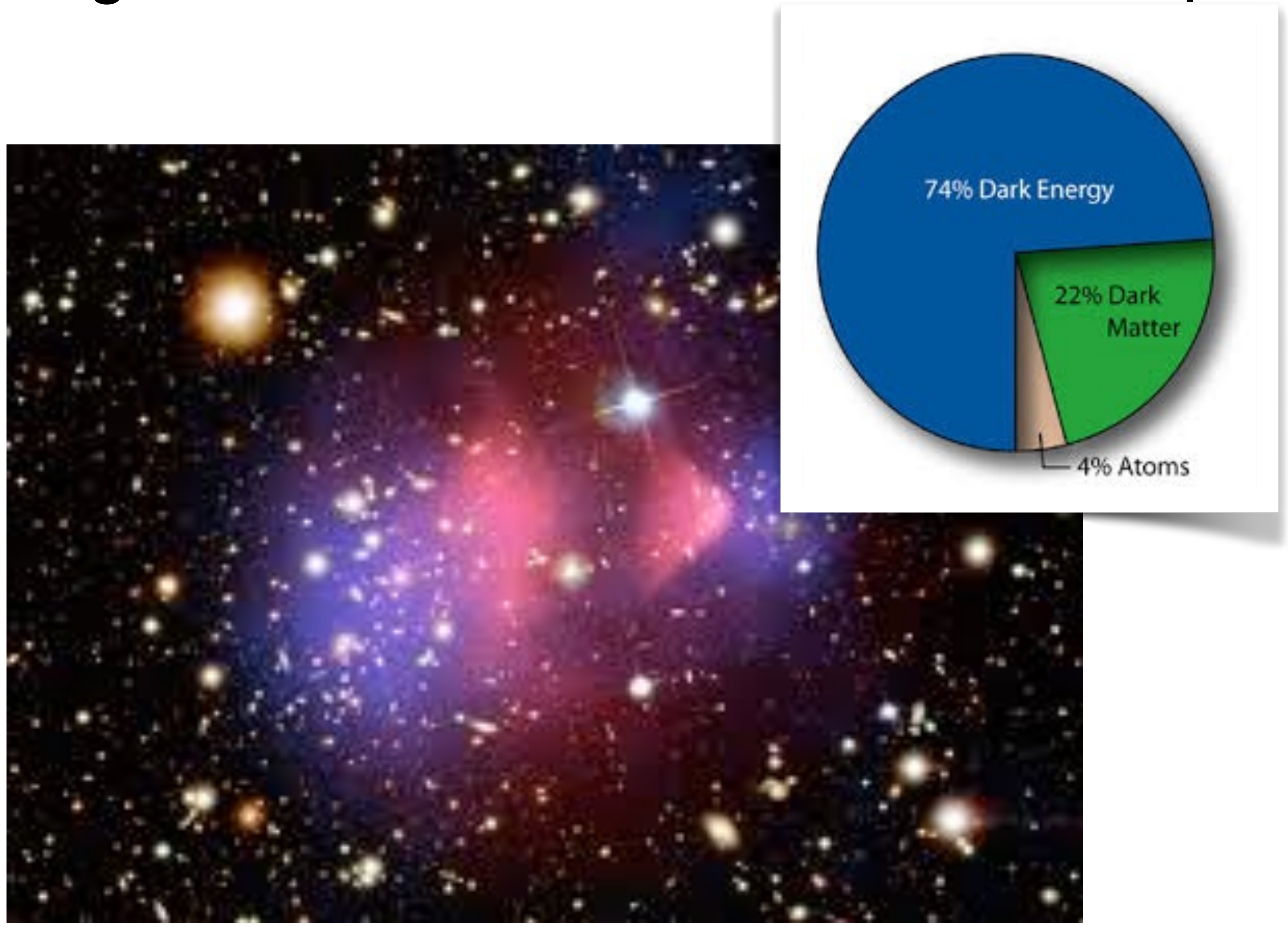
Special thanks to collaborators on these topics:
W. Dekens, J. de Vries, M. Graesser, M. Hoferichter, E. Mereghetti, S. Pastore, M. Piarulli,
S. Urrutia-Quiroga, U. van Kolck, A. Walker-Loud, R. Wiringa

# 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.

No Neutrino Mass, no Baryon Asymmetry, no Dark Matter, no Dark Energy

Addressing these shortcomings requires physics beyond the Standard Model (BSM)

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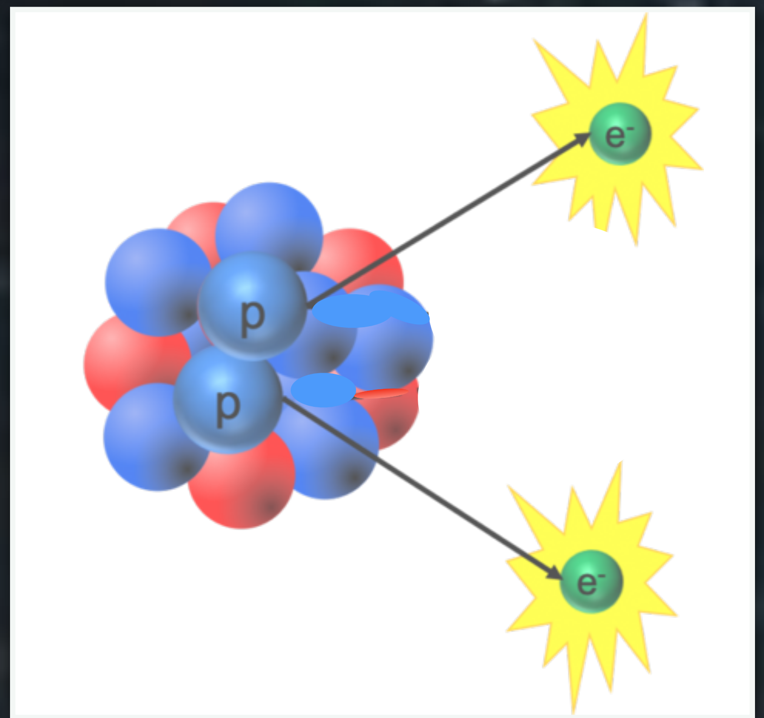



*$0\nu\beta\beta$ decay plays a prominent role in the quest for new physics by addressing two major questions related to shortcomings of the Standard Model*

Demonstrate Majorana nature of massive neutrinos (neutrino=antineutrino) $\Rightarrow$ Shed light on the origin of neutrino mass

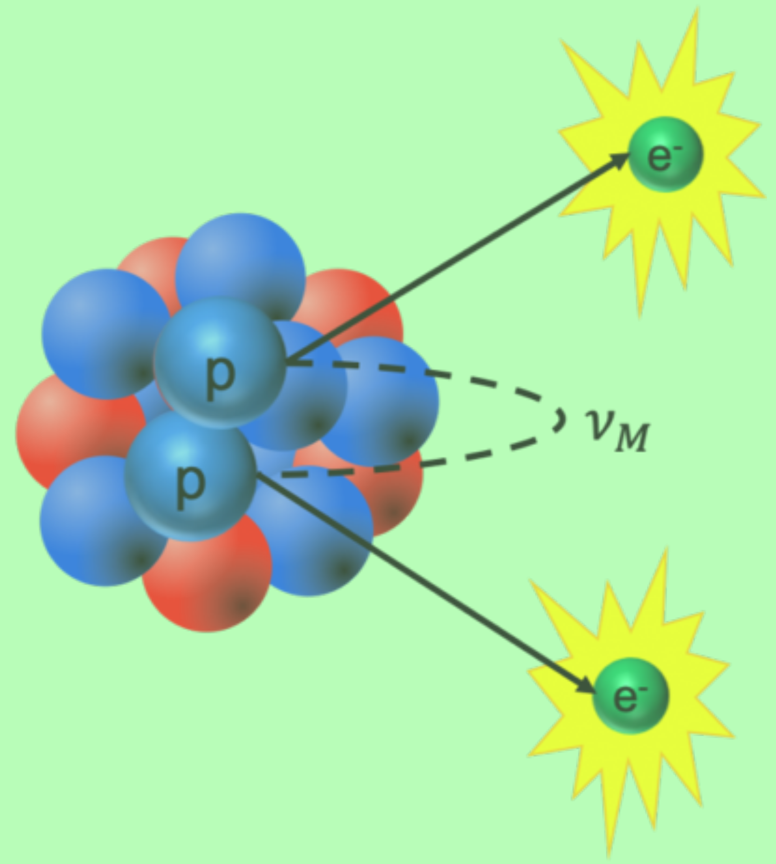
Demonstrate that an excess of matter over antimatter can be created in an elementary process $\Rightarrow$ Point to baryogengesis via leptogenesis

# $0\nu\beta\beta$ decay: significance

The neutrino and its mysteries

Nature of massive neutrinos:
is the neutrino its own antiparticle?

Nuclear $0\nu\beta\beta$ decay




A cosmic mystery

How did matter survive
the big bang?

# 0νββ decay: significance

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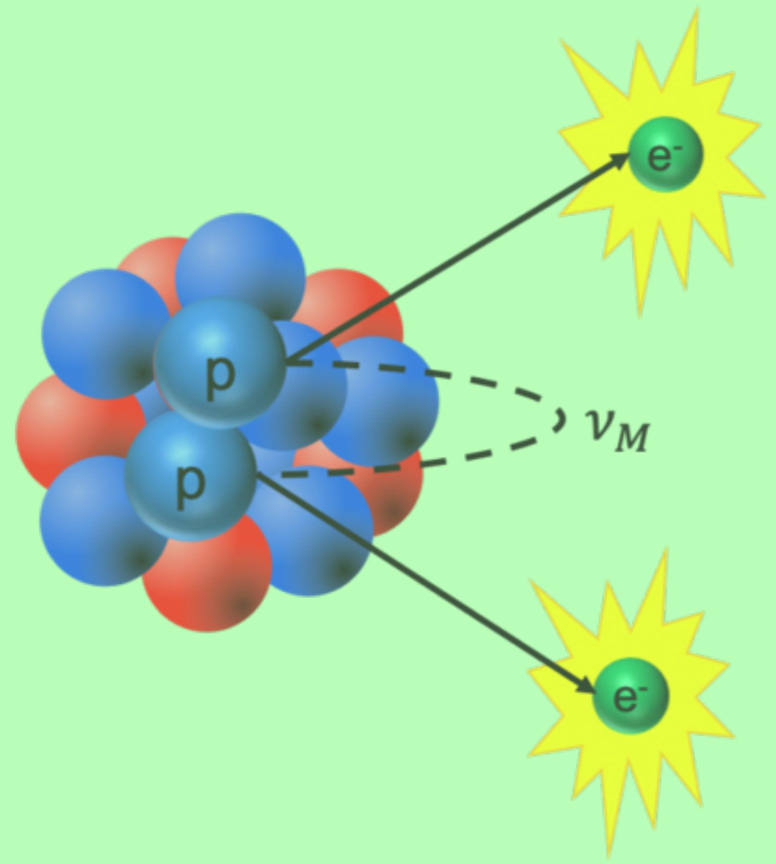
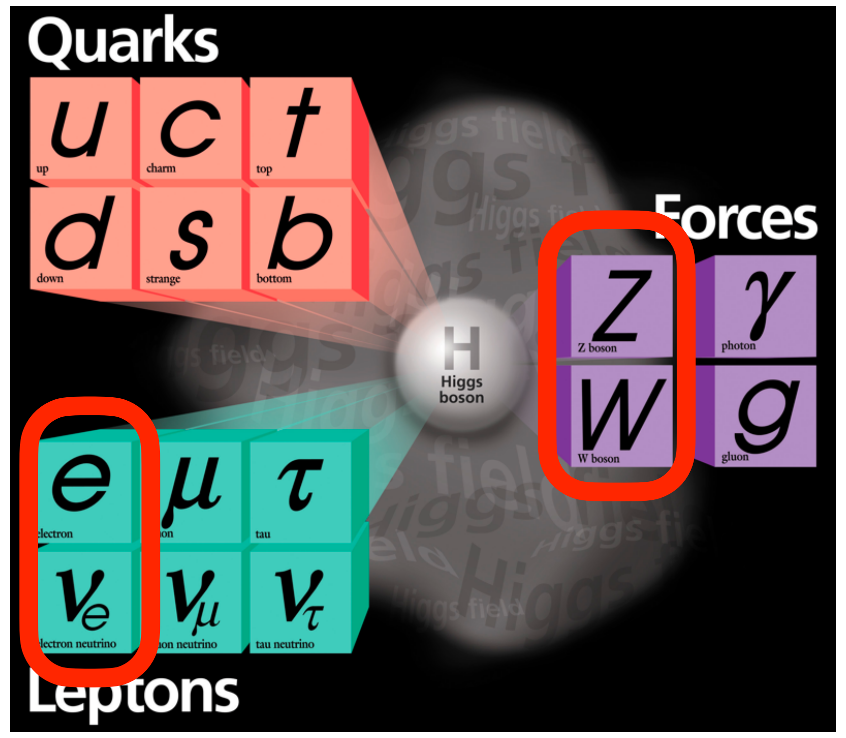
Nuclear 0νββ decay

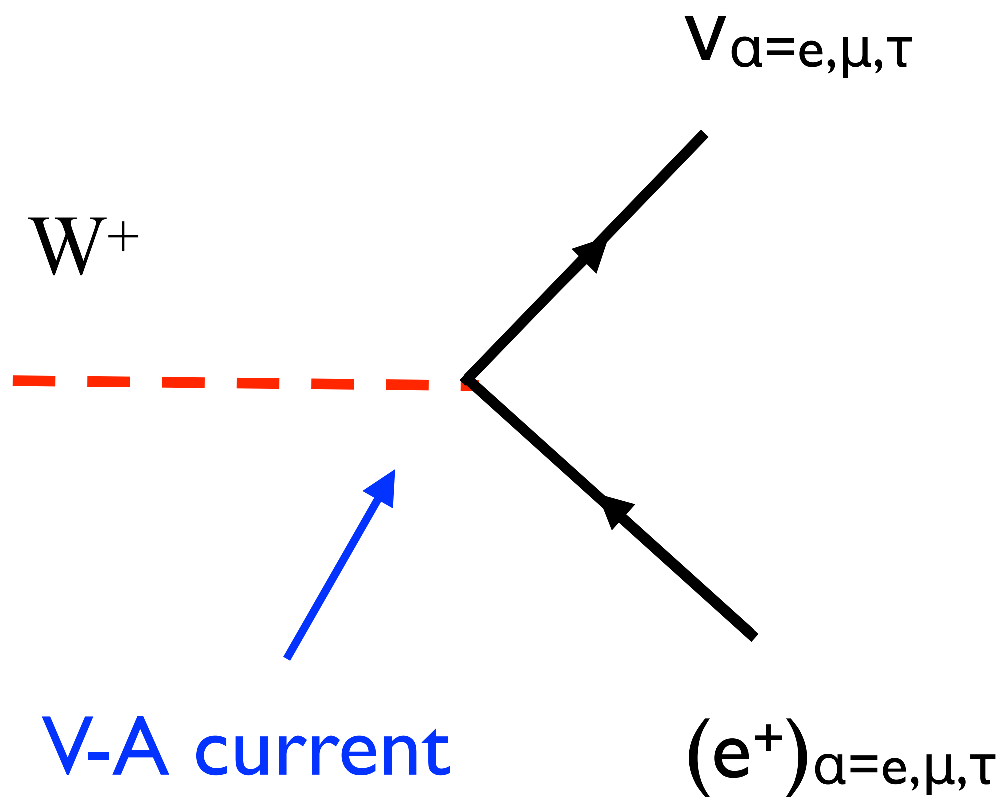


# Neutrinos

- Elusive particles: feel only the weak force, form a "weak isospin doublet" with electrons

$$L_L^\alpha = \begin{pmatrix} \nu_L^\alpha \\ e_L^\alpha \end{pmatrix}$$



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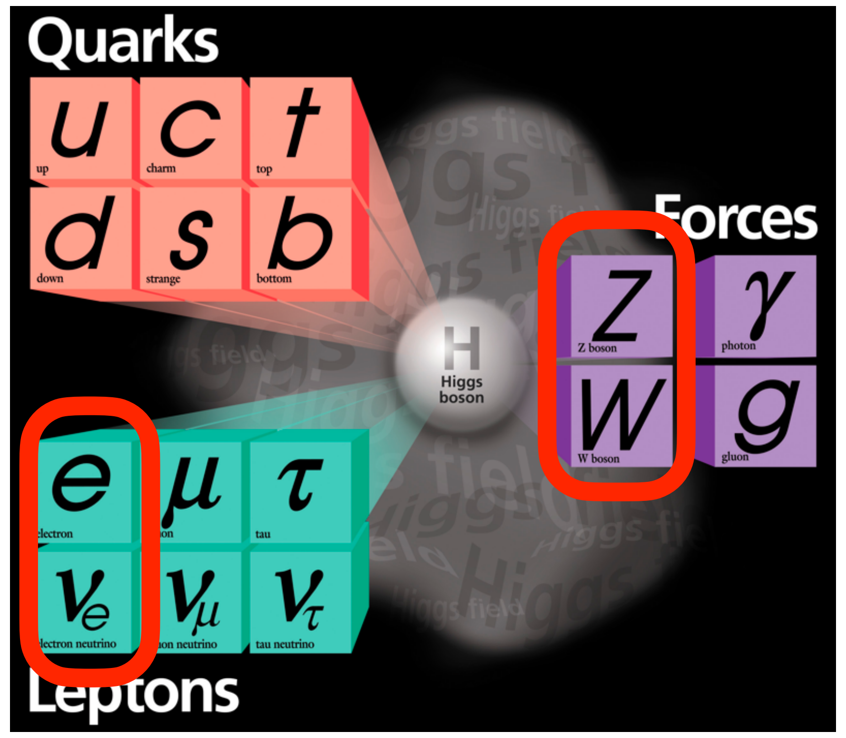
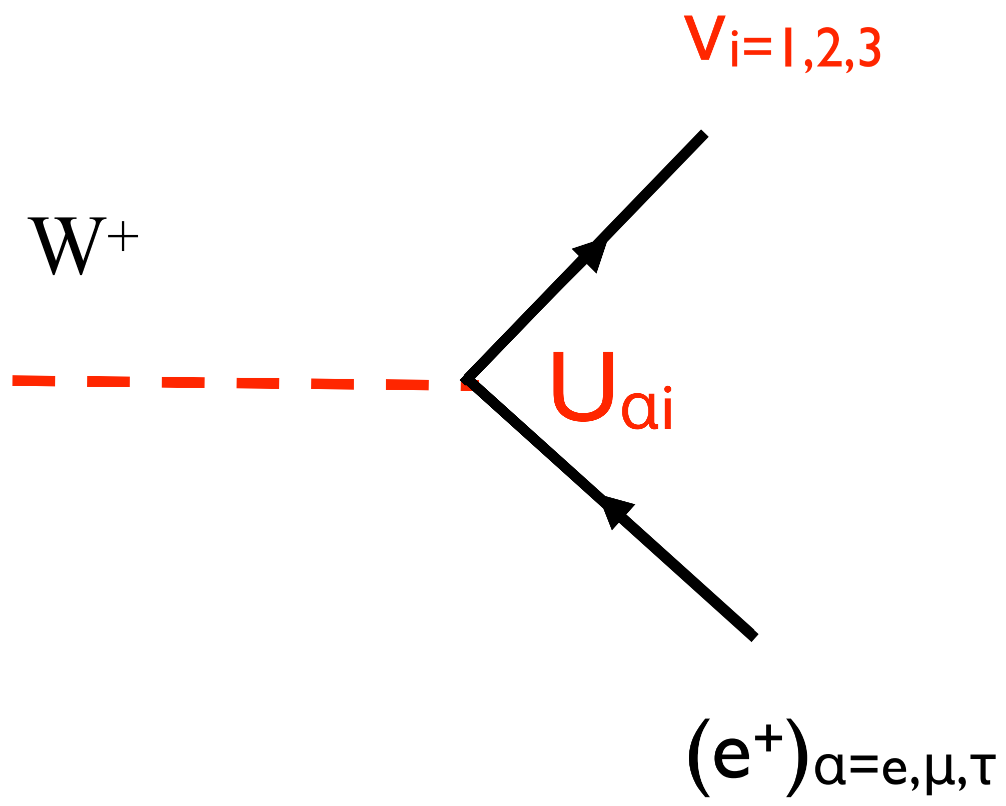
- Massive neutrinos produced in a given interaction ("flavor") state can "oscillate" into another flavor through QM interference




$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

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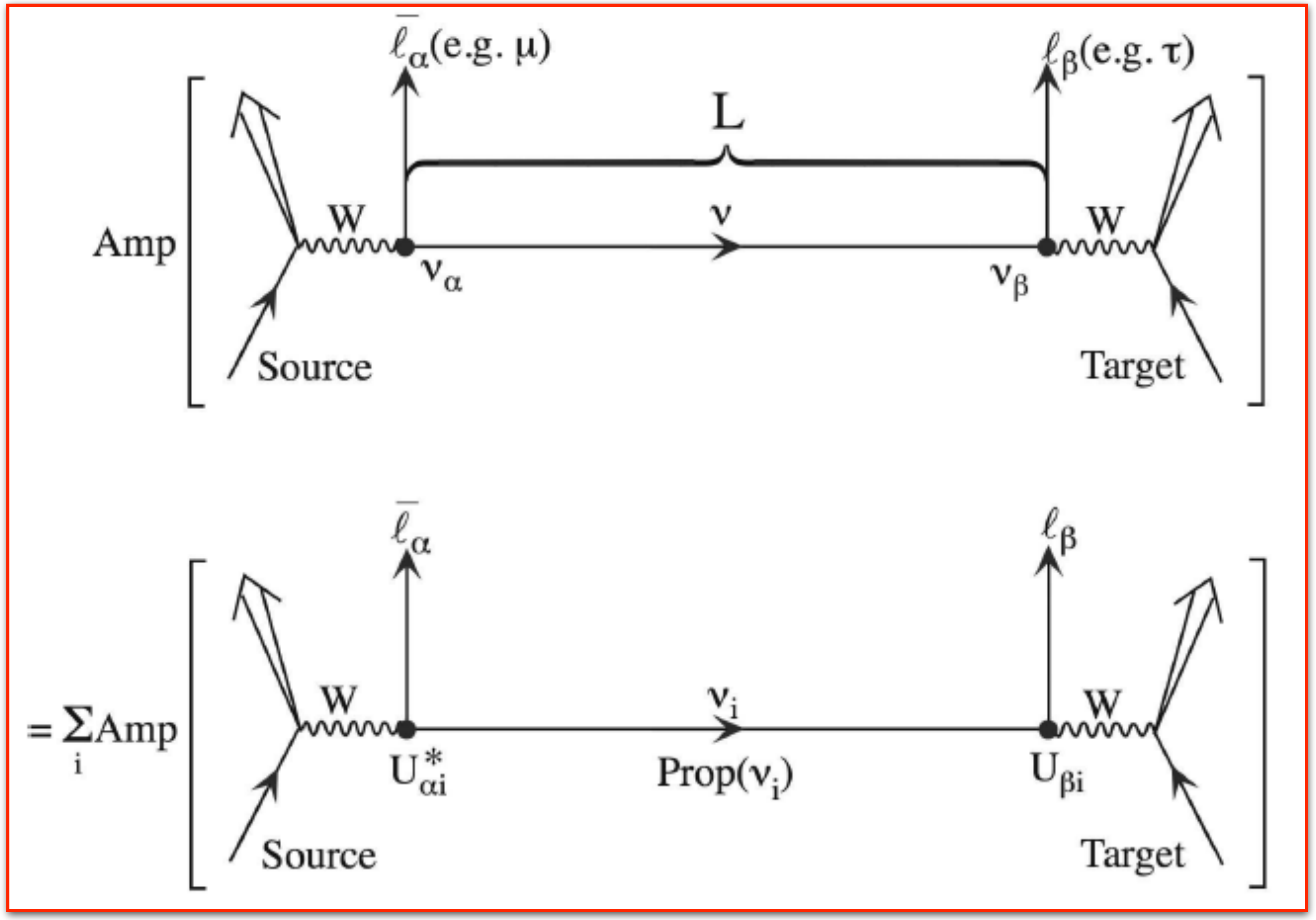
Image credit: B. Kayser

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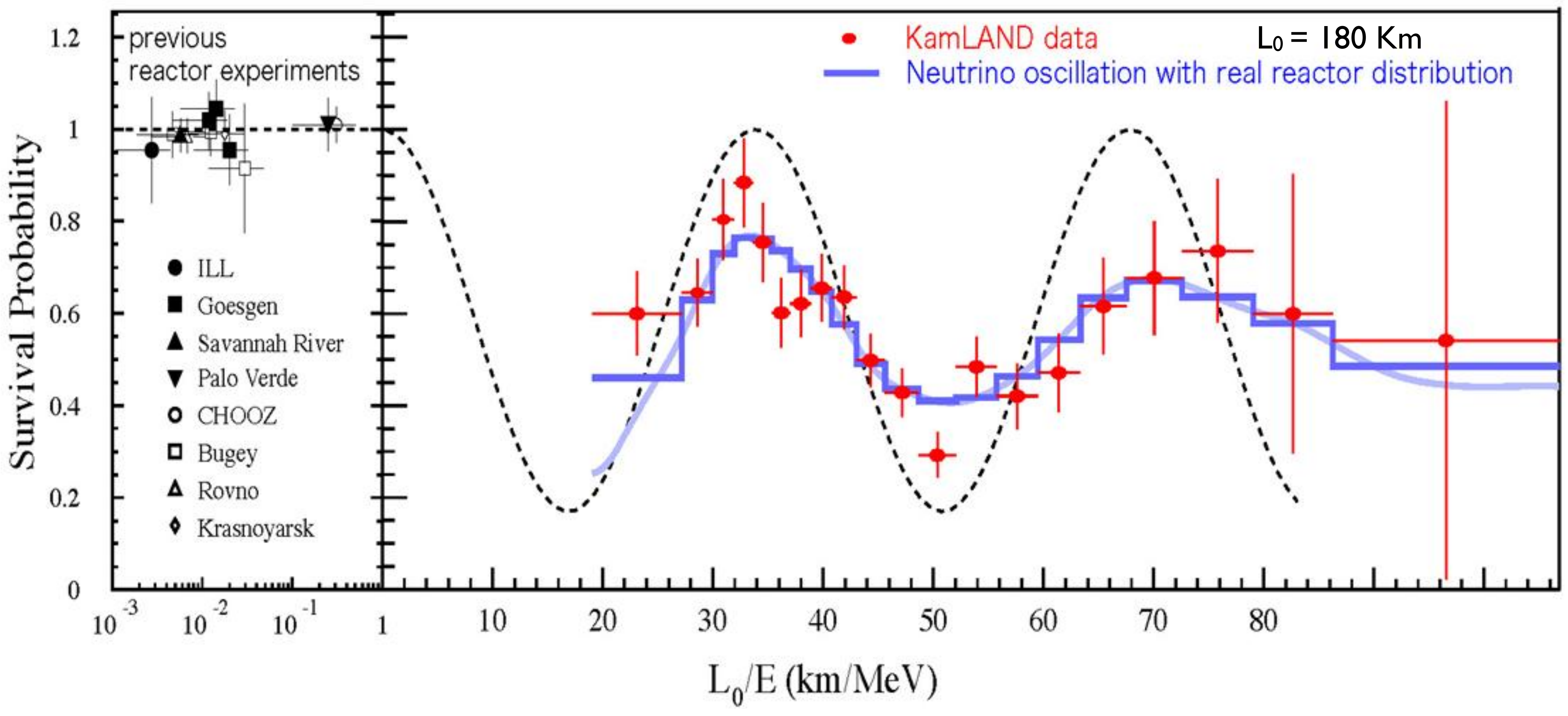
- Massive neutrinos produced in a given interaction ("flavor") state can "oscillate" into another flavor through QM interference

KAMLAND Reactor electron anti-neturino survival probability




$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

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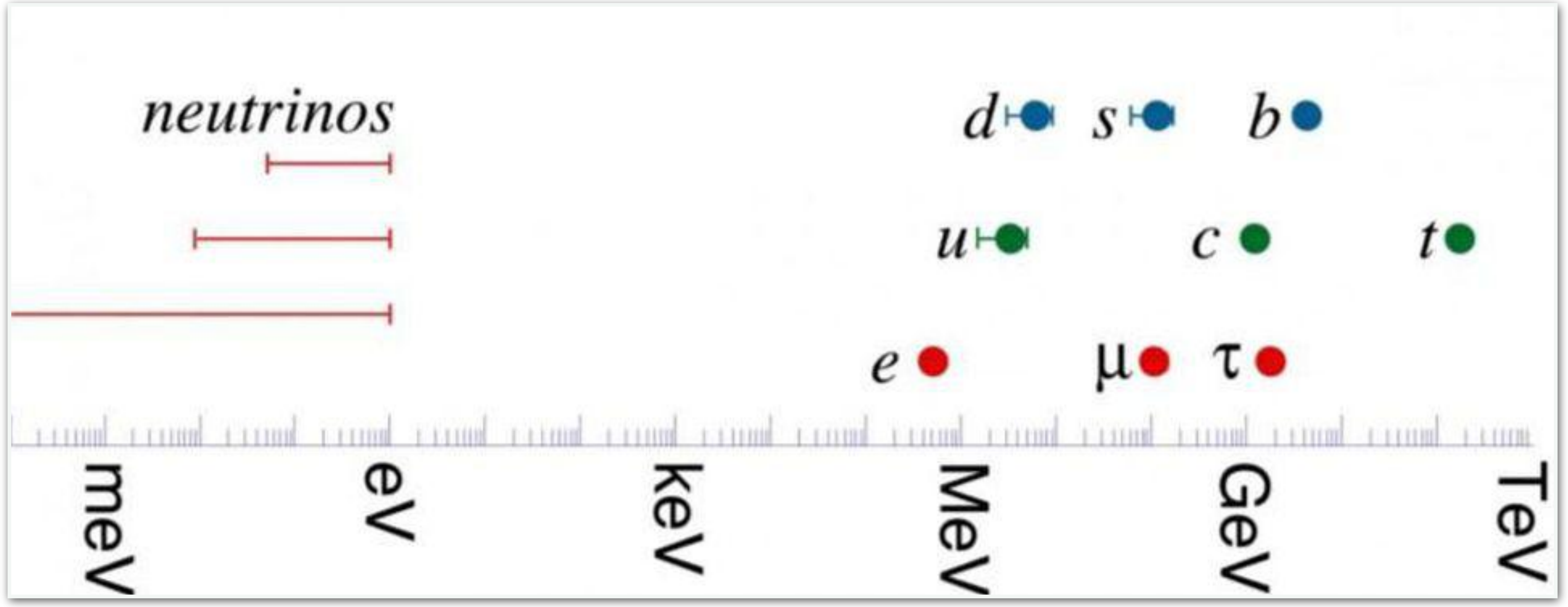
- Neutrinos have masses and they are tiny compared to other fermion's masses!




H. Murayama

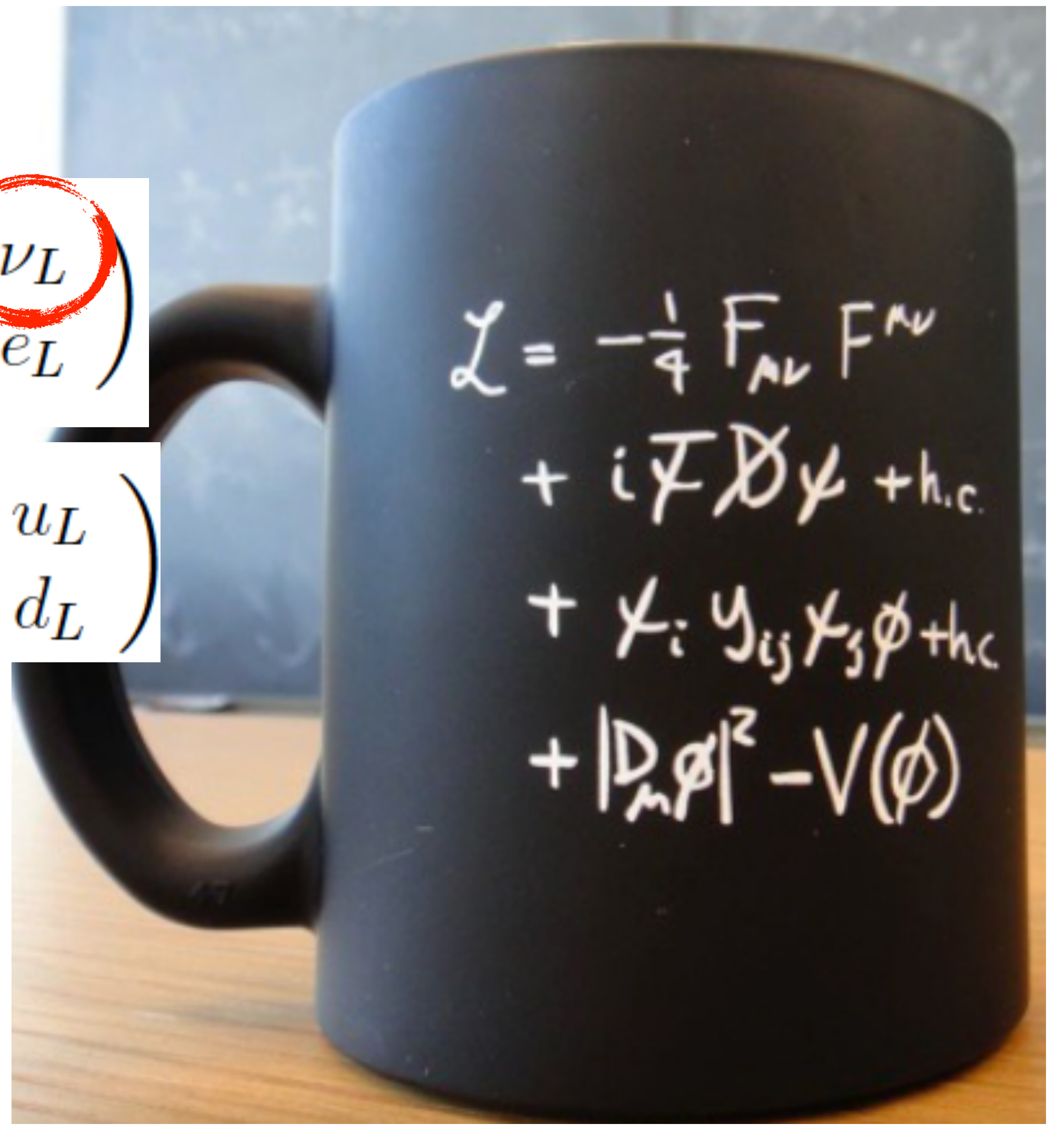
So what's the big deal?

# Neutrino mass = new physics

The Standard Model

$$\psi_i = \begin{pmatrix} \ell_L \\ e_R \\ q_L \\ u_R \\ d_R \end{pmatrix}_i \qquad i = 1,2,3$$

$$\ell_L \to \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \qquad q_L \to \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$




Credit: CERN

No neutrino mass

We currently don't even know what's the quantum mechanical nature of *massive* neutrinos!
(= we don't know what is the form of the neutrino mass term to be added to the SM Lagrangian)

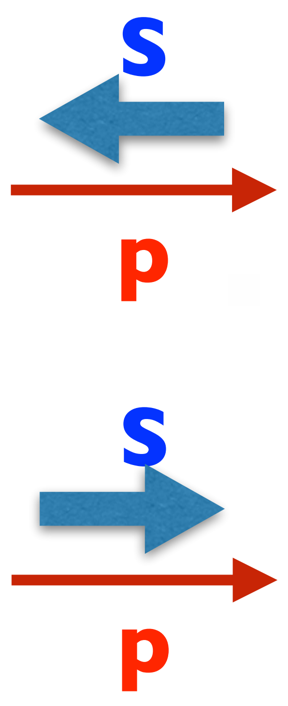
# Neutrino mass and symmetries

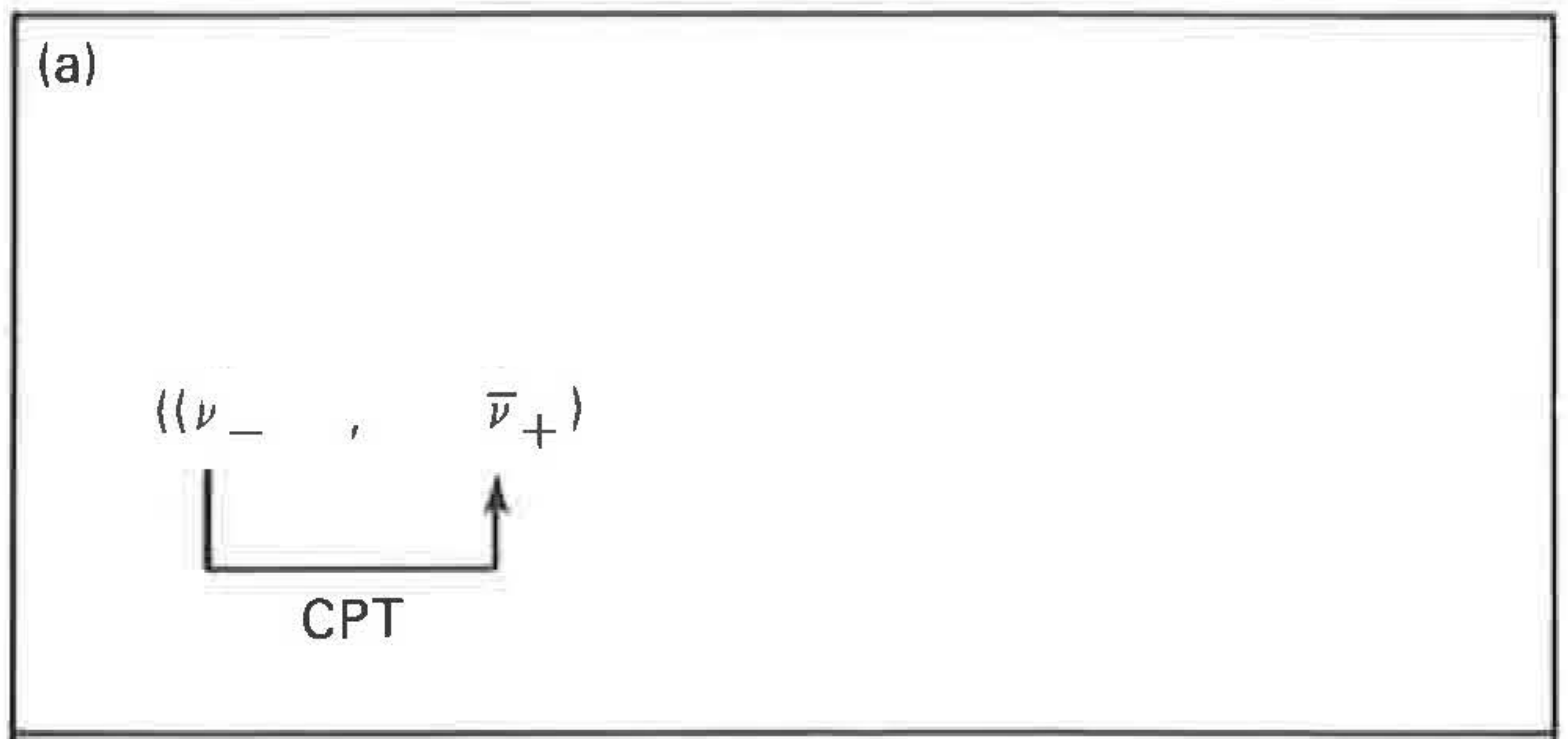
- Lorentz invariance ⇒ two options: Dirac or Majorana

B. Kayser 1984

$\nu(L)=\nu_-$

$\nu(R)=\nu_+$




Dirac:
4 states

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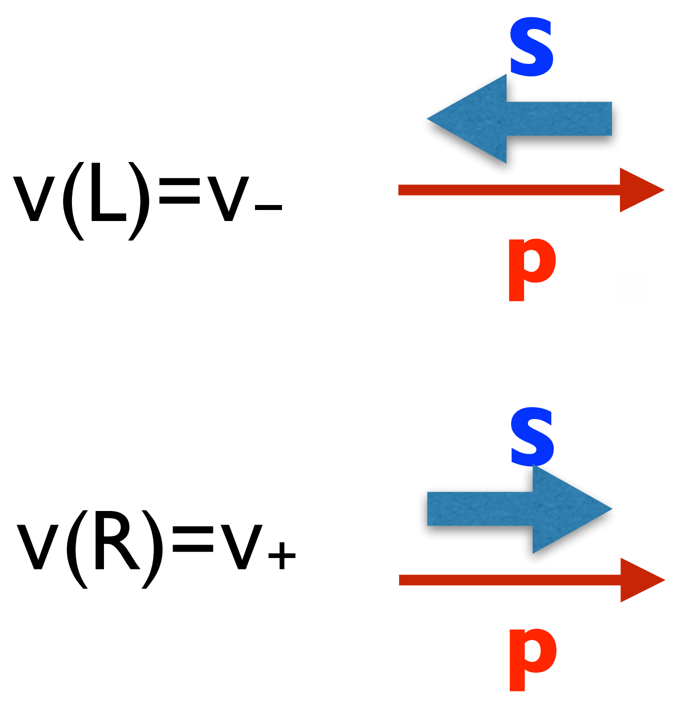


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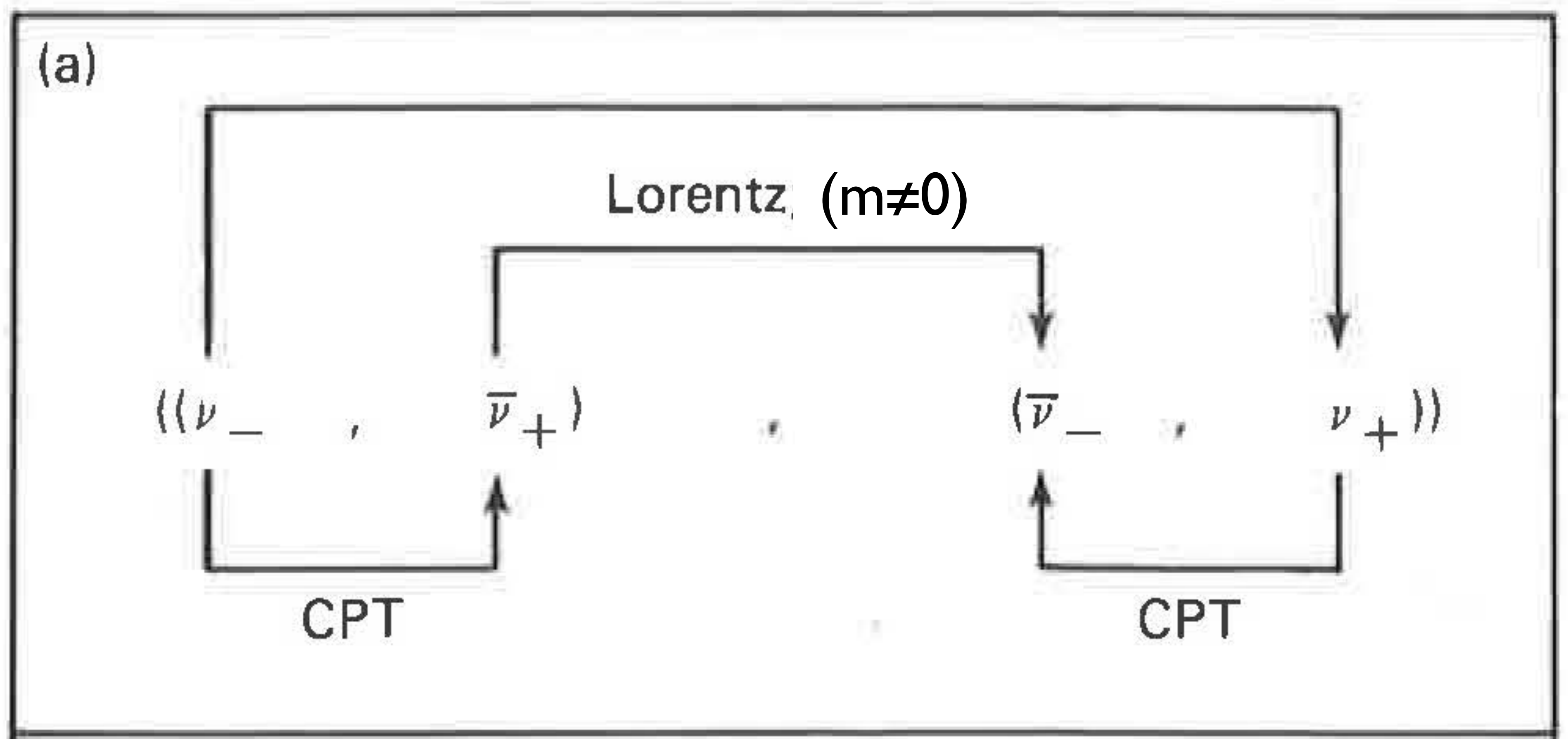


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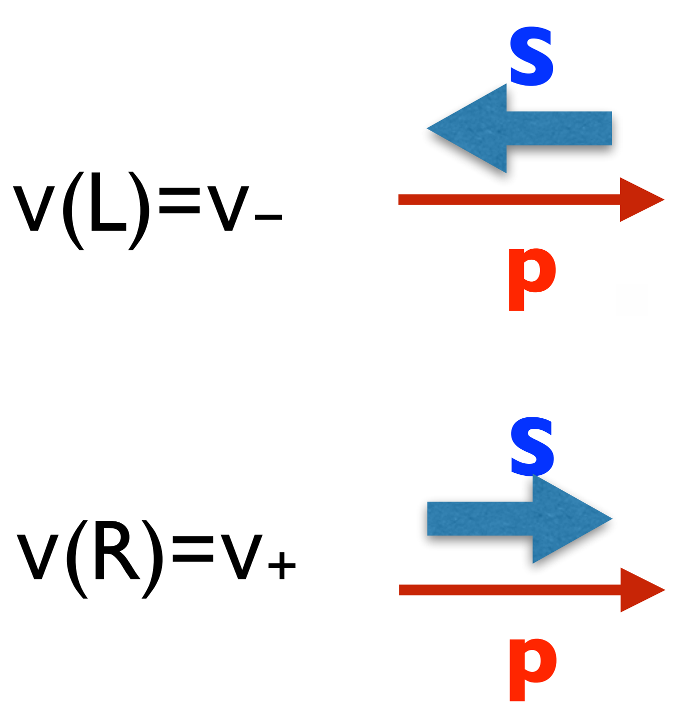


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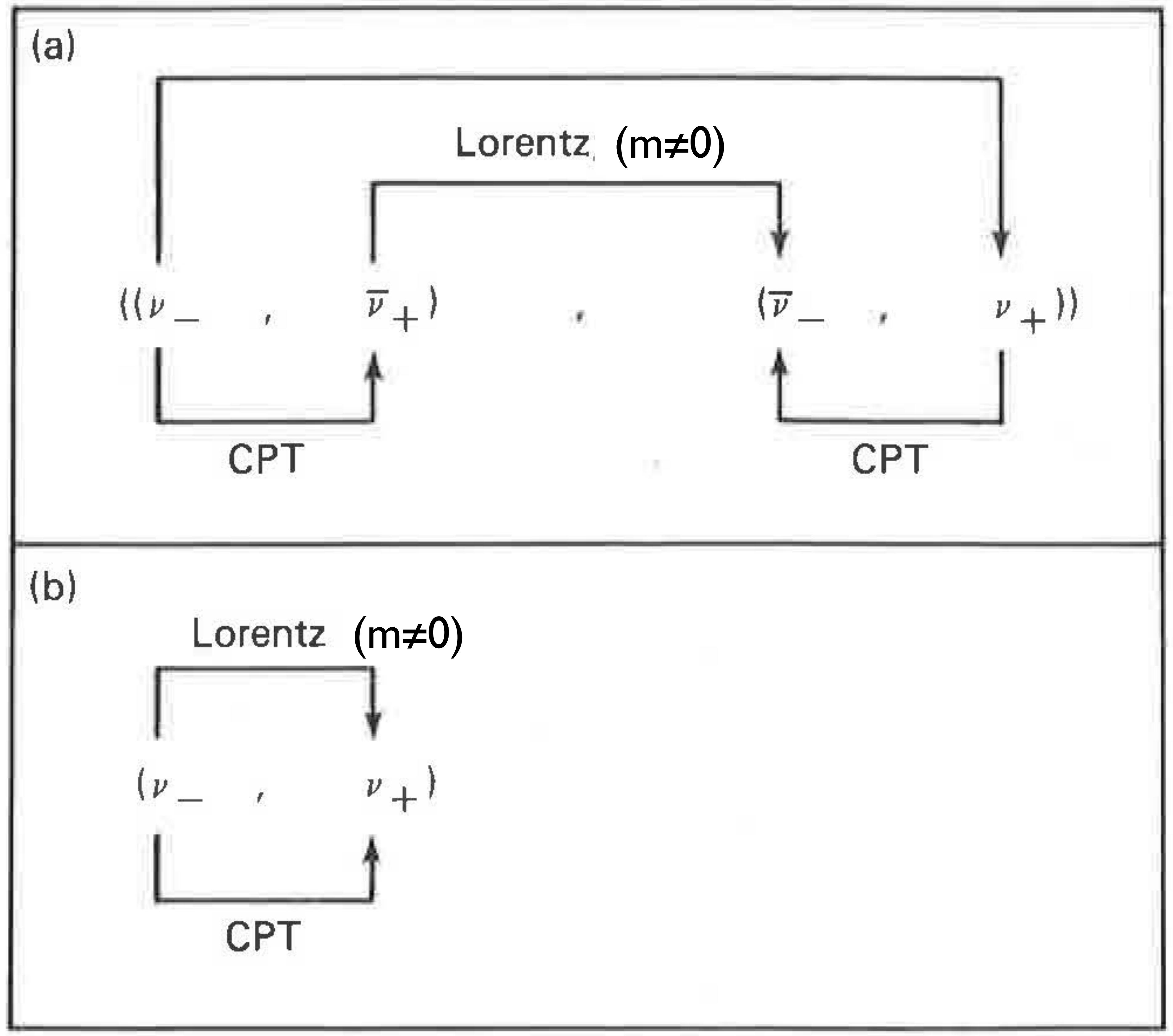


Dirac:
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Majorana:
2 states ($\bar{\nu}_+ = \nu_+$)

Only possible if there no internal quantum number that flips sign under "C"

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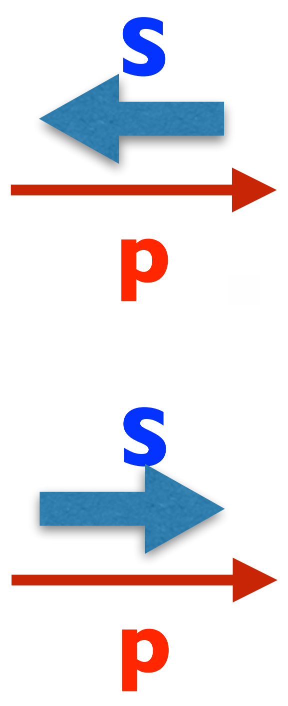


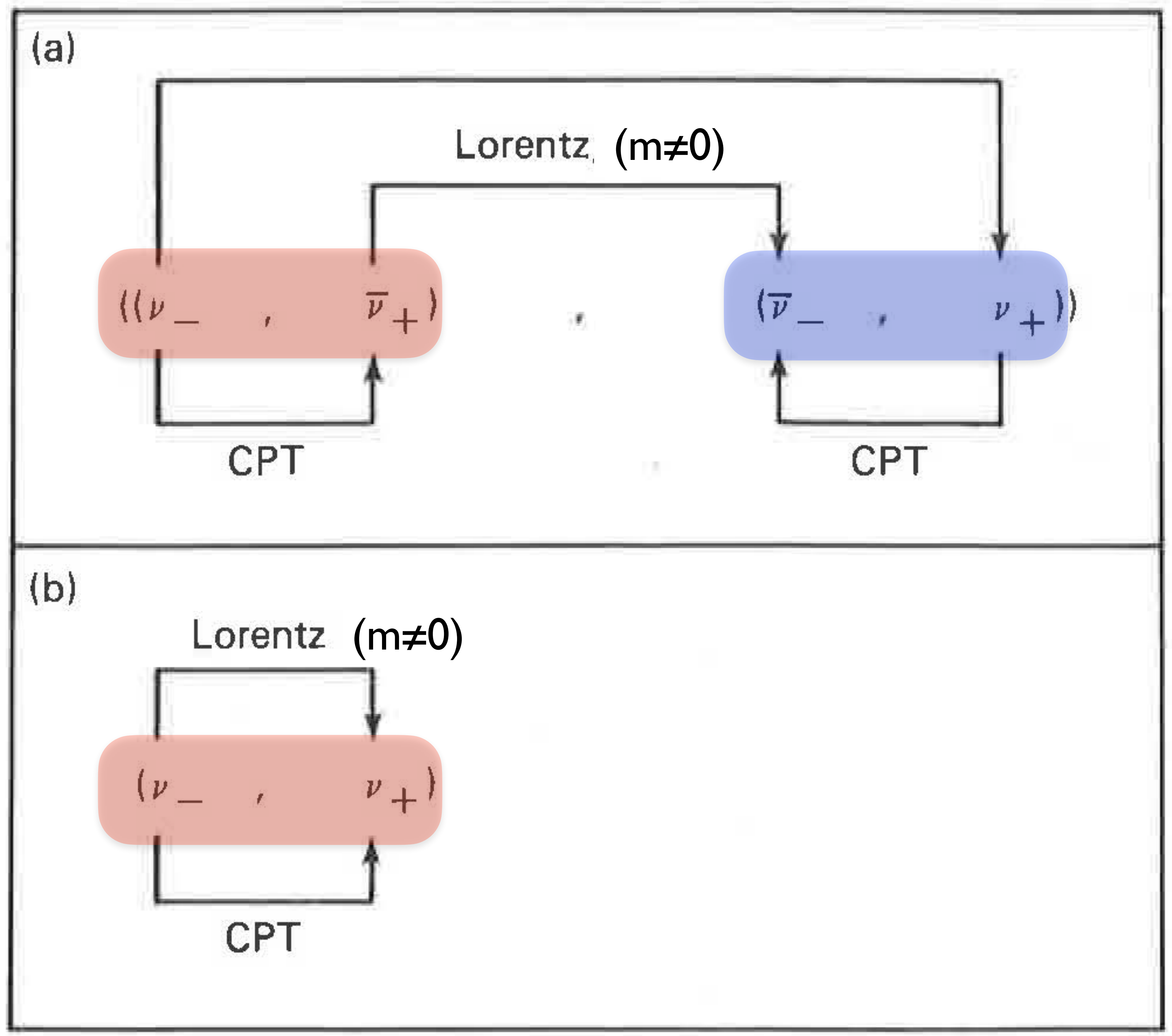


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$\nu_L(x)$ $\nu_R(x)$

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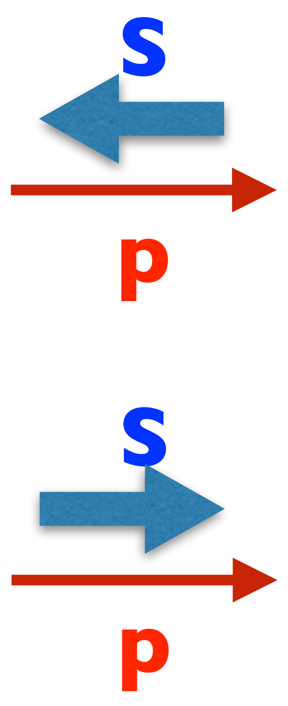


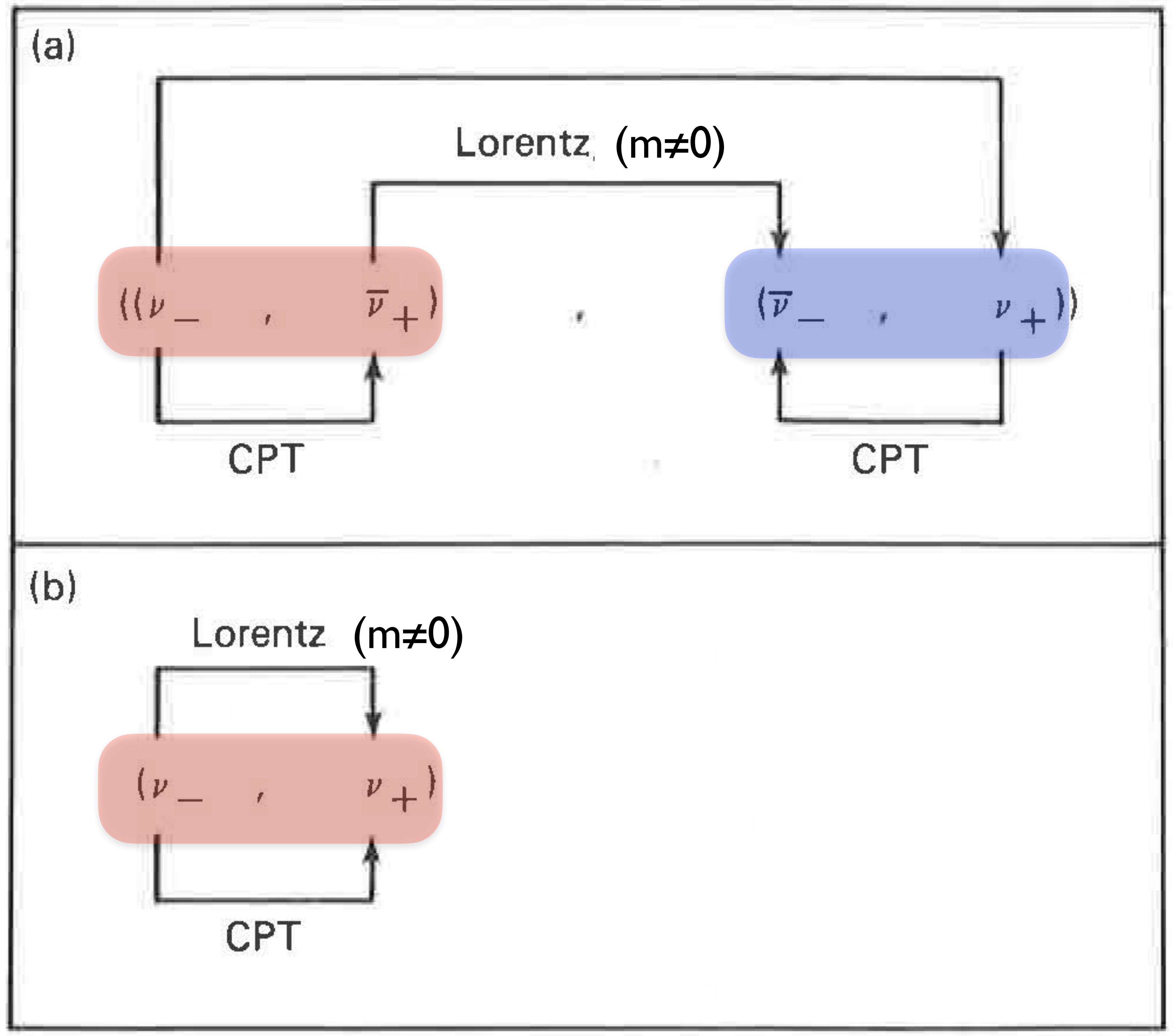


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Only possible if there no internal quantum number that flips sign under "C"

Up to effects of $O(m_\nu/E_\nu)$, only these states participate in SM (V-A) weak interactions

$\nu_-$ = will be pair-produced with $e^+$
$\overset{(-)}{\nu}_+$ = will be pair-produced with $e^-$

$\nu_L(x)$: takes part in weak interactions

$\nu_R(x)$: no interactions in the SM

# Neutrino mass and symmetries

- Lorentz invariance ⇒ two options: Dirac or Majorana

Recall: can build two Lorentz-invariant bilinears from spin-1/2 fields $\psi_{L,R}$

Dirac mass:

$$m_D \, \overline{\psi_L} \, \psi_R \; + \; \text{h.c.}$$

Majorana mass:

$$m_M \, \psi_L^T \, C\psi_L \; + \; \text{h.c.}$$

$$\boxed{\psi_{L/R} = \frac{1 \mp \gamma_5}{2}\psi \qquad C = i\gamma_2\gamma_0 \qquad \psi^c = C\bar{\psi}^T = i\gamma_2\psi^*}$$

# Neutrino mass and symmetries

- Lorentz invariance ⇒ two options: Dirac or Majorana

Dirac mass:

$$m\,\bar{\nu}_L \nu_R \; + \; \text{h.c.} = m\,\bar{\nu}\nu$$

$$\nu = \nu_L + \nu_R$$

Majorana mass:

$$m\,\nu_L^T C \nu_L \; + \; \text{h.c.} = m\,\bar{\nu}\nu$$

$$\nu = \nu_L + \nu_L^c = \nu^c$$

Both options written this way clash with the Standard Model particle content and symmetries

# Neutrino mass and symmetries

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- Lorentz and weak isospin [SU(2)$_w$] invariance ⇒ need new degrees of freedom

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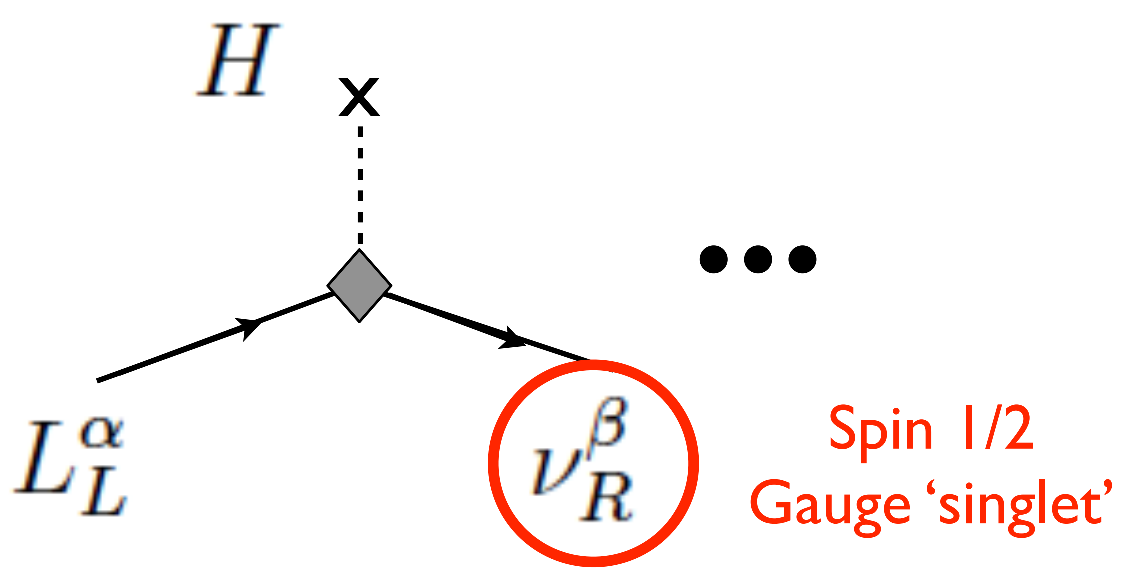


$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$\tilde{H} = \epsilon\, H^* = \begin{pmatrix} h^{0*} \\ -h^- \end{pmatrix}$$

$$\bar{L}^\alpha\, \tilde{H}\, \nu_R^{\alpha\prime}$$

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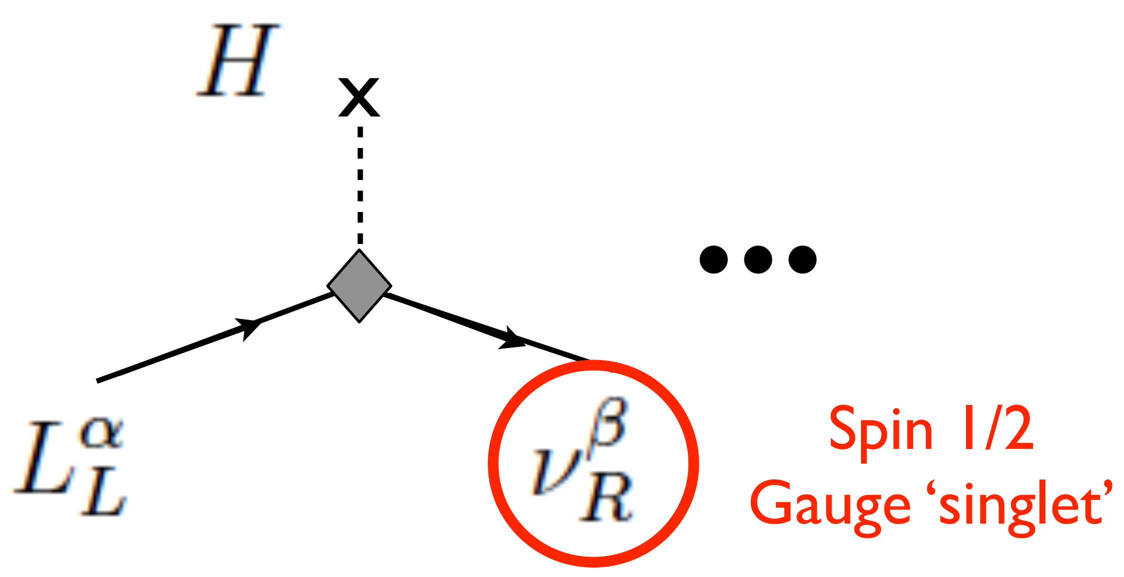


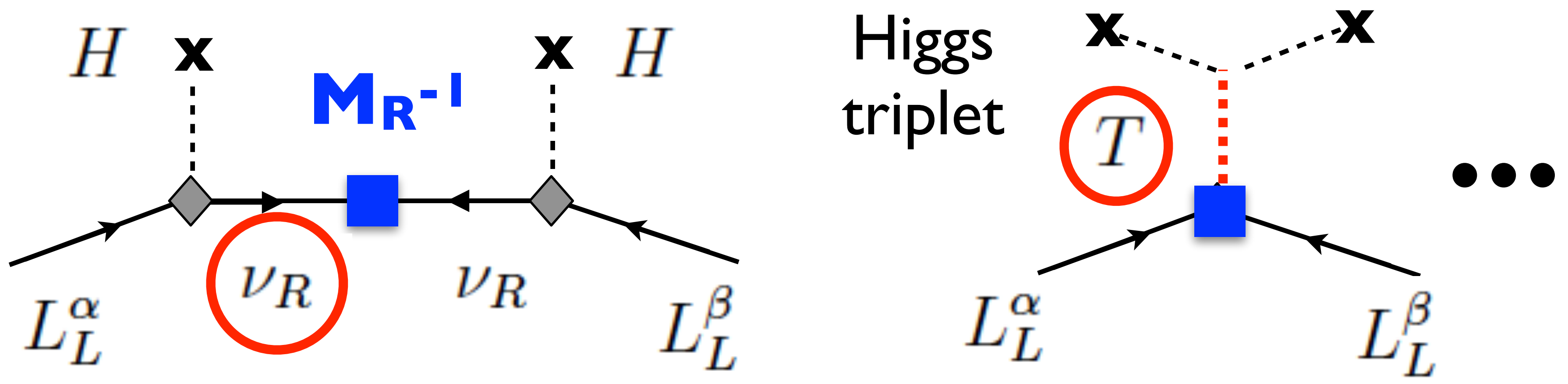


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$$L_\alpha^T C \epsilon H\, H^T \epsilon L_{\alpha\prime}$$

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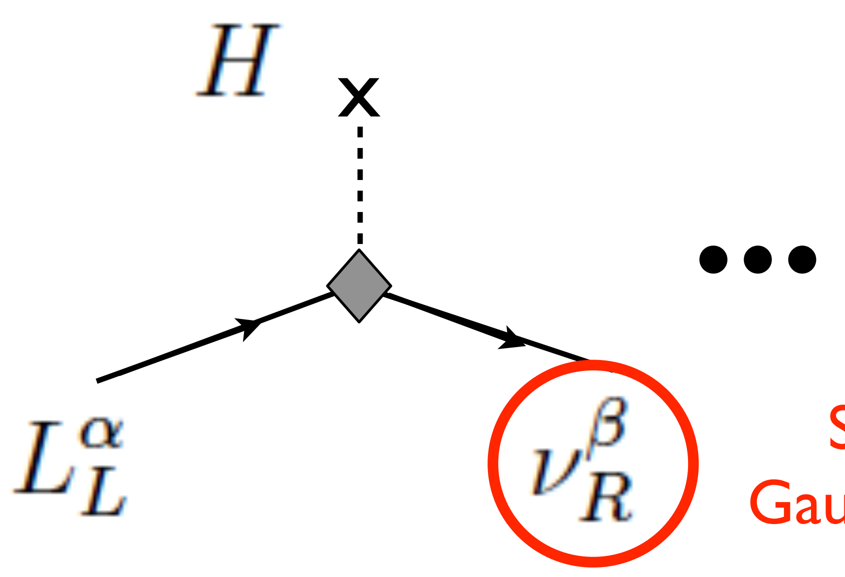
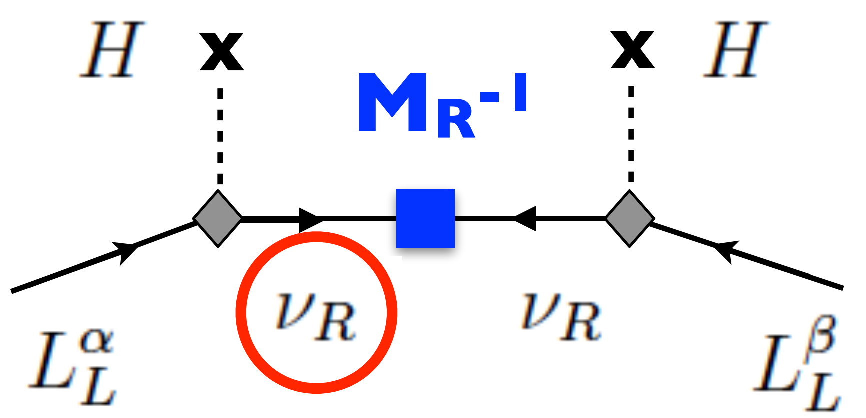
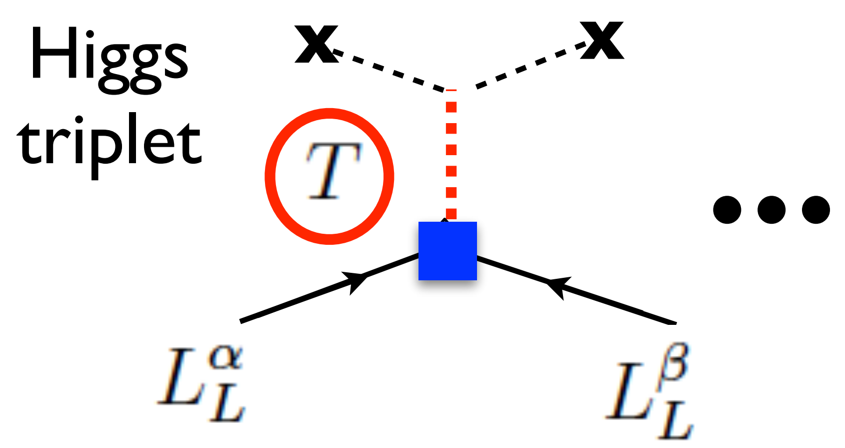



Spin 1/2
Gauge ‘singlet’




- Violates $L_{e,\mu,\tau}$, conserves L

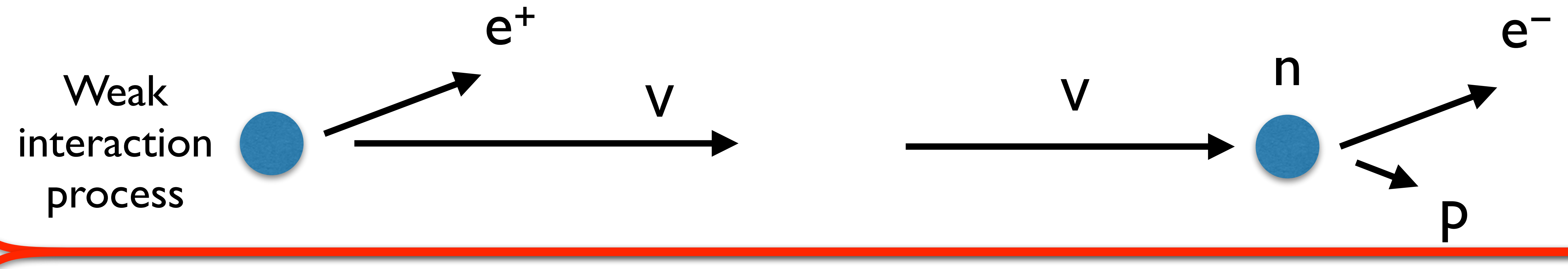
Violates $L_{e,\mu,\tau}$ and L ($\Delta L=2$)

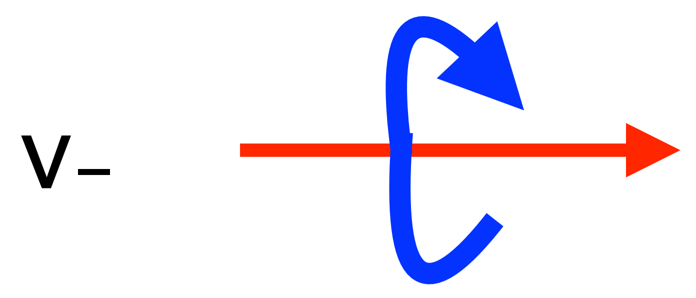
Crucial for experimental probes!

# A complementary point of view

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

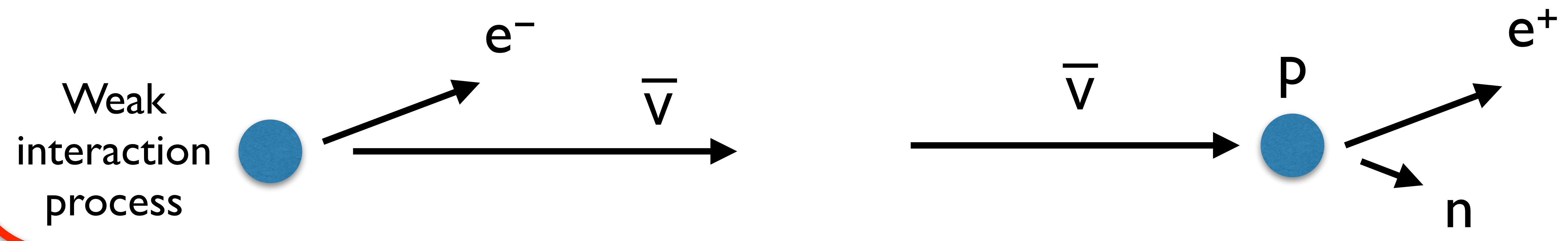
Left-handed: $\mathbf{s} \cdot \hat{\mathbf{p}} = -1/2$

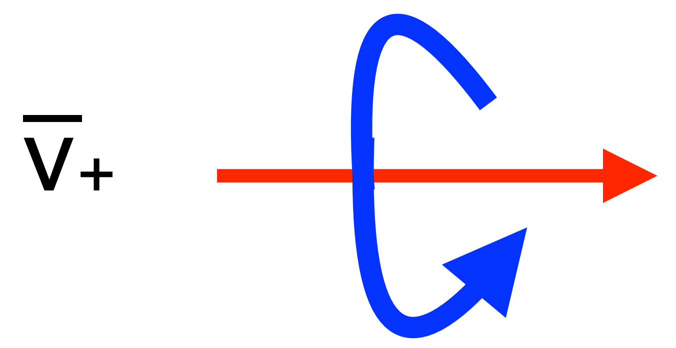



Anti-neutrino ($\bar{\nu}$): emitted with $e^-$, when interacts with matter can transform into $e^+$

Right-handed: $\mathbf{s} \cdot \hat{\mathbf{p}} = +1/2$



# A complementary point of view

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

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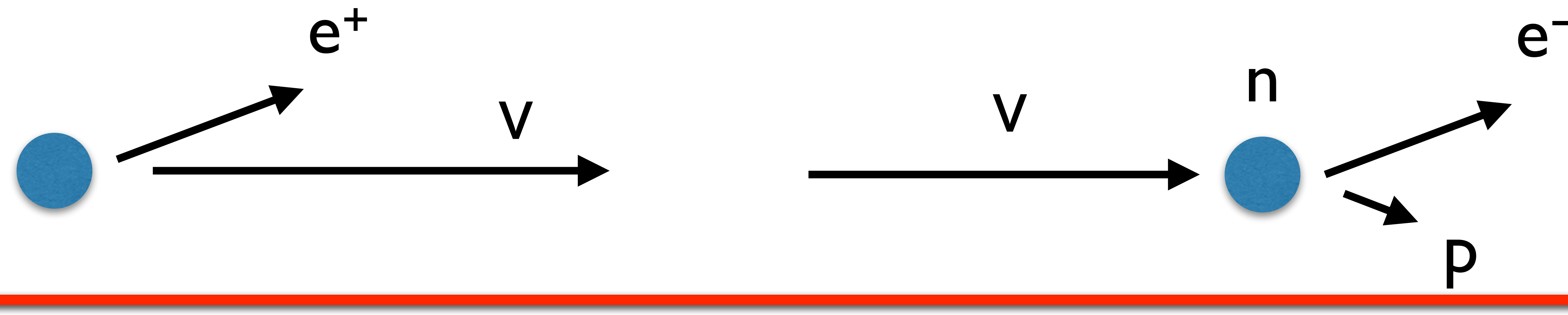
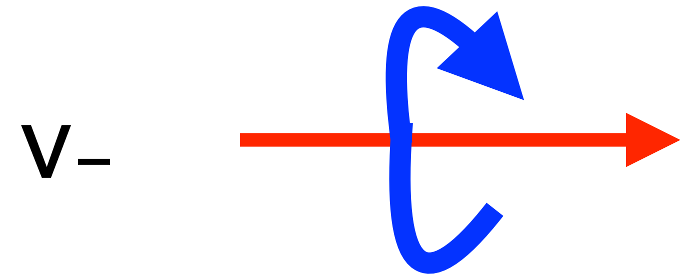
Weak interaction process

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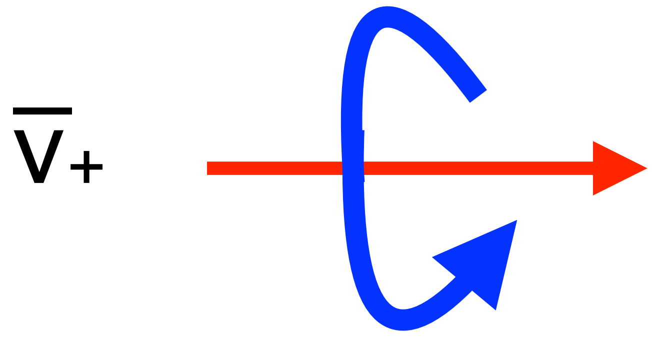
Weak interaction process


Are these two different spin states of the same particle?

No!

Dirac

Neutrino ≠ anti-neutrino

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!

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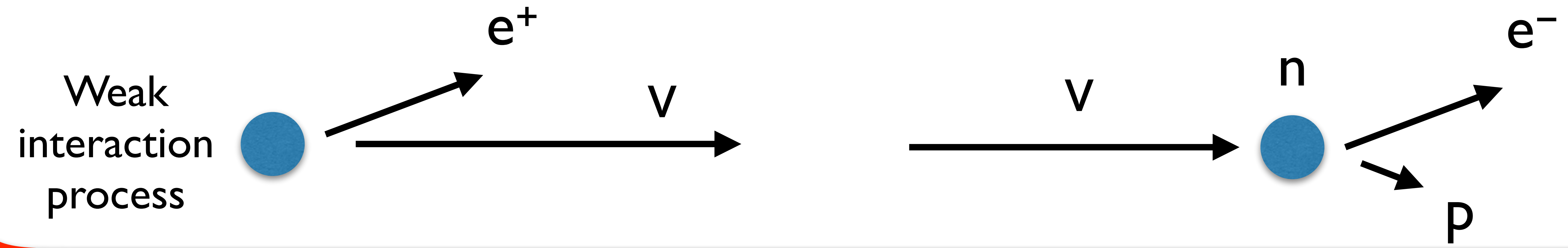
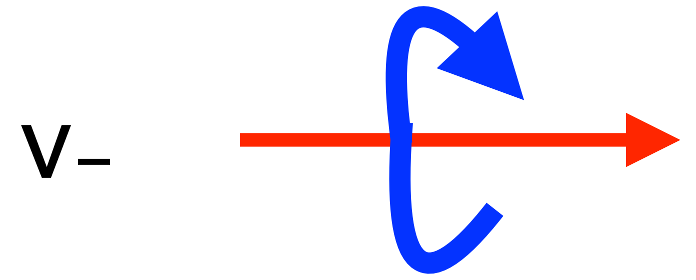
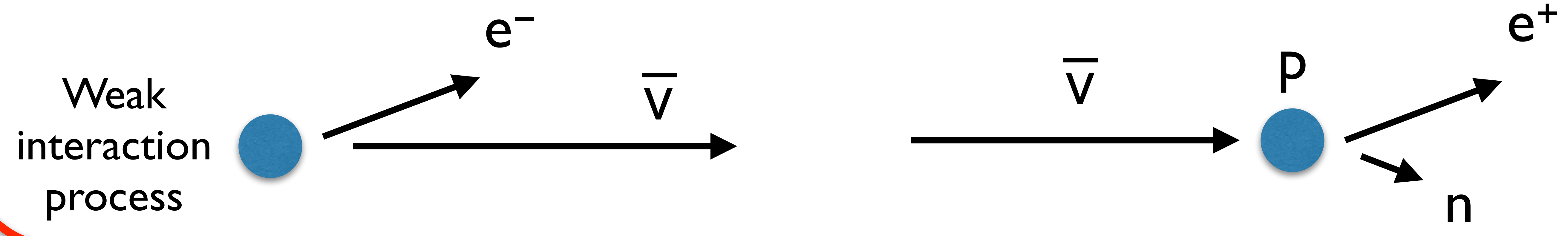
Left-handed: $\mathbf{s} \cdot \hat{\mathbf{p}} = -1/2$

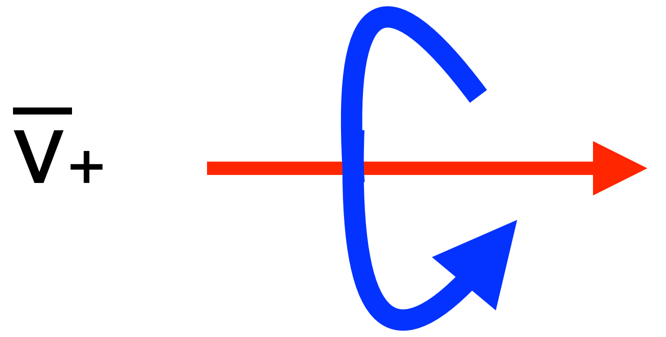



Anti-neutrino ($\bar{\nu}$): emitted with $e^-$, when interacts with matter can transform into $e^+$

Right-handed: $\mathbf{s} \cdot \hat{\mathbf{p}} = +1/2$




Can assign conserved lepton number

4 states:

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

Participate in weak interactions

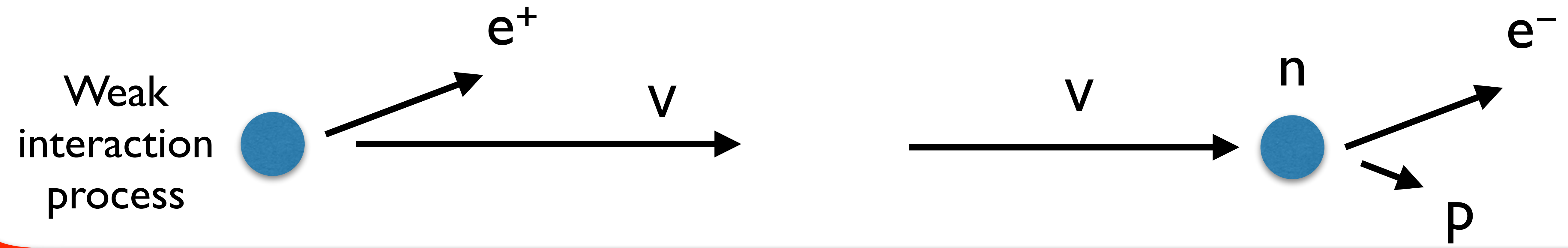
Cannot assign a conserved lepton number

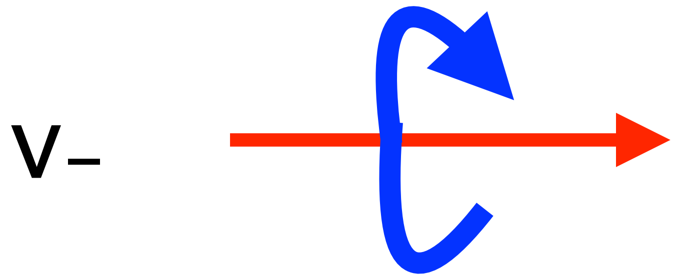
2 states: $\nu_-$ $\nu_+$

# A complementary point of view

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

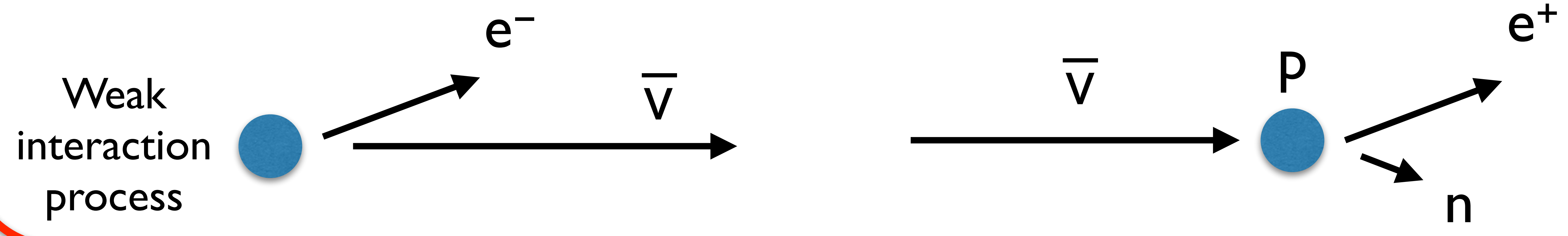
Left-handed: $\mathbf{s} \cdot \hat{\mathbf{p}} = -1/2$

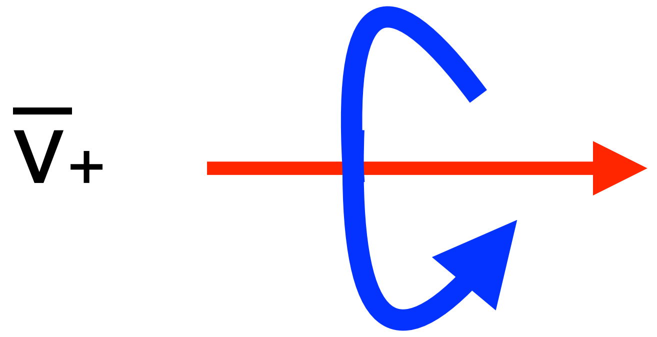



Anti-neutrino ($\bar{\nu}$): emitted with $e^-$, when interacts with matter can transform into $e^+$

Right-handed: $\mathbf{s} \cdot \hat{\mathbf{p}} = +1/2$




For $m = 0$ the two options are not distinguishable: Lepton Number = helicity

Can assign conserved lepton number

4 states:

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

Participate in weak interactions

Cannot assign a conserved lepton number

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

# A complementary point of view

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

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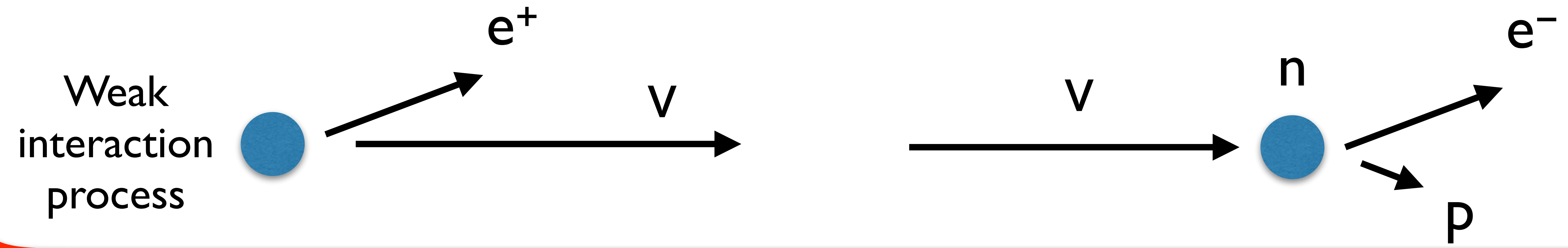
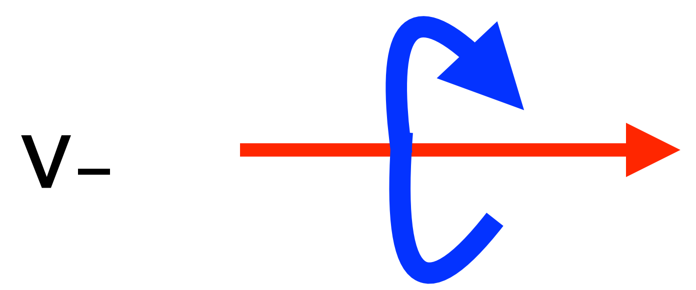
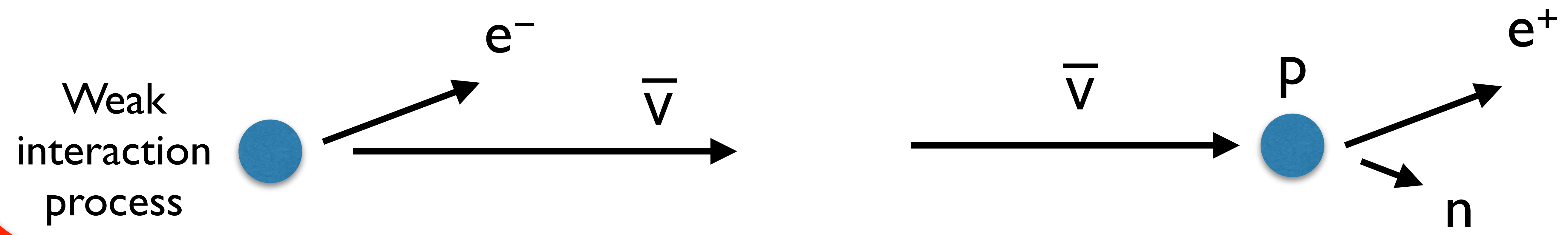
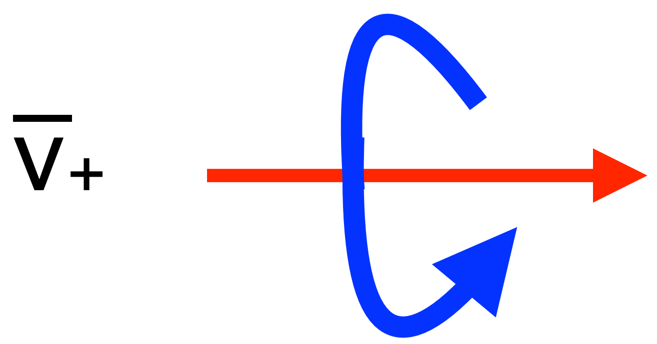



Anti-neutrino ($\bar{\nu}$): emitted with $e^-$, when interacts with matter can transform into $e^+$

Right-handed: $\mathbf{s} \cdot \hat{\mathbf{p}} = +1/2$




For $m \neq 0$ the distinction between Dirac and Majorana *matters*.
The Majorana option blurs the notion of matter and antimatter!

Can assign conserved lepton number

4 states:

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

Participate in weak interactions

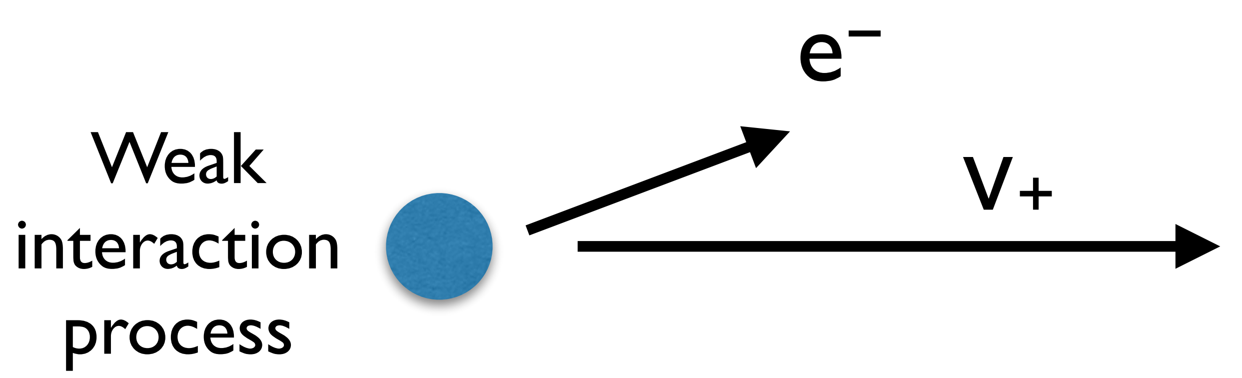
Cannot assign a conserved lepton number

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

# Distinguishing Dirac from Majorana?

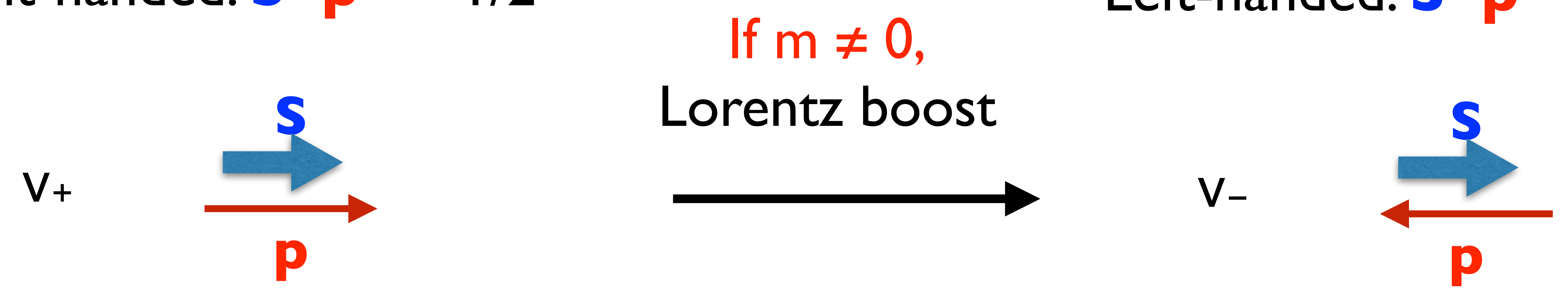
Majorana case

'Anti-neutrino' ($\bar{\nu}$): emitted with $e^-$




Right-handed: $\mathbf{s} \cdot \hat{\mathbf{p}} = +1/2$

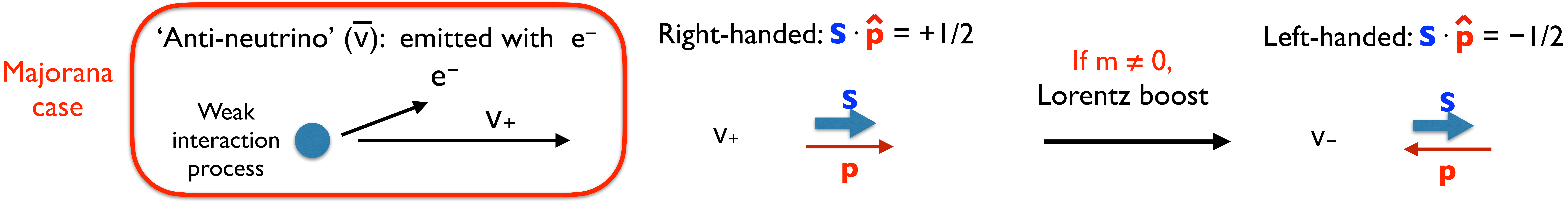
Left-handed: $\mathbf{s} \cdot \hat{\mathbf{p}} = -1/2$



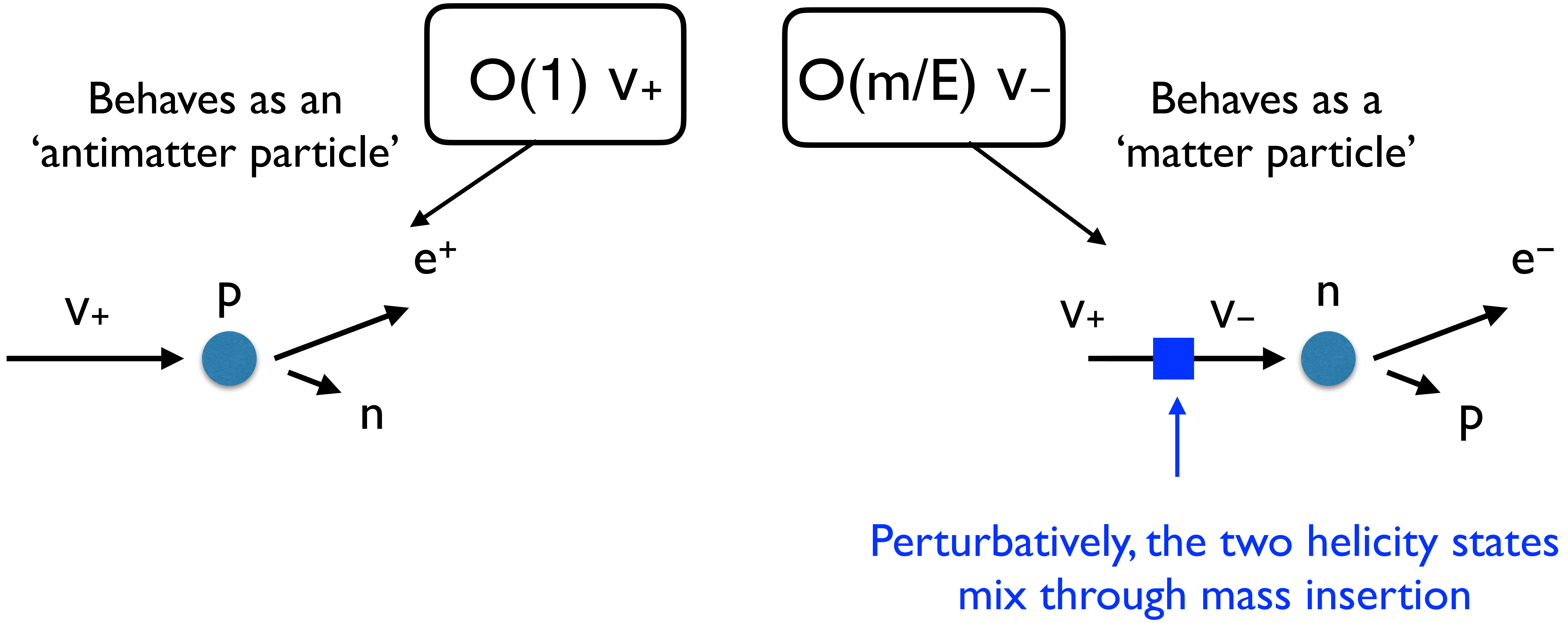

For a massive particle, helicity is frame-dependent $\Rightarrow$

The emitted massive (anti)neutrino can be in both $\nu_{+/-}$ states and hence can transform into both $e^+$ and $e^-$!

# Distinguishing Dirac from Majorana?

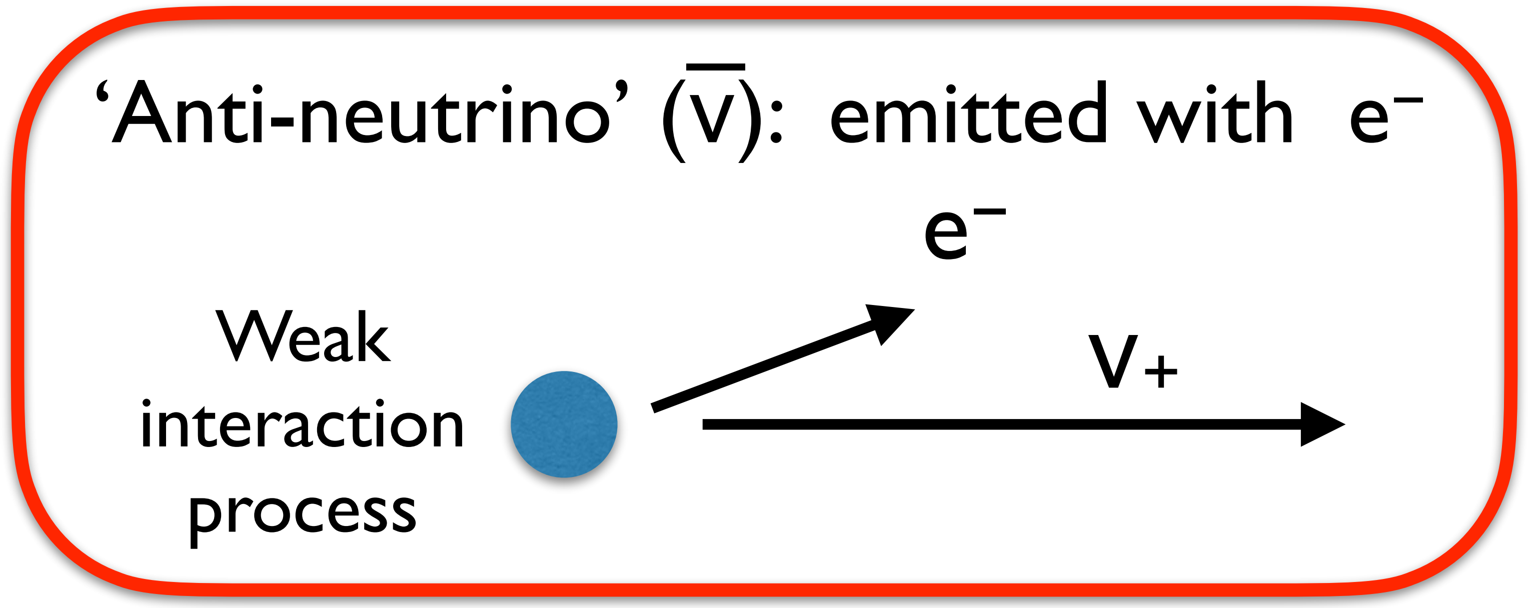


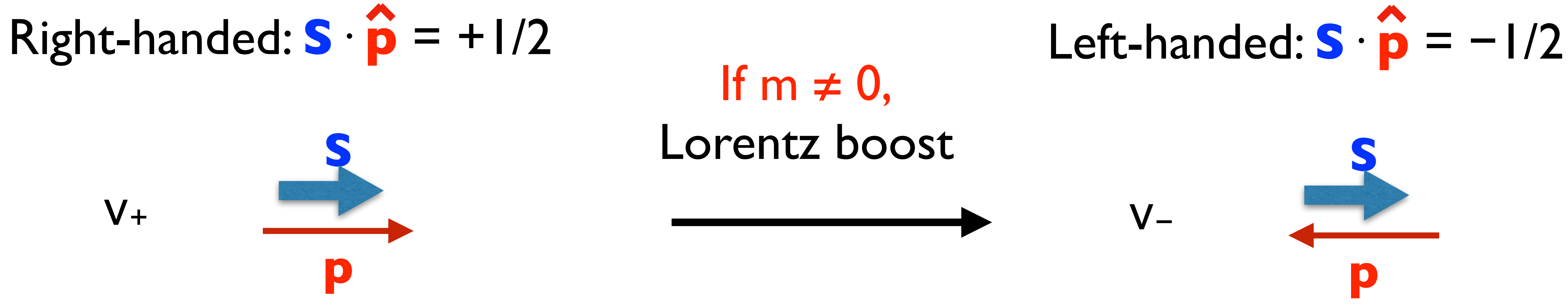

- Weak interactions produce massive 'antineutrino' in both helicity states



# Distinguishing Dirac from Majorana?

Majorana case

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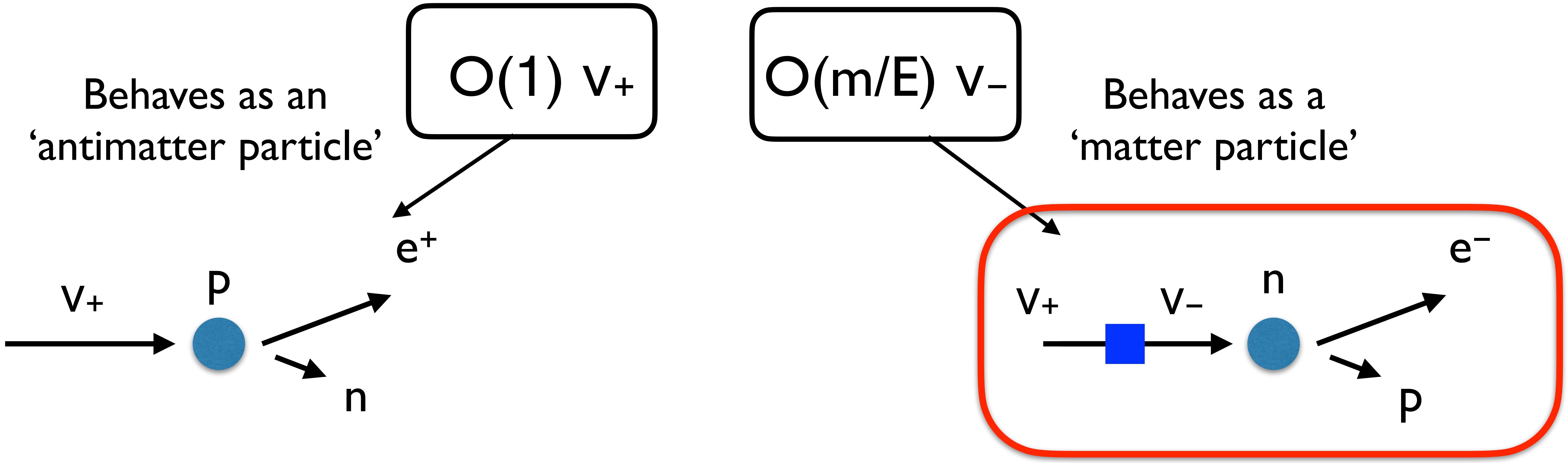



- To detect the Majorana signature ($e^-$ in final state) need to overcome the m/E factor

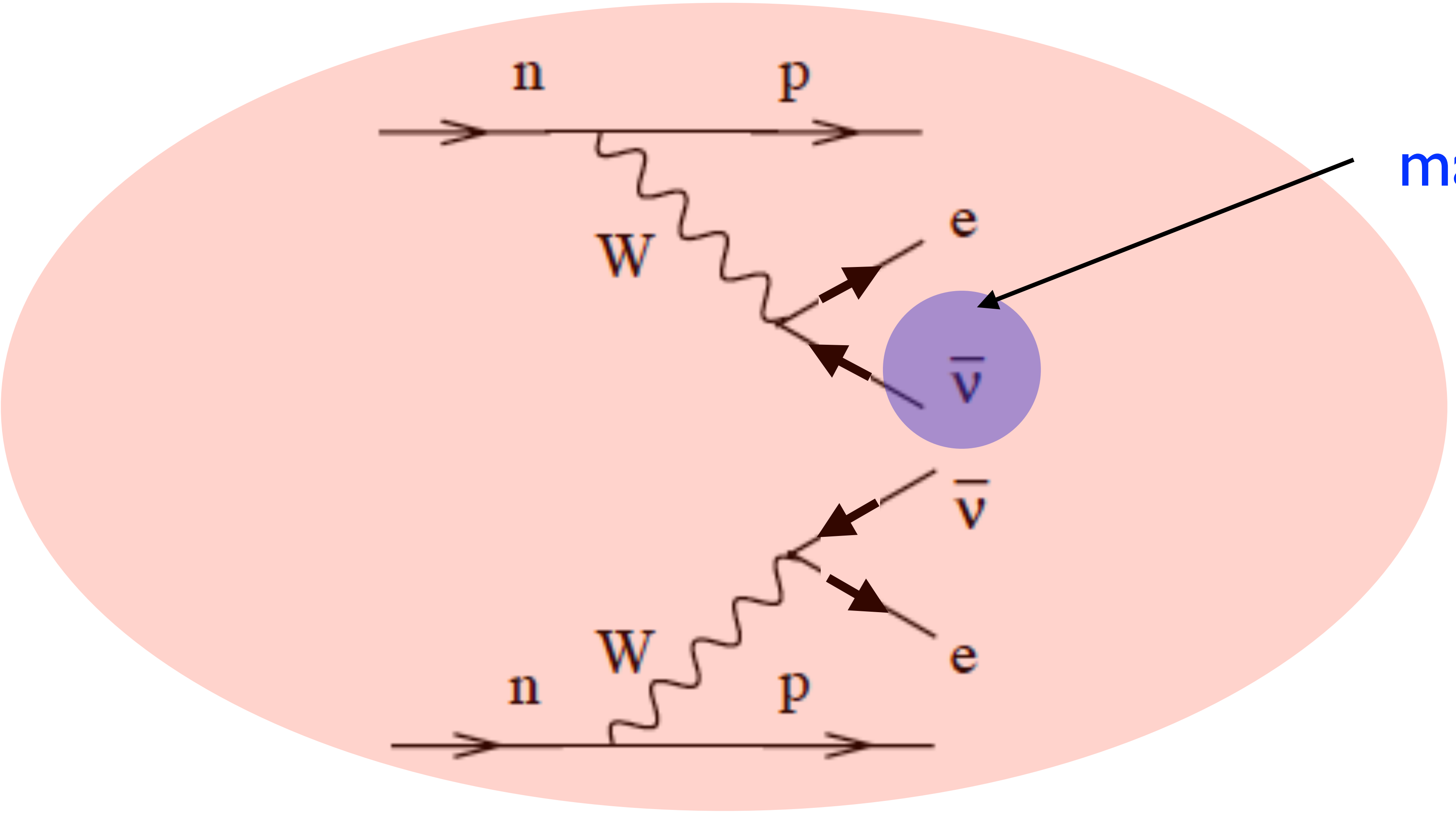
→ Non-relativistic neutrinos

→ Avogadro's number: double beta decay!

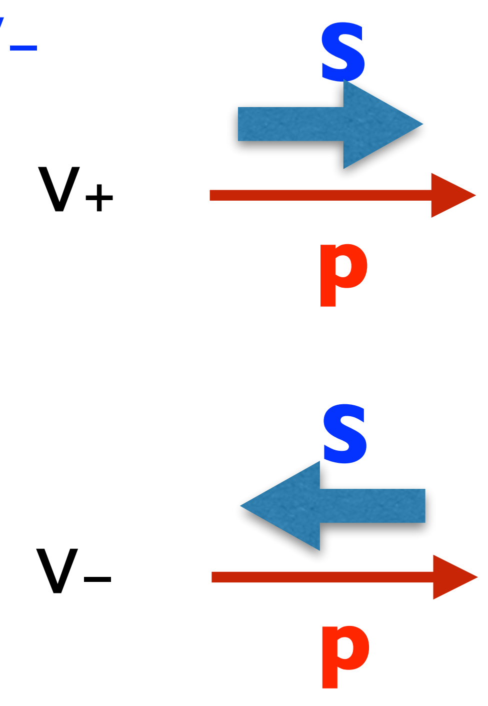
# 0νββ decay is the arbiter

- If neutrinos are Majorana particles, a *virtual* anti-neutrino can convert into a neutrino and mediate 0νββ

W. H. Furry, 1939




This is just $\nu_+$, which via mass insertion turns into $\nu_-$



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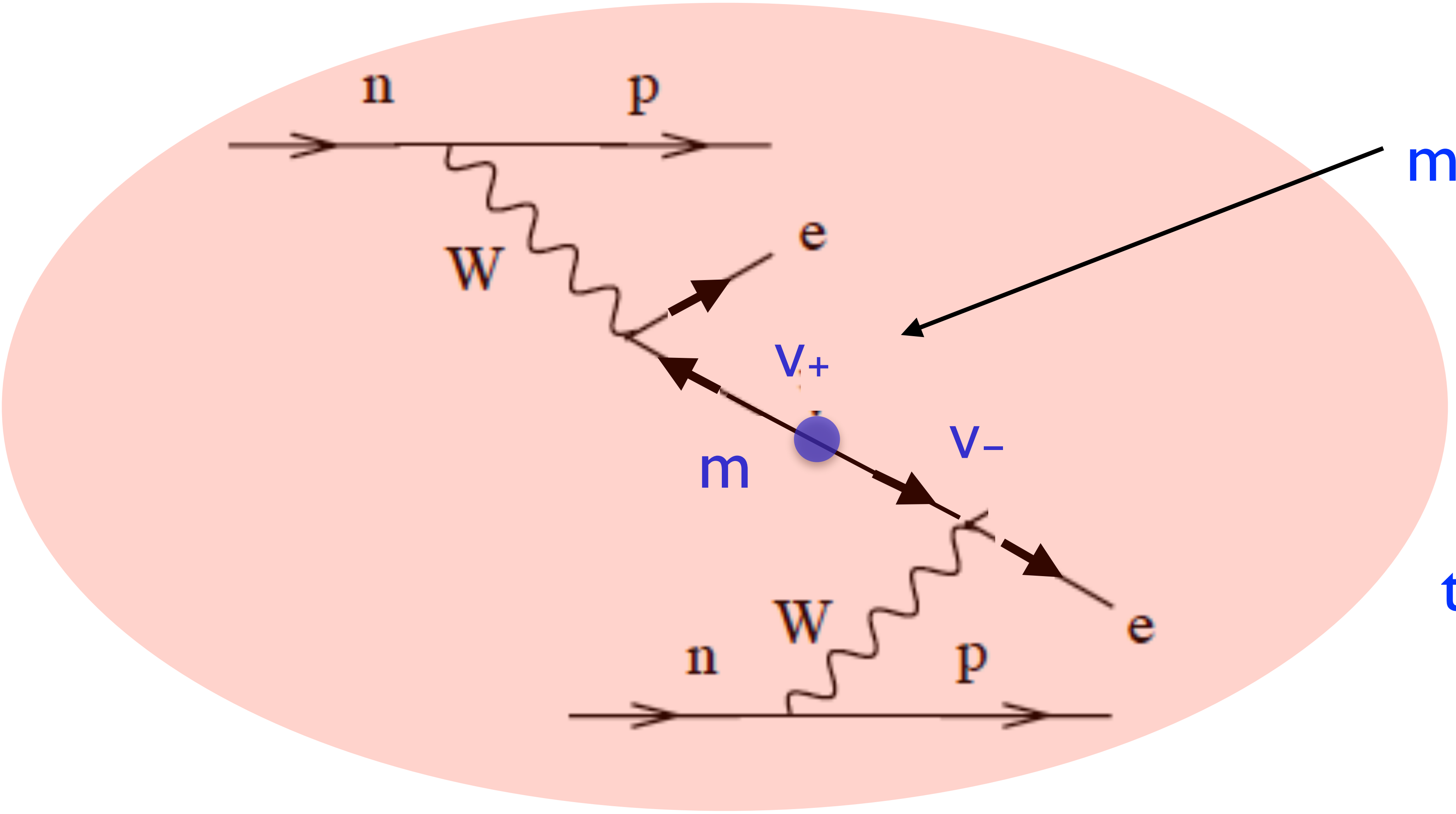
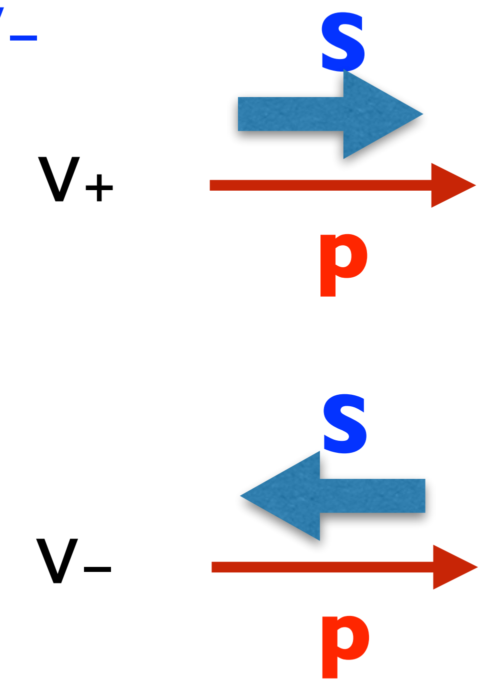



This is just ν+, which via mass insertion turns into ν−

ν− converts into $e^-$ in the second interaction

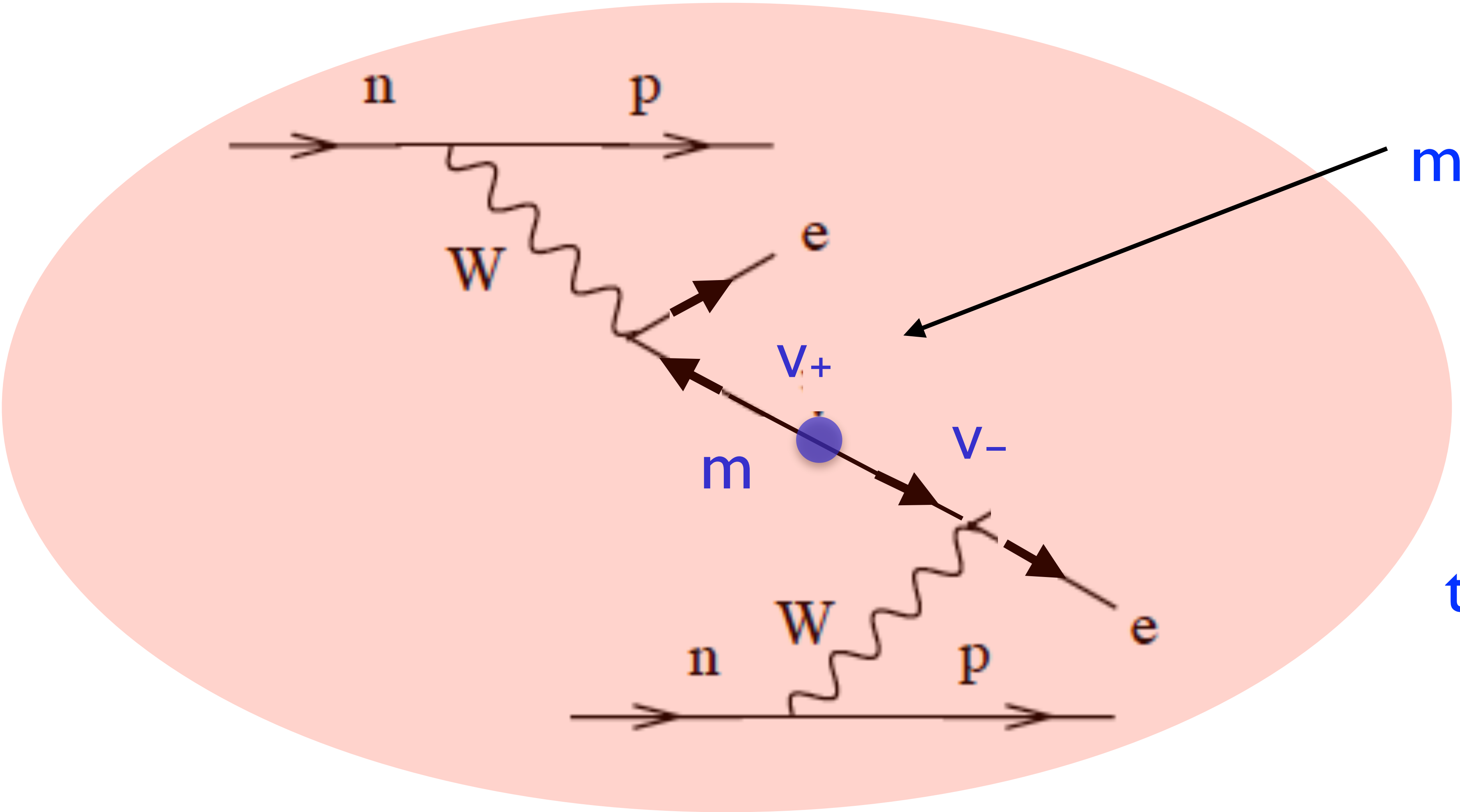



"Subject to the usual limitations on the meaning of such language, one can say that a (virtual) neutrino is emitted together with one of the electrons and reabsorbed when the other electron is emitted."

# $0\nu\beta\beta$ decay is the arbiter

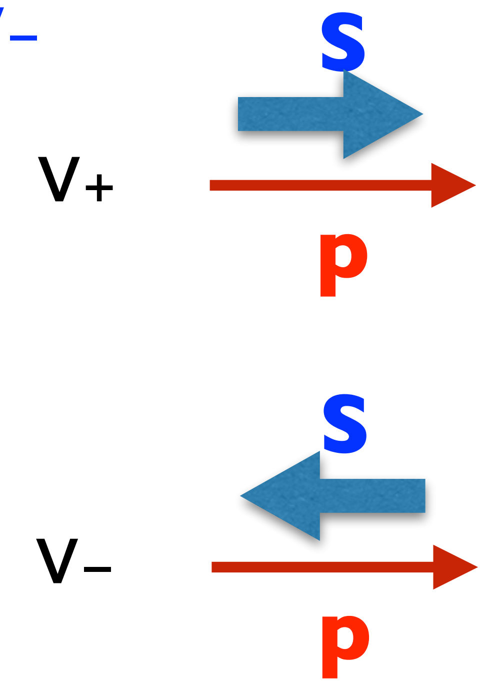
- If neutrinos are Majorana particles, a *virtual* anti-neutrino can convert into a neutrino and mediate $0\nu\beta\beta$

W. H. Furry, 1939




This is just $\nu_+$, which via mass insertion turns into $\nu_-$

$\nu_-$ converts into $e^-$ in the second interaction




- Key point: in $0\nu\beta\beta$ Lepton Number changes by two units. Majorana $\nu$ exchange is just one possible mechanism. Furry understood this:

"The Majorana form of the theory is not the only one that permits this new form of disintegration […]. The Majorana theory provides, so to speak, a canonical form."

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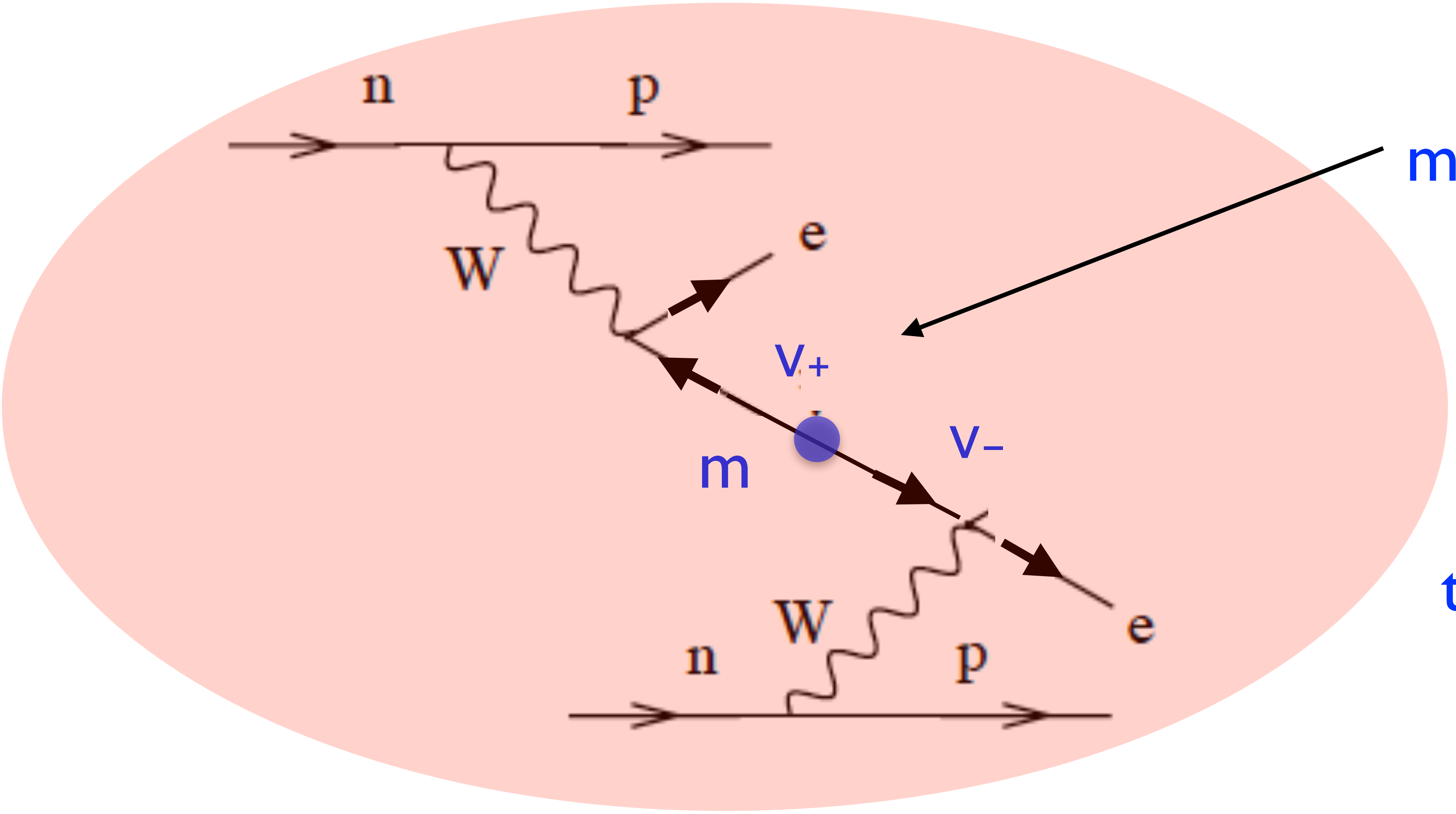
W. H. Furry, 1939

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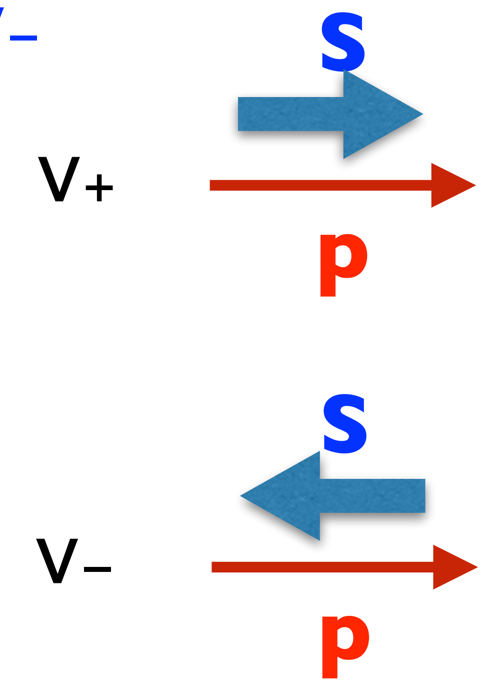
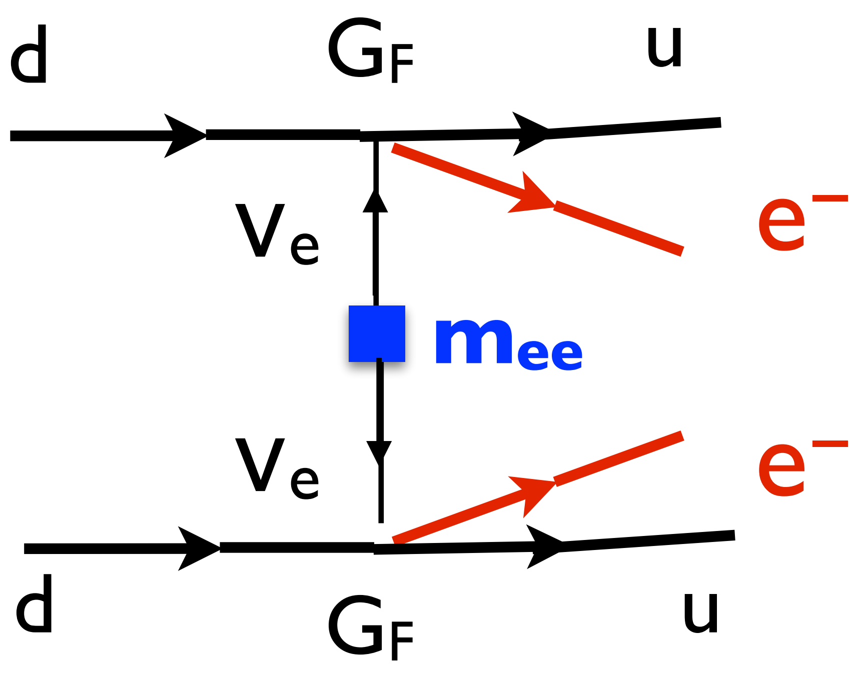
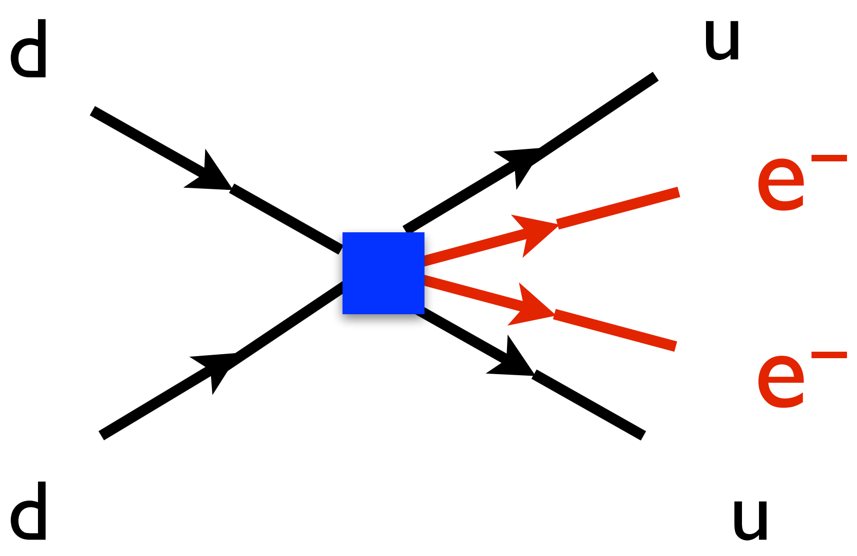



- Modern viewpoint on Lepton Number Violation:




but also

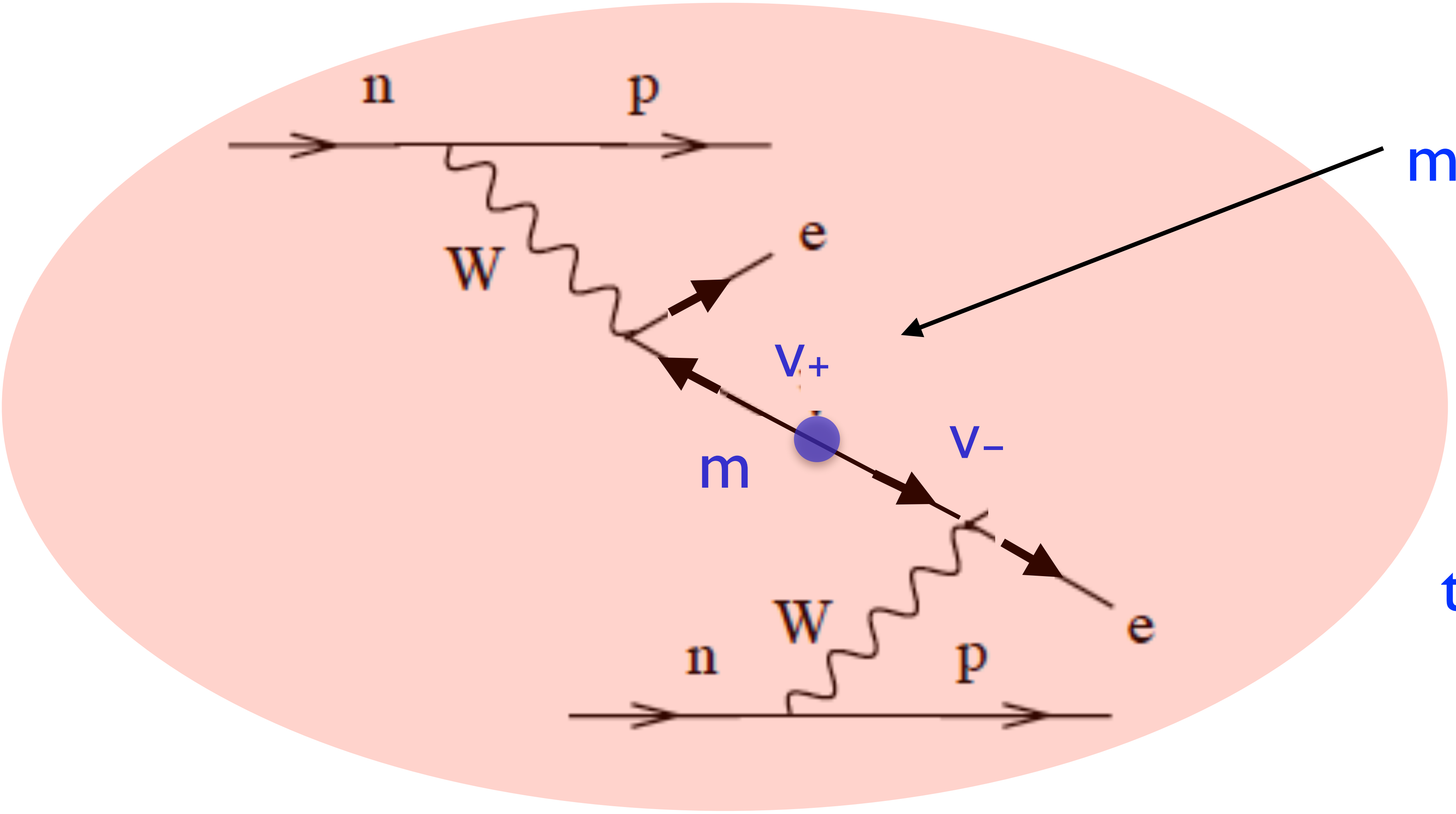



Exchange of heavier neutrinos or other Majorana particles. At low-energy induce six-fermion operator $\sim 1/\Lambda^5$

# 0νββ decay is the arbiter

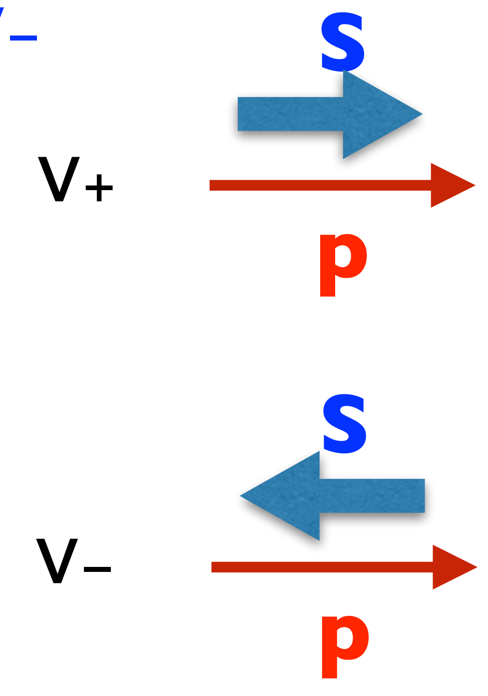
- If neutrinos are Majorana particles, a *virtual* anti-neutrino can convert into a neutrino and mediate 0νββ

W. H. Furry, 1939

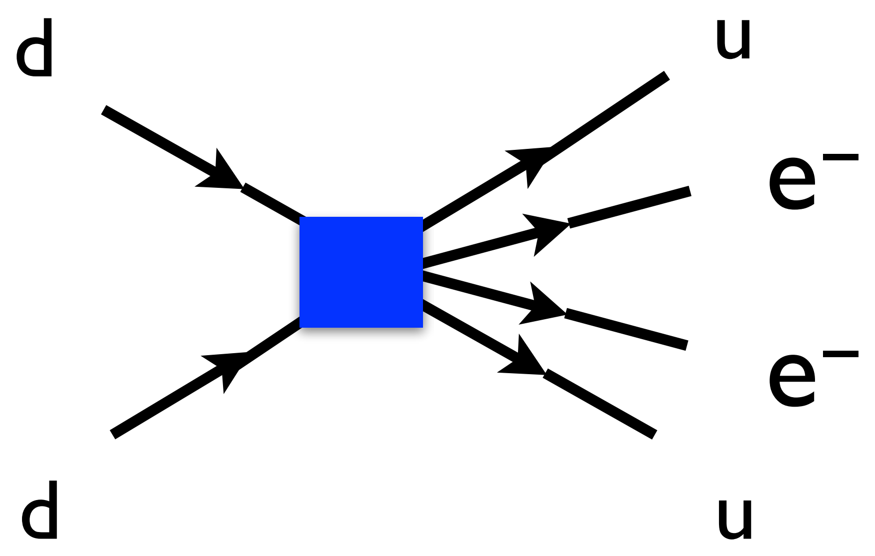


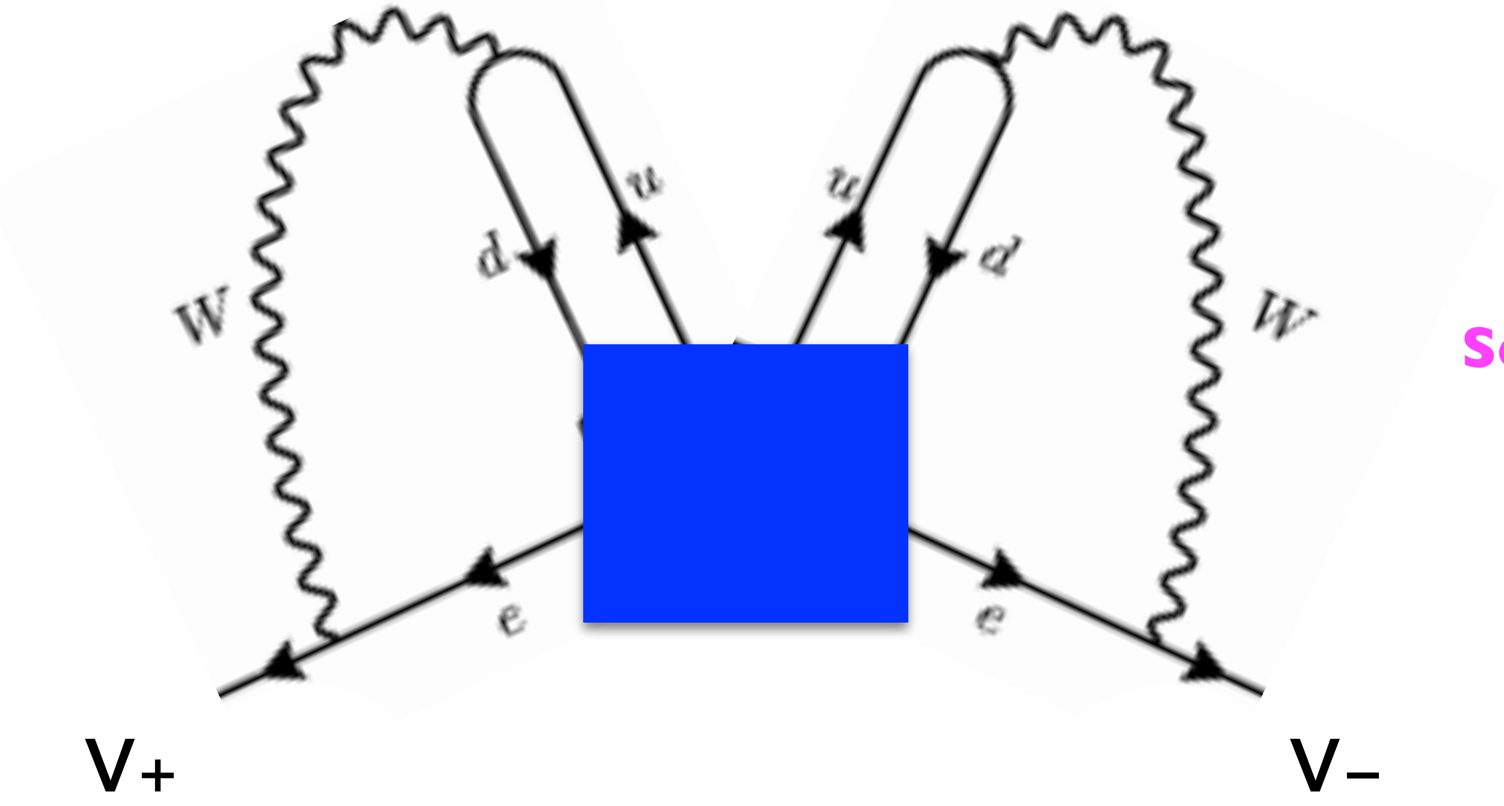

This is just ν+, which via mass insertion turns into ν−

ν− converts into e⁻ in the second interaction




- If 0νββ decay happens, through *quantum mechanical fluctuations a* ν+ *can convert into* ν− ⇒ hallmark of Majorana ν!

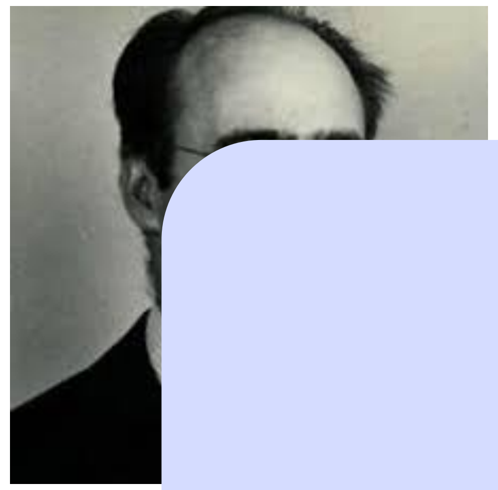


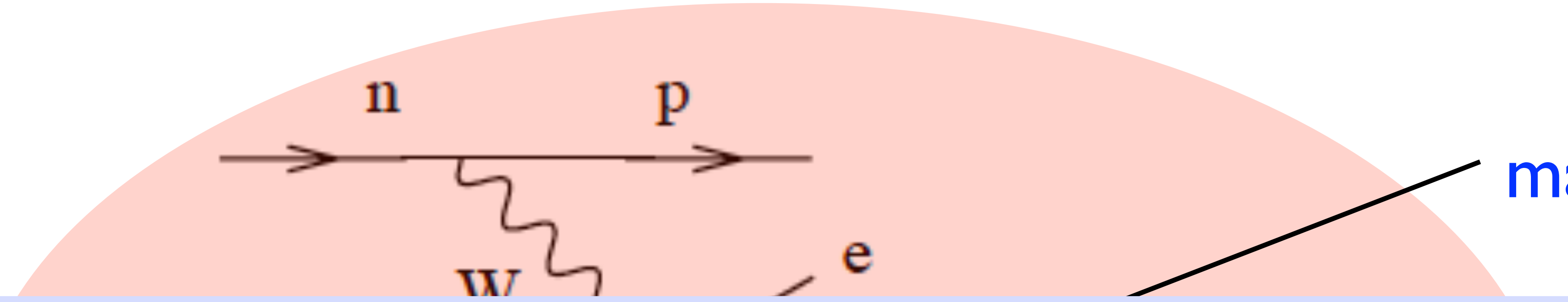

Schechter-Valle 1982

# 0νββ decay is the arbiter

- If neutrinos are Majorana particles, a *virtual* anti-neutrino can convert into a neutrino and mediate 0νββ



W. H.

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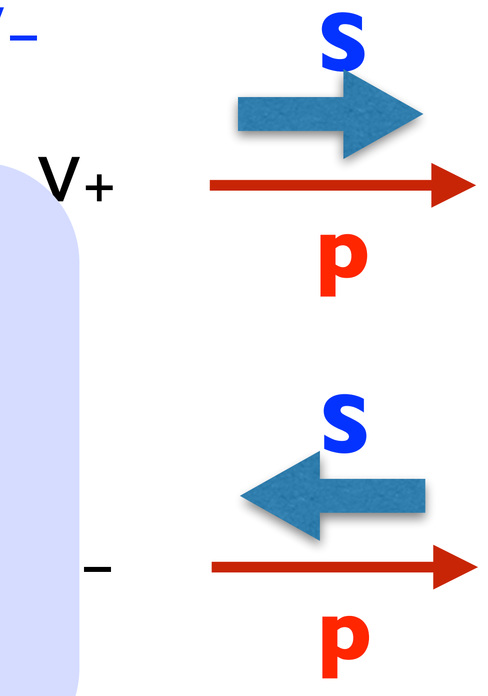
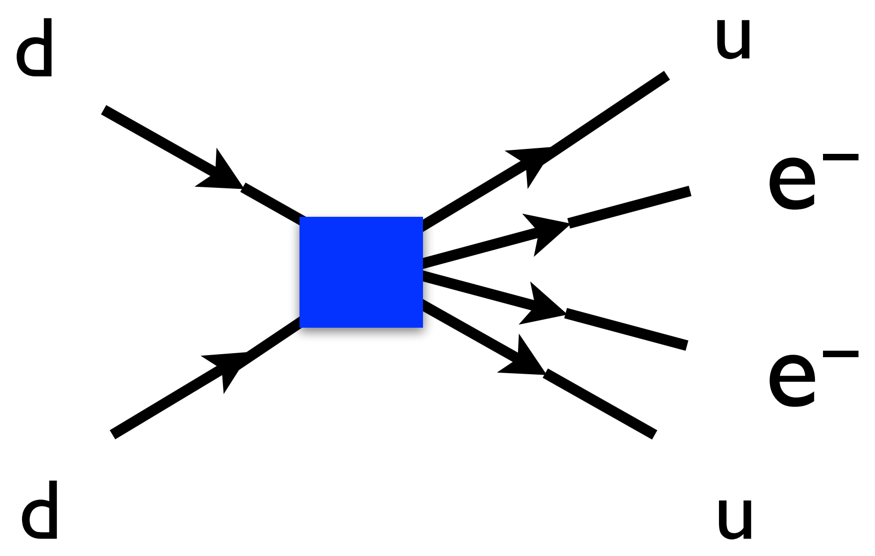
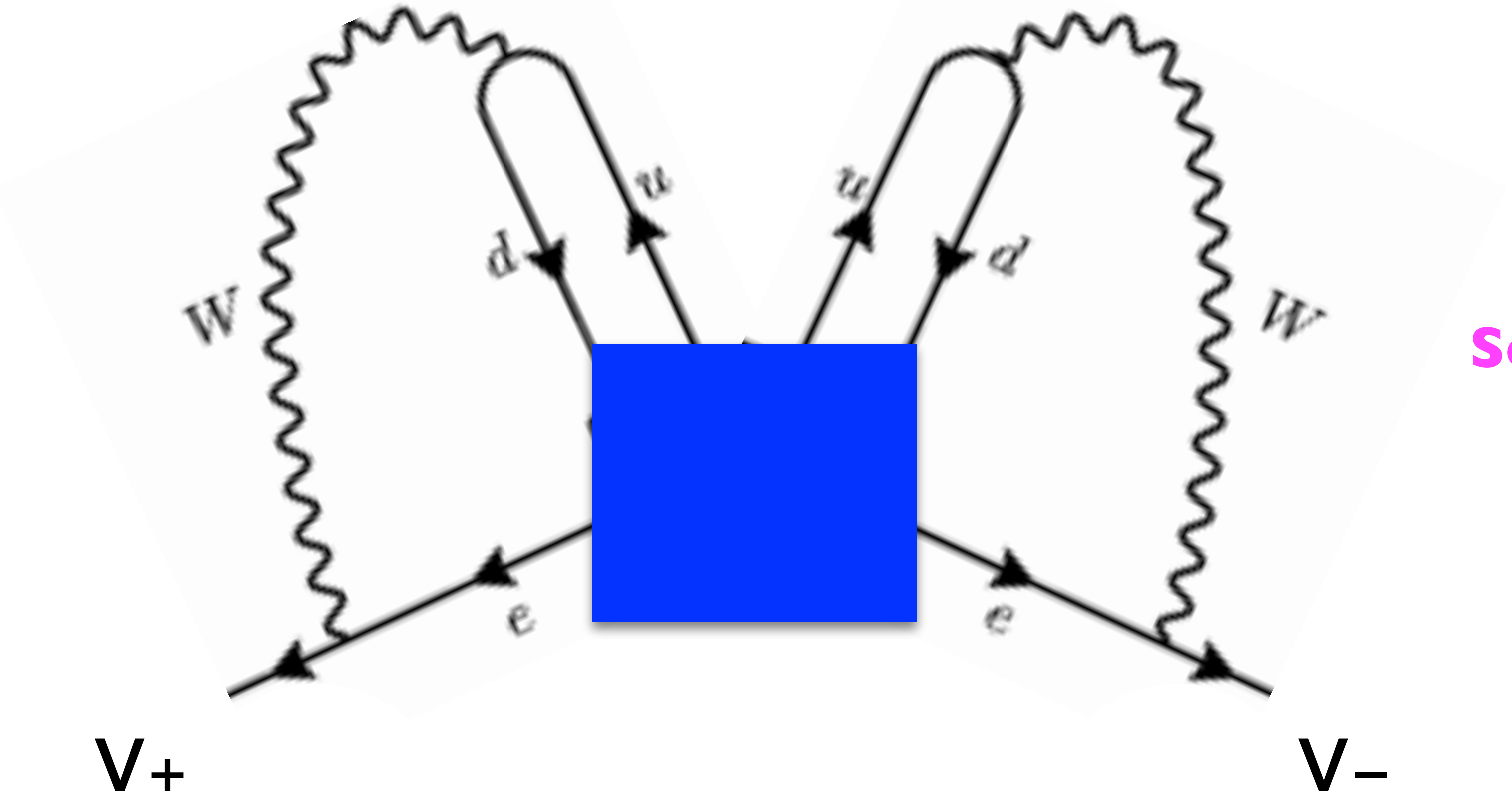



It's a two-way arrow:

Neutrino is a Majorana fermion $\Longleftrightarrow$ 0νββ decay happens at some rate

- If 0νββ decay happens, through *quantum mechanical fluctuations a* $\nu_+$ *can convert into* $\nu_-$ $\Rightarrow$ hallmark of Majorana ν!



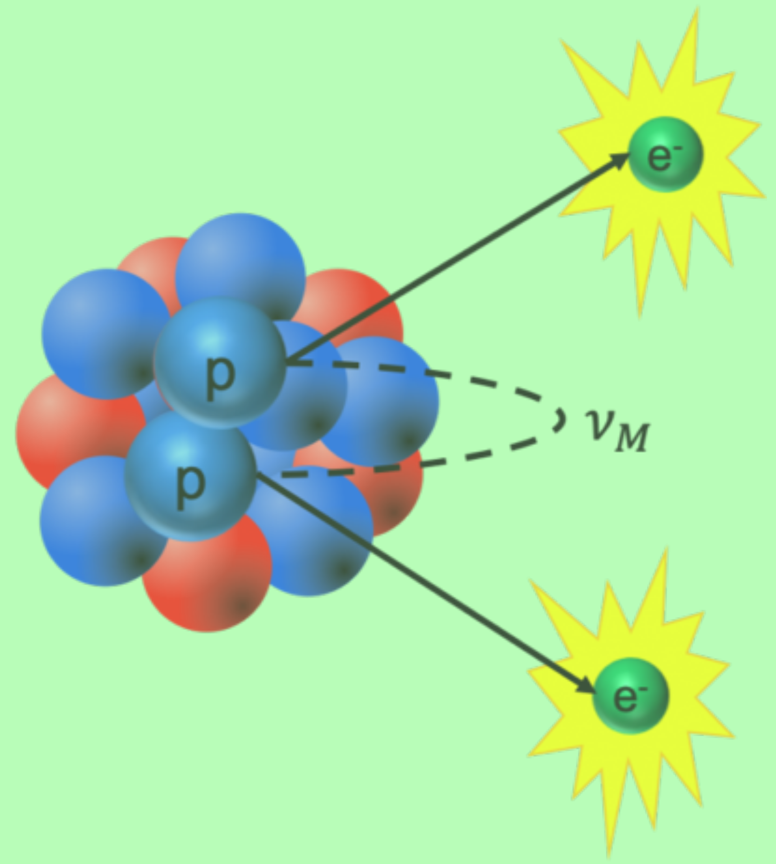

Schechter-Valle 1982

# 0νββ decay: significance

A cosmic mystery

How did matter survive
the big bang?

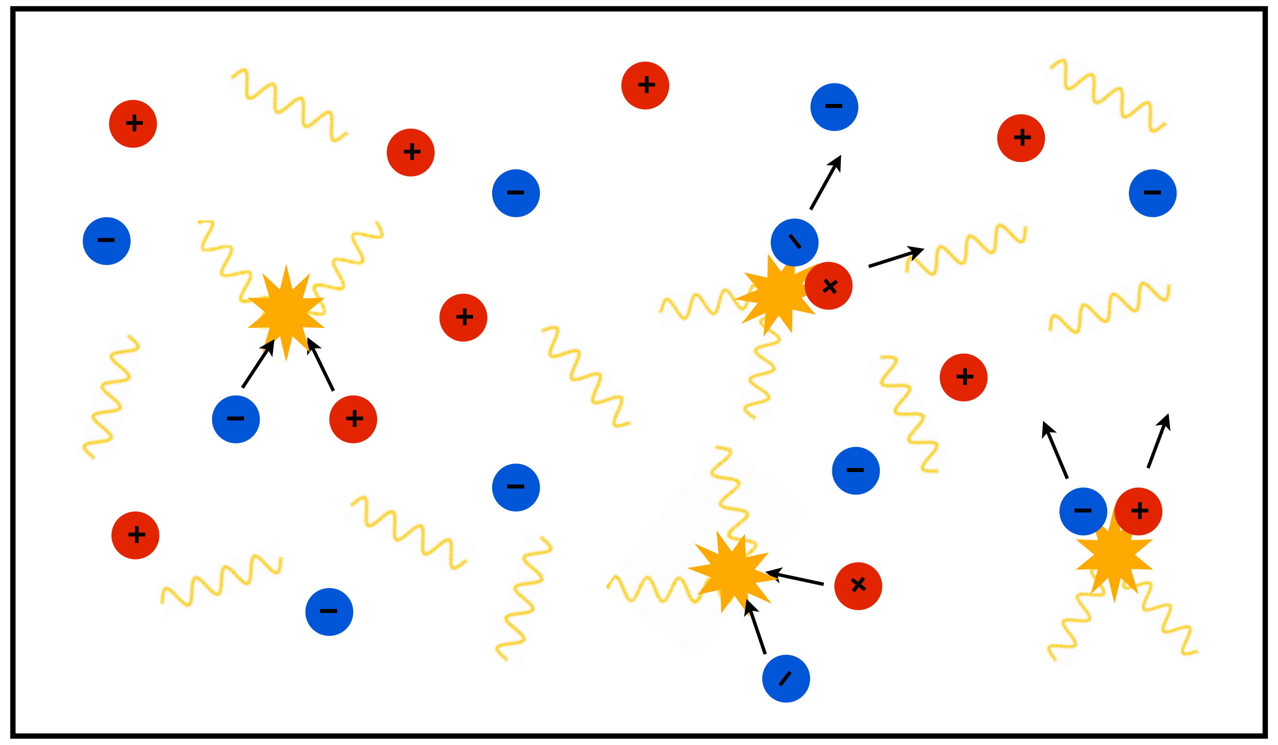
Nuclear 0νββ decay

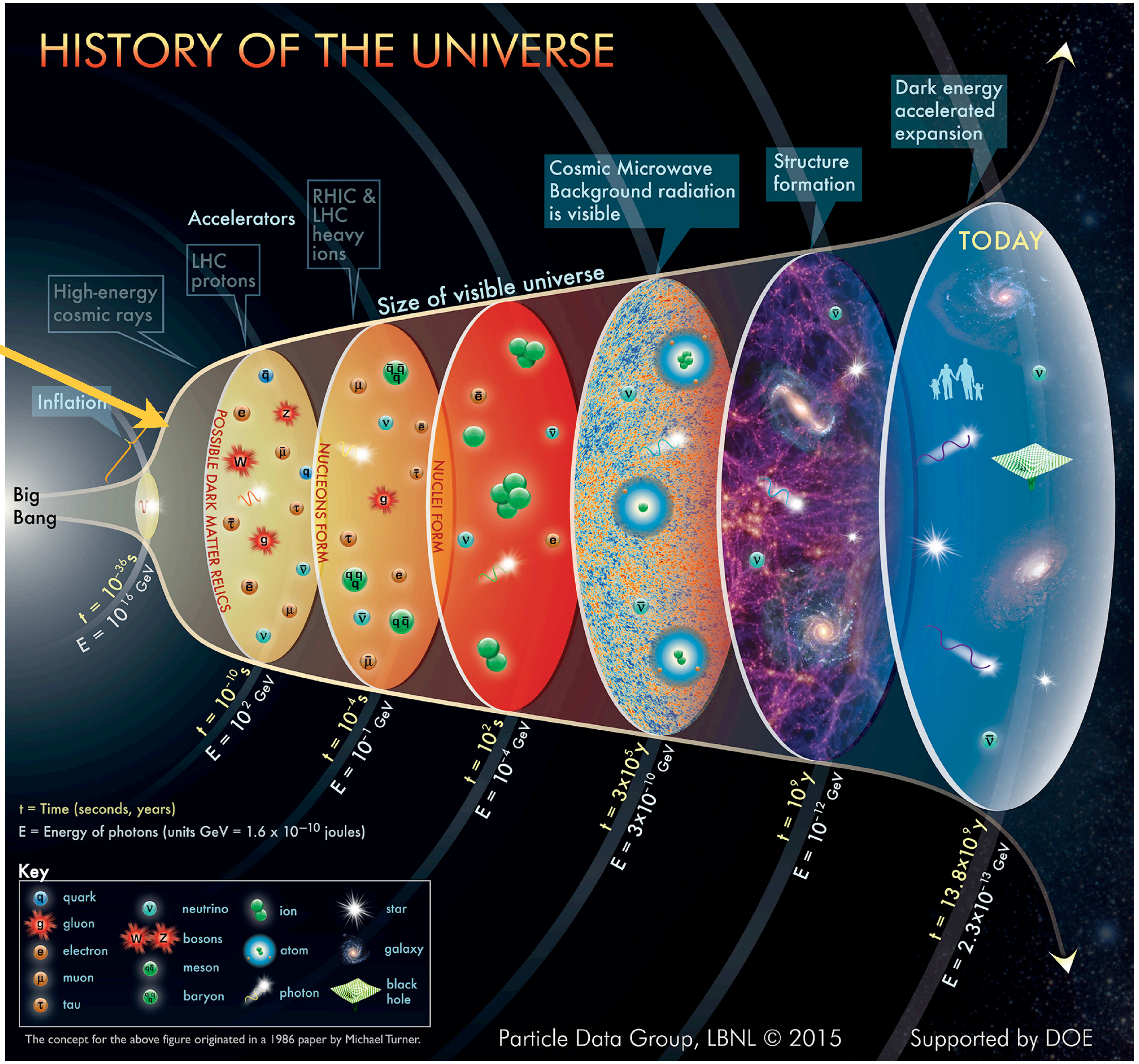


# What's the origin of matter in the universe?

Equal number of particles and antiparticles right after the big bang

t = 0.000001s






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

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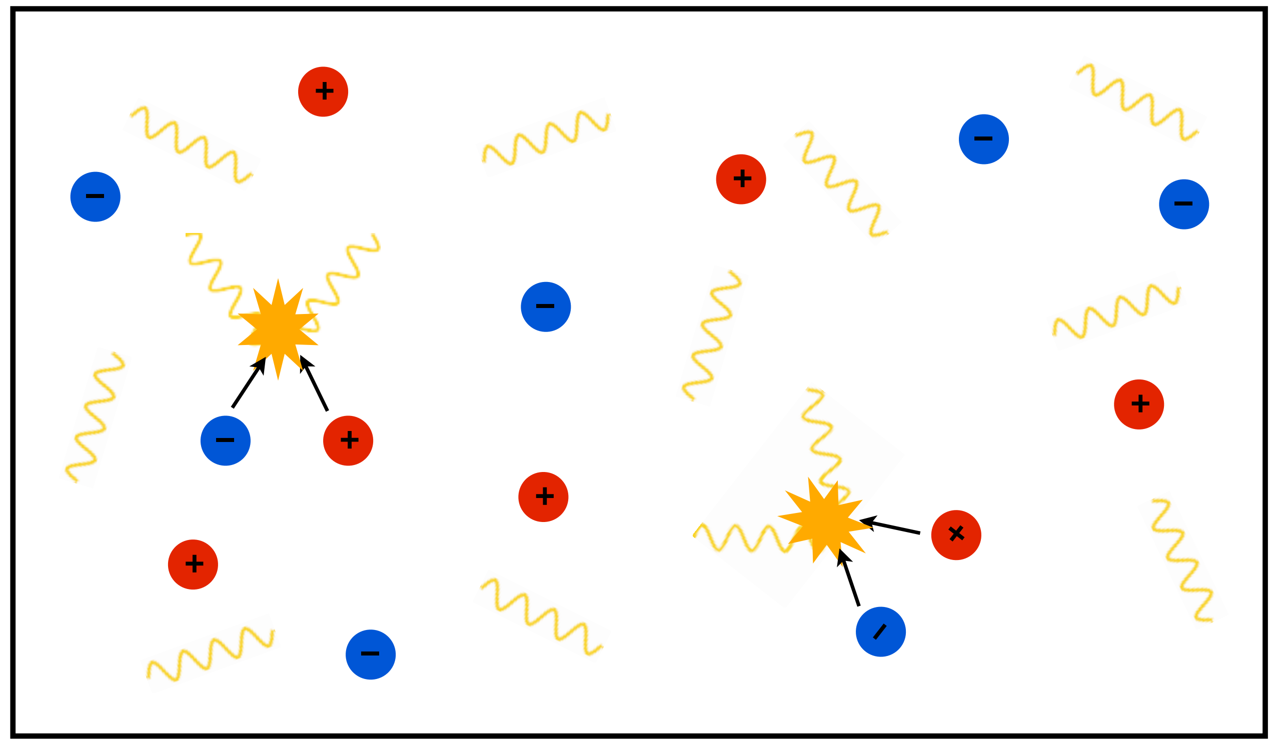

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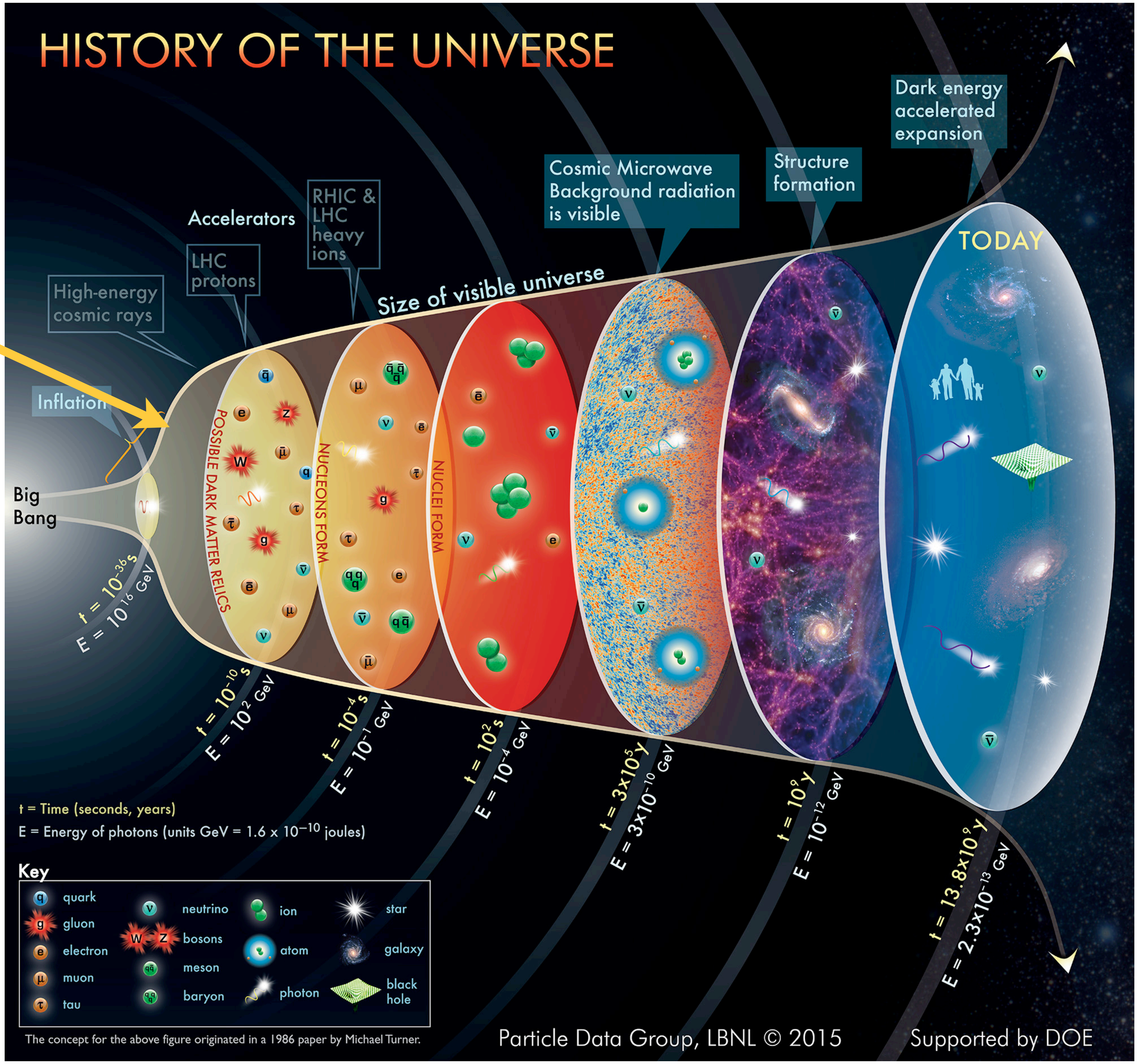

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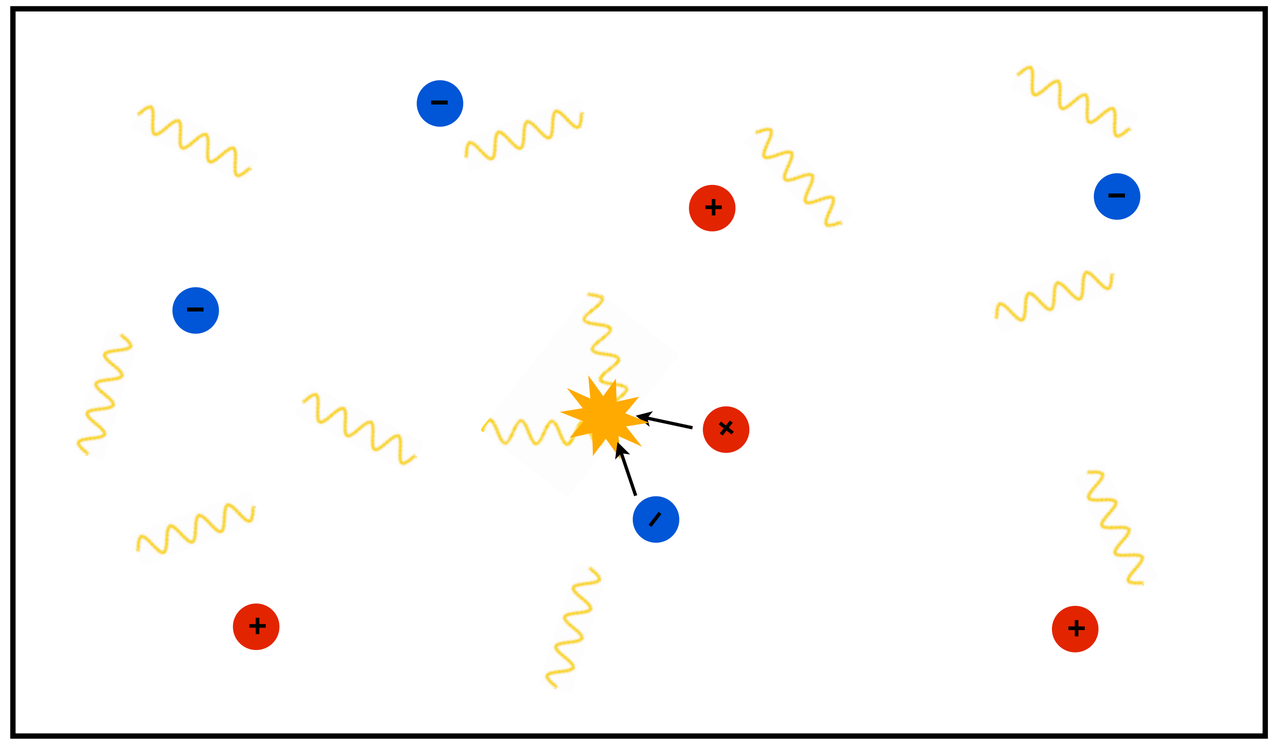
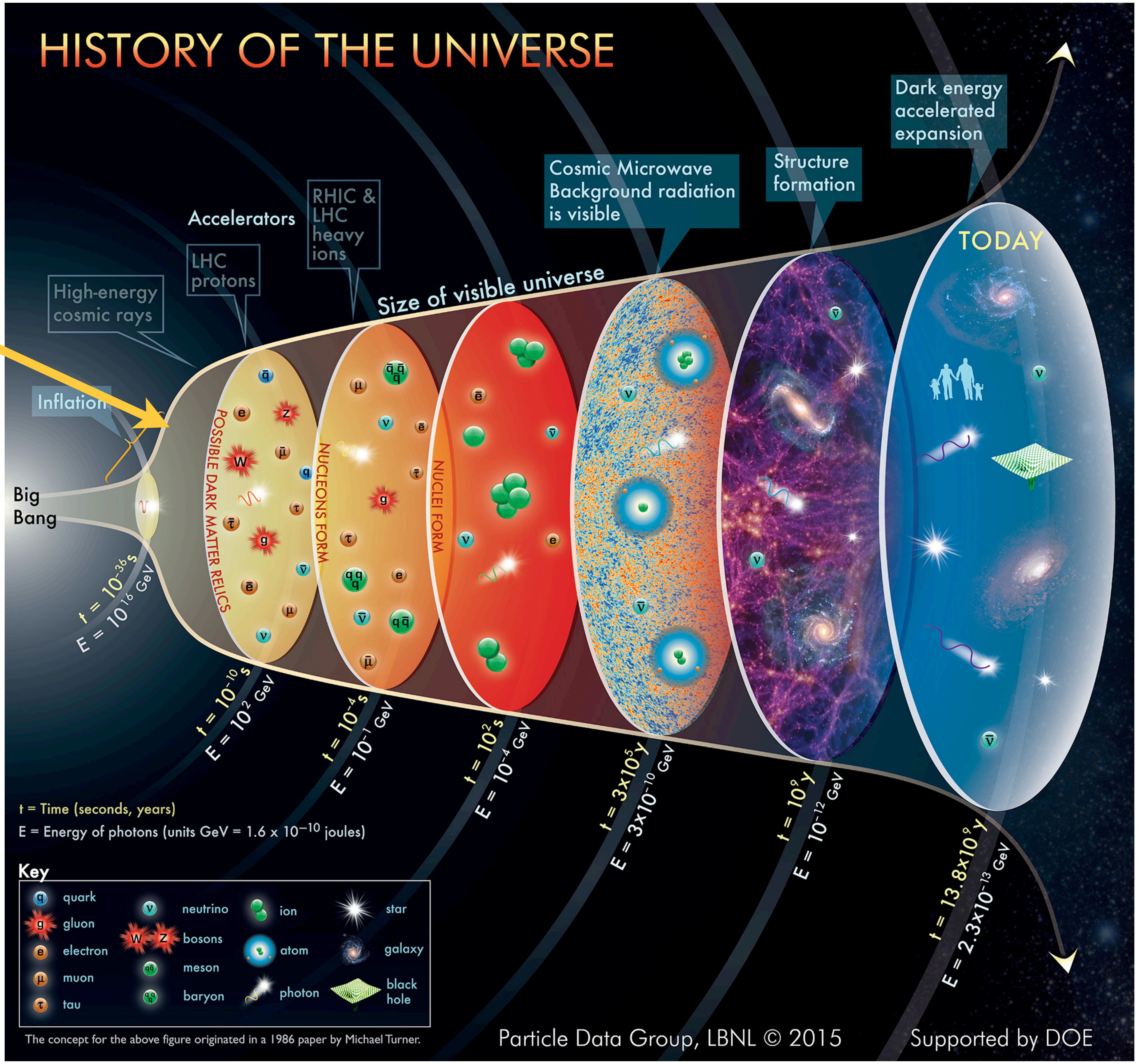


As the universe expands and cools, particle-antiparticle annihilation takes over: end up with just radiation!



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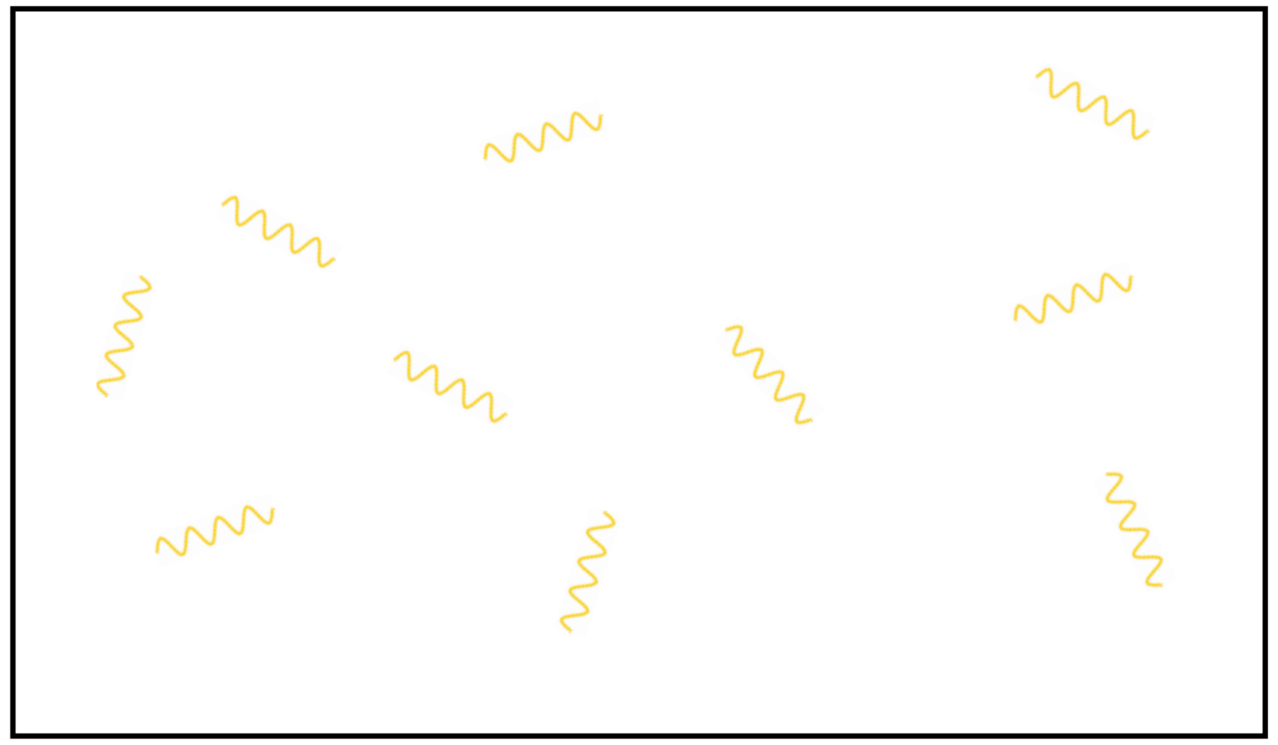
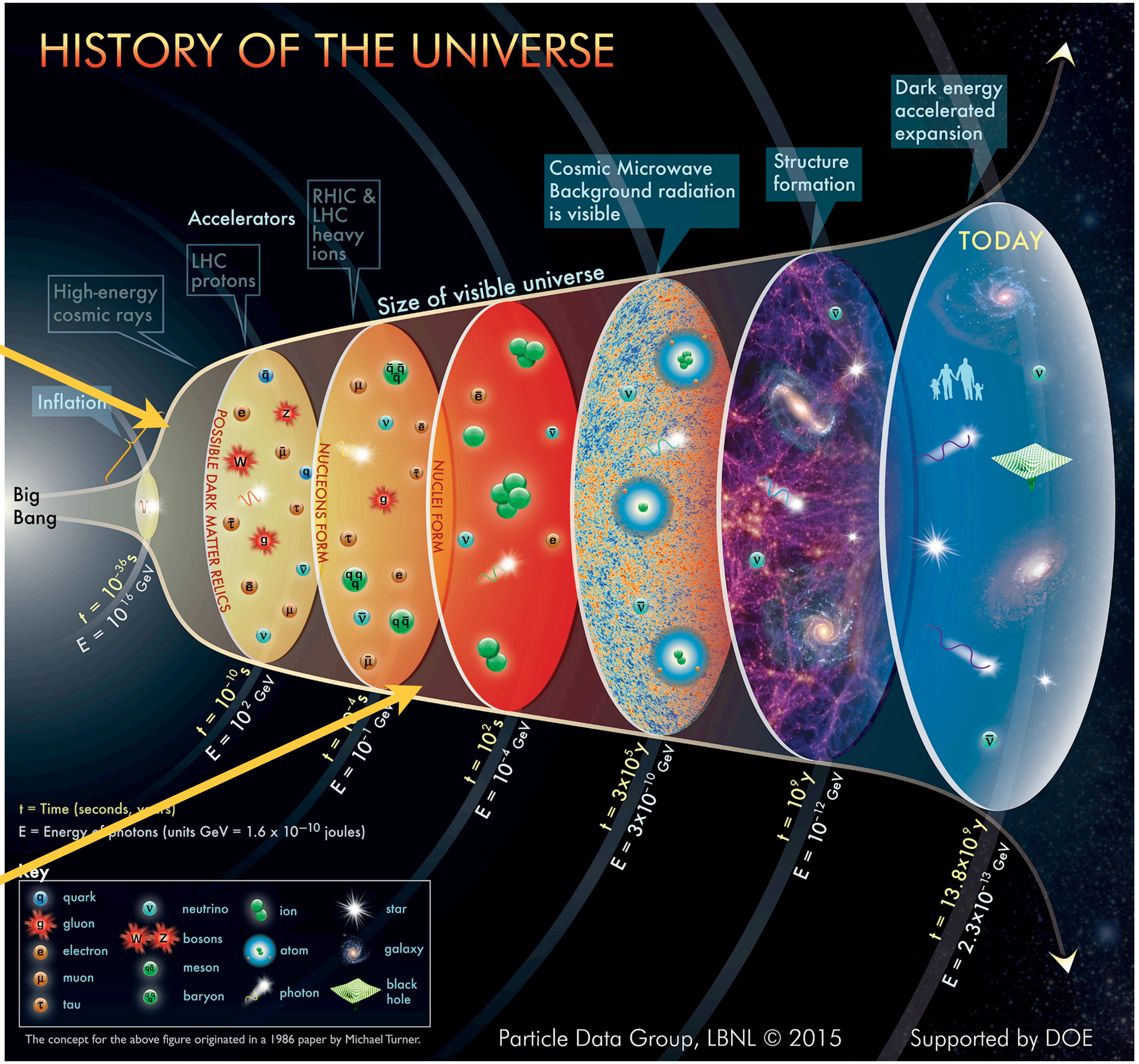


As the universe expands and cools, particle-antiparticle annihilation takes over: end up with just radiation!

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



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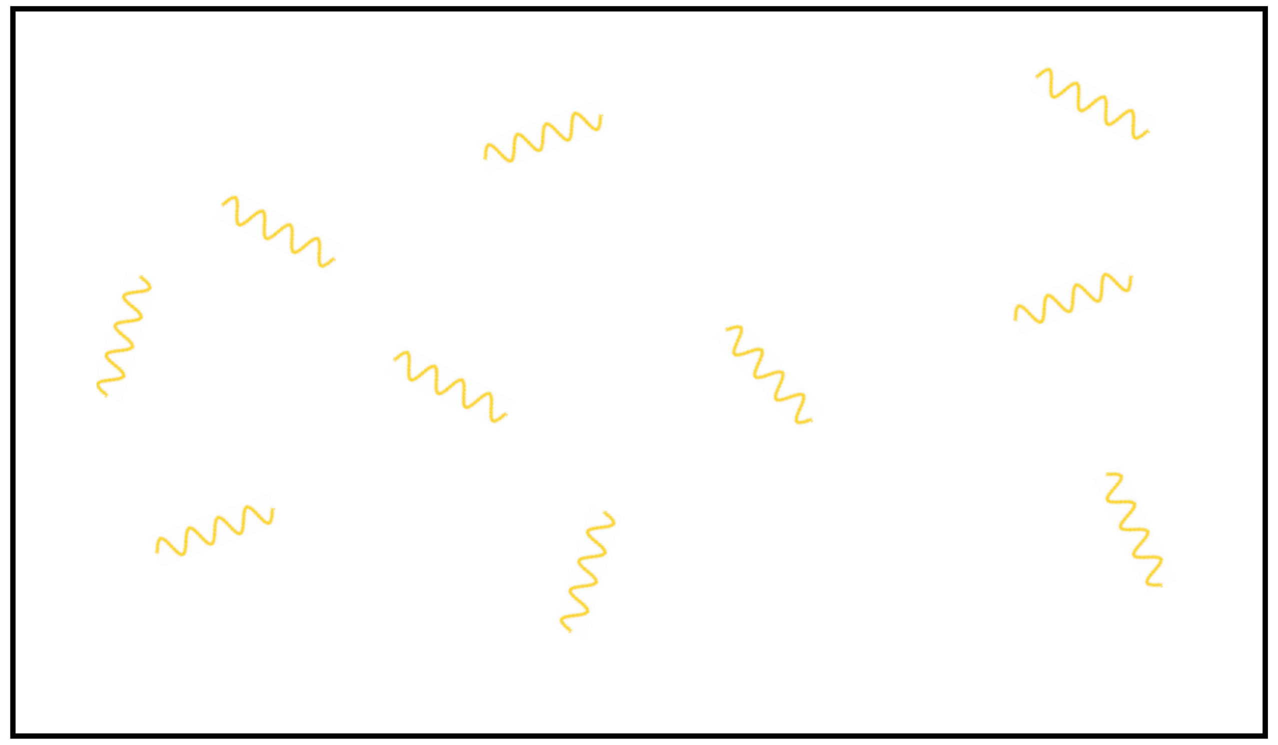
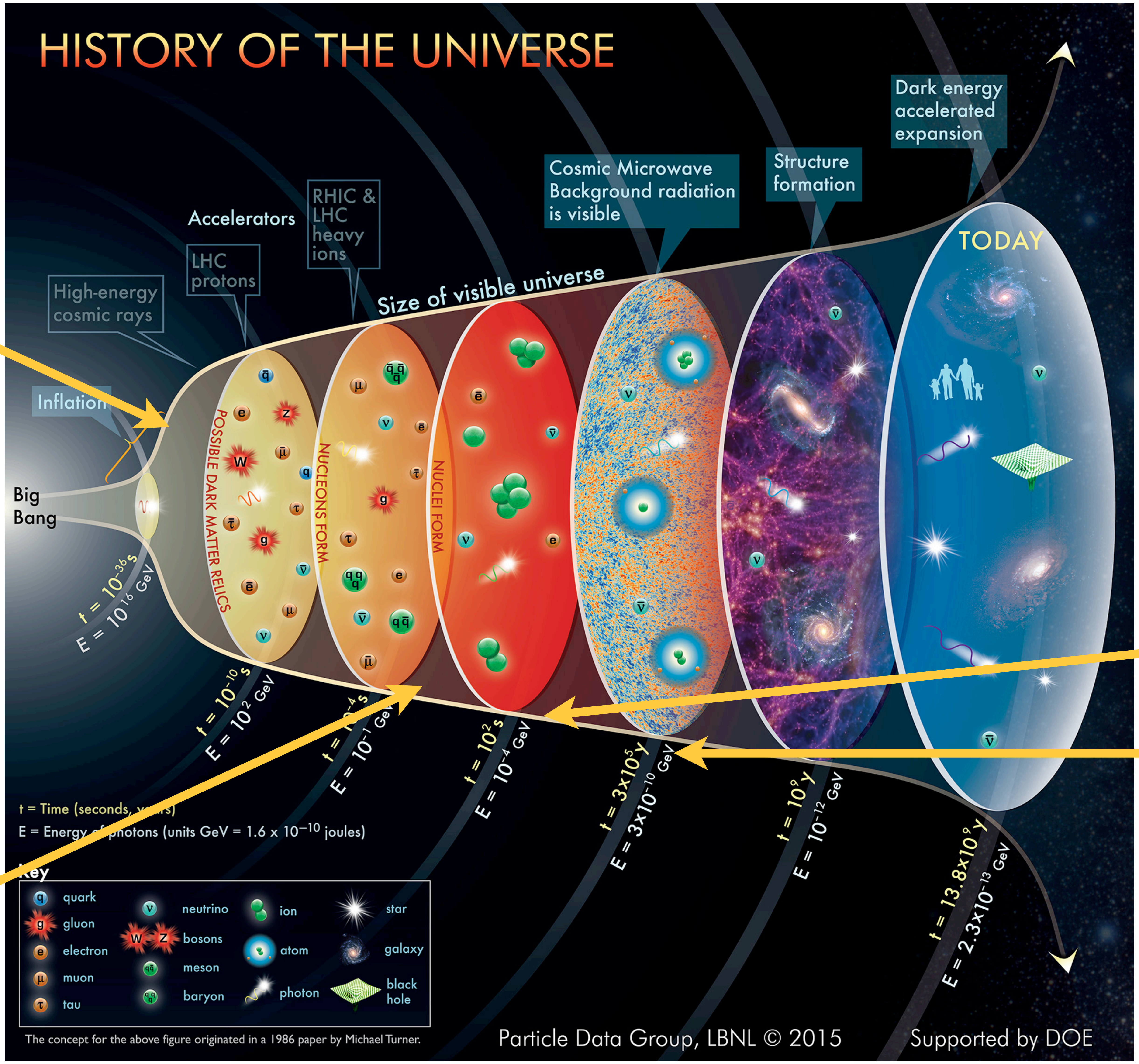
Equal number of particles and antiparticles right after the big bang

$t \sim 0.003$ s



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

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




But 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 $\eta \sim 6 \times 10^{-10}$

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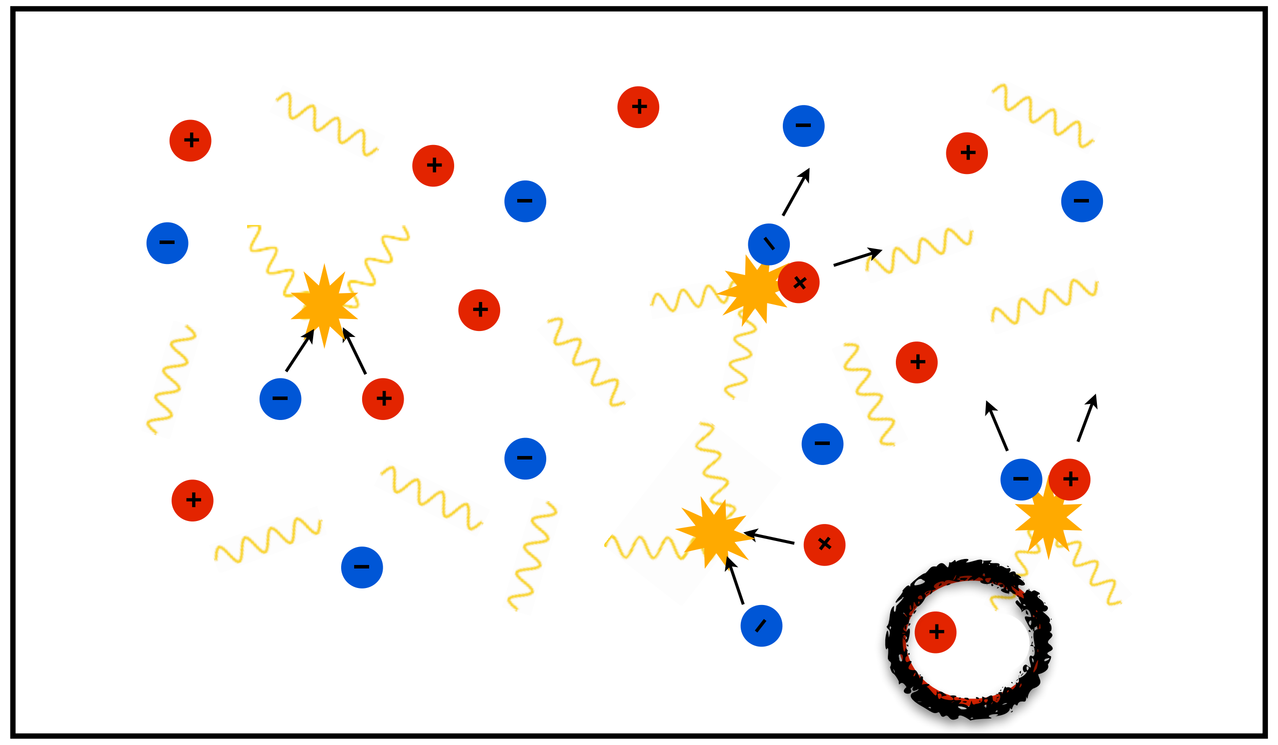
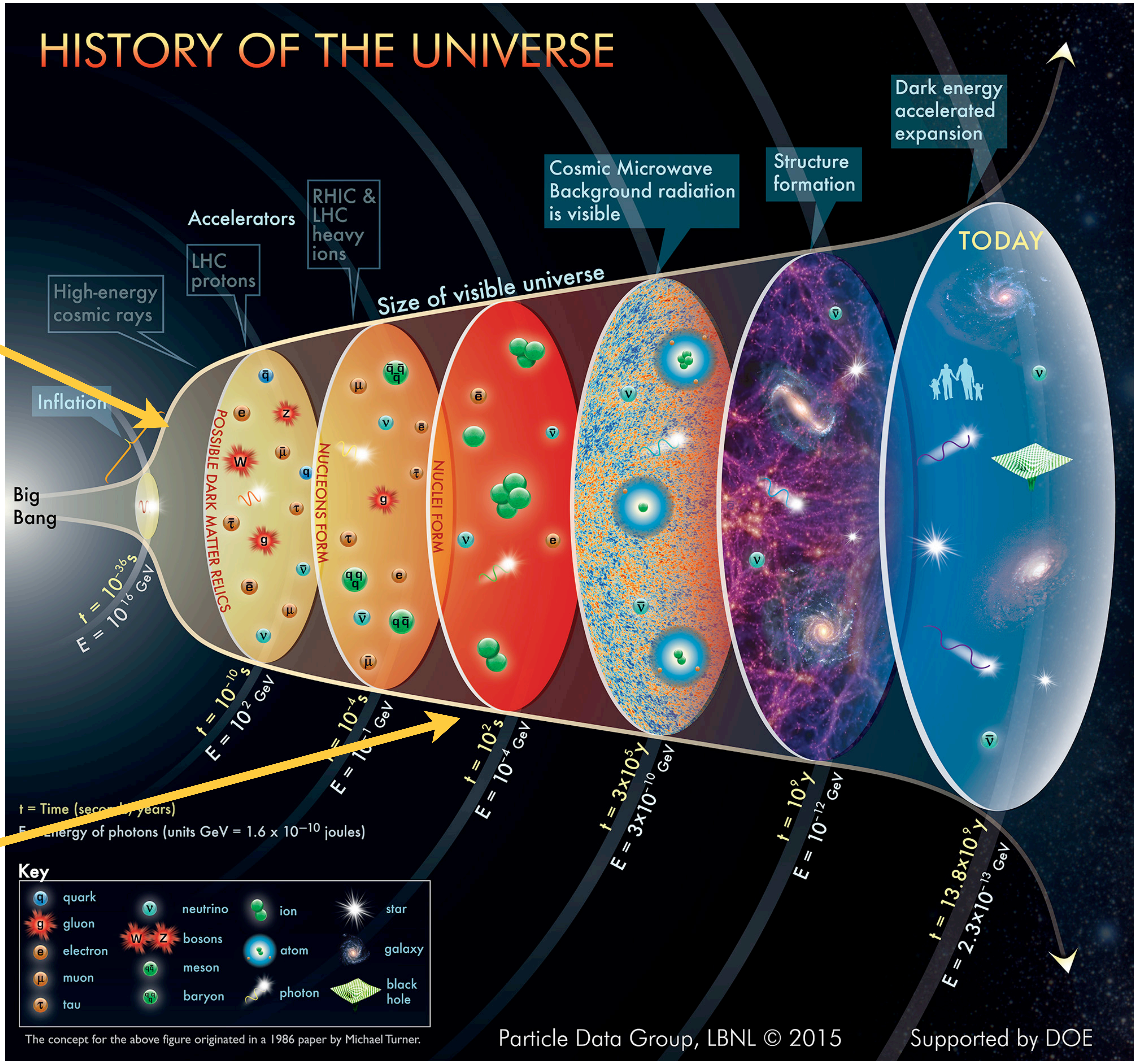
Equal number of particles and antiparticles right after the big bang

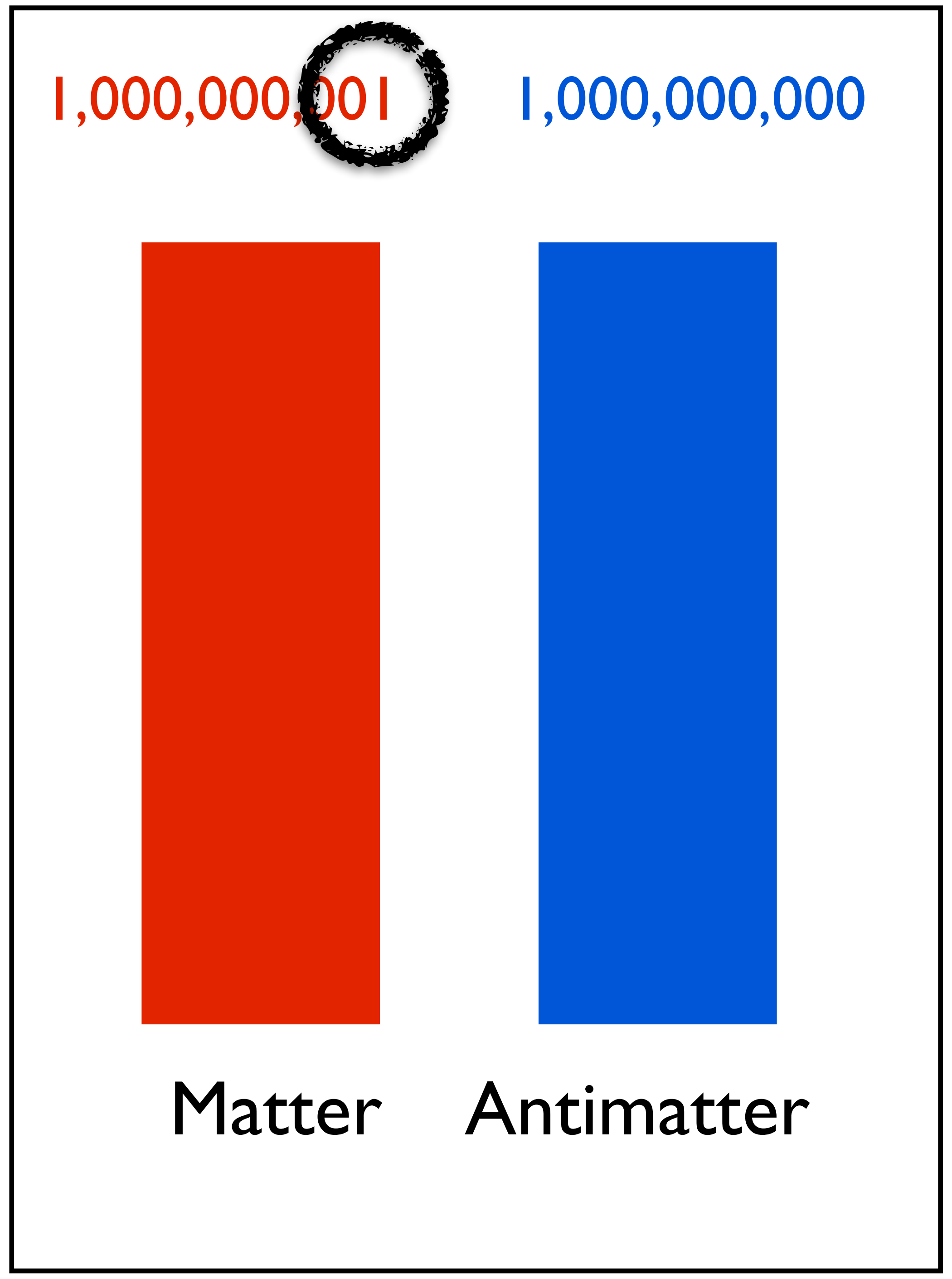
t ~ 0.000001s






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

Early universe

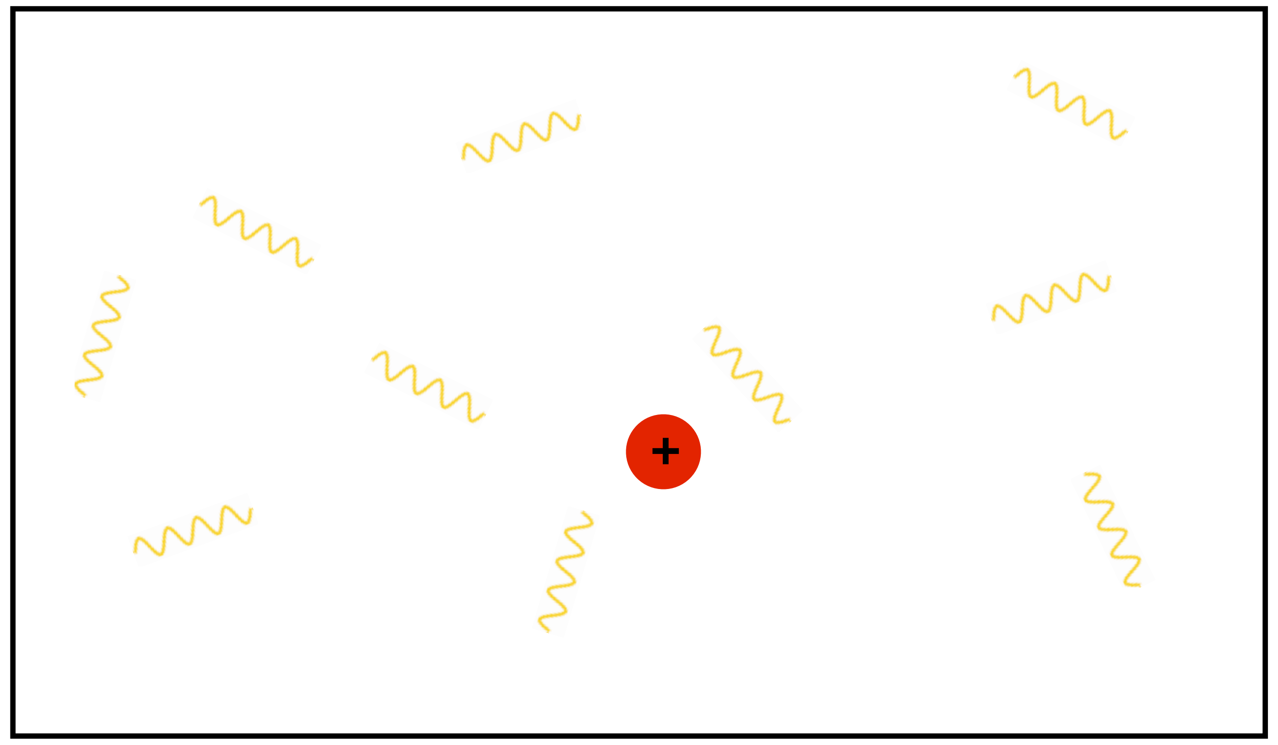


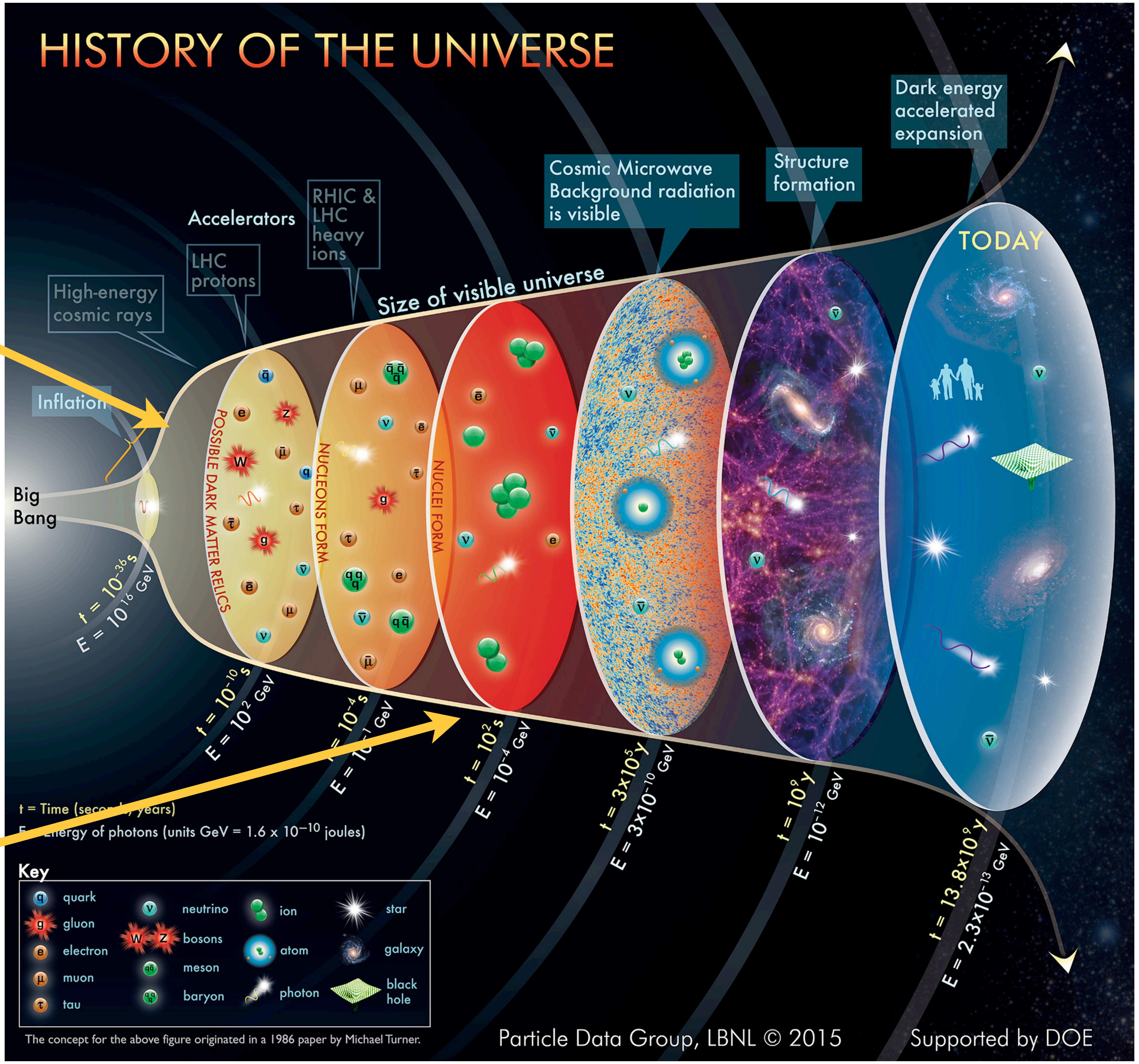

Credit: H. Murayama

# What's the origin of matter in the universe?

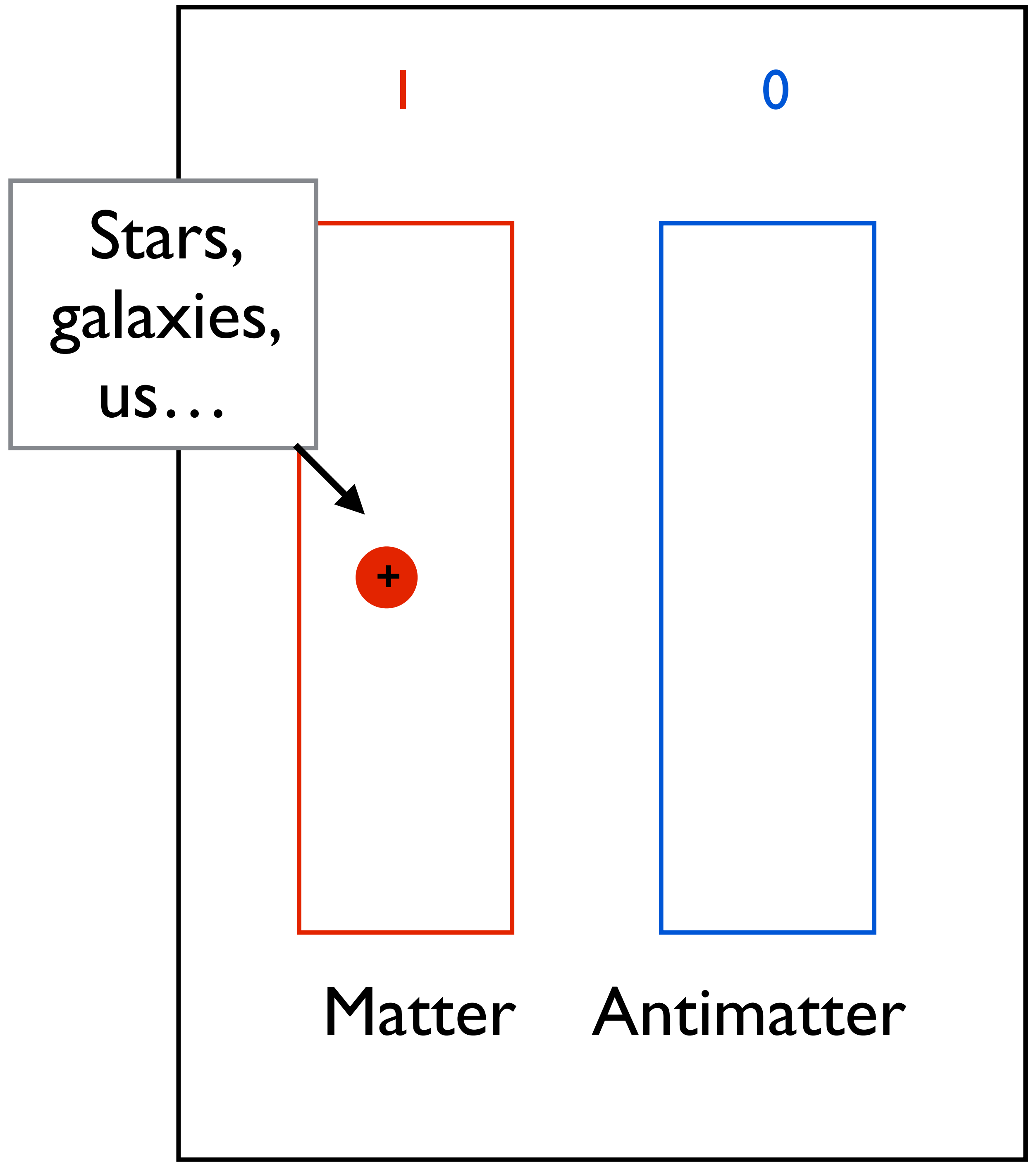
Equal number of particles and antiparticles right after the big bang

Today




Today

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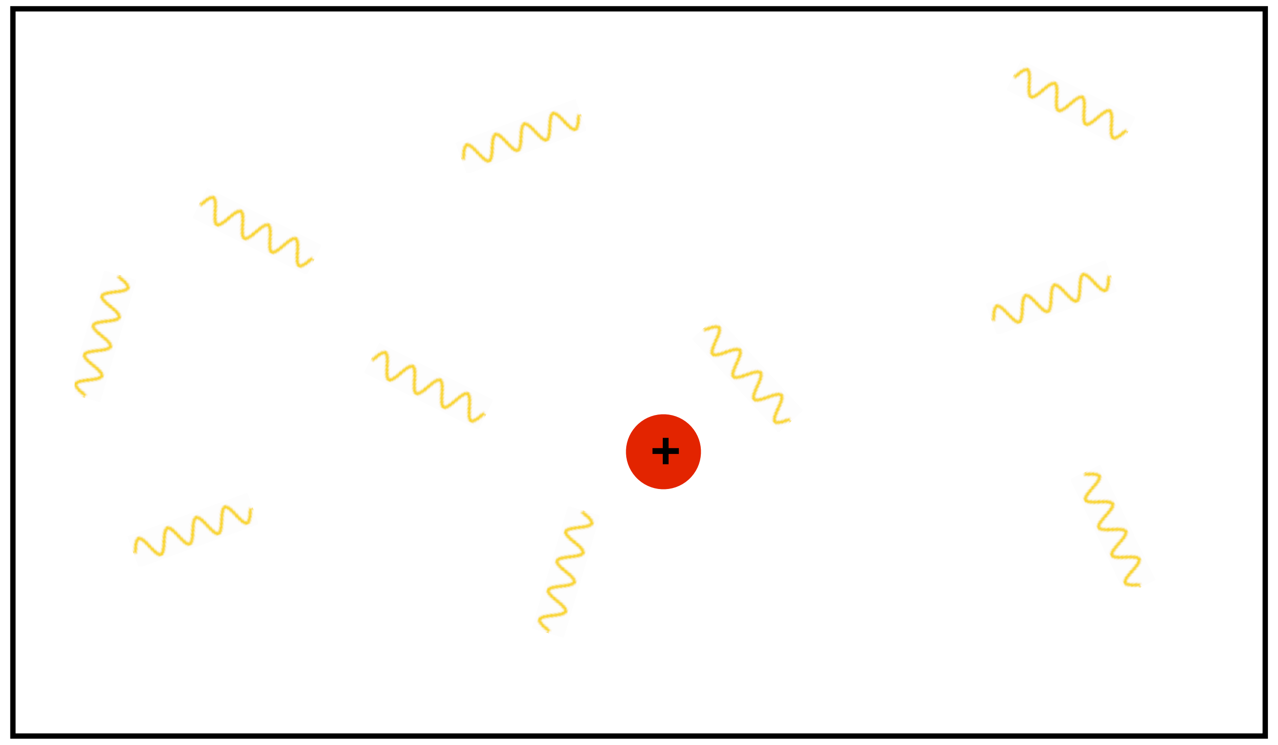
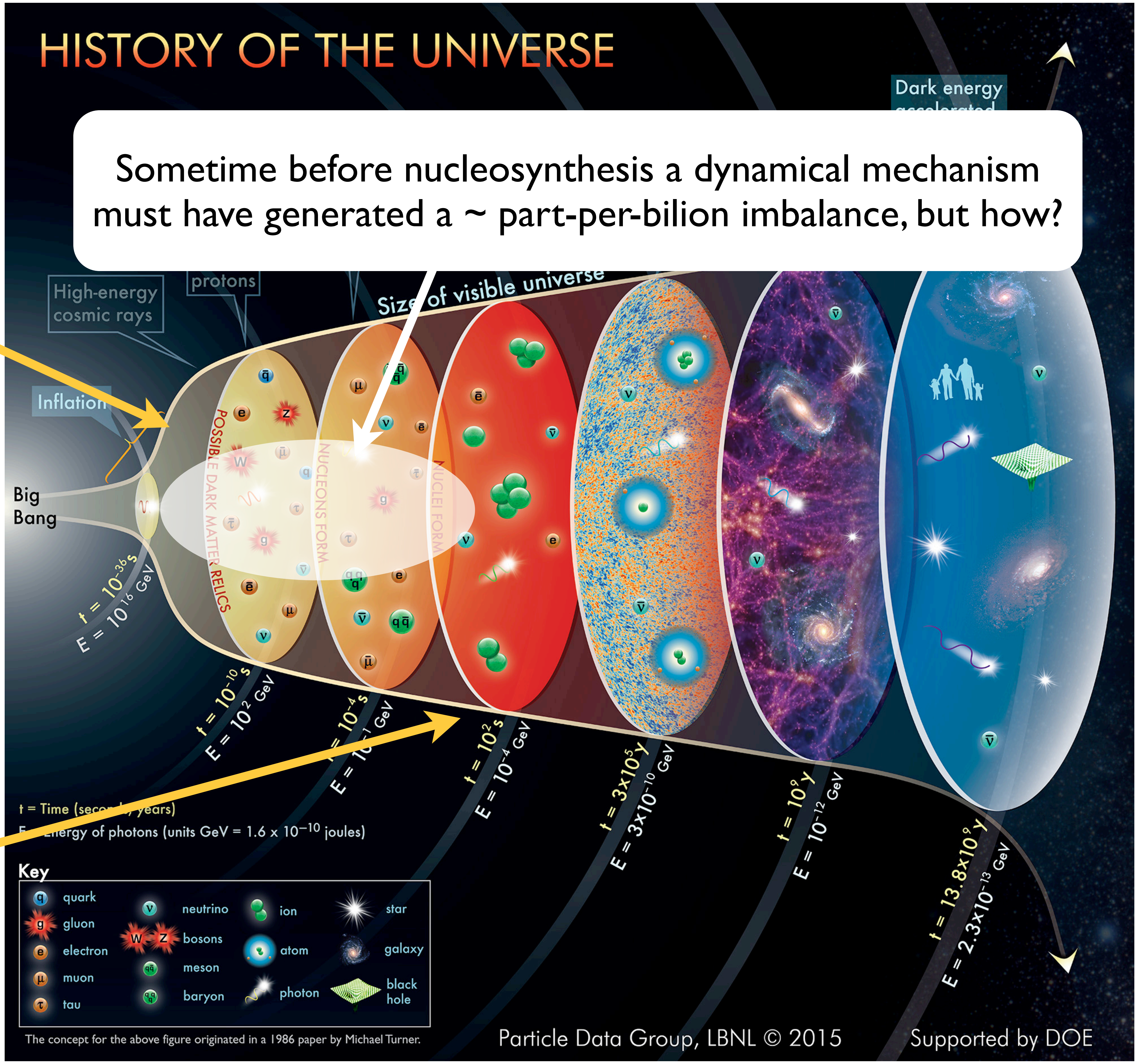
Today

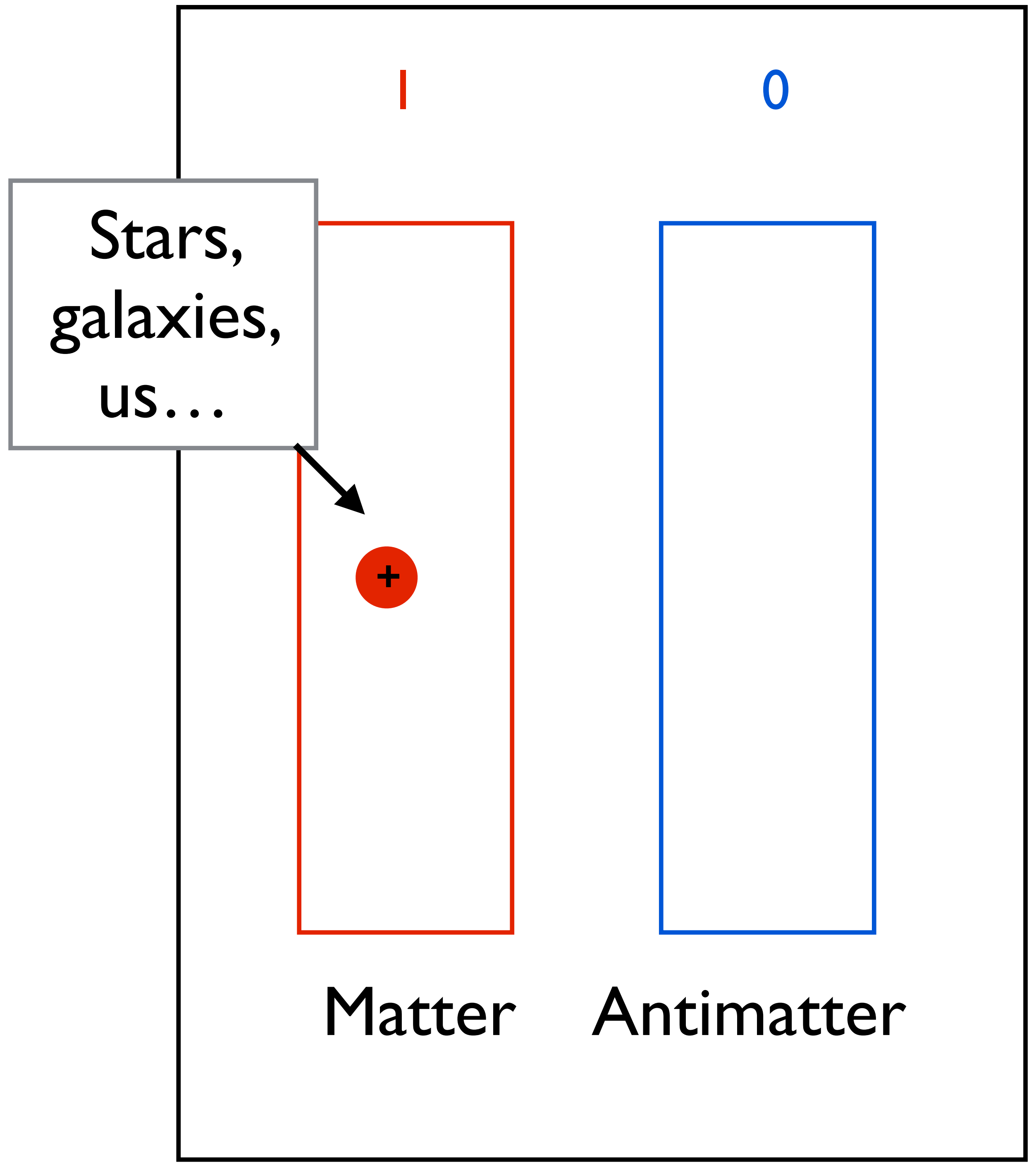


To obtain O(1) protons per cubic meter today, early on need a tiny imbalance of + over −




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

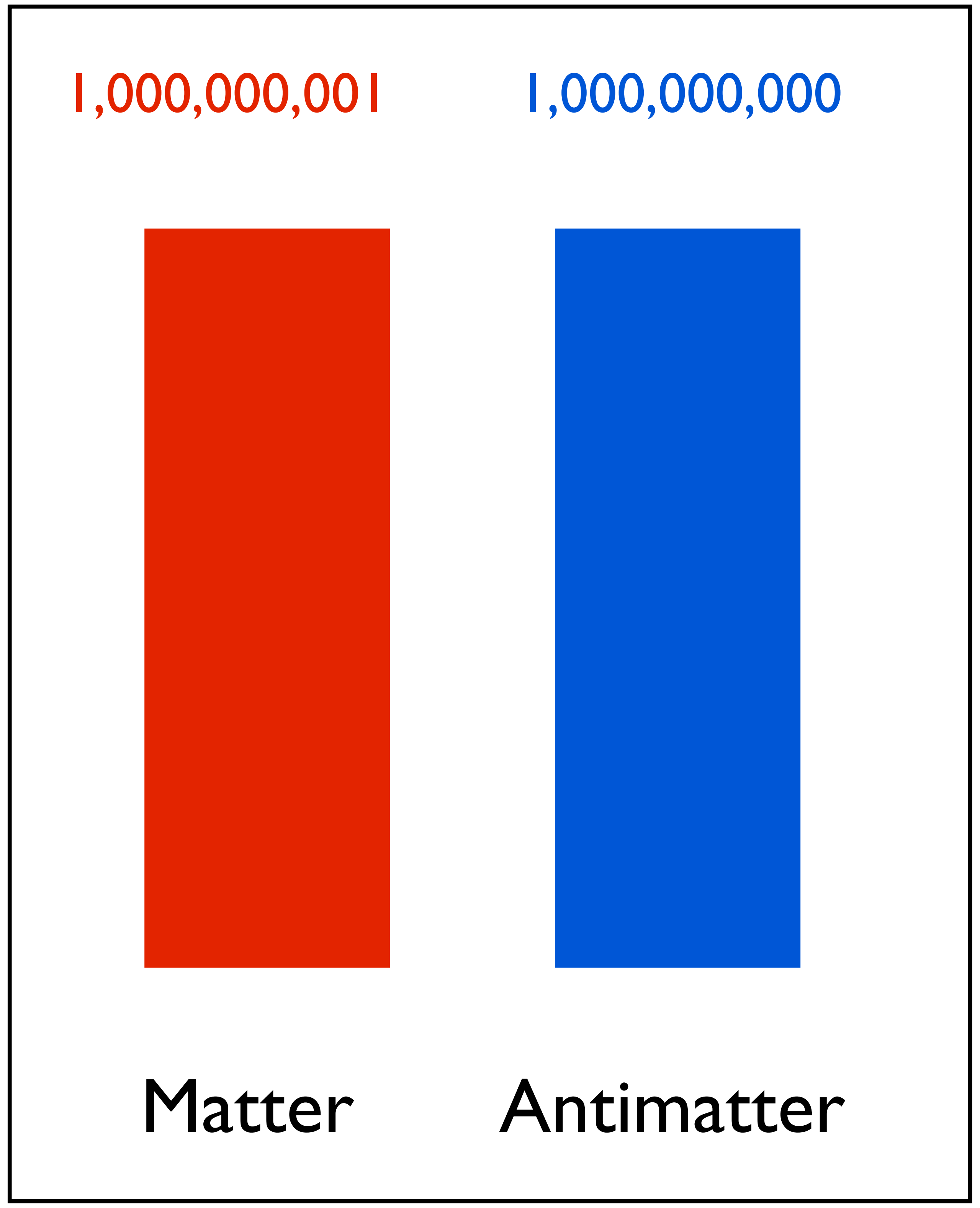
Today




Credit: H. Murayama

# Ingredients for a lopsided universe

Andrei Sakharov, 1967




Credit: H. Murayama

#1. Processes that "create matter" [B, L violation]

$$A \rightarrow B$$

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

#2. "Asymmetrically" (faster than corresponding antimatter-creating process) [$\not{C}$, $\not{C}\not{P}$]

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

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

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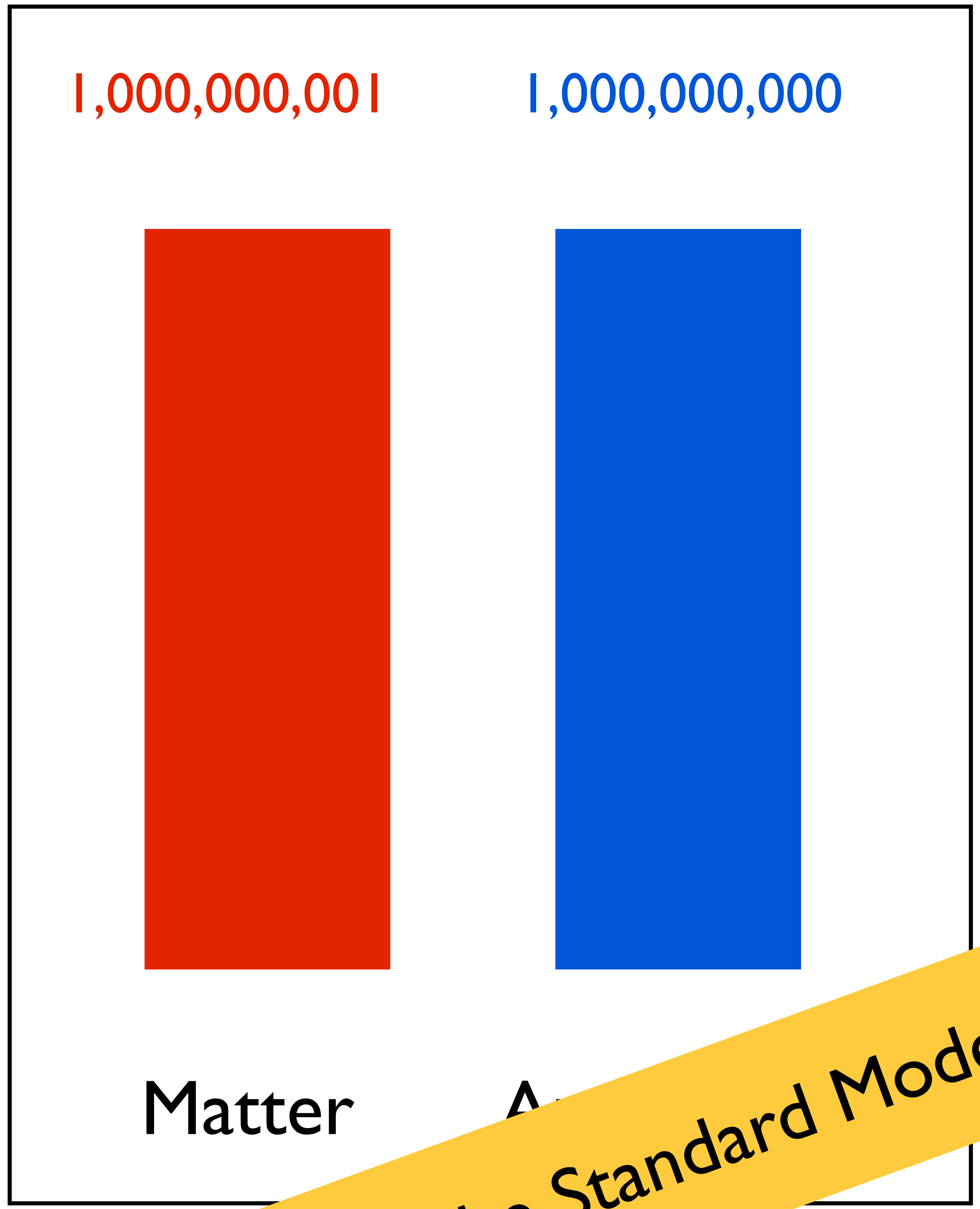


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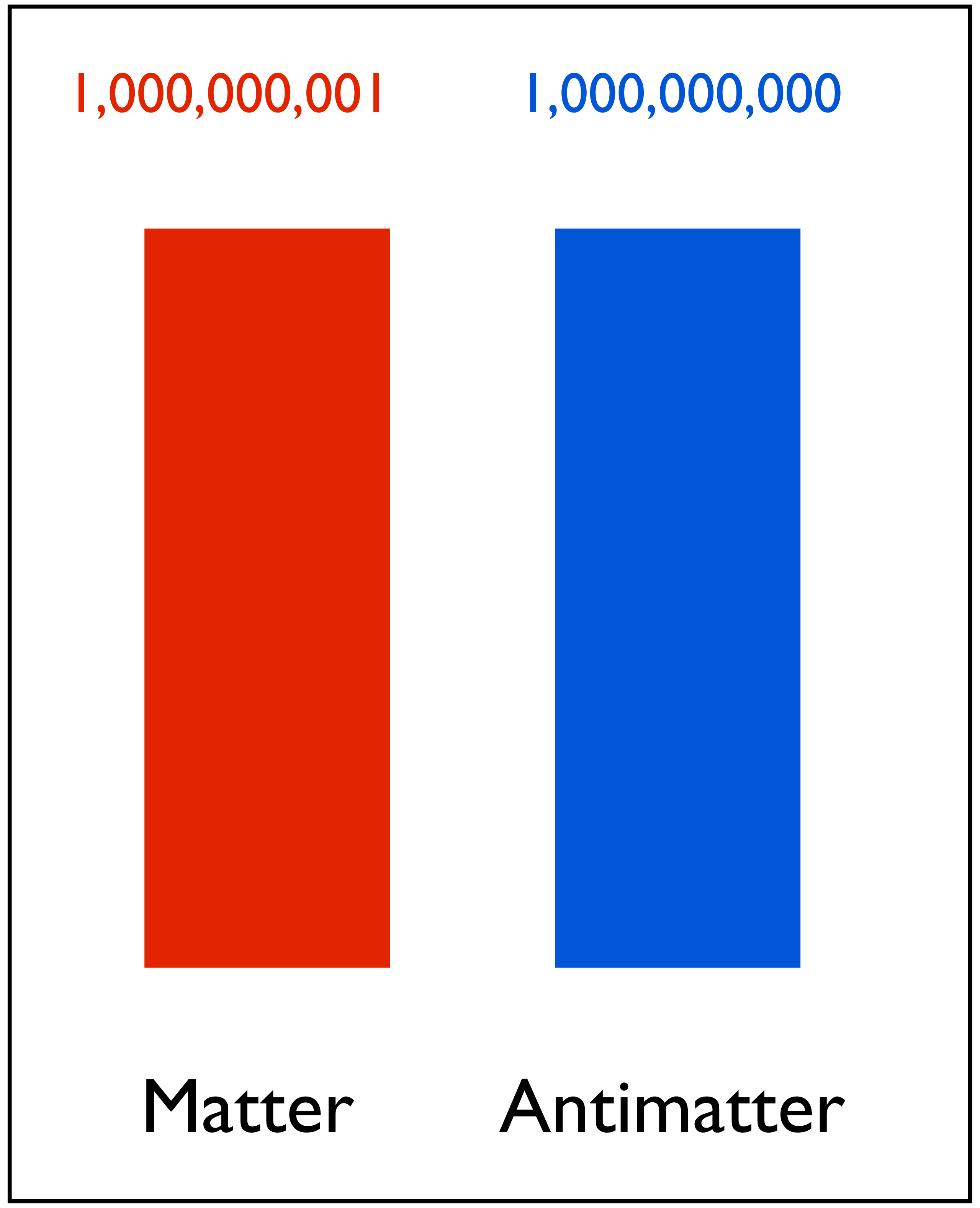
$A \rightarrow B \neq B \rightarrow A$

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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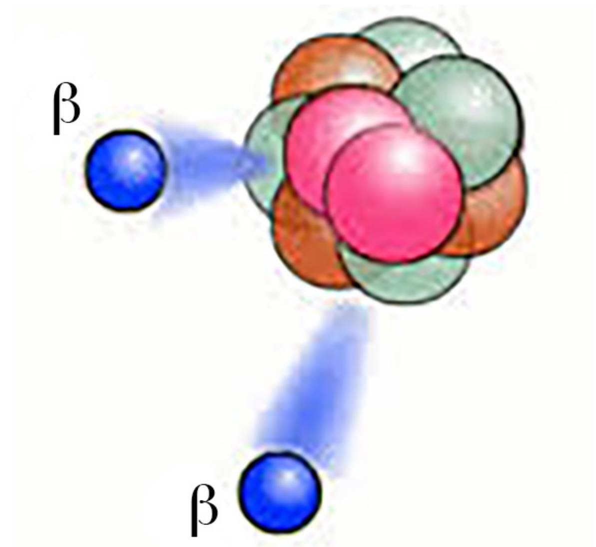


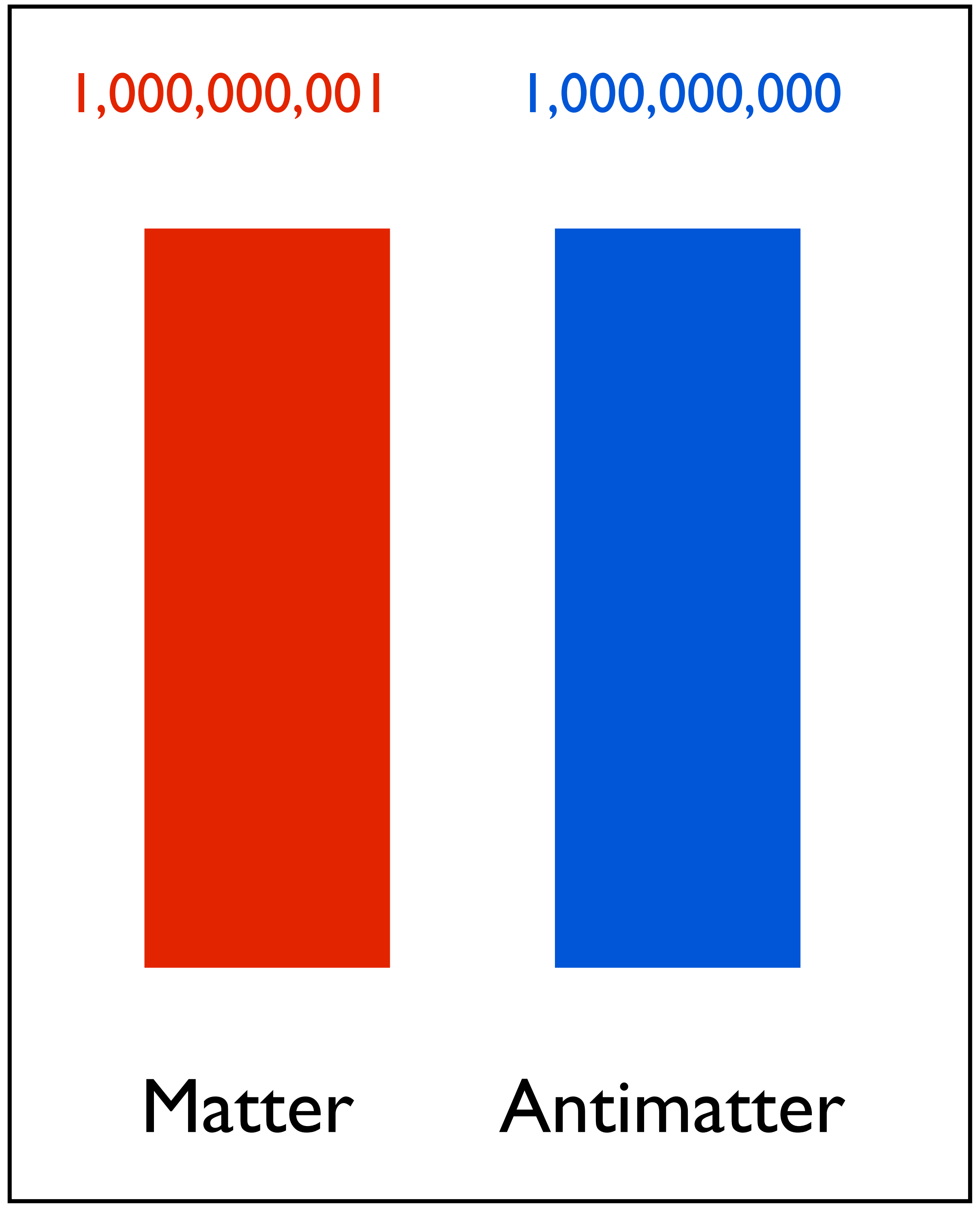

$$(N, Z) \rightarrow (N-2, Z+2) + e^- + e^-$$

Before: N + Z nucleons, no antiparticles

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

# How does 0νββ decay help?

Andrei Sakharov, 1967

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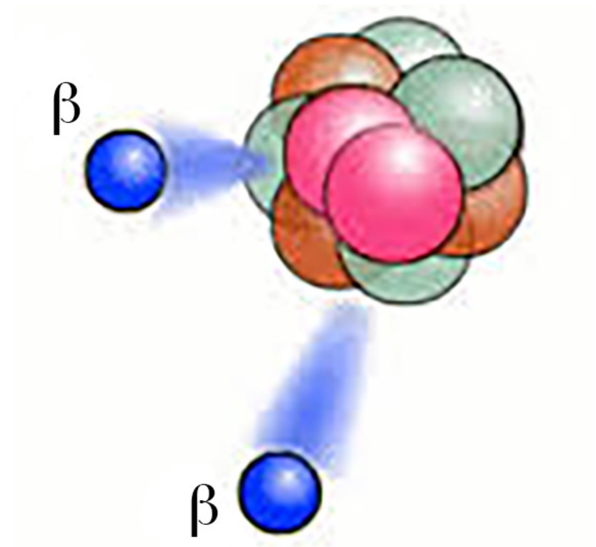


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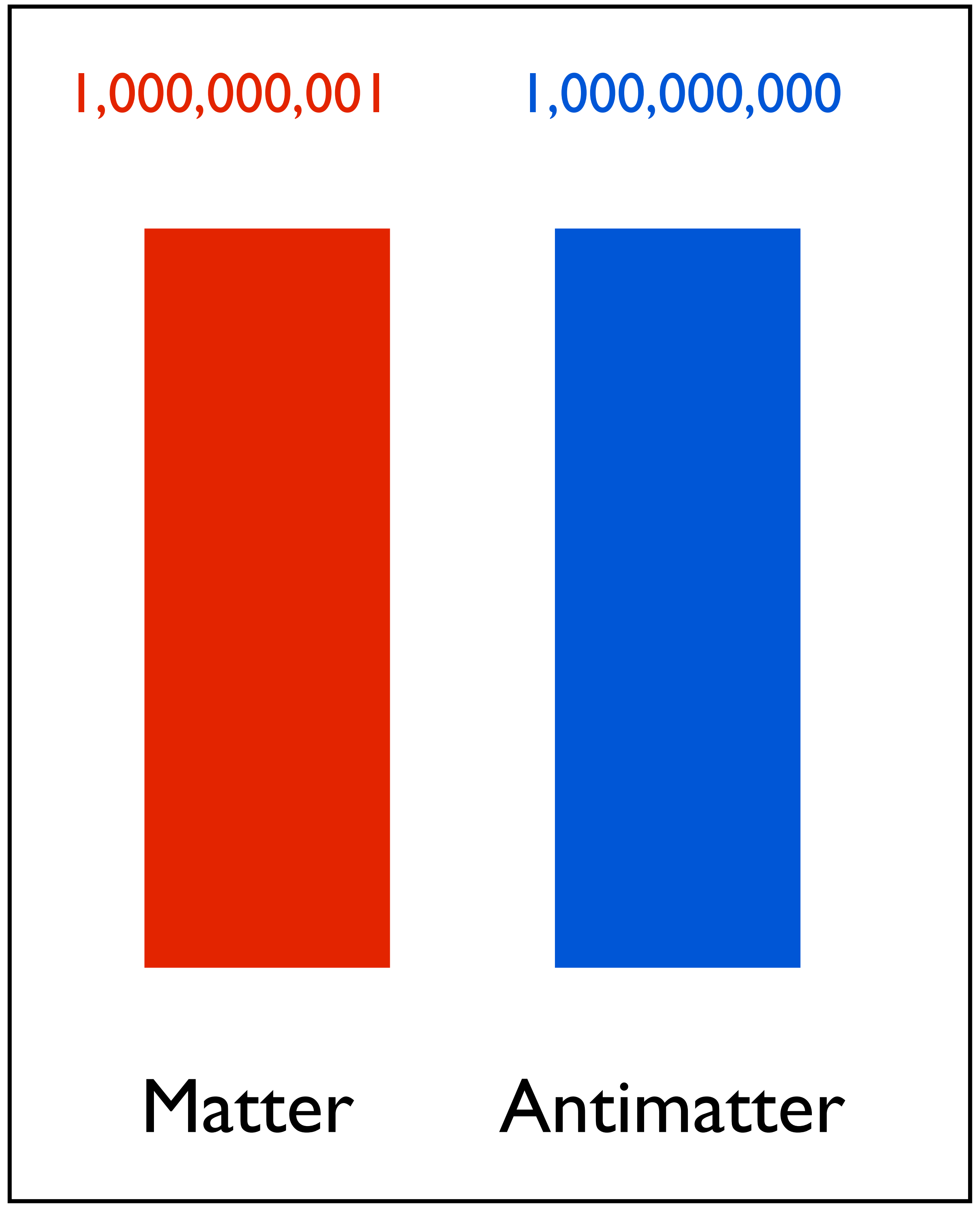
This is deeply related to the Majorana nature:
neutrino = anti-neutrino

# How does 0νββ decay help?

Andrei Sakharov, 1967

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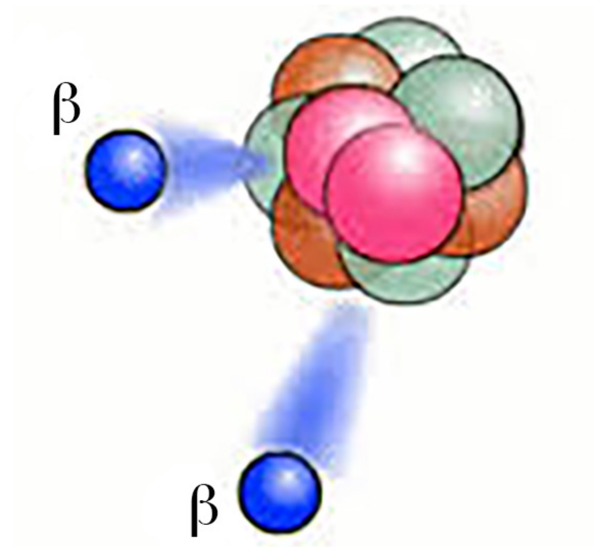


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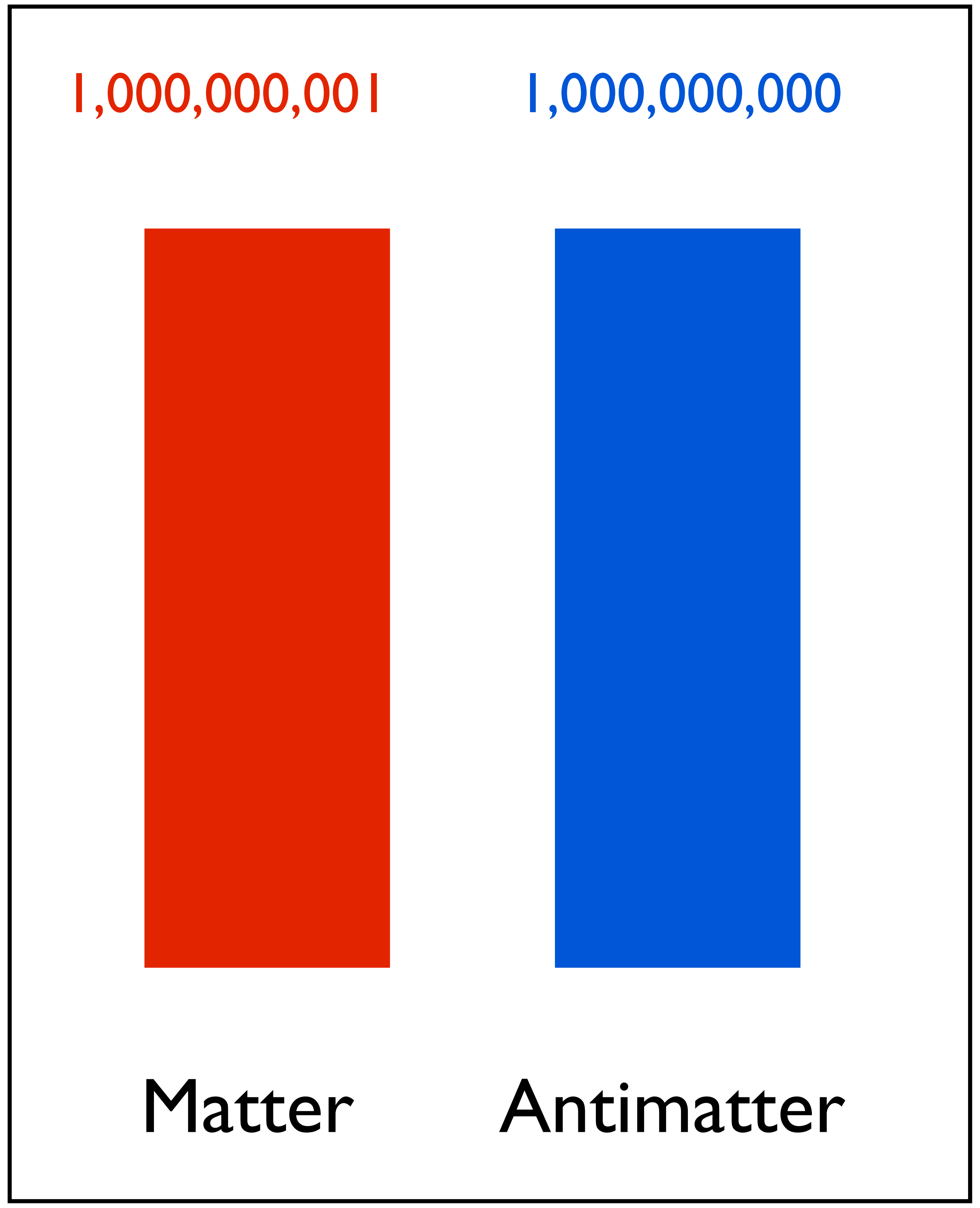
But there's more! The same physics could be responsible for both 0νββ decay and for generating the matter excess in the universe through the *leptogenesis mechanism*

# How does 0νββ decay help?

Andrei Sakharov, 1967

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#1. Processes that "create matter"

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

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

- 0νββ directly address first condition
- Explicit models of Majorana neutrino mass satisfy the other two conditions, as well: baryogengesis via leptogenesis

**Fukugita-Yanagida 1987**

# The simplest mass model

- Simple / natural option: add three R-handed neutrinos $\nu_{Ri}$ (gauge singlets = no interaction)

$$\mathcal{L}_{\nu SM} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \left(\frac{1}{2}\nu_R^T C M_R \nu_R + \bar{\ell} Y_\nu \nu_R \tilde{\varphi} + \text{h.c.}\right)$$

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- Dirac neutrinos: $M_R = 0$. Same as quarks & charged leptons , except for tiny ($O(10^{-10})$) Yukawa couplings

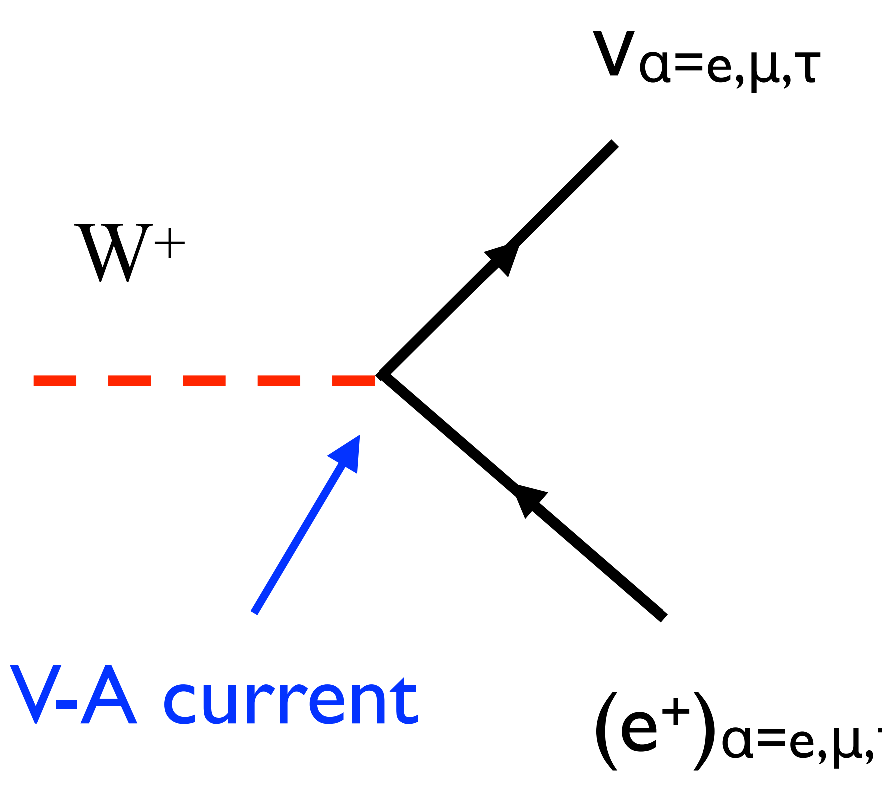
$$Y_e = V_{e_L}^\dagger Y_e^{\text{diag}} V_{eR}$$

$$Y_\nu = V_{\nu_L}^\dagger Y_\nu^{\text{diag}} V_{\nu R}$$

$$\Rightarrow \boxed{\frac{g}{\sqrt{2}} W_\mu^- \, \bar{e}_L^\alpha \gamma^\mu U^{\alpha i} \, \nu_L^i}$$

$$U = V_{e_L} V_{\nu_L}^\dagger$$

Unitary mixing in Charged Current vertex: 3 angles, 1 phase



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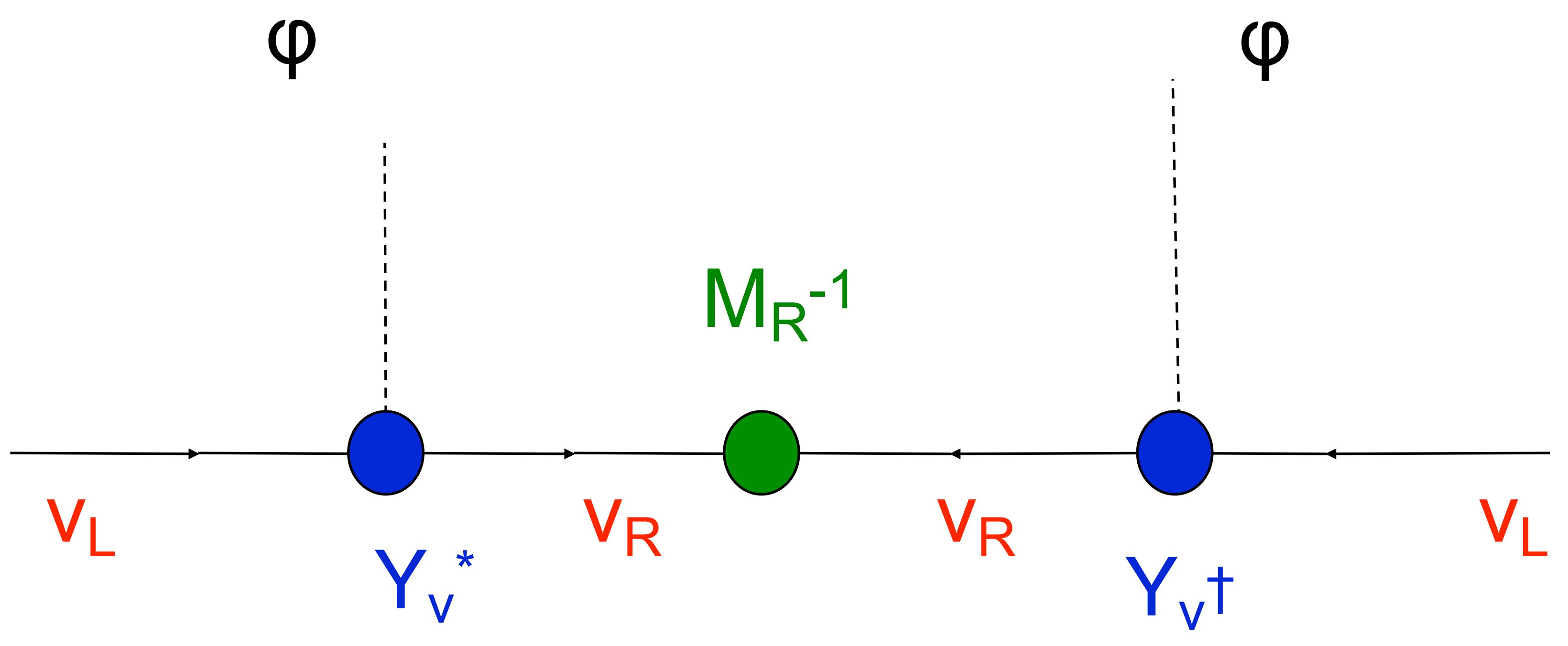
- Majorana neutrinos: $M_R \neq 0$ ⇒ L not conserved & 6x6 mass matrix for $\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$: six Majorana ($\nu=\nu^c$) eigenstates

- If $M_R >> vY_\nu$: 3 light ($\nu_L \to \nu_i$) and 3 heavy ($\nu_R \to N_i$) eigenstates

$$\mathcal{L}_{\nu SM} \supset -\frac{1}{2}\nu_L^T\, C\, m_\nu\, \nu_L$$

**Seesaw mechanism (Type I)**

$$m_\nu = v^2\, Y_\nu^*\, M_R^{-1}\, Y_\nu^\dagger$$



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$$m_\nu = V_{\nu_L}^T m_\nu^{\text{diag}} V_{\nu_L}$$

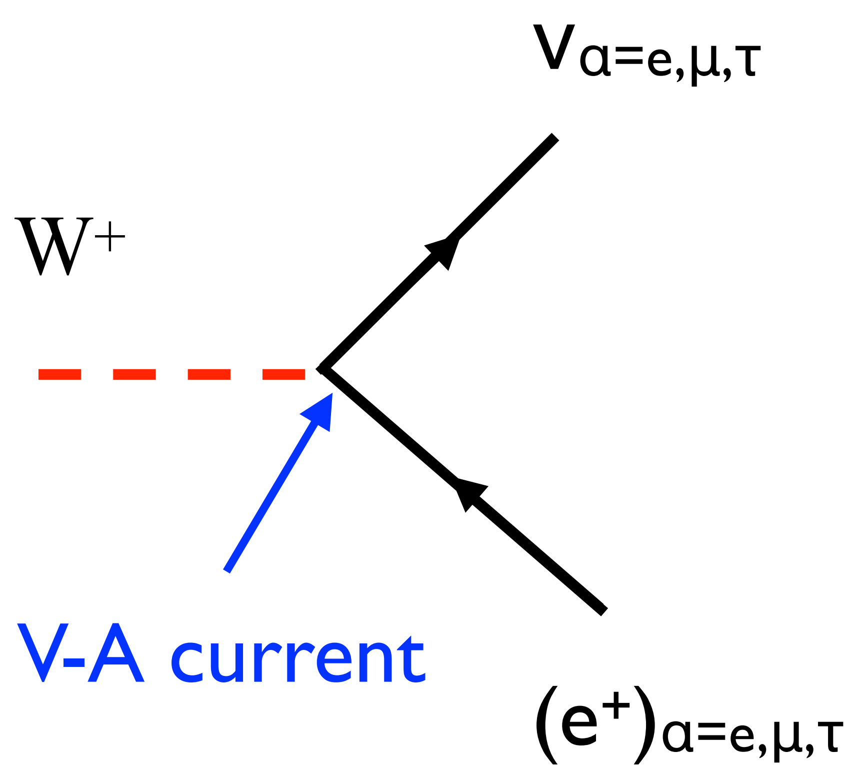
$$Y_e = V_{e_L}^\dagger Y_e^{\text{diag}} V_{e_R}$$

$$\Rightarrow \quad \boxed{\frac{g}{\sqrt{2}} W_\mu^- \; \bar{e}_L^\alpha \gamma^\mu U^{\alpha i} \nu_L^i}$$

$$U = V_{e_L} V_{\nu_L}^\dagger$$

Unitary mixing in CC vertex: 3 angles, 1+2 phases

$$U = U_{\text{Dirac}} \times \begin{pmatrix} 1 & & \\ & e^{i\alpha_1} & \\ & & e^{i\alpha_2} \end{pmatrix}$$

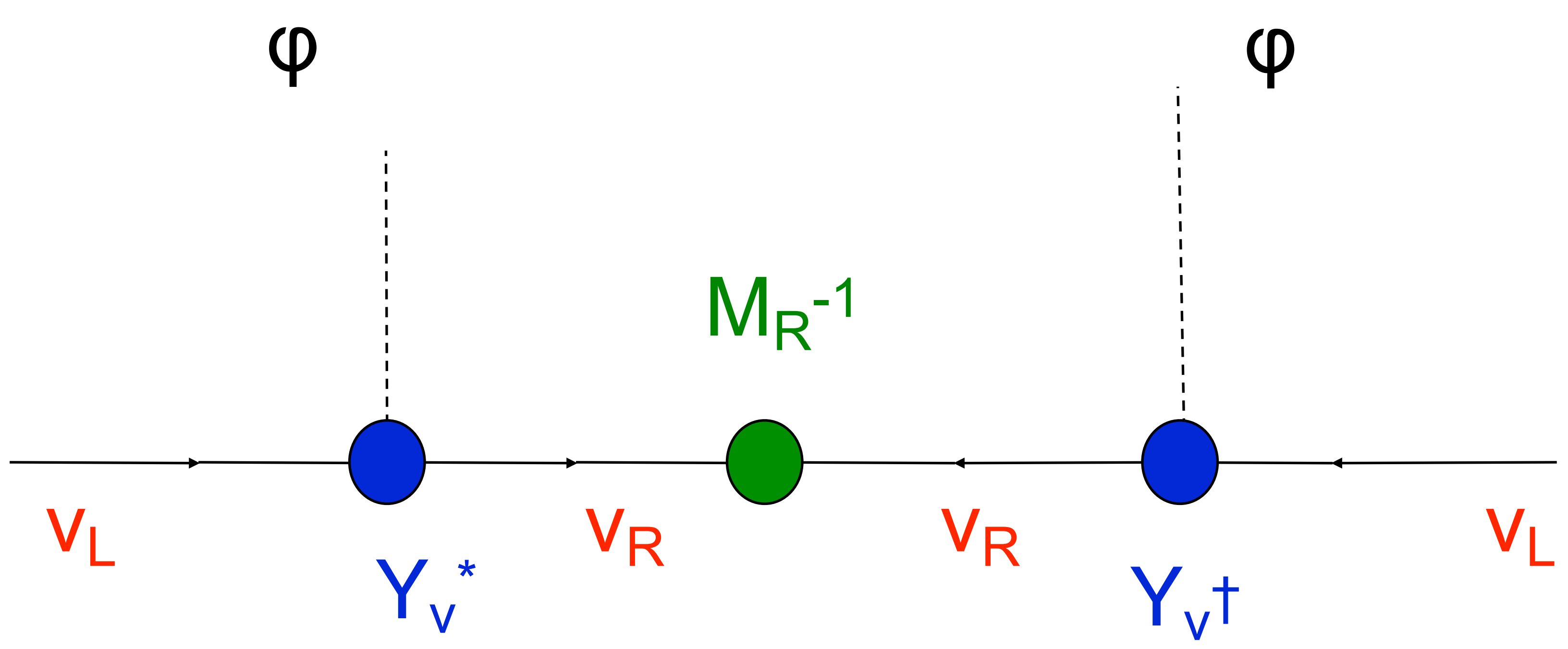


# The simplest mass model

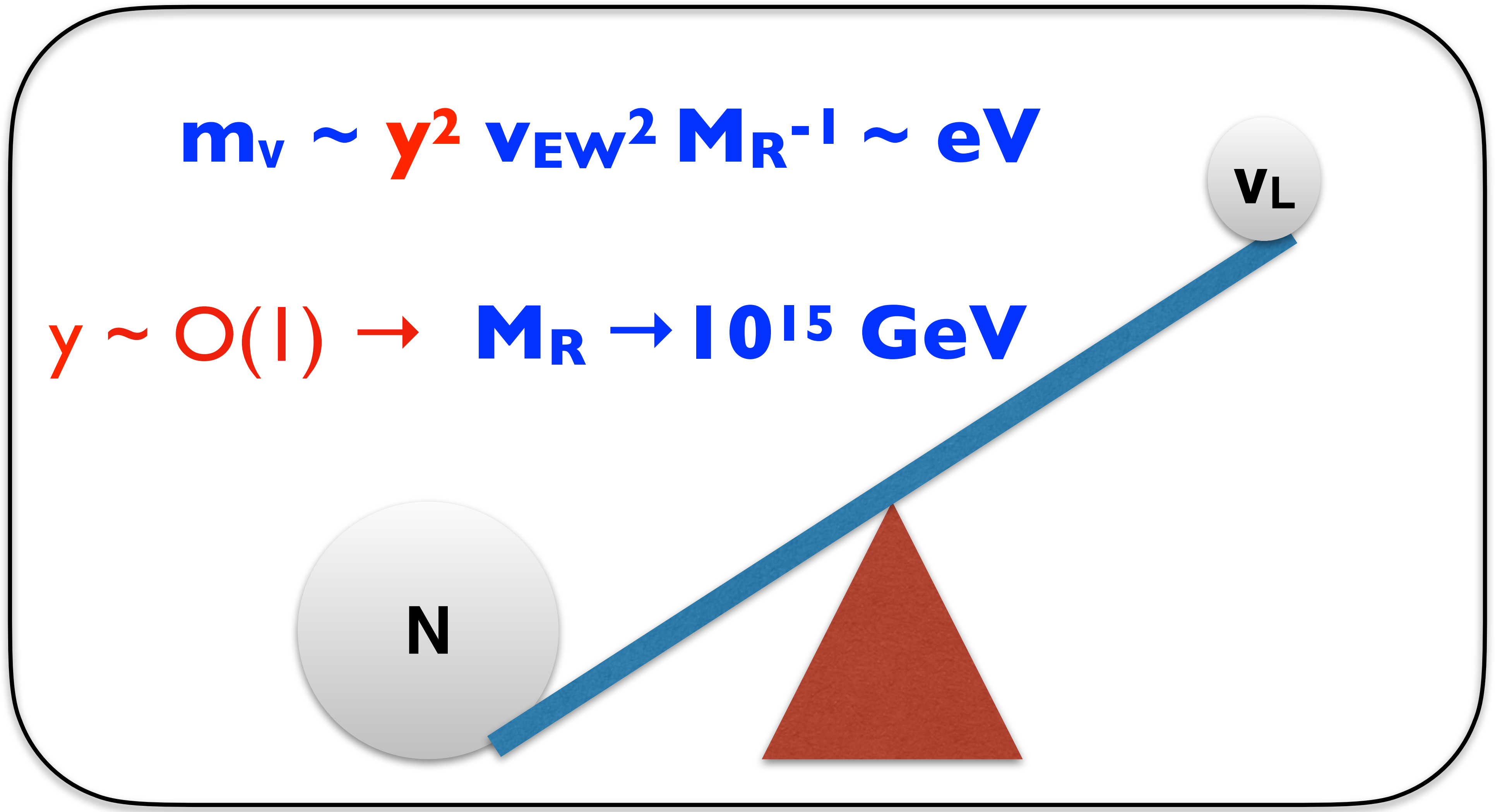
Seesaw mechanism summary:

Heavy (Majorana) singlets are introduced to give mass to the light neutrinos in a way consistent with Lorentz and weak interaction symmetries

They also provide an avenue to generate the baryon asymmetry…

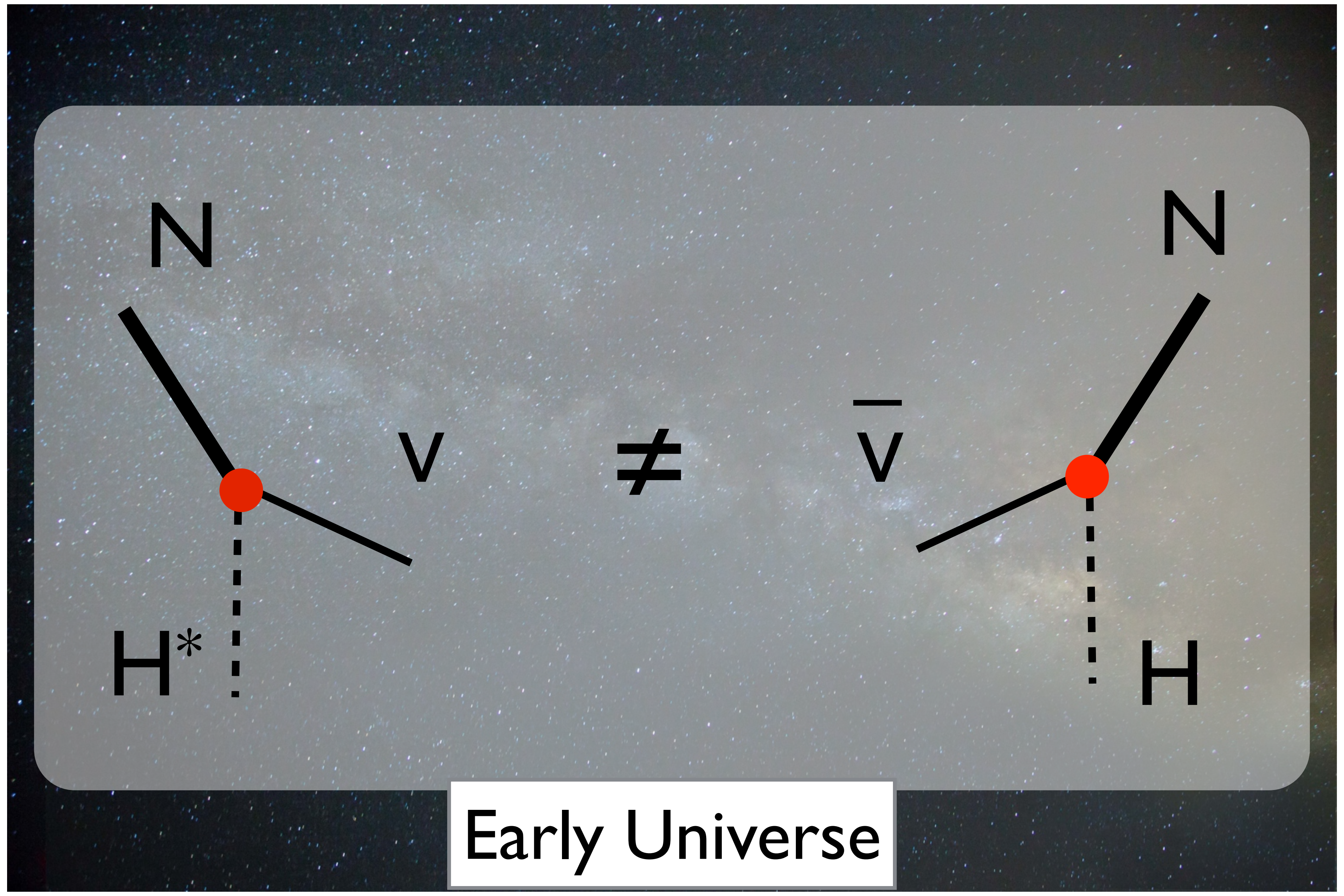



Minkowski 1977,
Gell-Mann, Ramond, Slanksy 1979, …



# Leptogenesis and 0νββ: a tantalizing connection

Fukugita-Yanagida 1987



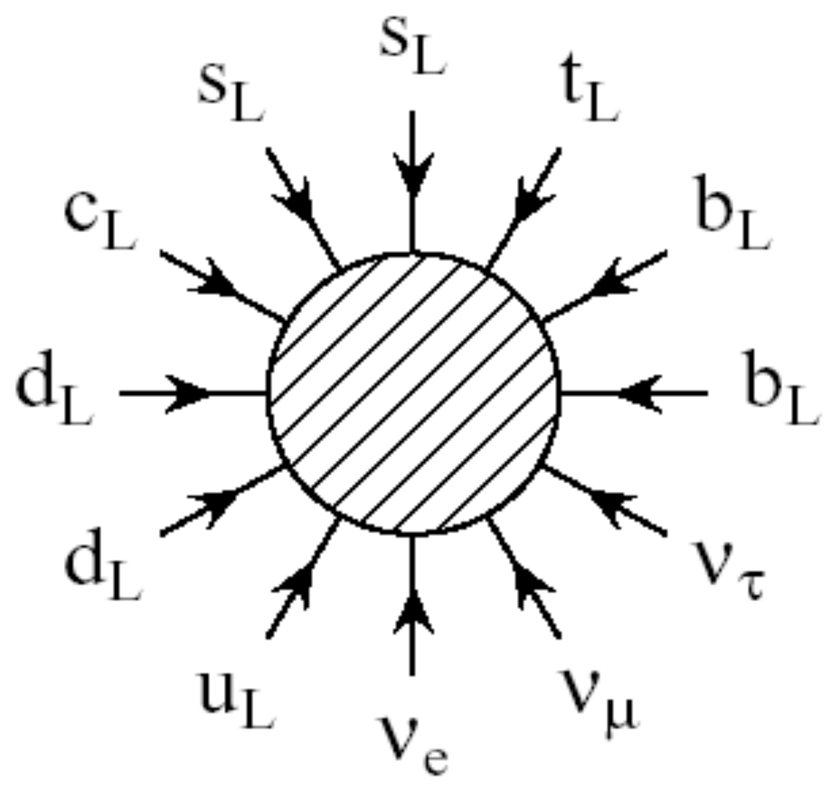

Heavy neutrinos (N) play key role in generating the matter-antimatter asymmetry by decaying into (anti)neutrinos and Higgs (H) particles 'asymmetrically' and 'slowly'

## Baryogengesis via Leptogenesis

1) CP- and L- violating out-of-equilibrium decays of heavy N ⇒ $n_L$

$$\boxed{\Gamma(N \to H^* \ell) \neq \Gamma(N \to H \bar{\ell})}$$

2) Electroweak sphalerons ⇒ $n_B$ = # $n_L$



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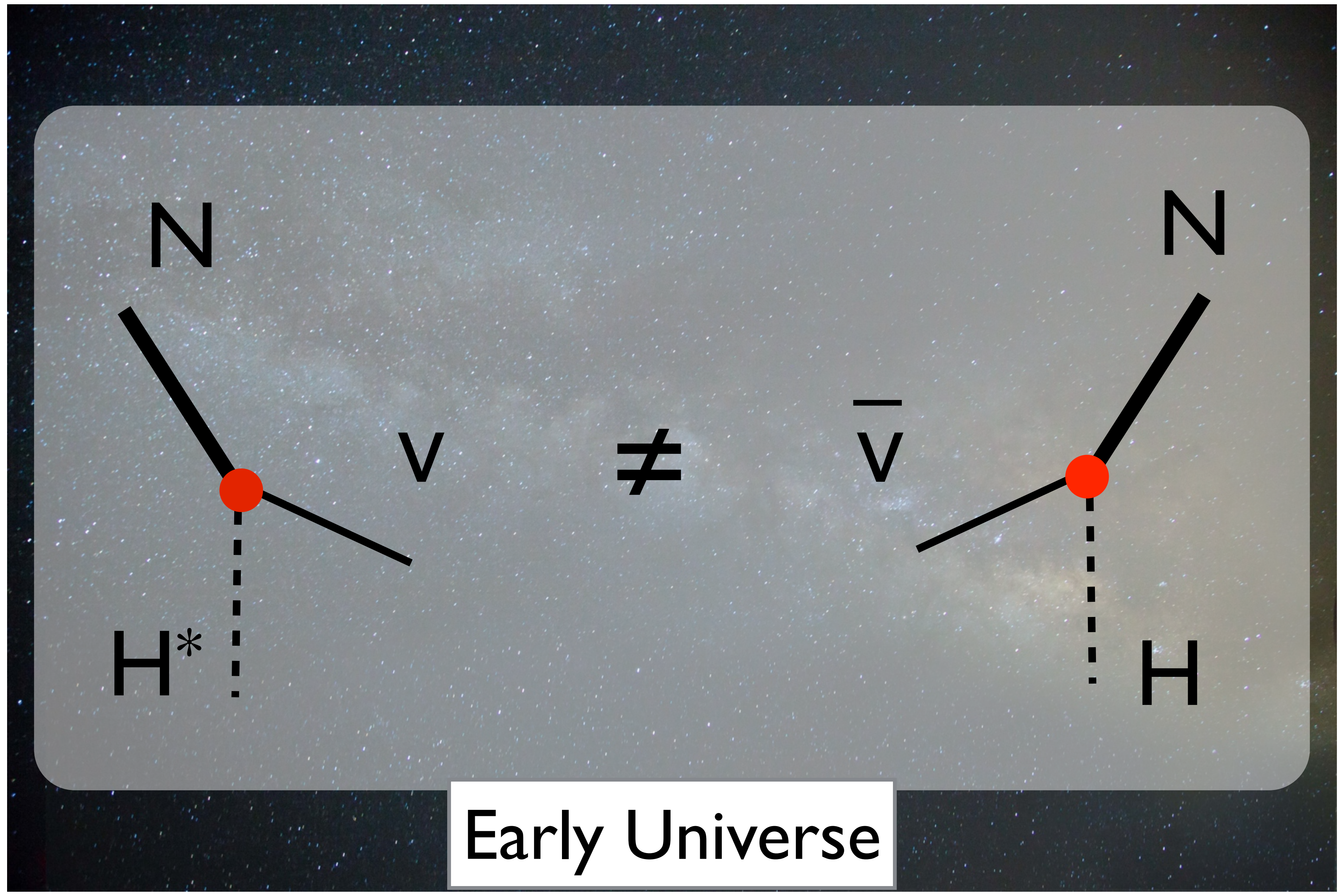
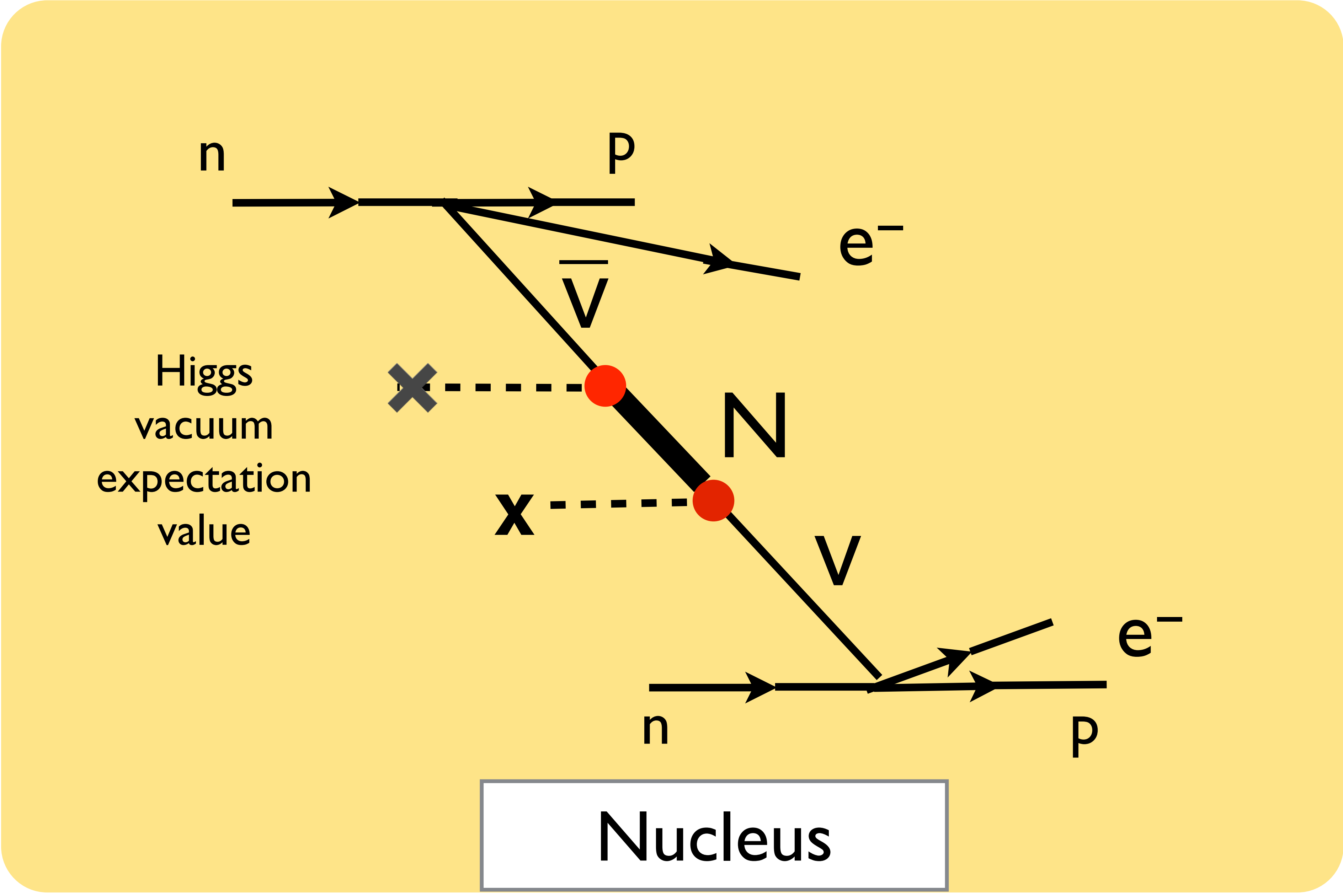



Heavy neutrinos (N) play key role in generating the matter-antimatter asymmetry by decaying into (anti)neutrinos and Higgs (H) particles 'asymmetrically' and 'slowly'

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

# $0\nu\beta\beta$ decay: summary of significance

The neutrino and its mysteries

Demonstrate Majorana nature of massive neutrinos (neutrino=antineutrino)

A cosmic mystery

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

Point to baryogengesis via leptogenesis

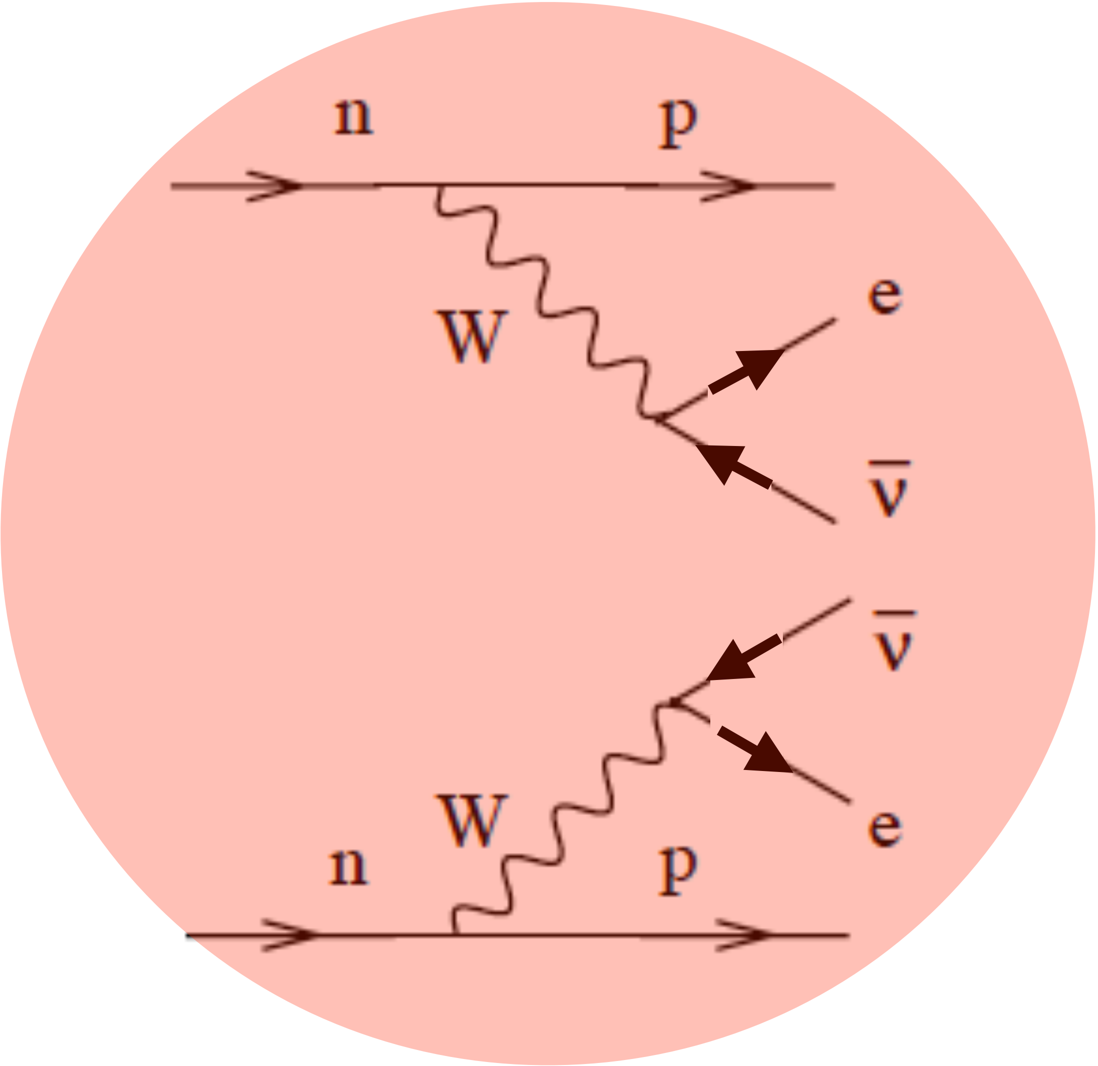
Nuclear $0\nu\beta\beta$ decay

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

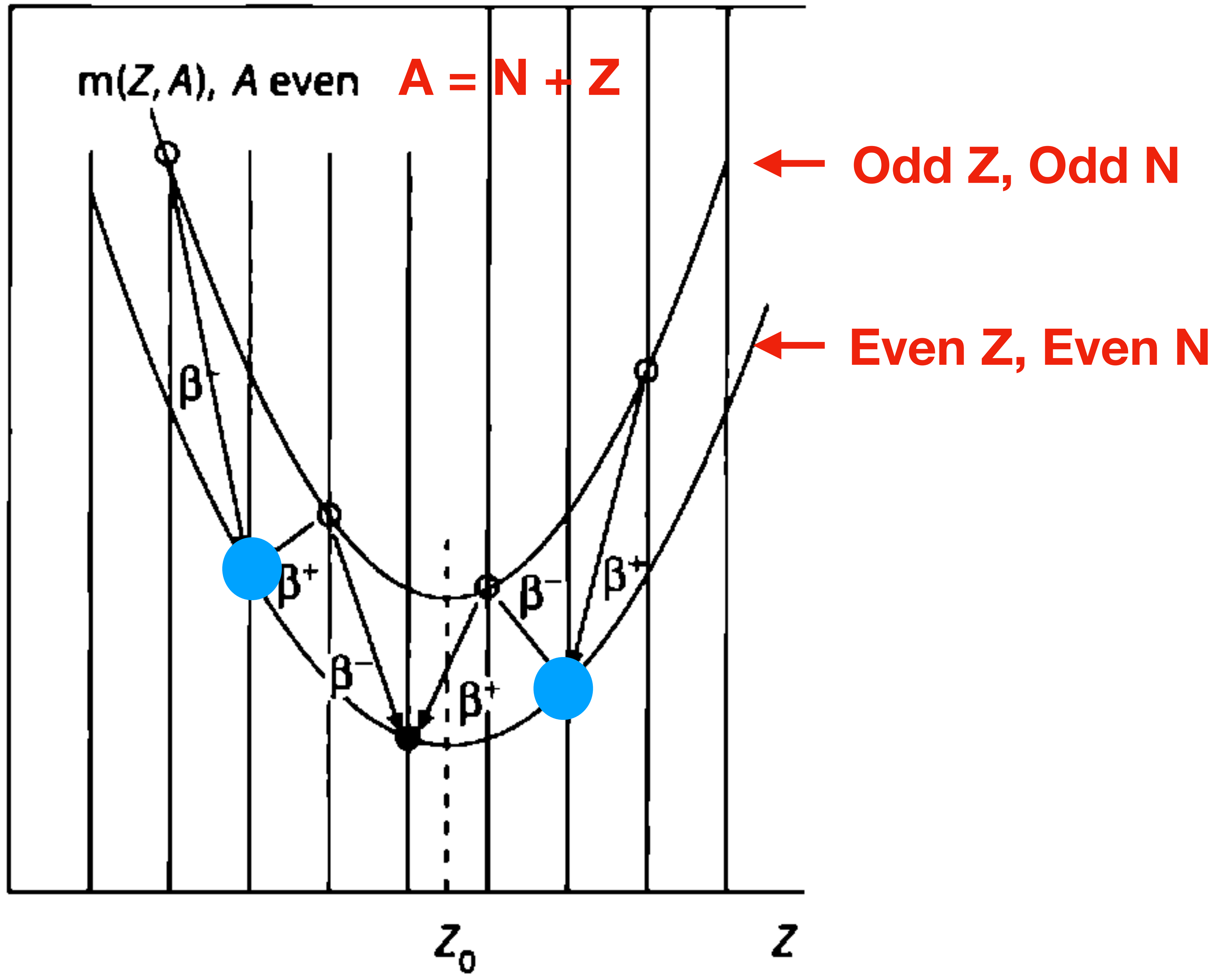
# The quest is on…

- For certain even-even nuclei ($^{48}Ca$, $^{76}Ge$, $^{136}Xe$, …), single β decay is energetically forbidden → ββ decay
- 2νββ is the rarest process ever observed, with $T_{1/2} \sim 10^{21}$ years

M. Goppert Mayer, 1935




Credit: C. Bertulani's book



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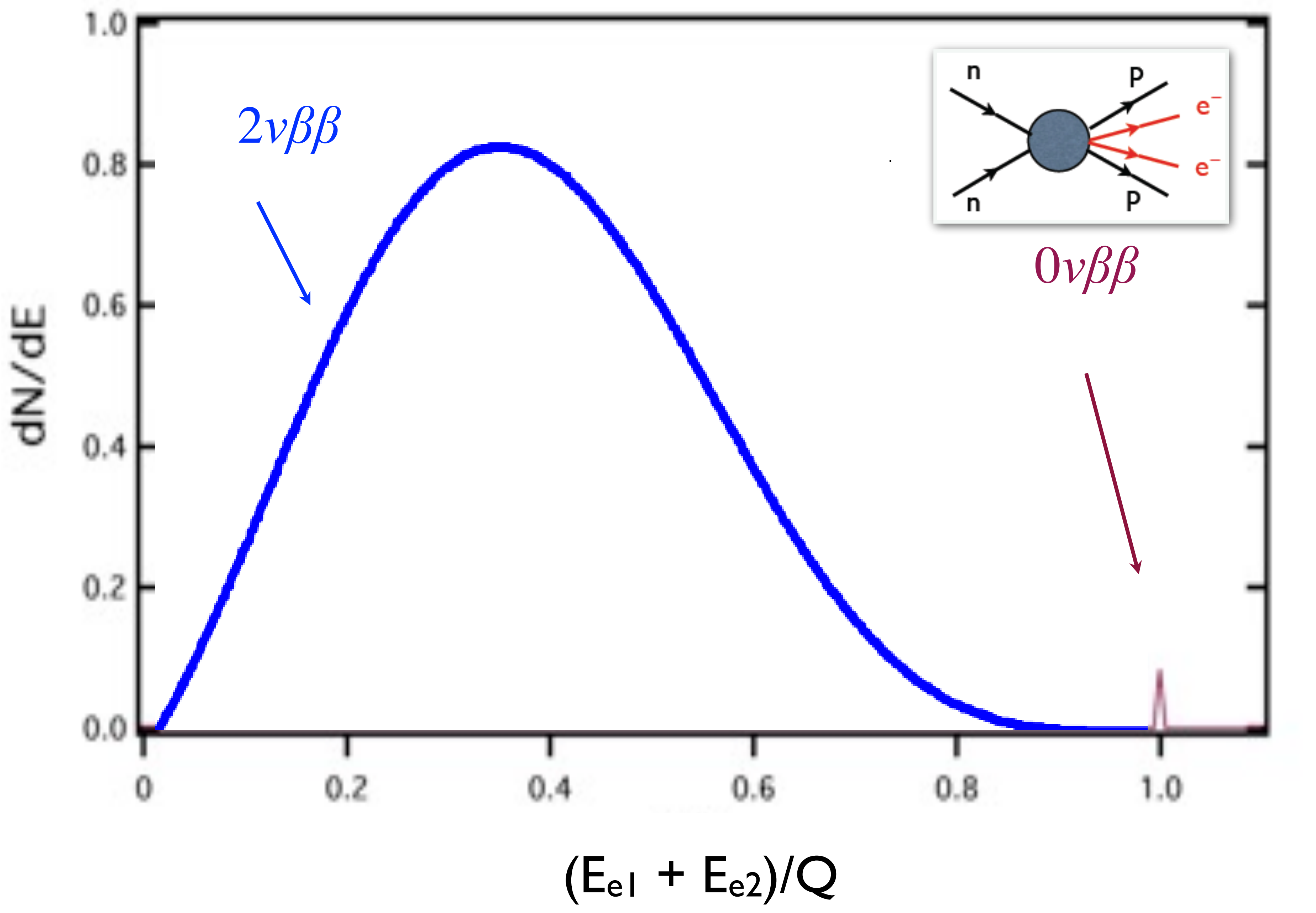
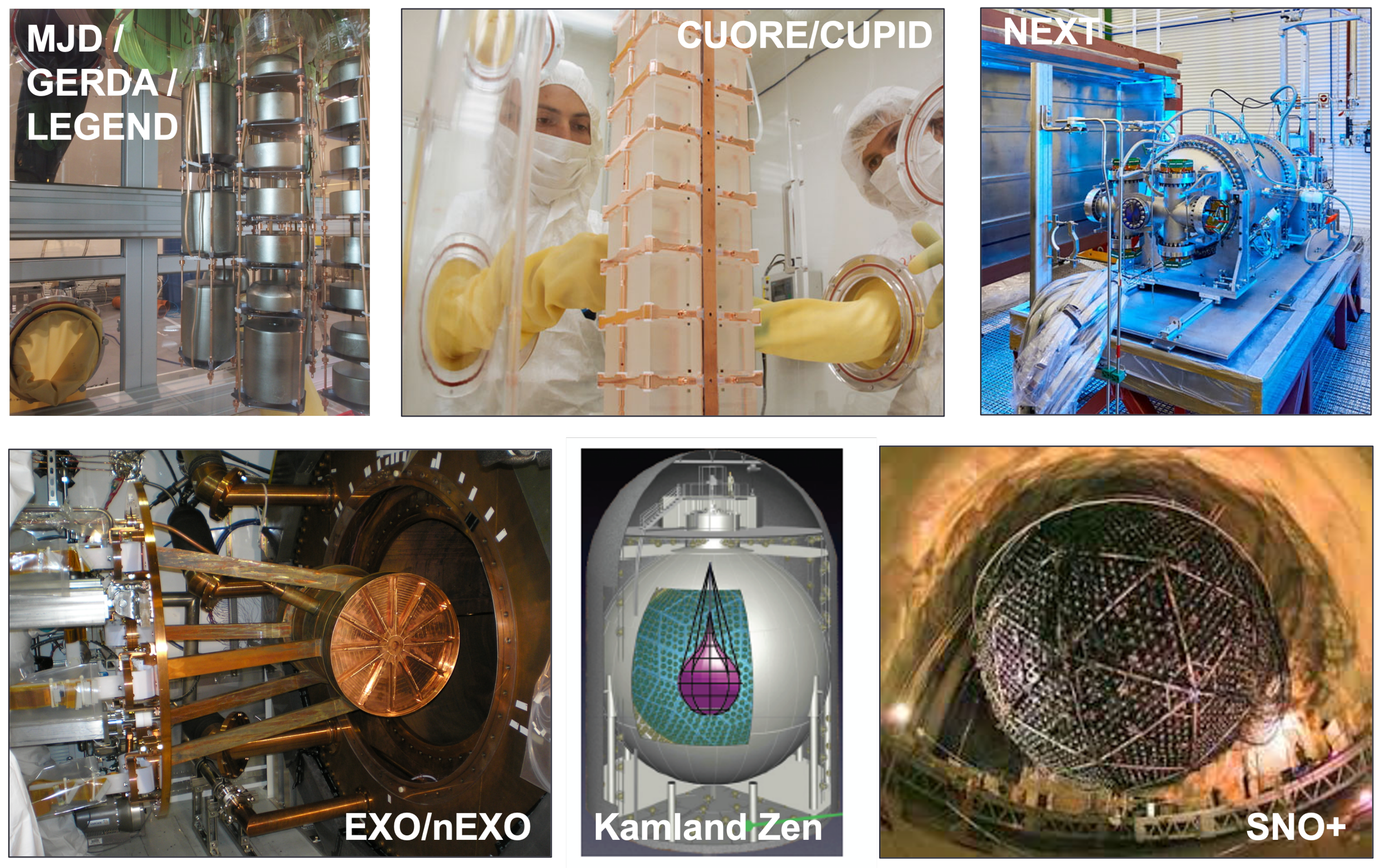
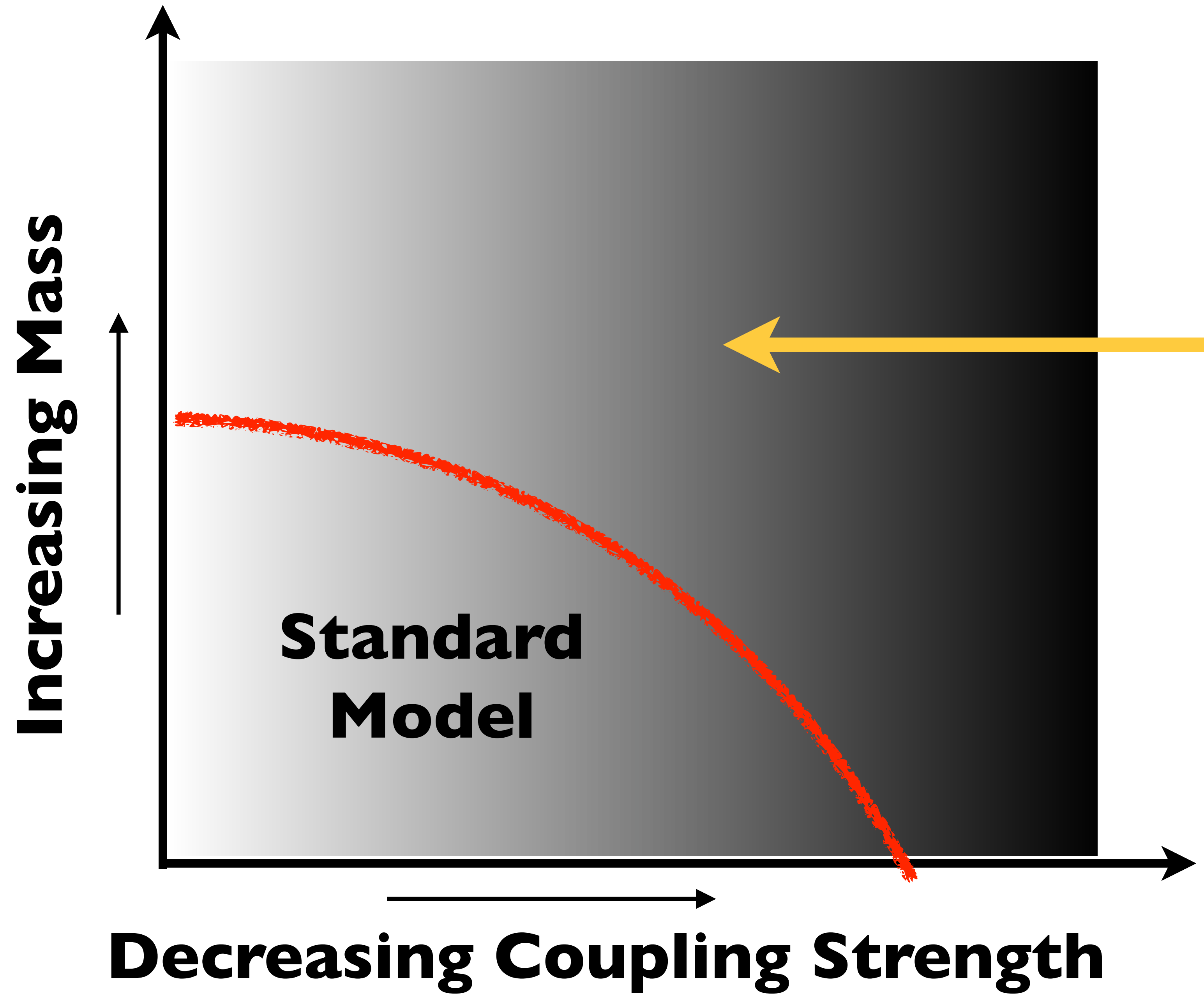
- 2νββ is the rarest process ever observed, with $T_{1/2} \sim 10^{21}$ years
- Several "ton-scale" experiments with different isotopes and technologies are searching for 0νββ, with sensitivity up to $T_{1/2} \sim 10^{28}$ yr, which is $10^{18}$ times the age of the universe!



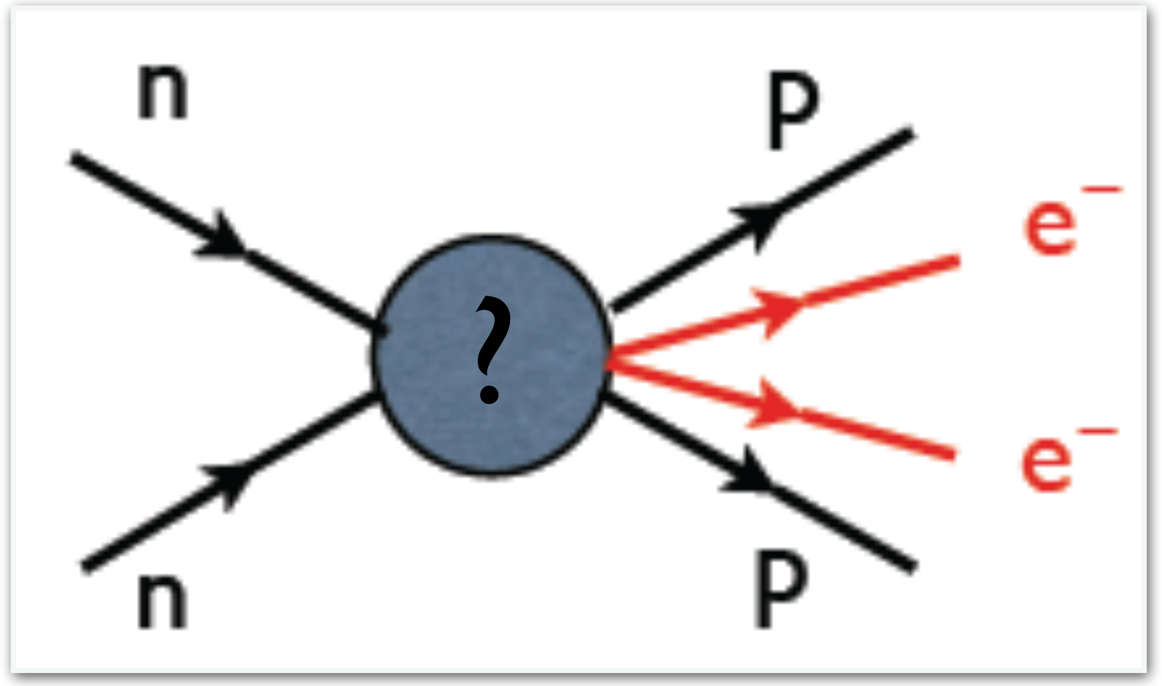
# 0νββ decay: broad discovery potential

- Ton-scale 0νββ searches 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 most of this uncharted territory can be explored only by 0νββ decay



# Backup

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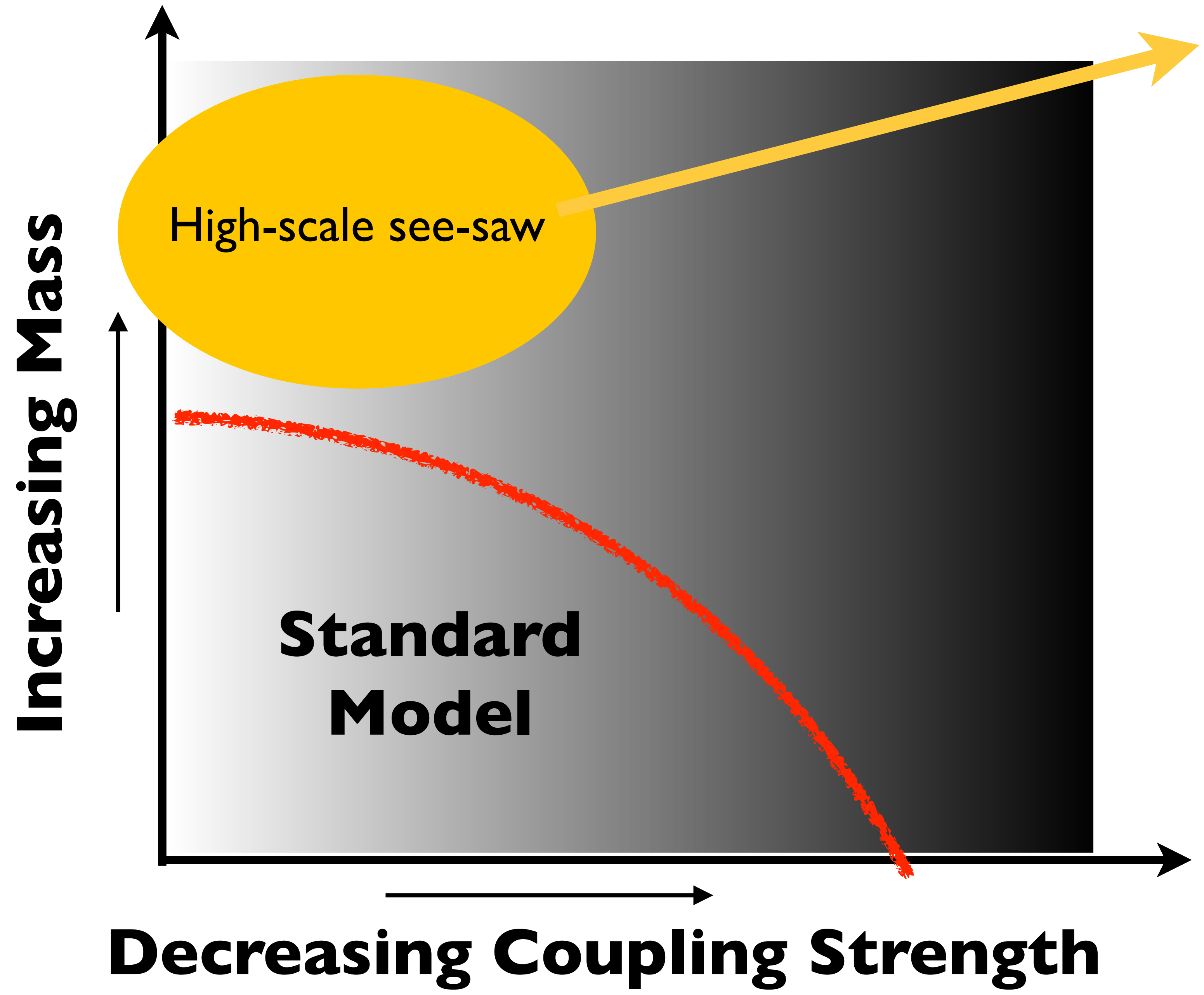
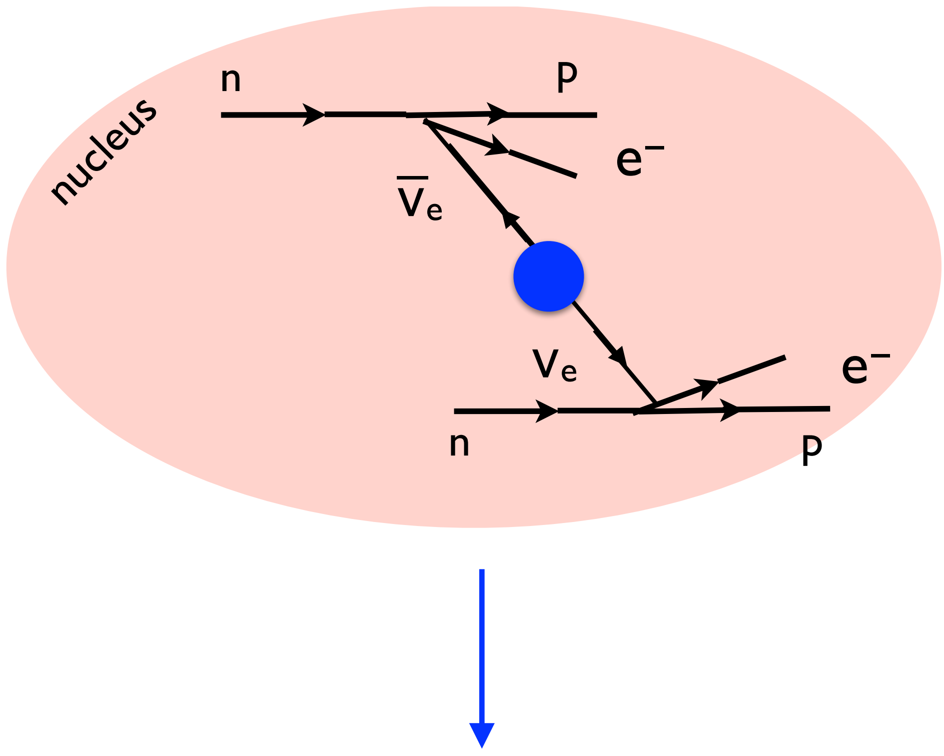



**LNV up to $10^{15}$ GeV scale:**
**$m_{\beta\beta} \sim (v_{ew})^2/\Lambda$**




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

Half-life is related to neutrino mass: concrete discovery targets & falsifiable correlations with other probes of $m_\nu$

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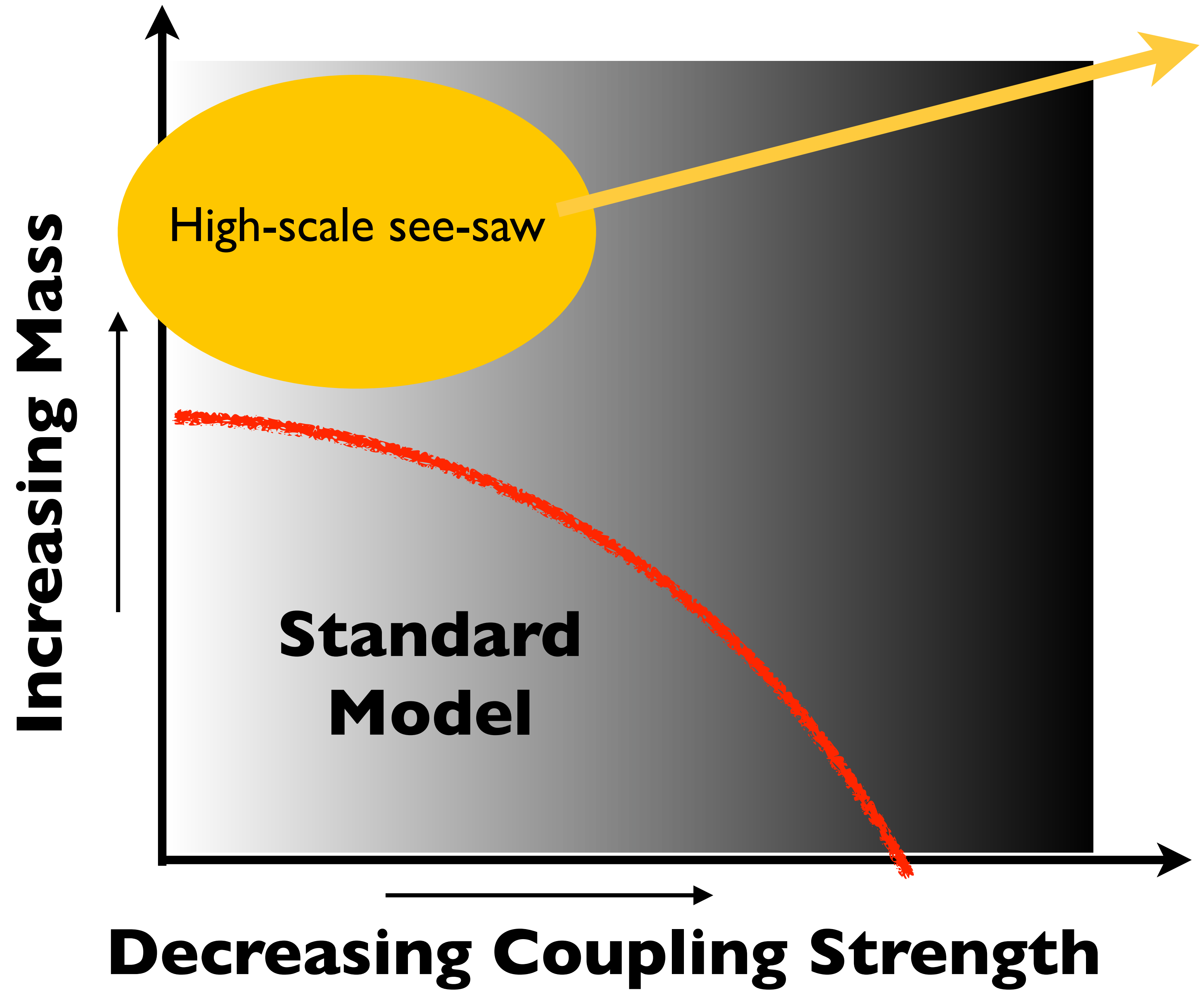


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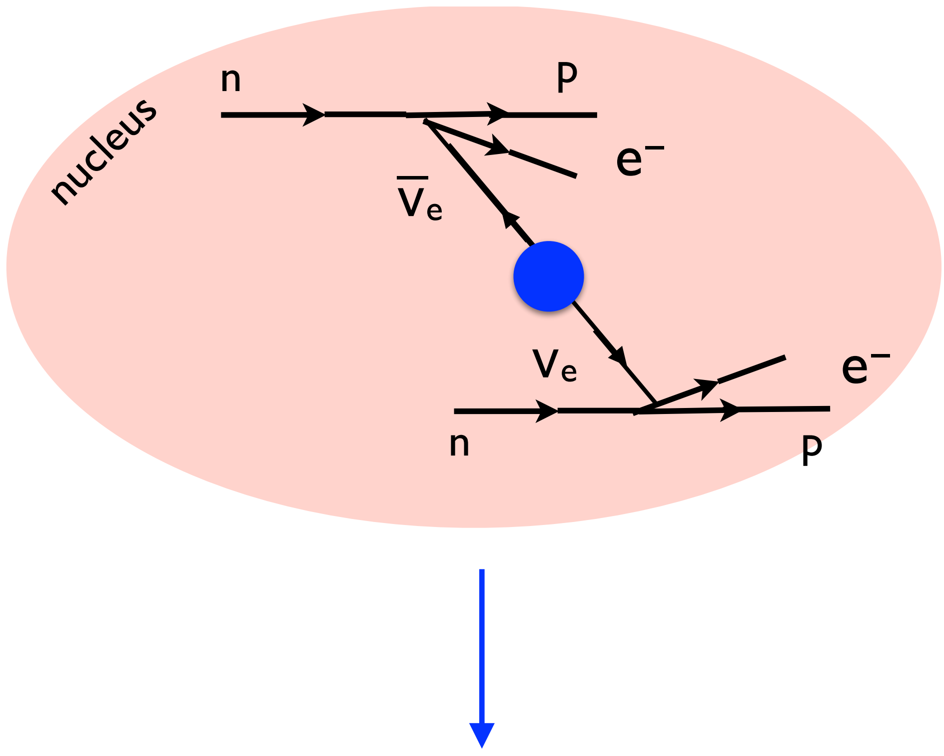


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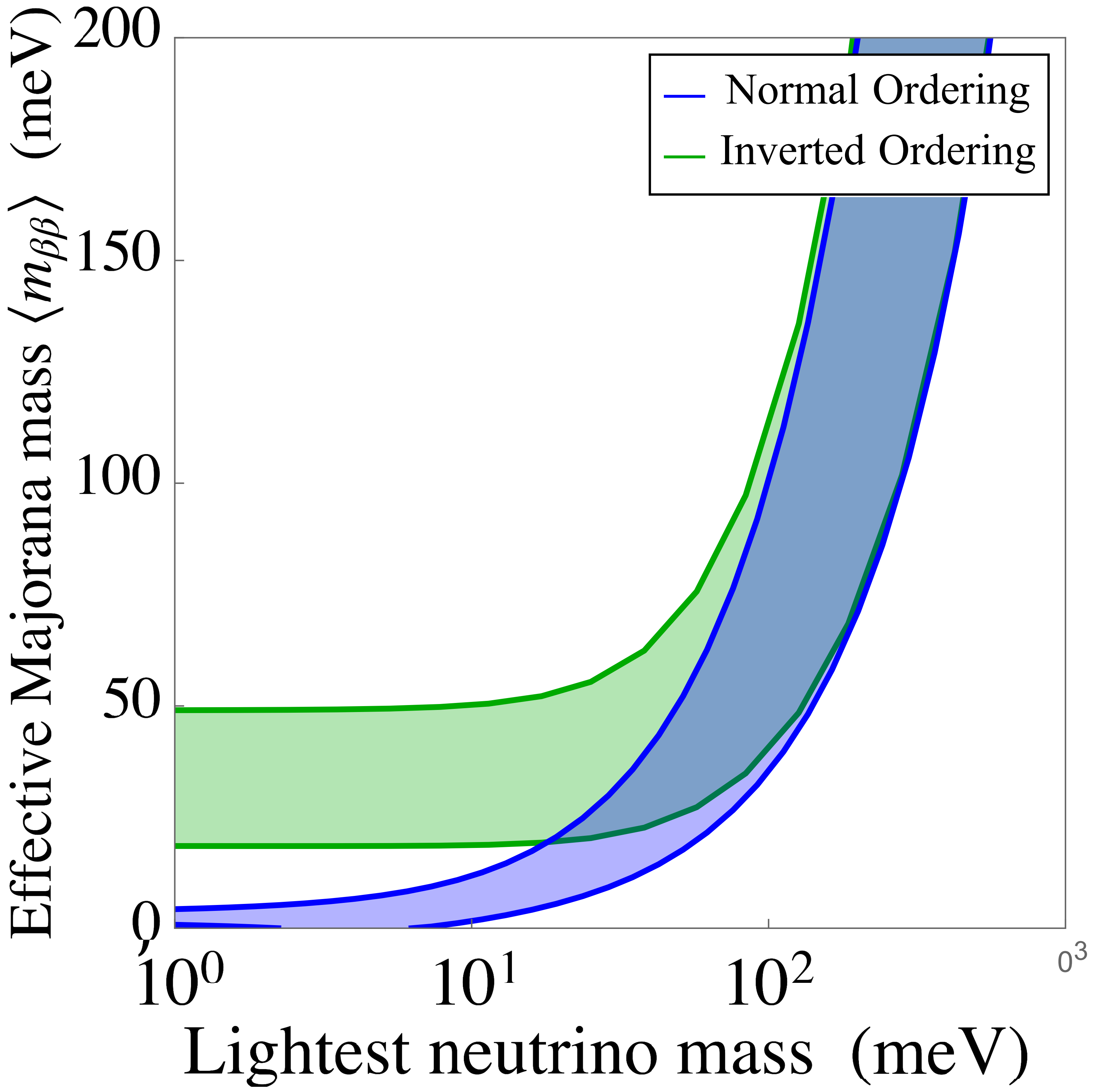


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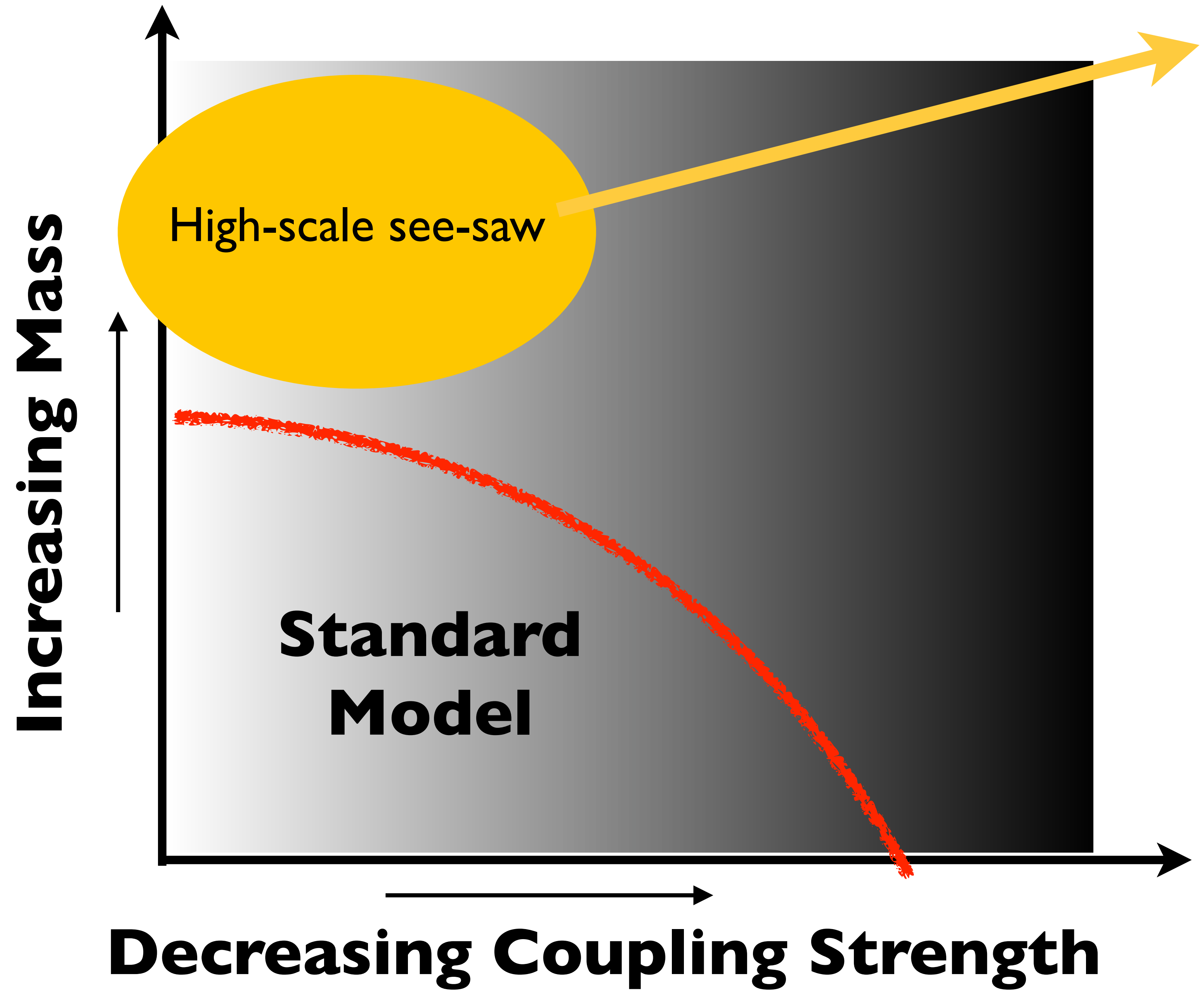


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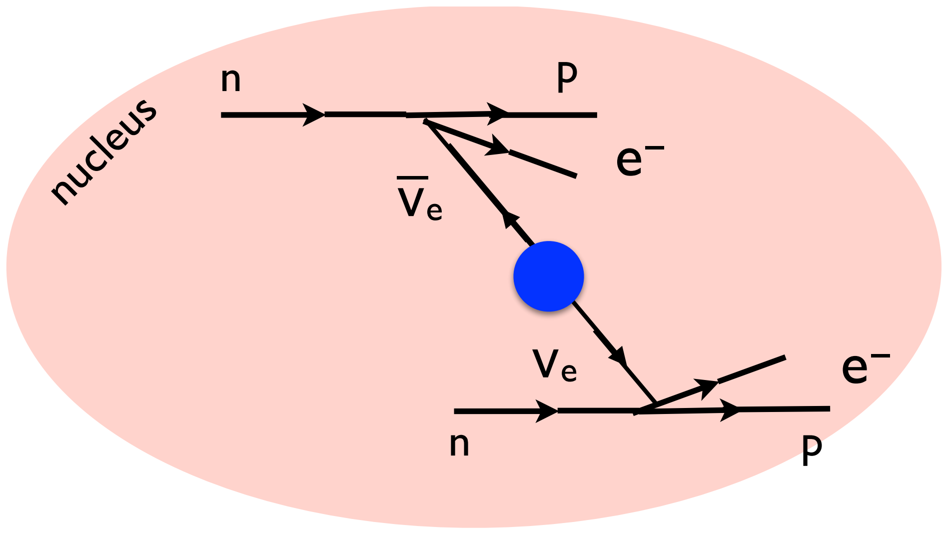


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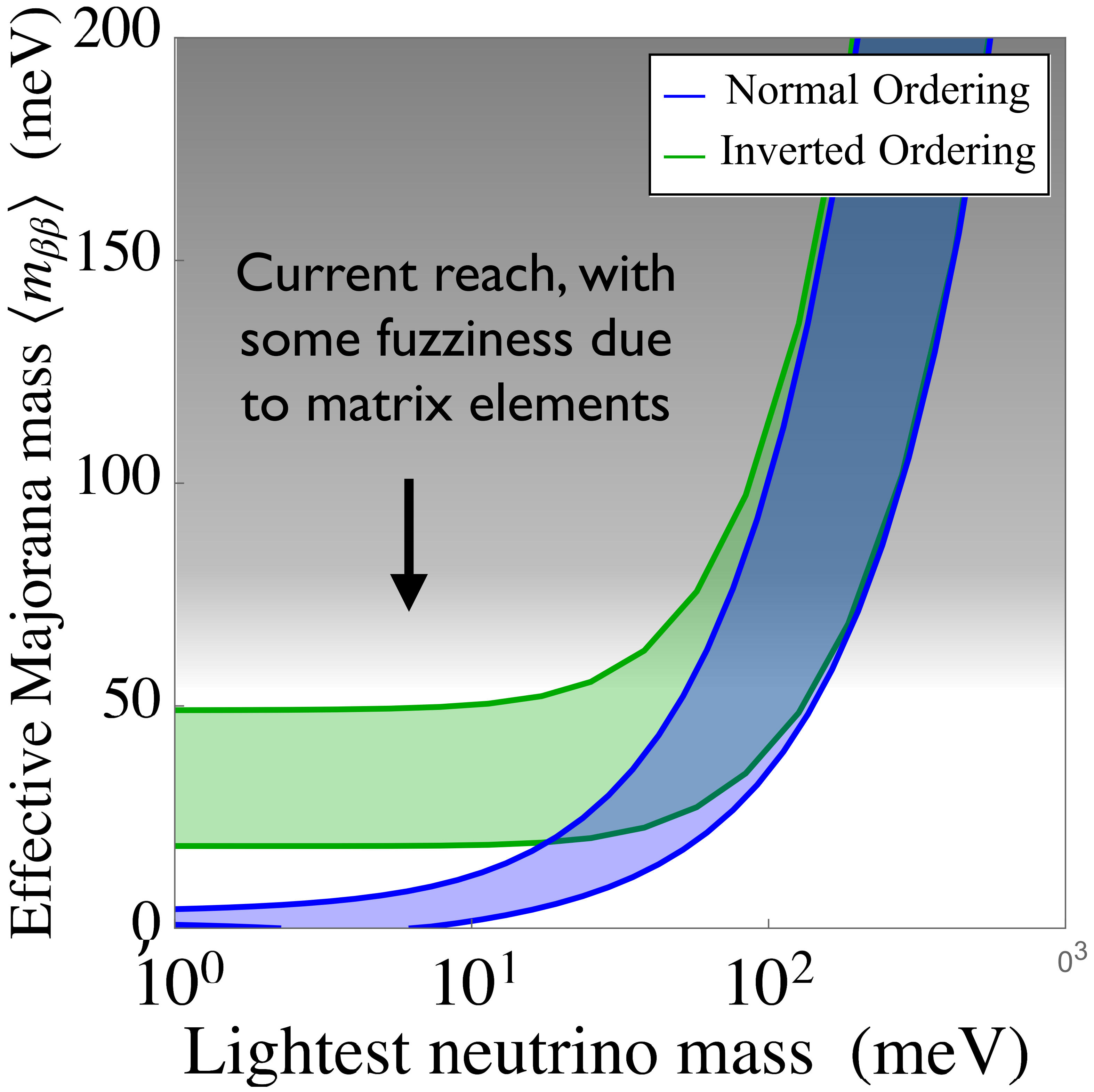


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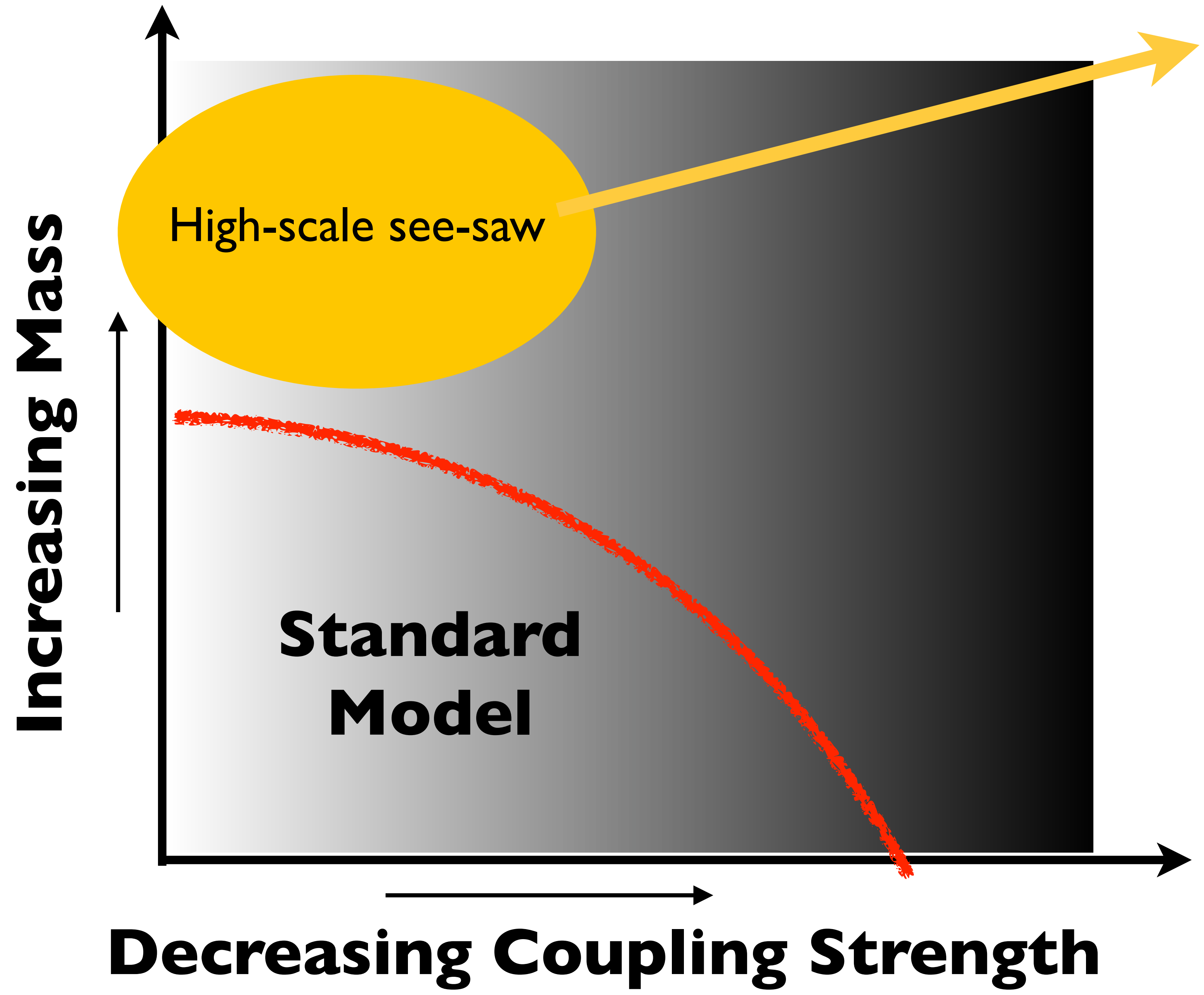


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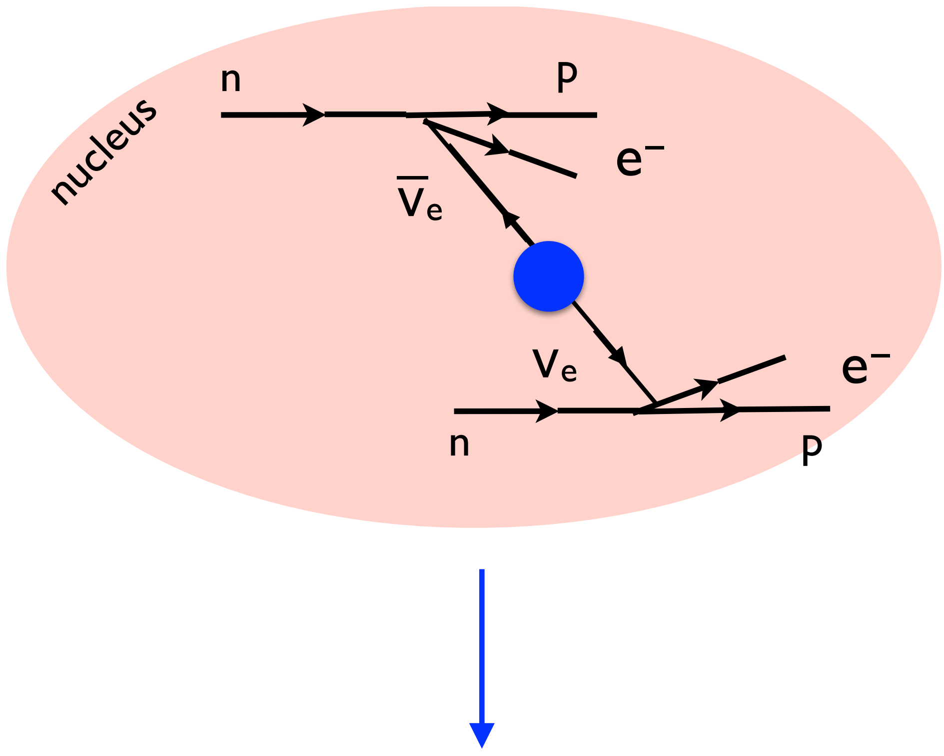


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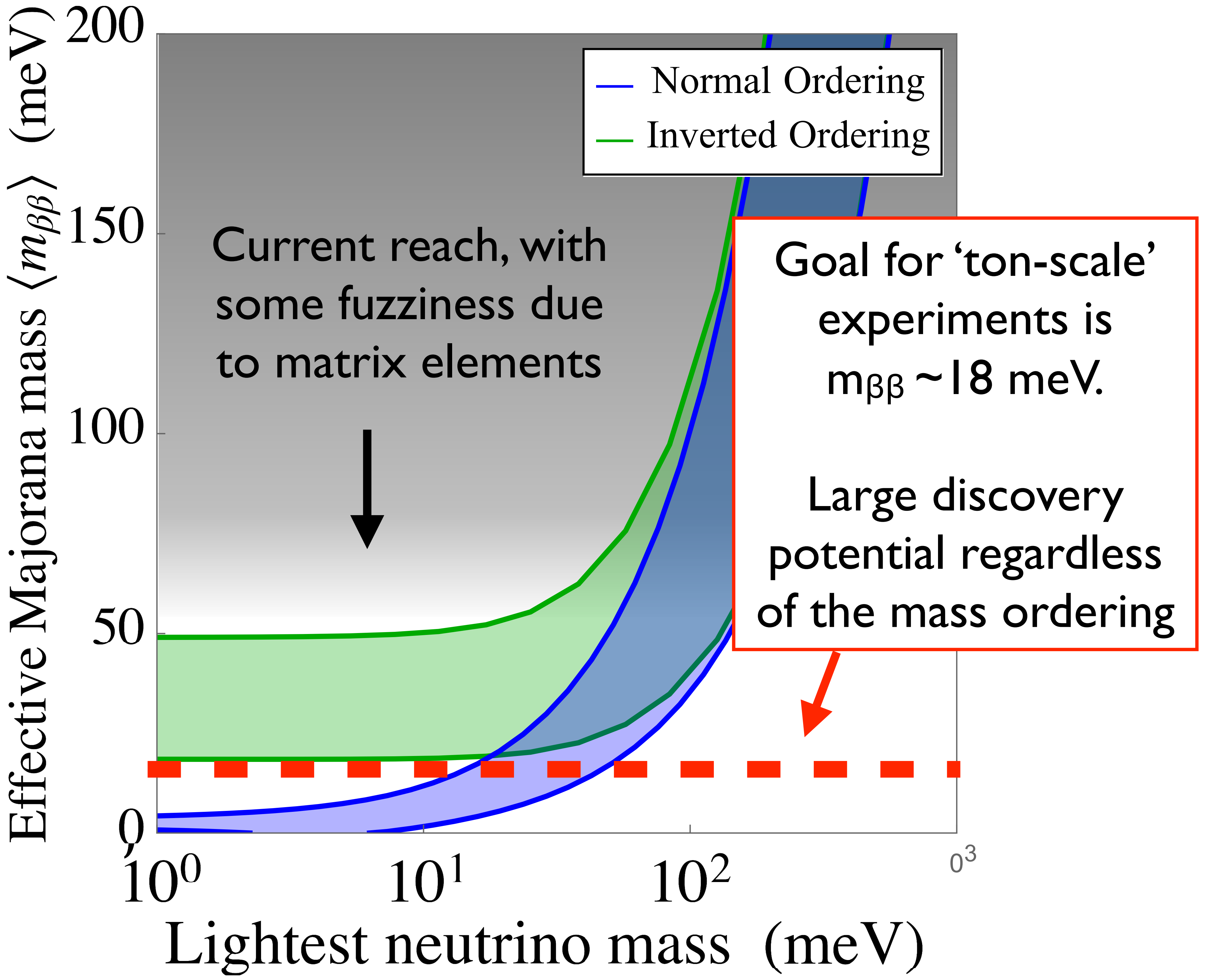


Half-life is related to neutrino mass: concrete discovery targets & falsifiable correlations with other probes of $m_\nu$

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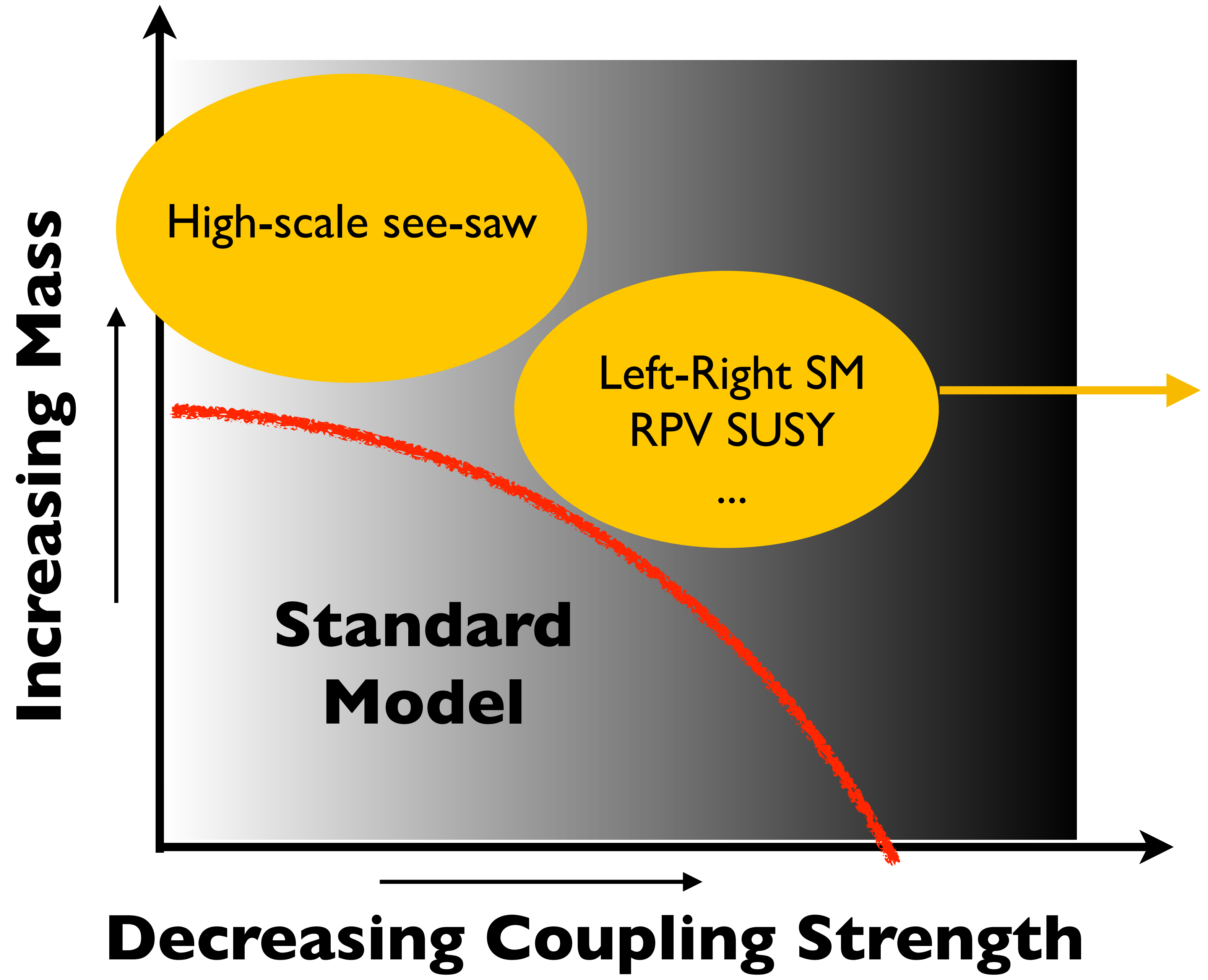
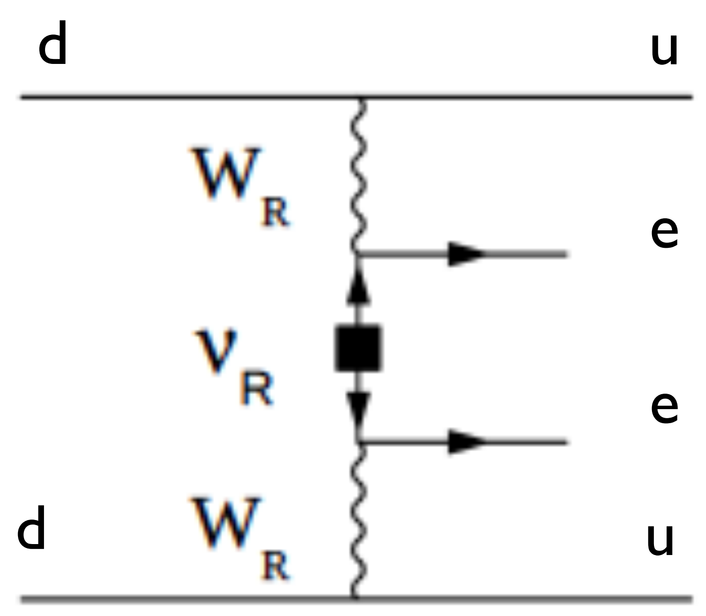
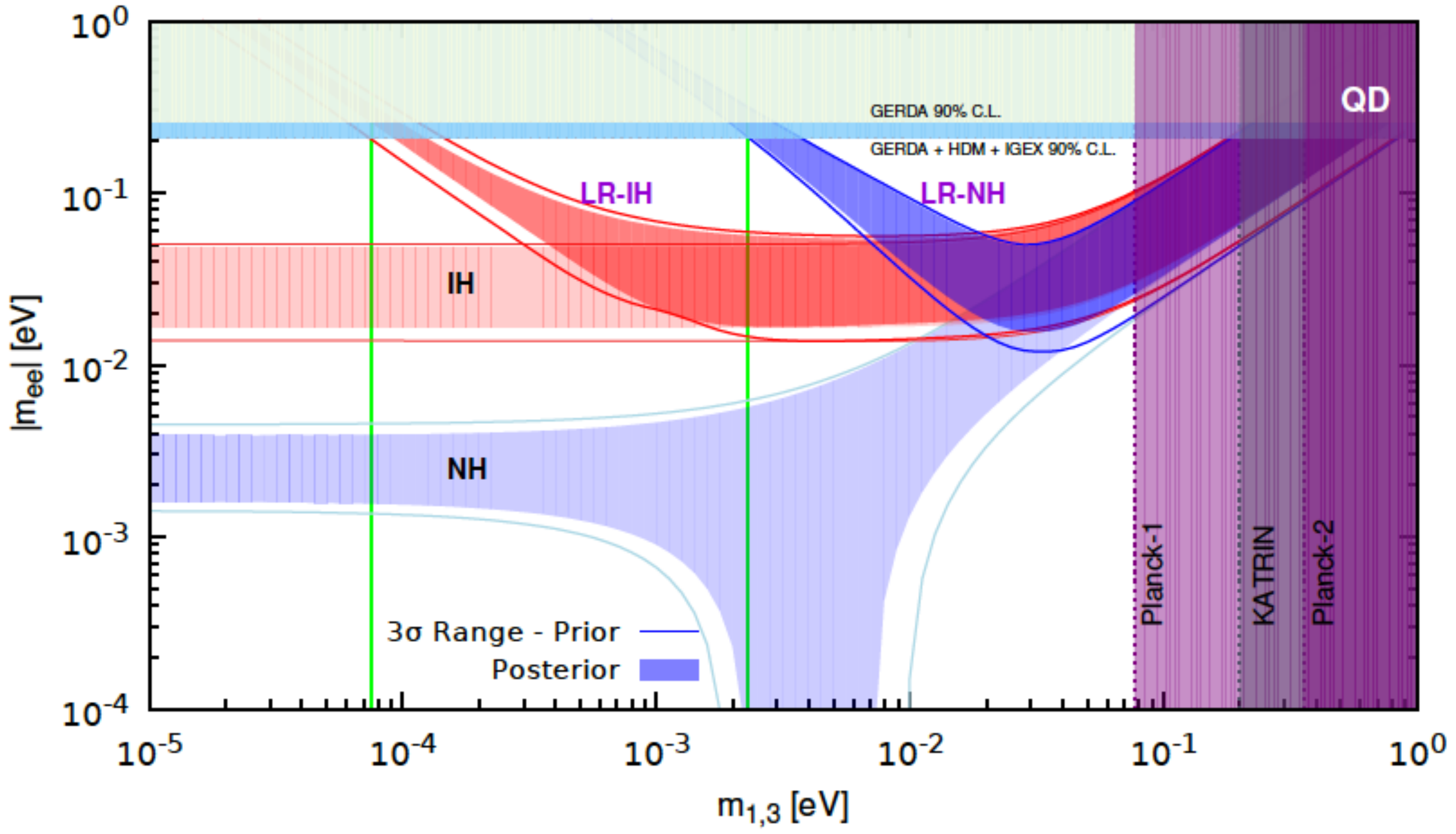



**LNV @ the TeV scale**




...

Example: LRSM with type-II seesaw

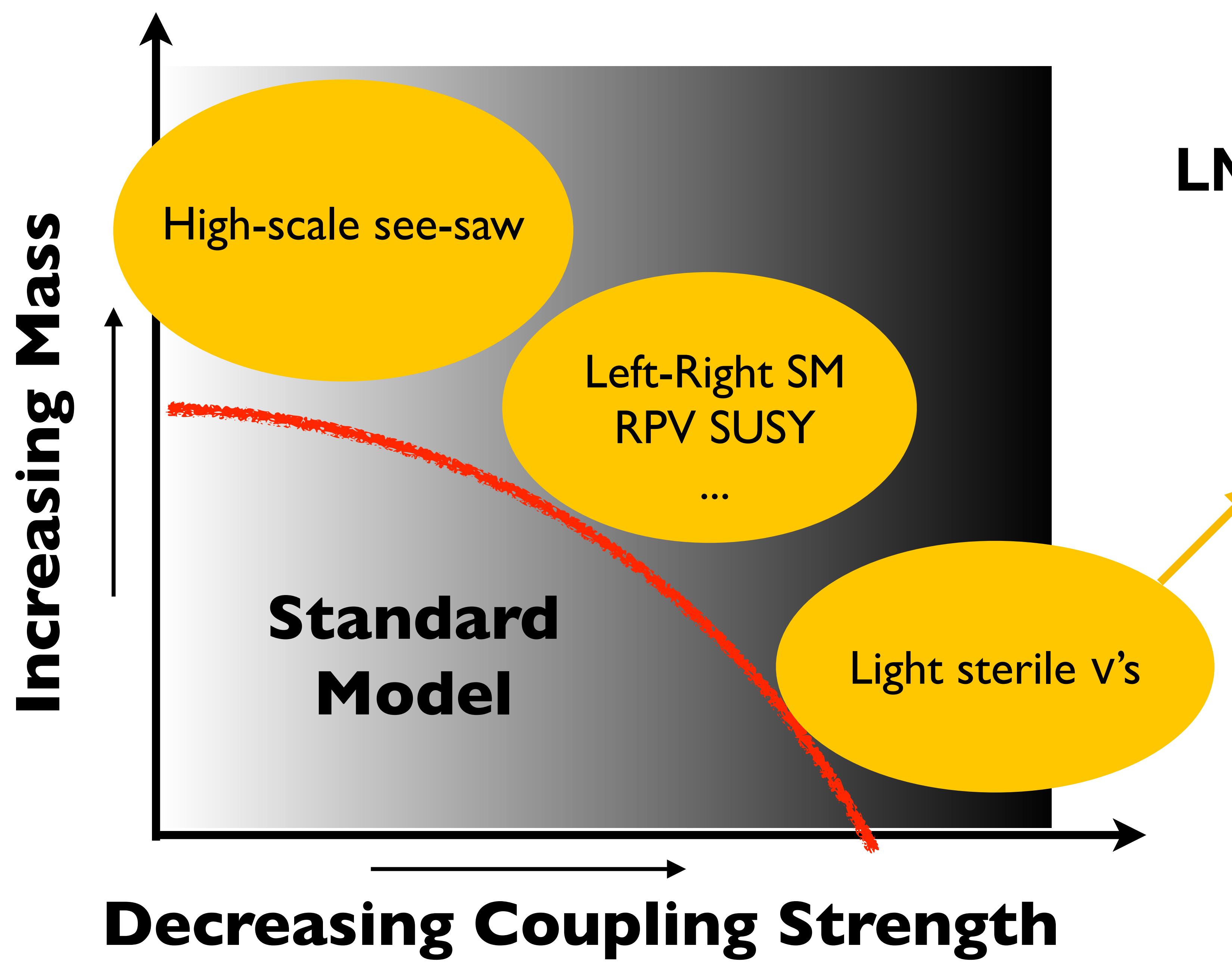



Tello-Nemevesek-Nesti-Senjanovic-Vissani 1011.3522
Ge-Lindner-Patra 1508.07286
Li, Ramsey-Musolf, Vasquez 2009.01257
...

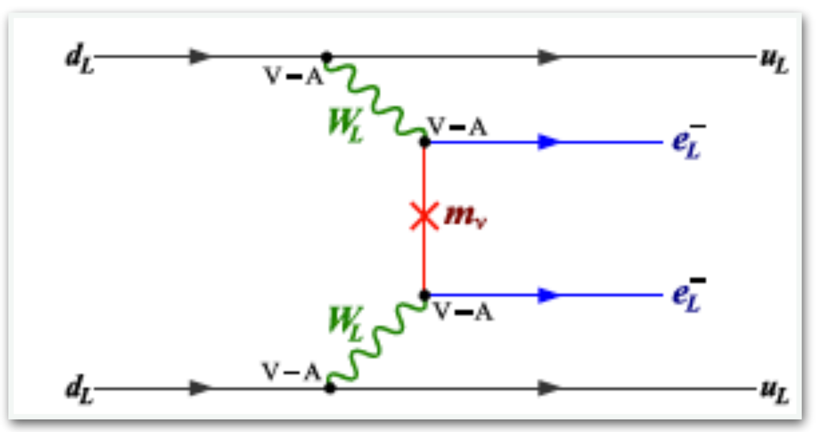
Contributions to $0\nu\beta\beta$ *not directly related to the exchange of light neutrinos:*
within reach of planned experiments & possibly correlated with signal at LHC in pp → ee jj

# 0νββ decay: broad discovery potential

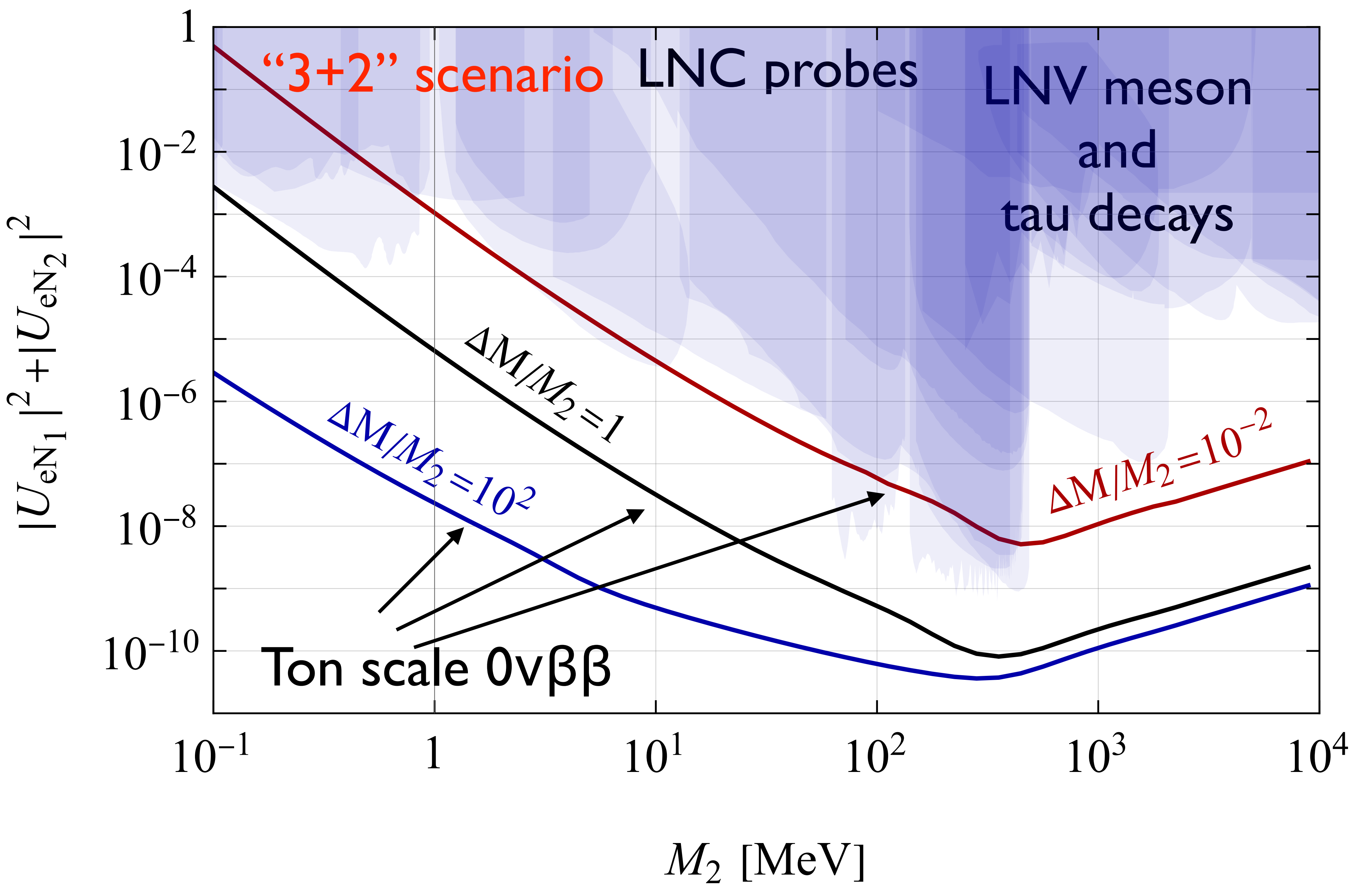
- Ton-scale 0νββ searches can discover Lepton Number Violation from a broad variety of mechanisms that involve different mass scales and interaction strengths




**LNV @ the MeV-GeV scale**



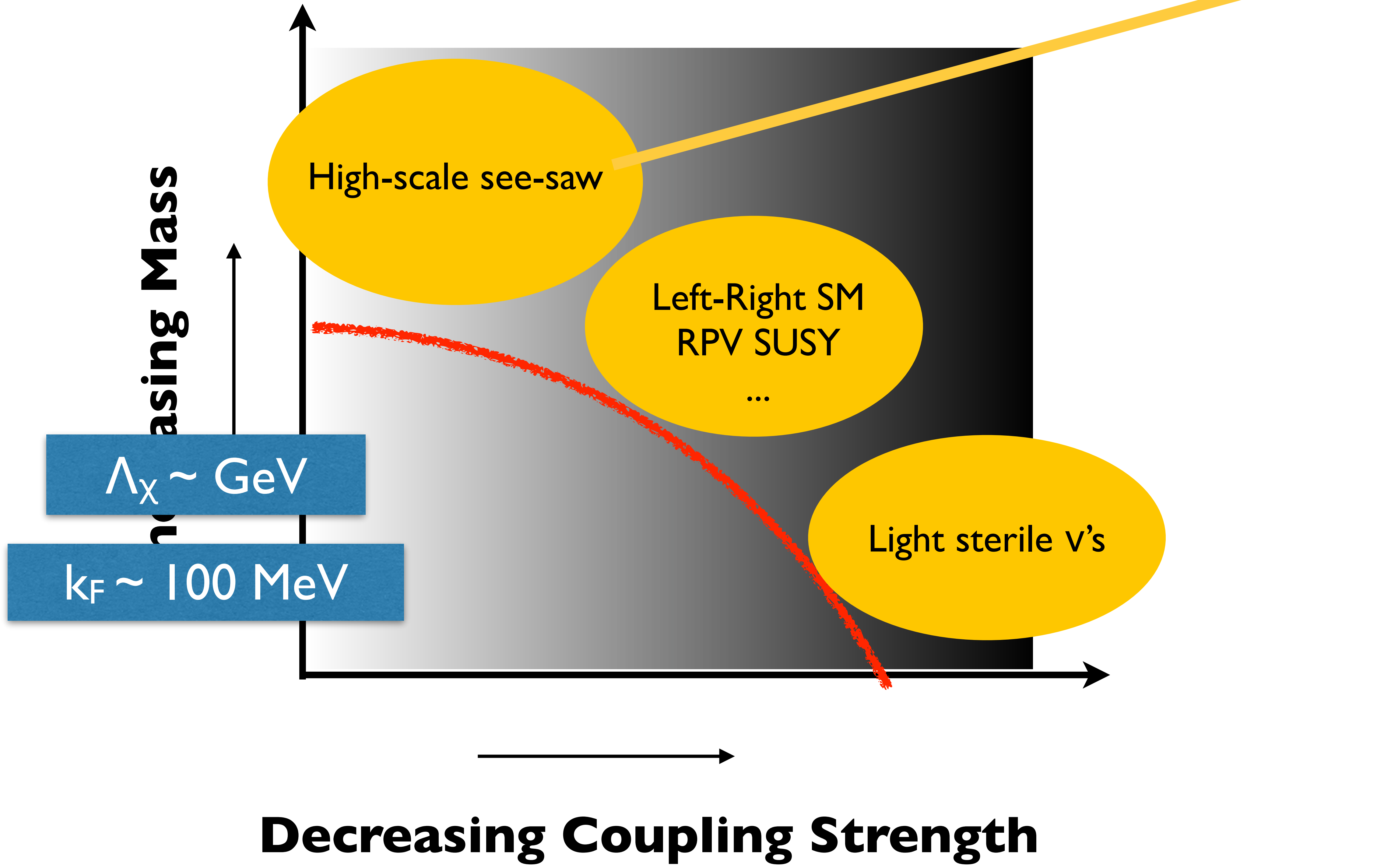
Dekens, de Vries, Mereghetti, Menendez, Soriano, 2303.04168



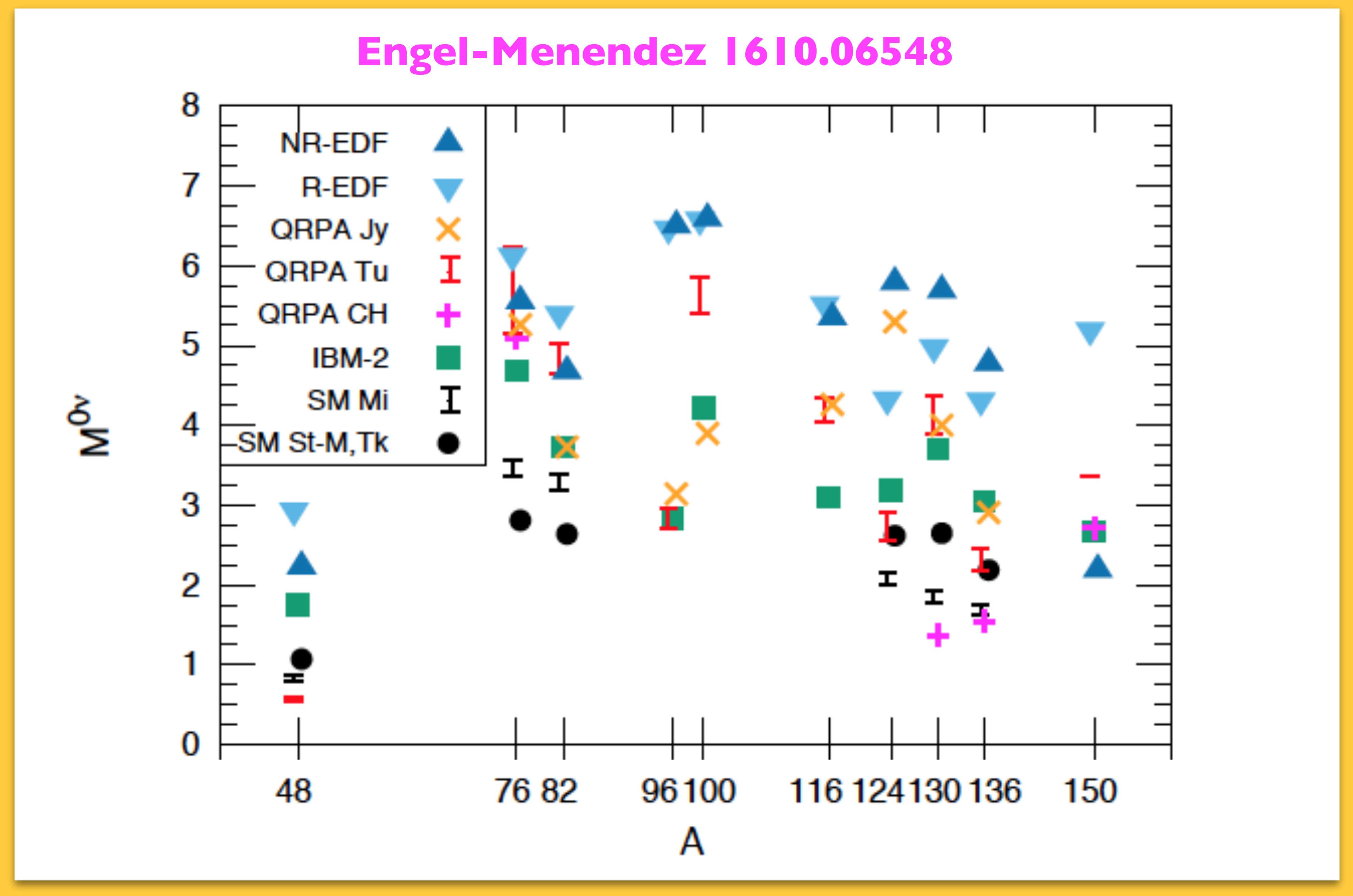

Contributions to 0νββ *not directly related to the exchange of light neutrinos:*
0νββ decay is an extremely competitive probe of $\nu_R$'s — plenty of opportunity for discovery

# 0νββ decay: theoretical challenges

- Connecting sources of LNV to nuclei is a multi-scale problem.



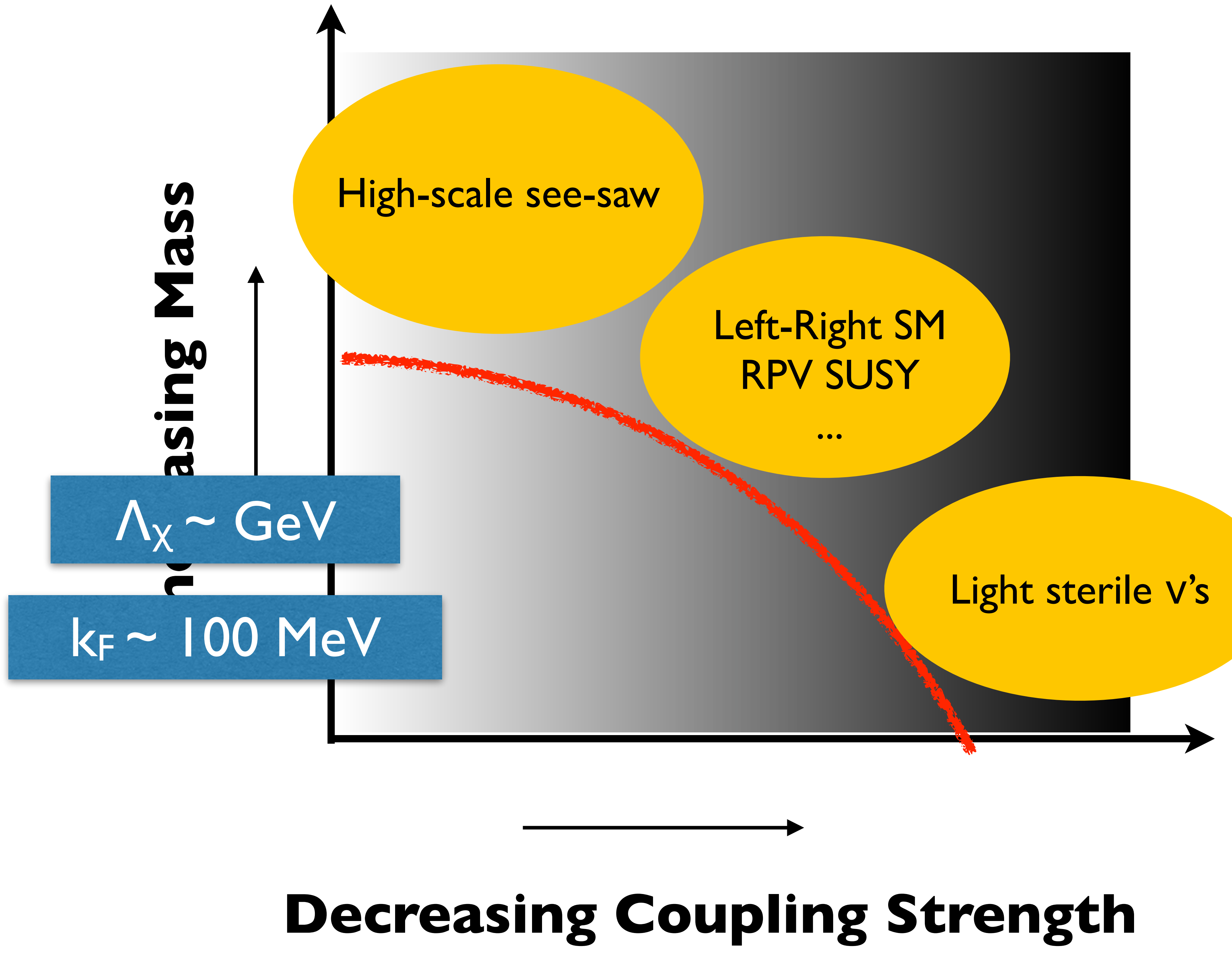

O(1) theoretical uncertainty in matrix elements hinders the interpretation of a positive or null experimental signal




$\Gamma \propto |M_{0\nu}|^2 \, (m_{\beta\beta})^2$

# $0\nu\beta\beta$ decay: theoretical challenges

- Connecting sources of LNV to nuclei is a multi-scale problem. Best tackled through a tower of EFTs** coupled to lattice QCD and ab-initio nuclear many-body calculations to achieve controlled uncertainty




** Effective Field Theory:
exploit separation of scales & use appropriate degrees of freedom at each scale

| LNV parameter | SMEFT | LEFT | Chiral EFT |
|---|---|---|---|

$$(T_{1/2})^{-1} \propto (g_{LNV})^2 \, (m_W/\Lambda)^A \, (\Lambda_\chi/m_W)^B \, (k_F/\Lambda_\chi)^C$$

White papers 2203. 21169 & 2207.01085 and refs therein

# The Standard Model

- Gauge group:

$$SU(3)_c \times SU(2)_W \times U(1)_Y$$

$$\psi'(x) = e^{ig_s \alpha_A(x) \frac{\lambda_A}{2}} \psi(x)$$

$$\psi'(x) = e^{ig' \gamma(x) Y} \psi(x)$$

$$\psi'(x) = e^{ig \beta_a(x) \frac{\sigma_a}{2}} \psi(x)$$

**Fundamental representation (color triplets and weak doublets)**

- Building blocks: gauge bosons

| | | $SU(3)_c \times SU(2)_W \times U(1)_Y$ representation |
|---|---|---|
| gluons: | $G^A_\mu\,,\quad A=1\cdots 8\,,$<br>$G^A_{\mu\nu}=\partial_\mu G^A_\nu-\partial_\nu G^A_\mu+g_s f_{ABC}G^B_\mu G^C_\nu\,.$ | (8,1,0) |
| W bosons: | $W^I_\mu\,,\quad I=1\cdots 3\,,$<br>$W^I_{\mu\nu}=\partial_\mu W^I_\nu-\partial_\nu W^I_\mu+g\varepsilon_{IJK}W^J_\mu W^K_\nu$ | (1,3,0) |
| B boson: | $B_\mu\,,$<br>$B_{\mu\nu}=\partial_\mu B_\nu-\partial_\nu B_\mu\,.$ | (1,1,0) |

Gauge transformation:

$$W^I_{\mu\nu}\frac{\sigma^I}{2}\longrightarrow V(x)\left[W^I_{\mu\nu}\frac{\sigma^I}{2}\right]V^\dagger(x)$$

$$V(x)\;=\;e^{ig\beta_a(x)\frac{\sigma_a}{2}}$$

- Building blocks: fermions and Higgs

$$\psi = \begin{pmatrix} q \\ \ell \\ u \\ d \\ e \end{pmatrix}$$

| | $SU(3)_c \times SU(2)_W \times U(1)_Y$ representation: (dim[$SU(3)_c$], dim[$SU(2)_W$], Y) | $SU(2)_W$ transformation |
|---|---|---|
| $l = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | (1,2,-1/2) | $l \to V_{SU(2)}\, l$ |
| $e = e_R$ | (1,1,-1) | |
| $q^i = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix}$ | (3,2,1/6) | $q \to V_{SU(2)}\, q$ |
| $u^i = u^i_R$ | (3,1,2/3) | |
| $d^i = d^i_R$ | (3,1,-1/3) | |
| $\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$ | (1,2,1/2) | $\varphi \to V_{SU(2)}\, \varphi$ |

$$\tilde{\varphi} = \epsilon\, \varphi^* = \begin{pmatrix} \varphi^{0*} \\ -\varphi^- \end{pmatrix} \qquad (1,2,-1/2) \qquad \tilde{\varphi} \to V_{SU(2)}\, \tilde{\varphi}$$

$\epsilon = i\sigma_2$

**Left- and right-handed fermions have different gauge charges**

- The SM Lagrangian: all operators of dimension $\leq 4$ that respect gauge and Lorentz symmetry

Homework: work out mass dimension of fields

- Spinor: $[\Psi]=3/2$
- Scalar and vector: $[\phi] = [V_\mu] = 1$

- The SM Lagrangian: all operators of dimension ≤ 4 that respect gauge and Lorentz symmetry

$$\mathcal{L}_{SM} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

$$D_\mu = I\,\partial_\mu - i g_s \frac{\lambda^A}{2} G_\mu^A - i g \frac{\sigma^a}{2} W_\mu^a - i g' Y B_\mu$$

$$\boxed{\begin{aligned}\mathcal{L}_{\text{Gauge}} &= -\frac{1}{4} G_{\mu\nu}^A G^{A\mu\nu} - \frac{1}{4} W_{\mu\nu}^I W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\ &+ \sum_{i=1,2,3} \left( i\bar{\ell}_i \not{D} \ell_i + i\bar{e}_i \not{D} e_i + i\bar{q}_i \not{D} q_i + i\bar{u}_i \not{D} u_i + i\bar{d}_i \not{D} d_i \right)\end{aligned}}$$

- The SM Lagrangian: all operators of dimension ≤ 4 that respect gauge and Lorentz symmetry

$$\boxed{\mathcal{L}_{SM} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}}$$

$$D_\mu = I\,\partial_\mu - ig_s \frac{\lambda^A}{2} G^A_\mu - ig\frac{\sigma^a}{2} W^a_\mu - ig' Y B_\mu$$

$$\boxed{\begin{aligned}\mathcal{L}_{\text{Gauge}} &= -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\ &+ \sum_{i=1,2,3} \left( i\bar{\ell}_i \not{D} \ell_i + i\bar{e}_i \not{D} e_i + i\bar{q}_i \not{D} q_i + i\bar{u}_i \not{D} u_i + i\bar{d}_i \not{D} d_i \right)\end{aligned}}$$

U(3) for each gauge multiplet, e. g. $q_i \to M_{ij} q_j$, $M \in U(3)$

No notion of "flavor": three identical copies

- The SM Lagrangian: all operators of dimension ≤ 4 that respect gauge and Lorentz symmetry

$$\mathcal{L}_{SM} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

$$D_\mu = I\,\partial_\mu - ig_s\frac{\lambda^A}{2}G^A_\mu - ig\frac{\sigma^a}{2}W^a_\mu - ig'YB_\mu$$

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$+ \sum_{i=1,2,3}\left(i\bar{\ell}_i \not{D}\ell_i + i\bar{e}_i \not{D}e_i + i\bar{q}_i \not{D}q_i + i\bar{u}_i \not{D}u_i + i\bar{d}_i \not{D}d_i\right)$$

$$\mathcal{L}_{\text{Higgs}} = (D_\mu\varphi)^\dagger(D^\mu\varphi) - \lambda(\varphi^\dagger\varphi - v^2)^2 \xrightarrow{\text{EWSB}}$$

$$\langle\varphi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\langle\tilde{\varphi}\rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$$\tilde{\varphi} = \epsilon\,\varphi^*$$

- The SM Lagrangian: all operators of dimension ≤ 4 that respect gauge and Lorentz symmetry

$$\mathcal{L}_{SM} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

$$D_\mu = I\,\partial_\mu - i g_s \frac{\lambda^A}{2} G^A_\mu - i g \frac{\sigma^a}{2} W^a_\mu - i g' Y B_\mu$$

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$+ \sum_{i=1,2,3} \left( i\bar{\ell}_i \not{D} \ell_i + i\bar{e}_i \not{D} e_i + i\bar{q}_i \not{D} q_i + i\bar{u}_i \not{D} u_i + i\bar{d}_i \not{D} d_i \right)$$

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \varphi)^\dagger (D^\mu \varphi) - \lambda(\varphi^\dagger \varphi - v^2)^2 \xrightarrow{\text{EWSB}} \langle \varphi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \langle \tilde{\varphi} \rangle = \begin{pmatrix} v \\ 0 \end{pmatrix} \quad \tilde{\varphi} = \epsilon\, \varphi^*$$

$$\mathcal{L}_{\text{Yukawa}} = \bar{\ell}\, Y_e\, e \varphi + \bar{q}\, Y_d\, d \varphi + \bar{q}\, Y_u\, u \tilde{\varphi} + \text{h.c.}$$

U(3)[5] symmetry broken by Yukawa couplings $Y_{e,u,d}$ : flavor physics & fermion masses

# Fermion masses in the SM

$$\mathcal{L}_{\text{Yukawa}} = \bar{e}_L Y_e e_R \left( v + \frac{h}{\sqrt{2}} \right) + \bar{d}_L Y_d d_R \left( v + \frac{h}{\sqrt{2}} \right) + \bar{u}_L Y_u u_R \left( v + \frac{h}{\sqrt{2}} \right) + \text{h.c.}$$

$$\varphi = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix}$$

- Fermion mass matrices diagonalized by bi-unitary transformation

$$Y_f = V_{f_L}^\dagger \, Y_f^{\text{diag}} \, V_{f_R} \qquad f = e, d, u \qquad \longrightarrow \qquad m_{f,i} = v \left( Y_f^{\text{diag}} \right)_{ii}$$

- Higgs coupling to fermions is flavor-diagonal and proportional to mass

$$\boxed{\mathcal{L}_{\text{Yukawa}} = \sum_{f=e,d,u} m_f \bar{f} f \left( 1 + \frac{h}{\sqrt{2} v} \right)} \qquad f = f_L + f_R$$