ÉCOLE POLYTECHNIQUE
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NuMSM as a minimal testable solution to BSM problems

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CERN, November 8, 2017

Outline

What are the problems and ideas for solutions?

- Charge asymmetry of the Universe
  - Baryogenesis
- Rotational curves of galaxies, matter content, large scale structure
  - Particle Dark Matter

Baryon asymmetry of the Universe and baryogenesis

The birth of antimatter

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Big theoretical issue: how to unify quantum mechanics and special relativity

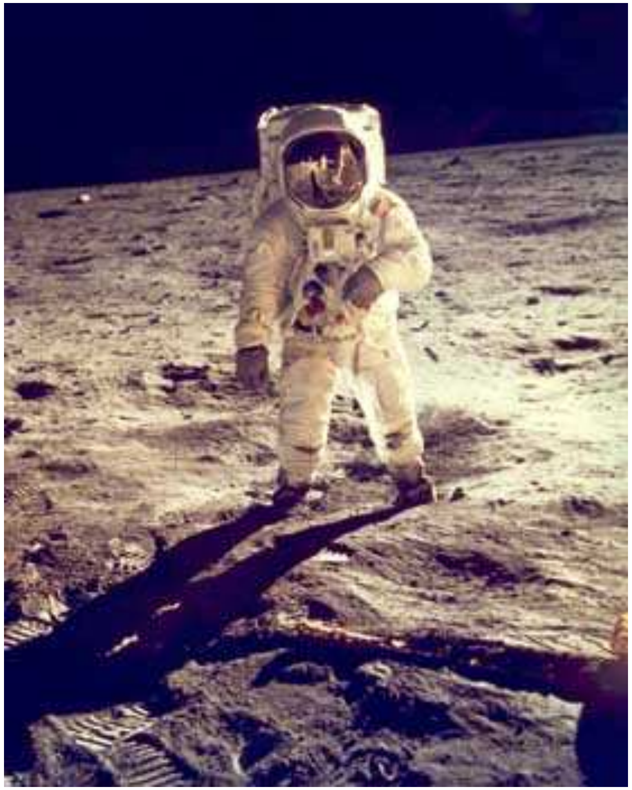
1930, Dirac: construction of relativistic equation describing quantum mechanics of electron (particle with spin $\frac{1}{2}$)

Dirac hypothesis: Nobel Prize Lecture, 1933

“If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regards it rather as an accident that the Earth (and presumably the whole solar system), contains a predominance of electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

Baryon asymmetry in the present universe

Dirac was perfectly correct that the solar system is constructed from matter!



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- The search of antinuclei in cosmic rays: the probability of the process

$$pp \to antinuclei + etc$$

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is very small!

Result: no antinuclei in cosmic rays have been found!

Detection of antimatter

- Annihilation: particles and antiparticles annihilate:

$$\begin{tikzcd}
& p\bar{p} \arrow[r] & \pi^+ \arrow[dl] & \pi^- \arrow[dr] & \pi^0 \arrow[r] & \gamma\gamma \\
& \nu_\mu\mu^+ \arrow[dl] & & & \mu^-\bar{\nu}_\mu \arrow[dr] & \\
e^+\nu_e\bar{\nu}_\mu & & & & & e^-\bar{\nu}_e\nu_\mu
\end{tikzcd}$$

Detection of γ-rays?

Detection of antimatter

- Annihilation: particles and antiparticles annihilate:

$$\begin{array}{ccccccccc}
 & & p\bar{p} & \rightarrow & \pi^+ \quad \pi^- & \pi^0 & \rightarrow & \gamma\gamma & \\
 & \nu_\mu \mu^+ \swarrow & & & & \searrow \mu^- \bar{\nu}_\mu & & & \\
e^+ \nu_e \bar{\nu}_\mu \swarrow & & & & & & \searrow e^- \bar{\nu}_e \nu_\mu & &
\end{array}$$

Detection of γ-rays?

However, this has not been observed!

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Dirac was wrong: cosmological observations do not support the hypothesis that the distant stars and galaxies may consist of antimatter.

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Where is antimatter?

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The problem

Where is antimatter?

Its absence looks really strange, as the properties of matter and antimatter are very similar!

On the way to a solution

Breaking of charge symmetry and parity

Till 1956: general belief that the nature is symmetric with respect to change of particle into antiparticle.

C - charge conjugation: $p \leftrightarrow \bar{p}, \quad n \leftrightarrow \bar{n}, \quad e^- \leftrightarrow e^+$

P - parity transformation: $\vec{x} \to -\vec{x}$, $\vec{v} \to -\vec{v}$, but for spin $\vec{m} \to +\vec{m}$

1956: discovery of P and C breaking in weak interactions (Lee, Yang).

Many manifestations, e.g. in $\pi^\pm$ decays. In particular, C-transformation change left-handed neutrino into left-handed antineutrino, which does not exist.

Conclusion: properties of particles and antiparticles are in fact (somewhat) different.

However, the combined CP symmetry was believed to be exact:

change particles to antiparticles AND simultaneously their momenta.

Now, CP works for neutrino

$$CP: \quad \nu(\vec{v}) \quad \longrightarrow \quad \bar{\nu}(-\vec{v})$$

So, an antiparticle has the same properties as a particle in the mirror!

Still no solution for the problem of baryon asymmetry of the universe...

Universe is isotropic, according to observations.

Breaking of combined CP symmetry

1964 (Cronin, Fitch, Christenson, Turlay):
decays of K^0 mesons.
In a small fraction of cases ($\sim 10^{-3}$), long-lived K_L (a mixture of K^0 and $\bar{K}^0$ decays into pair of two pions, what is forbidden by CP-conservation. There are other manifestations of CP breaking. For example, if CP were exact symmetry, an equal number of K^0 and $\bar{K}^0$ would produce an equal number of electrons and positrons in the reaction

$$K^0 \to \pi^- e^+ \nu_e, \quad \bar{K}^0 \to \pi^+ e^- \bar{\nu}_e,$$

However, this is not the case: the number of positrons is somewhat larger ($\sim \mathbf{10^{-3}}$) than the number of electrons.

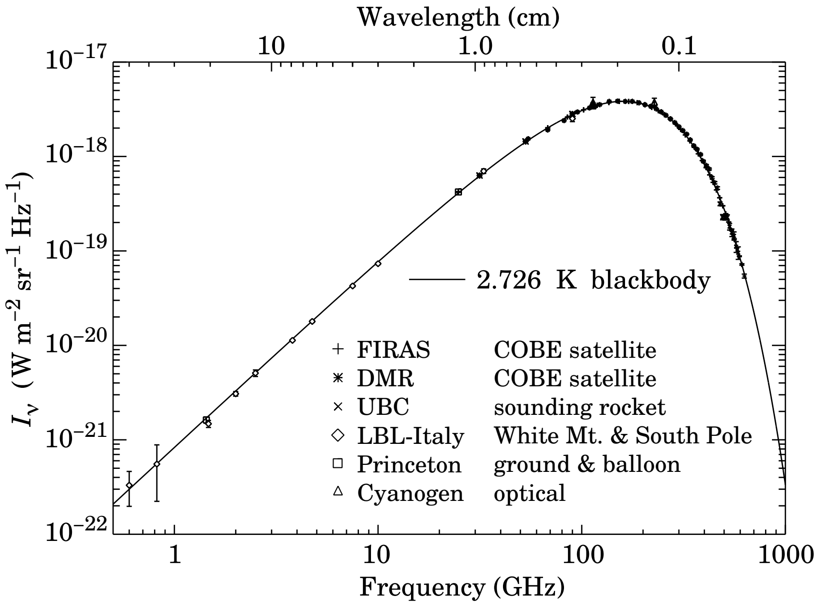
Conclusion: so, there is indeed a tiny difference between particles and antiparticles, on the level of $\mathbf{10^{-3}}$

How can this very small distinction be transformed in the 100% asymmetry of the universe we observe today?

Big Bang and baryon asymmetry

Cosmic microwave background

In 1965, Penzias and Wilson observed radio-waves in sub-millimeter range which were coming from all directions of the sky. They have a spectrum of black-body radiation with temperature $\mathbf{2.73^0}$.



The spectrum of the CMB

Big Bang and baryon asymmetry

Why do we care?

The existence of CMB is a proof of the Big Bang theory: universe expands and it was hot and dense in the past:

$$T[^oK] = \frac{10^{10}}{\sqrt{t[sec]}}$$

At temperatures $T > 10^{13}\ ^0$K $\simeq m_p c^2/k$ reactions like $\gamma + \gamma \to e^+ e^-, \quad \bar{p}p$ are effective: amount of antimatter is comparable with that of matter!

Big Bang and baryon asymmetry

Question: what is the baryon asymmetry

$$\Delta(t_0) = \frac{n_B - \bar{n}_B}{n_B + \bar{n}_B}$$

at this moment? $(T \sim 10^{13}\ {}^0K,\ \ t \sim 10^{-6}\text{s})$

Answer:

To find $\Delta(t_0)$ just take n_B/n_γ today!

Why?

Because of reaction $p\bar{p} \rightarrow$ few γ

Big Bang and baryon asymmetry

We have

- $n_\gamma \sim (410.4 \pm 0.5)$ photons/cm^3 (corresponds to temperature 2.73^0K)
- $n_B \sim (0.25 \pm 0.01)$ nucleon/m^3

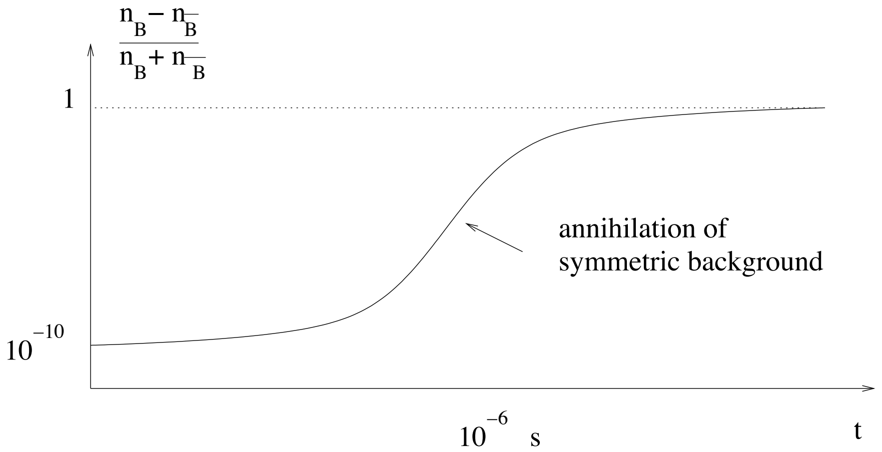
$$\Longrightarrow n_B/n_\gamma \simeq (6.1 \pm 0.2) \times 10^{-10}$$

Conclusion: Big Bang theory tells that the baryon asymmetry of the early universe is a very small number

$$\frac{(n_B - \bar{n}_B)}{(n_B + \bar{n}_B)} = 10^{-10}$$

Big Bang and baryon asymmetry

At $t \sim 10^{-6}$s after the big Bang for every 10^{10} quarks we have $(10^{10} - 1)$ antiquarks. Somewhat later the symmetric background annihilates into photons and neutrinos while the asymmetric part survives and gives rise to galaxies, stars, planets.



Dependence of baryon asymmetry on time

Big Bang and baryon asymmetry

Problems to solve:

- Why in the early universe the number of baryons is (a little bit, $\sim 10^{-10}$) greater than the number of antibaryons?

  Now, the comparison between of the baryon asymmetry in the early universe and the measure of the difference between particles and antiparticles in K^0 decays (10^{-3}) is much more comfortable!
- How to compute the primordial baryon asymmetry from fundamental theory?

Andrei Sakharov proposal, 1967:

“According to our hypothesis, the occurrence of C-asymmetry is the consequence of violation of CP-invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions."

In short: the universe is asymmetric because baryon number is not conserved in C- and CP-violating reactions which produce more baryons than antibaryons in expanding universe.

Consequence: Proton is not stable!

Sakharov model

Superheavy particles with mass $m \sim 10^{-5}$ grams,
and lifetime 10^{-43} s
Decay modes:

$$X \to p\, p, \quad p\, e^{+}, \quad \bar{X} \to \bar{p}\, \bar{p}, \quad \bar{p}\, e^{-}$$

If C and CP are broken, X and $\bar{X}$ will produce different number of protons et antiprotons, as K^0 and $\bar{K}^0$ produce the different numbers of electrons and positrons.
It is sufficient to produce a very small asymmetry 10^{-10} which will then be converted into 100% asymmetry later on.

Sakharov model

Revolutionary solution at that time: there was a believe that the proton is absolutely stable!

Paradox: there is no antimatter in the universe since matter is unstable!

Qualitatively, universe is asymmetric due to

- baryon number non-conservation
- breaking of C and CP
- universe expansion

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- B-violation?

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- B-violation?
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What kind of physics leads to

- B-violation?
- CP-violation?
- thermal nonequilibrium?

Dark matter in the universe

Problem since 1933, F. Zwicky.

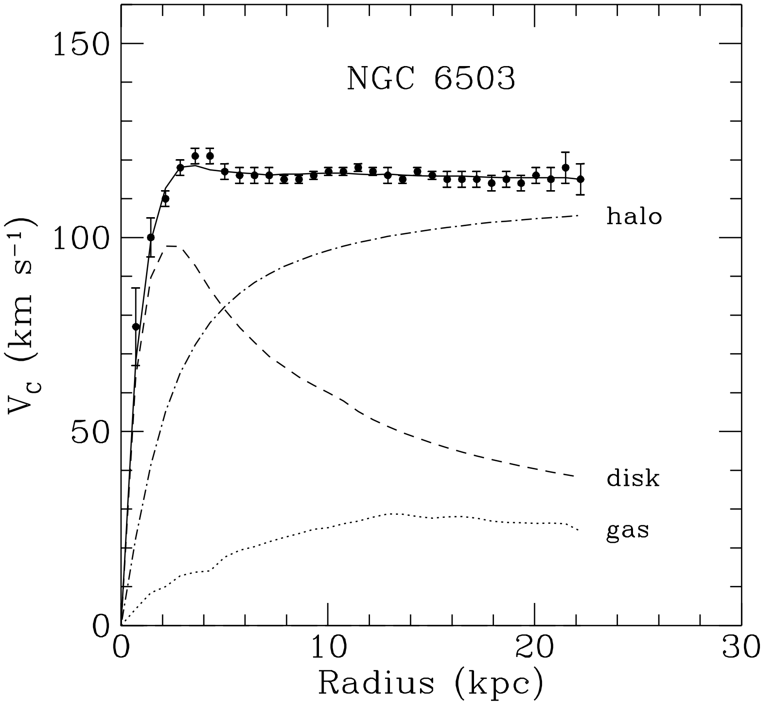
Most of the matter in the universe is dark

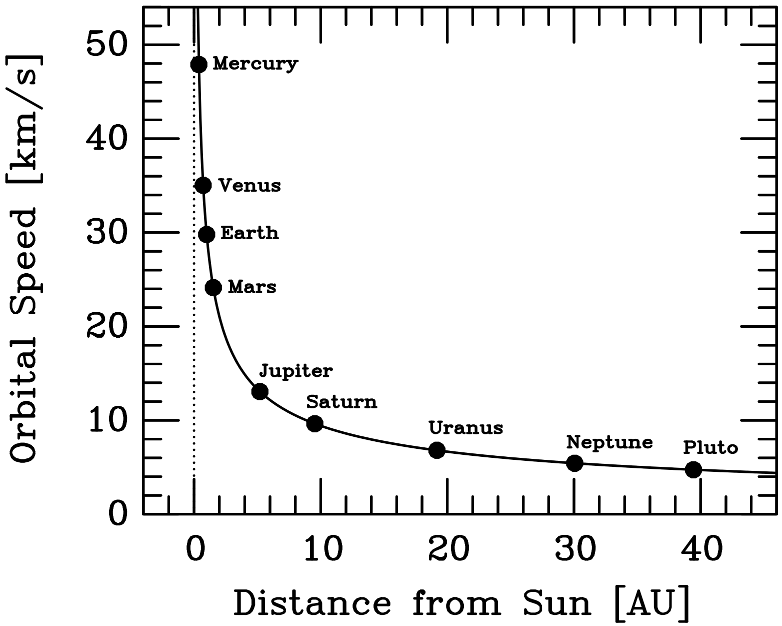
Evidence:

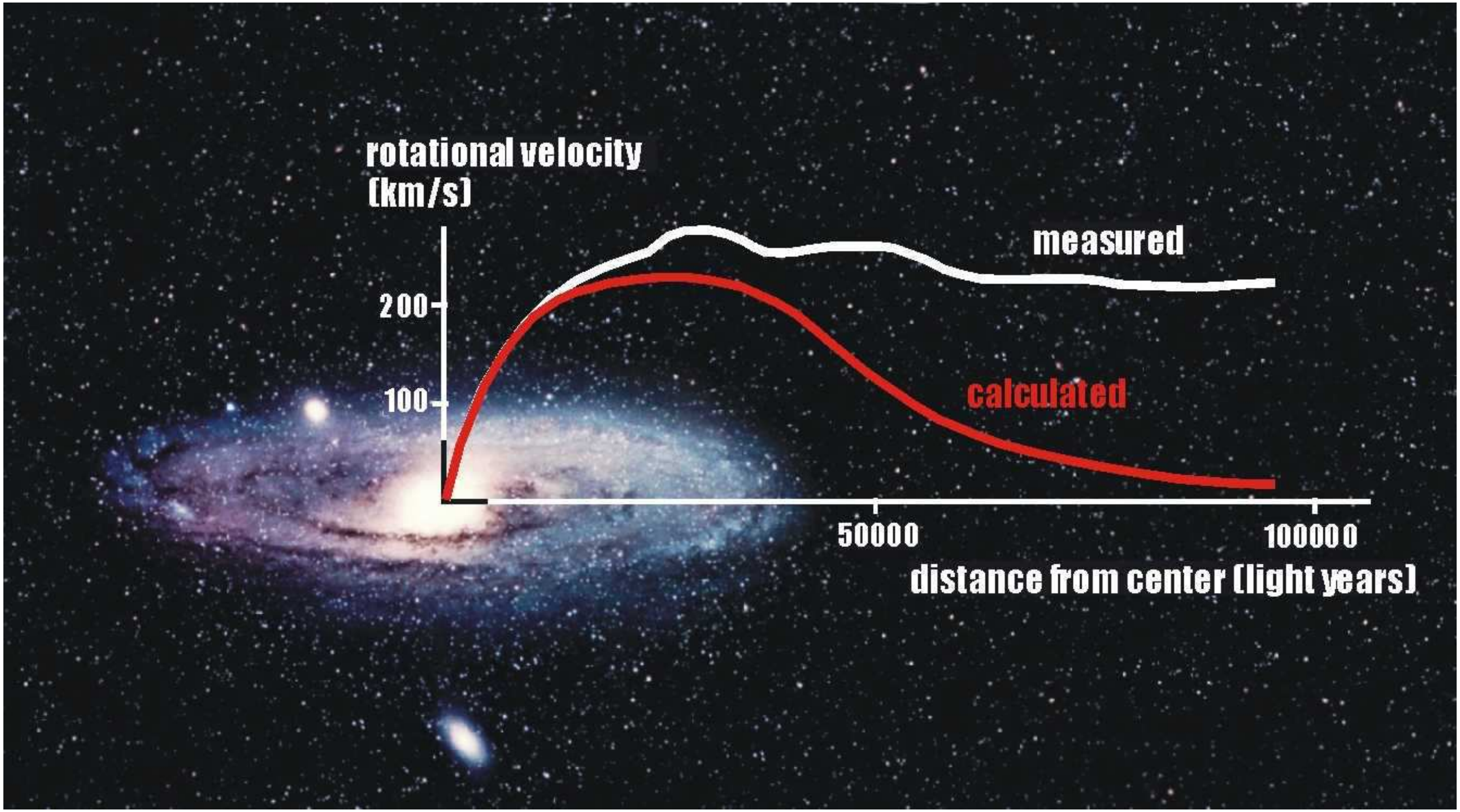
- Rotation curves of galaxies
- Big Bang nucleosynthesis
- Structure formation
- CMB anisotropies
- Supernovae observations

Non-baryonic dark matter:

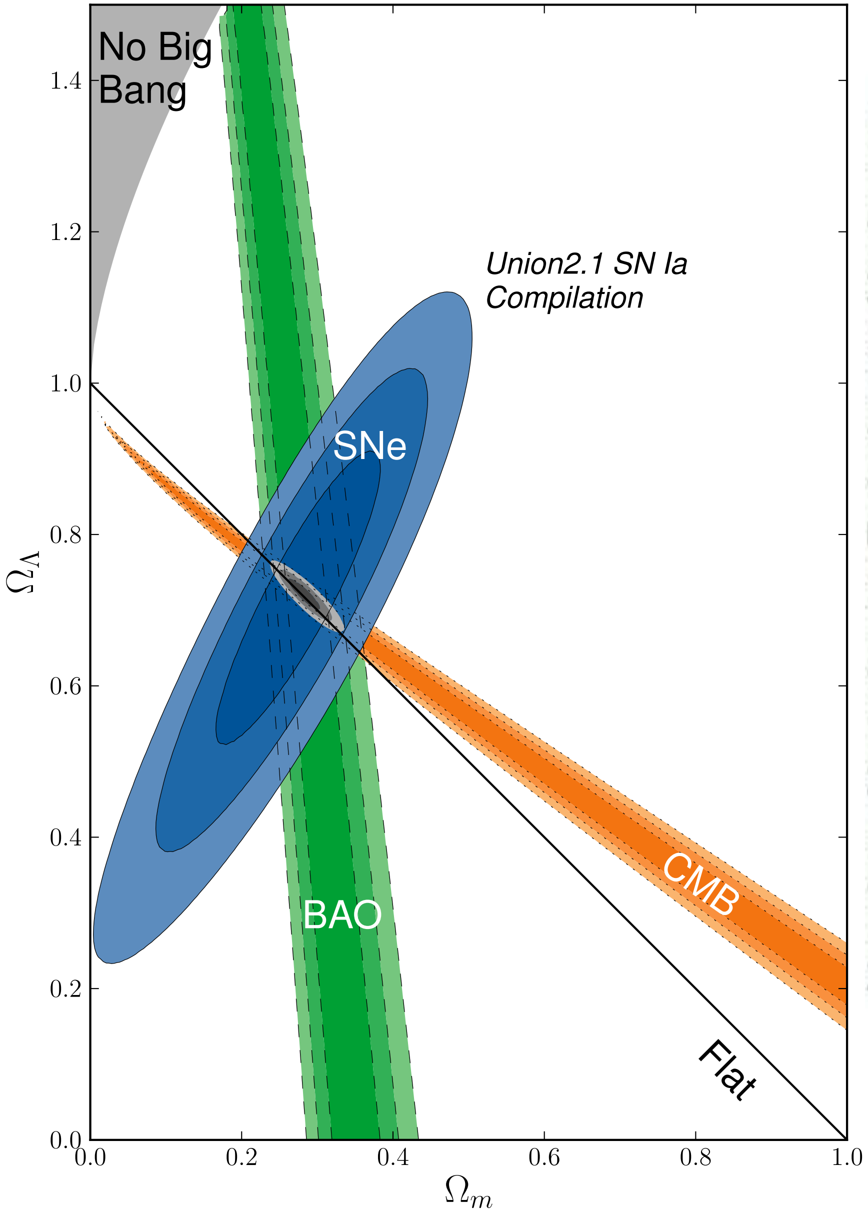
$\Omega_{DM} \simeq \mathbf{0.22}$

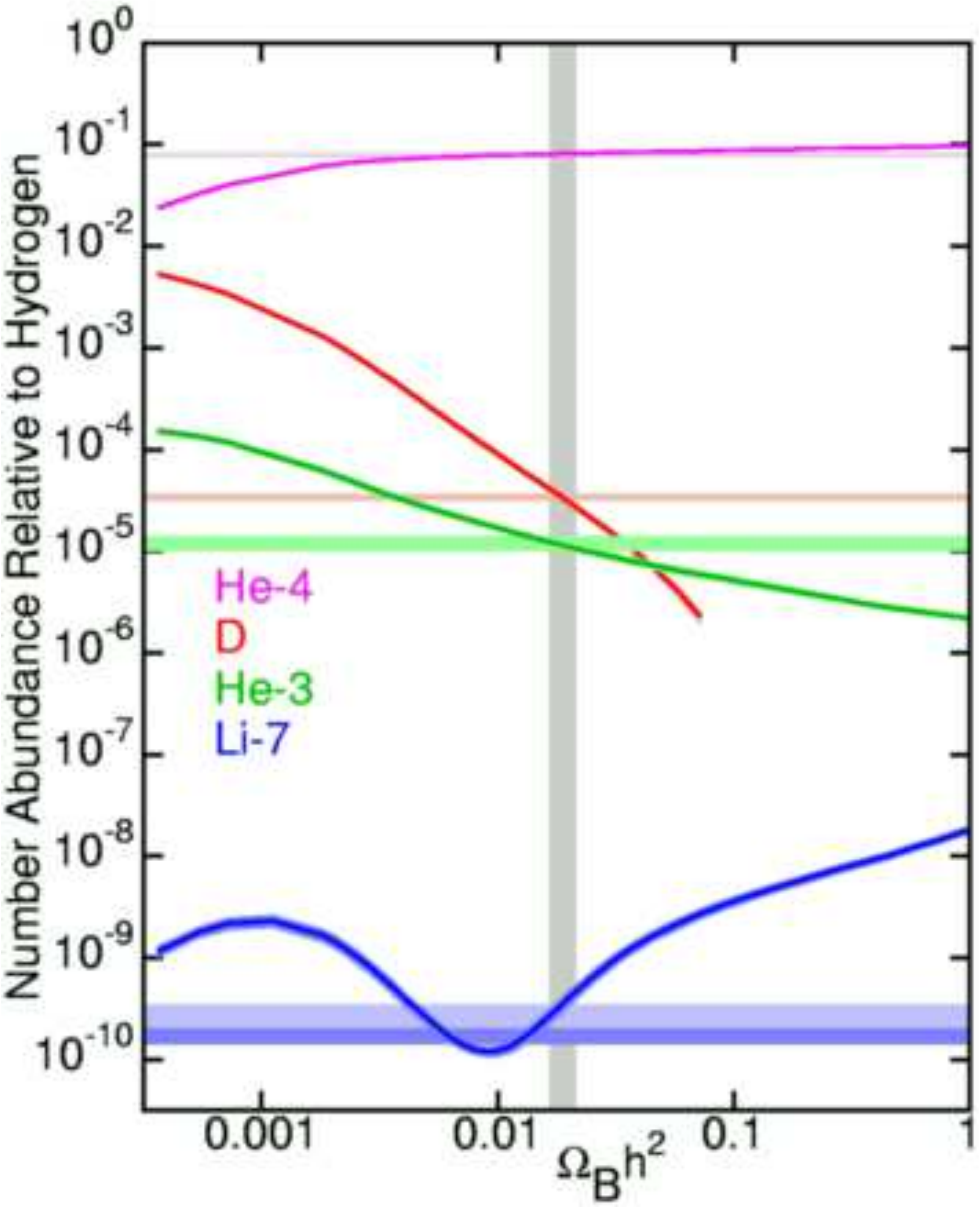


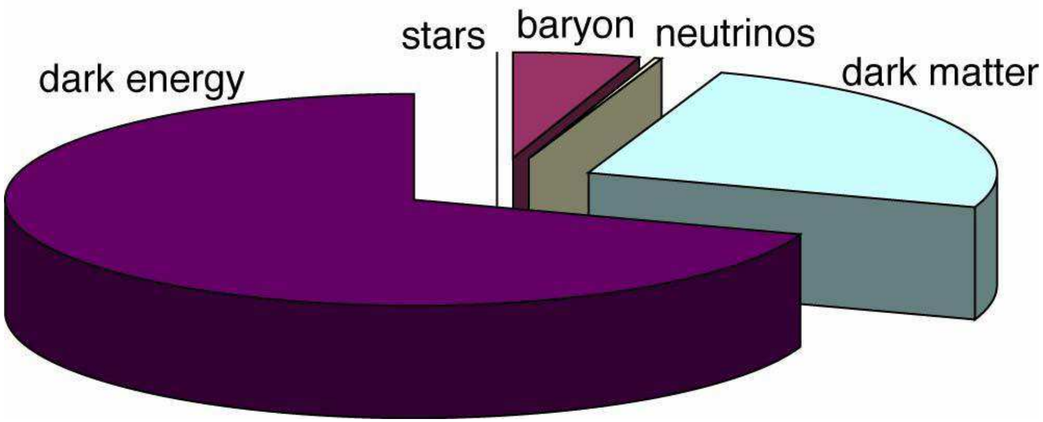



rotational velocity
(km/s)
200
100
measured
calculated
50000
100000
distance from center (light years)

Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)







Standard Model: no particle physics candidate for Dark Matter

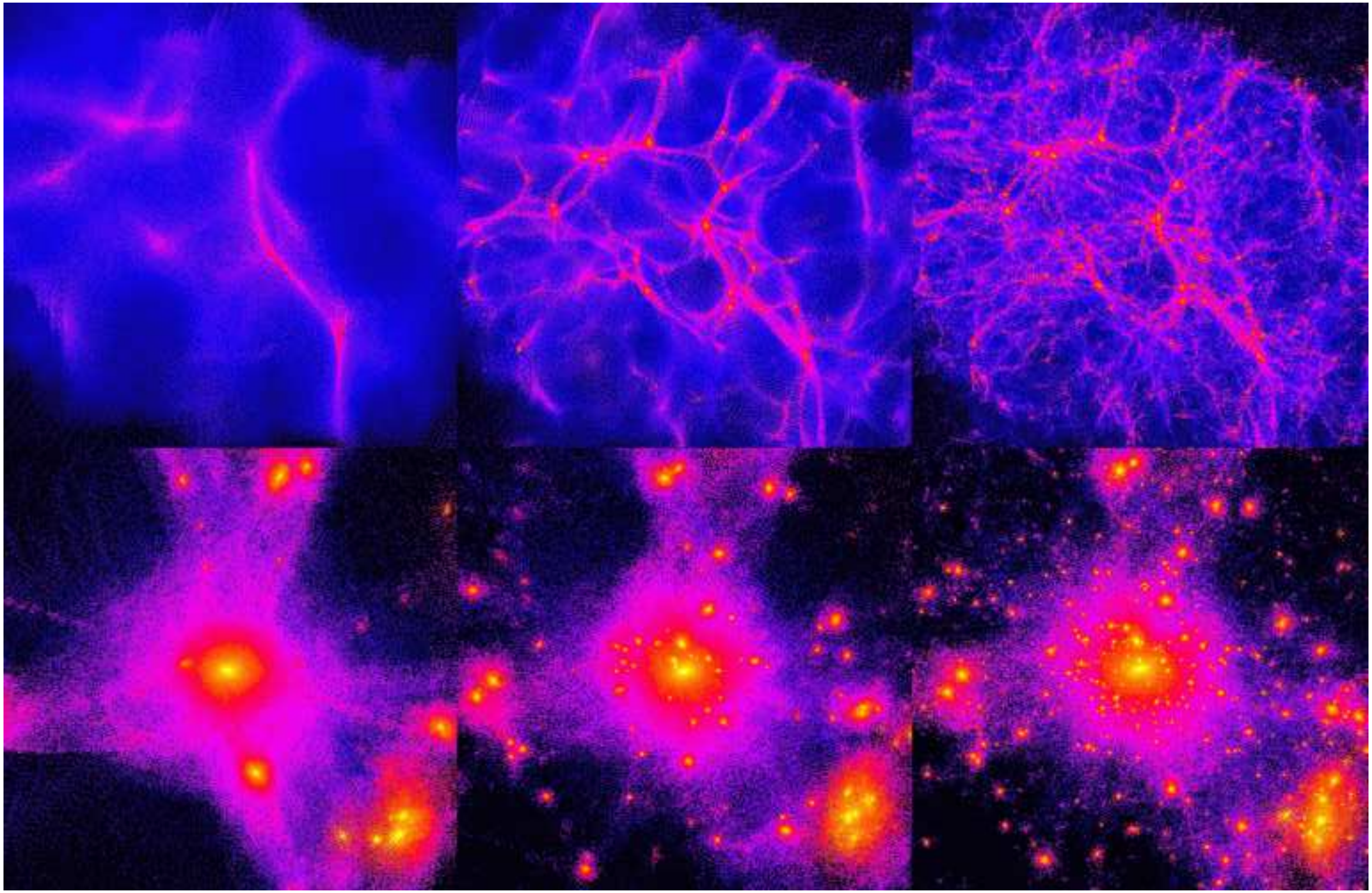
- The only neutral stable objects - atoms and neutrinos
- if atoms: contradiction with BBN - so many baryons are not admitted
- if neutrinos - hot DM: contradiction with structure formation - small scale inhomogeneities are erased

Dark Matter : new particle (?)

What do we know for sure about DM particles

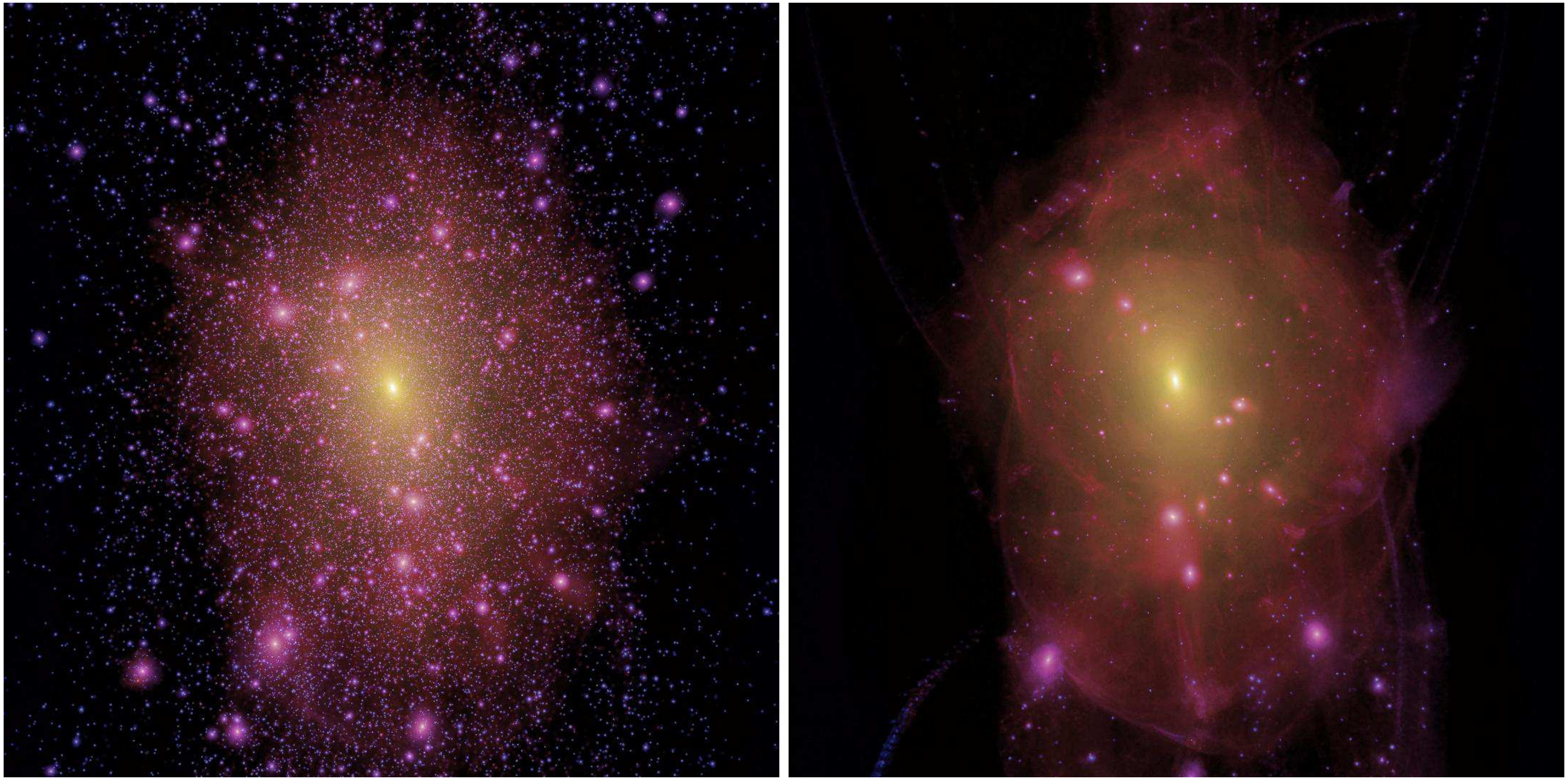
- They must have a lifetime exceeding the age of the Universe - otherwise they would have decayed.
- Relatively light particles ($M <$ few TeV) must be neutral and very weakly interacting - otherwise we would easily detect their cosmic flux.
- The DM particles should form the cold or warm DM – they must not be relativistic at the onset of structure formation, Lyman-α data puts $\lambda_{FS} < 150$ kpc.
- If they are fermions, their mass should not be below 400 eV – Tremaine-Gunn bound.

Hot DM Warm DM Cold DM



Ben Moore simulations

Number of satellites of the Milky way



CDM versus WDM, Carlos Frenk et al.

Lower mass bound on fermionic DM

- The smaller is the DM mass the bigger is the number of particles in an object with the mass M_{vir}
- Average phase-space density of **fermion** DM particles should be **smaller** than density of **degenerate Fermi gas**

$$\frac{M_{\text{vir}}}{\frac{4\pi}{3}R_{\text{vir}}^{3}}\frac{1}{\frac{4\pi}{3}v_{\infty}^{2}} \leq \frac{2{m_{\mathbf{DM}}}^{4}}{(2\pi\hbar)^{3}}$$

- Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the **lower bound** on the fermionic DM mass $m_{\text{DM}} \gtrsim 400$ **eV**

“Tremaine-Gunn bound”

What we do not know about DM particles

- Mass : the range from $\mathbf{10^{-33}}$ eV (stringy axions) to $\mathbf{10^{24}}$ GeV (supersymmetric Q-balls) was considered
- Spin : both fermions and bosons are OK
- Interaction strength and interaction type
- Production mechanism
- How they are embedded into Big Picture of particle physics

Conclusions

Particle physics offers solutions to outstanding cosmological problems:

- Baryon asymmetry of the Universe
  - Baryogenesis, requiring CP-violation and baryon number non-conservation
- Rotational curves of galaxies, matter content of the Universe
  - Particle dark matter

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Big questions for particle physics: What is the physics of B-violation leading to BAU? What is the dark matter particle?

The scene

There are hundreds of proposals for the models for baryogenesis, and for particle dark matter candidates

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There are hundreds of proposals for the models of inflations, for baryogenesis, and for particle dark matter candidates

How to navigate?

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Ockham’s razor principle (1288 - 1348): *“Frustra fit per plura quod potest fieri per pauciora”* or ”entities must not be multiplied beyond necessity”.

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For particle physics: entities = new hypothetical particles and new scales different from Fermi and Planck scales.

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Baryon asymmetry and dark matter

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- Ockham’s razor in action, 2 step logic:

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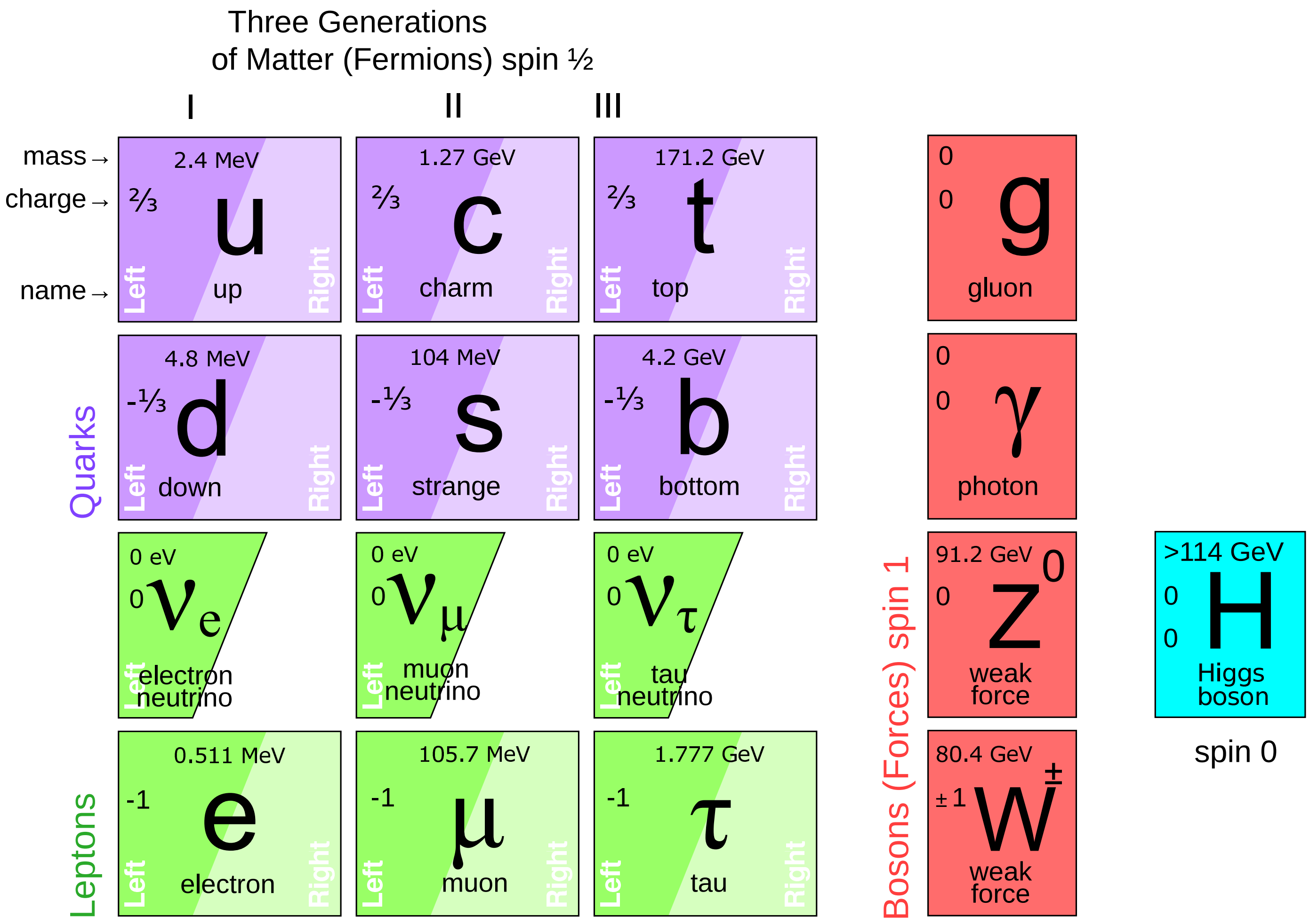
Baryon asymmetry and dark matter

- Ockham's razor in action, 2 step logic:
- To explain neutrino masses we better have right-handed neutrinos
- Let's use them for baryogenesis and dark matter!

the SM



Three Generations
of Matter (Fermions) spin ½

mass →
charge →
name →

	I	II	III	Bosons (Forces) spin 1	spin 0
Quarks	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	171.2 GeV ⅔ t top Left Right	0 0 g gluon	
	4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right	0 0 γ photon	
	0 eV 0 ν_e electron neutrino Left	0 eV 0 ν_μ muon neutrino Left	0 eV 0 ν_τ tau neutrino Left	91.2 GeV 0 Z^0 weak force	>114 GeV 0 0 H Higgs boson
Leptons	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right	80.4 GeV ±1 $W^{\pm}$ weak force	

The missing piece: sterile neutrinos

Most general renormalizable (see-saw) Lagrangian

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

Assumption: all Yukawa couplings with different leptonic generations are allowed.

$I \leq \mathcal{N}$ - number of new particles - HNLs - cannot be fixed by the symmetries of the theory.

Let us play with $\mathcal{N}$ to see if having some number of HNLs is good for something

- $\mathcal{N} = 1$: Only one of the active neutrinos gets a mass

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- $\mathcal{N} = \mathbf{3}$: All active neutrinos get masses: all neutrino experiments, can be explained (LSND with known tensions). The theory contains 6 new CP-violating phases: baryon asymmetry of the Universe can be understood. If LSND is dropped, dark matter in the Universe can be explained. The quantisation of electric charges follows from the requirement of anomaly cancellations (1-3-3, 1-2-2, 1-1-1, 1-graviton-graviton).

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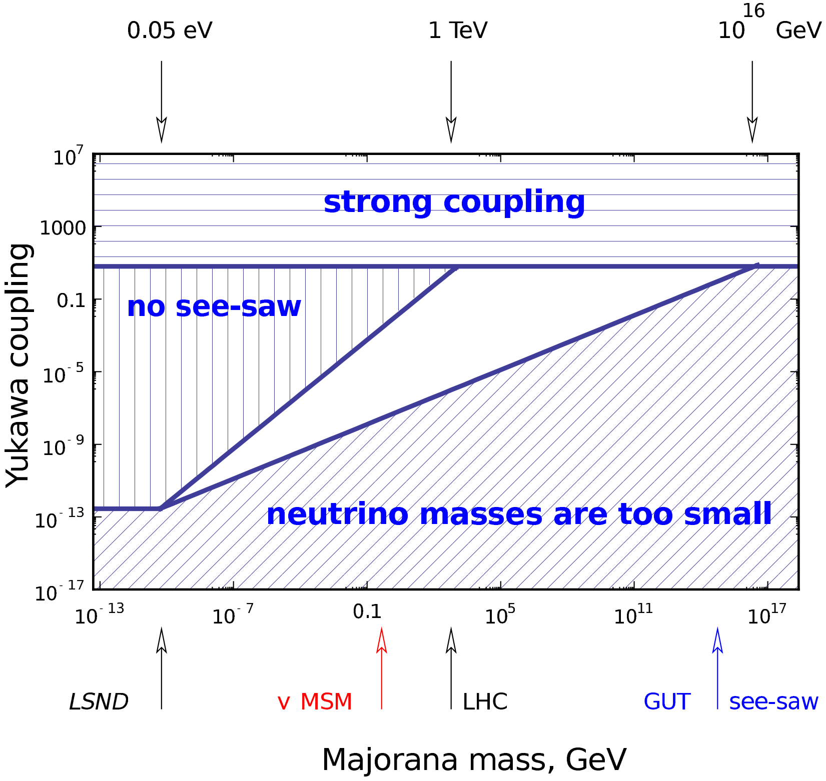
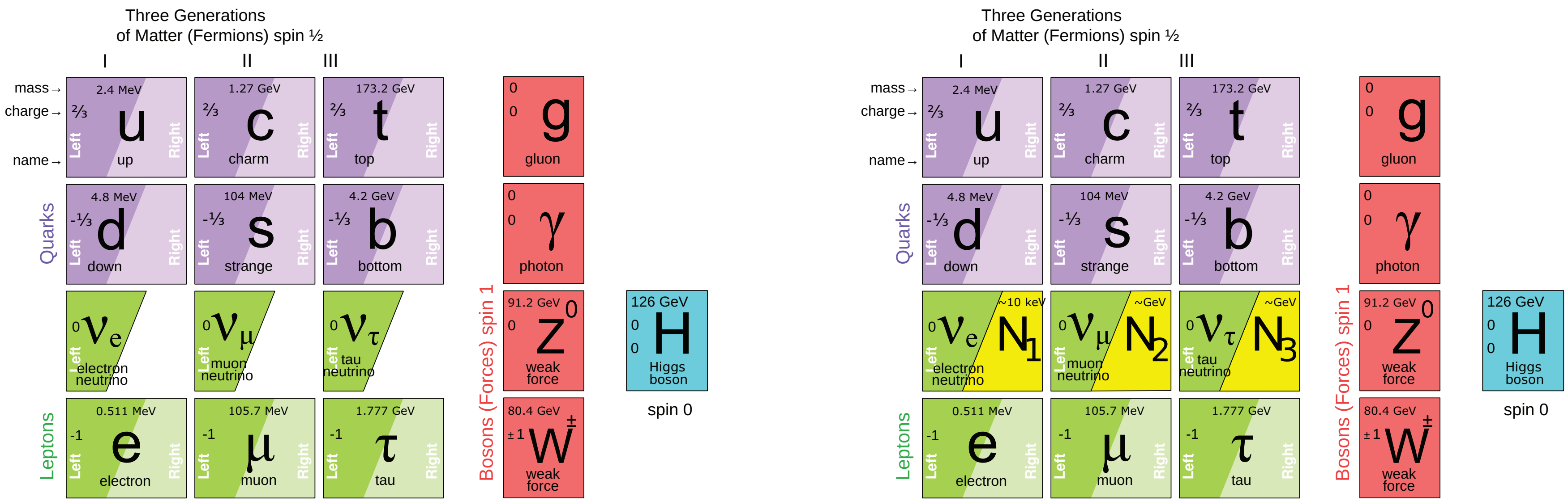
- $\mathcal{N} > 3$: Now you can do many things, depending on your taste - extra relativistic degrees of freedom in cosmology, neutrino anomalies, dark matter, different scenarios for baryogenesis, and different combinations of the above.

New mass scale and Yukawas

$$Y^2 = Trace[F^\dagger F]$$



$\mathcal{N} = 3$ with $M_I < M_W$: the νMSM



N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

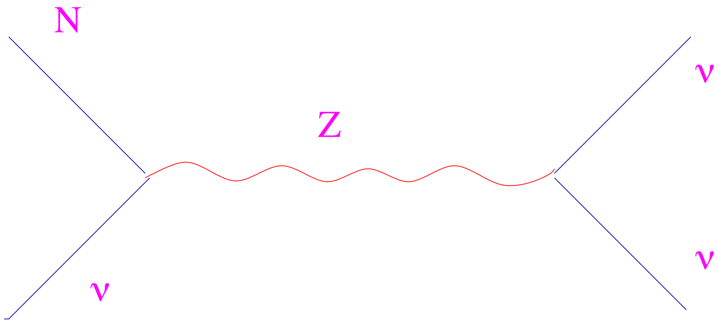
Role of $N_2,\ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

What should be the properties of $\boldsymbol{N}_{1,2,3}$ in the minimal setup - no any type of new physics between the Fermi and Planck scales ?

How to search for them experimentally?

DM candidate: the lightest Majorana ν, N_1

Yukawa couplings are small → sterile N can be very stable.



Main decay mode: $N \to 3\nu$.

For one flavour:

$$\tau_{N_1} = 5\times 10^{26}\,\text{sec}\left(\frac{1\text{keV}}{M_1}\right)^5\left(\frac{10^{-8}}{\Theta^2}\right)$$

$$\Theta = \frac{m_D}{M_I}$$

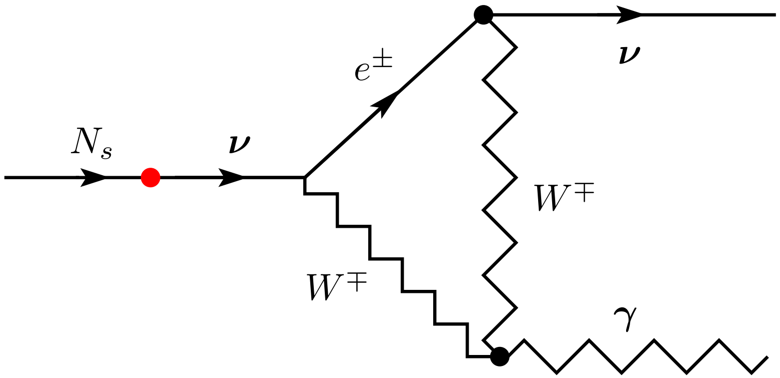
Dark Matter candidate: N_1

DM particle is not stable. Main decay mode $N_1 \rightarrow 3\nu$ is not observable.

Subdominant radiative decay channel: $N \rightarrow \nu\gamma$.

Photon energy:

$$E_\gamma = \frac{M}{2}$$



Radiative decay width:

$$\Gamma_{\mathrm{rad}} = \frac{9\,\alpha_{\mathrm{EM}}\,G_F^2}{256\cdot 4\pi^4}\ \sin^2(2\theta)\ M_s^5$$

Dark Matter production

Cosmological production of sterile neutrinos

Sterile neutrino never equilibrates, since their interactions are very weak

$$\Omega_N h^2 \sim 0.1 \sum_I \sum_{\alpha=e,\mu,\tau} \left(\frac{|\Theta_{\alpha I}|^2}{10^{-8}}\right)\left(\frac{M_I}{1\ \mathrm{keV}}\right)^2 .$$

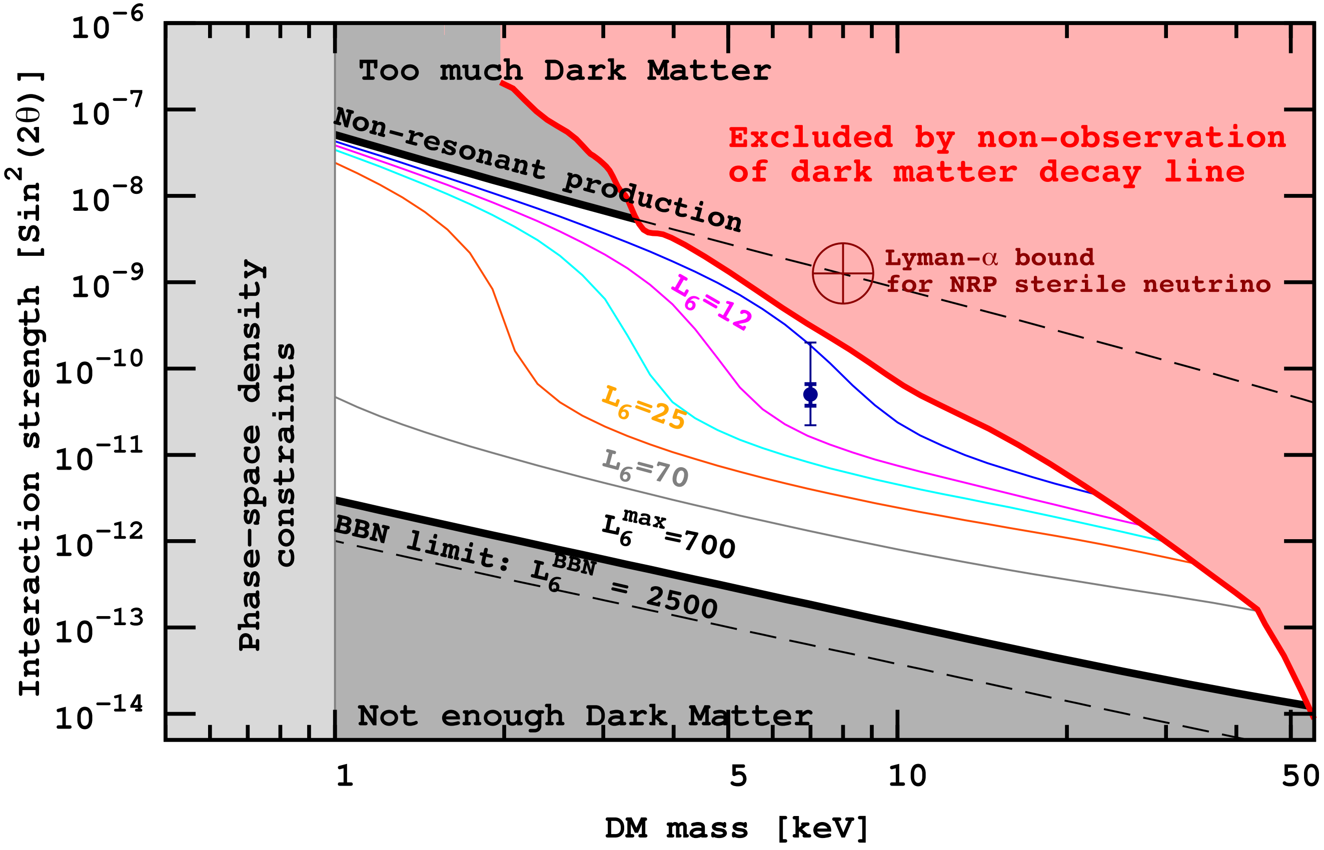
Production temperature $\sim 130\,\left(\frac{M_I}{1\ \mathrm{keV}}\right)^{1/3}$ MeV

Production rate depends on Yukawa couplings and on lepton asymmetry.

Note: DM sterile neutrino does not contribute to the number of relativistic species! Perfect agreement with Planck measurements.

Constraints on DM sterile neutrino N_1

- Stability. N_1 must have a lifetime larger than that of the Universe
- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \quad q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance
- Structure formation. If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars and structure of dwarf galaxies
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton).



Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall. e-Print: arXiv:1402.2301

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster. A. Boyarsky , O. Ruchayskiy, D. Iakubovskyi, J. Franse. e-Print: arXiv:1402.4119

Baryon asymmetry

Sakharov conditions:

- Baryon number violation - OK due co complex vacuum structure in the SM and chiral anomaly
- CP-violation - OK due to new complex phases in Yukawa couplings
- Deviations from thermal equilibrium - OK as HNL are out of thermal equilibrium for $T > \mathcal{O}(100)$ GeV

Baryon asymmetry

Akhmedov, Rubakov, Smirnov; Asaka, MS

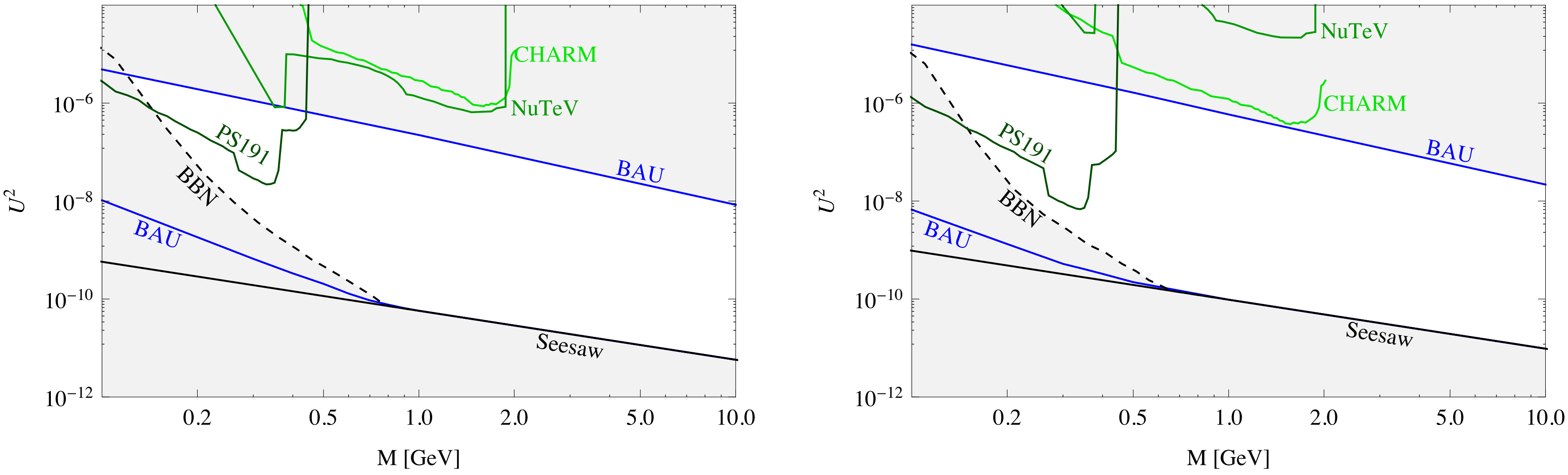
Idea - $N_{2,3}$ HNL oscillations as a source of baryon asymmetry.
Qualitatively:

- HNL are created in the early universe and oscillate in a coherent way with CP-breaking.
- Lepton number from HNL can go to active neutrinos.
- The lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes.

Constraints on BAU HNL $N_{2,3}$

Baryon asymmetry generation: CP-violation in neutrino sector+singlet fermion oscillations+sphalerons

- 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
- BBN. Decays of $N_{2,3}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $N_{2,3}$ have not been seen

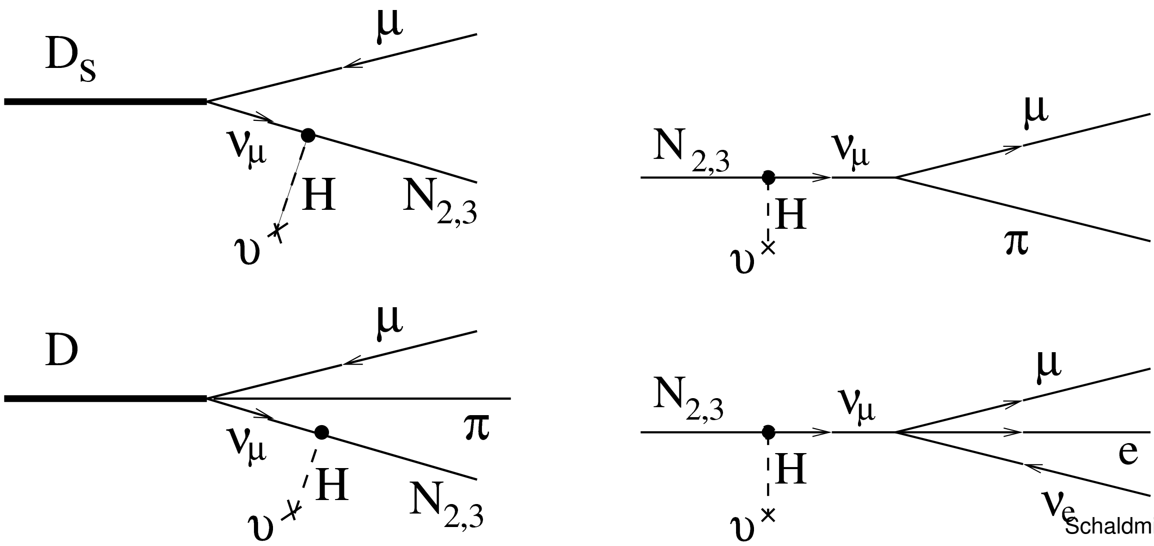


Constraints on U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS).

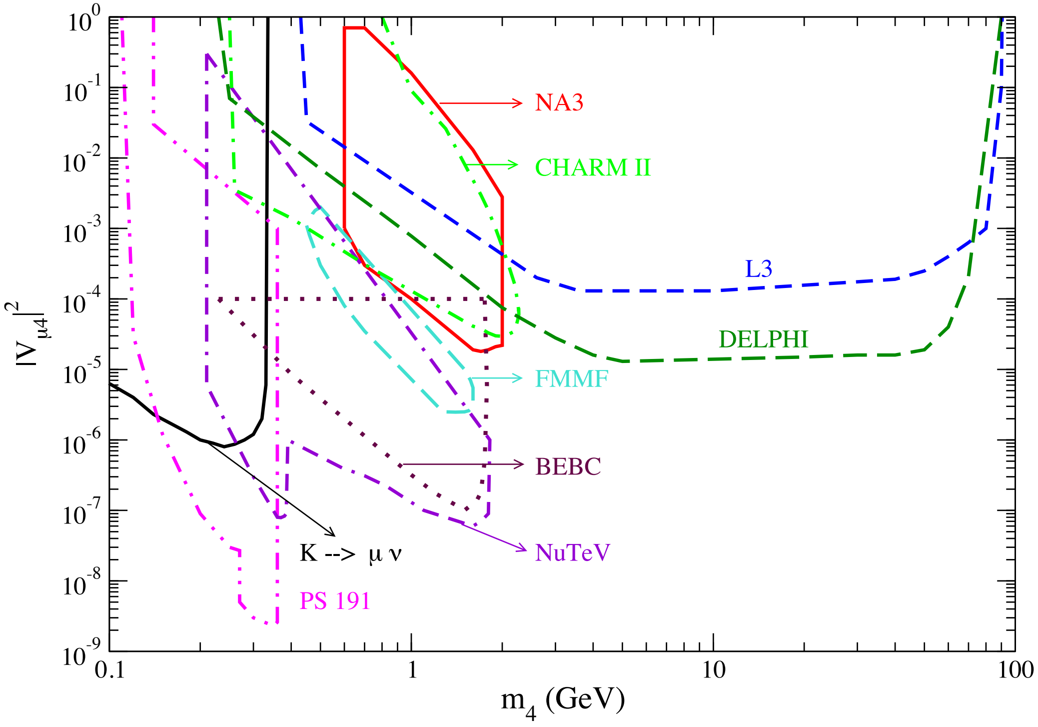
Experimental search for HNL

- Production
  - via intermediate (hadronic) state

    $\boldsymbol{p + \textbf{target} \rightarrow \textbf{mesons} + ...}$, and then hadron$\rightarrow$ $\boldsymbol{N + ...}$.
  - via $\boldsymbol{Z}$-boson decays: $\boldsymbol{e^+e^- \rightarrow Z \rightarrow \nu N}$
- Detection
  - Subsequent decay of $\boldsymbol{N}$ to SM particles



Survey of constraints



From arXiv:0901.3589, Atre et al

How to improve the bounds or to discover light very weakly interacting HNL's?

Dedicated experiments

Common features of all relatively light feebly interacting particles :

- Can be produced in decays of different mesons (π, K, charm, beauty)
- Can decay to SM particles ($l^+l^-, \gamma\gamma, l\pi$, etc)
- Can be long lived

Requirements to experiment:

- Produce as many mesons as you can
- Study their decays for a missing energy signal: charm or B-factories, NA62
- Search for decays of hidden sector particles - fixed target experiments
  - Have as many pot as you can, with the energy enough to produce charmed (or beauty) mesons
  - Put the detector as close to the target as possible, in order to catch all hidden particles from meson decays (to evade $1/R^2$ dilution of the flux)
  - Have the detector as large as possible to increase the probability of hidden particle decay inside the detector
  - Have the detector as empty as possible to decrease neutrino and other backgrounds

Most recent dedicated experiment - 1986, Vannucci et al

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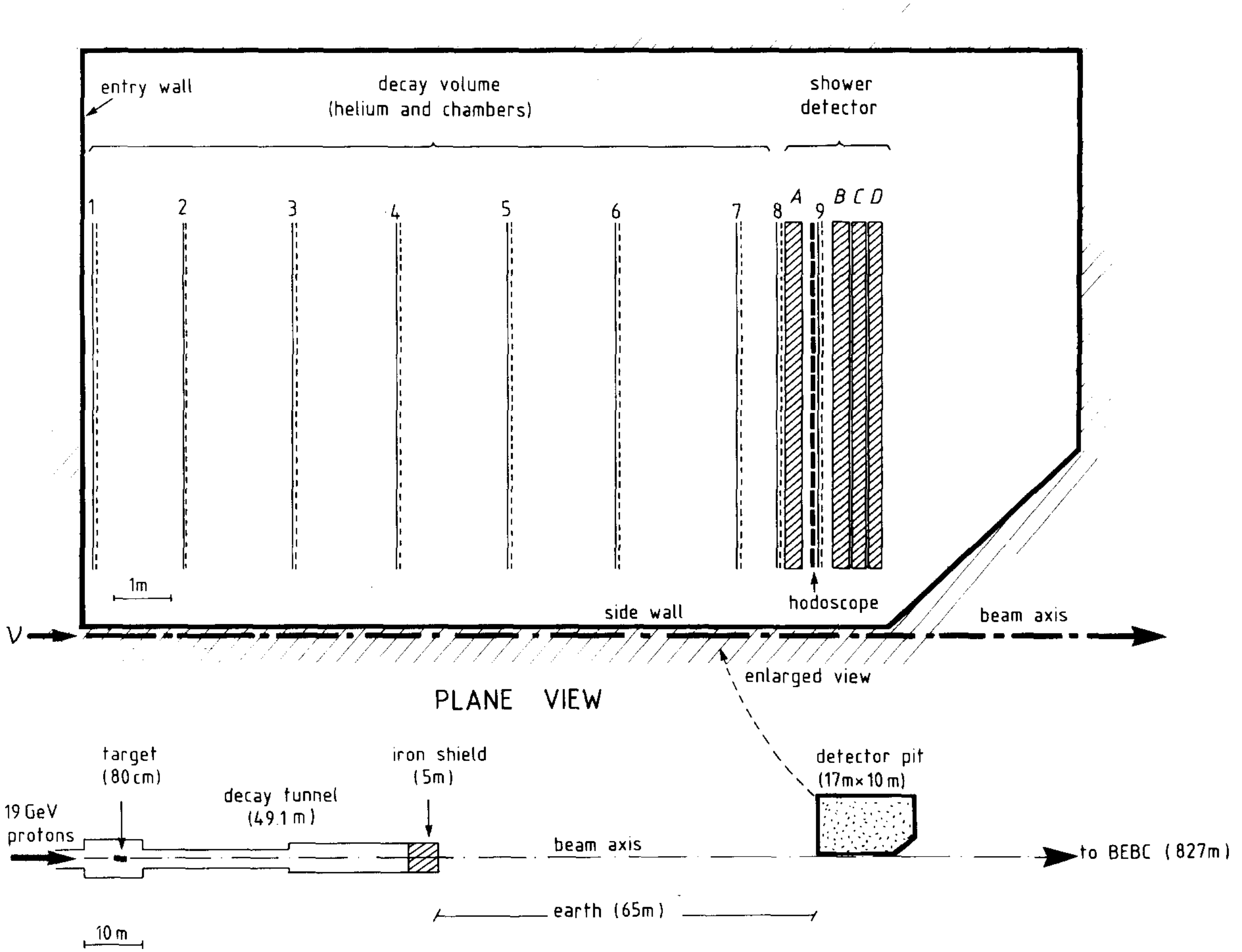


Fig. 1. Beam and layout of the detector.

No new particles are found with mass below K-meson, the best constraints are derived

Proposal to Search for Heavy Neutral Leptons at the SPS arXiv:1310.1762

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, O. Ruchayskiy, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

⇓

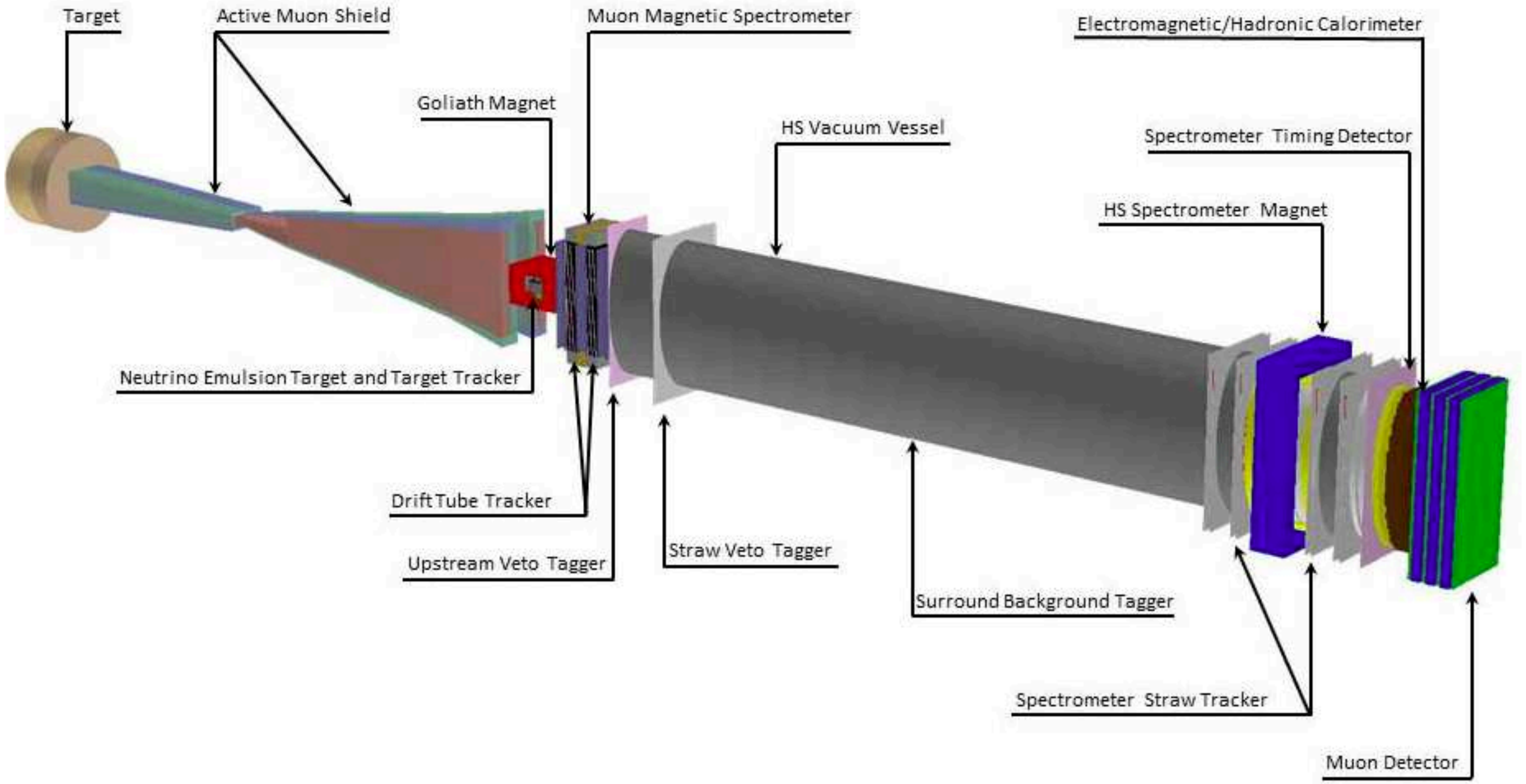
General beam dump facility: Search for Hidden Particles

SHiP

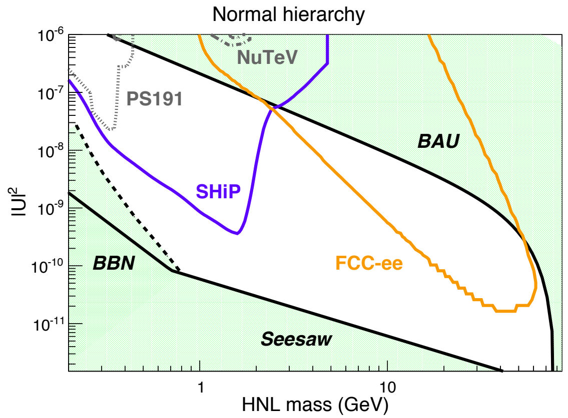
Search for Hidden Particles

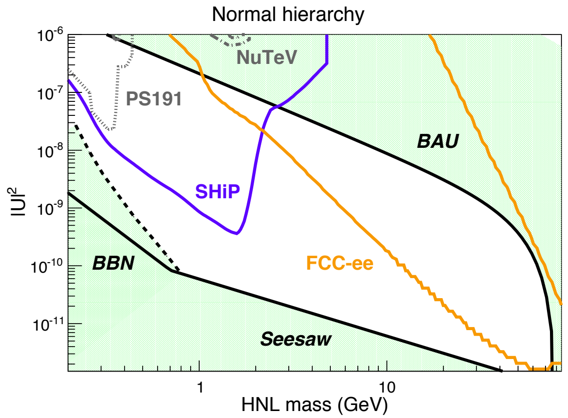
SHiP is currently a collaboration of 47 institutes from 15 countries

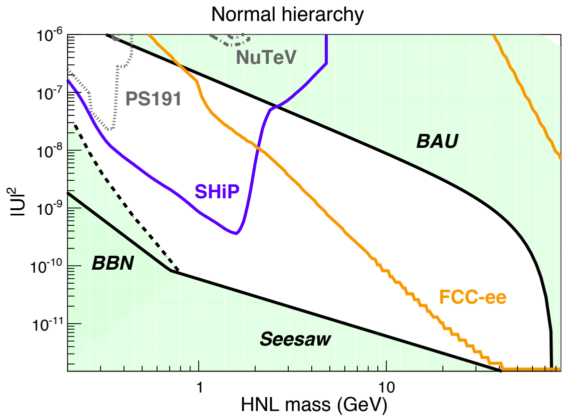
web-site: http://ship.web.cern.ch/ship/

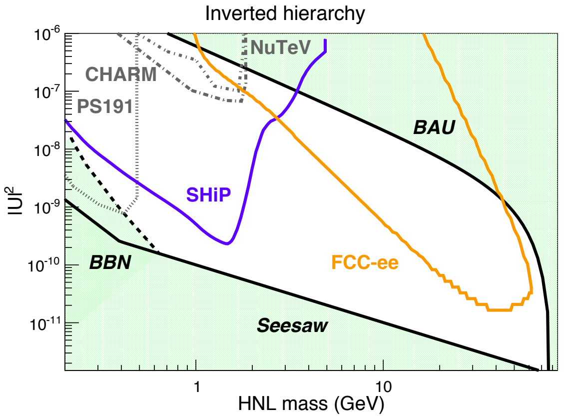


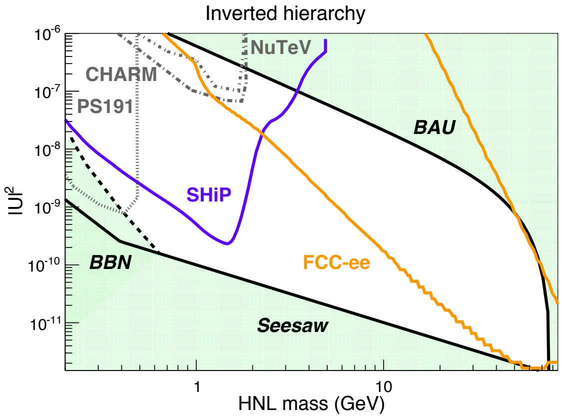
SHiP and FCC-ee sensitivity

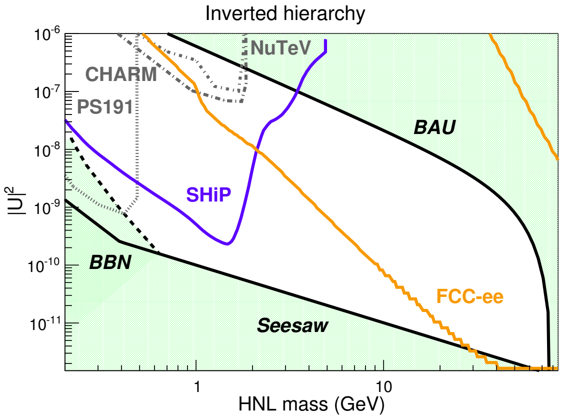












Decay length: 10-100 cm

10-100 cm

0.01-500 cm

$10^{12}\ Z^0$

$10^{13}\ Z^0$

$10^{13}\ Z^0$

Conclusions

- Heavy neutral leptons can be a key to (almost all) BSM problems:
  - neutrino masses and oscillations
  - dark matter
  - baryon asymmetry of the universe
- They can be found in Space and on the Earth
  - X-ray satellites
  - proton fixed target experiment - SHIP, $M \lesssim 2$ GeV
  - collider experiments at FCC-ee in Z-peak, $M \gtrsim 2$ GeV