Baryon asymmetry of the Universe

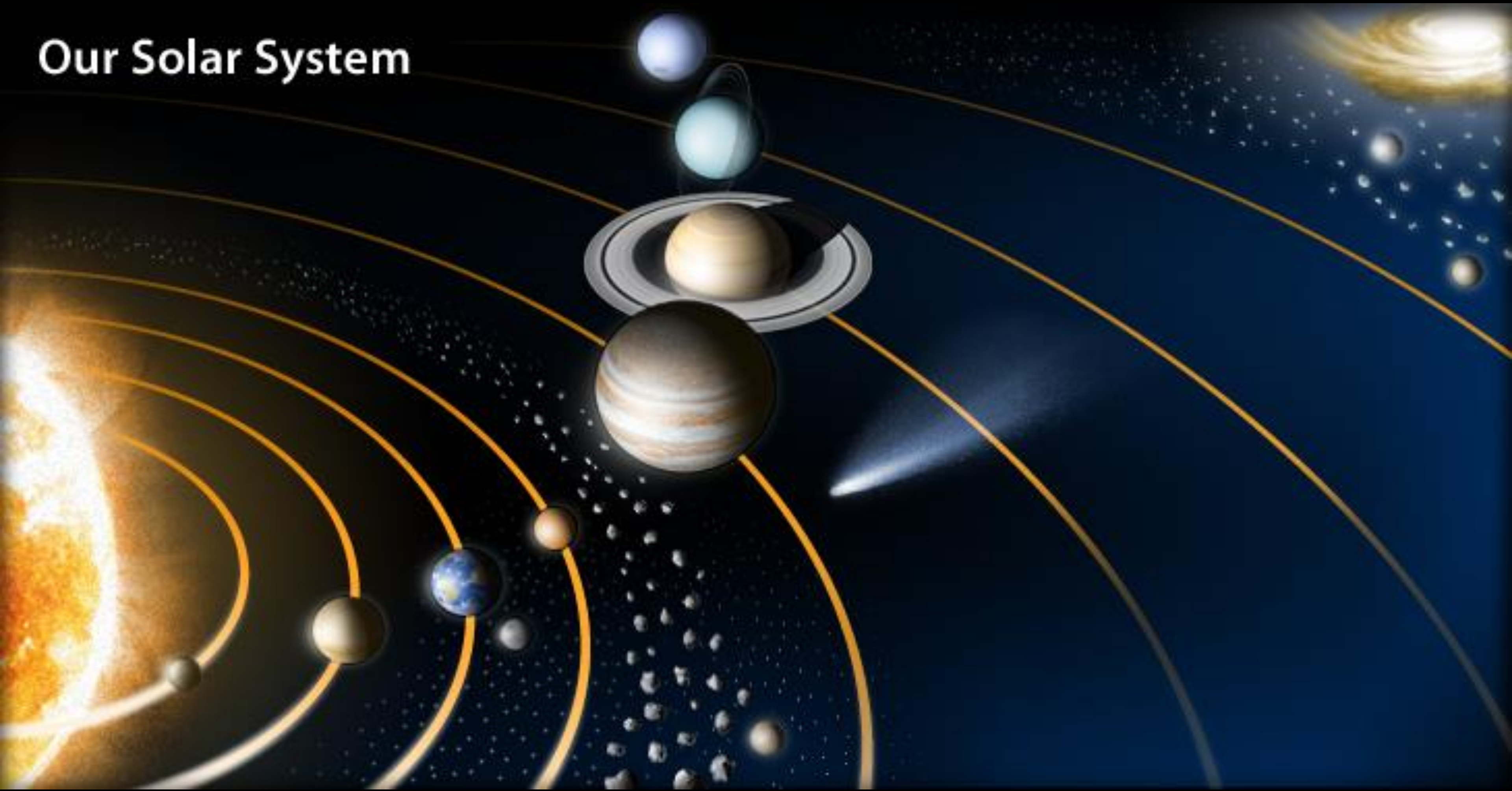
experiment and theory

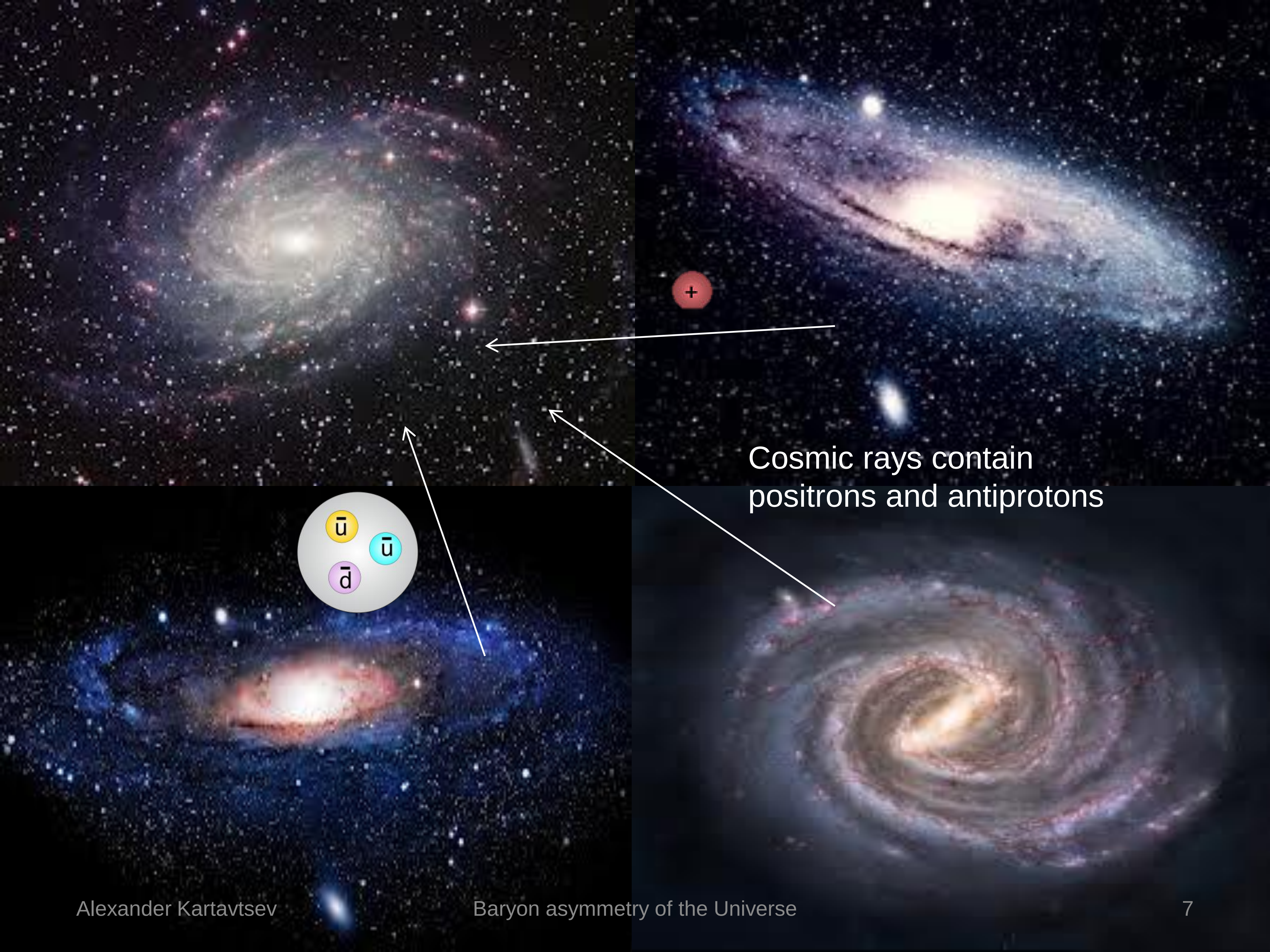
Alexander Kartavtsev, Max-Planck-Institut für Physik, München

Paul Dirac

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

Carl Anderson


Our Solar System

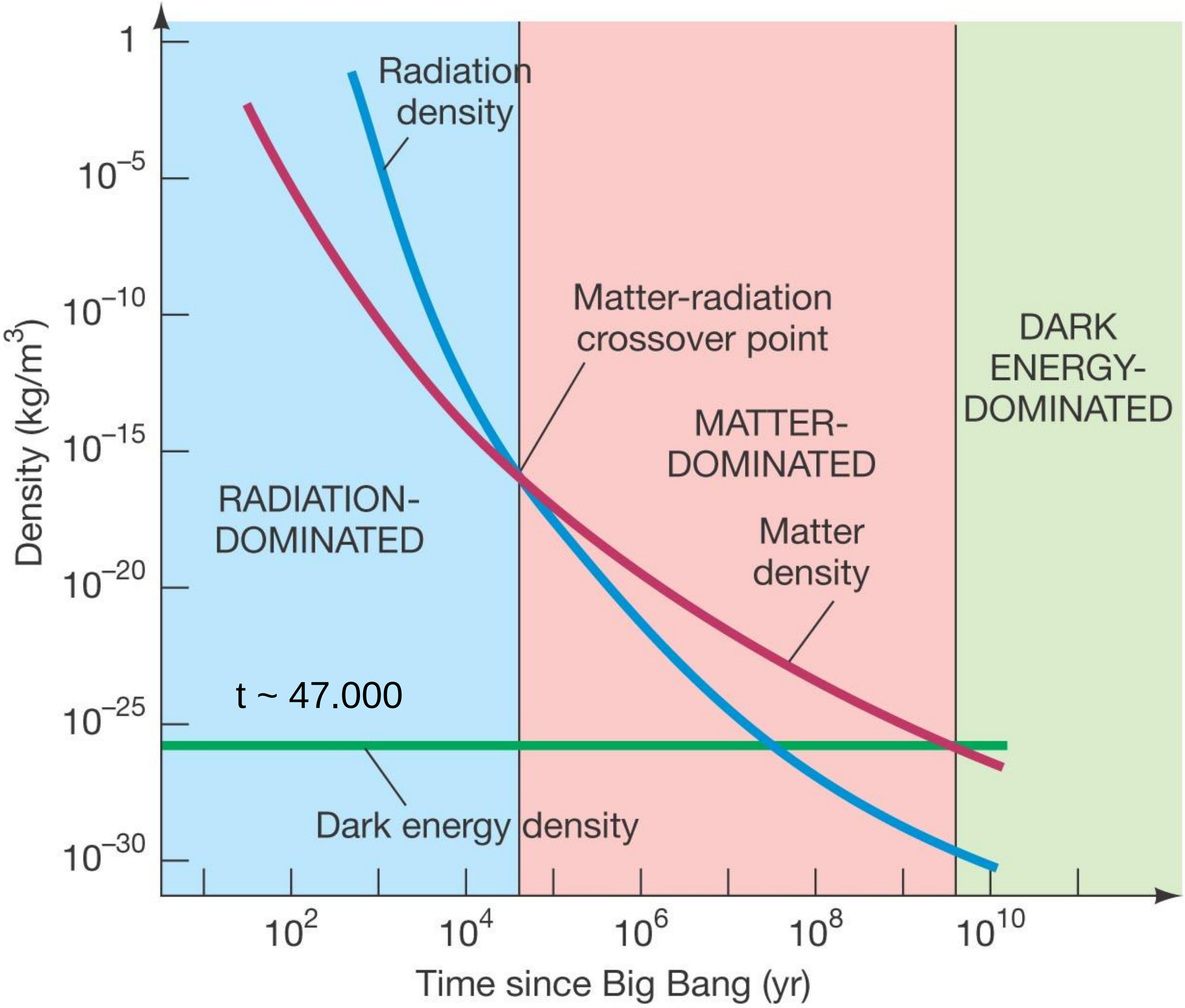

Cosmic rays contain
positrons and antiprotons
+
ū
ū
d̄

Why is the Universe baryonically asymmetric ?

Outline

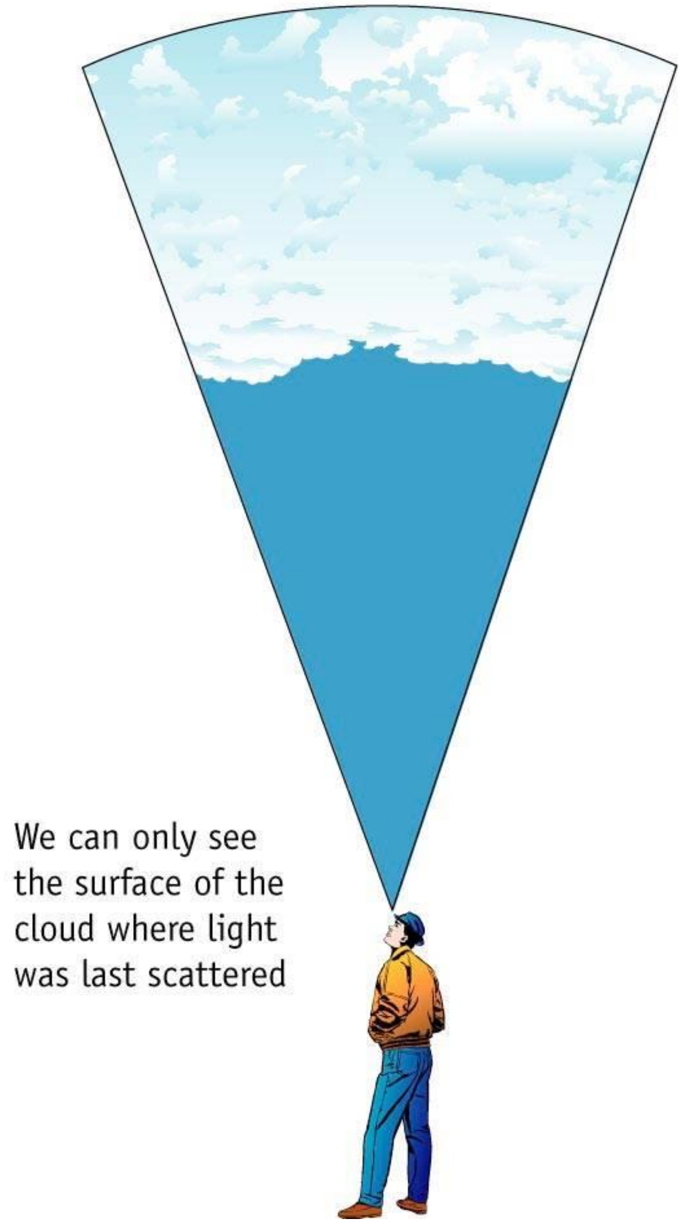
- Experimental evidence
  - Cosmic Microwave Background
  - Big Bang Nucleosynthesis
- Theoretical interpretation
  - Baryon number violation
  - Baryogenesis via leptogenesis

Cosmic microwave background

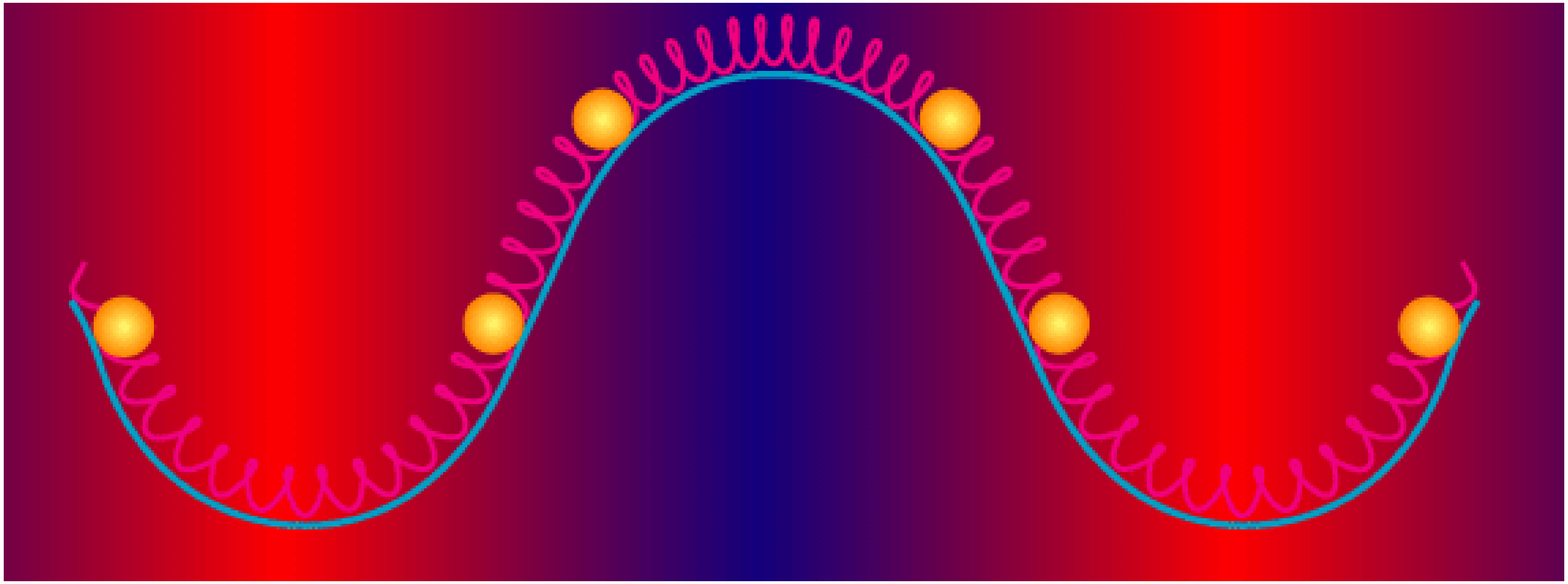


Radiation density
Matter-radiation crossover point
DARK ENERGY-DOMINATED
MATTER-DOMINATED
RADIATION-DOMINATED
Matter density
t ~ 47.000
Dark energy density
Density (kg/m^3)
1
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^2
10^4
10^6
10^8
10^{10}
Time since Big Bang (yr)

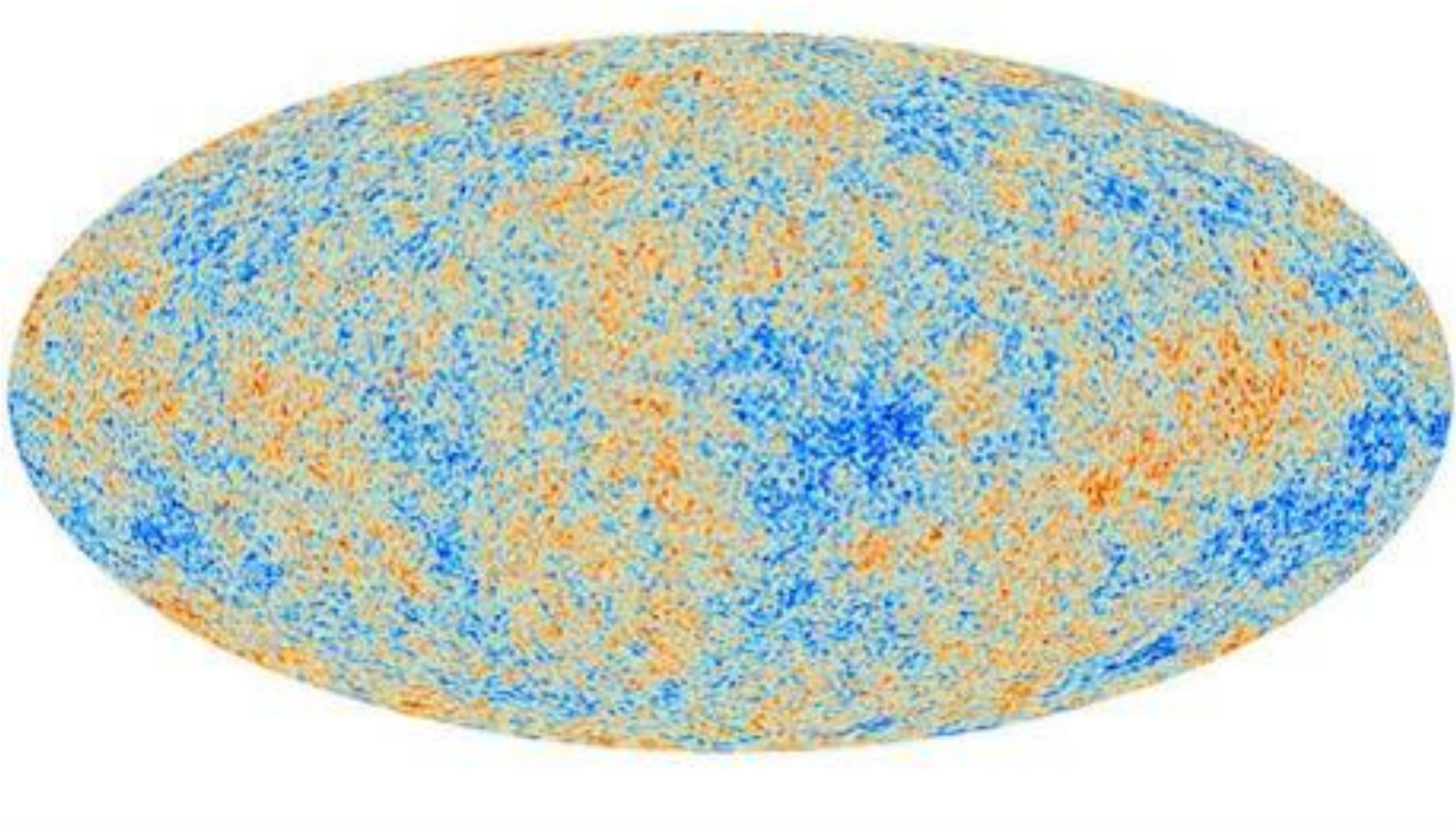
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



W. Hu, An Introduction to the CMB



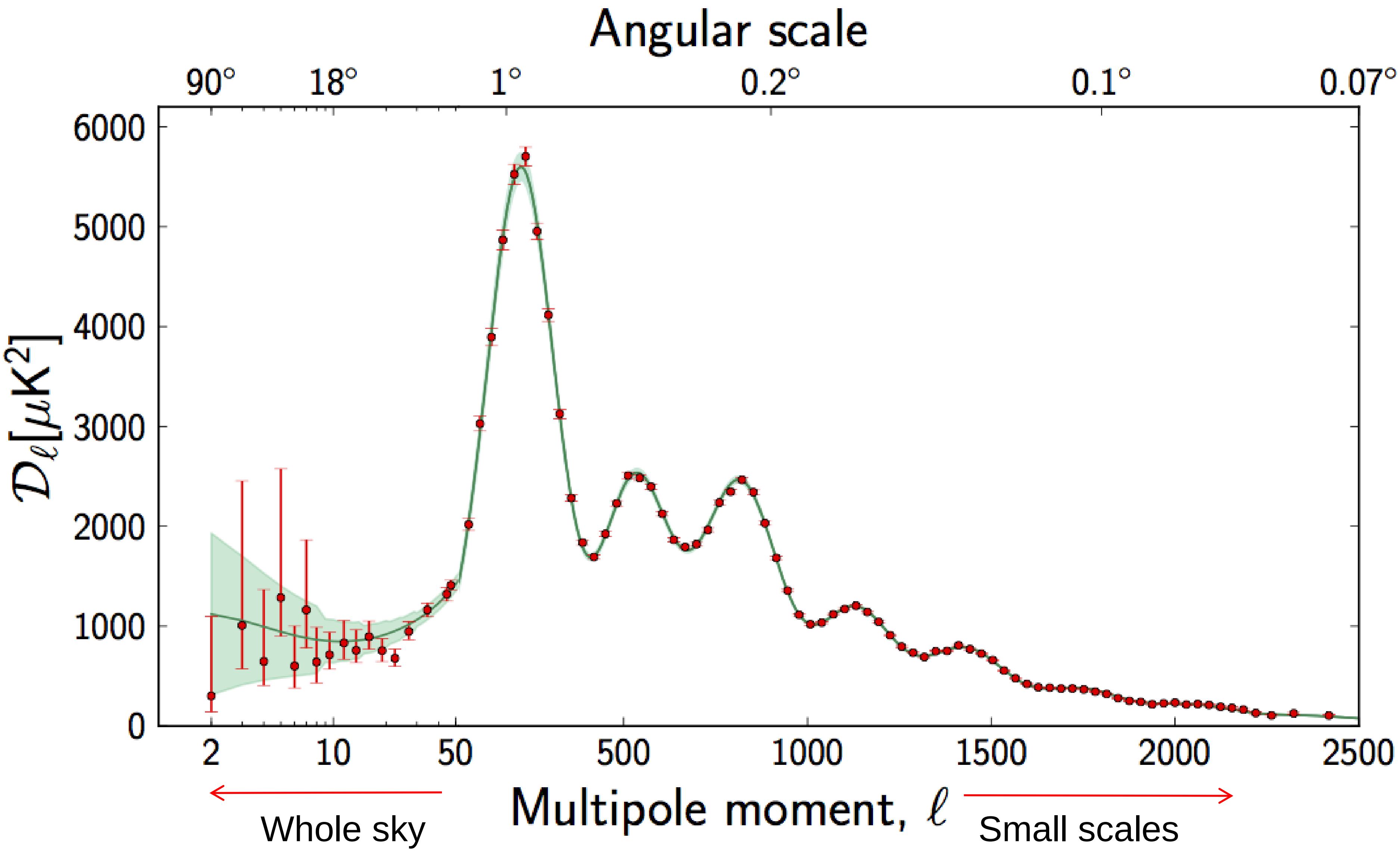
PLANCK 2013



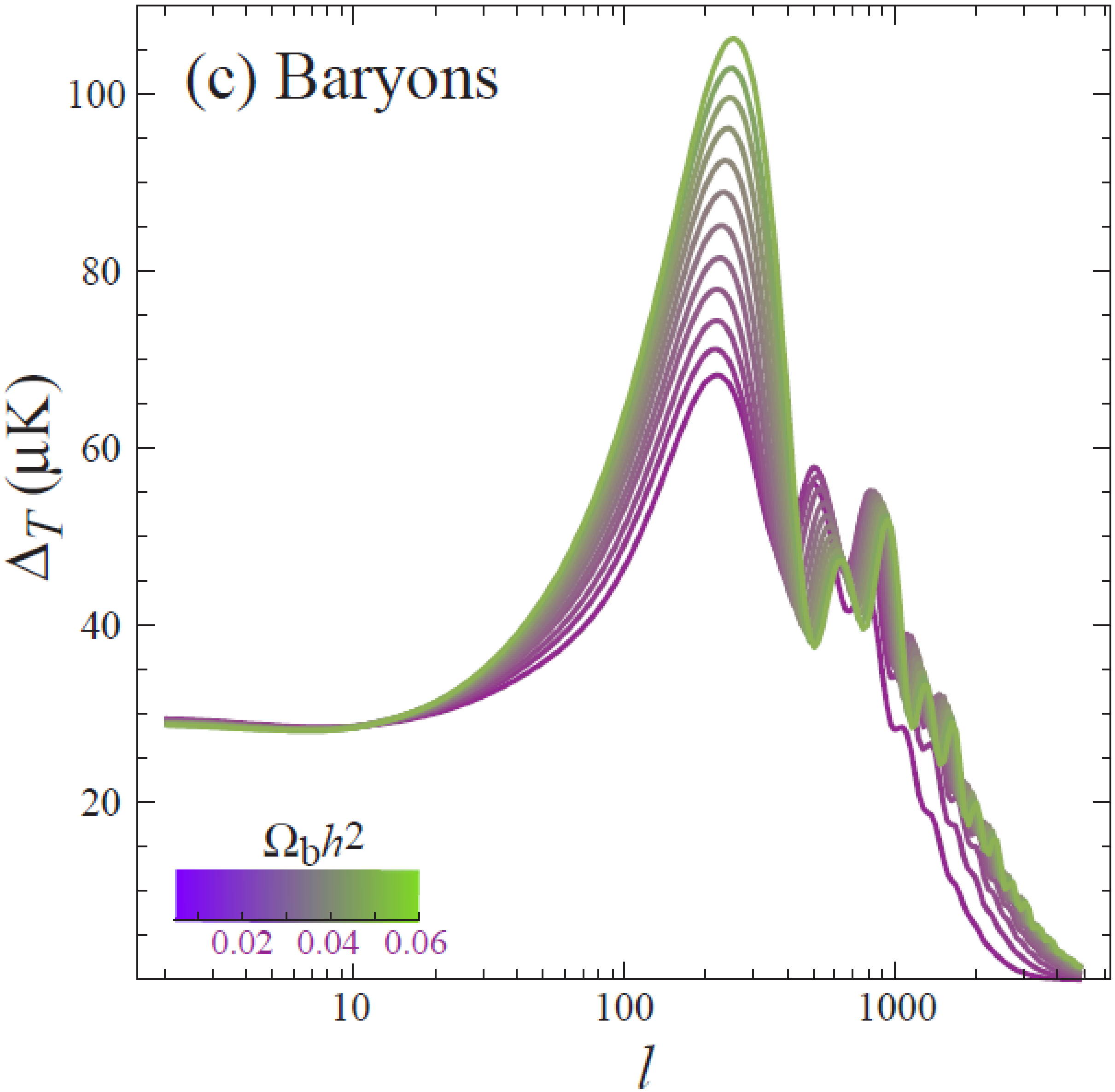
$$T(\theta,\phi) = \sum_{l,m} a_{lm} Y_l^m(\theta,\phi)$$

$$C_l = \langle a_{lm} a_{lm}^* \rangle_m$$

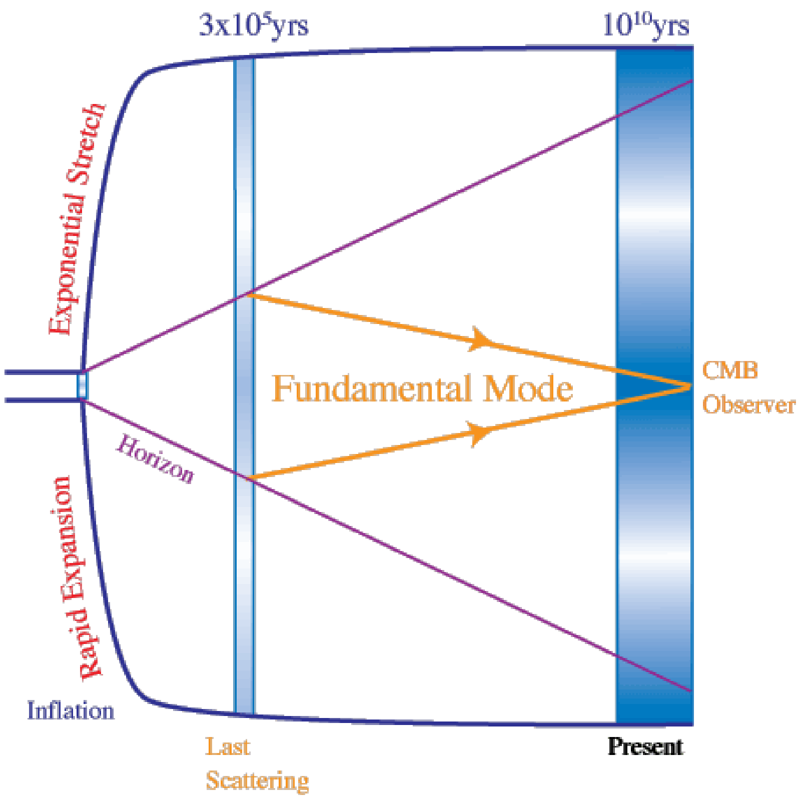
PLANCK 2013

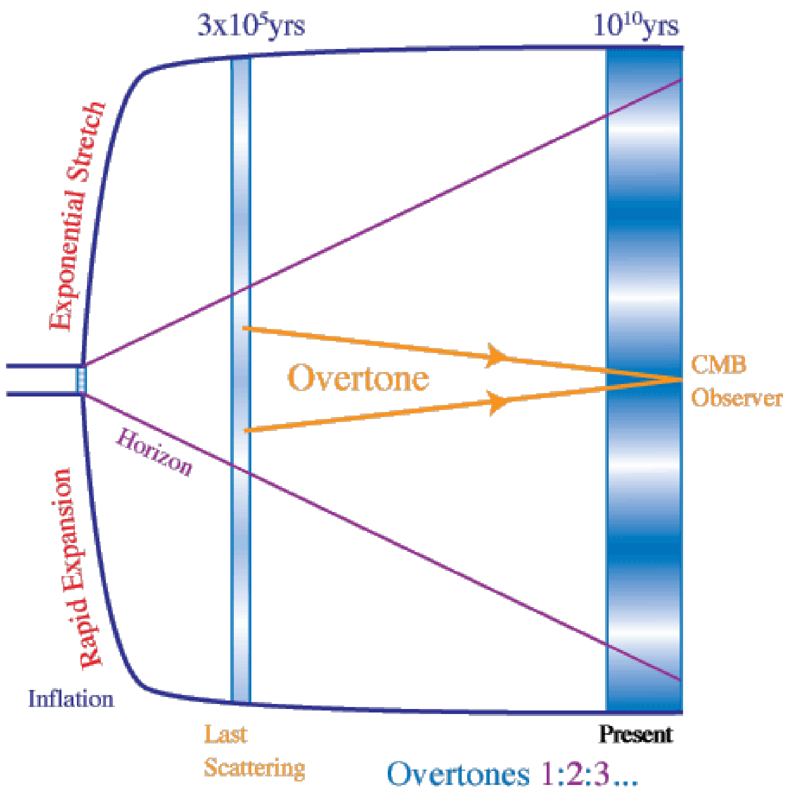

Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell[\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ
Whole sky
Small scales

Hu & Dodelson, astro-ph/0110414

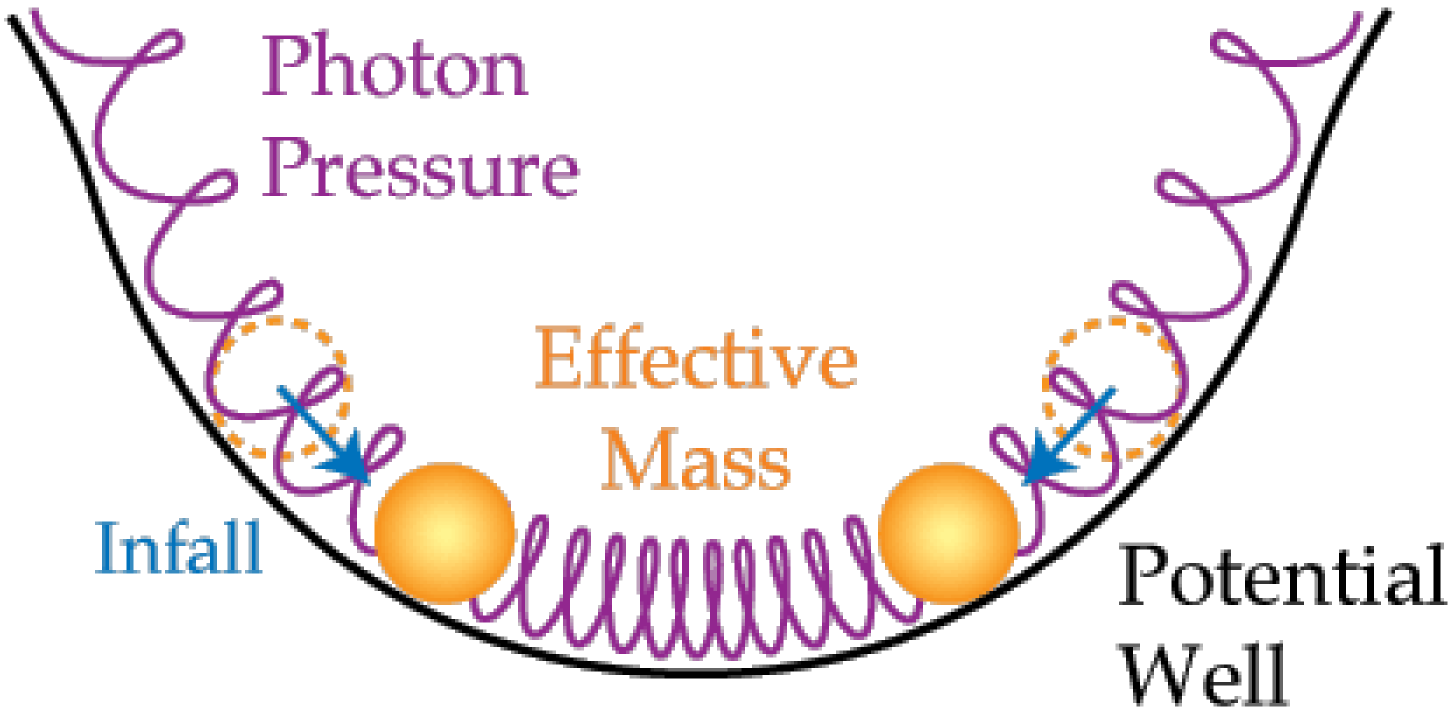


W. Hu, An Introduction to the CMB



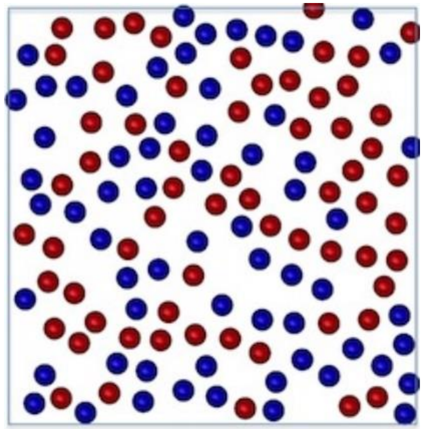


W. Hu, An Introduction to the CMB



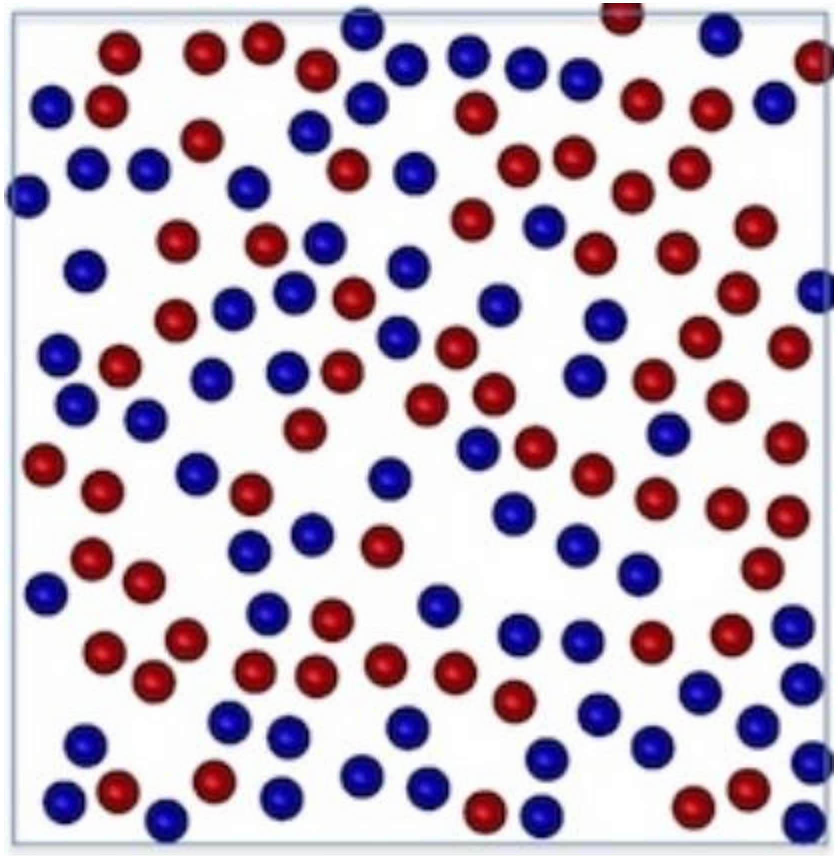
$$\eta = (6.19 +/- 0.14) \times 10^{-10}$$

$$\eta_B/\eta_\gamma = \text{const.}$$



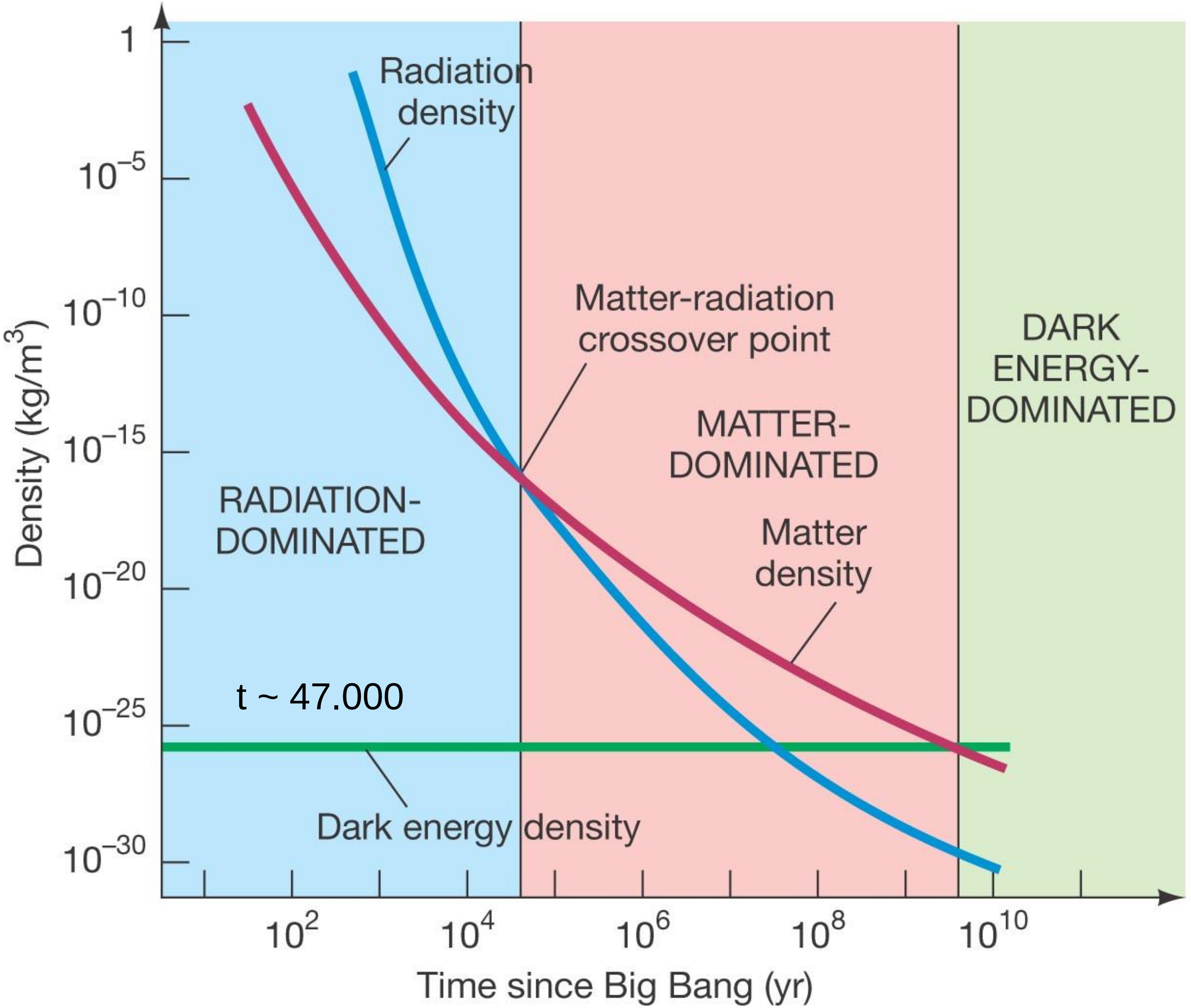
Comoving volume, $t=t_0$

time



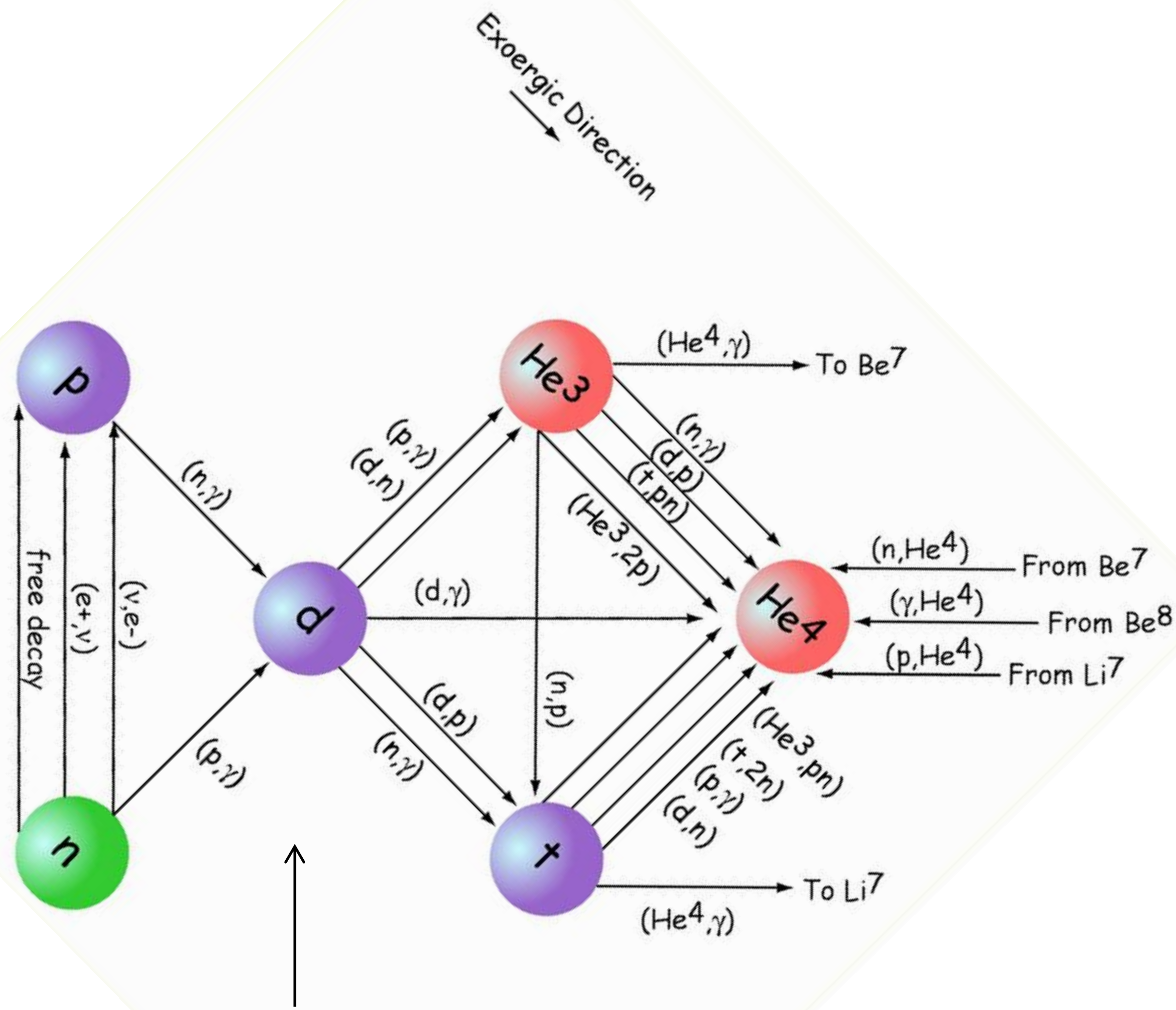
Comoving volume, $t=t_1$

Big Bang nucleosynthesis


Radiation density
Matter-radiation crossover point
DARK ENERGY-DOMINATED
MATTER-DOMINATED
RADIATION-DOMINATED
Matter density
t ~ 47.000
Dark energy density
Density (kg/m3)
1
10−5
10−10
10−15
10−20
10−25
10−30
102
104
106
108
1010
Time since Big Bang (yr)

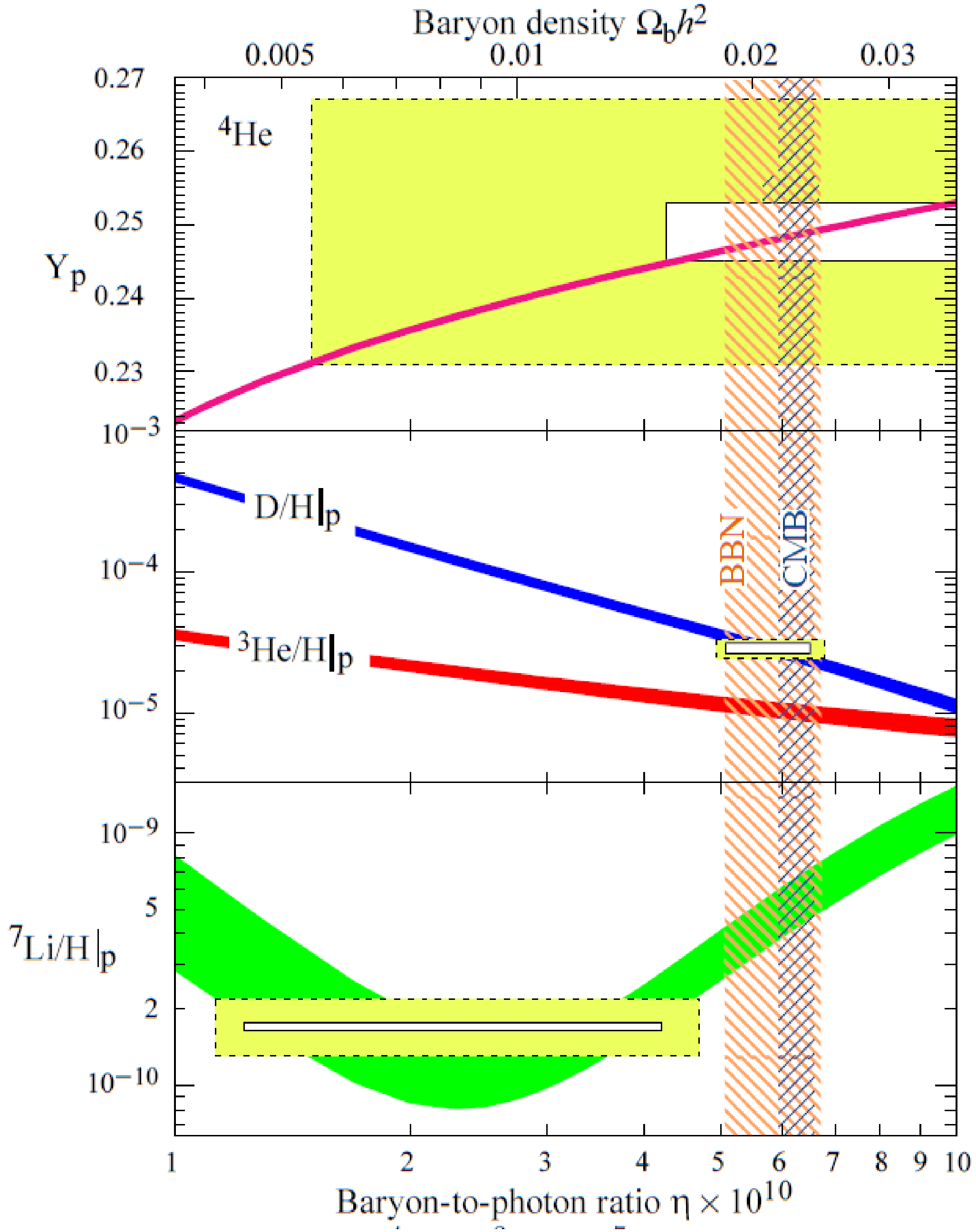
t ~ 3 min

T ~ 10^{10} K



Deuterium bottleneck = η dependence

PDG

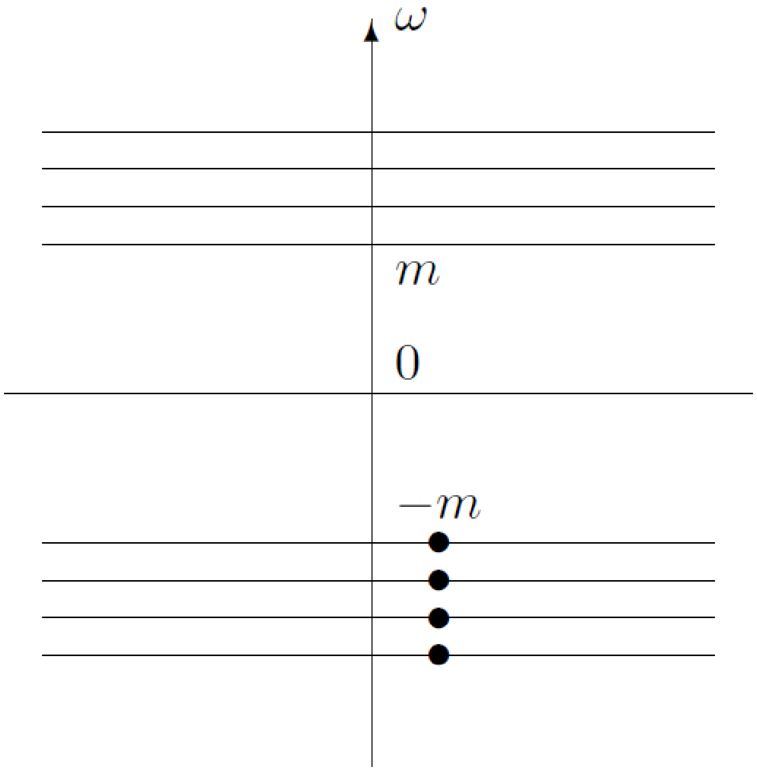

Baryon density $\Omega_b h^2$
0.005
0.01
0.02
0.03
0.27
0.26
0.25
0.24
0.23
Y_p
^{4}He
10^{-3}
10^{-4}
10^{-5}
D/H|p
^{3}He/H|p
BBN
CMB
10^{-9}
5
2
10^{-10}
^{7}Li/H|p
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio $\eta \times 10^{10}$

Intermediate summary I

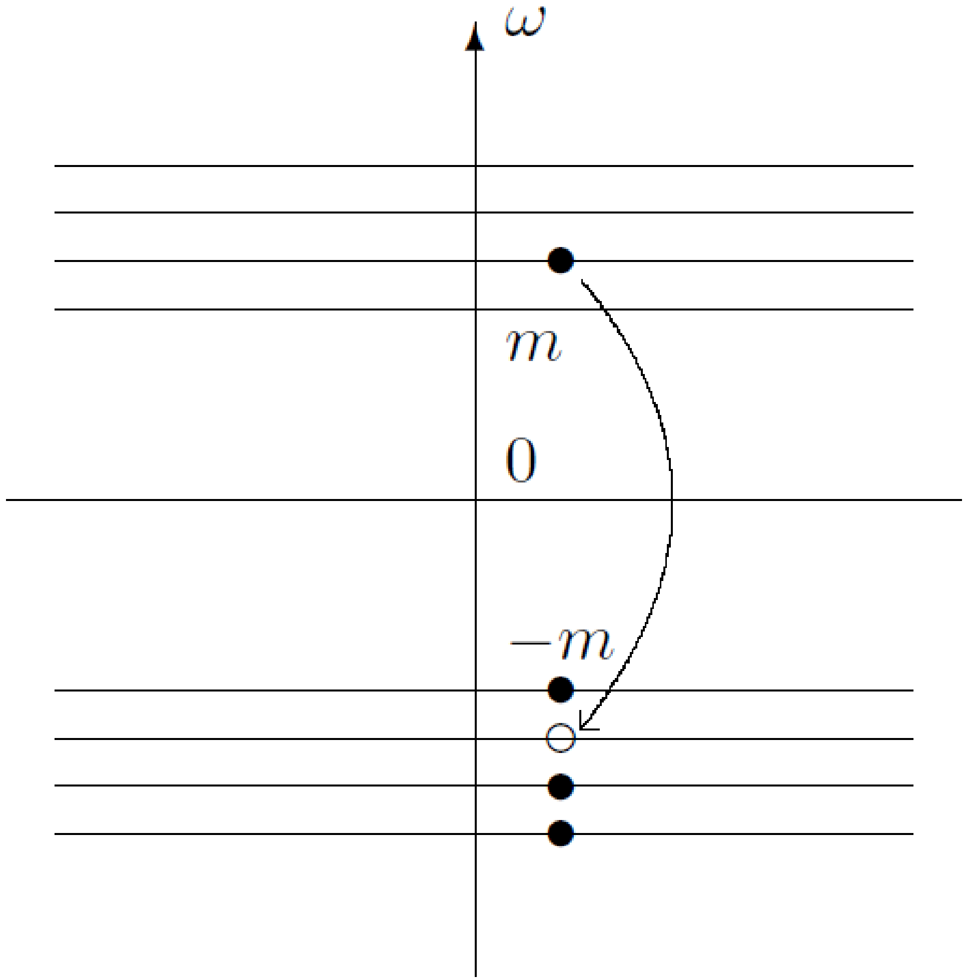
- Antimatter is a rare commodity nowadays
- Baryon to photon ratio: $\eta \approx 6.2 \times 10^{-10}$
- η_{BBN} is consistent with η_{CMB}

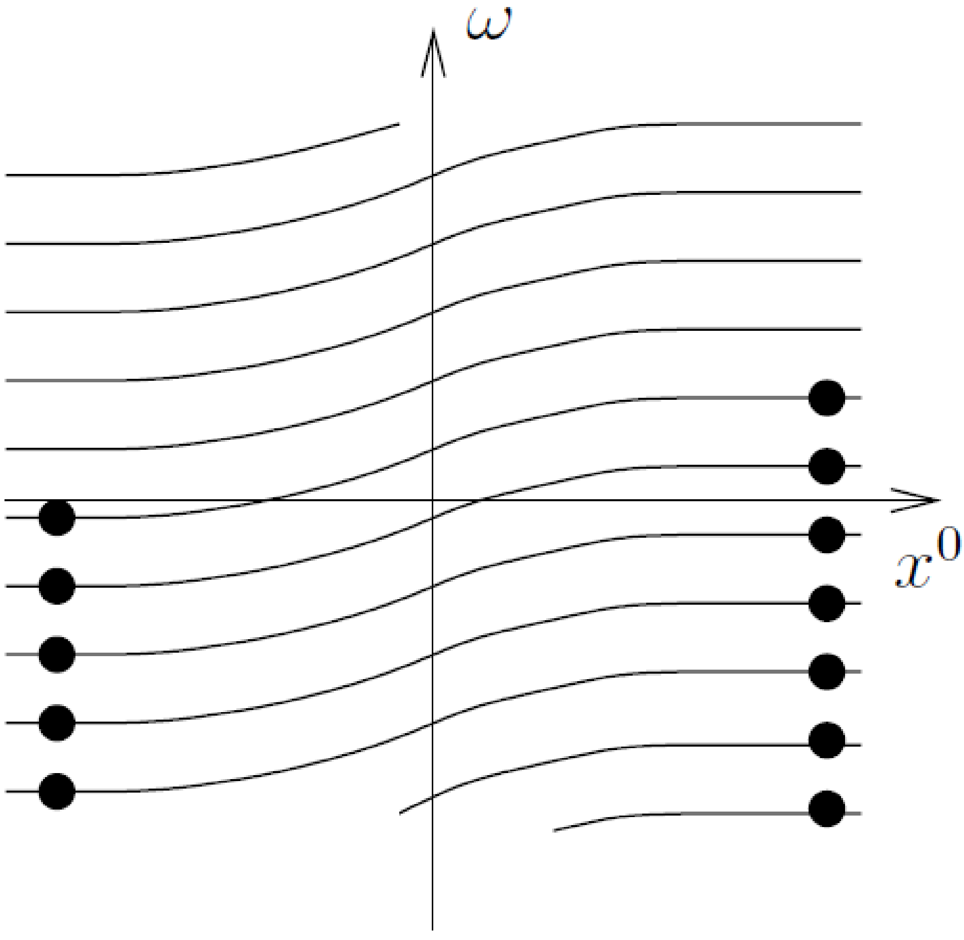
Why is the Universe baryonically asymmetric ?

Baryon number violation



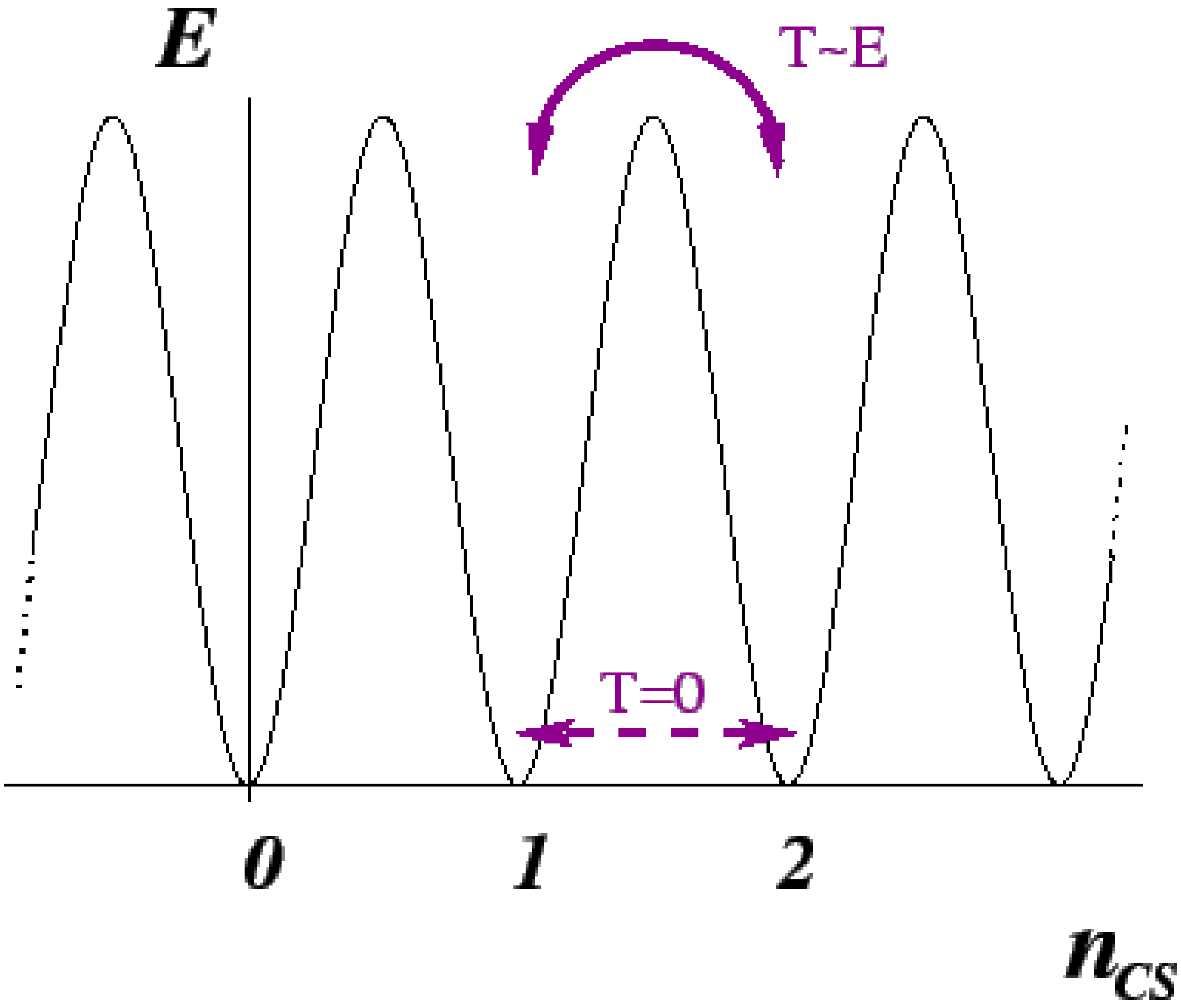
ω
m
0
$-m$


ω
m
0
$-m$


ω
x^0

n ! p + e +

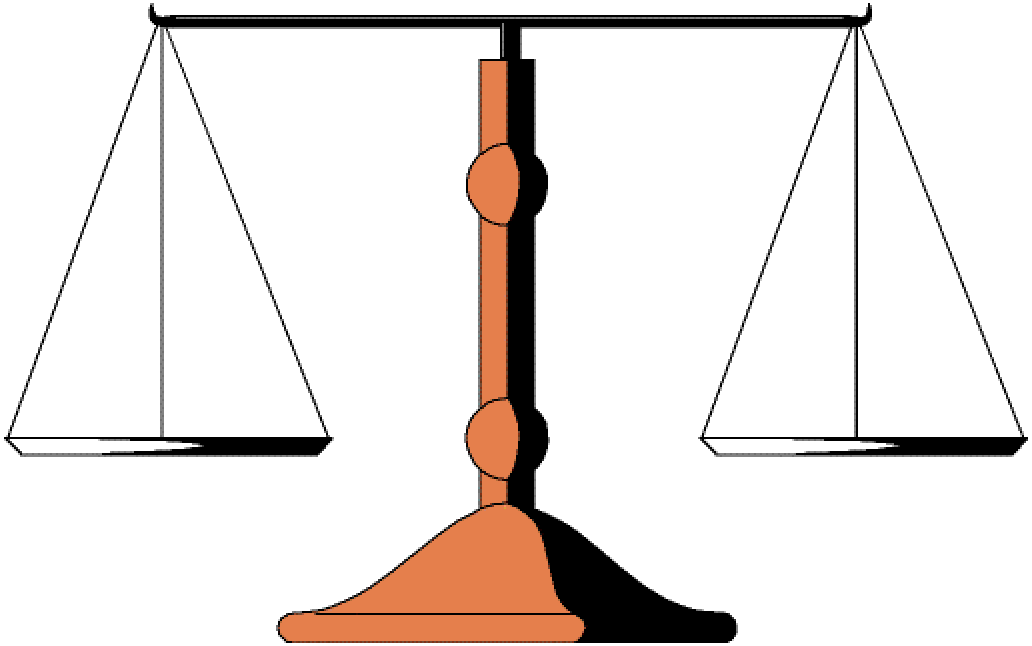
$t \sim 10^{146}$ years


E
T~E
T=0
0
1
2
n_{CS}

Baryogenesis via leptogenesis

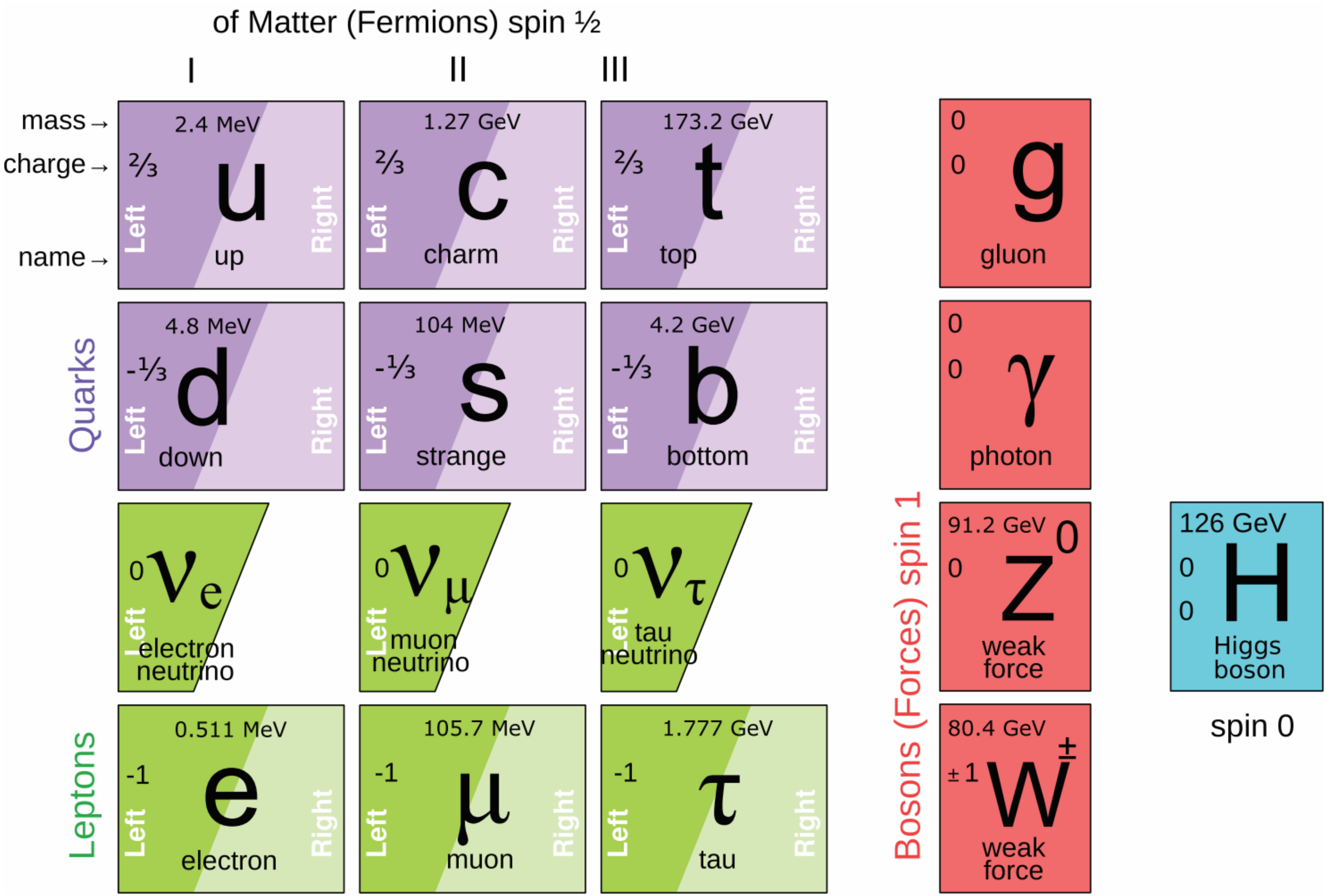
B-L=const.

Masataka Fukugita



sphaleron scales

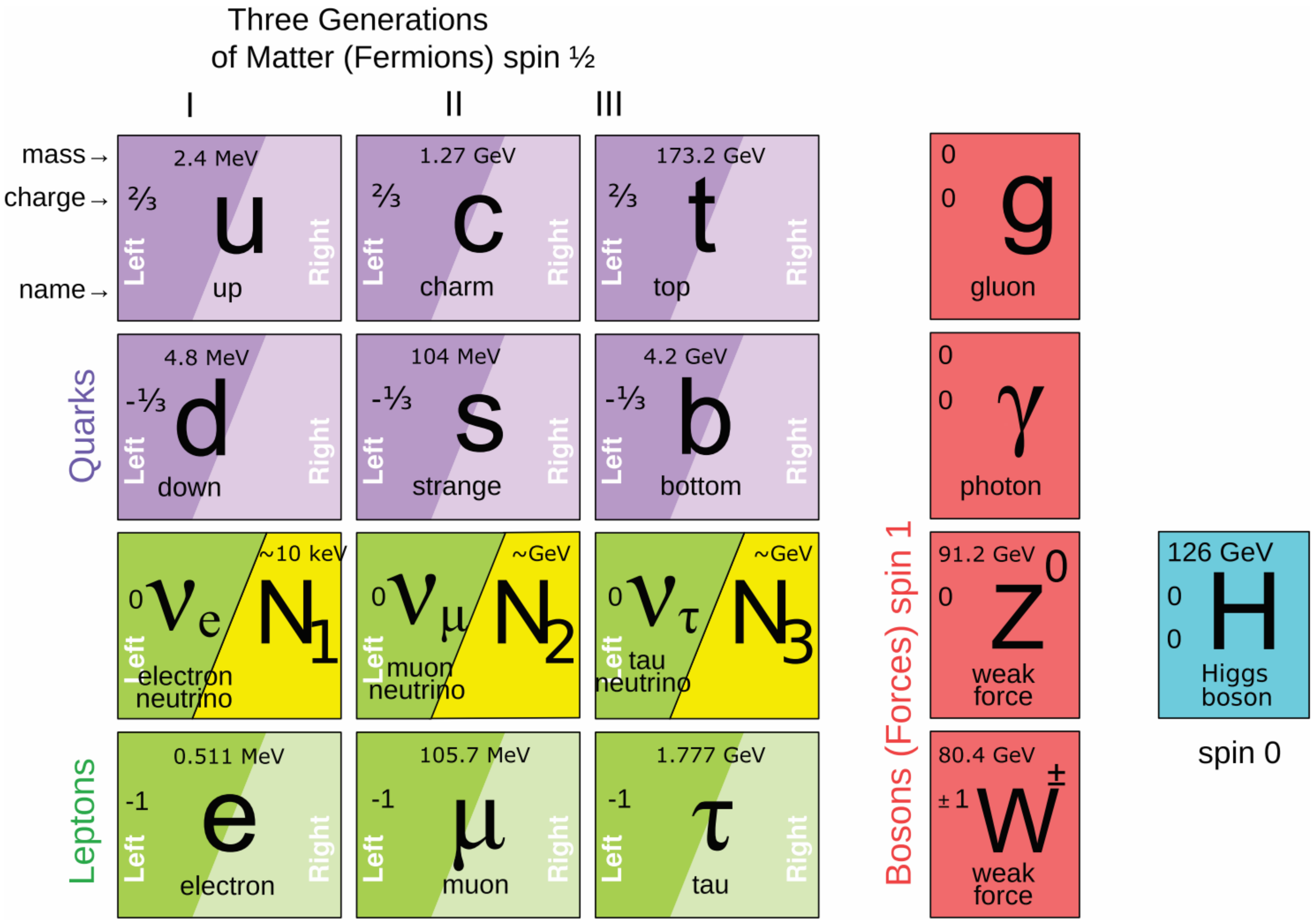
Tsutomu Yanagida



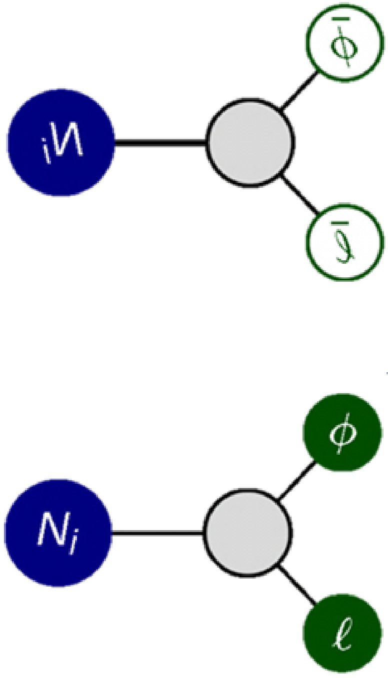
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
Quarks
Leptons
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
173.2 GeV
⅔
t
top
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
0
ν_e
electron neutrino
0
ν_μ
muon neutrino
0
ν_τ
tau neutrino
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
Left
Right
Bosons (Forces) spin 1
0
0
g
gluon
0
0
γ
photon
91.2 GeV
0
Z^0
weak force
80.4 GeV
±1
$W^\pm$
weak force
126 GeV
0
0
H
Higgs boson
spin 0

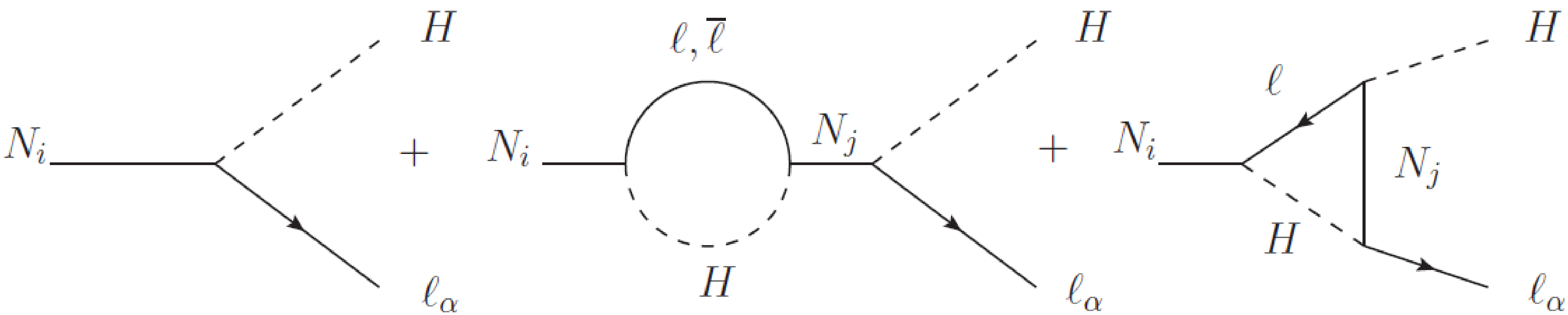
arXiv:1209.3023

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$	$0.311^{+0.013}_{-0.013}$	$0.273 \to 0.354$
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \to 35.89$	$33.87^{+0.82}_{-0.80}$	$31.52 \to 36.49$
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$	$0.416^{+0.036}_{-0.029} \oplus 0.600^{+0.019}_{-0.026}$	$0.341 \to 0.670$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$	$40.1^{+2.1}_{-1.6} \oplus 50.7^{+1.2}_{-1.5}$	$35.7 \to 55.0$
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$	$0.0255^{+0.0024}_{-0.0024}$	$0.0181 \to 0.0327$
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$	$9.20^{+0.41}_{-0.45}$	$7.73 \to 10.42$
$\delta_{\rm CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$	298^{+59}_{-145}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$	$7.51^{+0.21}_{-0.15}$	$7.04 \to 8.12$
$\frac{\Delta m^2_{31}}{10^{-3}\ \rm eV^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$	$+2.489^{+0.055}_{-0.051}$	$+2.294 \to +2.715$
$\frac{\Delta m^2_{32}}{10^{-3}\ \rm eV^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$	$-2.468^{+0.073}_{-0.065}$	$-2.678 \to -2.252$


Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
Left
Right
1.27 GeV
⅔
c
charm
173.2 GeV
⅔
t
top
0
0
g
gluon
Quarks
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
0
0
γ
photon
~10 keV
0
νe
N1
electron neutrino
~GeV
0
νμ
N2
muon neutrino
~GeV
0
ντ
N3
tau neutrino
91.2 GeV
0
Z0
weak force
126 GeV
0
0
H
Higgs boson
spin 0
Bosons (Forces) spin 1
Leptons
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
80.4 GeV
±1
W±
weak force


Right-handed neutrino
Left-handed neutrino


ϕ
N_i
ℓ



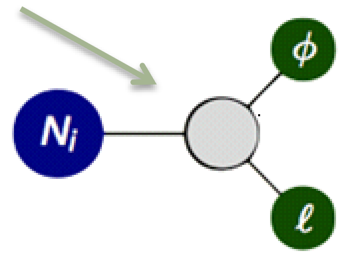
N_i
H
ℓ_α
+
N_i
$\ell, \overline{\ell}$
H
N_j
H
ℓ_α
+
N_i
ℓ
H
N_j
H
ℓ_α

Time derivative of lepton number = Phase space integral x Momentum-energy conserving delta-function x

[

$|M_0|^2(1+\epsilon)$

+ f_N

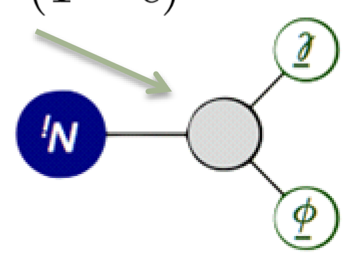


$1+f_\phi$

$1-f_\ell$

$|M_0|^2(1-\epsilon)$

- f_N

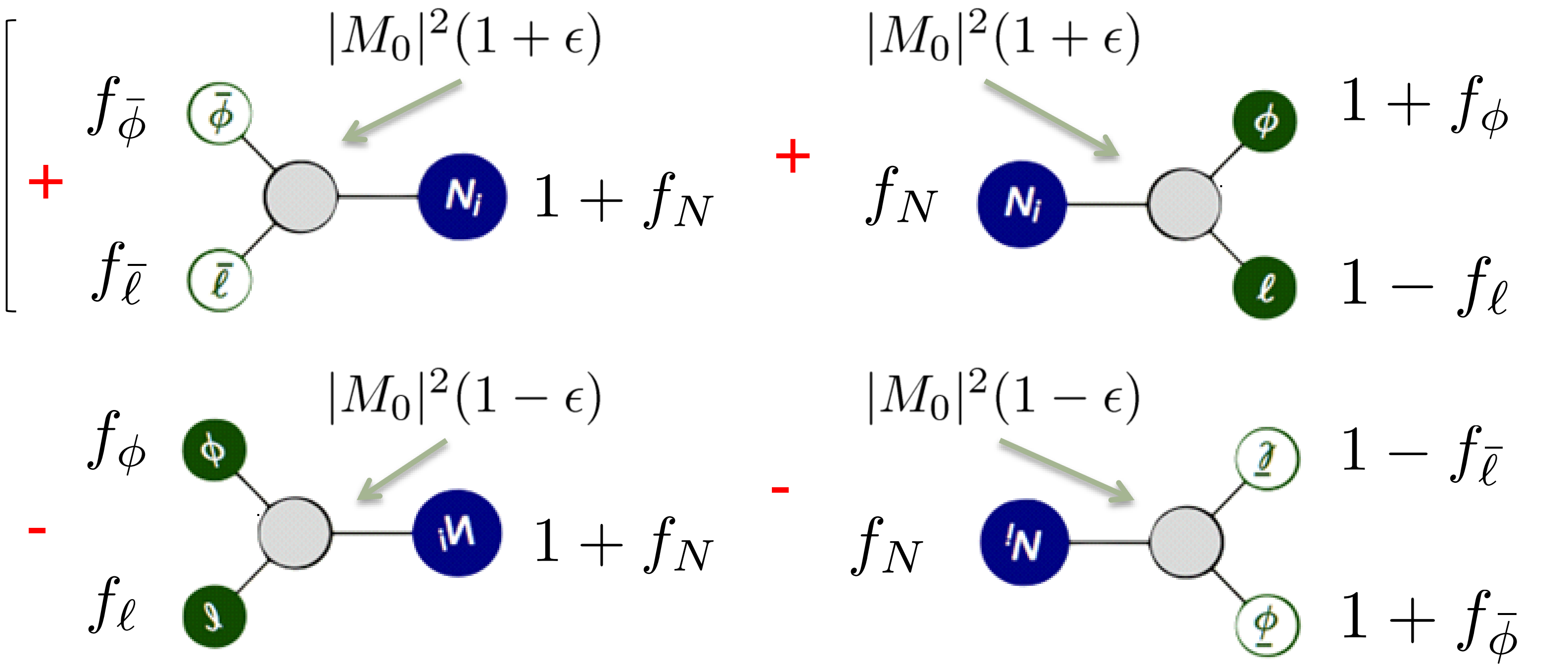


$1-f_{\bar{\ell}}$

$1+f_{\bar{\phi}}$

]

Time derivative of lepton number = Phase space integral x Momentum-energy conserving delta-function x



$$\frac{Y_N}{dz} = -\kappa\gamma_D (Y_N - Y_N^{eq})$$

$$\frac{Y_L}{dz} = \epsilon\kappa\gamma_D (Y_N + Y_N^{eq}) - \kappa\gamma_L Y_L$$

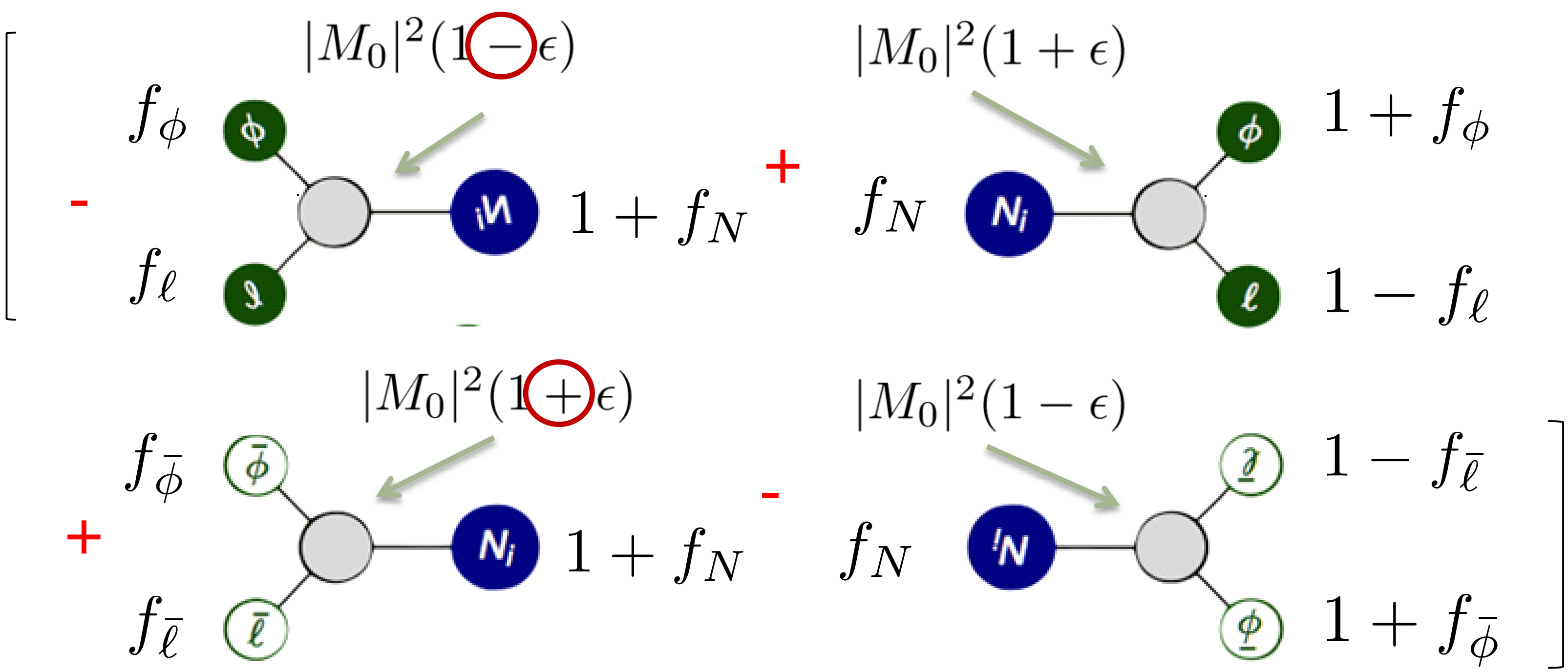
$$\kappa = \frac{\Gamma_N}{H(T = M_1)}$$

$$z \equiv \frac{M_1}{T}$$

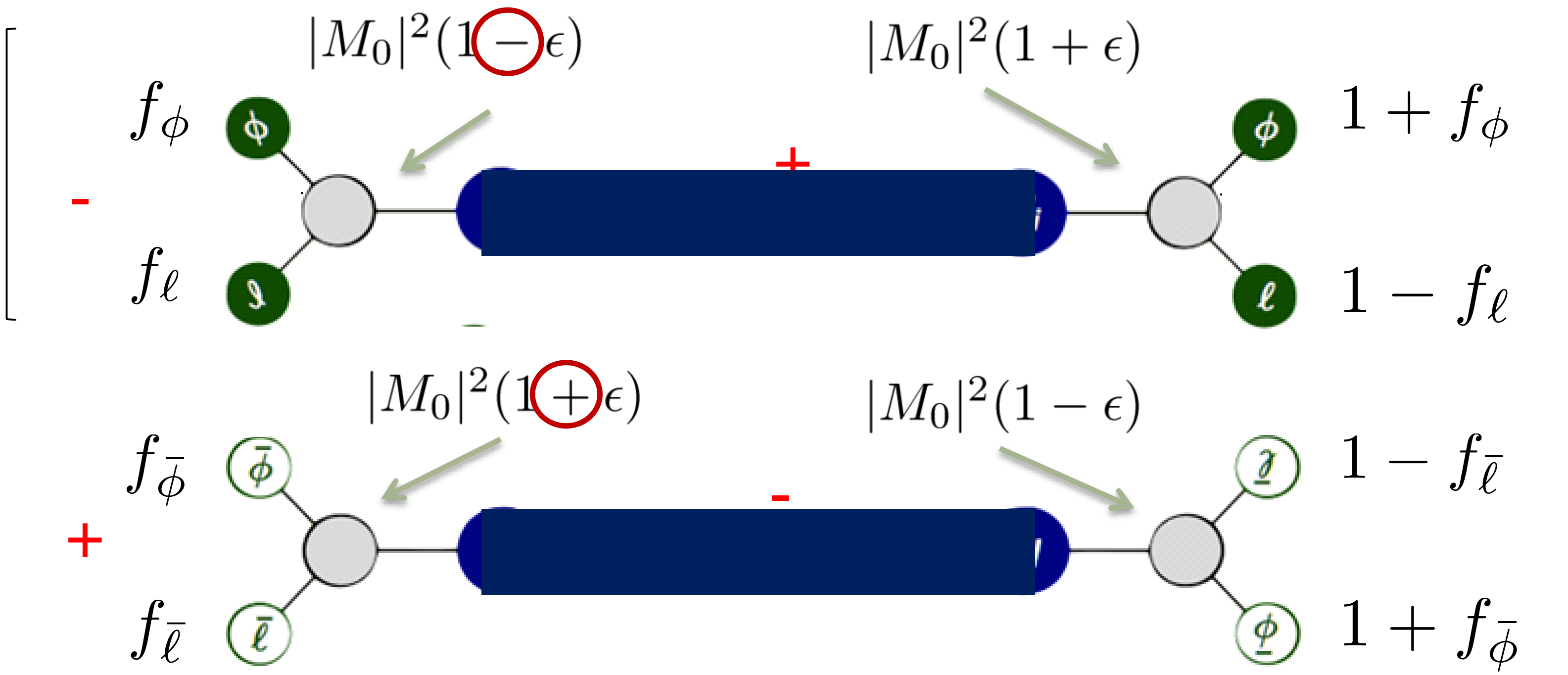
Andrei Sakharov

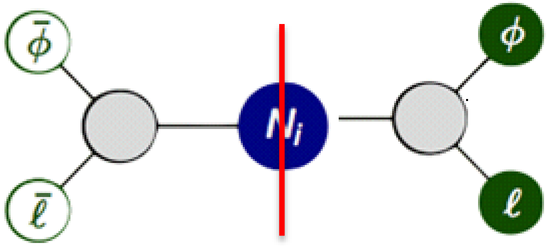
- Violation of baryon number
- C- and CP-violation
- Deviation from equilibrium

Time derivative of lepton number = Phase space integral x Momentum-energy conserving delta-function x



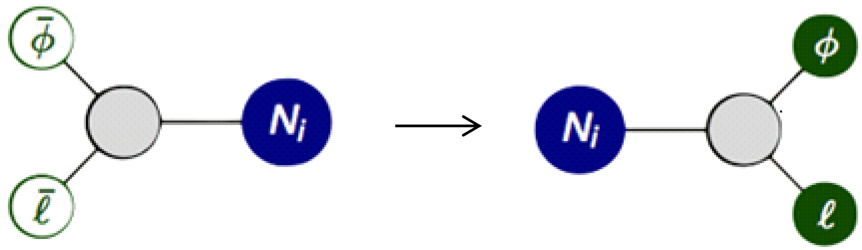
Time derivative of lepton number = Phase space integral x Momentum-energy conserving delta-function x





if the intermediate state
is on the mass shell, then

=



$$P_{ii}^{RIS}(s) \simeq \frac{1}{(s - M_i^2)^2 + (M_i\Gamma_i)^2} - \frac{\pi}{M_i\Gamma_i}\delta(s - M_i^2)\,;$$

$$\frac{dY_N}{dz} = \text{i} \; \cdot \; {}^{\circ}{}_D (Y_N \; \text{i} \; Y_N^{eq})$$

$$\frac{dY_L}{dz} = {}^2 \cdot \; {}^{\circ}{}_D (Y_N \; \text{i} \; Y_N^{eq}) \; \text{i} \; \cdot \; {}^{\circ}{}_L Y_L$$

$$\cdot \; = \frac{\text{i}_N}{H(T = M_1)}$$

$$z \; \acute{} \; \frac{M_1}{T}$$

$$´ \;»\; \frac{2}{\cdot\, Z_f}$$

$$\cdot = \frac{i_1}{H(M_1)} \;´\; \frac{\tilde{m}_1}{m_¤}$$

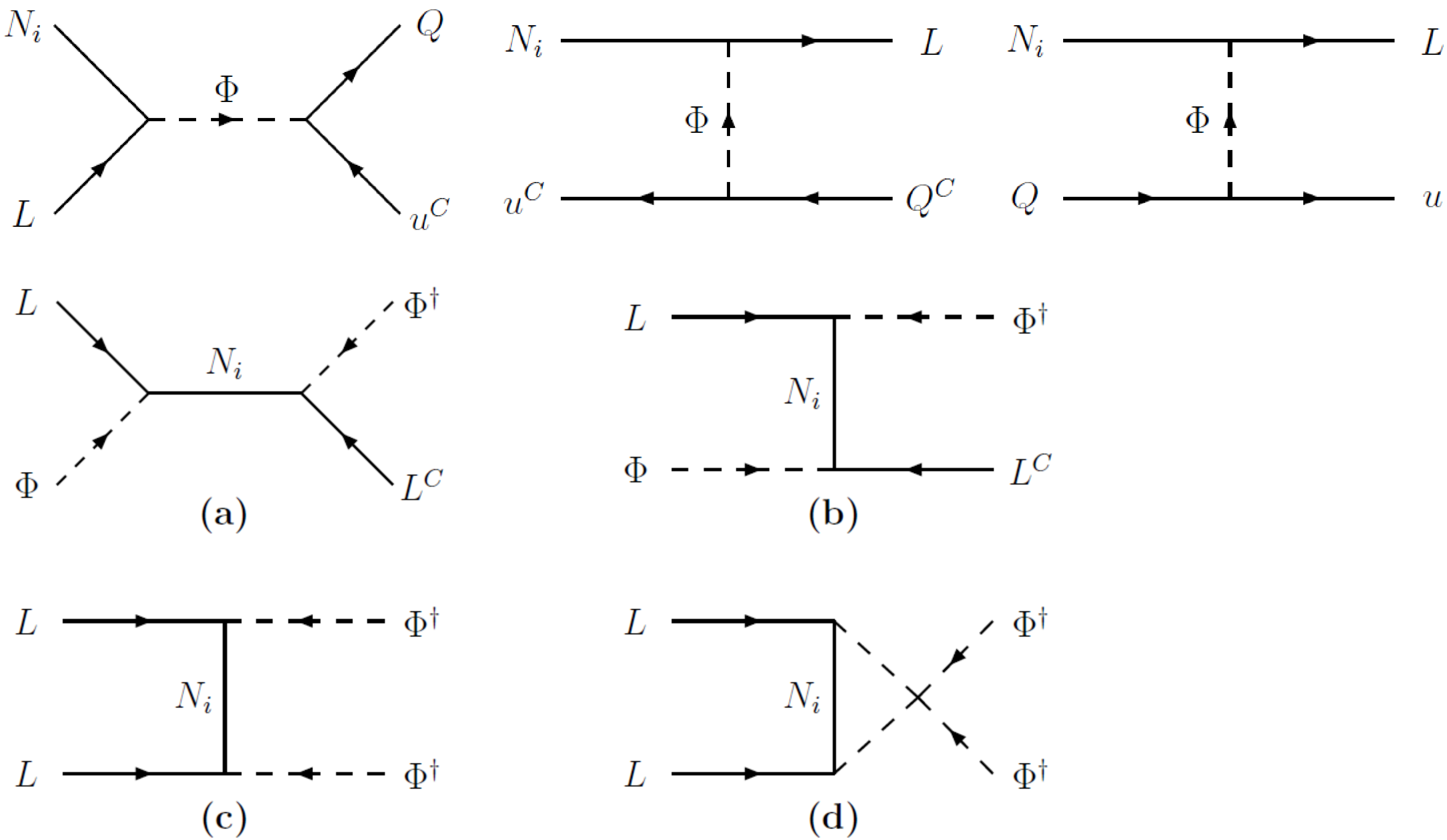
$$m_¤ \;»\; 10^{i\,3}\ \text{eV}$$

$$\tilde{m}_1 < 5\,¢\,10^{i\,3}\ \text{eV}$$

$${}^{2}{}_{1}\;\cdot\; \frac{3}{8¼}\,\frac{M_1 m_3}{v^2}$$

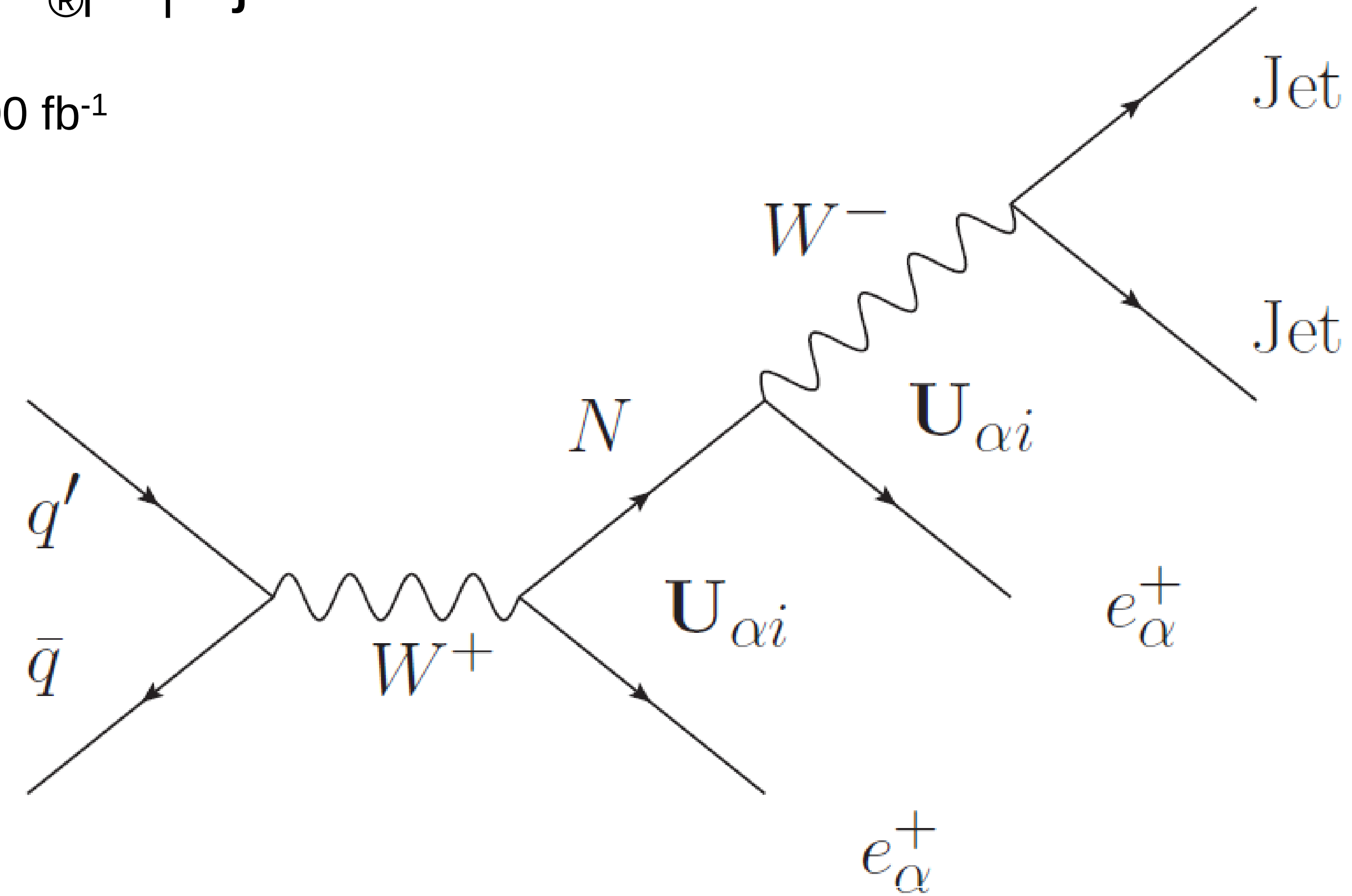
$$M_1 \;»\; 10^{8}\ \text{GeV}$$

hep-ph/0309342



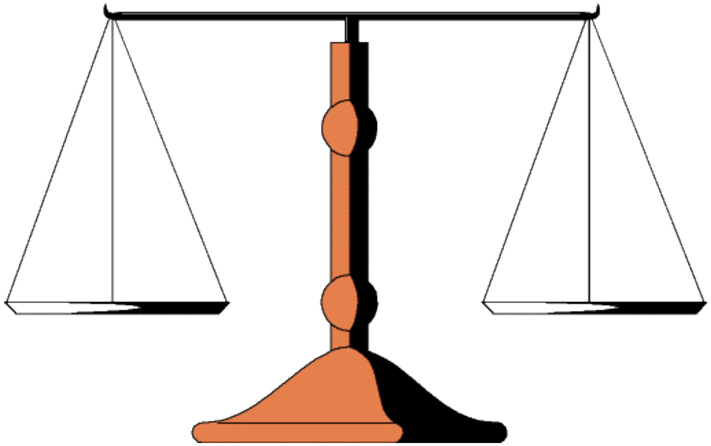
$$\left| \neg - U_{\alpha i}^{2} m_i^{-1} \right| \simeq 3.25 \times 10^{-3}\ \mathrm{TeV}^{-1}$$

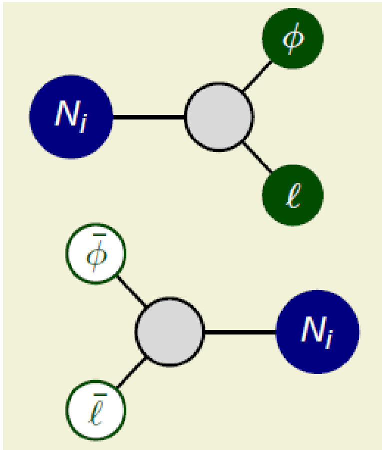
for 400 fb^{-1}

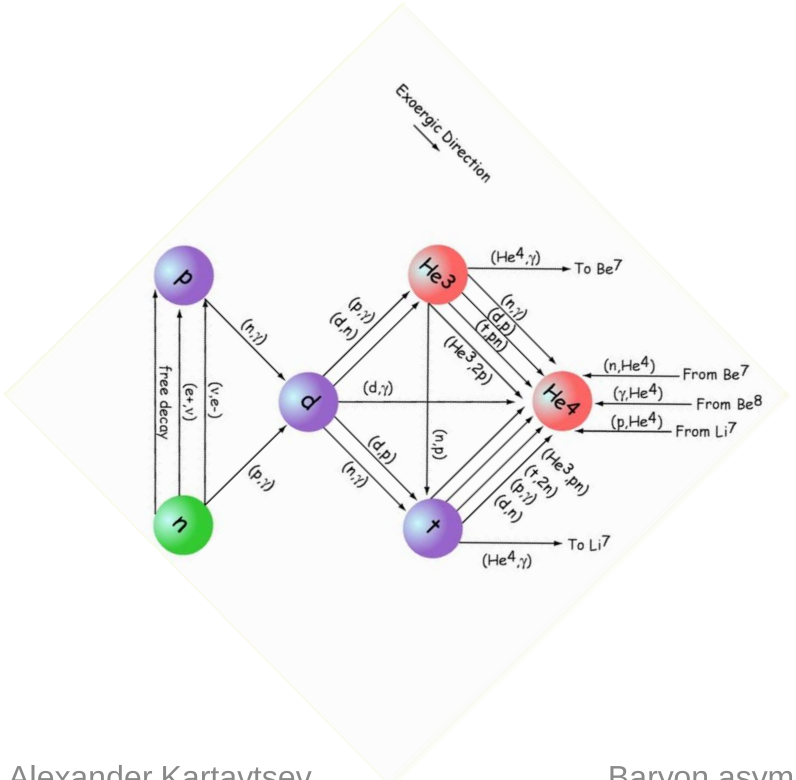


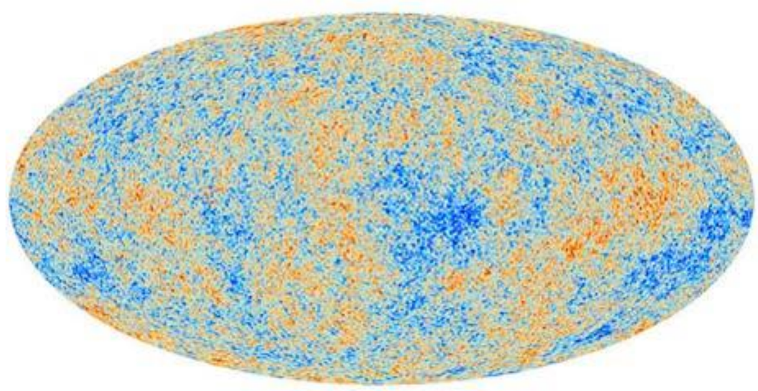
Intermediate summary II

- Heavy Majoranas explain the BAU
- predict $0\beta\beta$ decay
- and can be searched for in colliders




N_i
ϕ
ℓ
$\bar{\phi}$
$\bar{\ell}$
N_i


Exoergic Direction
p
n
d
t
He3
He4
free decay
(e+,ν)
(ν,e-)
(n,γ)
(p,γ)
(p,γ)
(d,n)
(d,γ)
(d,p)
(n,γ)
(n,p)
(He3,2p)
(n,γ)
(d,p)
(t,pn)
(He3,pn)
(t,2n)
(p,γ)
(d,n)
(He4,γ) To Be7
(He4,γ) To Li7
(n,He4) From Be7
(γ,He4) From Be8
(p,He4) From Li7



$$
\begin{aligned}
\langle B \rangle &= \mathrm{Tr}\, e^{-\beta \hat{H}} \hat{B} \\
&= \mathrm{Tr}\, (CPT)(CPT)^{-1} e^{-\beta \hat{H}} \hat{B} \\
&= \mathrm{Tr}\, e^{-\beta \hat{H}} (CPT)^{-1} \hat{B} (CPT) \\
&= -\mathrm{Tr}\, e^{-\beta \hat{H}} \hat{B} \\
&= -\langle B \rangle
\end{aligned}
$$

hep-ph/0202239

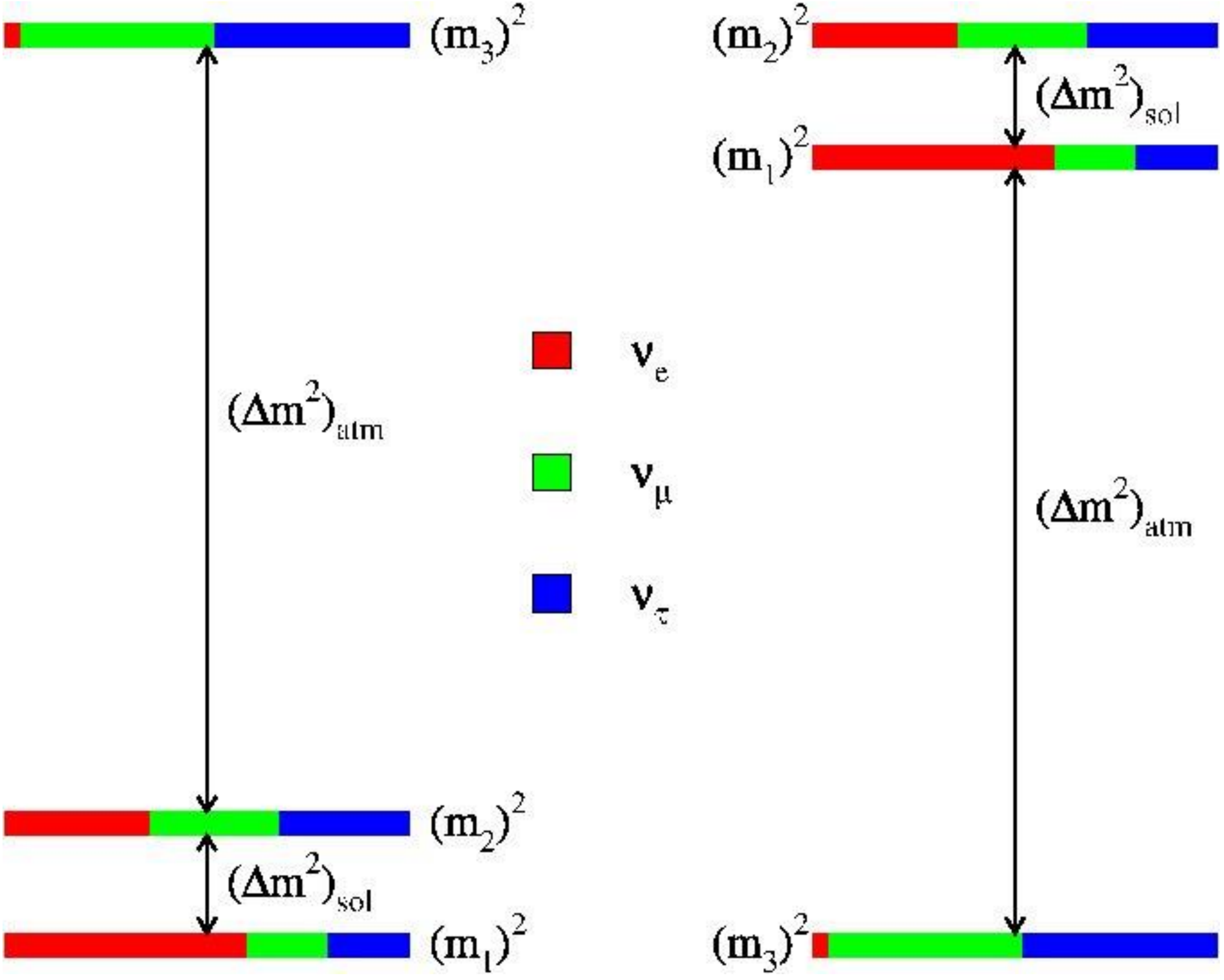
$$\mathbf{Y}_\nu = \frac{1}{\langle H_u^0 \rangle} D_{\sqrt{M}} R D_{\sqrt{m}} U^+$$

$$\epsilon_1 \simeq -\frac{3}{8\pi} \frac{1}{[\mathbf{Y}_\nu \mathbf{Y}_\nu{}^\dagger]_{11}} \sum_j \mathrm{Im}\left\{[\mathbf{Y}_\nu \mathbf{Y}_\nu^\dagger]_{1j}^2\right\} \left(\frac{M_1}{M_j}\right)$$

$$= -\frac{3}{8\pi} \frac{M_1}{\langle H_u^0 \rangle^2} \frac{1}{[\mathbf{Y}_\nu \mathbf{Y}_\nu{}^\dagger]_{11}} \mathrm{Im}\left\{[\mathbf{Y}_\nu \mathcal{M}_\nu{}^\dagger \mathbf{Y}_\nu{}^T]_{11}\right\}$$

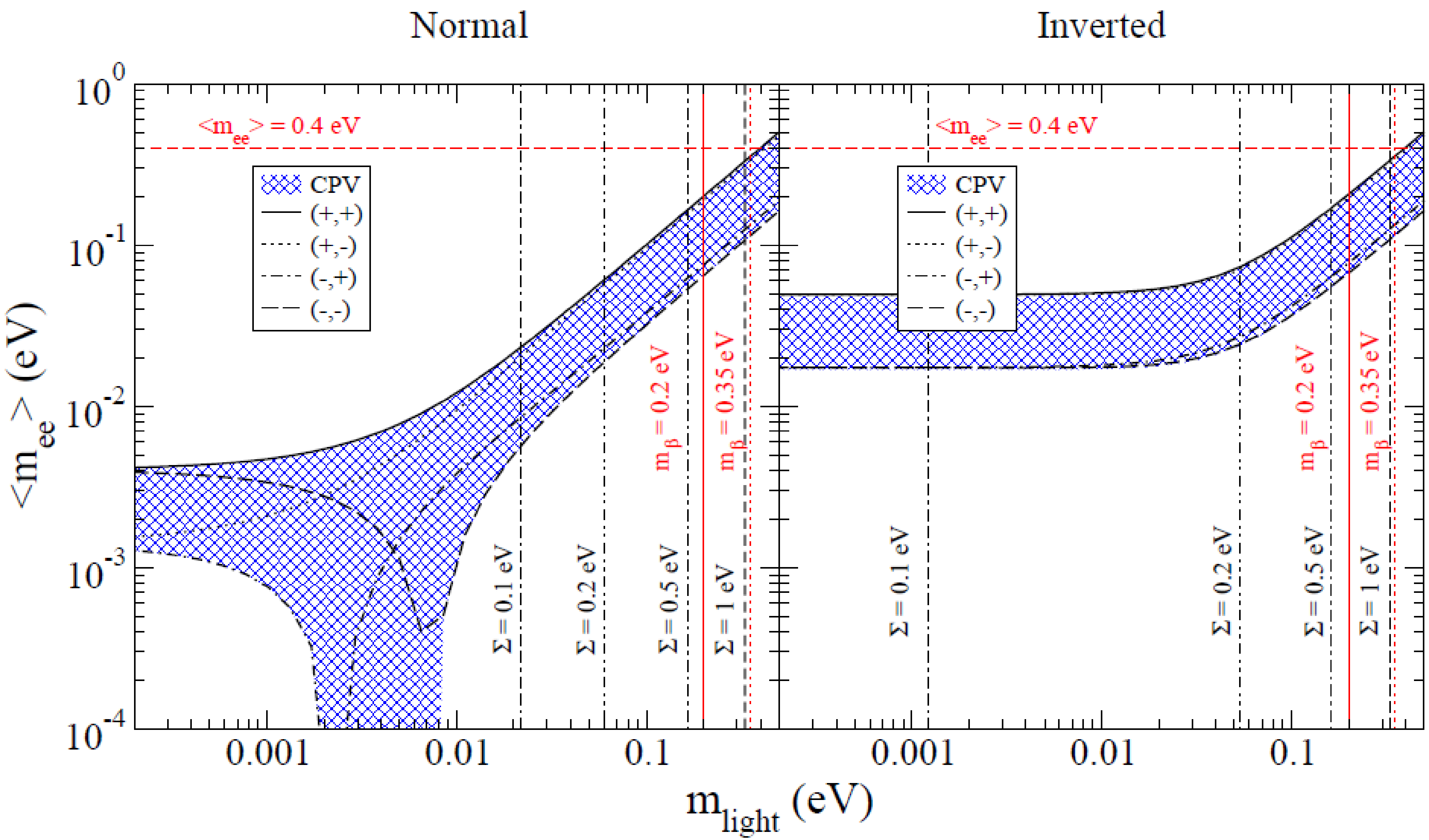
$$\epsilon_1 \quad \simeq \quad -\frac{3}{8\pi} \frac{M_1}{\langle H_u^0 \rangle^2} \frac{\sum_j m_j^2 \ \mathrm{Im}(R_{1j}^2)}{\sum_j m_j |R_{1j}|^2}$$

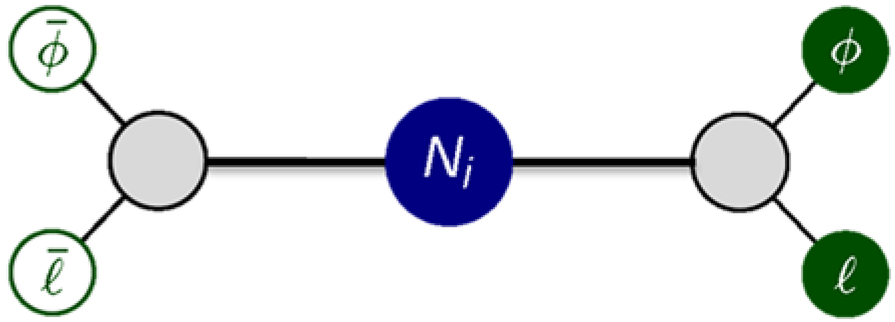
$$\widetilde{m}_1 = \sum_j m_j |R_{1j}|^2$$

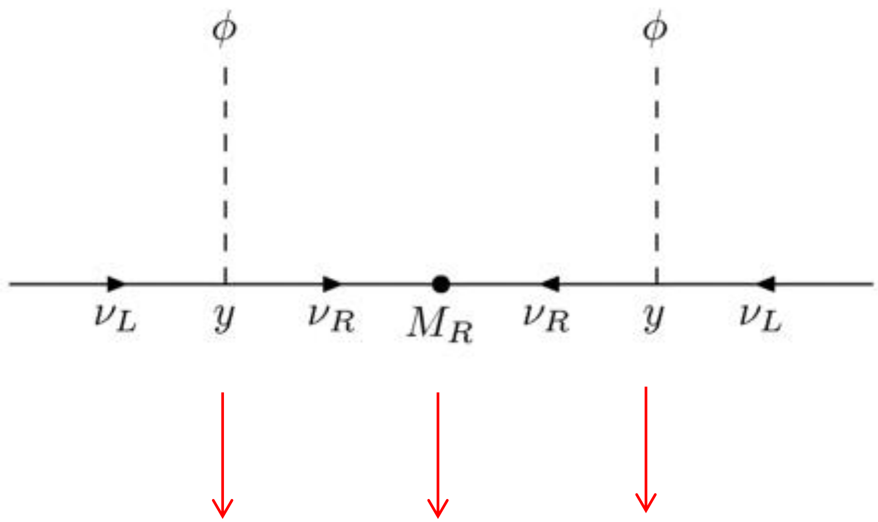


$(m_3)^2$
$(\Delta m^2)_{atm}$
$(m_2)^2$
$(\Delta m^2)_{sol}$
$(m_1)^2$
ν_e
ν_μ
ν_τ
$(m_2)^2$
$(\Delta m^2)_{sol}$
$(m_1)^2$
$(\Delta m^2)_{atm}$
$(m_3)^2$

arXiv:1206.2560







$$\mathcal{M}_\nu = \mathcal{M}_D^T \mathcal{M}_M^{-1} \mathcal{M}_D$$

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