ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

# Baryogenesis

**Mikhail Shaposhnikov**

On qualitative level:

Why there is no antimatter in the Universe?

On quantitative level:

Why

$$\frac{n_B}{s} \simeq +(8.8 - 9.8) \times 10^{-11}$$

# The solution

On qualitative level:

Sakharov

Since Universe is expanding (arrow of time), baryon number is not conserved and CP is broken

On quantitative level:

- How baryon and lepton numbers are broken: GUTs, Majorana masses, electroweak anomaly
- How arrow of time is realized: particle decoupling, inflation and/or preheating, phase transitions
- CP-violation: leptons versus quarks, low energy versus high energy

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Ignatiev, Krasnikov, Kuzmin and Tavkhelidze, 1977, 1978; Yoshimura, 1979; Weinberg, 1979;....

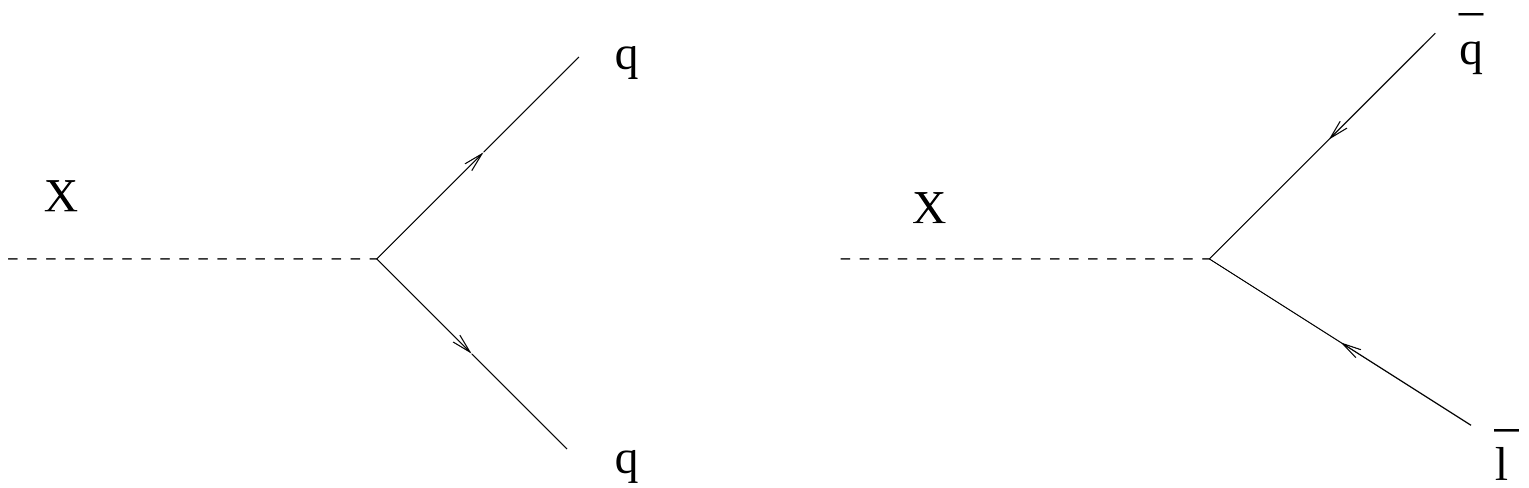
Grand Unification $\Rightarrow$ baryon and lepton number non-conservation

Scale of GUTS is close to the Planck scale $\Rightarrow$ rapid Universe expansion

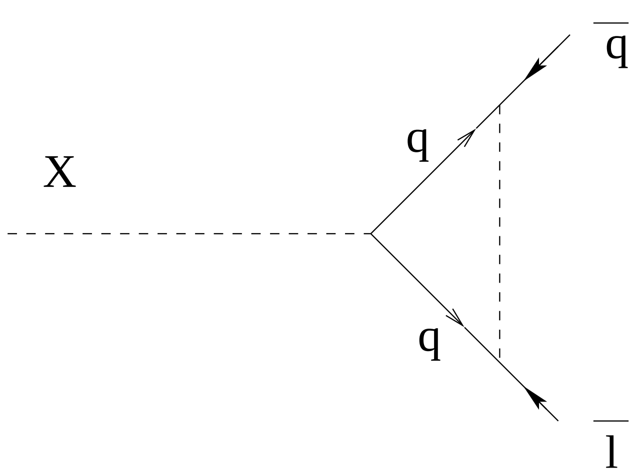
# Grand unified baryogenesis

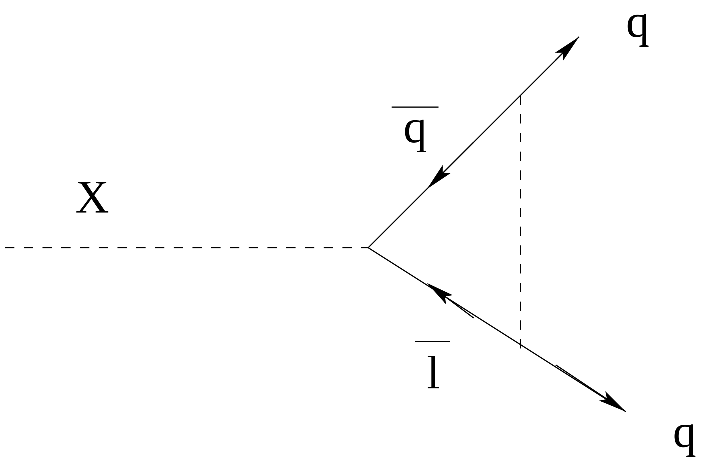
Step No 1: Consider B-violating leptoquark decays

$$X \to q\ell,\ \bar{q}\bar{q}\ \ and\ \ \bar{X} \to \bar{q}\bar{\ell}, qq$$



Step No 2: To account for CP-violation, compute radiative corrections



Step No 3: Find baryon asymmetry from

$$\frac{n_B}{n_\gamma} = \Delta \sim \frac{1}{N_{\rm eff}} \delta_{CP} \cdot S_{\rm macro},$$

$\delta_{CP}$ is the asymmetry in leptoquark decays,

$$\delta_{CP} = \frac{\Gamma(X \to qq) - \Gamma(\bar{X} \to \bar{q}\bar{q})}{\Gamma_{\rm tot}},$$

$\Gamma_{\rm tot}$ is the total width, $S_{\rm macro}$ is a factor taking into account the kinetics of the leptoquark decays

# Progress over last 30 years

44 different ways to create baryons in the Universe!

# How to create baryons

1. GUT baryogenesis
2. GUT baryogenesis after preheating
3. Baryogenesis from primordial black holes
4. String scale baryogenesis
5. Affleck-Dine (AD) baryogenesis
6. Hybridized AD baryogenesis
7. No-scale AD baryogenesis
8. Single field baryogenesis
9. Electroweak (EW) baryogenesis
10. Local EW baryogenesis
11. Non-local EW baryogenesis
12. EW baryogenesis at preheating

# How to create baryons

13. SUSY EW baryogenesis
14. String mediated EW baryogenesis
15. Baryogenesis via leptogenesis
16. Inflationary baryogenesis
17. Resonant leptogenesis
18. Spontaneous baryogenesis
19. Coherent baryogenesis
20. Gravitational baryogenesis
21. Defect mediated baryogenesis
22. Baryogenesis from long cosmic strings
23. Baryogenesis from short cosmic strings
24. Baryogenesis from collapsing loops

# How to create baryons

25. Baryogenesis through collapse of vortons
26. Baryogenesis through axion domain walls
27. Baryogenesis through QCD domain walls
28. Baryogenesis through unstable domain walls
29. Baryogenesis from classical force
30. Baryogenesis from electrogenesis
31. B-ball baryogenesis
32. Baryogenesis from CPT breaking
33. Baryogenesis through quantum gravity
34. Baryogenesis via neutrino oscillations
35. Monopole baryogenesis
36. Axino induced baryogenesis

## How to create baryons

37. Gravitino induced baryogenesis
38. Radion induced baryogenesis
39. Baryogenesis in large extra dimensions
40. Baryogenesis by brane collision
41. Baryogenesis via density fluctuations
42. Baryogenesis from hadronic jets
43. Thermal leptogenesis
44. Nonthermal leptogenesis

# How to create baryons

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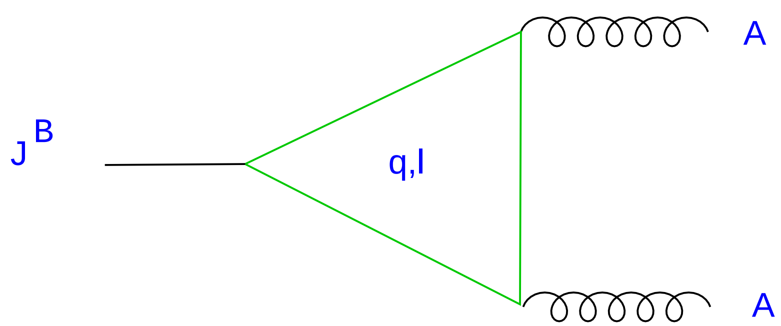
What else?

# Experimentally testable scenarios

- Electroweak baryogenesis
- Resonant leptogenesis
- Baryogenesis via neutrino oscillations

## Common feature

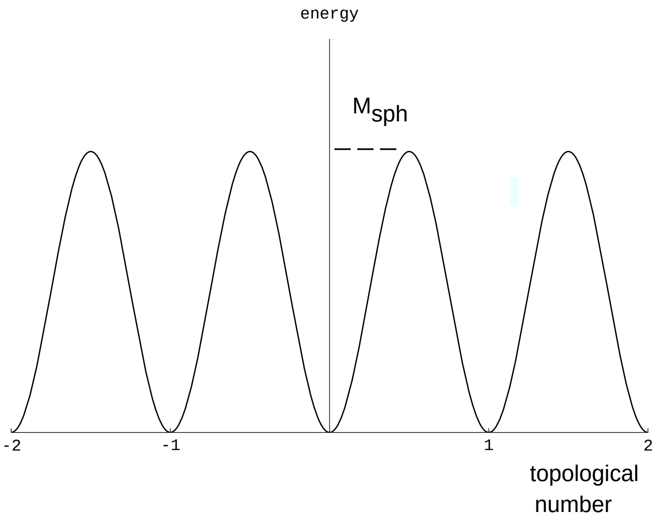
The source of baryon number non-conservation: rapid anomalous EW baryon number violating processes at high temperatures




$$\partial_\mu J^B_\mu = \partial_\mu J^L_\mu = \frac{n_f}{32\pi^2} \mathrm{Tr} \left( F_{\mu\nu} \tilde{F}_{\mu\nu} \right)$$

# Rate of B-nonconservation

$T=0$, t'Hooft; $T\neq 0$, Kuzmin, Rubakov, MS




$$\Gamma \sim \begin{cases} \exp(-\frac{4\pi}{\alpha_W}) \sim 10^{-160}, & T=0 \\ \exp\left(-\frac{M_{sph}}{T}\right), & T<T_c \\ (\alpha_W)^5 T^4, & T>T_c \end{cases}$$

These reactions are in thermal equilibrium for

$$100 \text{ GeV} \sim T_c < T < (\alpha_W)^5 M_{Pl} \sim 10^{12} \text{ GeV}$$

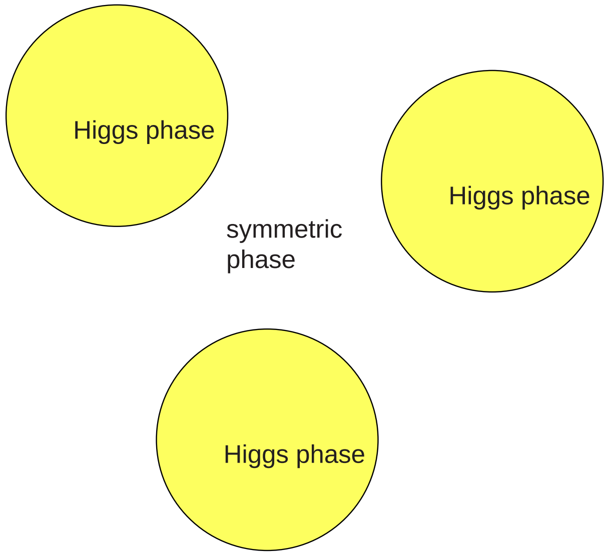
# Electroweak baryogenesis

- Non-equilibrium: first order phase transition
- B-nonconservation: EW anomaly
- CP-violation: complex phases in Higgs-fermion couplings

# Electroweak phase transition

First order phase transition: a mechanism to go out of thermal equilibrium.

The universe is supercooled in the symmetric phase $\longrightarrow$ bubbles of new (Higgs) phase are nucleated.




Size of the critical bubble:

$R \sim (\alpha_W T_c)^{-1}$

$T_c \sim 100$ GeV

Bubble size at percolation:

$\sim 10^{-6}$ cm.

# Mechanism

Cohen, Kaplan, Nelson

1. Symmetric phase: $\langle \phi^\dagger \phi \rangle \simeq \mathbf{0} \longrightarrow$ fermions are almost massless and B-nonconservation is rapid.

2. Higgs phase: $\langle \phi^\dagger \phi \rangle \neq \mathbf{0} \longrightarrow$ fermions are massive and B-nonconservation is exponentially suppressed.

$\Downarrow$

Fermions interact in a CP-violating way (reflected and transmitted) with the surface of the bubble

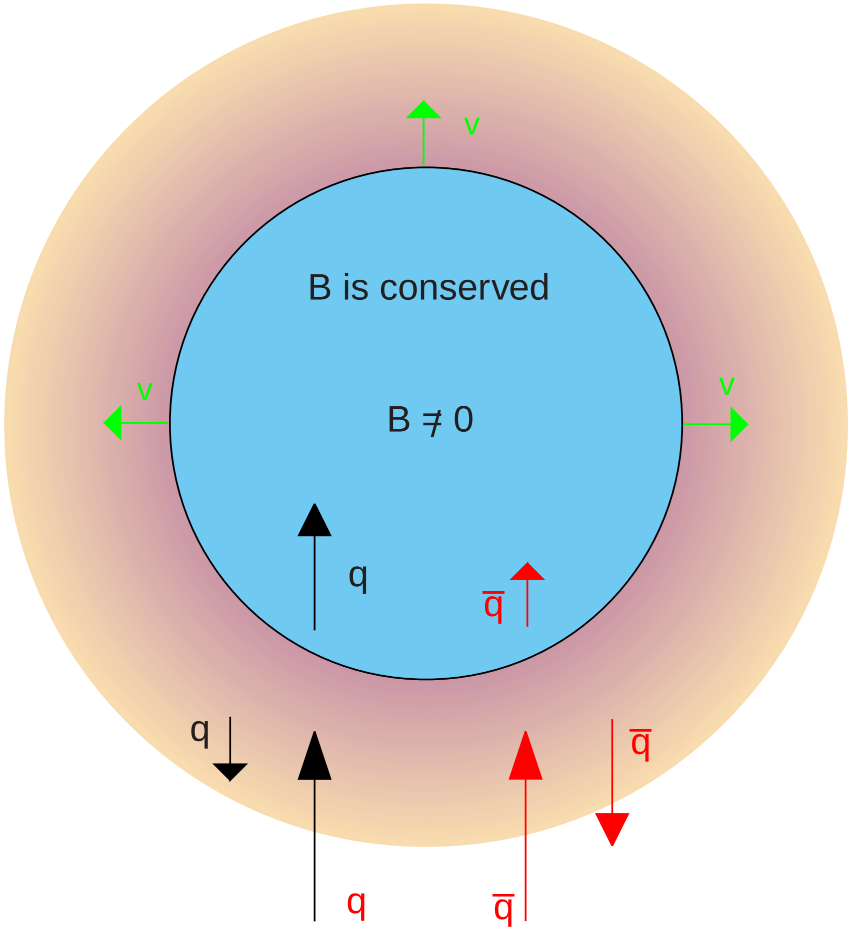
$\Downarrow$

Baryon asymmetry of the Universe after EW phase transition.

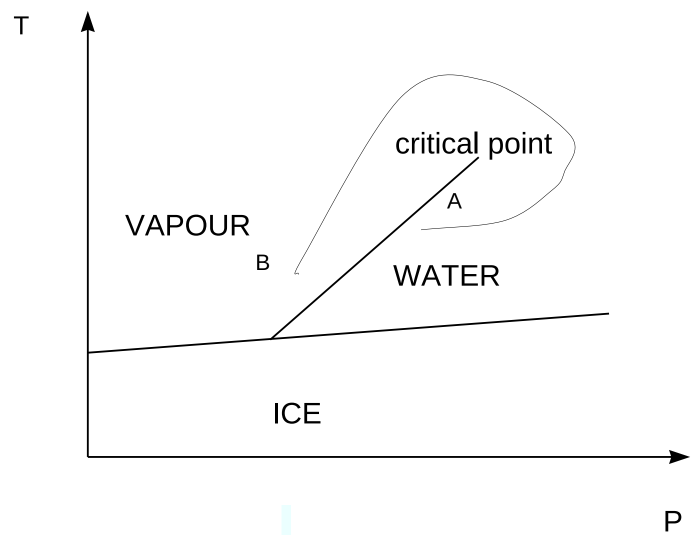
# Mechanism

B is not conserved

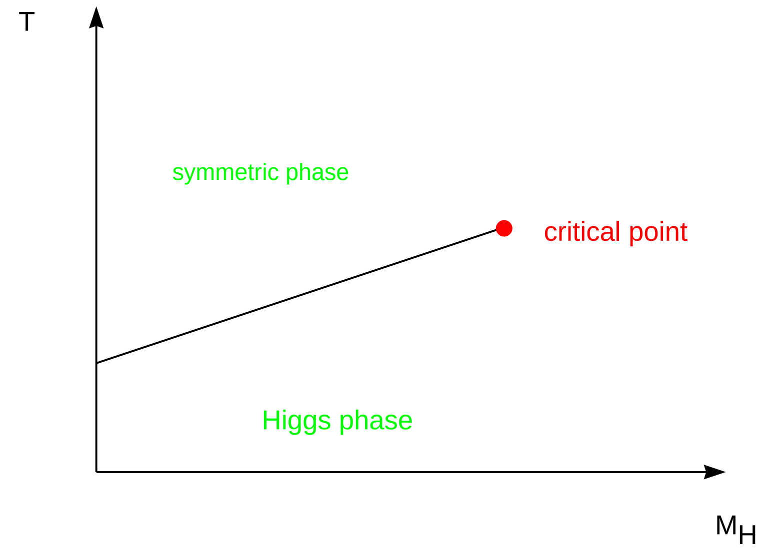
B = 0



Kajantie, Laine, Rummukainen, MS




Typical condensed matter phase diagram (pressure versus temperature)




Electroweak theory

$\langle \phi^\dagger \phi \rangle \ll (250GeV)^2$

$T = 109.2 \pm 0.8GeV,$

$M_H = 72.3 \pm 0.7GeV$

$\langle \phi^\dagger \phi \rangle_{T=0} \sim (250\ \mathrm{GeV})^2$

# How to make EWPT strongly first order?

MS Required for successful baryogenesis: freeze out of anomalous processes in the broken phase:

$$\frac{v(T_c)}{T_c} > 1$$

- Add singlet scalar field
- Add extra Higgs doublet
- SUSY: light stop
- Higher dimensional operators such as $(H^\dagger H)^3$

# How to make CP violation stronger?

- Add extra Higgs doublet(s)
- SUSY: sparticle interaction with bubble wall
- Higher dimensional operators with CP-breaking

# Experimental predictions

Carena, Quiros, Wagner; Laine, Losada,...

MSSM

- light Higgs, $M_H < 120$ GeV
- light stop, $120$ GeV $< M < M_t$
- large CP-violation in chargino sector
- EDM of electron and neutron
- $b \longrightarrow s\gamma$ decays
- ...

Simplest possibility: Minimal Standard Model + 3 (or 2) singlet right-handed fermions.

Most general renormalizable Lagrangian

$$L_{\nu MSM} = L_{MSM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\, \bar{N}_I^c N_I + h.c.,$$

Extra coupling constants:

3 (2) Majorana masses of new neutral fermions $N_i$,

15 (9) new Yukawa couplings in the leptonic sector

(3 (2) Dirac neutrino masses $M_D = F_{\alpha I} v$, 6 (4) mixing angles and 6 (3) CP-violating phases),

18 (11) new parameters in total.

Fukugita, Yanagida

- Non-equilibrium: freezing out
- B-nonconservation: EW anomaly; L-nonconservation: Majorana masses of singlet leptons
- CP-violation: 6 (3) CP-violating phases in the lepton sector

Physics: non-equilibrium decays of $N$ produce lepton asymmetry, which is then processed into baryon asymmetry due to electroweak anomaly.

Out of equilibrium and conversion to baryon asymmetry conditions:

$$M_W < T_{decay} < M_N$$

Constraint on the decay Yukawa coupling $\Gamma_{\rm tot} \simeq f^2 M_N$:

$$\frac{M_W^2}{M_N M^*} < f^2 < \frac{M_N}{M^*}, \quad M^* \simeq 10^{18}\text{GeV}$$

Baryon asymmetry for non-degenerate case ($\Delta M_{ij} \sim M_k$):

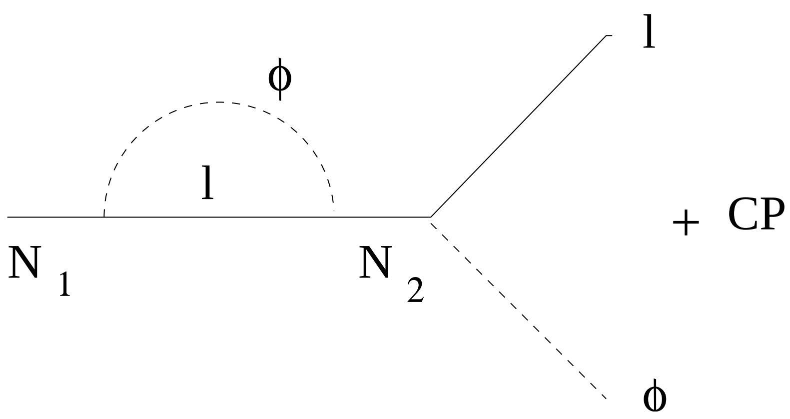
$$\frac{n_B}{s} \sim 10^{-3} f^2 \simeq 10^{-10}$$

for $f^2 \sim 10^{-7}$; works for $M_N > 10^{11}$ GeV.

Pilaftsis, Underwood

Is it possible to have $M_N \sim M_W$?

Yes, for degenerate case:




$$\frac{n_B}{s} \sim 10^{-3} f^2 \frac{M_2^2}{M_2^2 - M_3^2}$$

May work for $\frac{\Delta M^2}{M^2} \sim f^2 \sim 10^{-16}$

Challenge: difficult to test directly: relatively large mass and small Yukawa couplings. Perhaps, possible in future $e^+e^-$ and $\mu^+\mu^-$ colliders.

Indirect signatures: rare decays $\mu \to e\gamma, \;\; \mu \to eee$.

# Baryogenesis via neutrino oscillations

Consider previous model with the masses of singlet fermions – sterile neutrinos considerably smaller than $M_W$, say $\mathcal{O}(1)$ GeV (the $\nu$MSM). Then these particles decay well below temperatures $100$ GeV – no way for baryogenesis due to their decays. They also may only thermalize below $M_W$ as Yukawas are small.

- Non-equilibrium: $n_N \neq n_{eq}$ for all $T > M_W$
- B-nonconservation: EW anomaly; L-nonconservation: effectively absent as $m_N \ll M_W$.
- CP-violation: 6 CP-violating phases in the lepton sector

# The mechanism

Akhmedov, Rubakov, Smirnov

Asaka,MS

Idea - sterile neutrino oscillations as a source of baryon asymmetry.

Qualitatively:

- Sterile neutrino are created in the early universe and oscillate in a coherent way with CP-breaking.
- The total lepton number gets unevenly distributed between active and sterile neutrinos.
- The lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes.

# Value of BAU

$$\frac{n_B}{s} \simeq 1.7 \cdot 10^{-10}\, \delta_{\rm CP} \left(\frac{10^{-5}}{\Delta M^2_{32}/M_3^2}\right)^{\frac{2}{3}} \left(\frac{M_3}{10\text{GeV}}\right)^{\frac{5}{3}}.$$

$$\delta_{\rm CP} = 4 s_{R23} c_{R23} \Big[ s_{L12} s_{L13} c_{L13} \big( (c^4_{L23} + s^4_{L23}) c^2_{L13} - s^2_{L13} \big) \cdot \sin(\delta_L + \alpha_2) + c_{L12} c^3_{L13} s_{L23} c_{L23} \, (c^2_{L23} - s^2_{L23}) \cdot \sin \alpha_2 \Big].$$

$\delta_{\rm CP} \sim 1$ is consistent with observed $\nu$ oscillations.

Nontrivial requirement: $|M_2 - M_3| \ll M_{2,3}$, i.e. heavier neutrinos must be degenerate in mass.

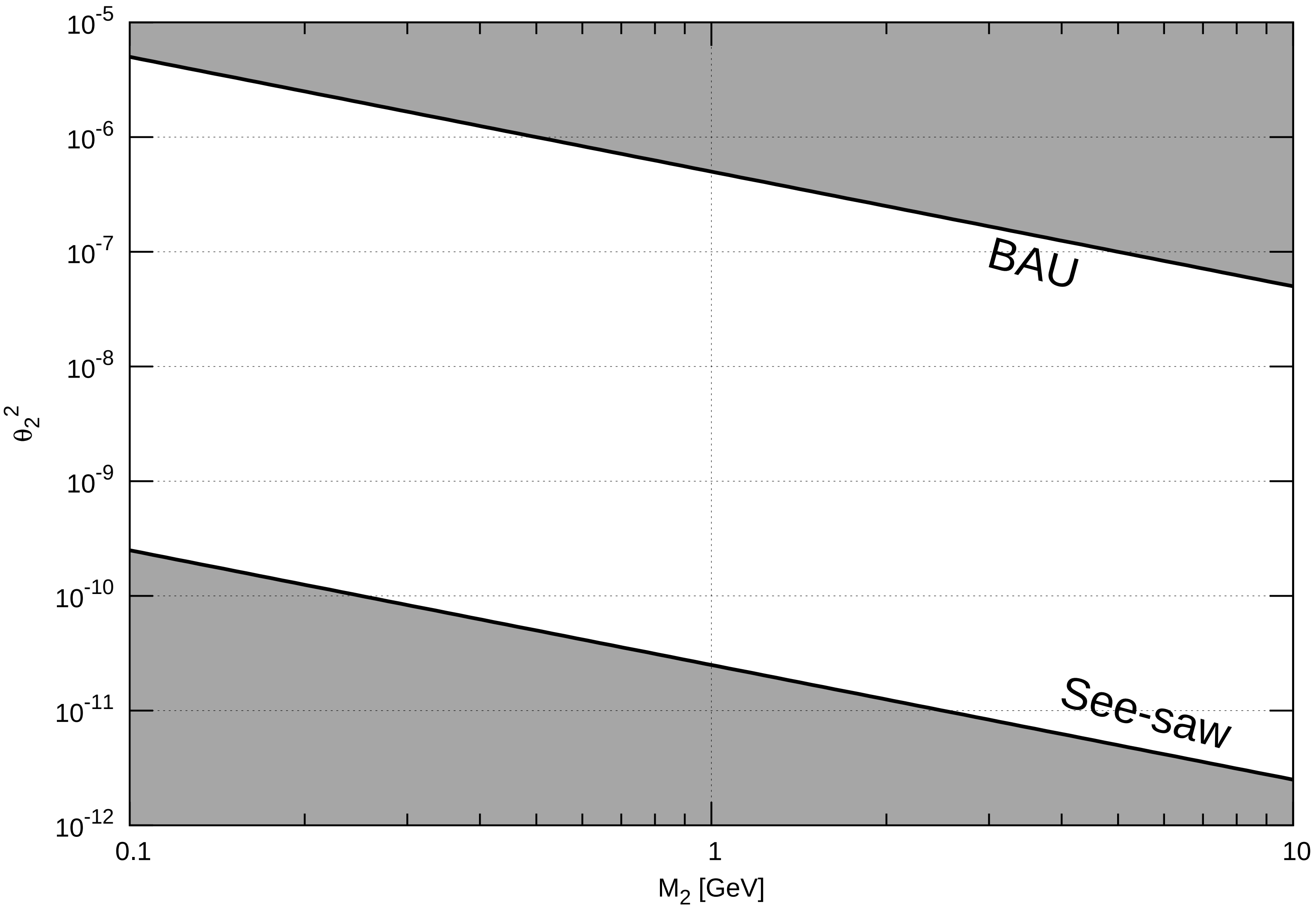
Works best if

$$M_2^2 - M_3^2 \sim T_W^3/M_0 \simeq 4\,(\text{keV})^2, \;\; |\mathrm{M}_2^2 - \mathrm{M}_3^2| \sim \mathrm{M}_1^2 \;\; ???$$

# Constraints on BAU neutral leptons

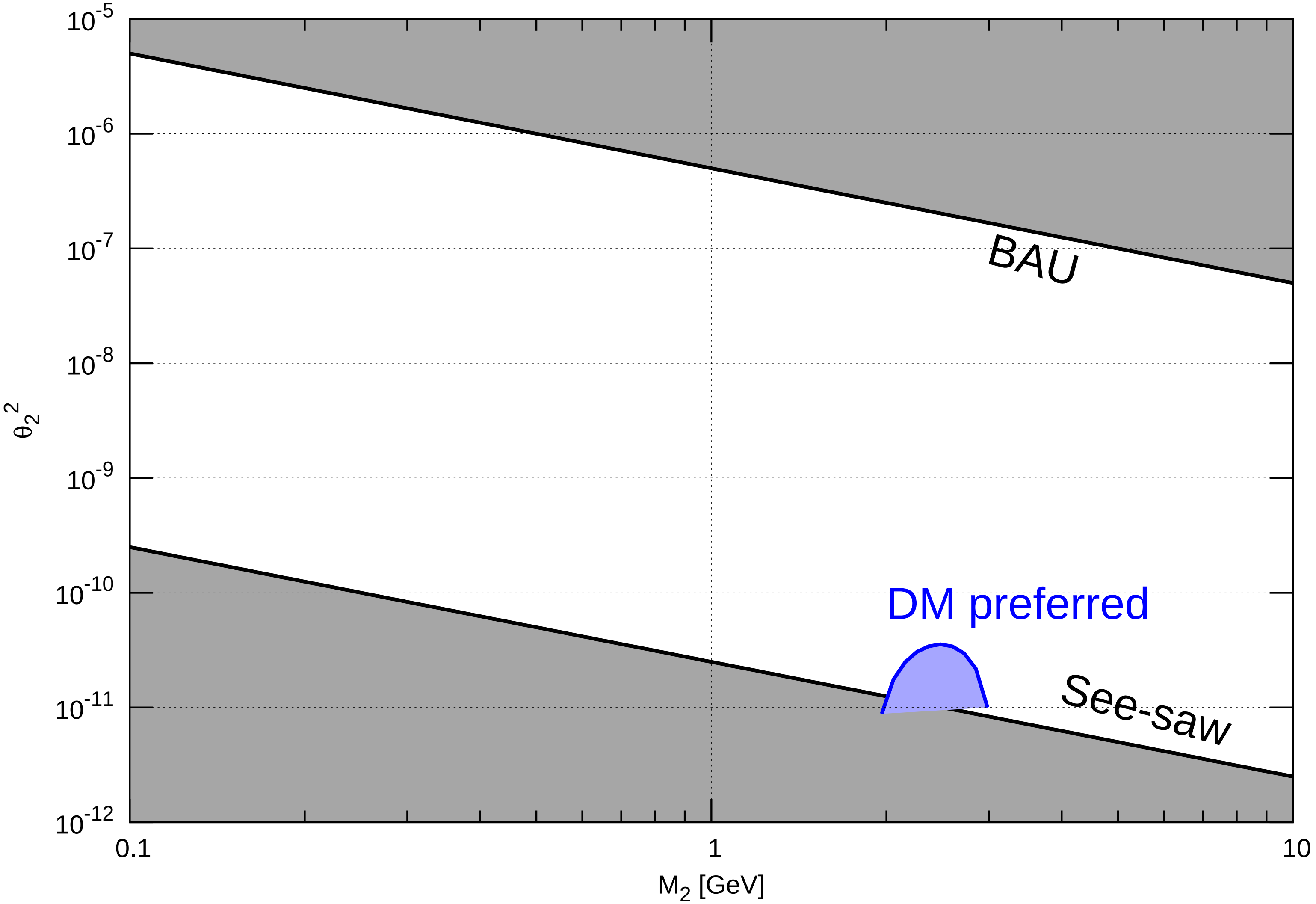
- BAU generation requires out of equilibrium: mixing angle of $N_{2,3}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $N_{2,3}$ to active neutrinos cannot be too small
- Dark matter and BAU. Concentration of DM sterile neutrinos must be much larger than concentration of baryons
- BBN. Decays of $N_{2,3}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $N_{2,3}$ have not been seen (yet).

## $N_{2,3}$: BAU



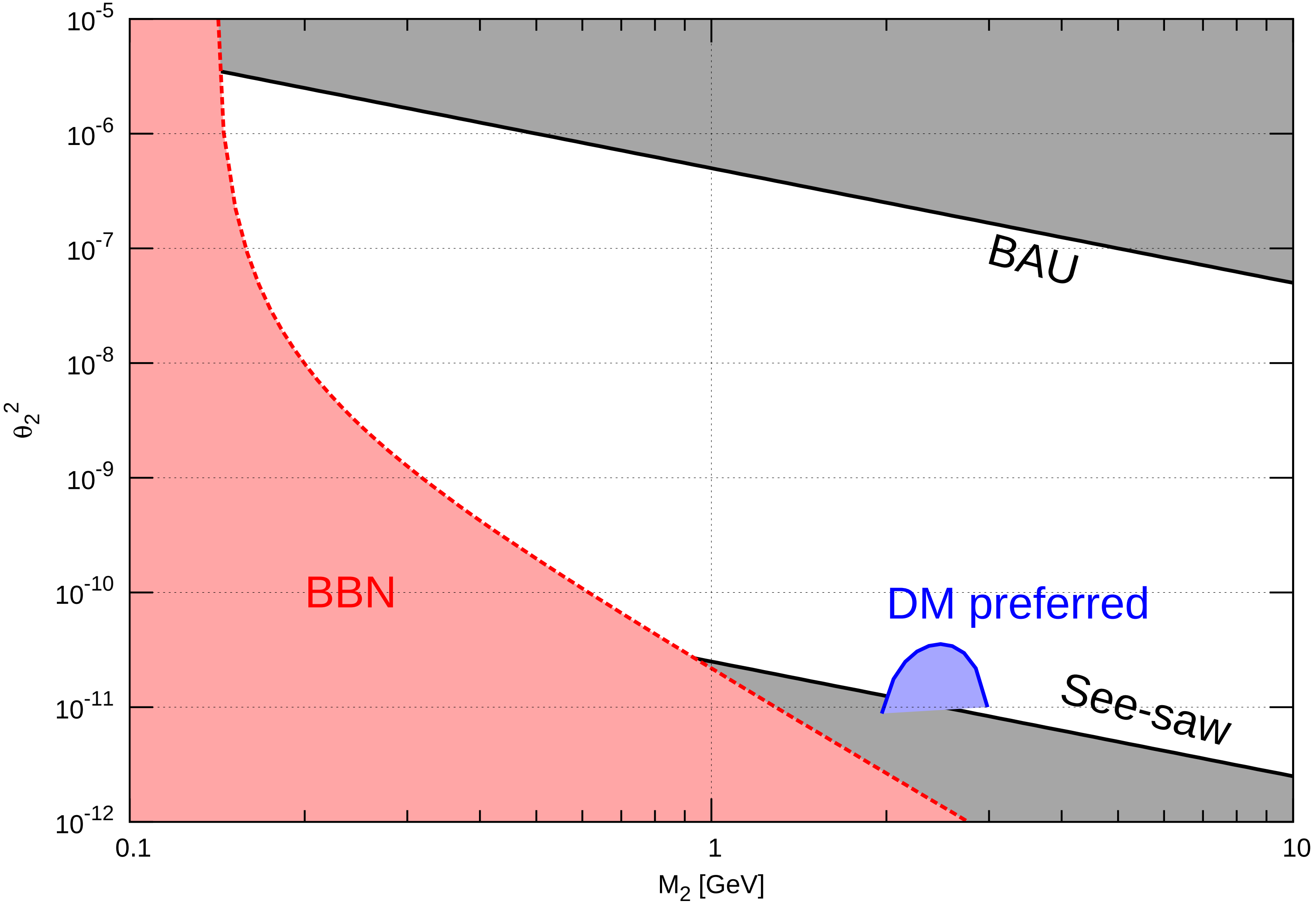
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$\theta_2^2$
BAU
See-saw
0.1
1
10
$M_2$ [GeV]

# $N_{2,3}$: BAU + DM

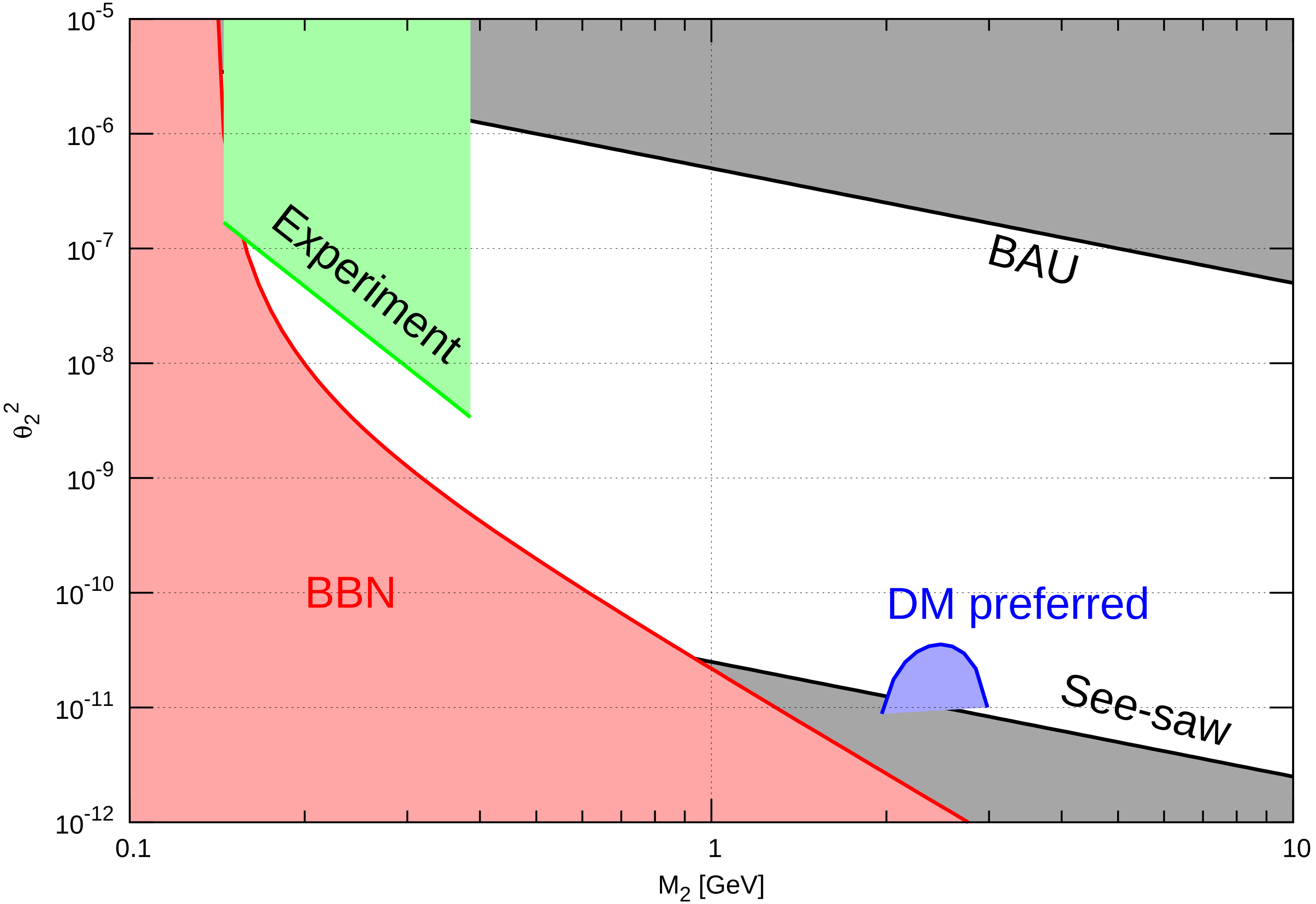


10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
θ2^2
BAU
DM preferred
See-saw
0.1
1
10
M2 [GeV]

# $N_{2,3}$: BAU + DM + BBN



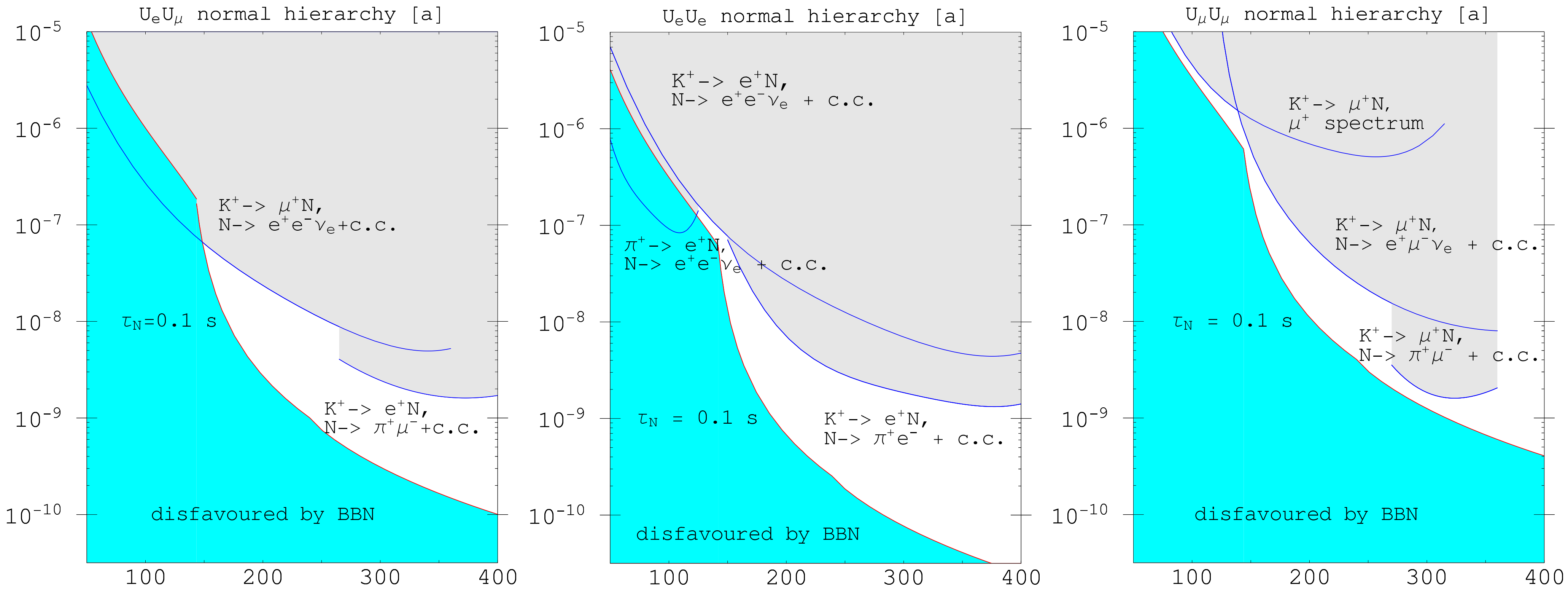
# $N_{2,3}$: BAU + DM + BBN + Experiment



# Previous searches

- T. Yamazaki *et al.*, “Search for heavy neutrinos in kaon decay”, 1984
- M. Daum *et al.* “The KARMEN time anomaly: Search for a neutral particle of mass 33.9-MeV in pion decay”, 2000
- A. Vaitaitis *et al.* [NuTeV Collaboration], “Search for neutral heavy leptons in a high-energy neutrino beam”, 1999
- P. Astier *et al.* [NOMAD Collaboration], “Search for heavy neutrinos mixing with tau neutrinos”, 2001
- P. Achard *et al.* [L3 Collaboration], “Search for heavy neutral and charged leptons in e+ e- annihilation at LEP”, 2001
- G. Bernardi *et al.*, “Search For Neutrino Decay”, 1986; “Further Limits On Heavy Neutrino Couplings”, 1988

# CERN PS191 experiment, F. Vannucci (1988)




Conclusion: $M_{2,3} > 140$ MeV

# How to search for new leptons: laboratory

- Missing energy signal in $K,\ D$ and $B$ decays ($\theta^2$ effect)
  Example:

$$K^+ \to \mu^+ N, \quad M_N^2 = (p_K - p_\mu)^2 \neq 0$$

  Similar for charm and beauty.

  - $M_N < M_K$: KLOE, NA48, E787
  - $M_K < M_N < 1$ GeV: charm and $\tau$ factories
  - $M_N < M_B$: B-factories (planned luminosity is not enough)

# How to search for new leptons: laboratory

- Decay processes $N \to \mu^+\mu^-\nu$, etc ("nothing"$\to \mu^+\mu^-$) ($\theta^4$ effect)

  First step: proton beam dump, creation of $N$ in decays of $K,\ D$ or $B$ mesons

  Second step: search for decays of $N$ in a near detector, to collect all $N$s.

  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of MiniBooNE, NuMi, CNGS, T2K)
  - $M_N < M_D$: NuMi or CNGS or T2K beam + near detector
  - $M_N < M_B$: Project X (?) + near detector
  - $M_N > M_B$: extremely difficult

MINER$\nu$A, NuSOnG, HiResM$\nu$

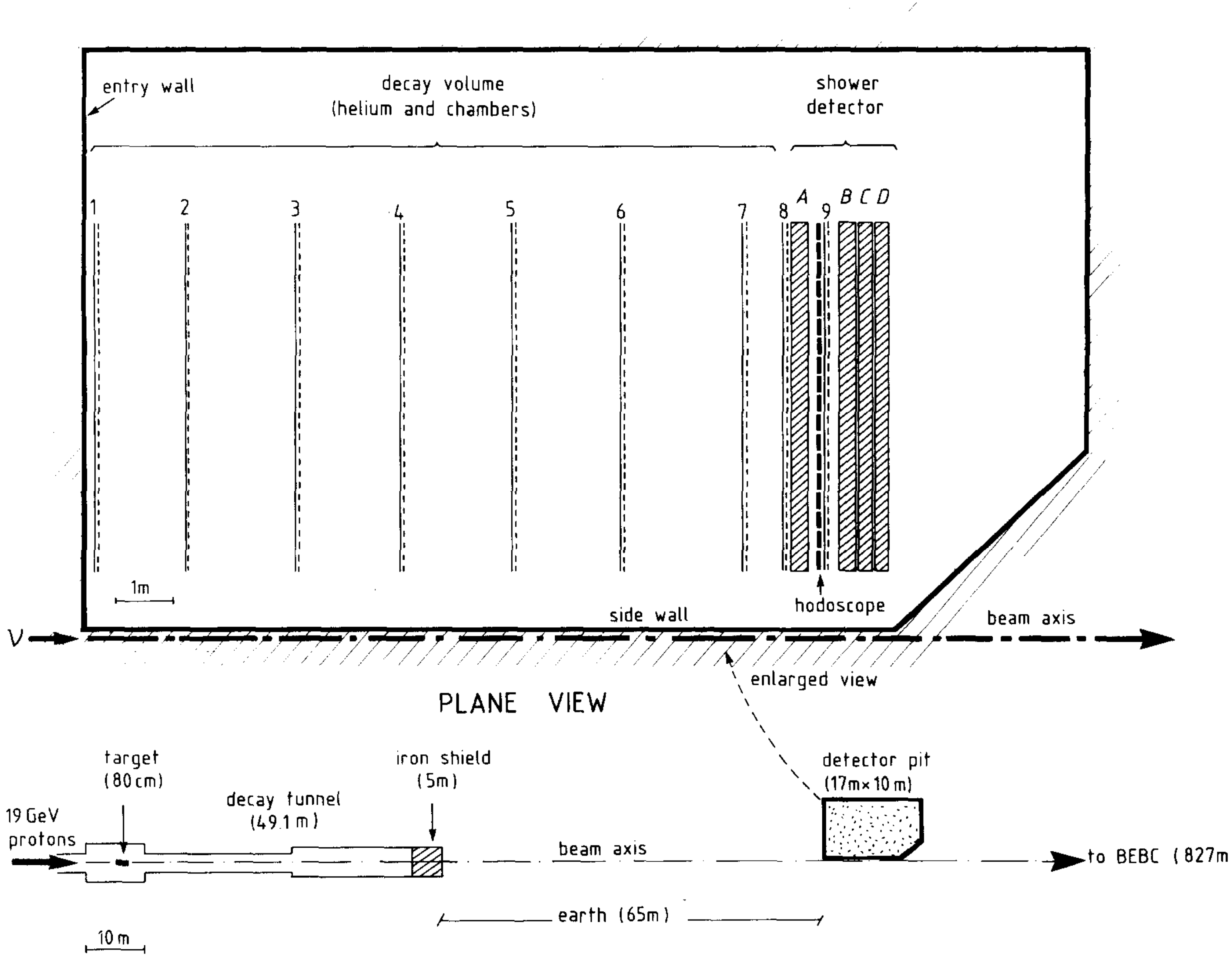
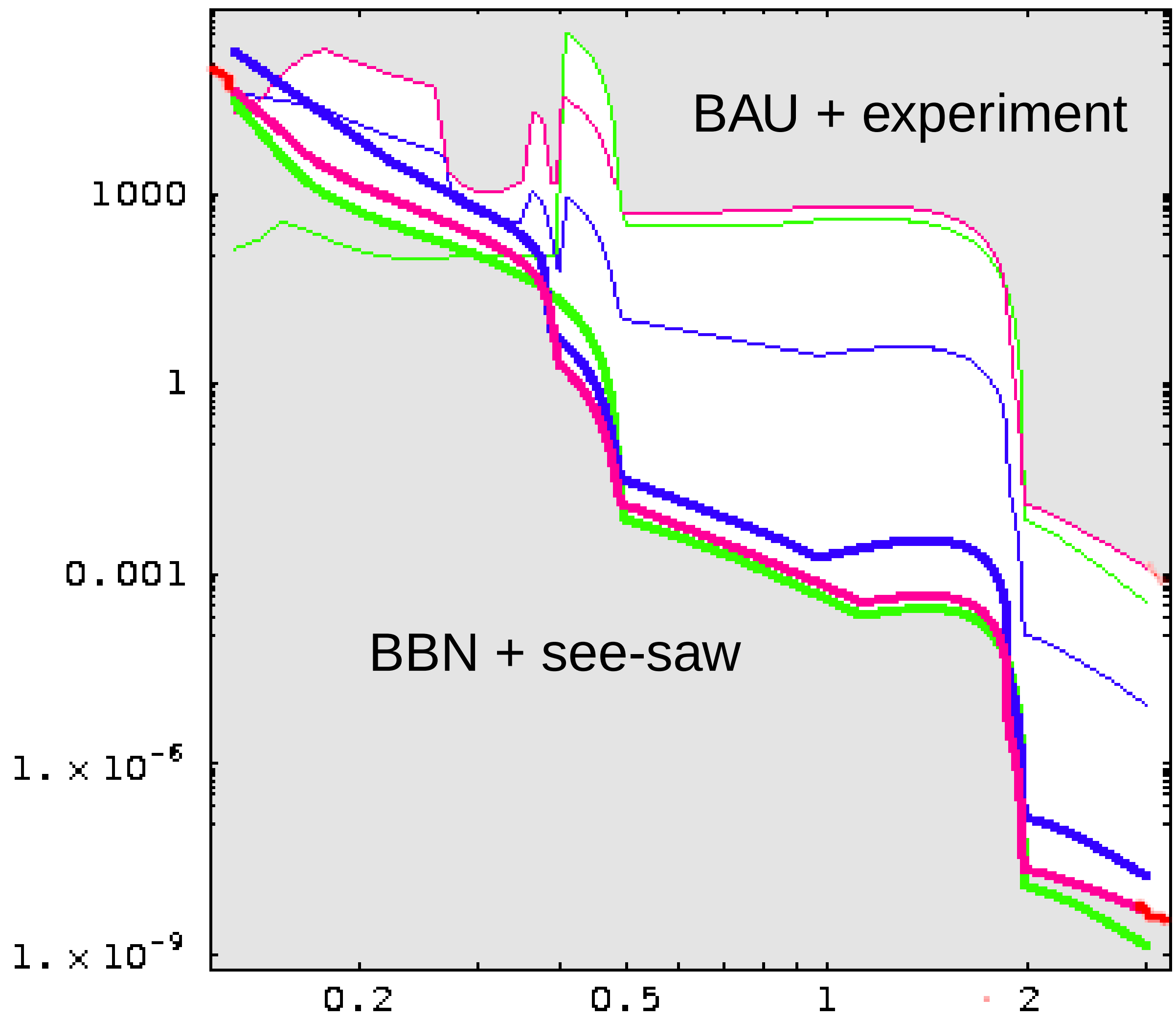



Fig. 1. Beam and layout of the detector.

# Number of N-decays in near detector, CNGS

5 m long detector

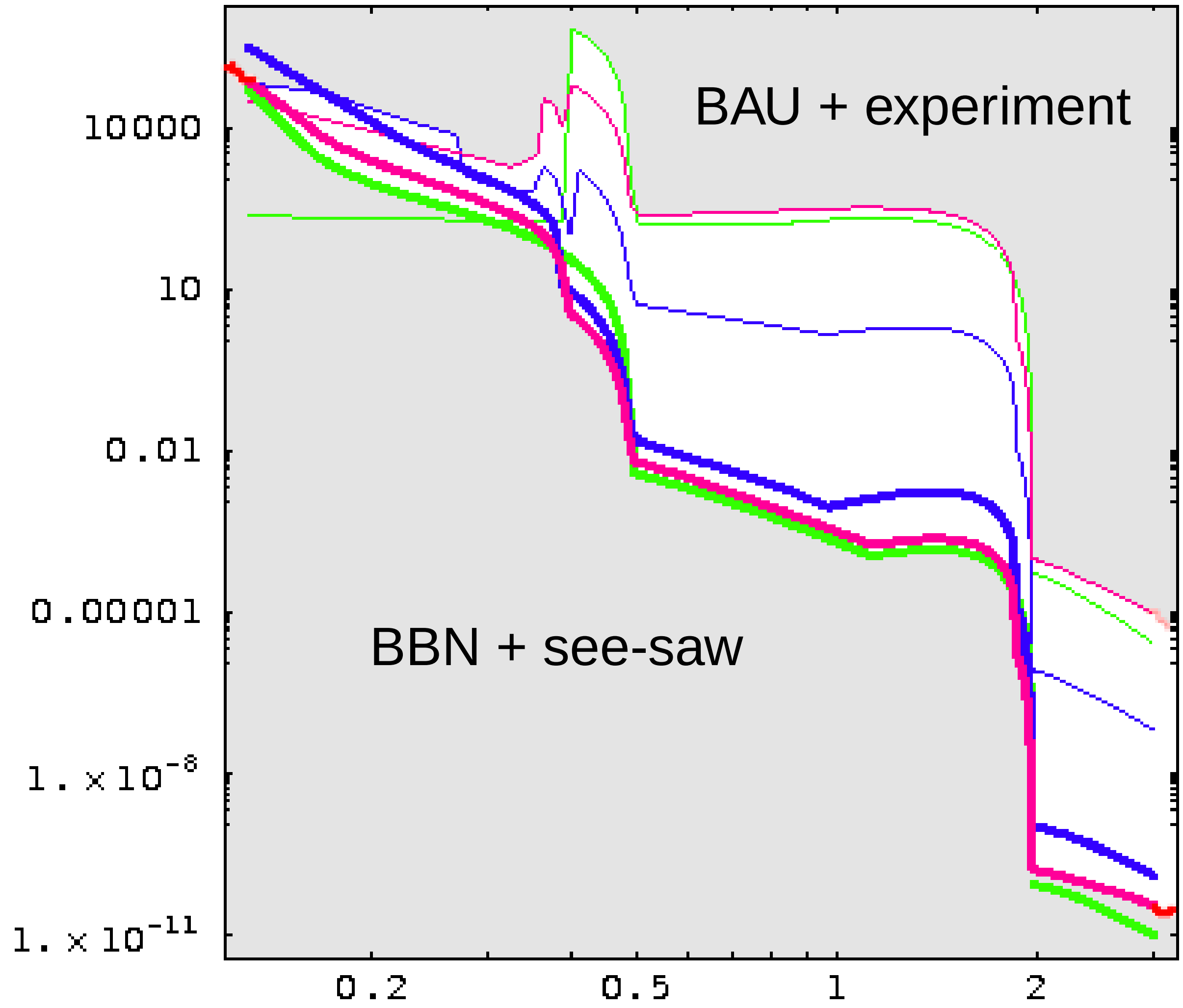
1 year of observations



# Number of N-decays in near detector, NuMi

5 m long detector

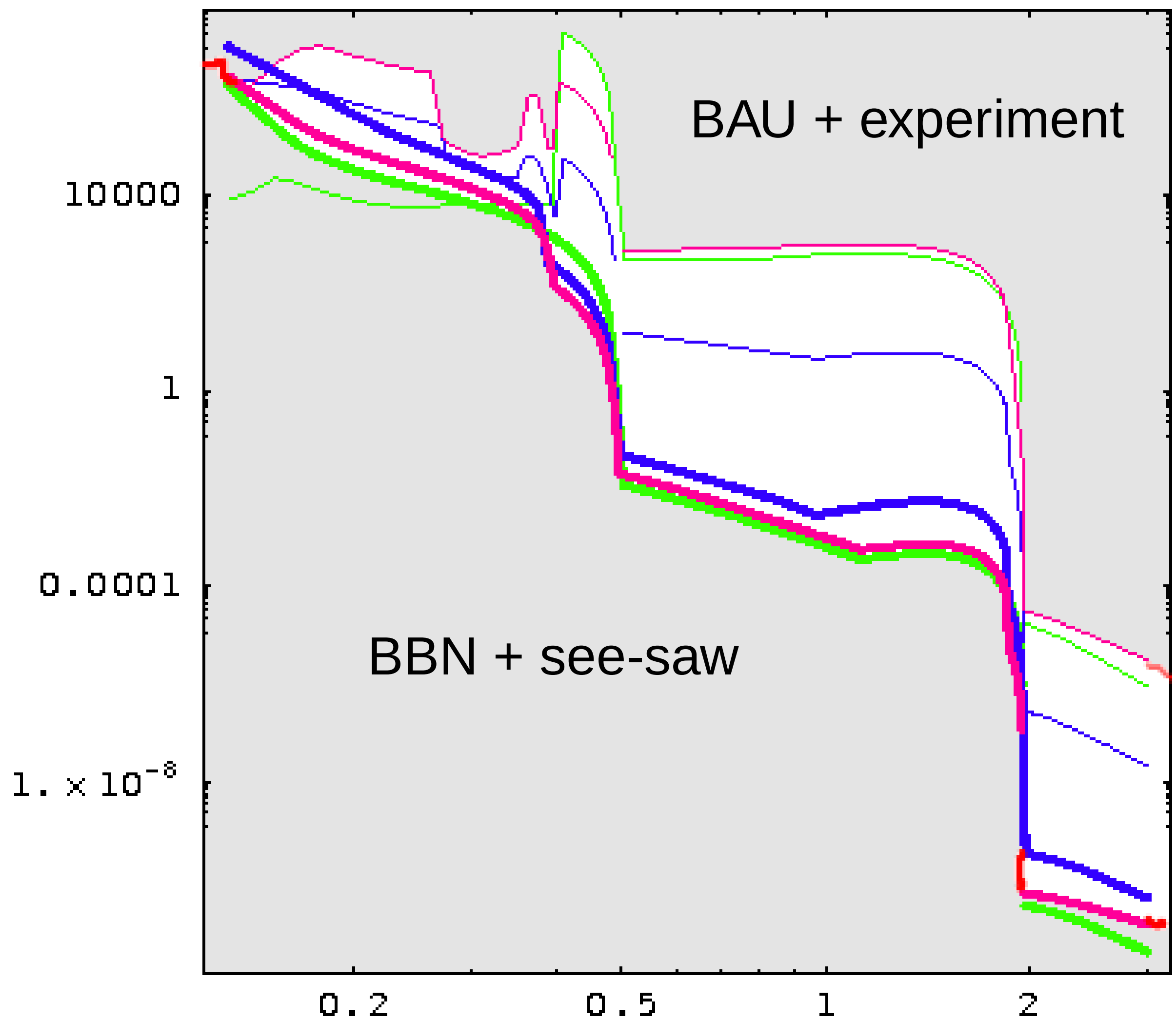
1 year of observations



# Number of N-decays in near detector, JPARC

5 m long detector

1 year of observations



# Conclusions

Crucial experiments to reveal the origin of baryon asymmetry of the Universe

- Electroweak baryogenesis
  - high energy (LHC) physics: standard Higgs plus extra scalars (or non-standard Higgs interactions), to make the EW phase transition be of the first order
  - high energy (LHC) physics: new fermions or scalars (e.g. SUSY) for extra CP violation
  - low energy physics: electric dipole moment of $e$ and $n$, exotic rare decays

- Resonant leptogenesis
  - high energy (LHC, $e^+e^-$) physics: standard Higgs plus heavy neutral leptons
  - low energy physics: processes like $\mu \to e\gamma, \quad \mu \to eee$

- Baryogenesis via neutrino oscillations in the $\nu$MSM:
  - high energy (LHC) physics: nothing but the Higgs in the mass interval $M_H \in [129, 189]$ GeV
  - low energy physics: Missing energy signal in $K,\ D$ and $B$ decays, decay processes $N \to \mu^+\mu^-\nu$, etc ("nothing"$\to \mu^+\mu^-$)