National Nuclear Physics Summer School 2026
University of Washington, Seattle, June 29- July 11 2026

Fundamental Symmetries (Theory)

Vincenzo Cirigliano
University of Washington

INSTITUTE for NUCLEAR THEORY

U.S. DEPARTMENT OF ENERGY
Office of Science

UNIVERSITY of WASHINGTON

National Nuclear Physics Summer School 2026
University of Washington, Seattle, June 29- July 11 2026

Low energy probes of physics beyond the Standard Model (1)

Vincenzo Cirigliano
University of Washington

U.S. DEPARTMENT OF ENERGY
Office of Science

INSTITUTE for NUCLEAR THEORY

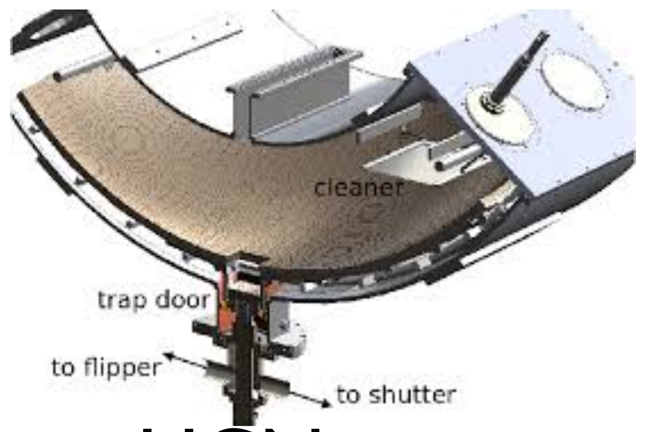
UNIVERSITY of WASHINGTON

Goal of these lectures

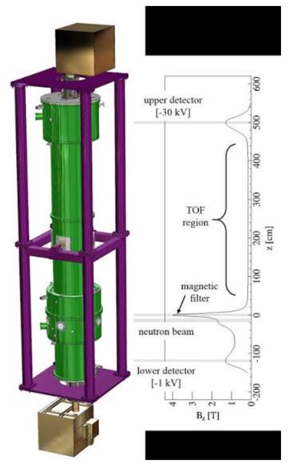
Provide a theoretical introduction to the ‘BSM frontier’ of nuclear science

Search for new phenomena beyond the Standard Model through precision tests or the study of rare processes *at low energy*

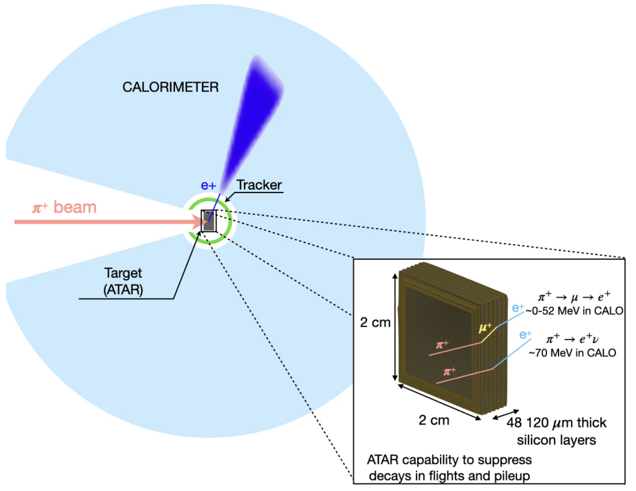
Through a variety of probes: leptons, mesons, nucleons, nuclei, atoms, molecules, …



UCNτ

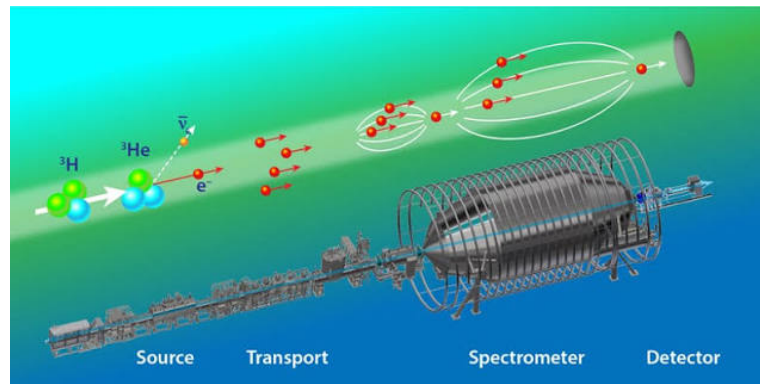


Nab

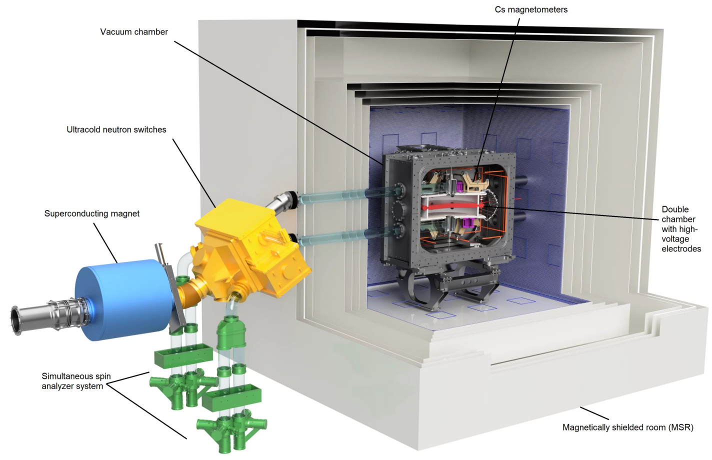


PIONEER

muon g-2

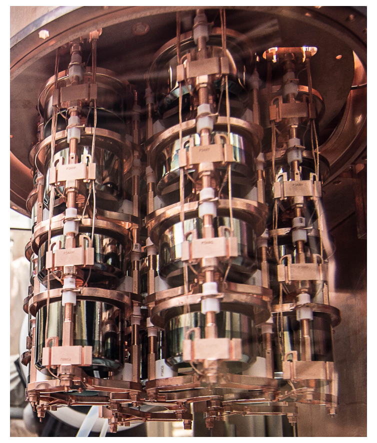


KATRIN

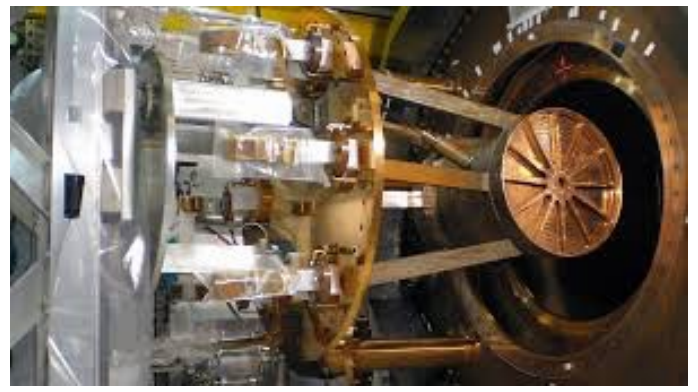


n2EDM

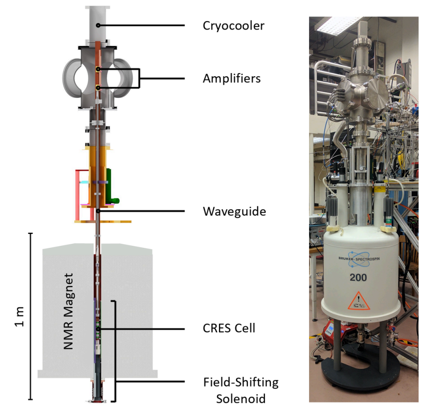
GERDA



Majorana



EXO 200



Project 8

…

Flow of the lectures

- The quest for new physics at the low-energy frontier: overview of *questions* and *probes*

- How does the precision / intensity frontier work?
  - Basics & example from history: the making of the Standard Model
  - The Standard Model and its symmetries
  - BSM effective field theory (EFT) framework

Flow of the lectures

- The quest for new physics at the low-energy frontier: overview of *questions* and *probes*

- How does the precision / intensity frontier work?
  - Basics & example from history: the making of the Standard Model
  - The Standard Model and its symmetries
  - BSM effective field theory (EFT) framework

- “Zoom in” on selected low-energy probes: illustrate methods and impact
  - Search for symmetry violation
    - Neutrinos mass and symmetries: Lepton Number and Lepton Flavor Violation
    - CP-violation and permanent Electric Dipole Moments
  - Precision tests
    - Weak charged current (β decays), neutral current (parity-violating e-scattering), muon g-2

Flow of the lectures

- The quest for new physics at the low-energy frontier: overview of *questions* and *probes*

- How does the precision / intensity frontier work?
    - Basics & example from history: the making of the Standard Model
    - The Standard Model and its symmetries
    - BSM effective field theory (EFT) framework

Lecture 1

- "Zoom in" on selected low-energy probes: illustrate methods and impact
    - Search for symmetry violation
        - Neutrinos mass and symmetries: Lepton Number and Lepton Flavor Violation

Lecture 2

        - CP-violation and permanent Electric Dipole Moments
    - Precision tests
        - Weak charged current (β decays), neutral current (parity-violating e-scattering), muon g-2

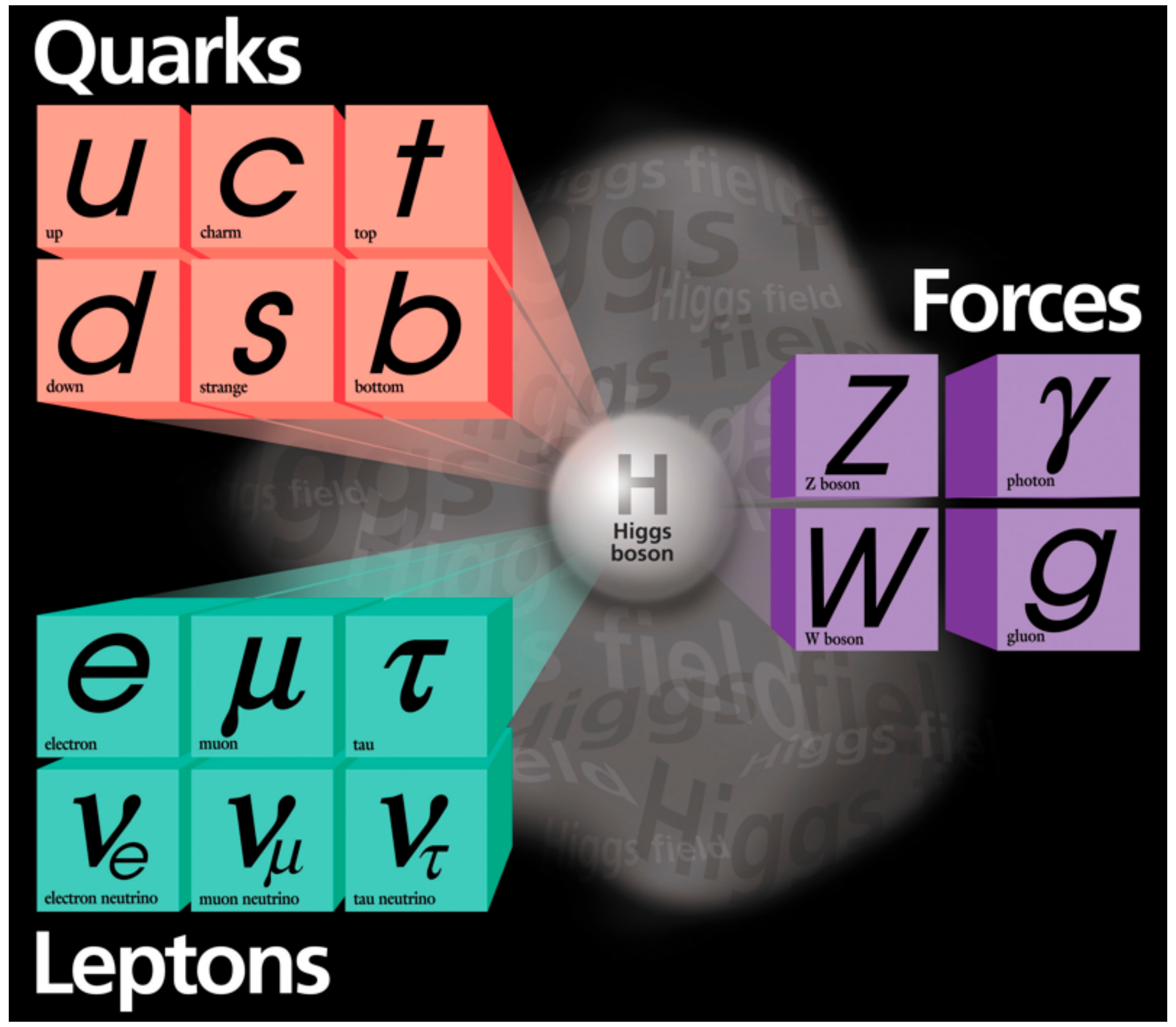
Lecture 3

The quest for new physics at the low energy frontier

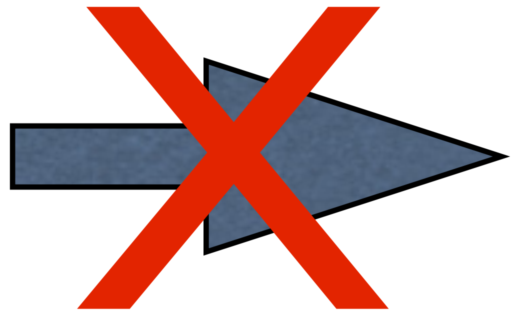
New physics: why?

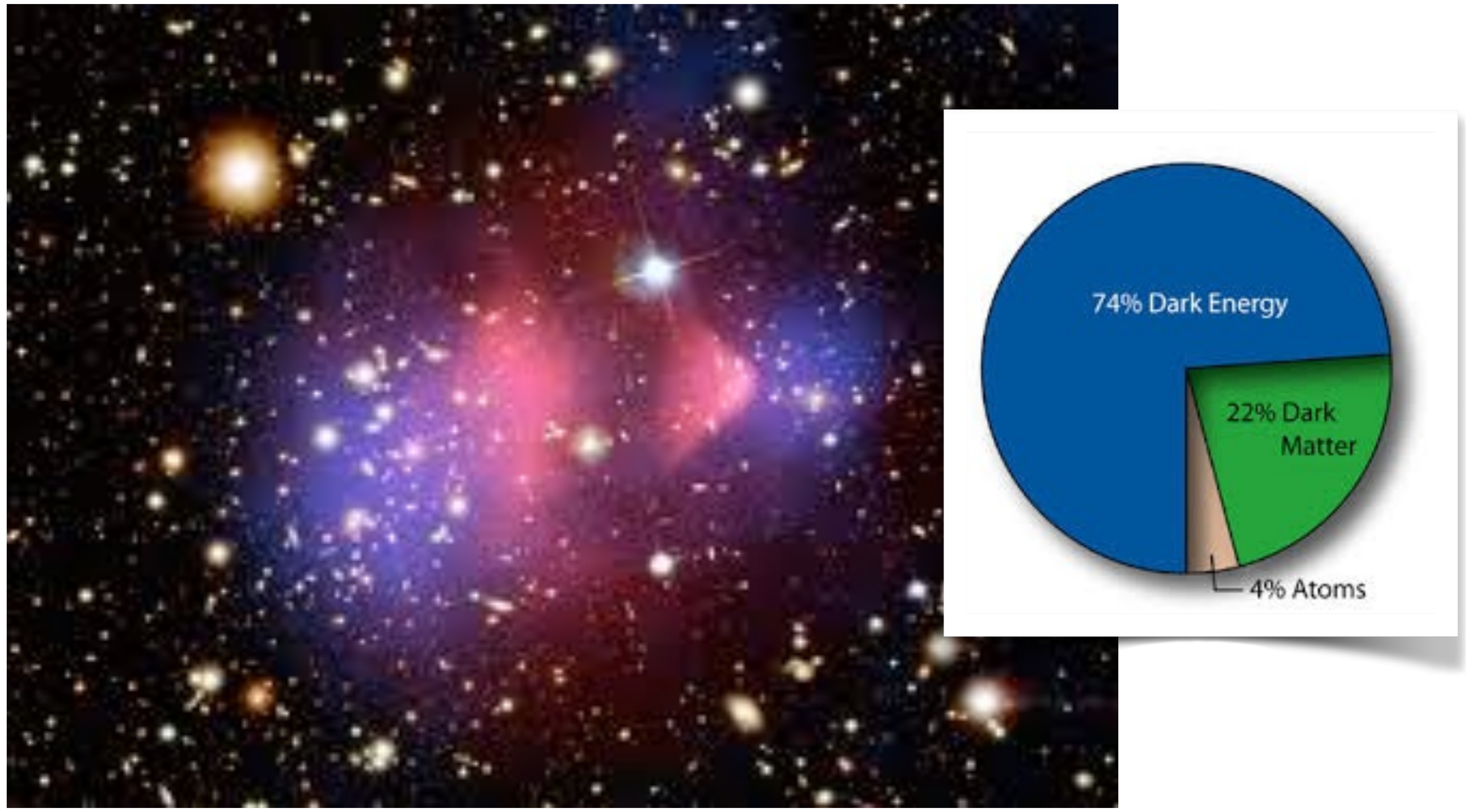
The Standard Model encodes our knowledge of nature's building blocks and interactions (up to gravity)

but it's at best incomplete …



Credit: Fermilab





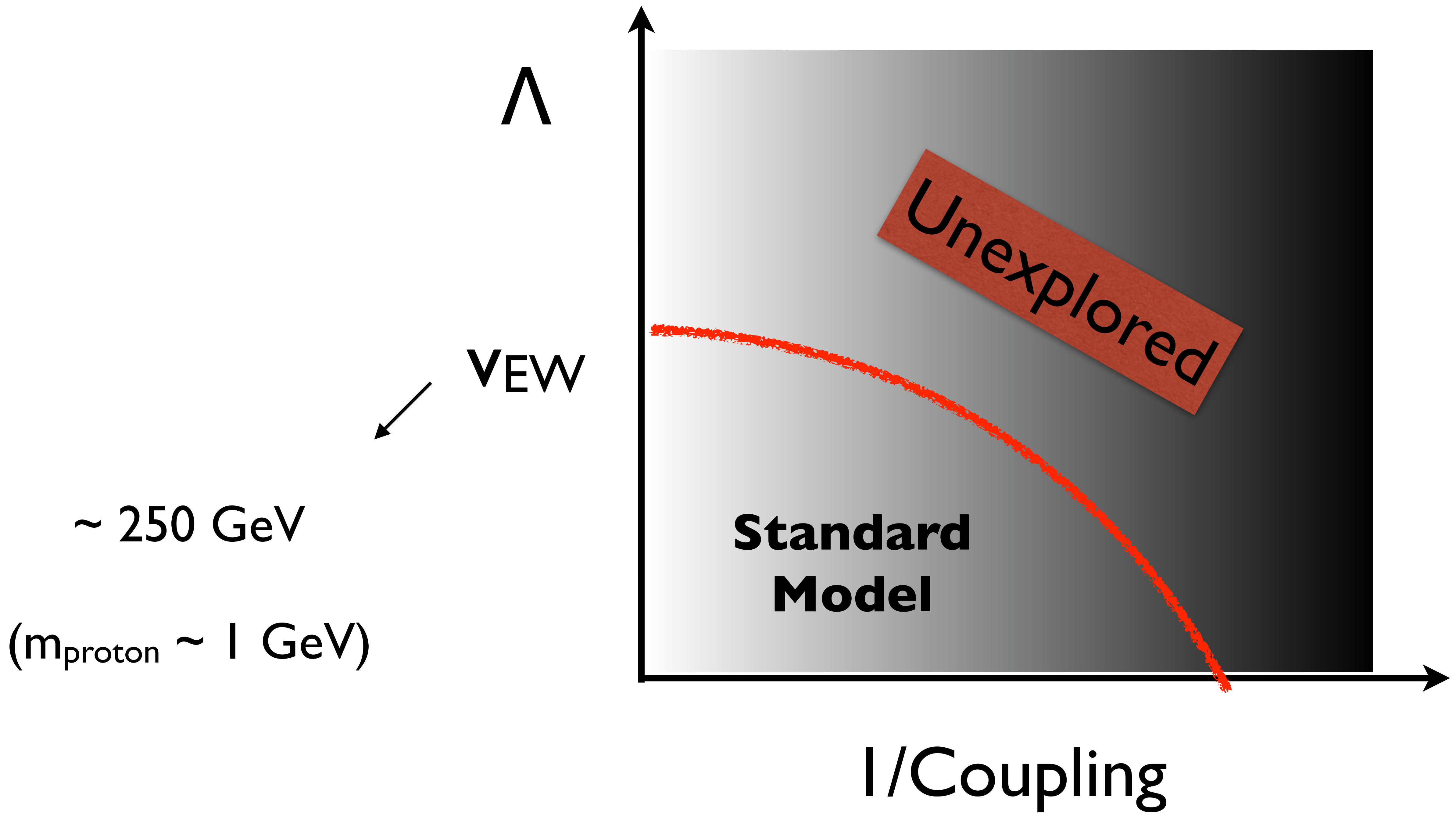
Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/ D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

No Neutrino Mass, no Baryon Asymmetry, no Dark Matter, no Dark Energy
Origin of families, Strong CP problem, Unification,…

Addressing these shortcomings & puzzles requires new physics

New physics: where?

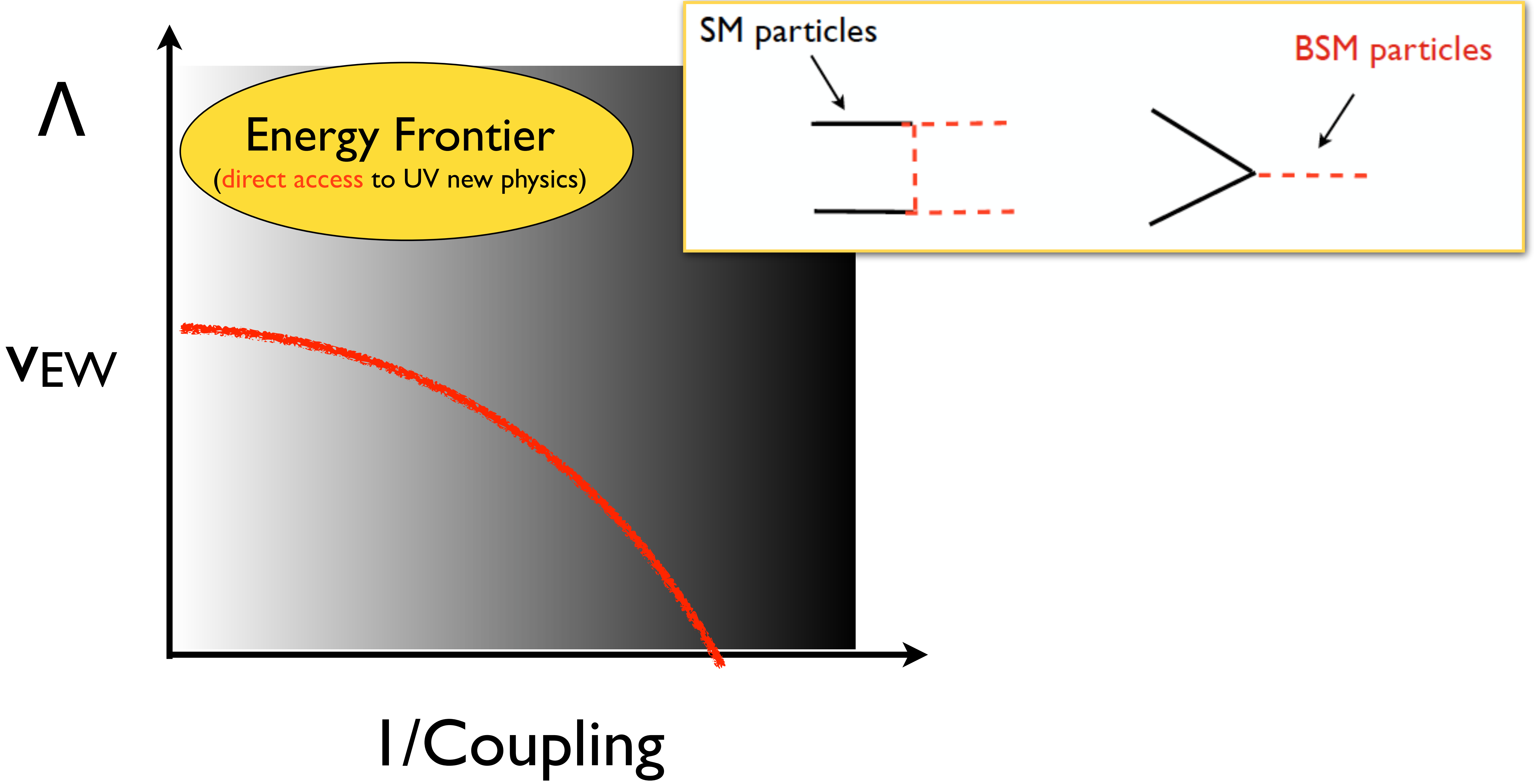
- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?



New physics: how?

- Two complementary paths to search for new physics

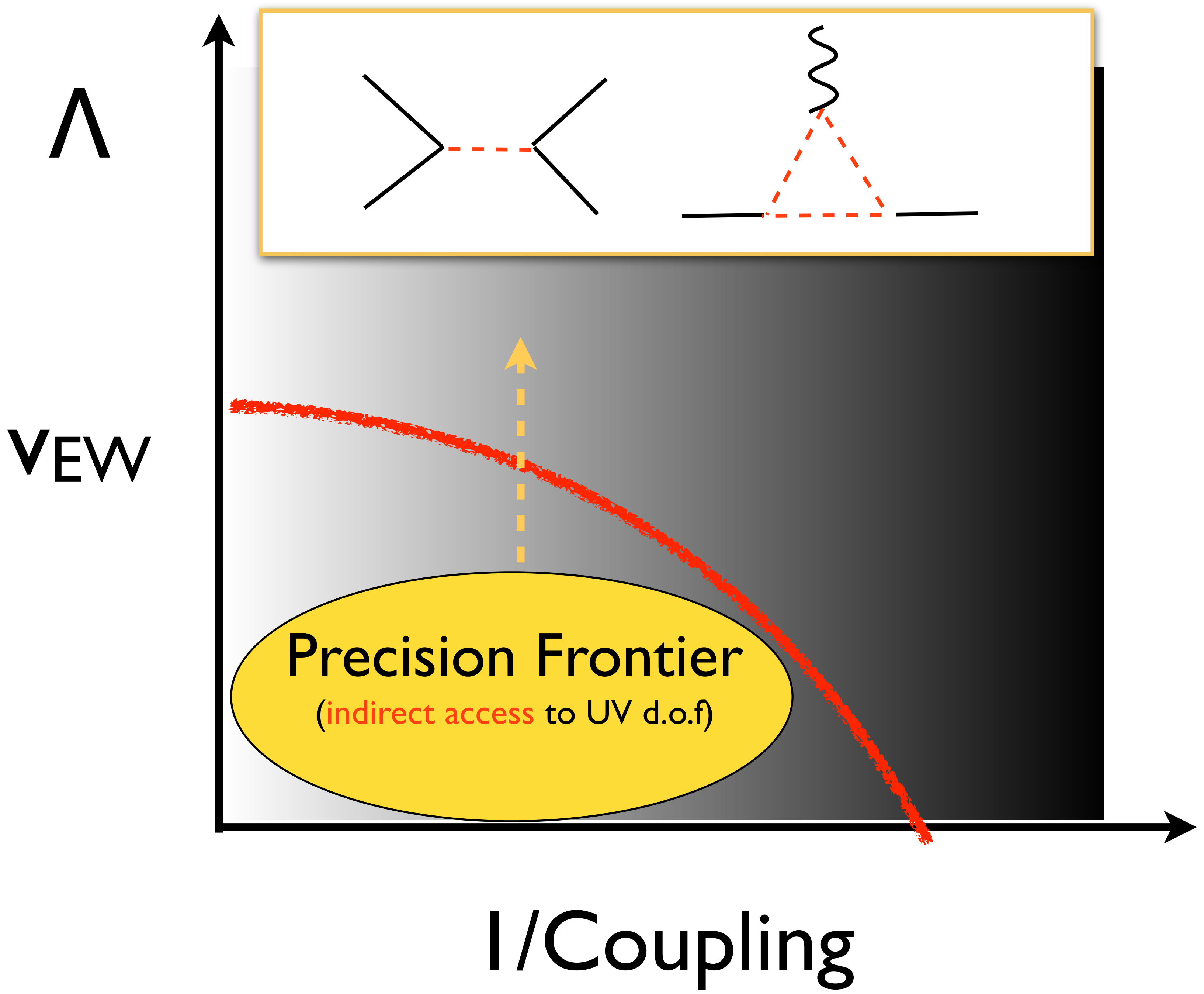
$$E = mc^2$$

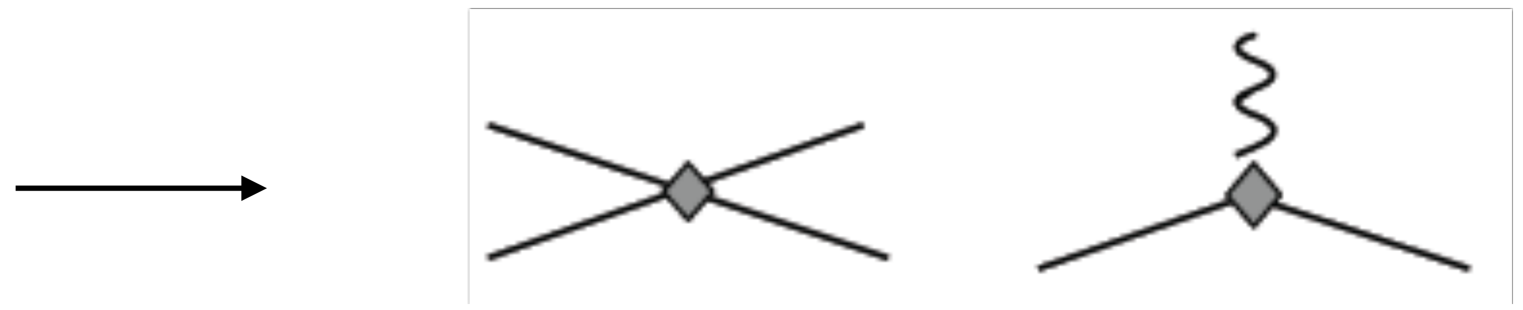


New physics: how?

- Two complementary paths to search for new physics

$$\Delta E\, \Delta t \sim h$$

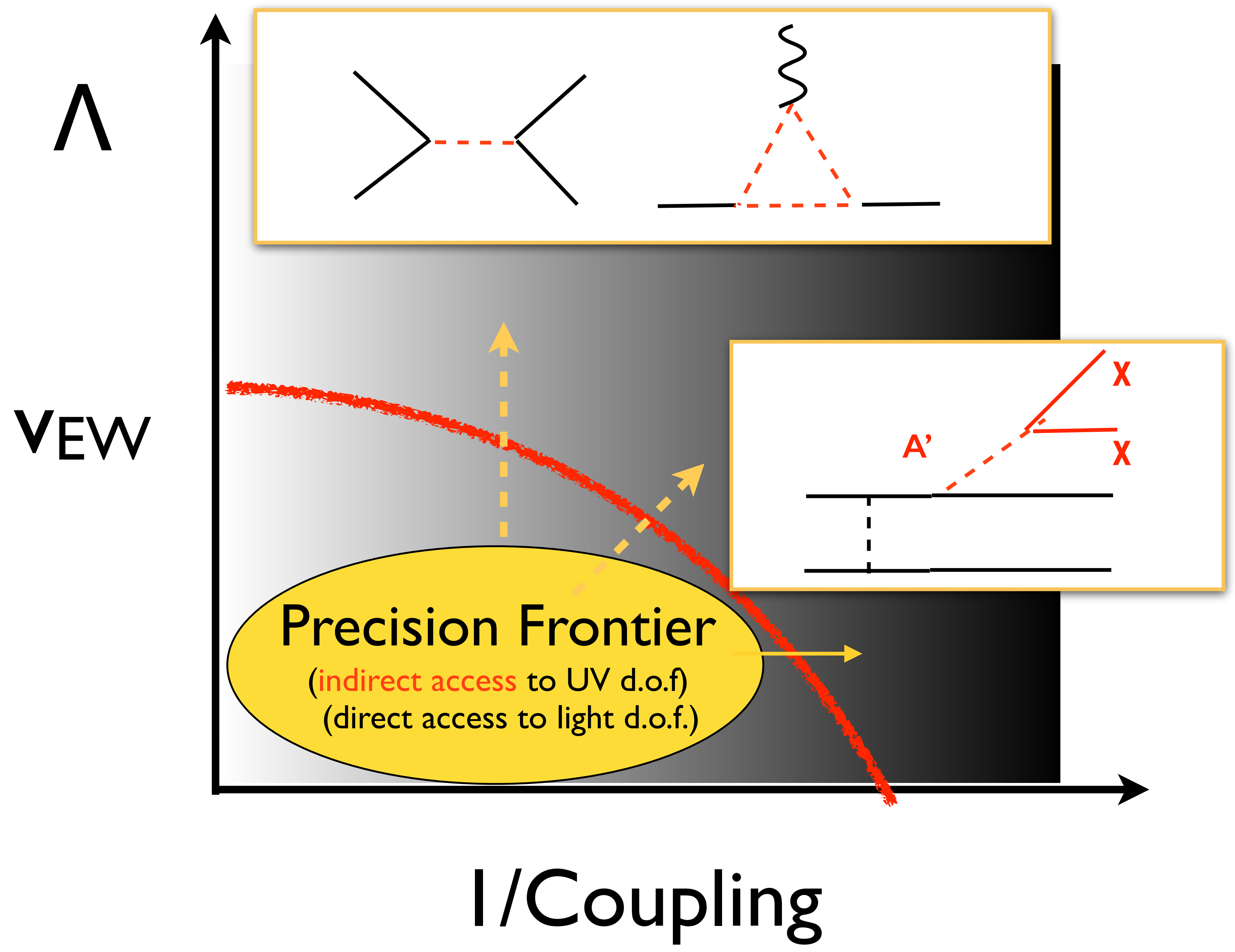




Imprints of heavy BSM physics: new local interactions suppressed by inverse powers of mass

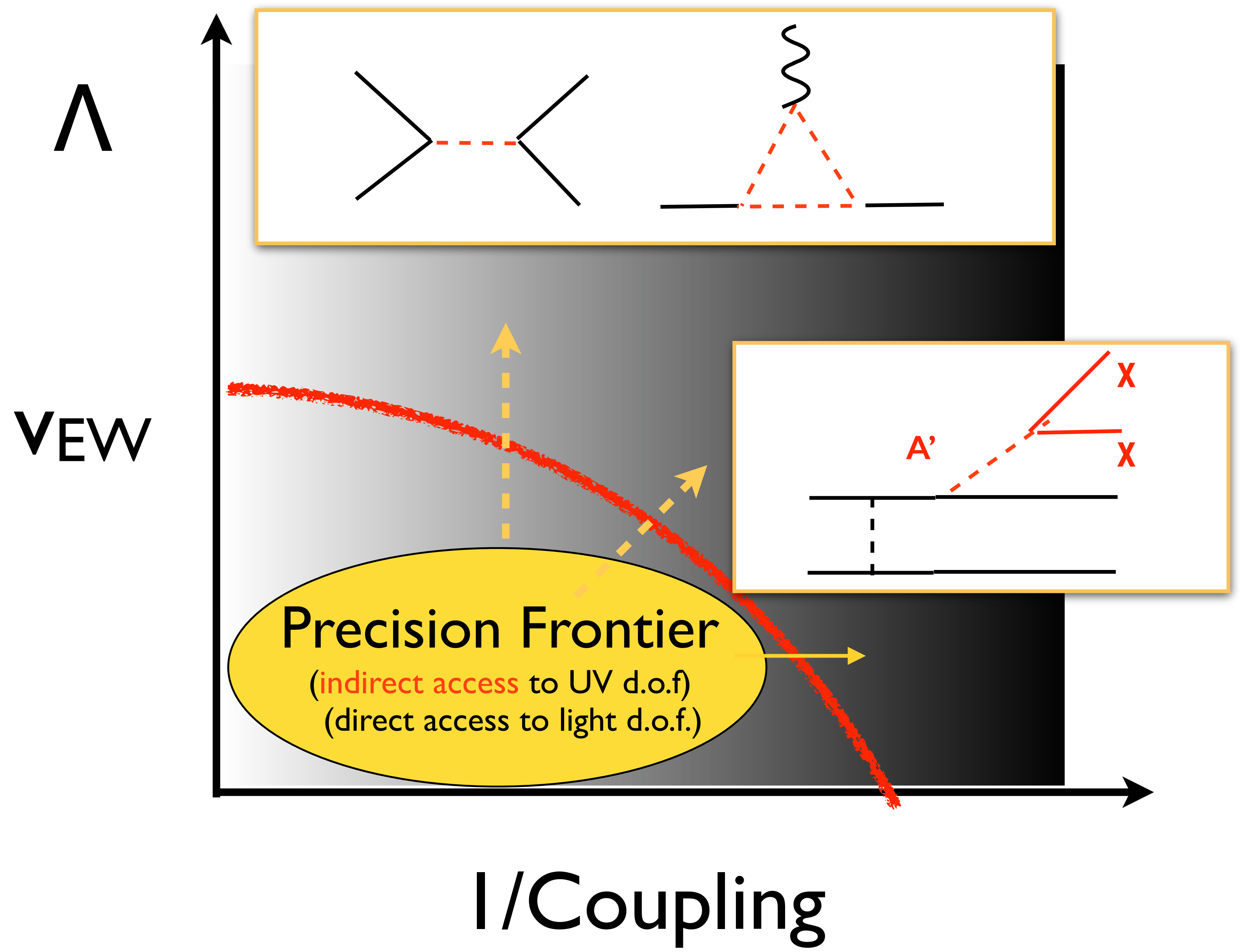
New physics: how?

- Two complementary paths to search for new physics



New physics: how?

- Two complementary paths to search for new physics

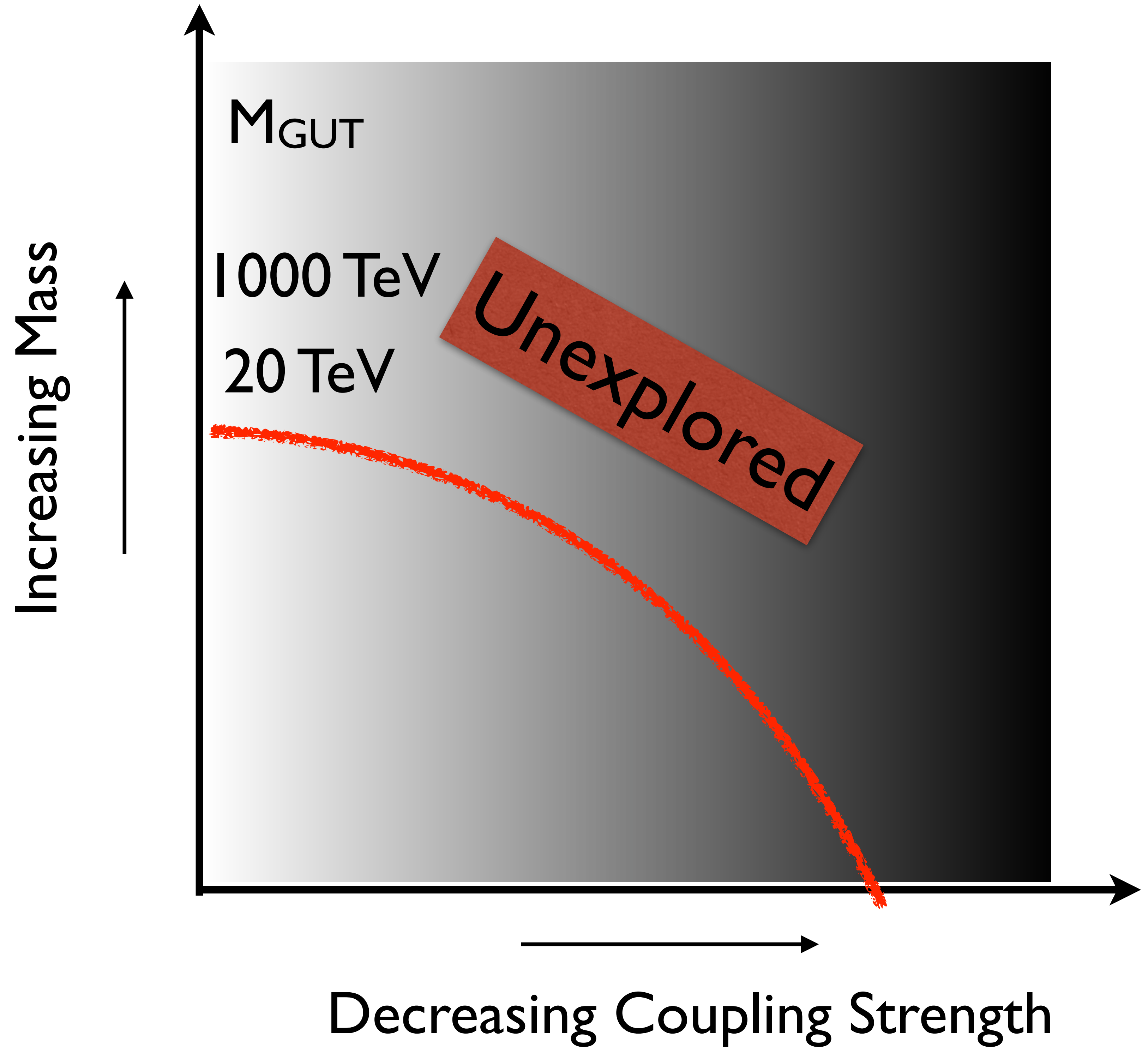


- Both frontiers needed to probe the particle content & symmetries of $\mathcal{L}_{BSM}$ and address the open questions

The Precision Frontier cuts across AMO, HEP & NP

Three classes of low-E & nuclear probes

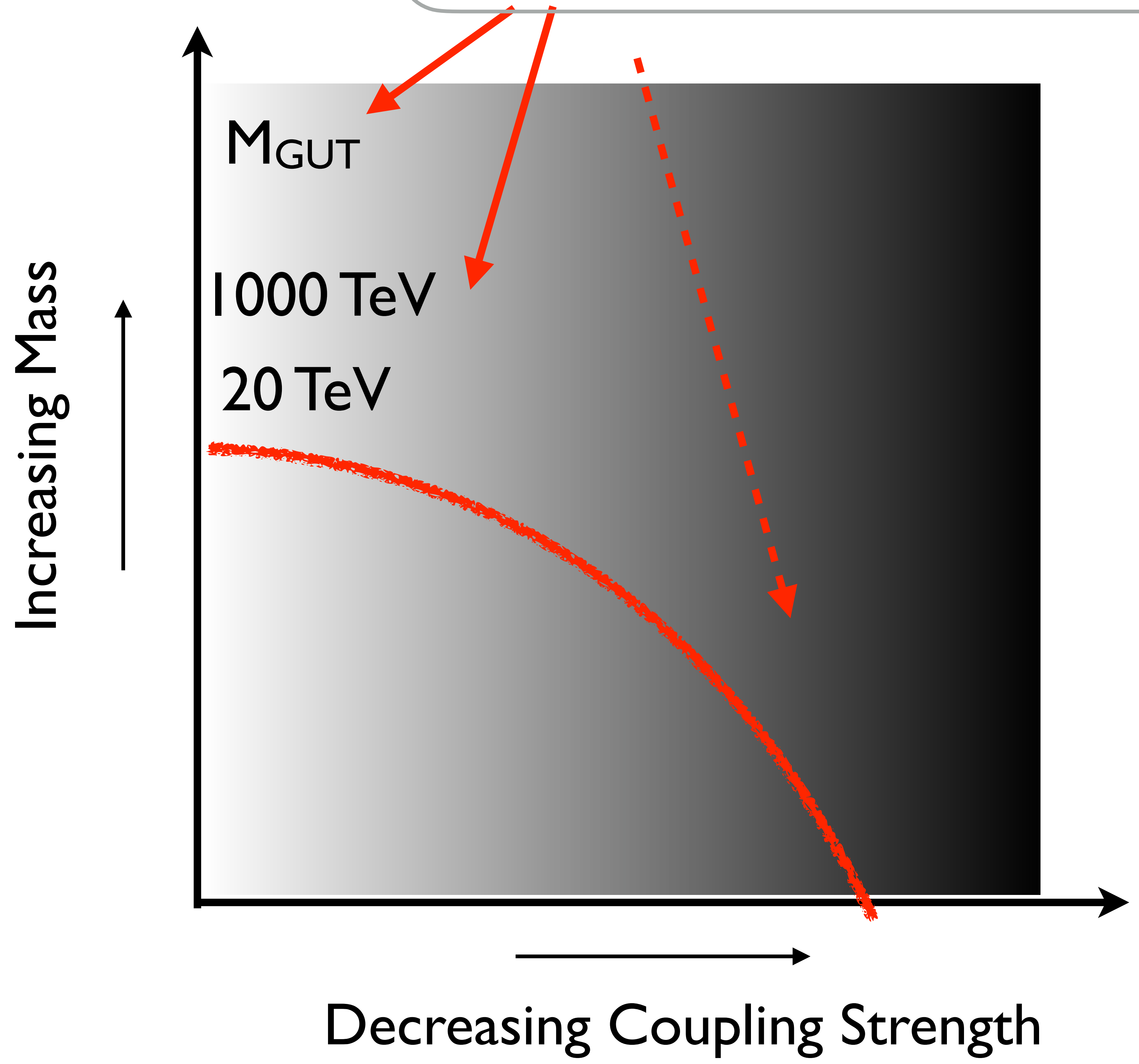
- Exploring new physics at high mass or weak coupling in qualitatively different ways



Three classes of low-E & nuclear probes

- Exploring new physics at high mass or weak coupling in qualitatively different ways

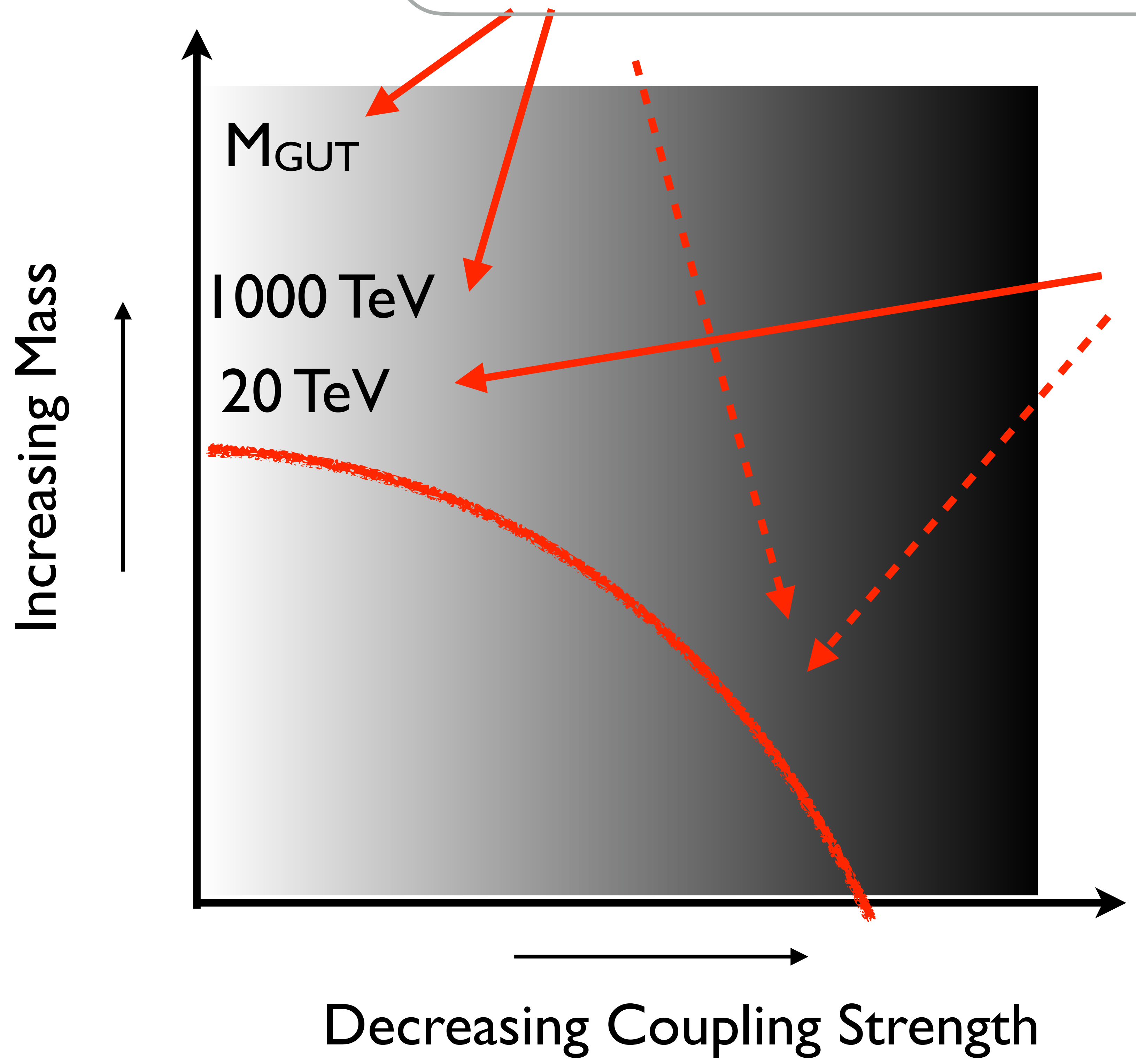
1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_α): $0\nu\beta\beta$ decay, proton decay, n-nbar, EDMs, LFV ($\mu \to e$ conversion, $ep \to \tau X$, …),
…
High scale physics, neutrino mass mechanism, Sakharov conditions for baryogengesis



Three classes of low-E & nuclear probes

- Exploring new physics at high mass or weak coupling in qualitatively different ways

1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_α): $0\nu\beta\beta$ decay, proton decay, n-nbar, EDMs, LFV ($\mu \to e$ conversion, $ep \to \tau X$, …),
…
High scale physics, neutrino mass mechanism, Sakharov conditions for baryogengesis

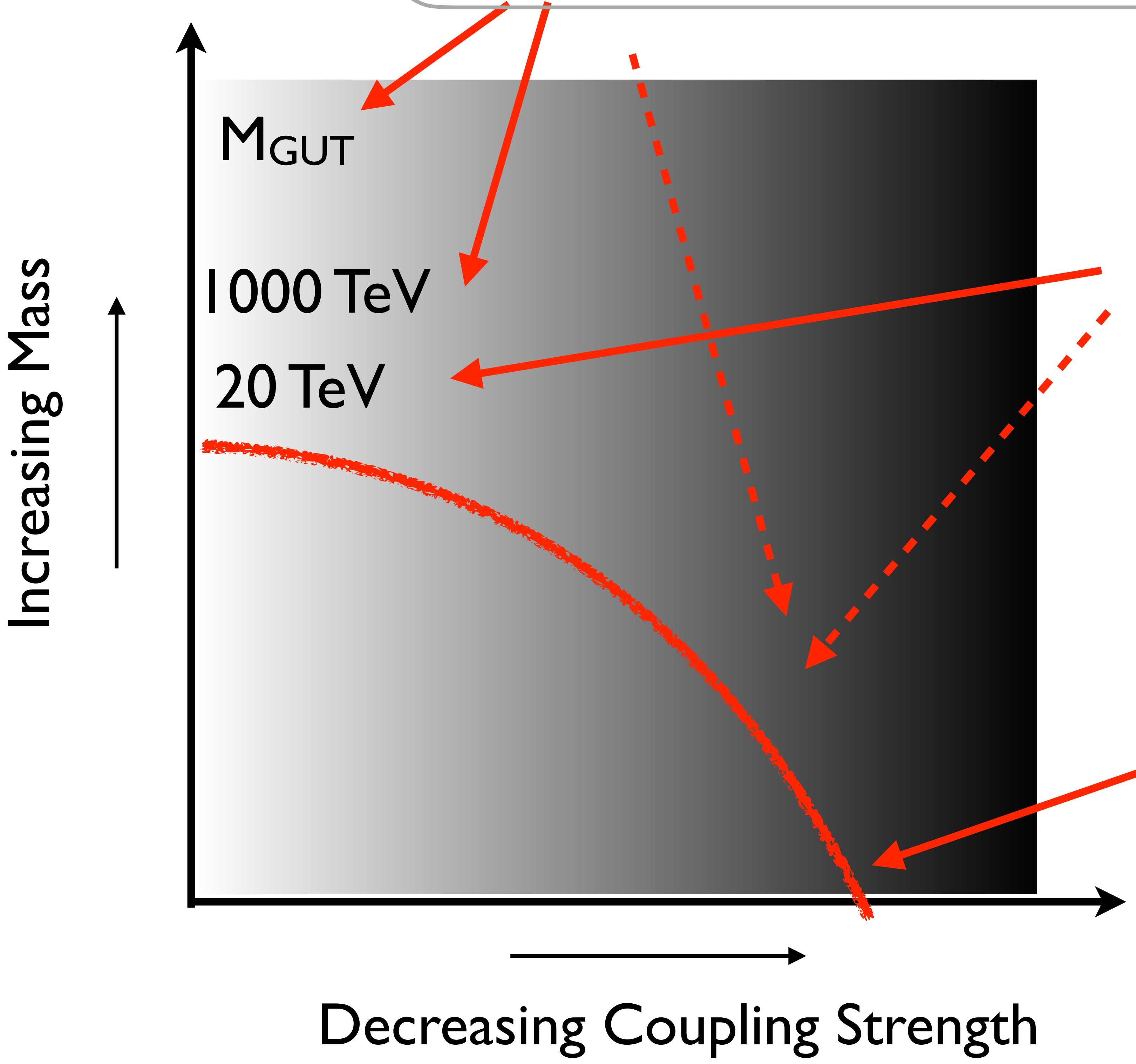


2. Precision tests of SM-allowed processes:
β-decays (mesons, neutron, nuclei), PV electron scattering, muon g-2,
…
Footprints of multi-TeV force mediators & light mediators

Three classes of low-E & nuclear probes

- Exploring new physics at high mass or weak coupling in qualitatively different ways

1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_α): $0\nu\beta\beta$ decay, proton decay, n-nbar, EDMs, LFV ($\mu \to e$ conversion, $ep \to \tau X$, …), …
High scale physics, neutrino mass mechanism, Sakharov conditions for baryogengesis



2. Precision tests of SM-allowed processes:
β-decays (mesons, neutron, nuclei), PV electron scattering, muon g-2, …
Footprints of multi-TeV force mediators & light mediators

3. Searches / characterization of light and weakly coupled particles:
active ν's, sterile ν's, dark sector particles and mediators, axions, …
Neutrino properties, dark matter & dark sectors

Impact of low-energy probes

- Discovery potential
  - Explore physics that is otherwise difficult / impossible to access: high mass scale; symmetry breaking; ultralight particles
  - A single deviation from SM expectation → new physics!

- Diagnosing power when combining multiple probes
  - $0\nu\beta\beta$ decay, absolute ν mass measurements, ν oscillations, LFV ($\mu\to e$, $e \to\tau$, …) → origin of neutrino mass
  - Multiple EDM searches → underlying sources of CP violation
  - Low-E precision tests (+ collider) → identify possible new force mediators

- Connection to open questions

Shedding light on open questions

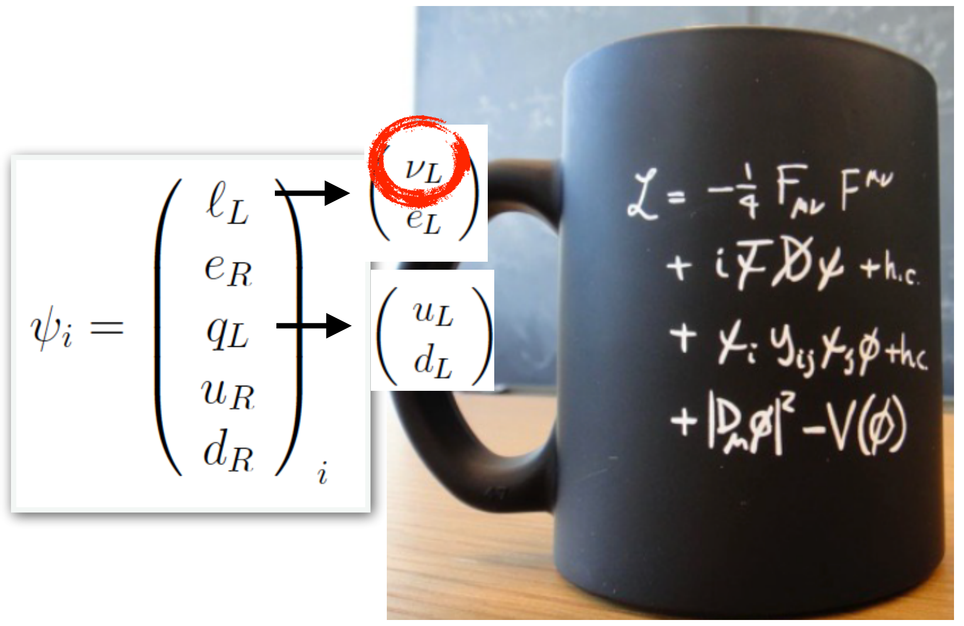
Low-energy probes of BSM physics cluster around four inter-connected questions

Shedding light on open questions

Low-energy probes of BSM physics cluster around four inter-connected questions

Origin of neutrino mass

The Standard Model



?

Dirac

Majorana

No neutrino mass

Shedding light on open questions

Low-energy probes of BSM physics cluster around four inter-connected questions

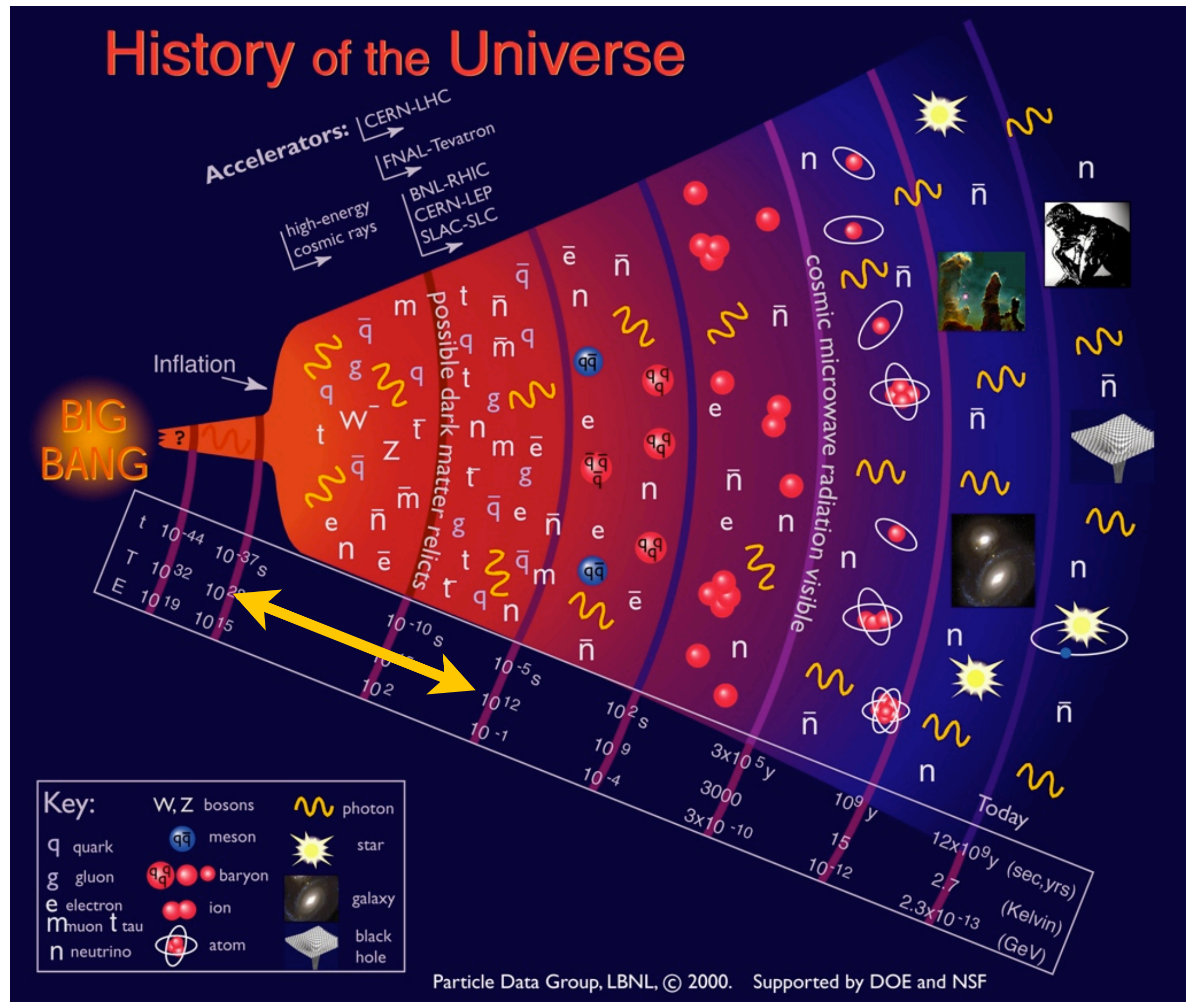
Origin of neutrino mass

Baryon asymmetry
(violation of B, L, CP)

Baryogenesis requires (Sakharov)

- B (L) violation
- C and CP violation
- Departure from equilibrium

Baryogenesis does not work in the Standard Model

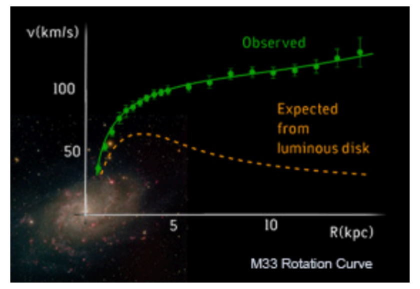


Shedding light on open questions

Low-energy probes of BSM physics cluster around four inter-connected questions

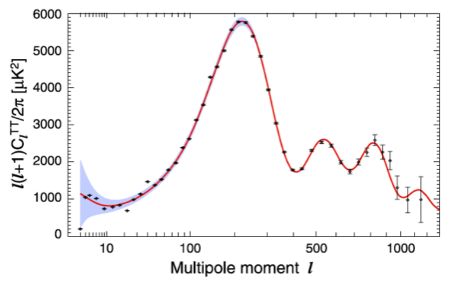
Origin of neutrino mass

Baryon asymmetry
(violation of B, L, CP)

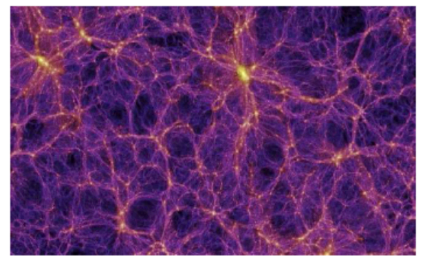


rotation curves

gravitational lensing + X-ray obs



CMB anisotropy



structure formation

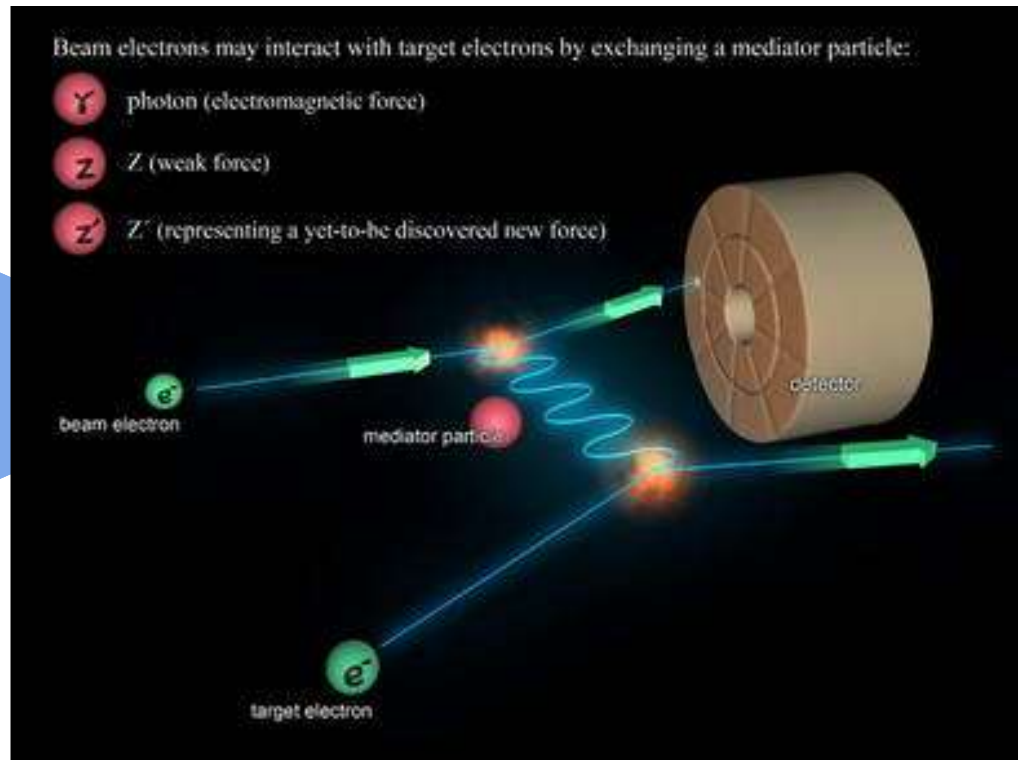
Nature of dark matter
Light & weakly interacting particles

Shedding light on open questions

Low-energy probes of BSM physics cluster around four inter-connected questions

Origin of neutrino mass

Baryon asymmetry
(violation of B, L, CP)



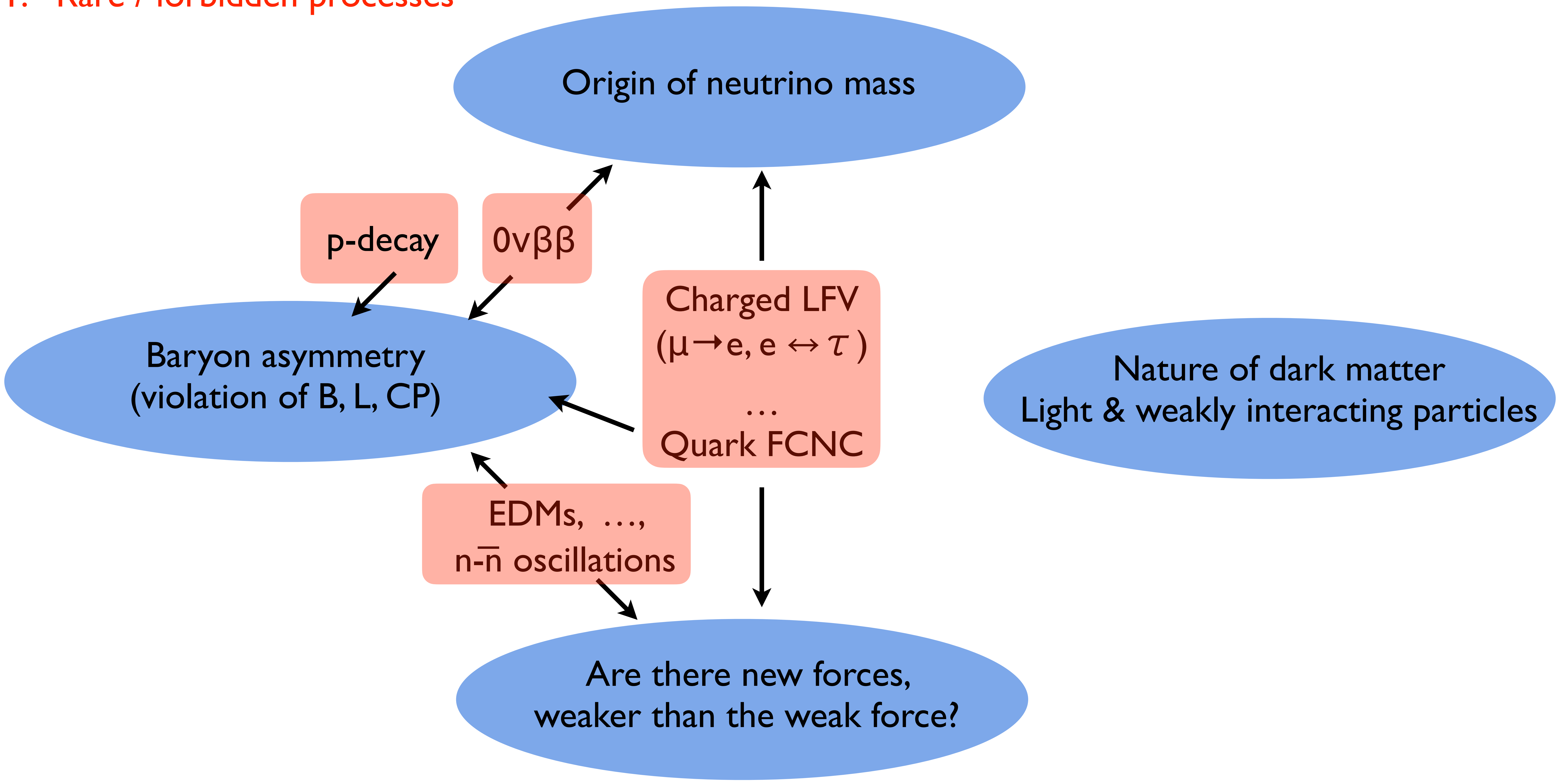
Nature of dark matter
Light & weakly interacting particles

Are there new forces,
weaker than the weak force?

Shedding light on open questions

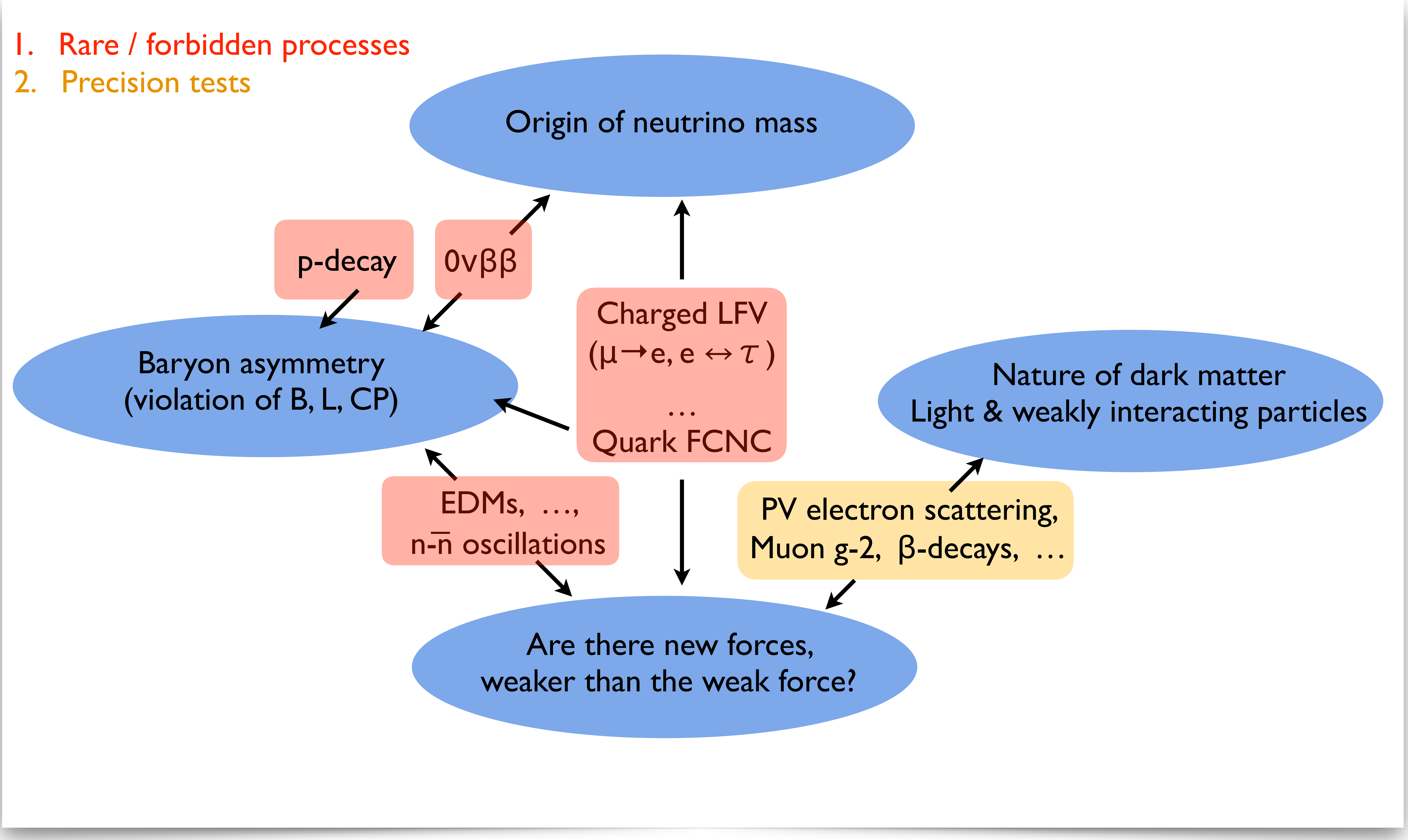
Low-energy probes of BSM physics cluster around four inter-connected questions

1. Rare / forbidden processes



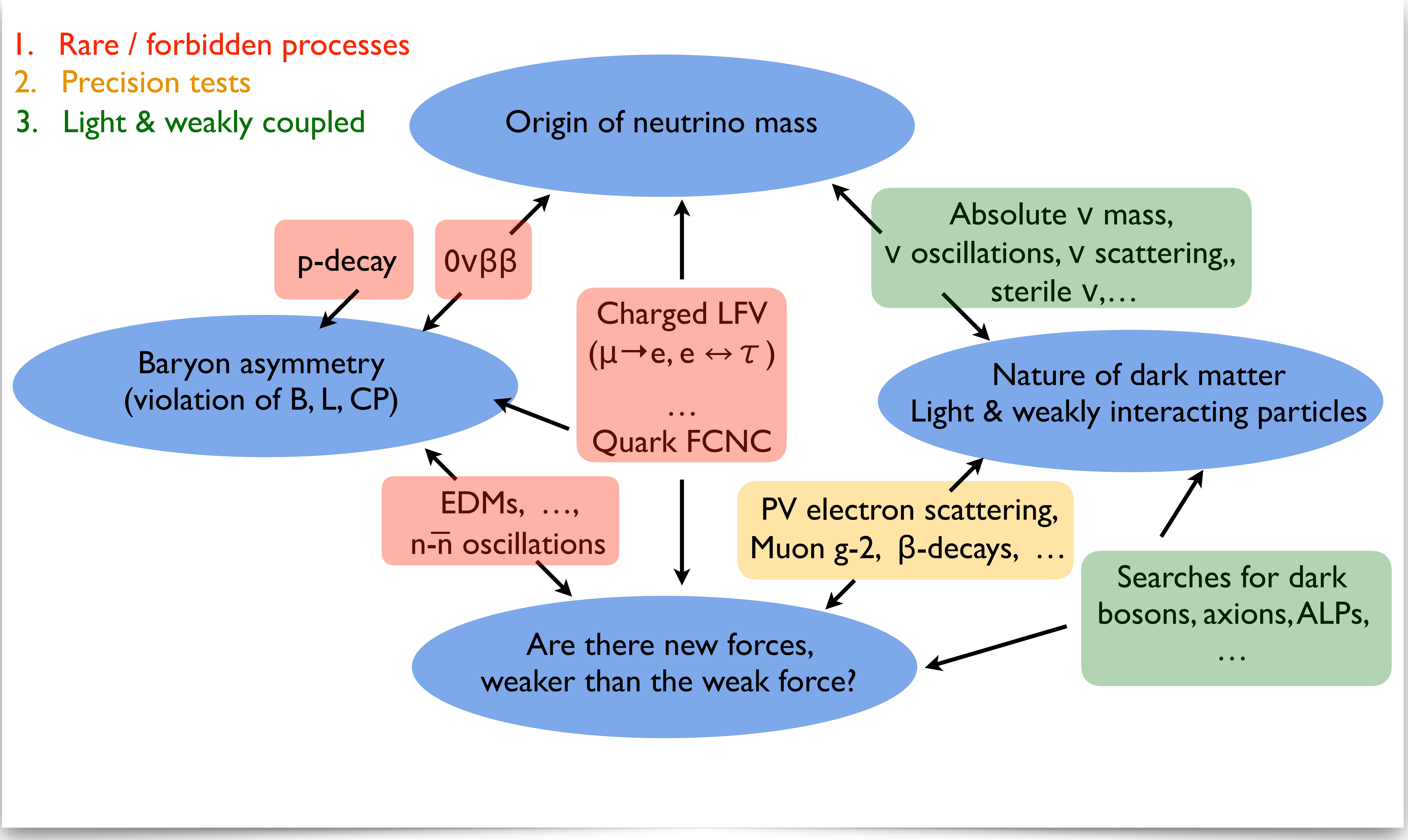
Shedding light on open questions

Low-energy probes of BSM physics cluster around four inter-connected questions



Shedding light on open questions

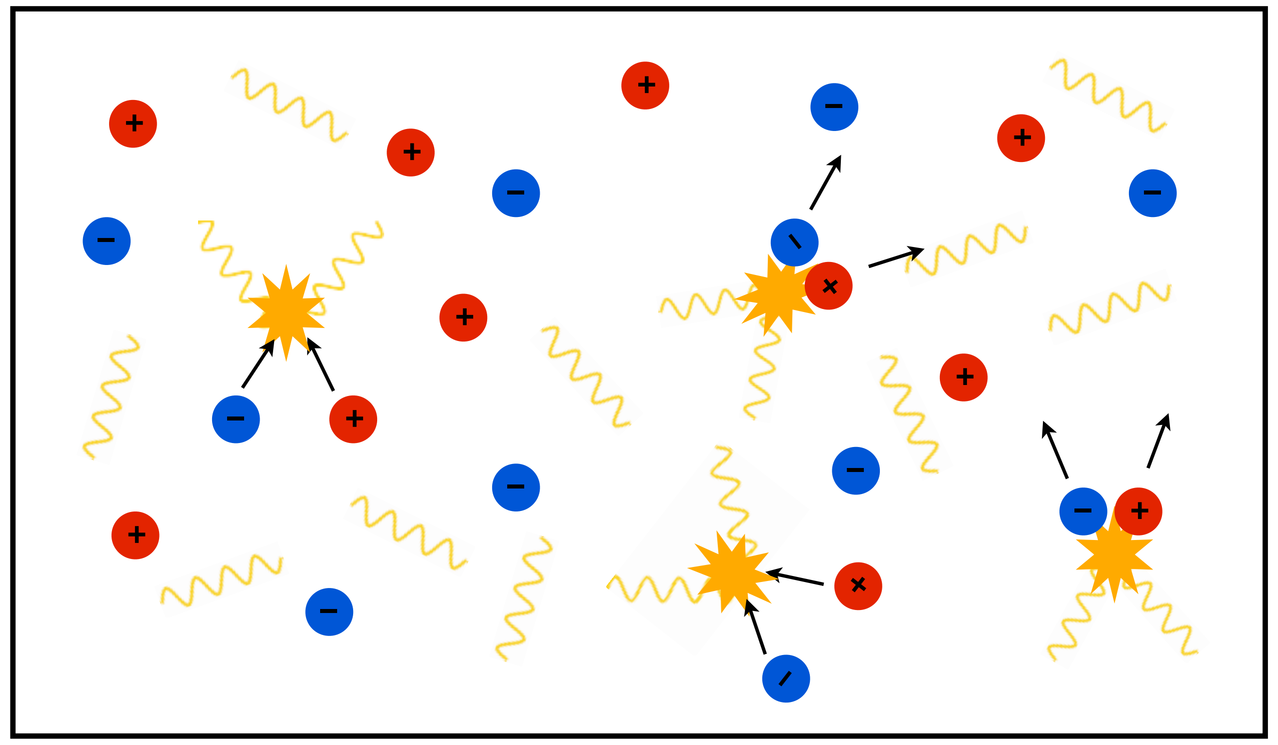
Low-energy probes of BSM physics cluster around four inter-connected questions



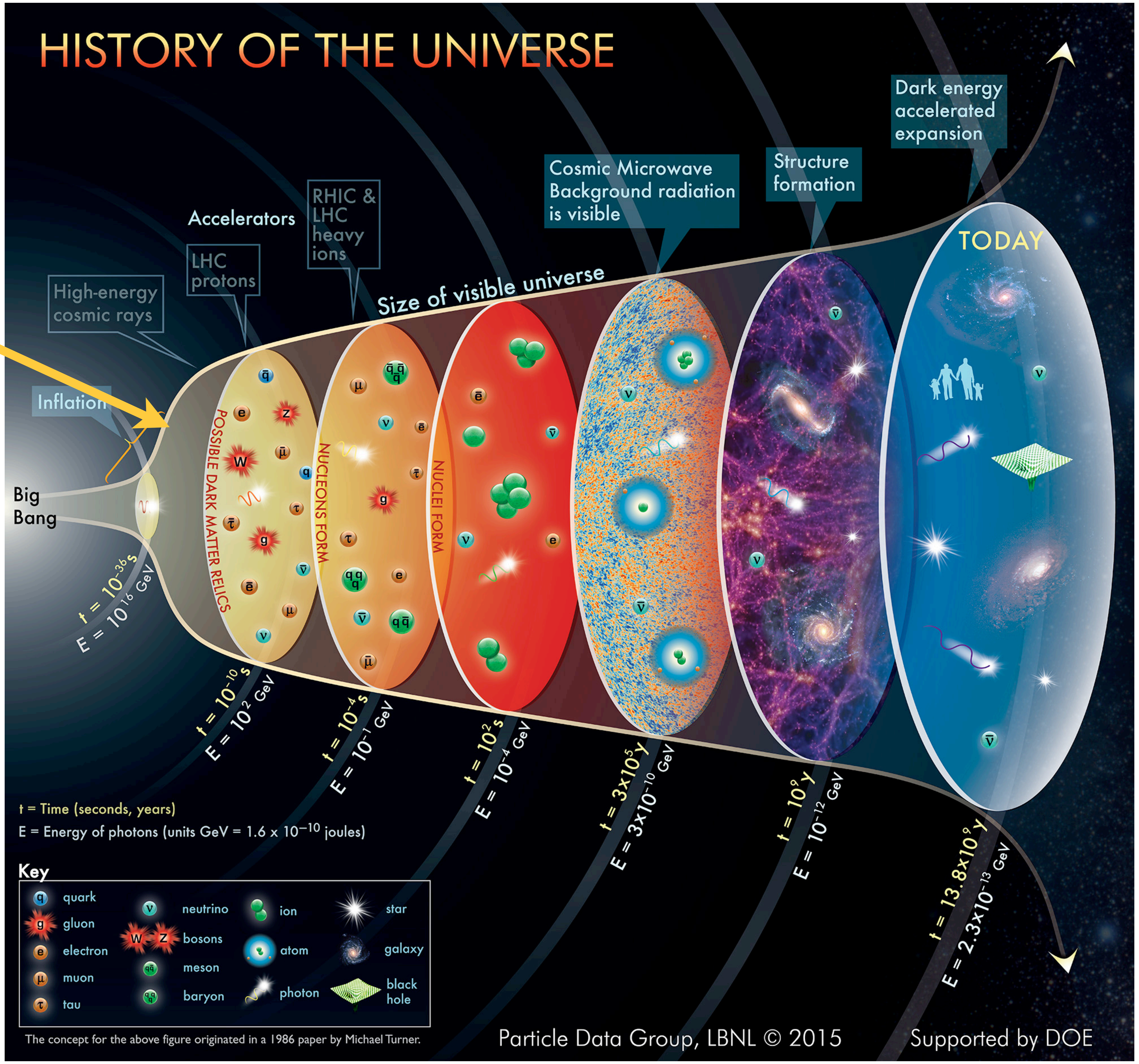
More on the baryon asymmetry of the universe

Equal number of particles and antiparticles right after the big bang

t = 0.000001s



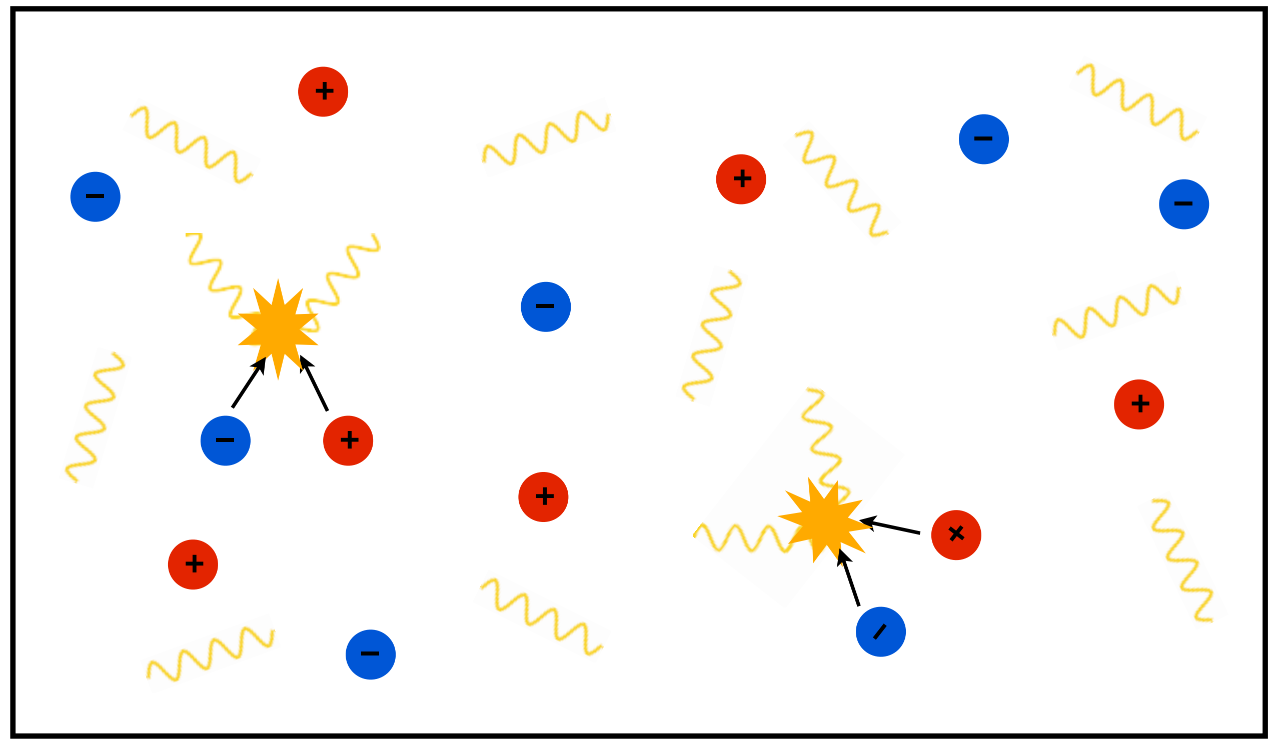
As the universe expands and cools, particle-antiparticle annihilation takes over: end up with just radiation!



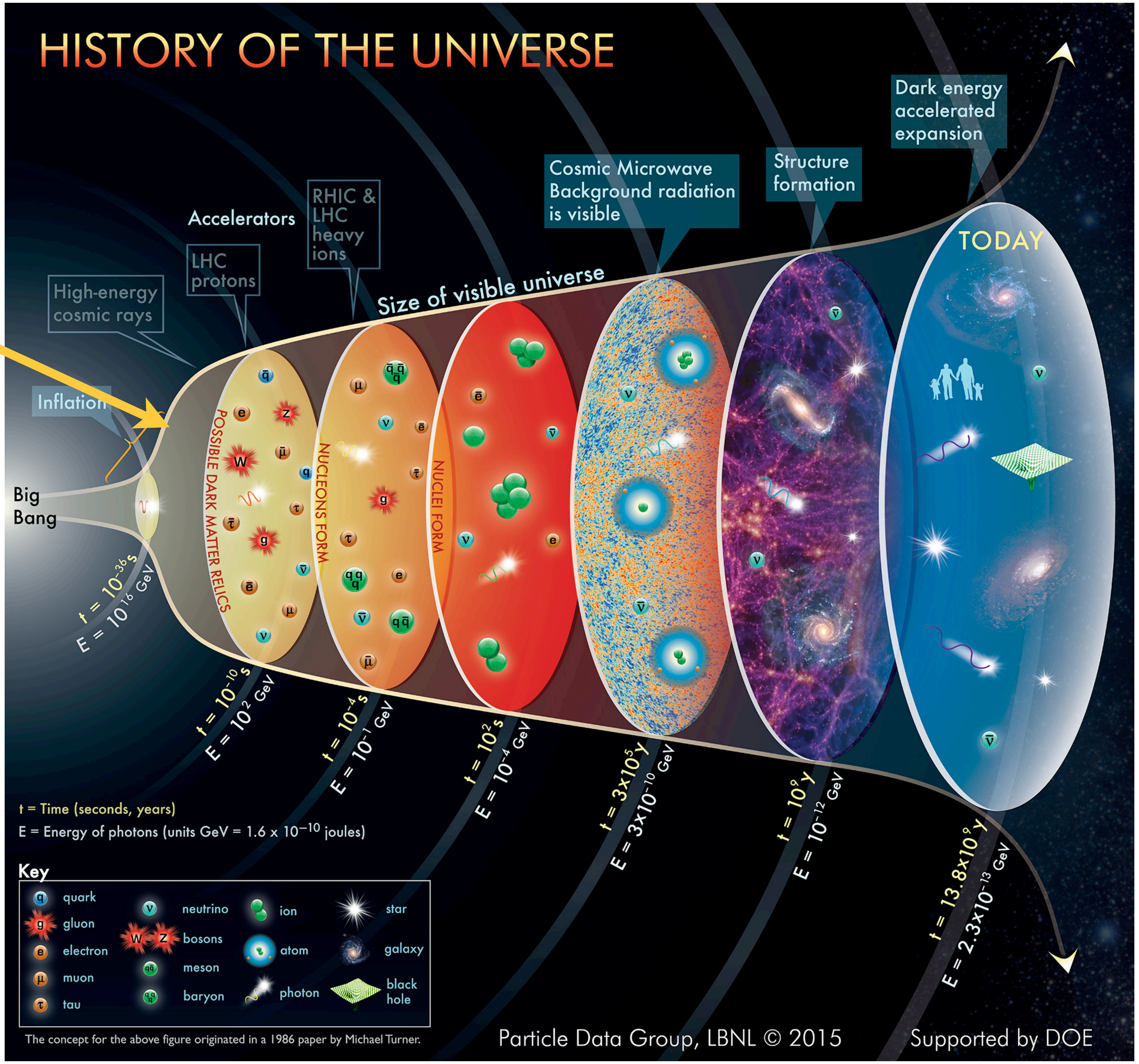
More on the baryon asymmetry of the universe

Equal number of particles and antiparticles right after the big bang

t ~ 0.00001s



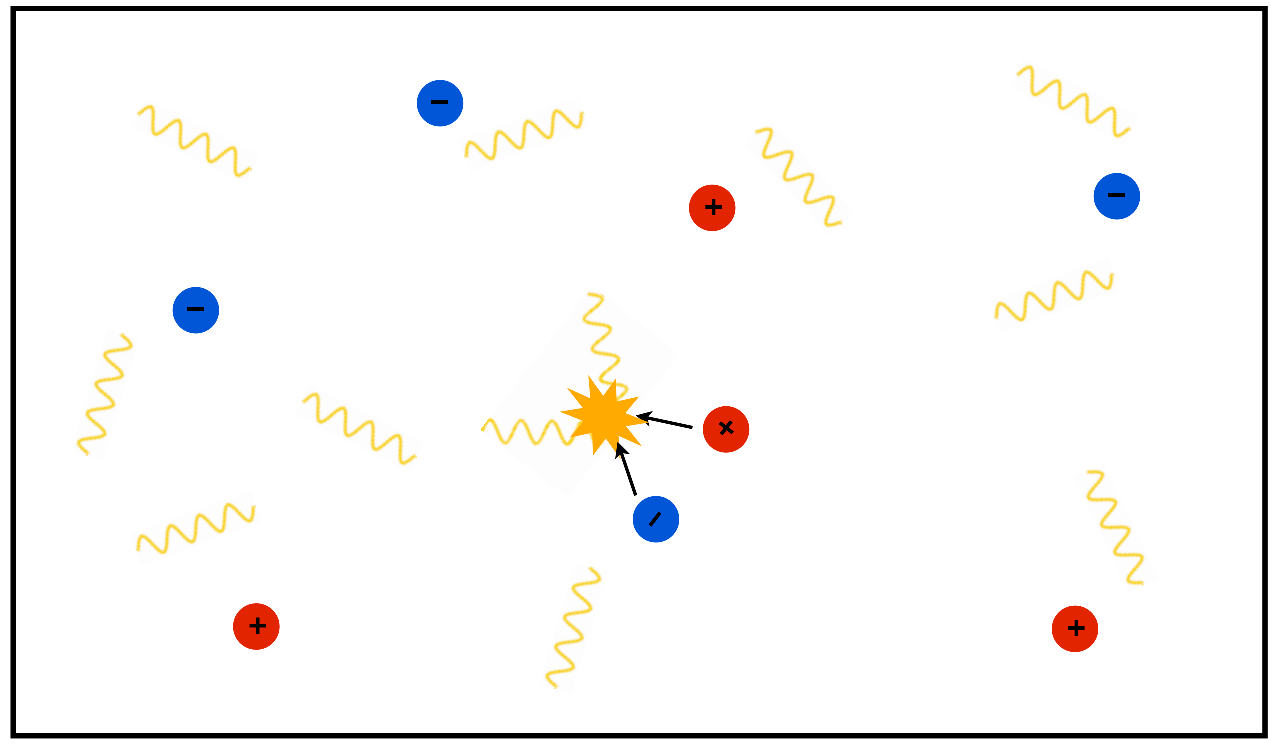
As the universe expands and cools, particle-antiparticle annihilation takes over: end up with just radiation!



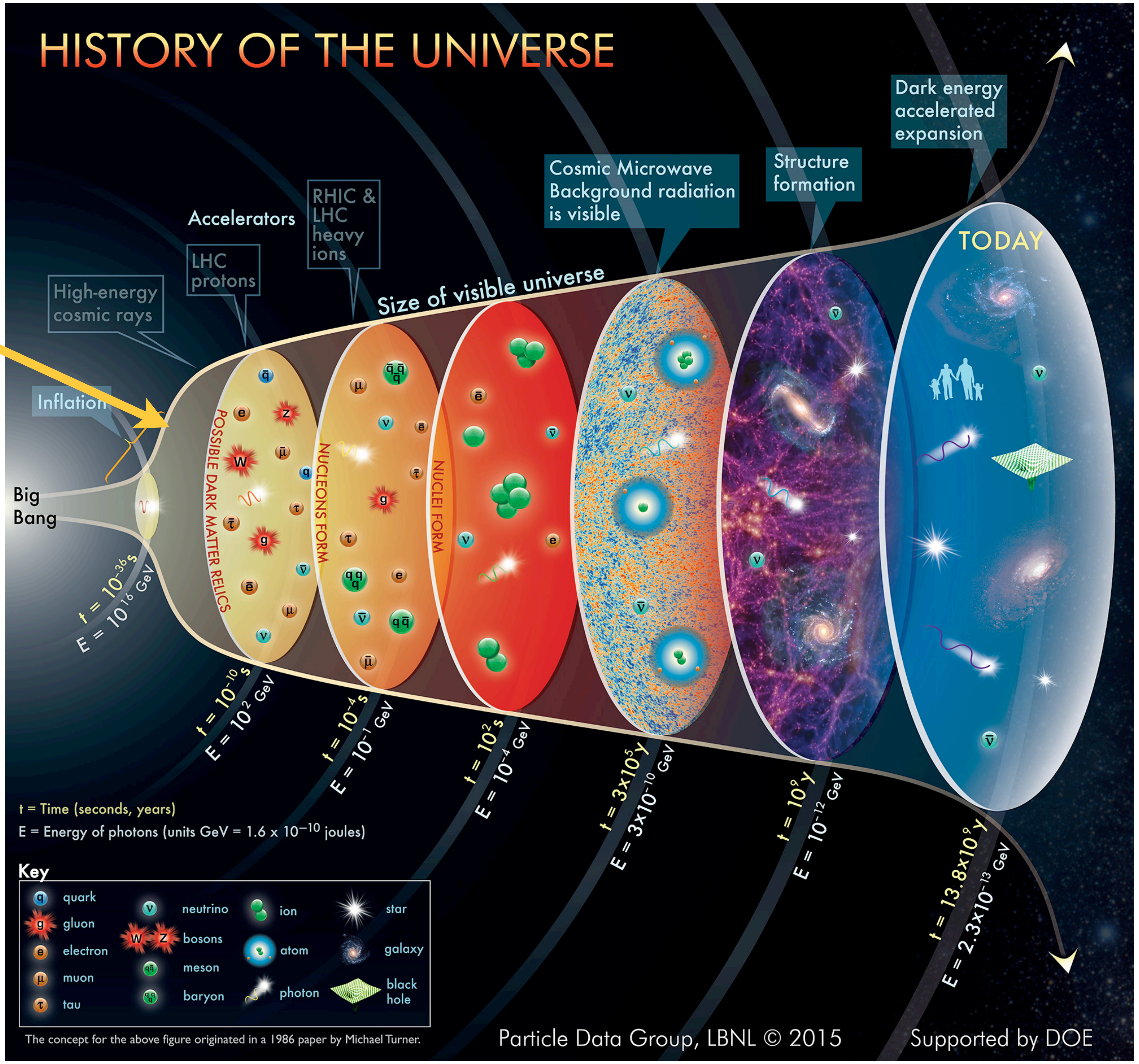
More on the baryon asymmetry of the universe

Equal number of particles and antiparticles right after the big bang

t ~ 0.0001 s



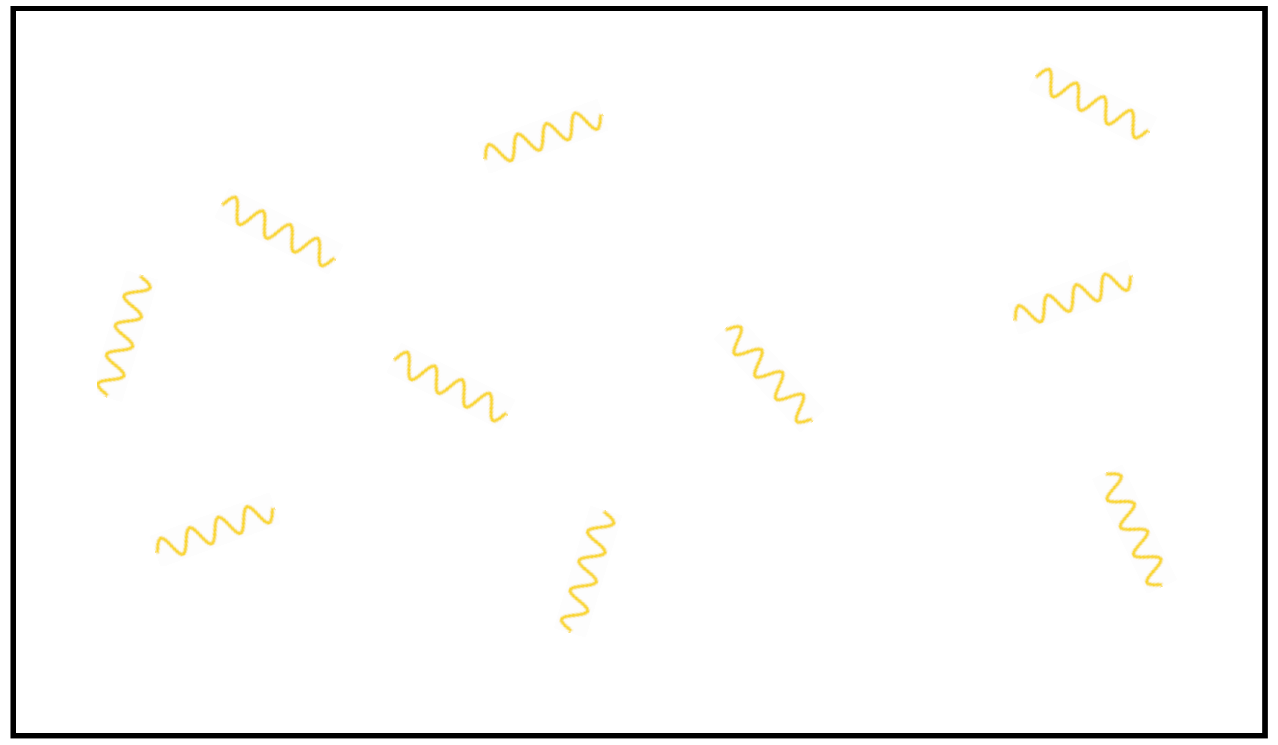
As the universe expands and cools, particle-antiparticle annihilation takes over: end up with just radiation!

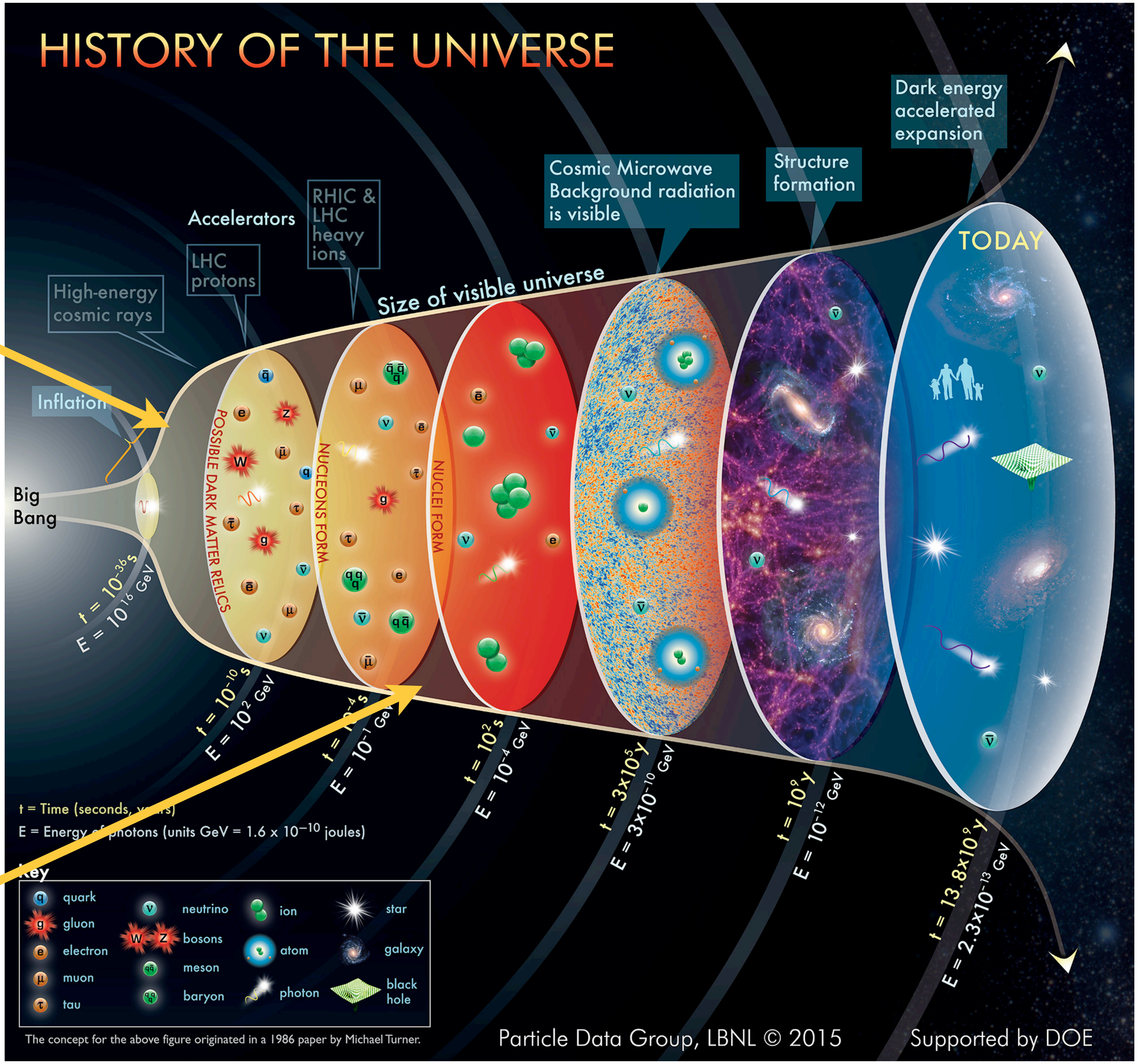


More on the baryon asymmetry of the universe

Equal number of particles and antiparticles right after the big bang

t ~ 0.003 s





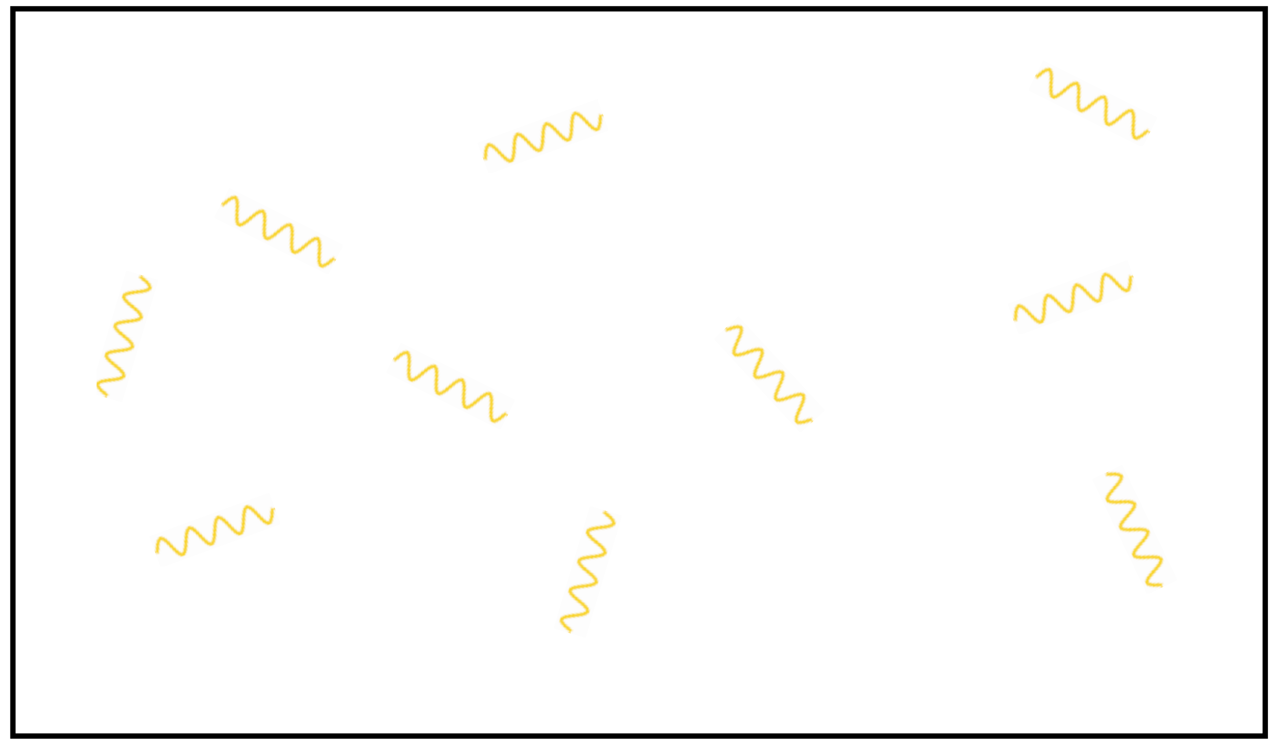
As the universe expands and cools, particle-antiparticle annihilation takes over: end up with just radiation!

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

More on the baryon asymmetry of the universe

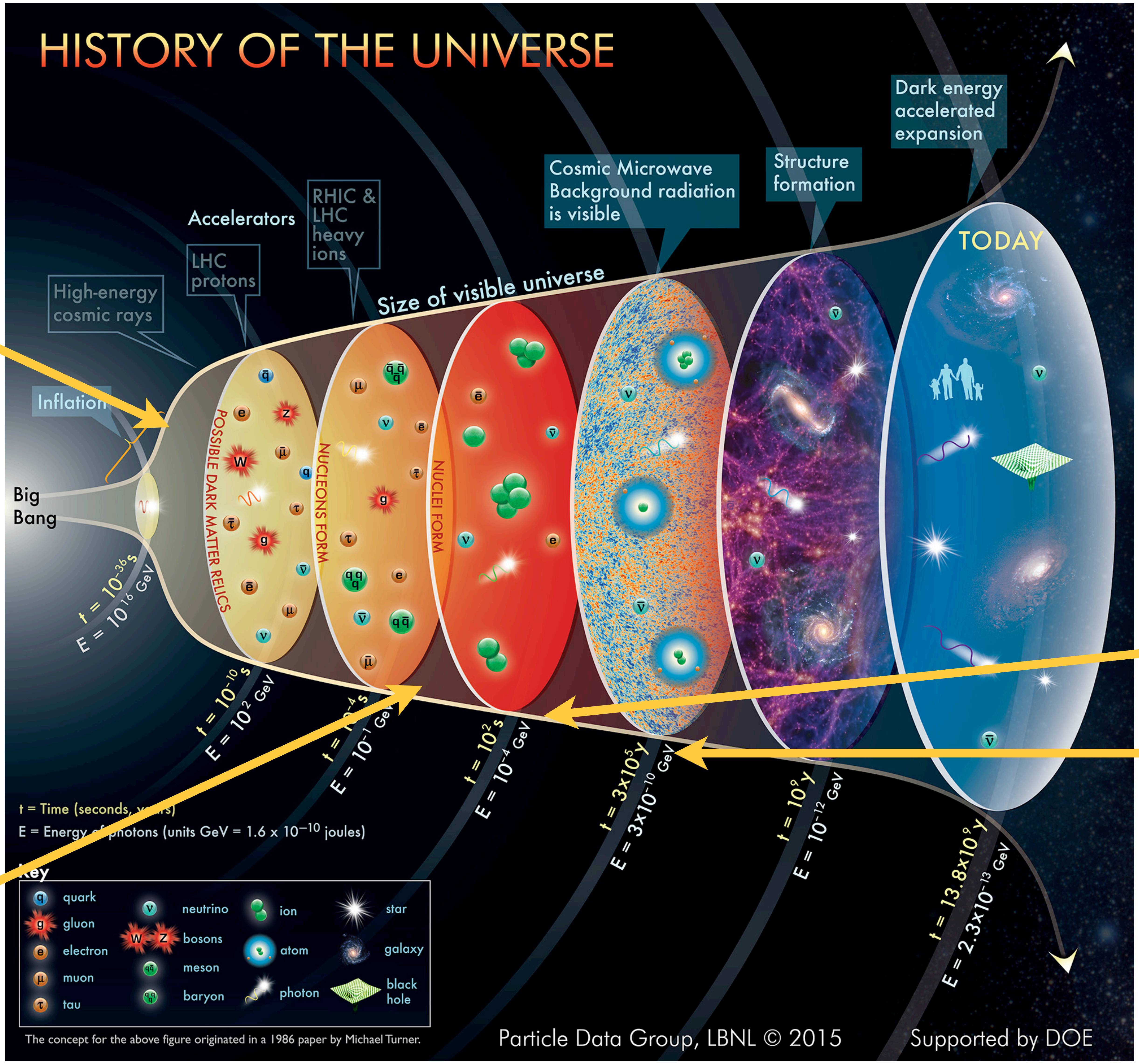
Equal number of particles and antiparticles right after the big bang

t ~ 0.003 s



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

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



But cosmological observations require a non-zero matter-antimatter asymmetry!

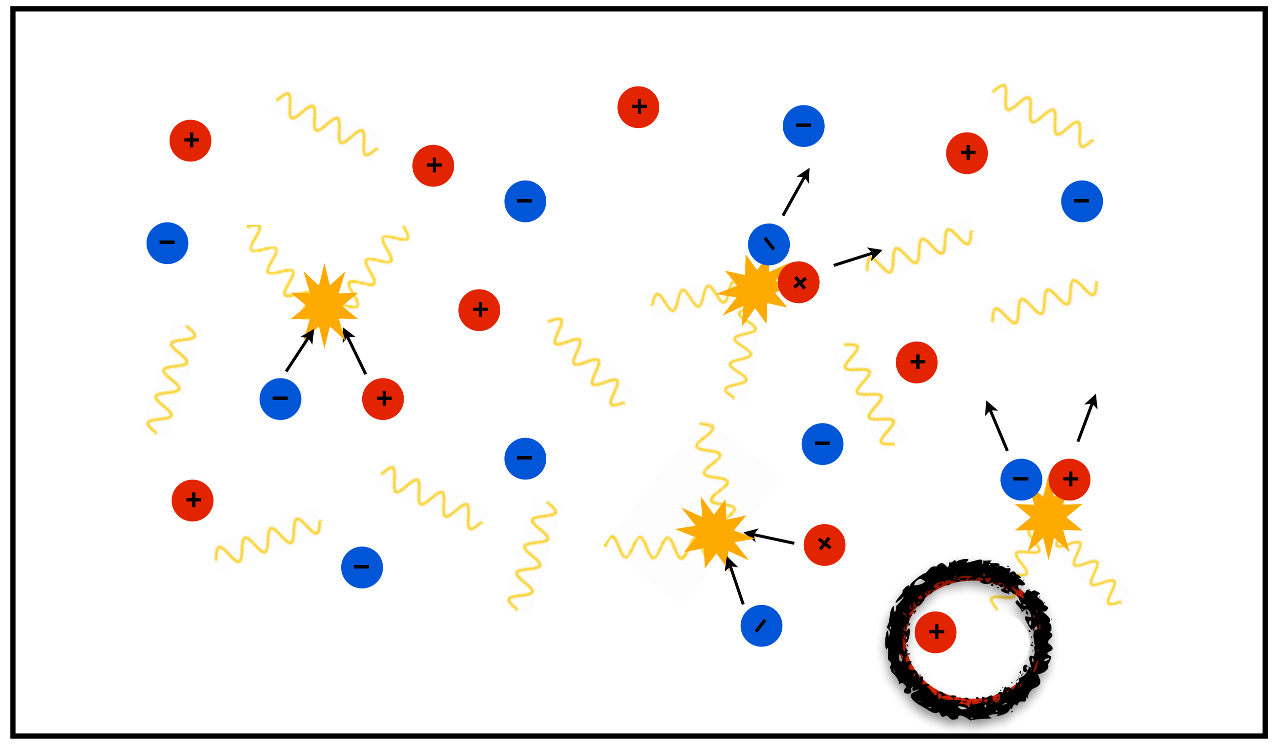
$\eta \equiv (n_B - n_{\bar{B}})/n_\gamma$

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

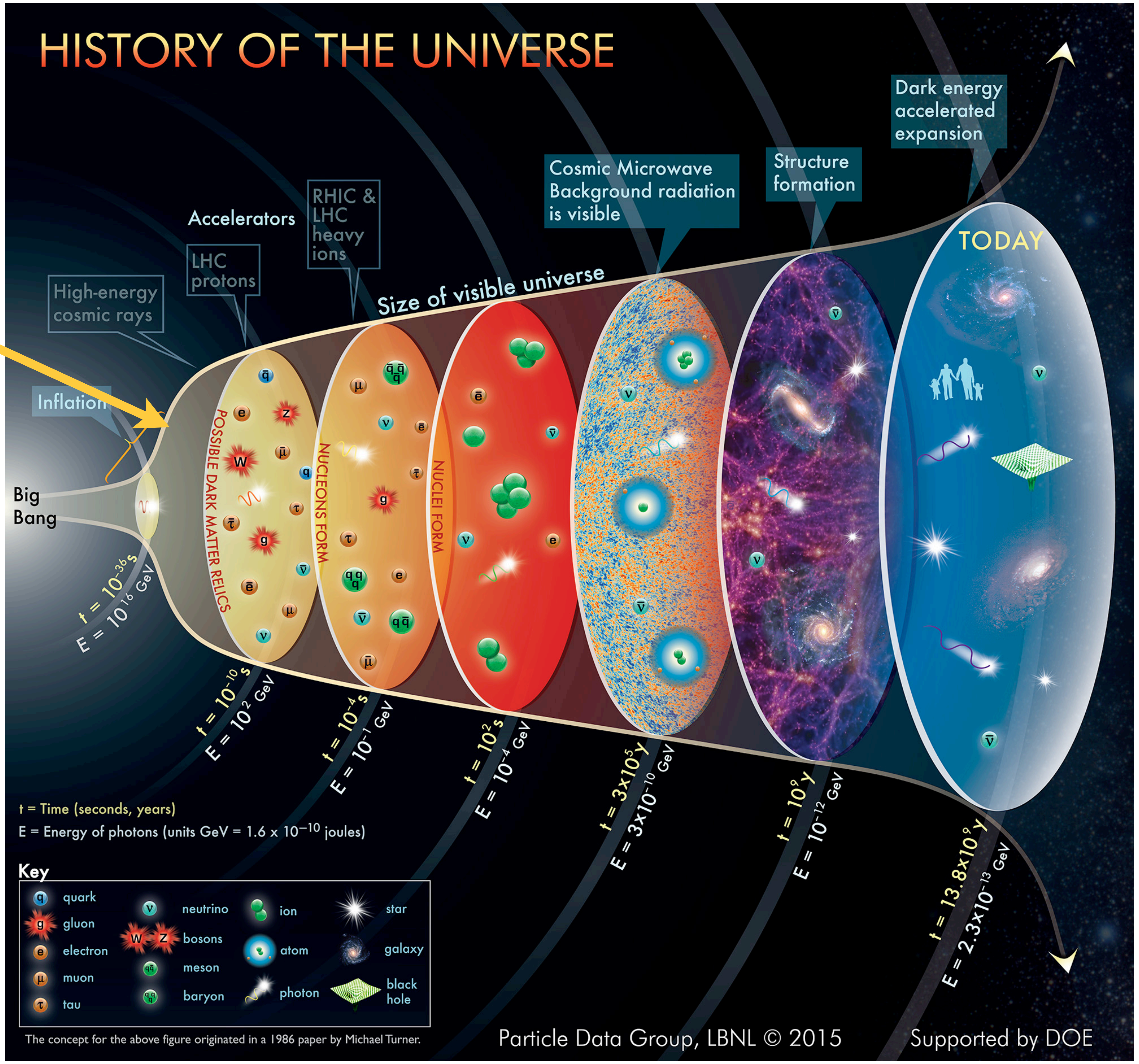
More on the baryon asymmetry of the universe

Equal number of particles and antiparticles right after the big bang

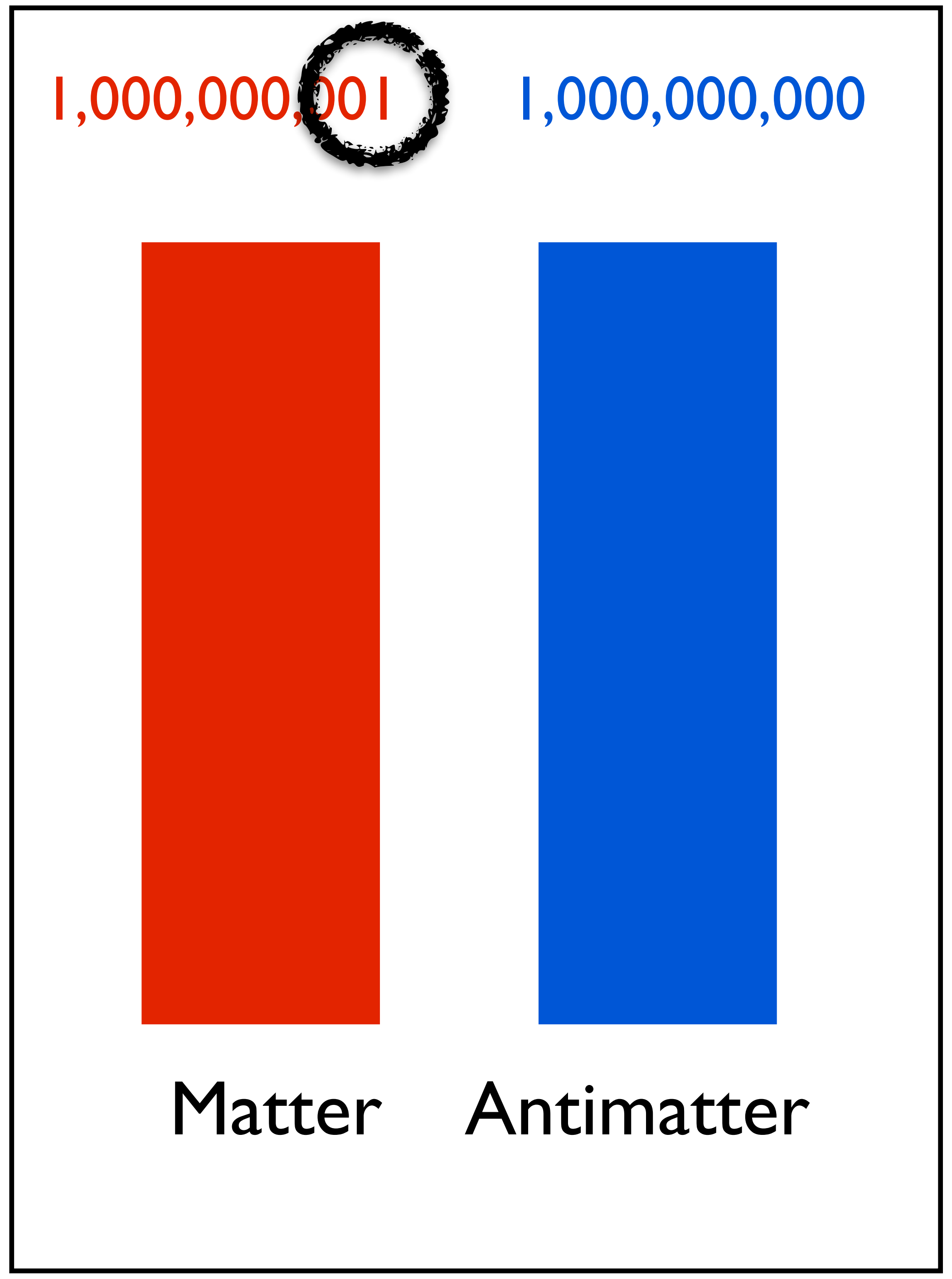
t ~ 0.000001s



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



Early universe

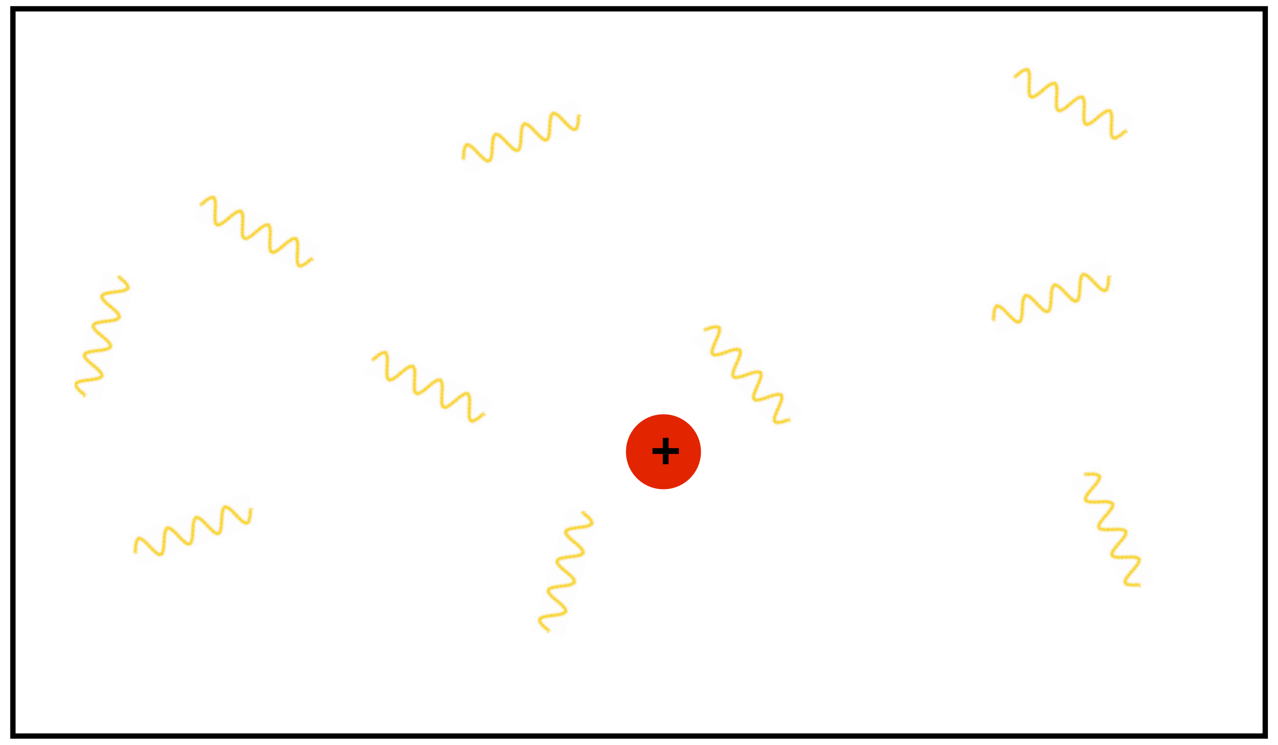


Credit: H. Murayama

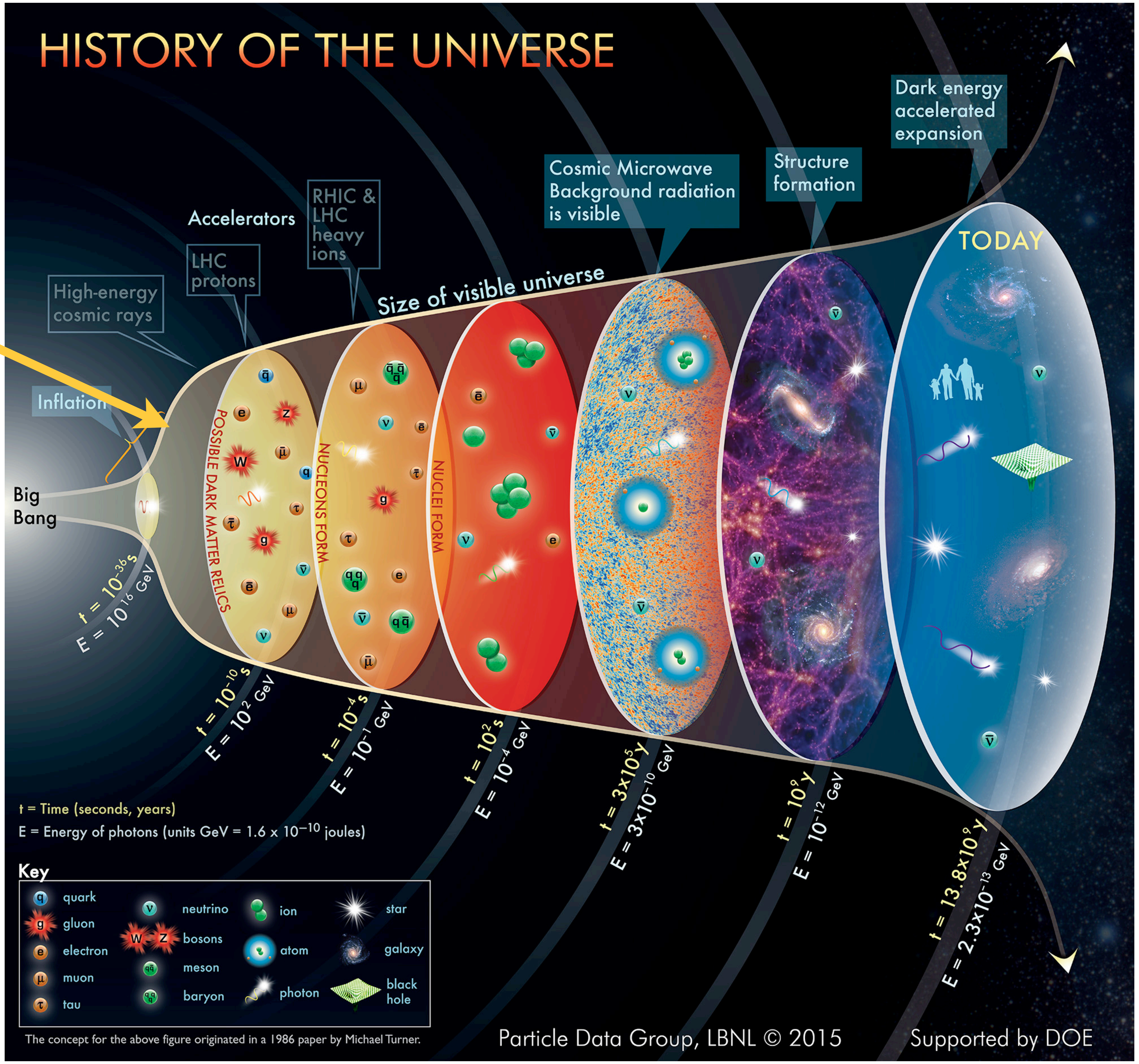
More on the baryon asymmetry of the universe

Equal number of particles and antiparticles right after the big bang

Today

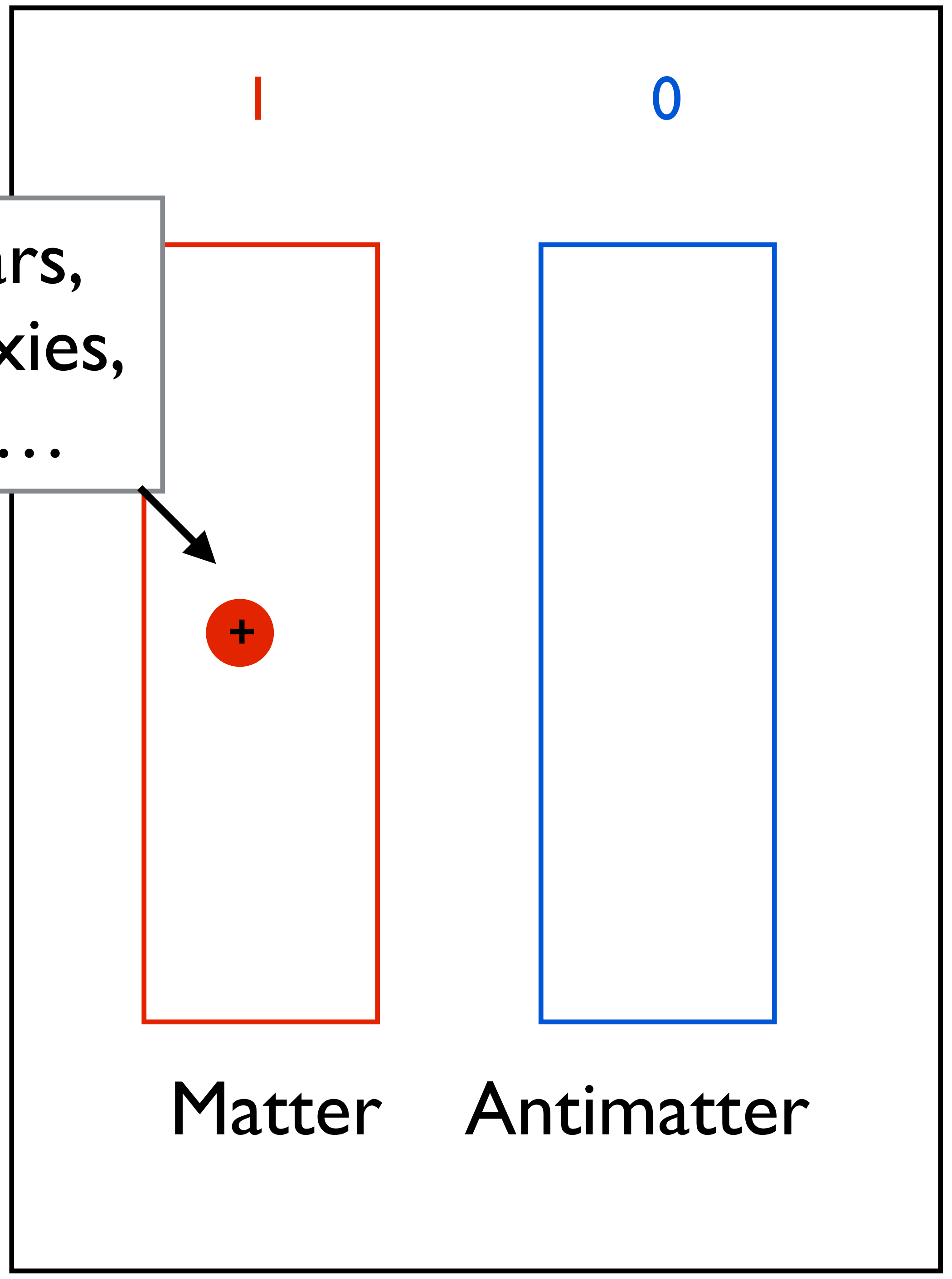


To obtain O(1) protons per cubic meter today, early on need a tiny imbalance of (+) over (−)



Today

Stars, galaxies, us…

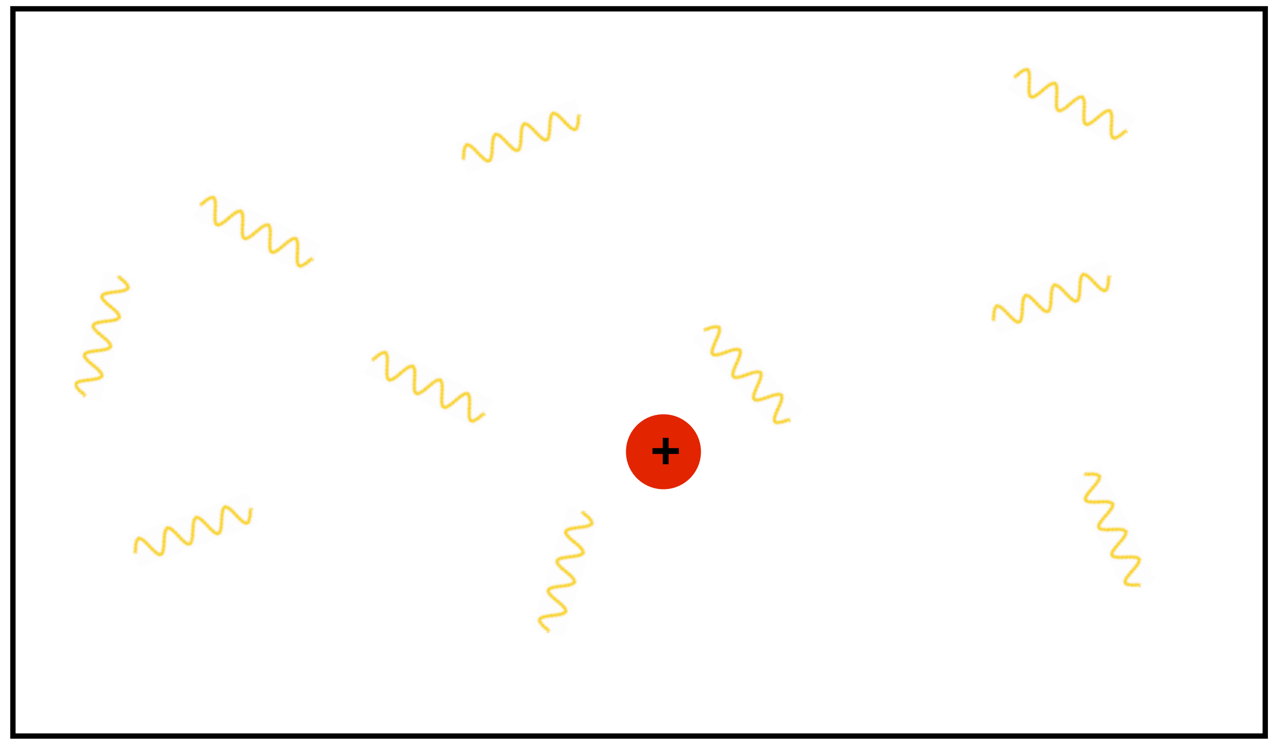


Credit: H. Murayama

More on the baryon asymmetry of the universe

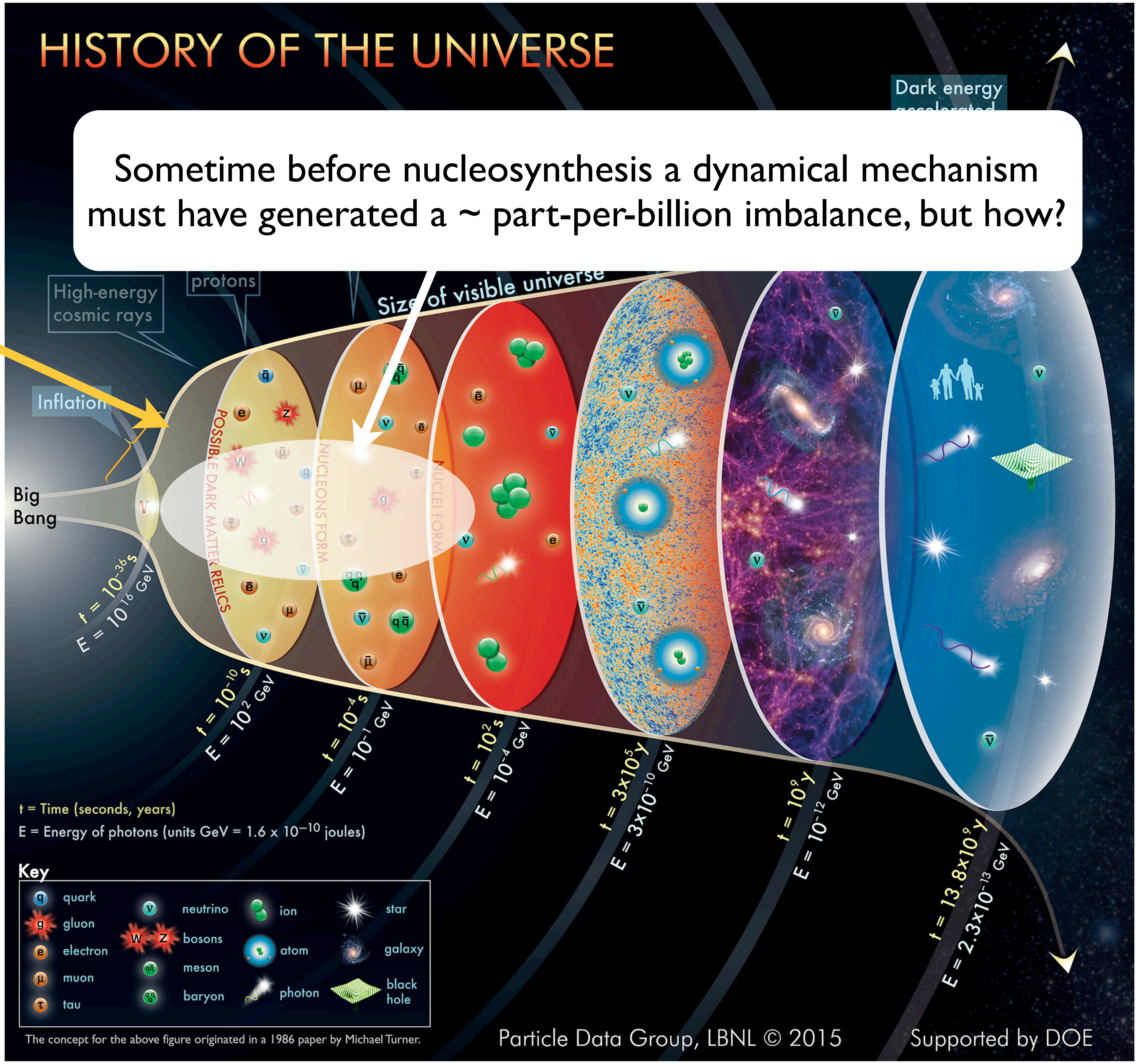
Equal number of particles and antiparticles right after the big bang

Today

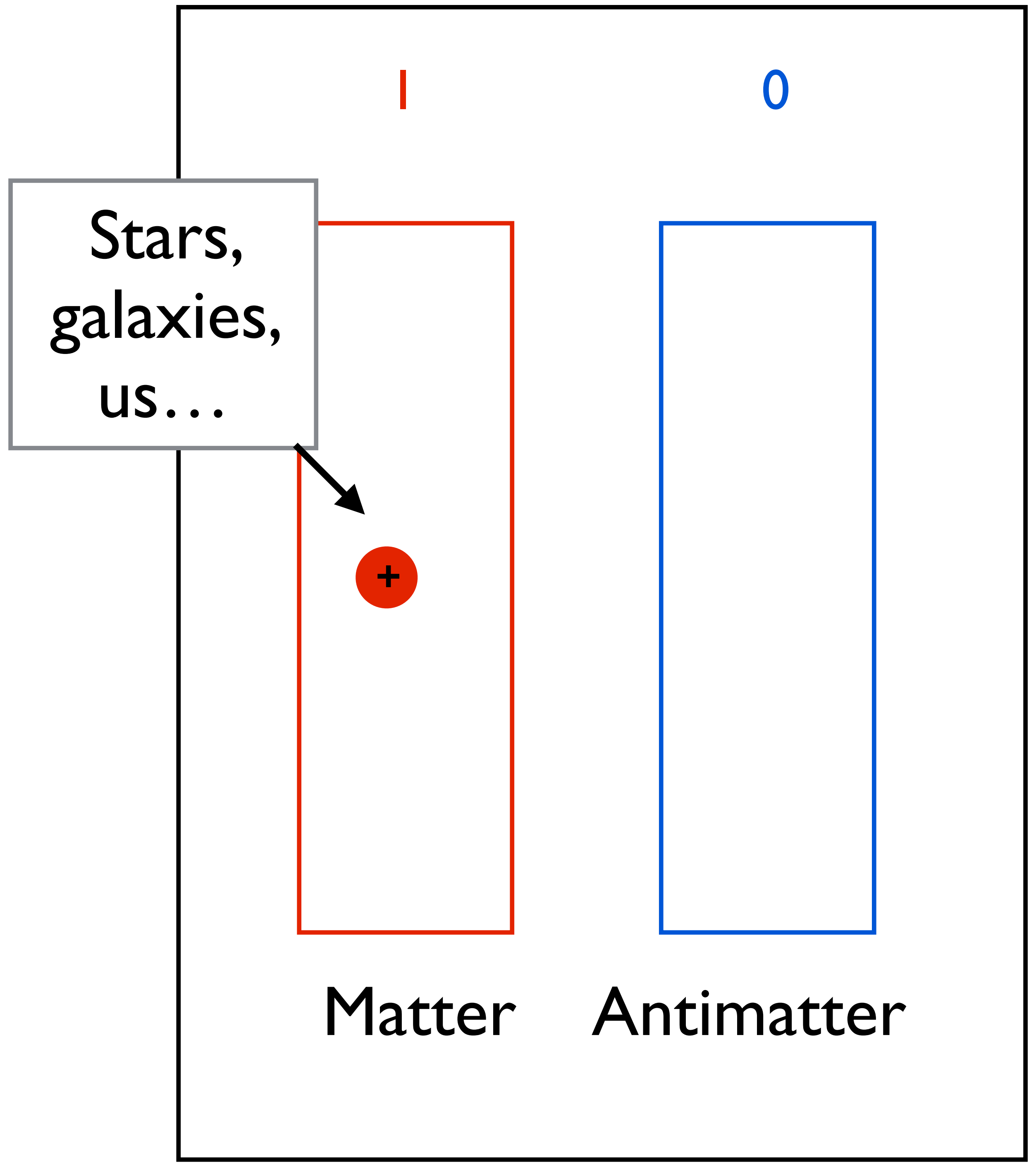


To obtain O(1) protons per cubic meter today, early on need a tiny imbalance of + over −

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



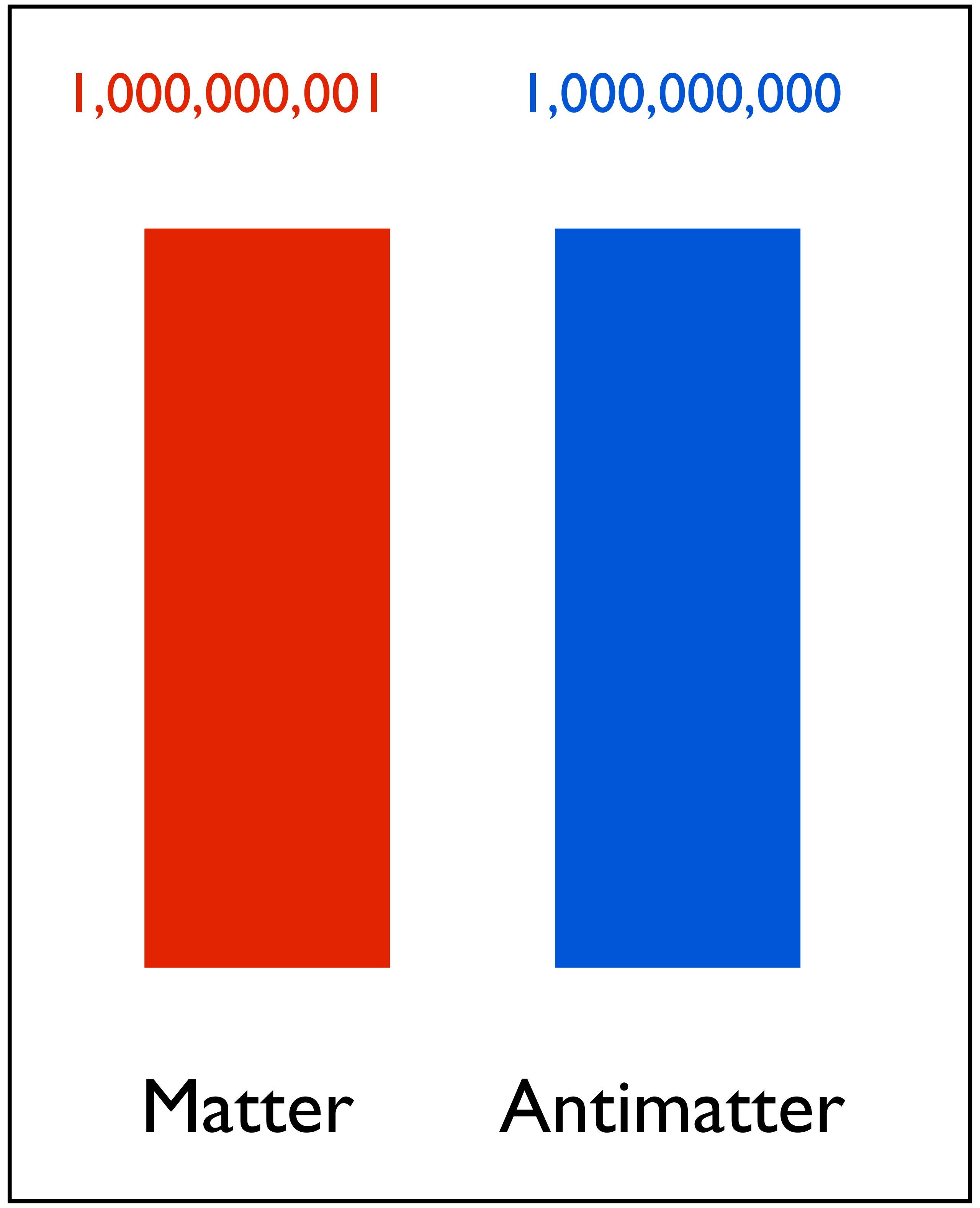
Today



Credit: H. Murayama

Ingredients for a lopsided universe

Andrei Sakharov, 1967



Credit: H. Murayama

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

$A \rightarrow B$

# of baryons − # of anti-baryons is different in A and B

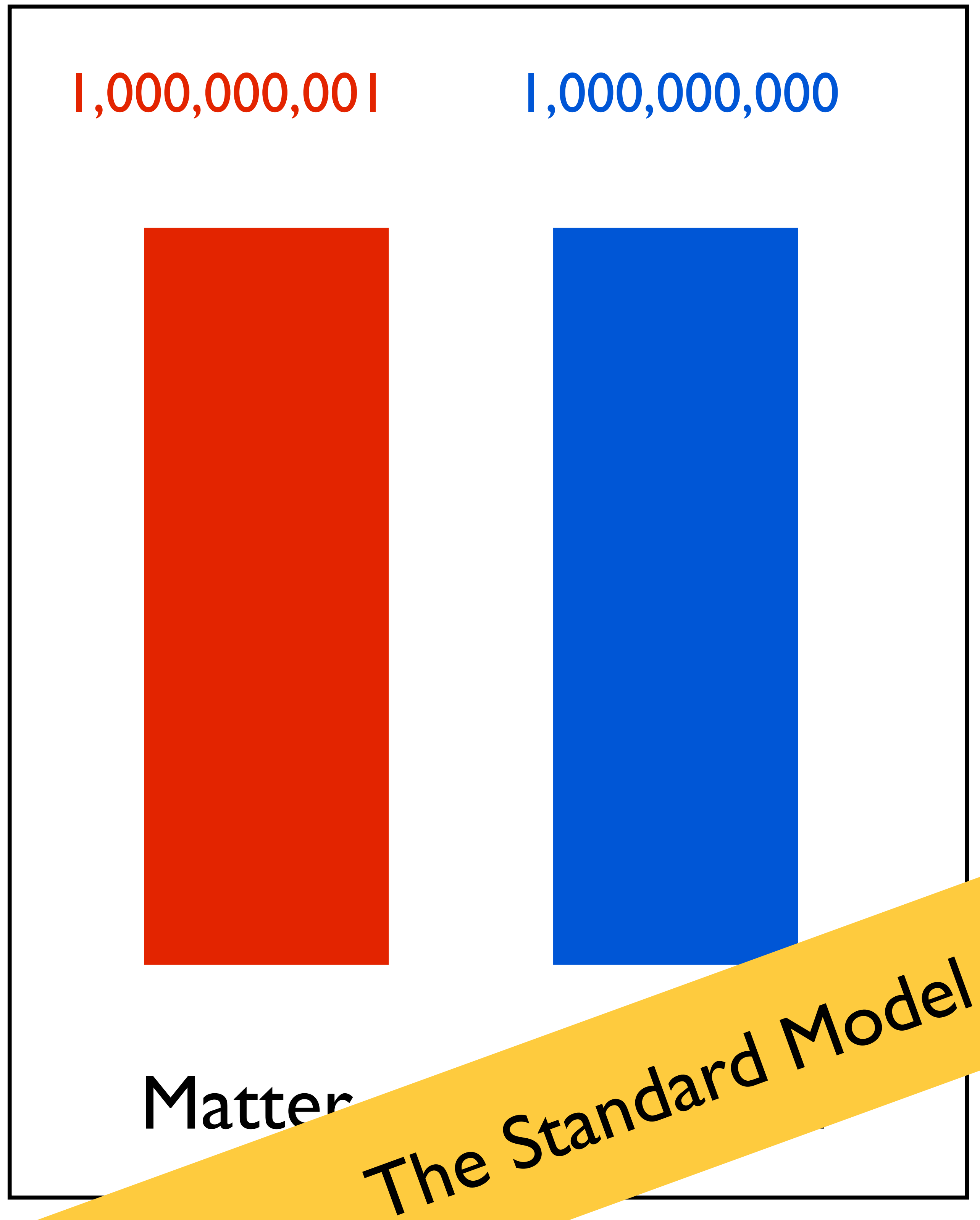
#2. "Asymmetrically" (faster than corresponding antimatter-creating process) $[\not{C}, \not{C}P]$

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

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

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

Ingredients for a lopsided universe



…H. Murayama

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

$$A \rightarrow B$$

# of bary… …ons … and B

#2. "Asymmetrically" (faster th… …ng antimatter-creating process) [$\not{C}$, $\not{CP}$]

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

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

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

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

How does the precision frontier work?
(Theory perspective)

Probing UV (‘heavy’) new physics

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M, consistent with the underlying symmetries

…. Appelquist-Carazzone 1975 ….

Probing UV ('heavy') new physics

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M, consistent with the underlying symmetries

…. Appelquist-Carazzone 1975 ….

You are familiar with this concept from perturbation theory in QM

$$H = H_0 + \lambda V \qquad H|n^{(0)}\rangle = E_n^{(0)}|n^{(0)}\rangle$$

$$E_n(\lambda) = E_n^{(0)} + \lambda\langle n^{(0)}|V|n^{(0)}\rangle + \lambda^2 \sum_{k\neq n} \frac{\langle n^{(0)}|V|k^{(0)}\rangle\langle k^{(0)}|V|n^{(0)}\rangle}{E_n^{(0)} - E_k^{(0)}} + O(\lambda^3)$$

Probing UV (‘heavy’) new physics

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M, consistent with the underlying symmetries

…. Appelquist-Carazzone 1975 ….

You are familiar with this concept from perturbation theory in QM

$$H = H_0 + \lambda V \qquad H|n^{(0)}\rangle = E_n^{(0)}|n^{(0)}\rangle$$

$$E_n(\lambda) = E_n^{(0)} + \lambda\langle n^{(0)}|V|n^{(0)}\rangle + \lambda^2 \sum_{k\neq n} \frac{\langle n^{(0)}|V|k^{(0)}\rangle\langle k^{(0)}|V|n^{(0)}\rangle}{\cancel{E_n^{(0)}} - E_k^{(0)}} + O(\lambda^3)$$

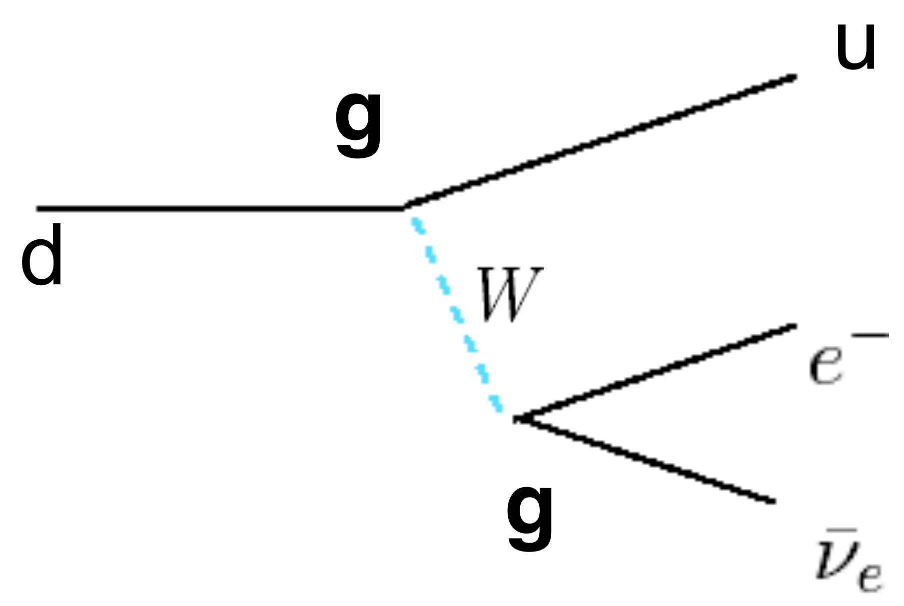
$$\simeq \langle n^{(0)}|H_{\rm eff}|n^{(0)}\rangle + O\left(\frac{E_n^{(0)}}{E_k^{(0)}}\right) \qquad H_{\rm eff} = \lambda^2 \sum_{k\neq n} \frac{V|k^{(0)}\rangle\langle k^{(0)}|V}{-E_k^{(0)}}$$

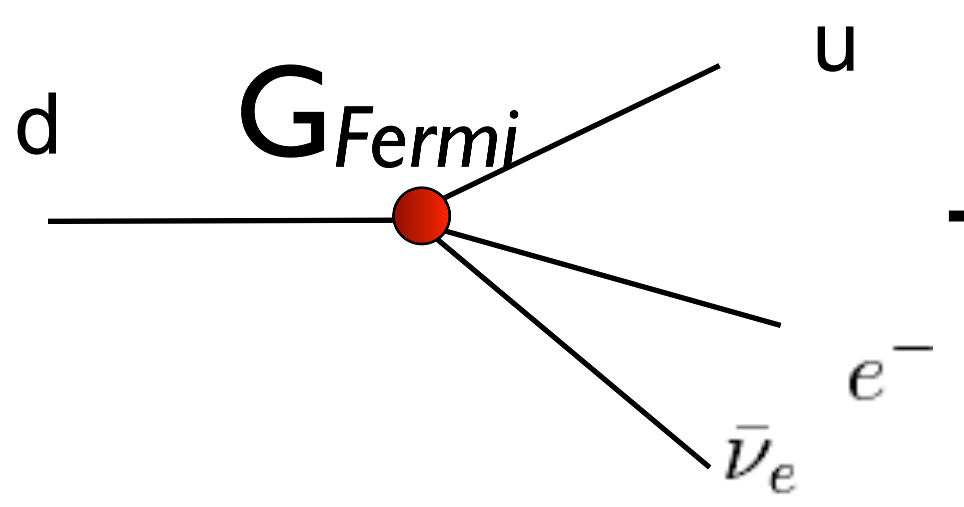
Sensitivity to high-energy states through ‘energy denominators’

Probing UV ('heavy') new physics

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M, consistent with the underlying symmetries

"Top-down": heavy particle exchange generates new local interaction





$+ O(q^2/M_W^2)$

$$\frac{g^2}{M_W^2 - q^2}$$

$q^2 = (p_e + p_\nu)^2 << M_W^2$

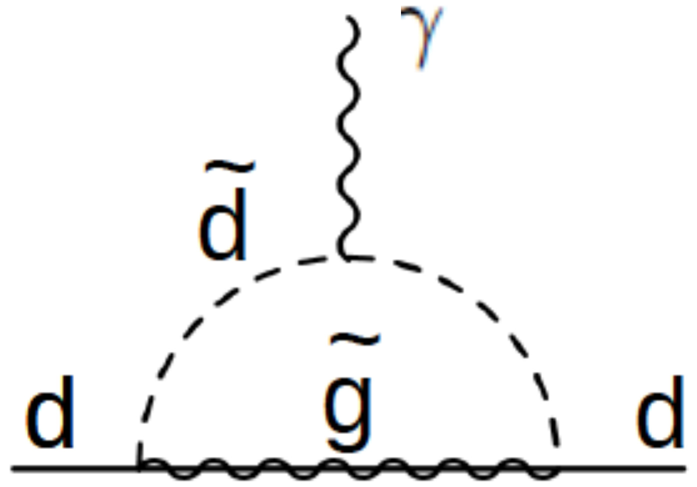
$$G_{Fermi} \sim \frac{g^2}{M_W^2}$$

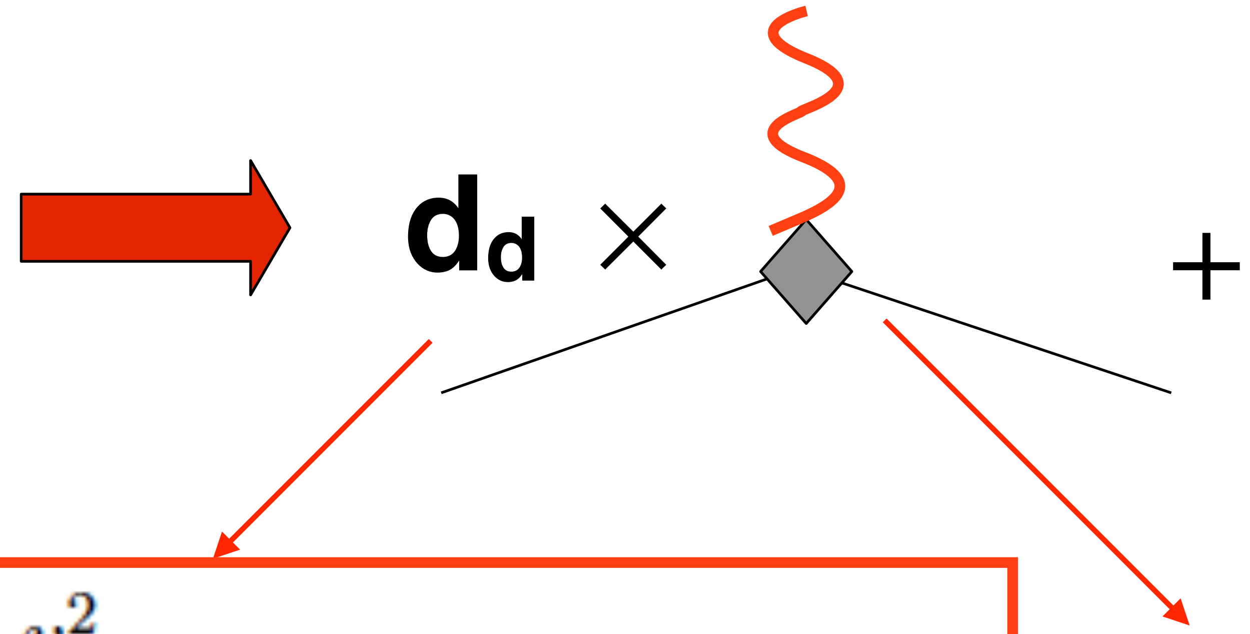
Tree level example

Probing UV ('heavy') new physics

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M, consistent with the underlying symmetries

"Top-down": heavy particle exchange generates new local interaction





$+ O(v^4/M_{SUSY}^4)$

$$\frac{\alpha_s}{4\pi}\,\frac{v^2}{M_{SUSY}^2} \times \phi_{CP} \times 10^{-22}\, e\,\mathrm{cm}$$

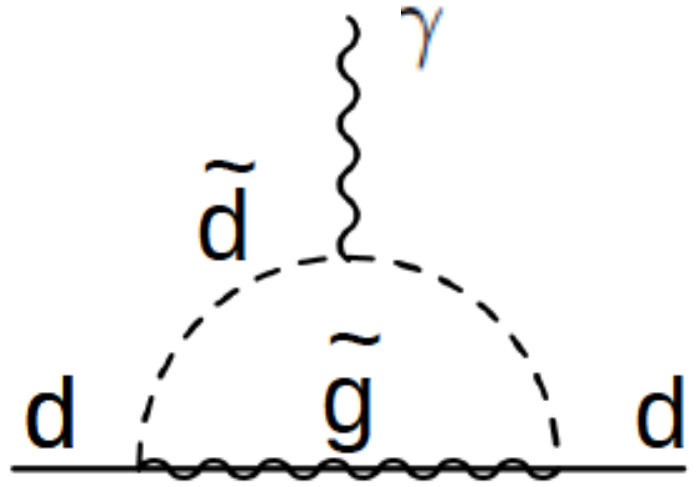
$S_d \cdot E$

Loop level example

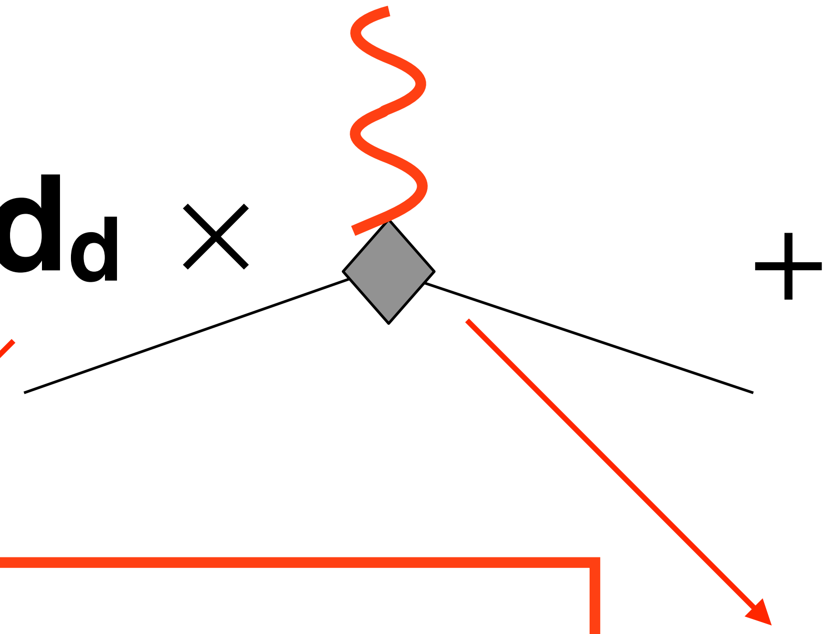
Probing UV ('heavy') new physics

- Key point: particles of mass M affect physics at E << M by inducing
  - a shift in coupling constants of known interactions
  - new local interactions suppressed by powers of E/M, consistent with the underlying symmetries

"Top-down": heavy particle exchange generates new local interaction



$\Longleftrightarrow$ $\mathbf{d_d} \times$



$+ \; O(v^4/M_{SUSY}^4)$

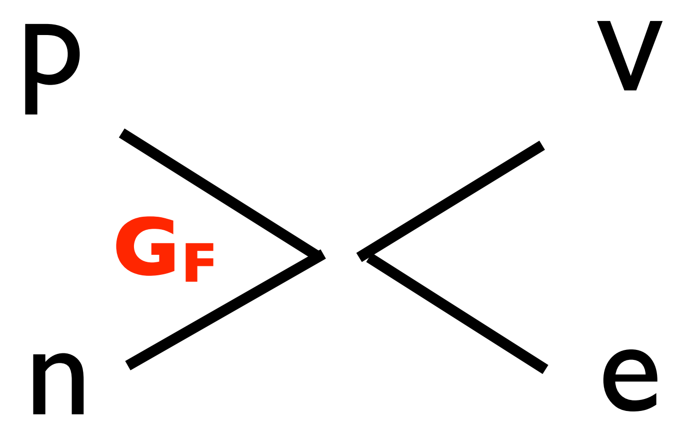
$$\frac{\alpha_s}{4\pi}\,\frac{v^2}{M_{SUSY}^2} \times \phi_{CP} \times 10^{-22}\, e\,\mathrm{cm}$$

$\mathbf{S_d \cdot E}$

But one can take a "bottom-up" approach, too, in order to infer properties of underlying new physics. (This is the SMEFT approach)

Classic example: the making of the SM

Fermi, 1934



Current-current (VxV), parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Fermi's theory of beta decays ($n \to p\, e\, \bar{\nu}_e$):

Postulate new local interaction (that respects Lorentz invariance and charge conservation) in terms of "light" degrees of freedom (n,p,e,ν_e):

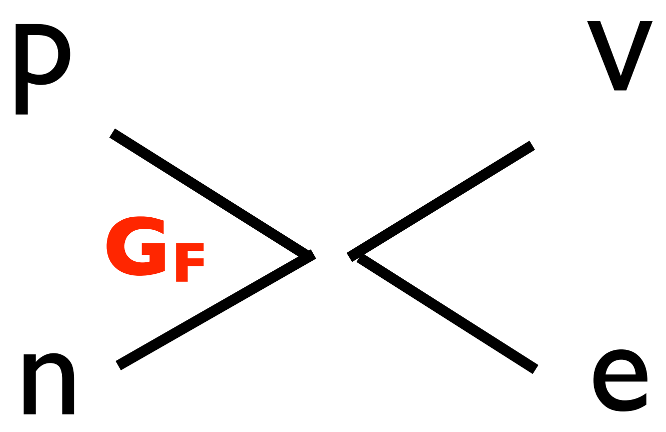
$$H \sim G_F\, \bar{p}\Gamma n\, \bar{e}\Gamma \nu_e$$

(Fermi assumed Vector currents, in analogy with EM)

Coupling constant $G_F \equiv 1/\Lambda_F^2$ determined by fitting the "slow" beta decay rates ⇒ point to mass scale $\Lambda_F >> m_n \sim$ GeV

Classic example: the making of the SM

Fermi, 1934



Current-current (VxV), parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Understand dimensions of Fermi constant:

- Work out mass dimension of fields:
  - Spin 1/2: $[\Psi]=3/2$
  - Spin 0 and 1: $[\phi] = [V_\mu] = 1$

Postulate new local interaction (that respects Lorentz invariance and charge conservation) in terms of "light" degrees of freedom (n,p,e,ν_e):

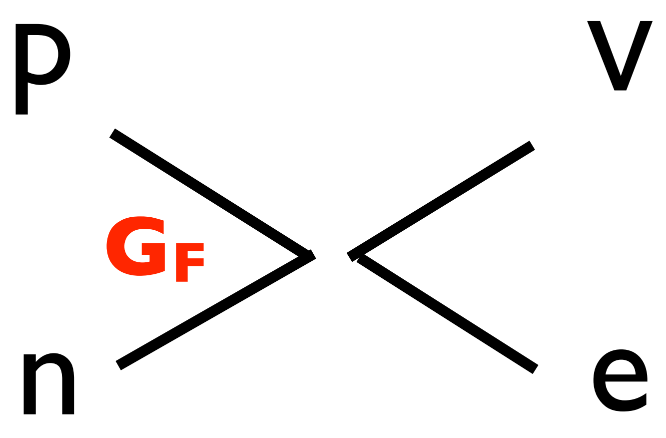
$$H \sim G_F\, \bar{p}\Gamma n\; \bar{e}\Gamma \nu_e$$

(Fermi assumed Vector currents, in analogy with EM)

Coupling constant $G_F \equiv 1/\Lambda_F^2$ determined by fitting the "slow" beta decay rates ⇒ point to mass scale $\Lambda_F >> m_n \sim$ GeV

Classic example: the making of the SM

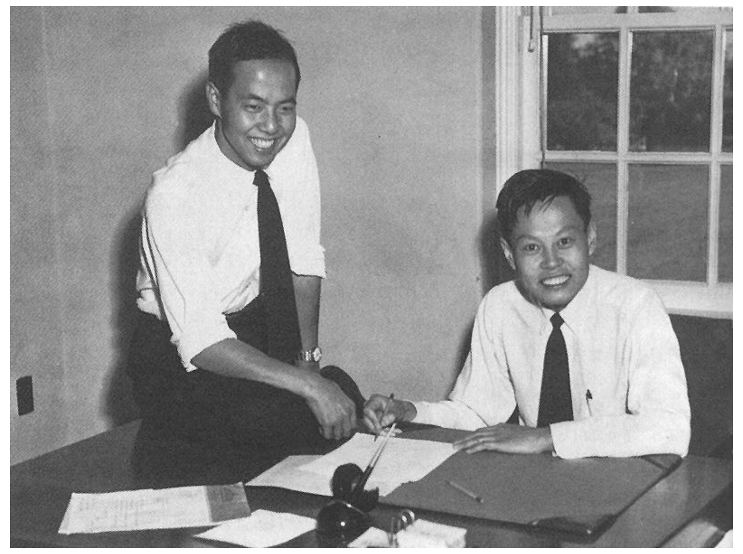
Fermi, 1934

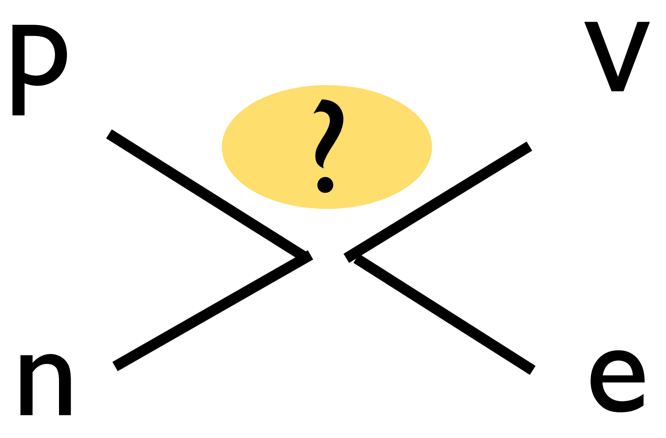


Current-current (VxV), parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956





Parity conserving: VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Most general Lorentz-invariant interaction

Dimensionless coefficients

$$\mathcal{L}_{\rm eff} \supset \frac{c_{12}}{\Lambda_W^2} \; \bar{p}\,\Gamma_1\, n \;\; \bar{e}\,\Gamma_2\, \nu_e$$

Scale of weak interactions

Operators of mass dimension 6 (recall $[\Psi] = m^{3/2}$) that conserve electric charge

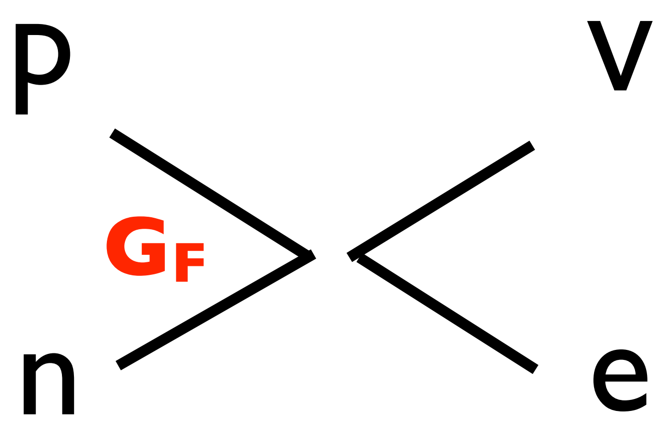
Dirac structures:

$$\Gamma_i = I, \; \gamma_5, \; \gamma_\mu, \; \gamma_\mu\gamma_5, \; \sigma_{\mu\nu} = i/2[\gamma_\mu, \gamma_\nu]$$

S P V A T

Classic example: the making of the SM

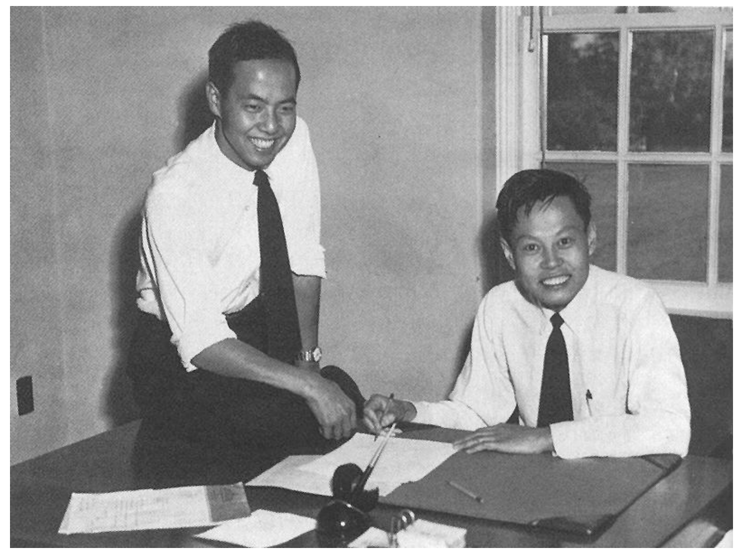
Fermi, 1934

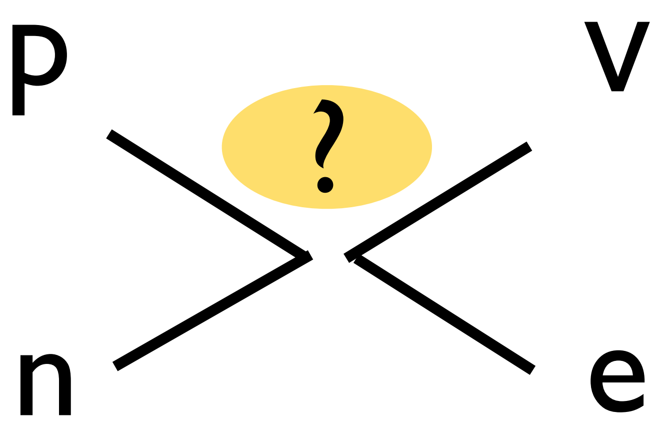


Current-current (VxV), parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956





Parity conserving: VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Most general Lorentz-invariant interaction

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{V,A} + \mathcal{L}_{S,P} + \mathcal{L}_T$$

$C_i \sim (1/\Lambda_W)^2$

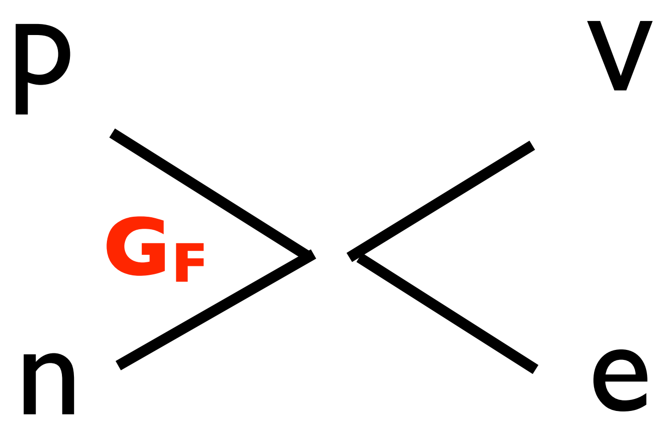
$$-\mathcal{L}_{V,A} = \bar p \gamma_\mu n \; \bar e \gamma^\mu (C_V + C'_V \gamma_5)\nu_e + \bar p \gamma_\mu \gamma_5 n \; \bar e \gamma^\mu \gamma_5 (C_A + C'_A \gamma_5)\nu_e$$

$$-\mathcal{L}_{S,P} = \bar p n \; \bar e (C_S + C'_S \gamma_5)\nu_e + \bar p \gamma_5 n \; \bar e \gamma_5 (C_P + C'_P \gamma_5)\nu_e + {\rm h.c.}$$

$$-\mathcal{L}_T = \frac{1}{2} \bar p \sigma_{\mu\nu} n \; \bar e \sigma^{\mu\nu} (C_T + C'_T \gamma_5)\nu_e + {\rm h.c.}$$

Classic example: the making of the SM

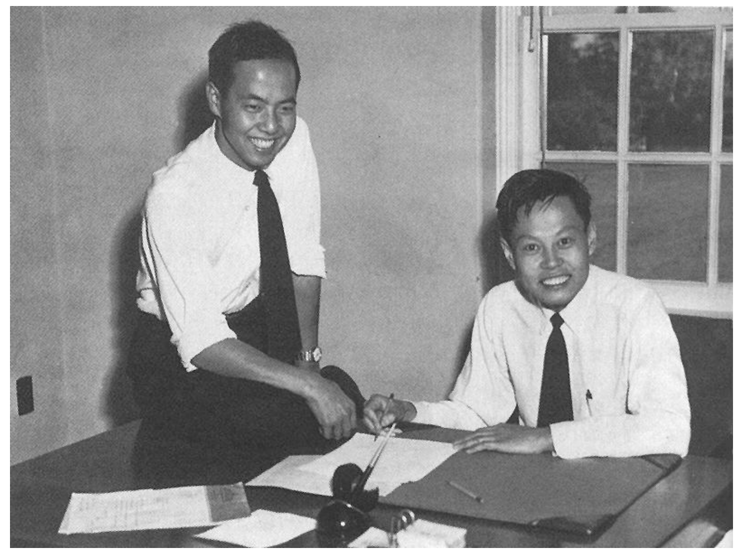
Fermi, 1934

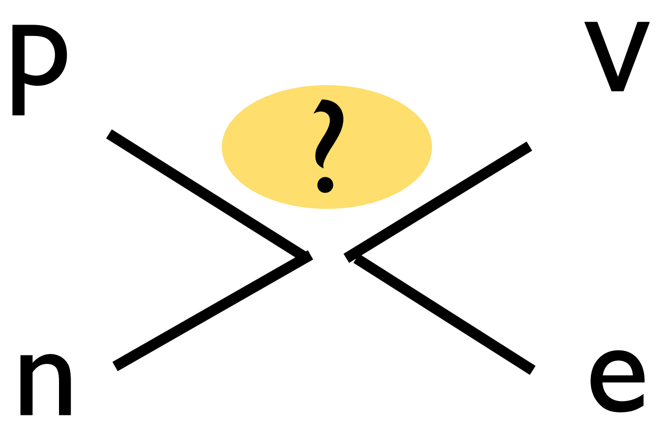


Current-current (VxV), parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956





Parity conserving: VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Most general Lorentz-invariant interaction

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{V,A} + \mathcal{L}_{S,P} + \mathcal{L}_T$$

$C_i \sim (1/\Lambda_W)^2$

$$-\mathcal{L}_{V,A} = \bar{p}\gamma_\mu n \; \bar{e}\gamma^\mu (C_V + C_V' \gamma_5)\nu_e \; + \; \bar{p}\gamma_\mu\gamma_5 n \; \bar{e}\gamma^\mu\gamma_5 (C_A + C_A' \gamma_5)\nu_e$$

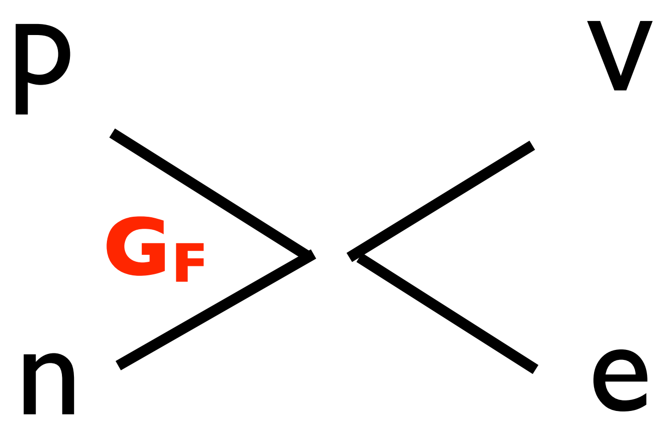
$$-\mathcal{L}_{S,P} = \bar{p}n \; \bar{e}(C_S + C_S' \gamma_5)\nu_e \; + \; \bar{p}\gamma_5 n \; \bar{e}\gamma_5 (C_P + C_P' \gamma_5)\nu_e + \text{h.c.}$$

$$-\mathcal{L}_T = \frac{1}{2} \bar{p}\sigma_{\mu\nu} n \; \bar{e}\sigma^{\mu\nu} (C_T + C_T' \gamma_5)\nu_e \; + \; \text{h.c.}$$

- P-invariance ⇔ $C_i' = 0$ or $C_i = 0$
- C-invariance ⇔ C_i real, C_i' imaginary (up to overall phase)
- T-invariance ⇔ C_i, C_i' real (up to overall phase)

Classic example: the making of the SM

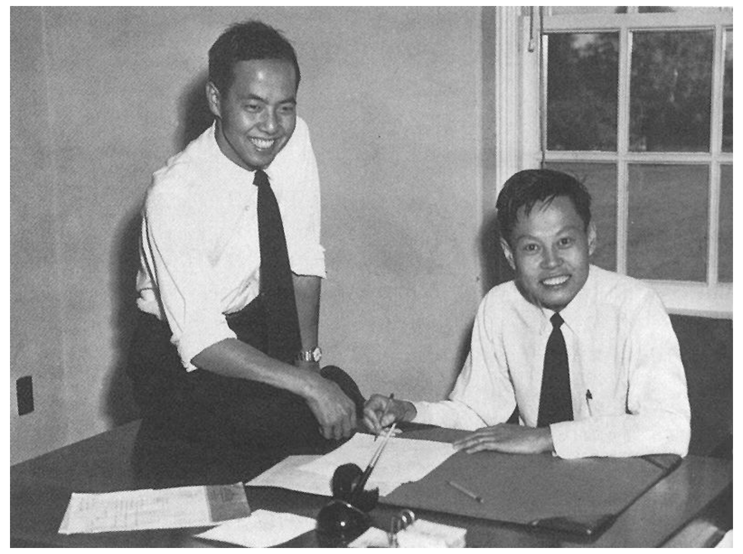
Fermi, 1934

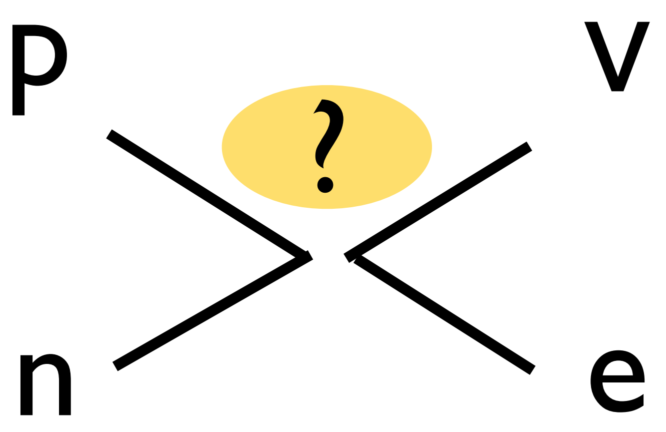


Current-current (VxV), parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956



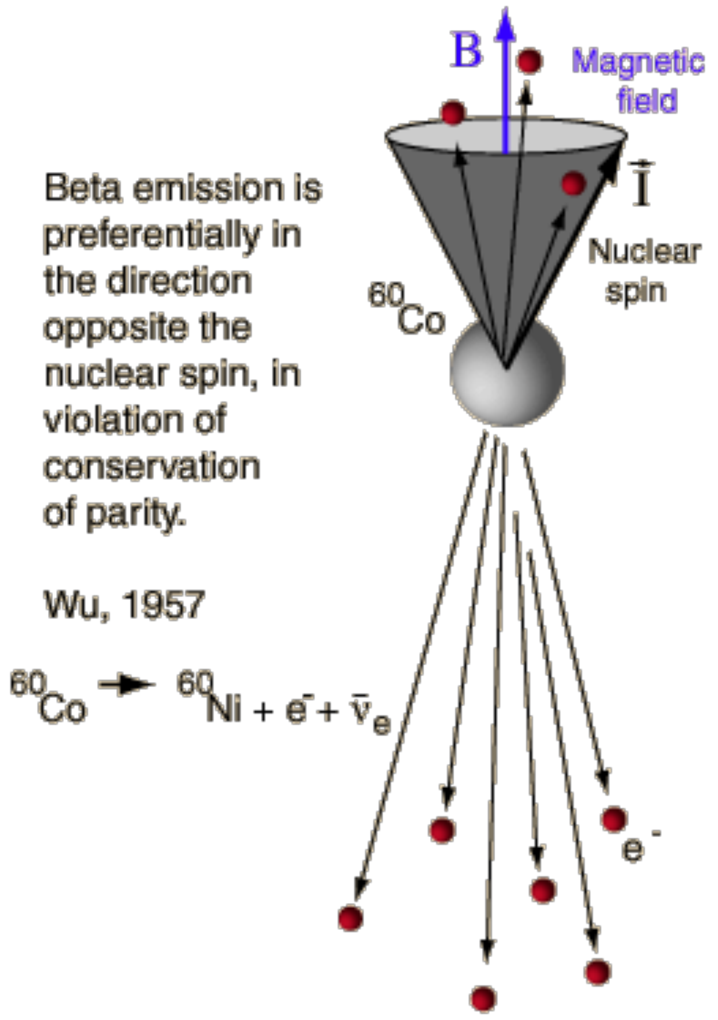


Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Experiment: parity is violated!

$d\Gamma \sim A\ \mathbf{J}\cdot\mathbf{p}_e$

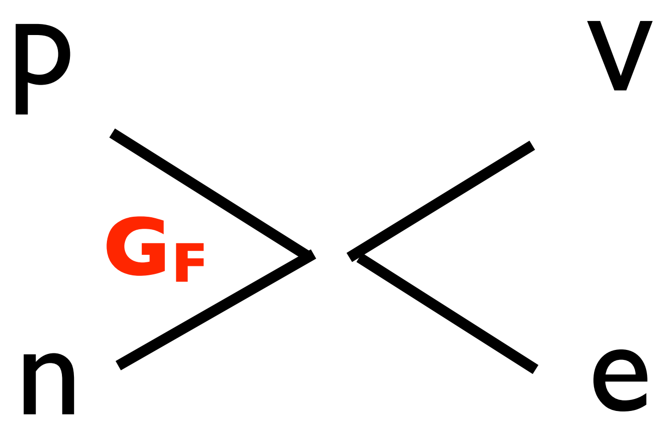
$A \sim -1$



C-S Wu

Classic example: the making of the SM

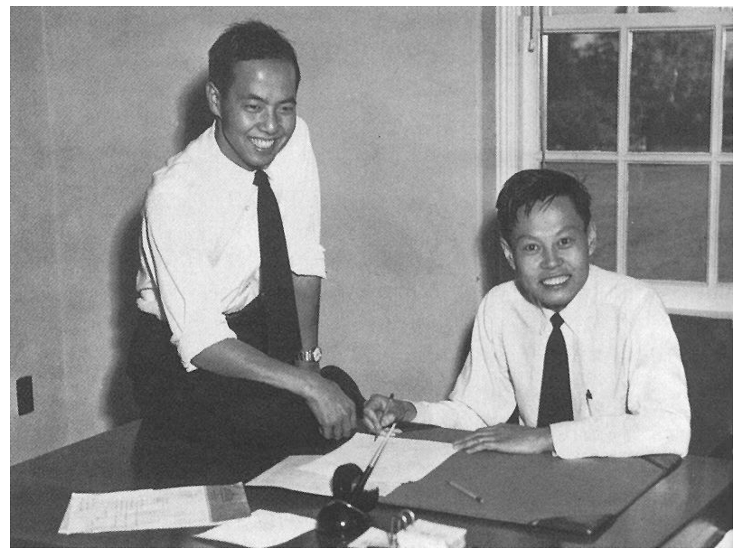
Fermi, 1934

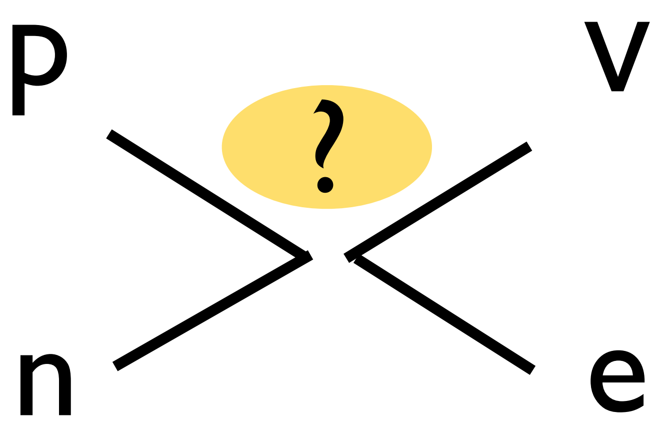


Current-current (VxV), parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956



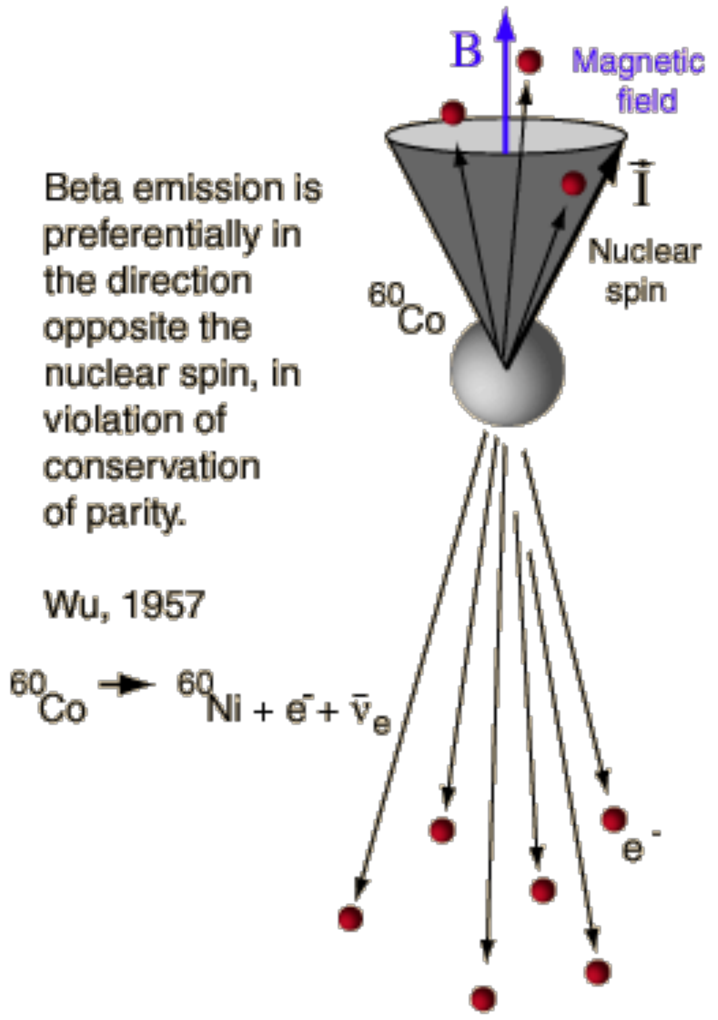


Parity conserving: VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Experiment: parity is violated!

$d\Gamma \sim A\ \mathbf{J}\cdot\mathbf{p}_e$

$A \sim -1$



C-S Wu

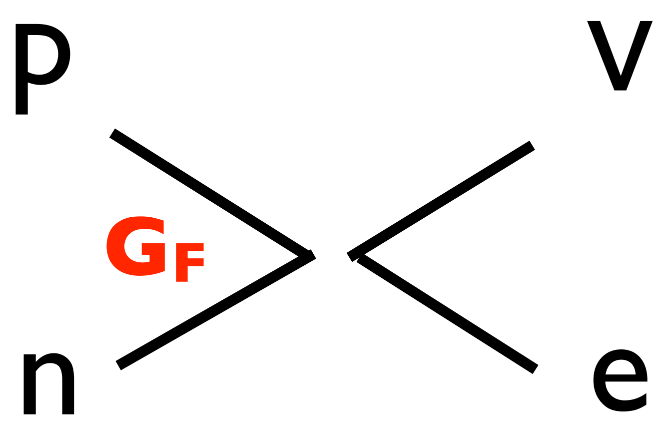
Information on lepton helicity $h_e = \hat{J}_e \cdot \hat{p}_e$

- $\Delta J_{nucl} = 1$ & $L_{lept}=0$ → e (and ν) spin aligned with J_{nucl} (B)
- Therefore $\langle h_e \rangle = \dfrac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-} = A\, v_e/c = -v_e/c$

Decay rate with electron spin parallel or antiparallel to the momentum

Classic example: the making of the SM

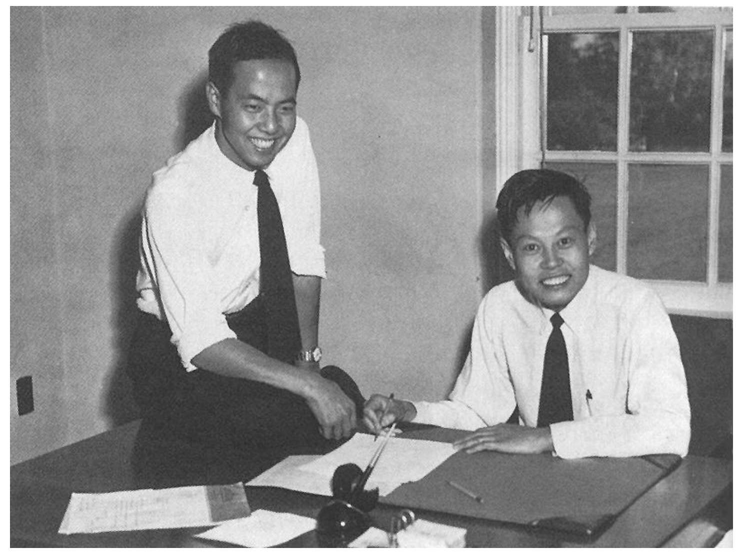
Fermi, 1934

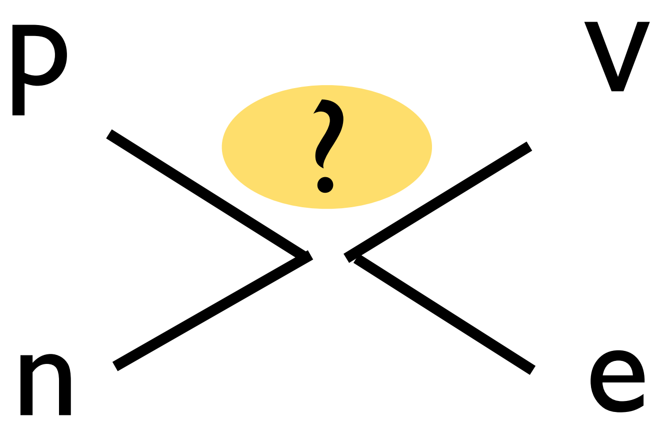


Current-current (VxV), parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956



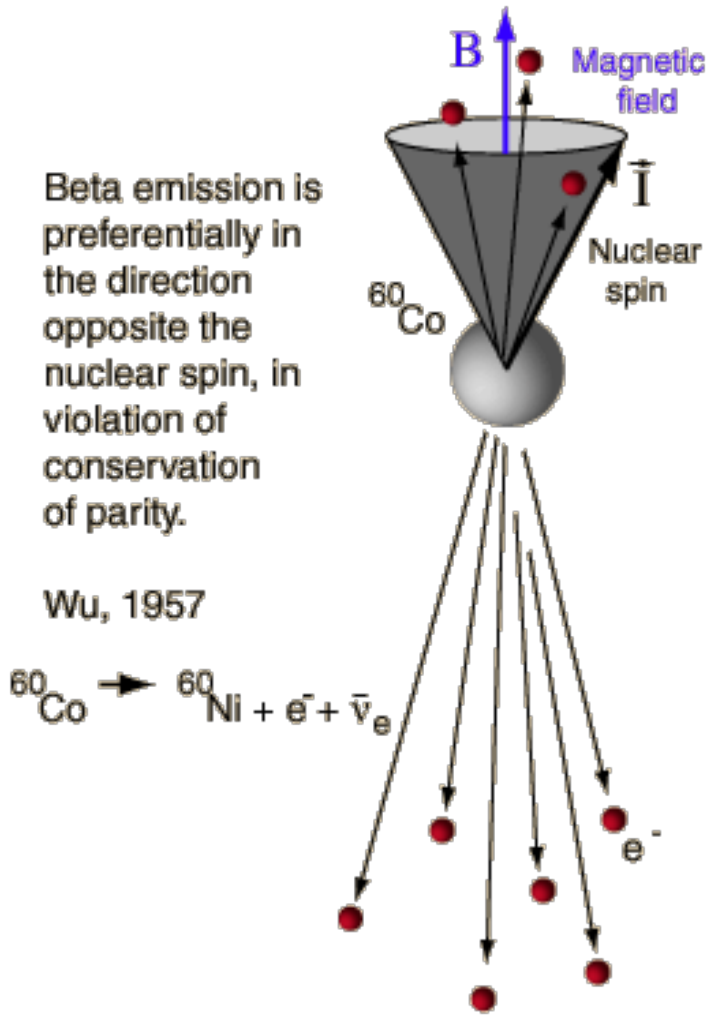


Parity conserving: VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Experiment: parity is violated!

$d\Gamma \sim A\ \mathbf{J}\cdot\mathbf{p}_e$

$A \sim -1$



C-S Wu

From e-capture measurements, $h_\nu = -1$, so

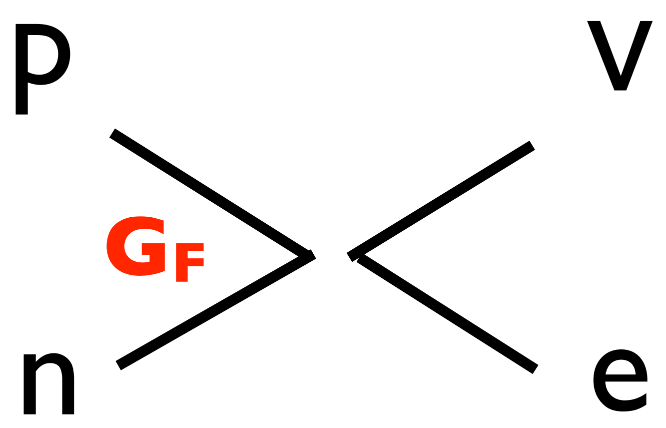
$$h(e^-) = -v/c \qquad h(\nu) = -1$$

$$h(e^+) = +v/c \qquad h(\bar{\nu}) = +1$$

P (and C) are maximally violated!

Classic example: the making of the SM

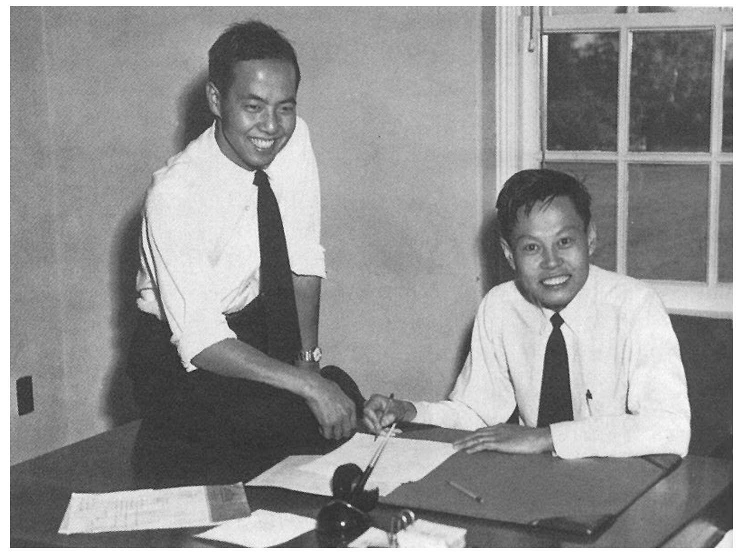
Fermi, 1934

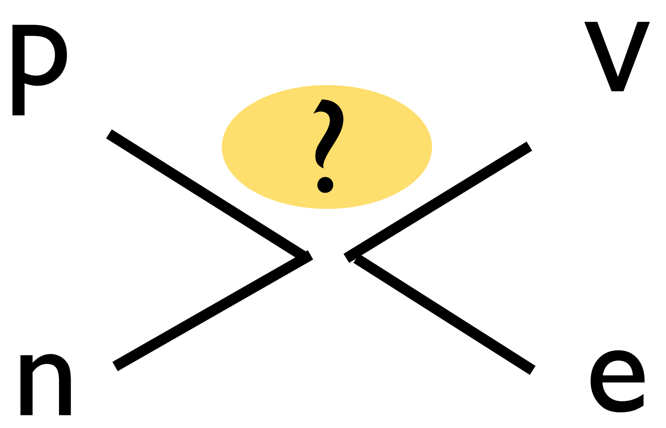


Current-current (VxV),
parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956



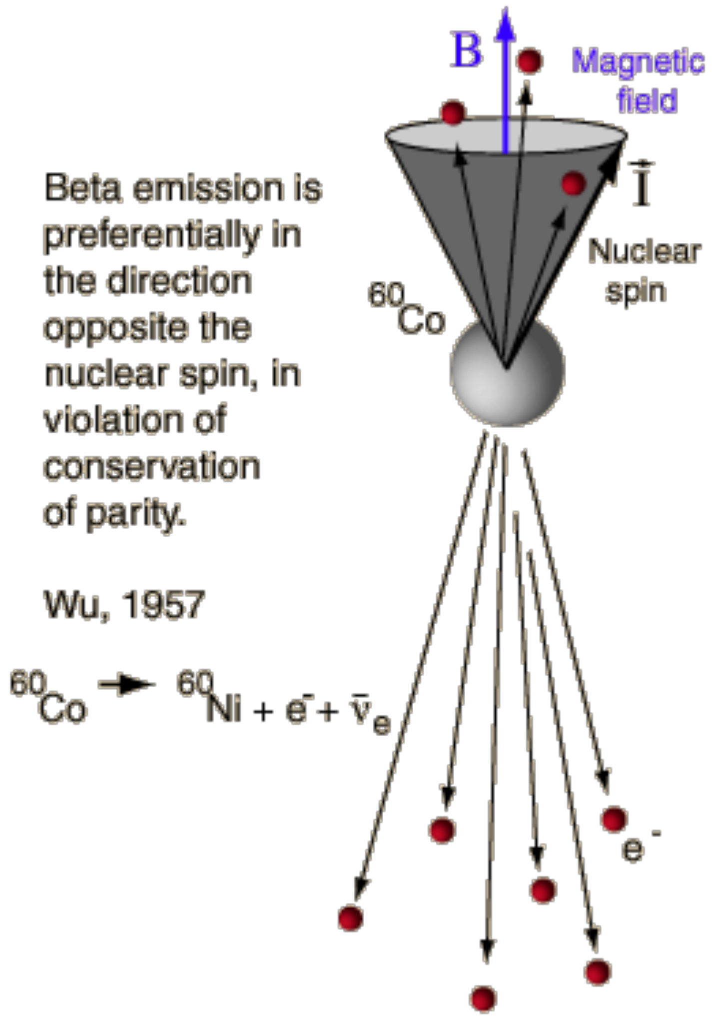


Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Experiment: parity is violated!

$d\Gamma \sim A\ \mathbf{J}\cdot\mathbf{p}_e$

$A \sim -1$



C-S Wu

From e-capture measurements, $h_\nu = -1$, so

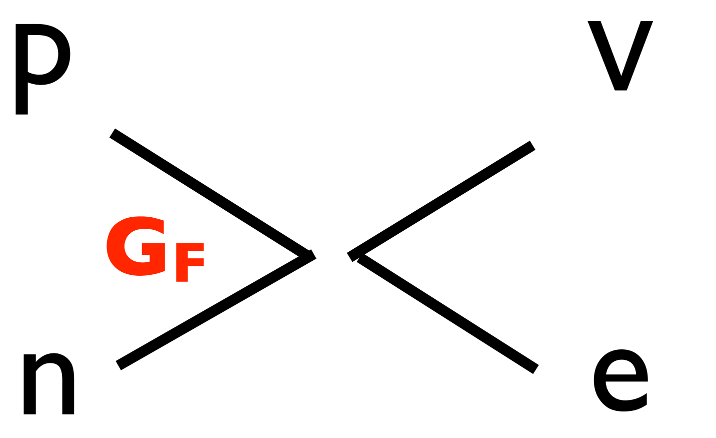
$$h(e^-) = -v/c \qquad h(\nu) = -1$$

$$h(e^+) = +v/c \qquad h(\bar{\nu}) = +1$$

Weak interactions involves only L-chiral fields
$(\nu_e)_L = (1 - \gamma_5)/2\ \nu_e$ and $e_L = (1 - \gamma_5)/2\ e$

Classic example: the making of the SM

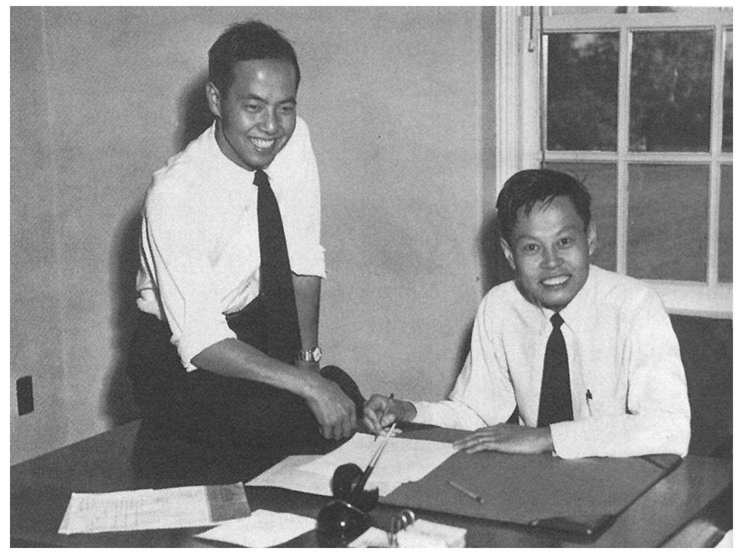
Fermi, 1934

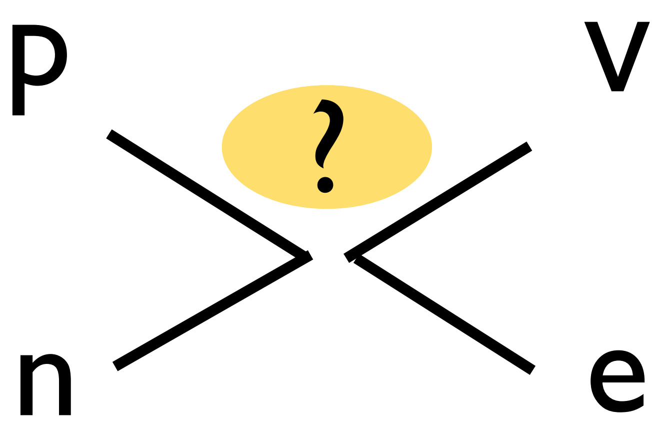


Current-current (VxV), parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956



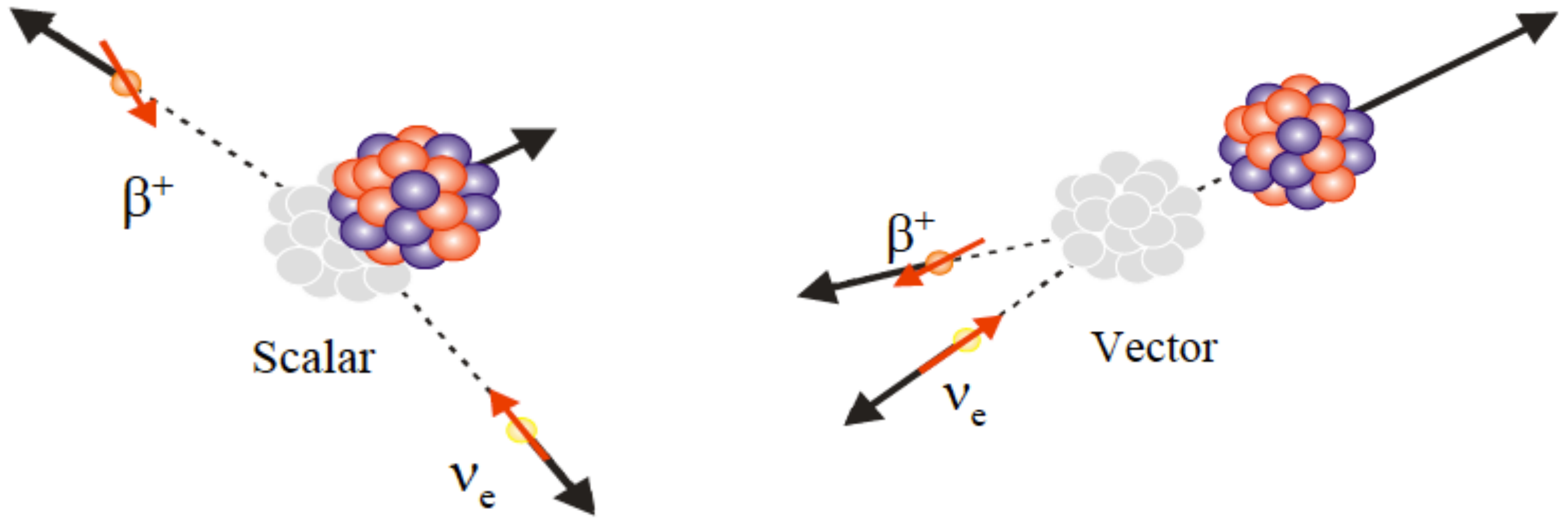


Parity conserving: VV, AA, SS, TT ...

Parity violating: VA, SP, ...

Differential decay distributions depend on structure of currents

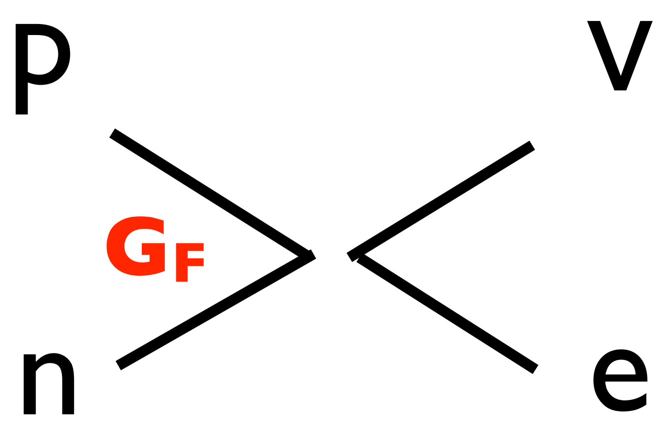
Example; e-ν correlation in Fermi β^+ decay (a(V)=+1, a(S)=−1)



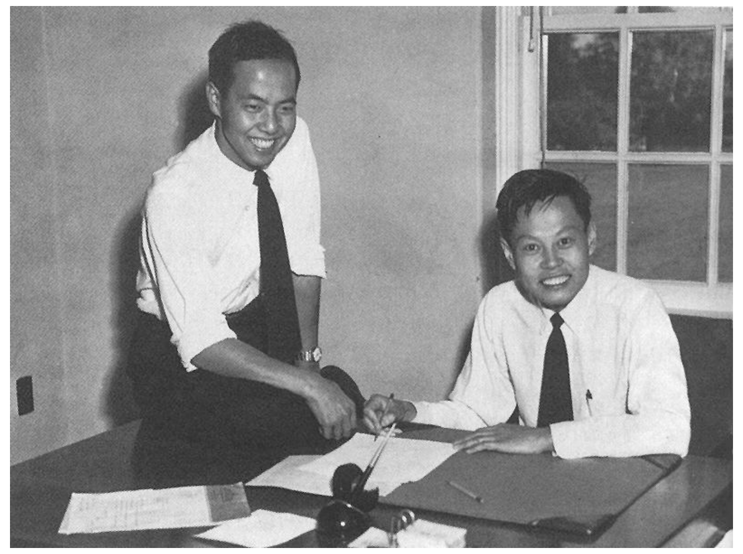
Model diagnosing!

Classic example: the making of the SM

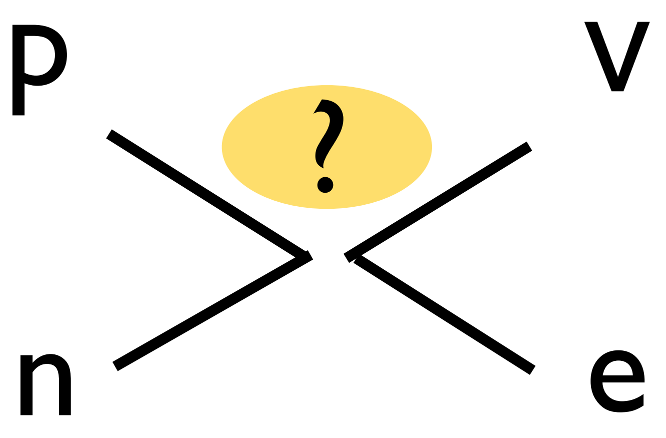
Fermi, 1934



Current-current (VxV), parity conserving



Lee and Yang, 1956



Parity conserving: VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Marshak & Sudarshan, Feynman & Gell-Mann 1958

It's (V-A)*(V-A) !!

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

$$C_V \equiv \frac{1}{\Lambda_W^2} \qquad \Lambda_W \sim 350\,\mathrm{GeV}$$

$$C_A \sim C_V$$

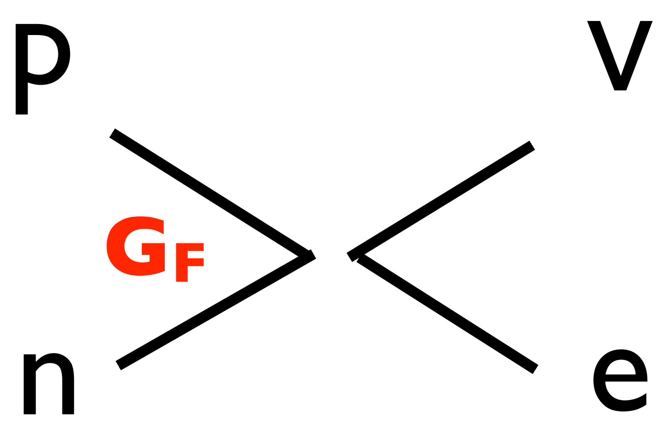
$$C_V = C_V' \qquad C_A = C_A'$$

$$C_{S,P,T}/C_V,\; C'_{S,P,T}/C_V \;\leq\; \text{few } \%$$

- Weak decays probe scales of O(100 GeV) >> $m_{n,p}$!!
- P (and C) maximally violated; chiral nature of the weak couplings
- Information on nature of underlying force mediators ($\Lambda_{S,T} \geq$ TeV)

Classic example: the making of the SM

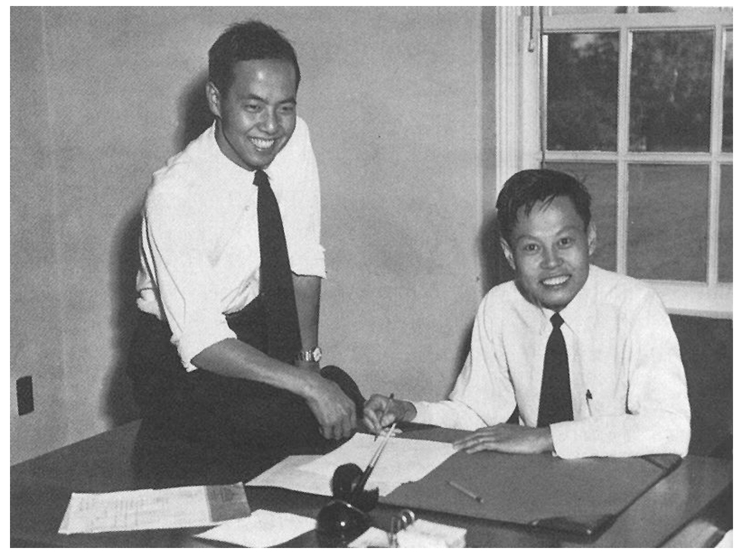
Fermi, 1934

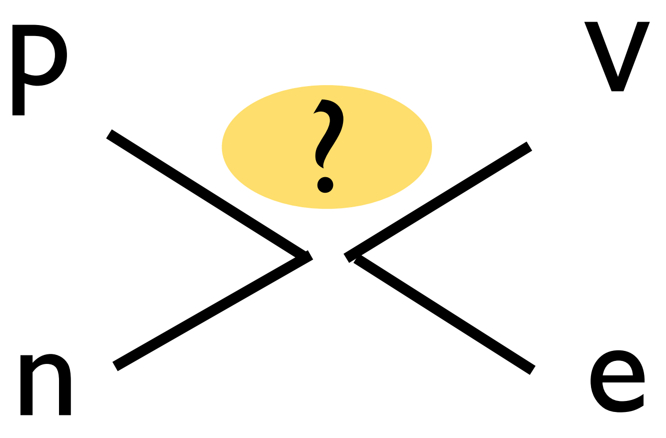


Current-current (VxV), parity conserving

Fermi scale:
$\Lambda_F = G_F^{-1/2} \sim 250$ GeV

Lee and Yang, 1956





Parity conserving: VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Marshak & Sudarshan,
Feynman & Gell-Mann 1958

It's (V-A)*(V-A) !!

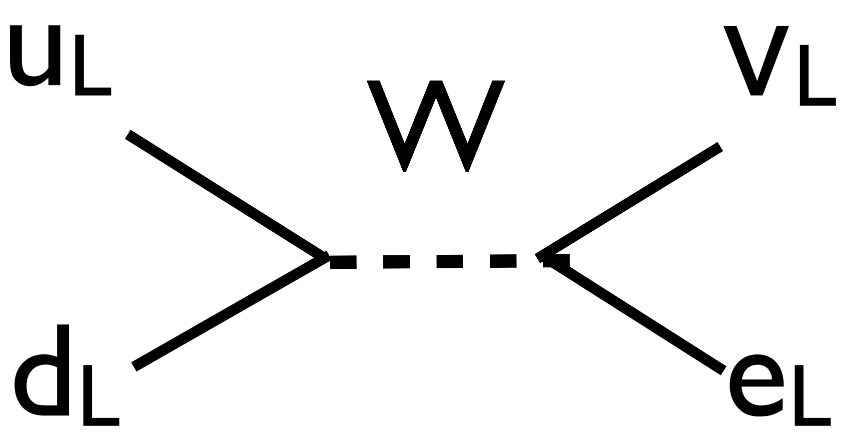
"V-A was the key"
S. Weinberg

Glashow, Salam, Weinberg


Sheldon Lee Glashow


Abdus Salam

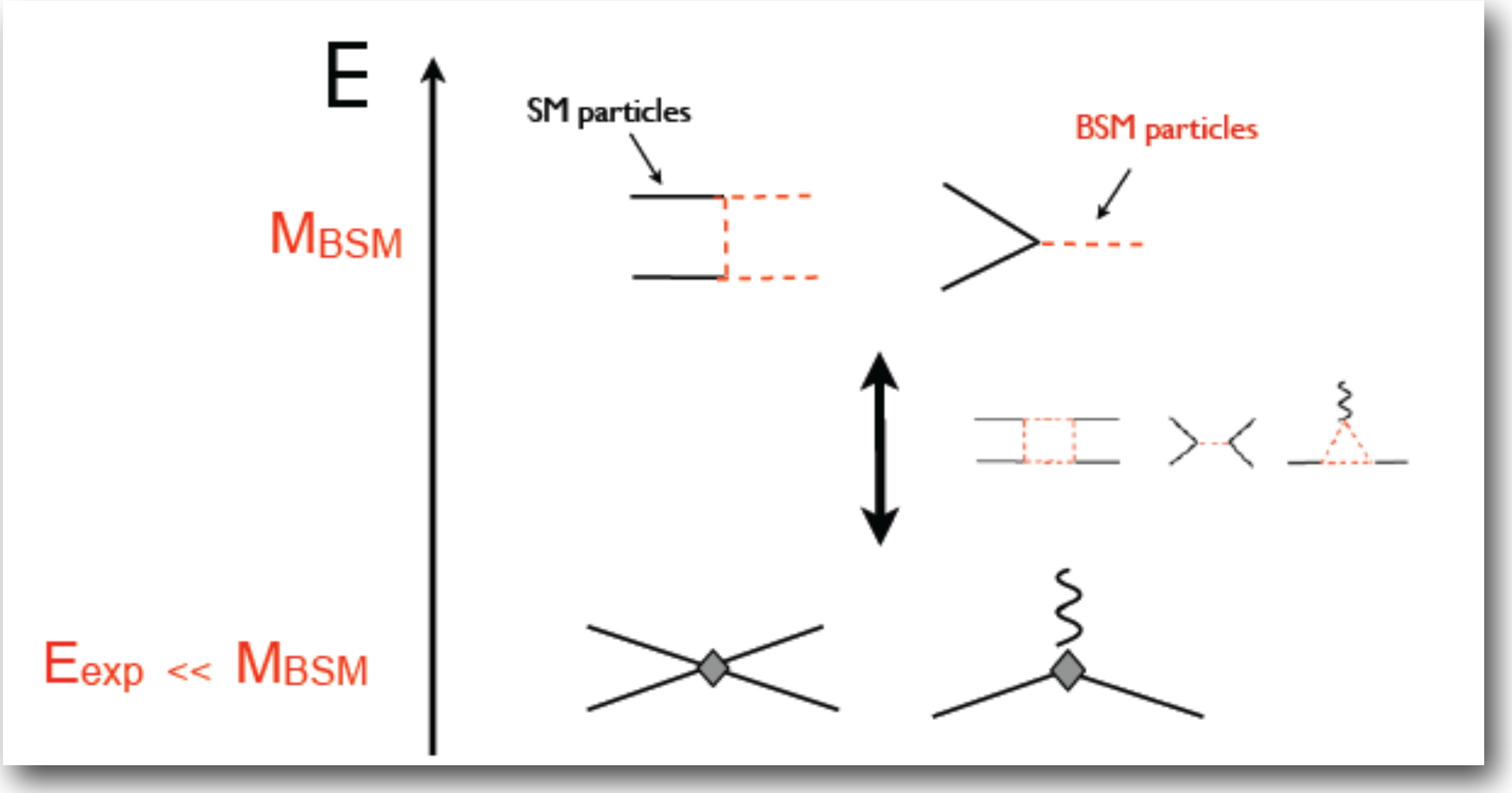

Steven Weinberg



Embed in non-abelian chiral gauge theory, predict neutral currents

Fast forward from 1956 to now: SMEFT

- In a model-independent way, describe effects of new physics originating at $\Lambda >> v_{ew}$ through local operators



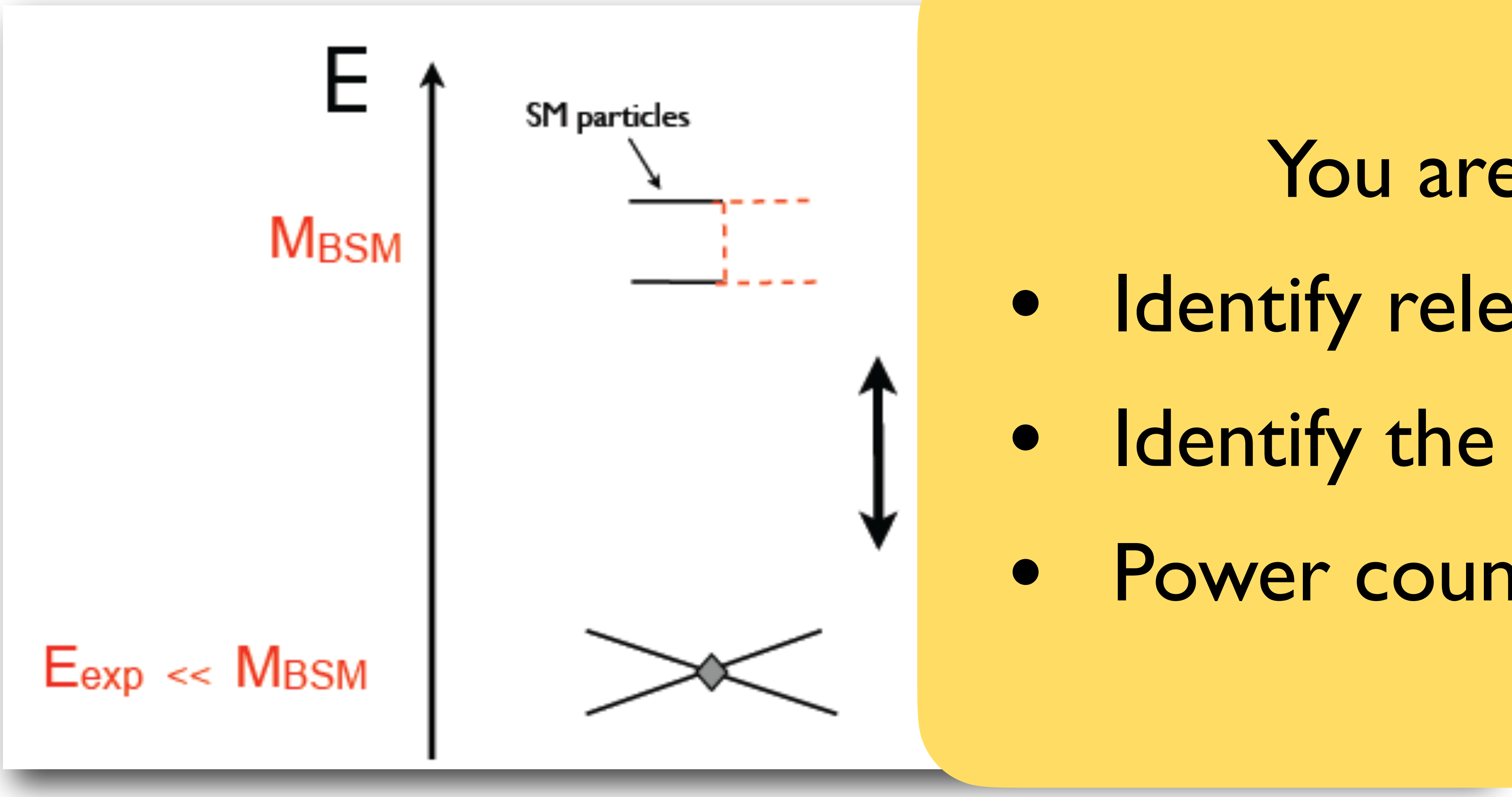
[$\Lambda \leftrightarrow M_{BSM}$] $C_i\ [g_{\rm BSM},\ M_a/M_b]$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

- "Standard Model EFT" (SMEFT):
  - ★ Build operators out of SM fields
  - ★ Impose Lorentz + SM gauge symmetry, but no other symmetry (B, L, CP, flavor)**
  - ★ Organize operators according to mass dimension: power counting in E/Λ, M_W/Λ. At a given order the EFT is renormalizable and predictive

Fast forward from 1956 to now: SMEFT

- In a model-independent way, describe effects of new physics originating at $\Lambda \gg v_{ew}$ through local operators



You are seeing again the 3 tenets of any EFT:

- Identify relevant degrees of freedom
- Identify the symmetries of the problem
- Power counting — expansion parameter

$$\ldots \mathrm{M},\ M_a/M_b]$$

$$\ldots \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

- "Standard Model EFT" (SMEFT):
  - ★ Build operators out of SM fields
  - ★ Impose Lorentz + SM gauge symmetry, but no other symmetry (B, L, CP, flavor)**
  - ★ Organize operators according to mass dimension: power counting in E/Λ, M_W/Λ.
    At a given order the EFT is renormalizable and predictive

The Standard Model and its symmetries

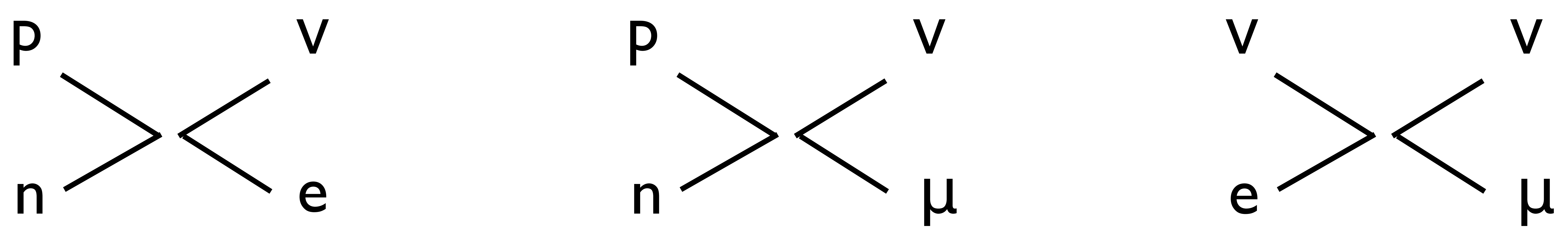
A closer look to the V-A theory

- By 1958 it became clear that a “universal” theory of weak interaction accounting for μ and β decays and e/μ capture had the V-A structure

$$\mathcal{L}_{\rm eff} \; = \; 2\sqrt{2} G_F \; J_\mu^- J^{\mu +} \qquad G_F^{-1/2} \simeq 250 \text{ GeV}$$

$$J_\mu^+ = \bar{p}\gamma_\mu \frac{1-\gamma_5}{2} n \; + \; \bar{\nu}\gamma_\mu \frac{1-\gamma_5}{2} e \qquad J_\mu^+ = (J_\mu^-)^\dagger$$

There is a similar term involving muons



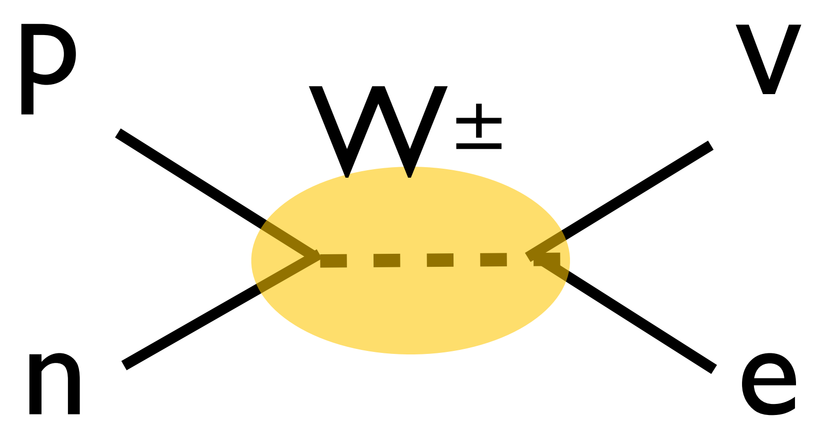
A closer look to the V-A theory

- By 1958 it became clear that a "universal" theory of weak interaction accounting for μ and β decays and e/μ capture had the V-A structure

$$\mathcal{L}_{\text{eff}} = 2\sqrt{2} G_F \, J_\mu^- J^{\mu+} \qquad G_F^{-1/2} \simeq 250 \text{ GeV}$$

$$J_\mu^+ = \bar{p}\gamma_\mu \frac{1-\gamma_5}{2} n + \bar{\nu}\gamma_\mu \frac{1-\gamma_5}{2} e \qquad J_\mu^+ = (J_\mu^-)^\dagger$$

- By analogy with QED, it was conjectured early on that this interaction results from the exchange of a massive spin-1 vector boson



$$\mathcal{L}_{\text{int}} = \frac{g}{\sqrt{2}} W_\mu^+ J_\mu^+ + h.c. \longrightarrow \frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

- Theory developments in the 60's: only consistent theory of massive vector bosons is gauge with Higgs mechanism

From V-A theory to the Standard Model

- To identify the gauge symmetry group, match interaction suggested by EFT analysis …

$$\mathcal{L}_{\rm int} = \frac{g}{\sqrt{2}} W^+_\mu J^+_\mu + h.c. \qquad J^+_\mu = \bar{p}\gamma_\mu \frac{1-\gamma_5}{2} n + \bar{\nu}\gamma_\mu \frac{1-\gamma_5}{2} e \qquad J^+_\mu = (J^-_\mu)^\dagger$$

- … to the general form of (non-abelian) gauge interaction

$$\mathcal{L} = \bar{\psi}\,(i\gamma_\mu \partial^\mu - m)\,\psi + g\,\bar{\psi}\gamma^\mu\, T^a A^a_\mu\, \psi - \frac{1}{2}{\rm Tr}\,(F_{\mu\nu}F^{\mu\nu})$$

$$g\, A^a_\mu\, J^{\mu,a} \qquad J^{\mu,a} = \bar{\psi}\gamma^\mu T^a \psi$$

From V-A theory to the Standard Model

- To identify the gauge symmetry group, match interaction suggested by EFT analysis …

$$\mathcal{L}_{\rm int} = \frac{g}{\sqrt{2}} W_\mu^+ J_\mu^+ + h.c. \qquad J_\mu^+ = \bar{p}\gamma_\mu \frac{1-\gamma_5}{2} n + \bar{\nu}\gamma_\mu \frac{1-\gamma_5}{2} e \qquad J_\mu^+ = (J_\mu^-)^\dagger$$

- … to the general form of (non-abelian) gauge interaction

$$\mathcal{L} = \bar{\psi}\,(i\gamma_\mu\partial^\mu - m)\,\psi + g\,\bar{\psi}\gamma^\mu\,T^a A_\mu^a\,\psi - \frac{1}{2}\mathrm{Tr}\,(F_{\mu\nu}F^{\mu\nu})$$

$$g\,A_\mu^a\,J^{\mu,a} \qquad J^{\mu,a} = \bar{\psi}\gamma^\mu T^a \psi$$

U(x) ϵ G → Gauge group

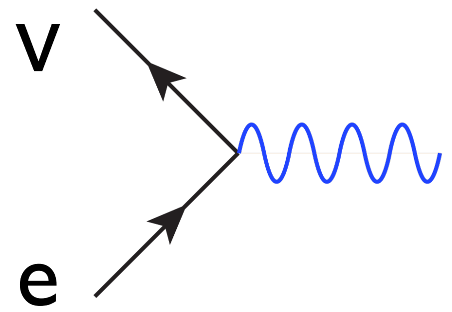
$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \cdots \end{pmatrix} \qquad \psi(x) \to U(x)\,\psi(x) \qquad U(x) = e^{i\epsilon^a(x)T^a} \qquad [T^a, T^b] = i f^{abc} T^c$$

$$A_\mu = A_\mu^a T^a \qquad A^\mu \to U\,A^\mu\,U^\dagger - \frac{i}{g}(\partial^\mu U)U^\dagger \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu, A_\nu] \qquad F_{\mu\nu} \to U\,F_{\mu\nu}\,U^\dagger$$

From V-A theory to the Standard Model

- By re-writing the current in terms of L-handed fermion "doublets", key features of gauge theory emerge

$$J^{\mu,a} = \bar{\psi}\gamma^{\mu}T^{a}\psi$$



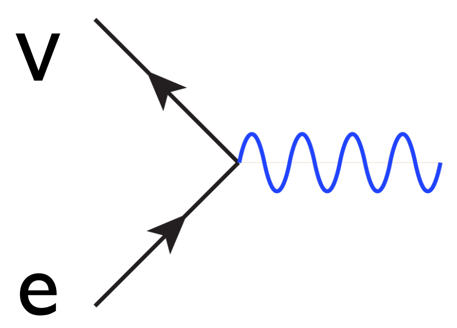
$$J_{\mu}^{+} = \bar{p}\gamma_{\mu}\frac{1-\gamma_5}{2}n \; + \; \bar{\nu}\gamma_{\mu}\frac{1-\gamma_5}{2}e \quad \longrightarrow \quad J_{\mu}^{+} = \bar{N}_L\gamma_{\mu}\frac{\sigma^{+}}{2}N_L \; + \; \bar{L}_L\gamma_{\mu}\frac{\sigma^{+}}{2}L_L$$

$$N_L = \frac{1-\gamma_5}{2}\begin{pmatrix} p \\ n \end{pmatrix} \qquad L_L = \frac{1-\gamma_5}{2}\begin{pmatrix} \nu \\ e \end{pmatrix} \qquad \sigma^{\pm} = \sigma_1 \pm i\sigma_2 \qquad \frac{\sigma^{+}}{2} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

From V-A theory to the Standard Model

- By re-writing the current in terms of L-handed fermion "doublets", key features of gauge theory emerge

$J^{\mu,a} = \bar{\psi}\gamma^\mu T^a \psi$



$$J_\mu^+ = \bar{p}\gamma_\mu \frac{1-\gamma_5}{2} n \; + \; \bar{\nu}\gamma_\mu \frac{1-\gamma_5}{2} e \quad \longrightarrow \quad J_\mu^+ = \bar{N}_L \gamma_\mu \frac{\sigma^+}{2} N_L \; + \; \bar{L}_L \gamma_\mu \frac{\sigma^+}{2} L_L$$

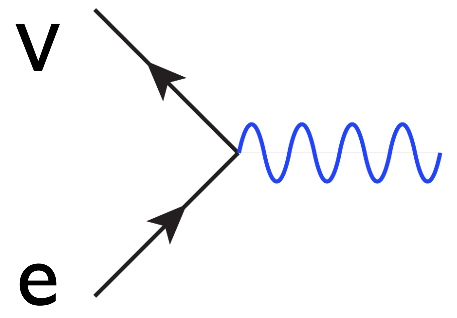
$$N_L = \frac{1-\gamma_5}{2}\begin{pmatrix} p \\ n \end{pmatrix} \qquad L_L = \frac{1-\gamma_5}{2}\begin{pmatrix} \nu \\ e \end{pmatrix} \qquad \sigma^\pm = \sigma_1 \pm i\sigma_2 \qquad \frac{\sigma^+}{2} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

1. It involves the non-abelian gauge group SU(2) under which (n,p) [or (u,d)] and (e,v) transform as doublets. Prediction of neutral currents! Quantum numbers are such that 3rd gauge boson cannot be the photon. Minimal group is SU(2)xU(1)

From V-A theory to the Standard Model

- By re-writing the current in terms of L-handed fermion "doublets", key features of gauge theory emerge

$J^{\mu,a} = \bar{\psi}\gamma^\mu T^a \psi$



$$J^+_\mu = \bar{p}\gamma_\mu \frac{1-\gamma_5}{2} n + \bar{\nu}\gamma_\mu \frac{1-\gamma_5}{2} e \longrightarrow J^+_\mu = \bar{N}_L \gamma_\mu \frac{\sigma^+}{2} N_L + \bar{L}_L \gamma_\mu \frac{\sigma^+}{2} L_L$$

$$N_L = \frac{1-\gamma_5}{2}\begin{pmatrix} p \\ n \end{pmatrix} \qquad L_L = \frac{1-\gamma_5}{2}\begin{pmatrix} \nu \\ e \end{pmatrix} \qquad \sigma^\pm = \sigma_1 \pm i\sigma_2 \qquad \frac{\sigma^+}{2} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

1. It involves the non-abelian gauge group SU(2) under which (n,p) [or (u,d)] and (e,ν) transform as doublets. Prediction of neutral currents! Quantum numbers are such that 3rd gauge boson cannot be the photon. Minimal group is SU(2)xU(1)

2. It involves chiral fermions (V-A structure). L and R fermions have different 'weak charges'

$$\psi_{L,R} = \frac{1 \mp \gamma_5}{2}\psi$$

$\Psi_{L,R}$: chiral fields. For m=0,
Ψ_L : L-handed (h=-1) particles, R-handed anti-particles (h=+1)
Ψ_R : R-handed (h=+1) particles, L-handed anti-particles (h=-1)

The Standard Model gauge group

(No time to review the fascinating story of the 'color' group of strong interactions)

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

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

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

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

Fundamental representation (color triplets and weak doublets)

SM(EFT): building blocks

- Gauge group: G= $SU(3)_c$ x $SU(2)_W$ x $U(1)_Y$
- Building blocks: fields and their "charges" (transformation properties under G)

	$SU(3)_c$ x $SU(2)_W$ x $U(1)_Y$ 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)	$\varphi \to V_{SU(2)}\, \varphi$

$Q = T_3 + Y$

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

Gauge transformation:

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

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

SM(EFT): building blocks

- Gauge group: G= $SU(3)_c \times SU(2)_W \times U(1)_Y$
- Building blocks: fields and their "charges" (transformation properties under G)

	$SU(3)_c \times SU(2)_W \times U(1)_Y$ 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)	$\varphi \to V_{SU(2)}\, \varphi$

$Q = T_3 + Y$

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

Gauge transformation:

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

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

- Recipe to build the SM Lagrangian: write down all Lorentz and gauge invariant operators of dimension ≤ 4
- SMEFT: go beyond mass dimension 4

Backup

(Incomplete) List of acronyms

- ALPs: Axion-Like Particles
- BNV: Baryon Number Violation
- CC: (weak) charged current
- CP: Charge-Parity
- CPV: CP Violation
- EDM: Electric Dipole Moment
- EFT: Effective Field Theory
- FCNC: Flavor Changing Neutral Currents
- IR: infrared
- LEFT: Low Energy EFT (below the weak scale)
- LFV: Lepton Flavor Violation
- LNV: Lepton Number Violation
- NC: (weak) neutral current
- SM: Standard Model
- SMEFT: Standard Model EFT
- UV: ultraviolet

Non abelian gauge symmetry

- Recall U(1) (abelian) example

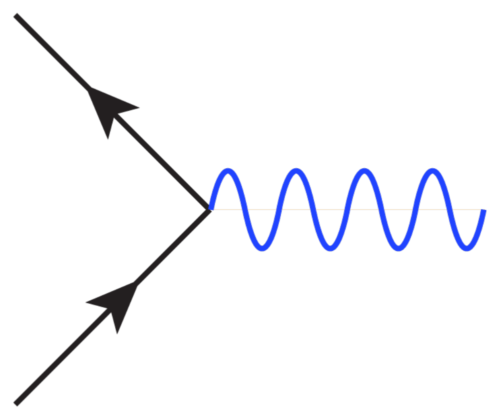
$$\psi(x) \rightarrow e^{i\epsilon(x)}\psi(x) \qquad \mathcal{L} = \bar{\psi}\left(i\gamma_\mu\partial^\mu - m\right)\psi$$

$$A^\mu \rightarrow A^\mu + \frac{1}{g}\partial^\mu\epsilon \qquad + g\,\bar{\psi}\gamma_\mu A^\mu \psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

- Form of the interaction:

$$\mathcal{L}_{\text{int}} = g\,A_\mu\,J^\mu$$



$$J^\mu = \bar{\psi}\gamma^\mu\psi$$

conserved current associated with global U(1)

Non abelian gauge symmetry

- Generalize to non-abelian group G (e.g. SU(2), SU(3), …).

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \cdots \end{pmatrix}$$

$$\psi(x) \;\rightarrow\; U(x)\,\psi(x) \qquad U(x) = e^{i\epsilon^a(x)T^a} \qquad [T^a, T^b] = i f^{abc} T^c$$

- Invariant dynamics if introduce new vector fields transforming as

$$A_\mu = A_\mu^a\, T^a$$

$$A^\mu \;\rightarrow\; U\,A^\mu\,U^\dagger - \frac{i}{g}(\partial^\mu U)U^\dagger$$

$$\mathcal{L} = \bar{\psi}\,(i\gamma_\mu\partial^\mu - m)\,\psi \;+\; g\,\bar{\psi}\gamma^\mu\,T^a A_\mu^a\,\psi \;-\; \frac{1}{2}\mathrm{Tr}\,(F_{\mu\nu}F^{\mu\nu})$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu, A_\nu] \qquad F_{\mu\nu} \rightarrow U\,F_{\mu\nu}\,U^\dagger$$

Non abelian gauge symmetry

- Generalize to non-abelian group G (e.g. SU(2), SU(3), …). $\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \cdots \end{pmatrix}$

$$\psi(x) \to U(x)\,\psi(x) \qquad U(x) = e^{i\epsilon^a(x)T^a} \qquad [T^a, T^b] = i f^{abc} T^c$$

- Invariant dynamics if introduce new vector fields transforming as $A_\mu = A_\mu^a\, T^a$

$$A^\mu \to U\, A^\mu\, U^\dagger - \frac{i}{g}(\partial^\mu U)U^\dagger$$

$$\mathcal{L} = \bar\psi\,(i\gamma_\mu \partial^\mu - m)\,\psi + g\,\bar\psi\gamma^\mu\, T^a A_\mu^a\,\psi - \frac{1}{2}\mathrm{Tr}\,(F_{\mu\nu}F^{\mu\nu})$$

$$\bar\psi\, i\gamma^\mu D_\mu\,\psi \qquad D_\mu \equiv \partial_\mu - igT^a A_\mu^a$$

covariant derivative

Non abelian gauge symmetry

- Generalize to non-abelian group G (e.g. SU(2), SU(3), …). $\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \cdots \end{pmatrix}$

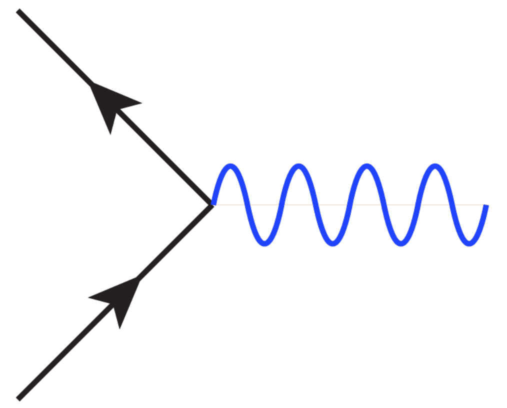
$$\psi(x) \;\to\; U(x)\,\psi(x) \qquad U(x) = e^{i\epsilon^a(x)T^a} \qquad [T^a, T^b] = i f^{abc} T^c$$

- Invariant dynamics if introduce new vector fields transforming as $A_\mu = A_\mu^a\, T^a$

$$A^\mu \;\to\; U\, A^\mu\, U^\dagger - \frac{i}{g}(\partial^\mu U) U^\dagger$$

- Form of the interaction:

$$\mathcal{L}_{\rm int} \;=\; g\, A_\mu^a\, J^{\mu,a} \qquad J^{\mu,a} = \bar\psi \gamma^\mu T^a \psi$$



Fermion part of the conserved currents associated with global G symmetry