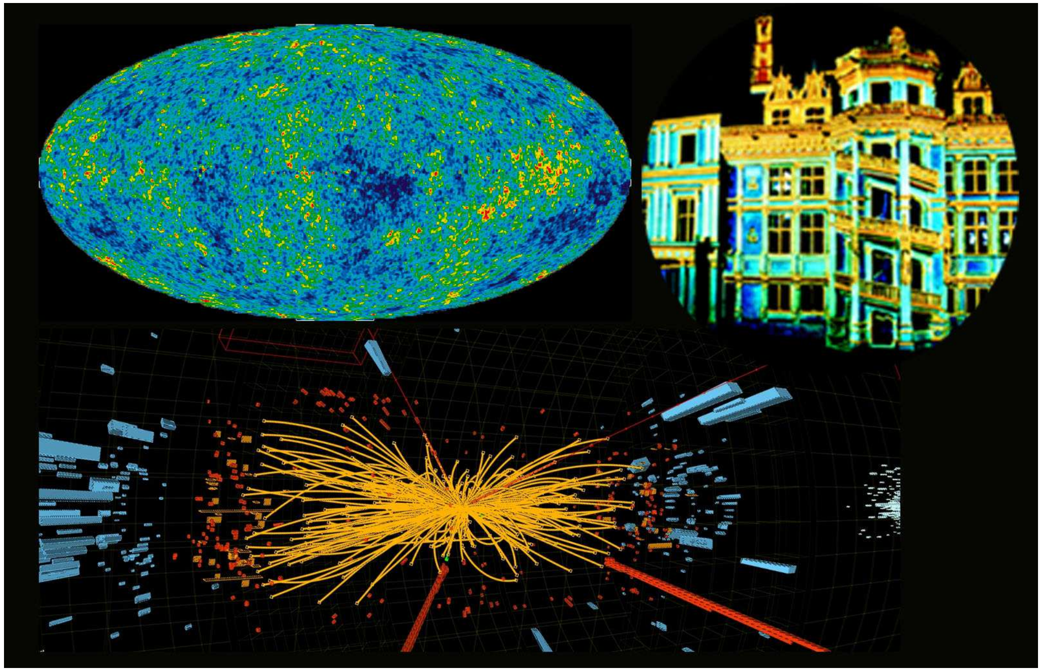
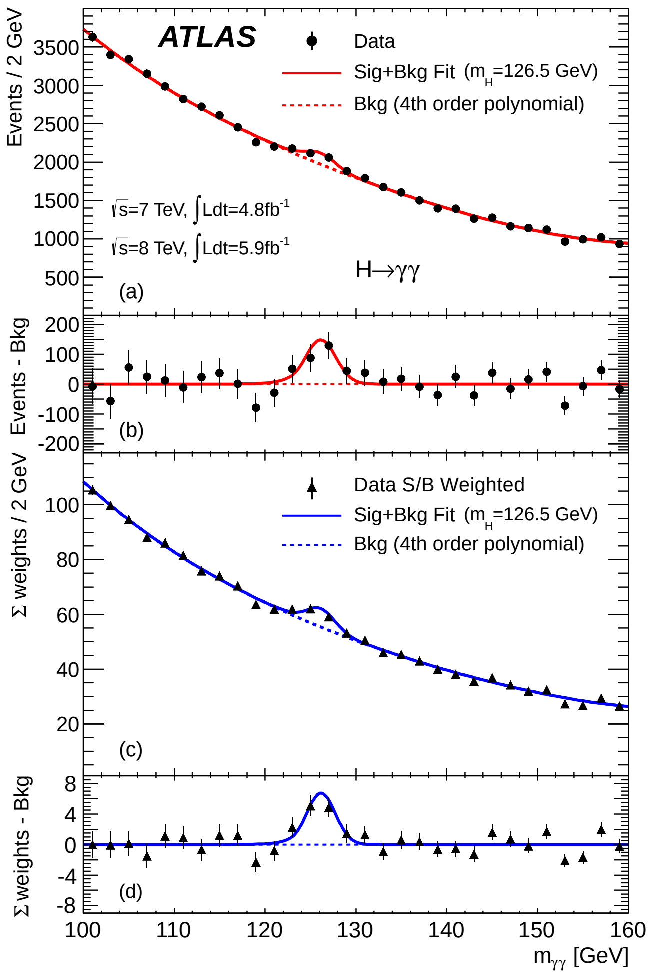
The Higgs Boson and the Cosmology of the Early Universe

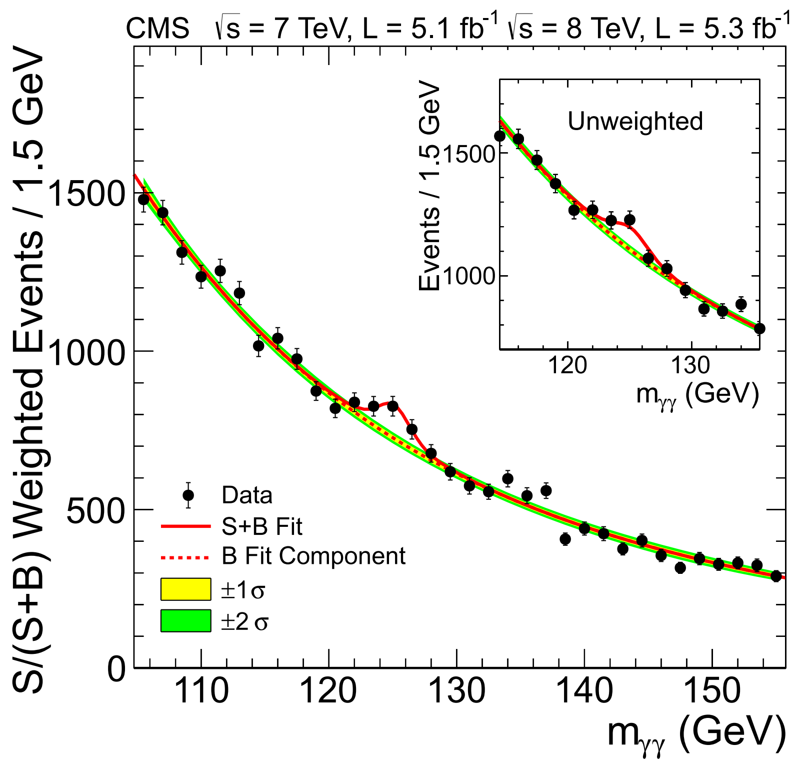
Mikhail Shaposhnikov



Blois 2018

Almost 6 years with the Higgs boson: July 4, 2012, Higgs at ATLAS and CMS





What did we learn from the Higgs discovery for particle physics?

The ideas of the authors of the BEH mechanism were right

The Standard Model is now complete



Triumph of the SM in particle physics

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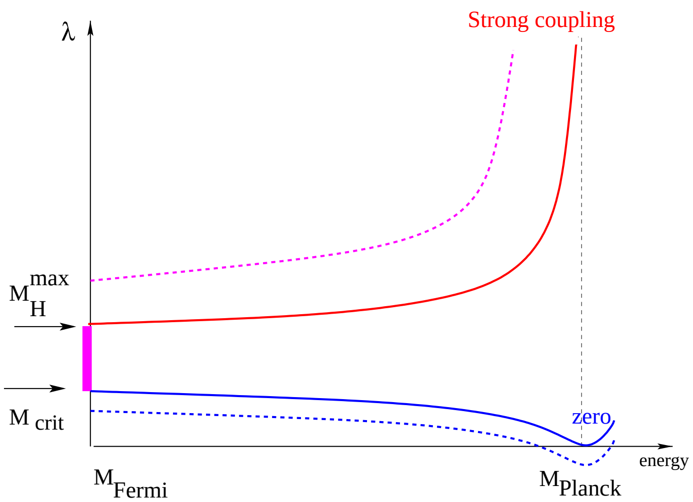
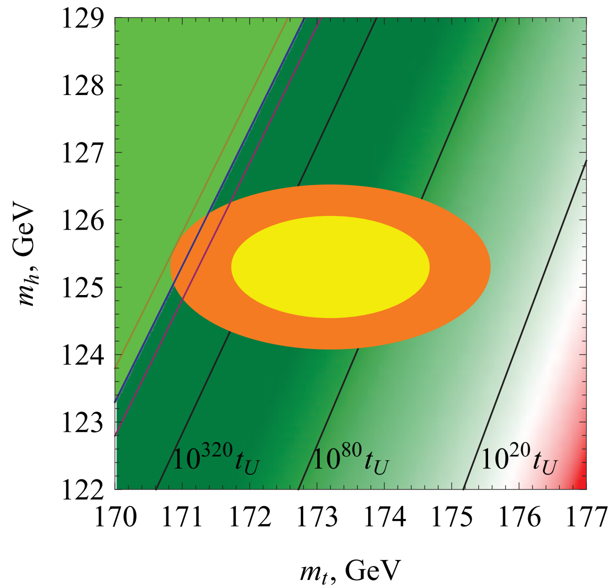
- No significant deviations from the SM have been observed
- The masses of the top quark and of the Higgs boson, the Nature has chosen, make the SM a self-consistent effective field theory all the way up to the quantum gravity Planck scale M_P.
- $M_H < 175$ GeV : SM is a weakly coupled theory up to Planck energies
- $M_H > 111$ GeV: Our EW vacuum is stable or metastable with a lifetime greatly exceeding the Universe age.





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Since the SM a self-consistent effective field theory all the way up to the Planck scale, we can try describe the evolution of the Universe within the SM from the very early stages, such as inflation and Big Bang, till the present days!

Universe with the Strandard Model: very early times

SM + gravity

Higgs field in general must have non-minimal coupling to gravity:

$$S_G = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2} R - \frac{\xi h^2}{2} R \right\}$$

Jordan, Feynman, Brans, Dicke,...

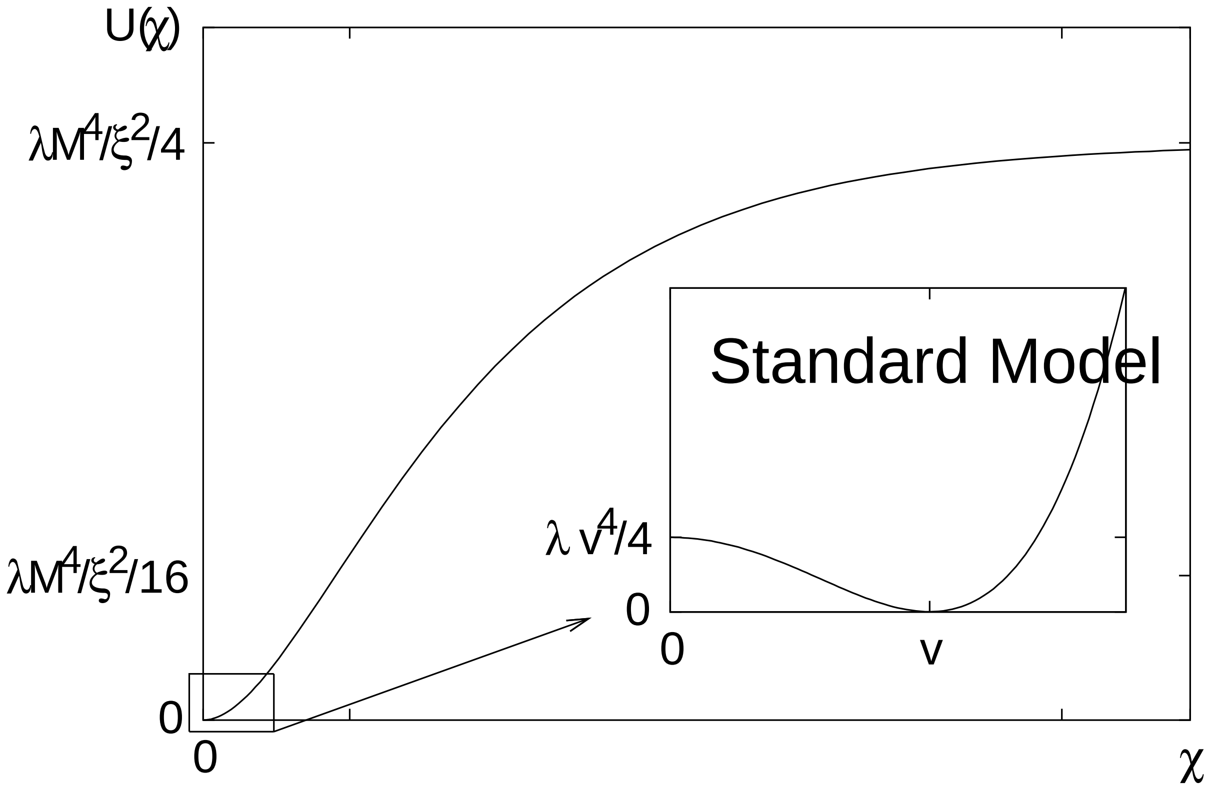
Consider large Higgs fields $h > M_P/\sqrt{\xi}$, which may have existed in the early Universe

The Higgs field not only gives particles their masses $\propto h$, but also determines the gravity interaction strength:

$M_P^{\text{eff}} = \sqrt{M_P^2 + \xi h^2} \propto h$

For $h > \frac{M_P}{\sqrt{\xi}}$ (classical) physics is the same (M_W/M_P^{eff} does not depend on h)!

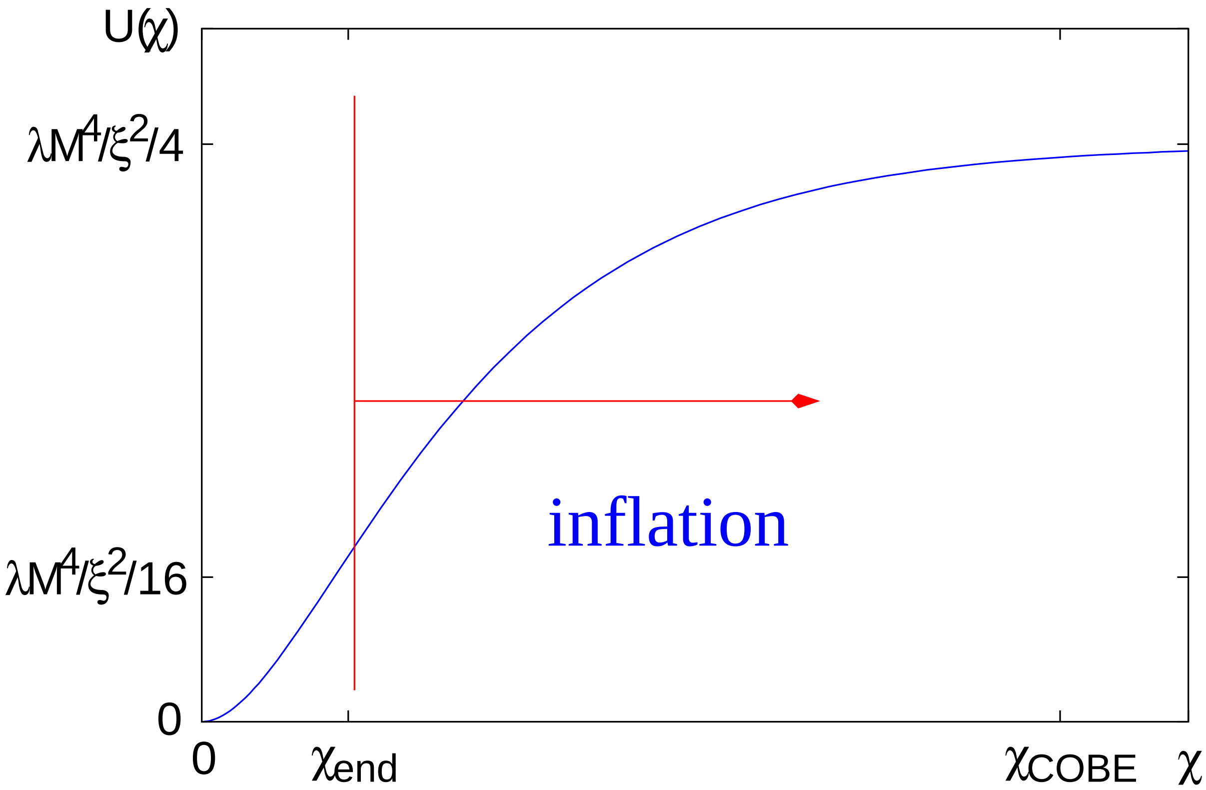
Potential in Einstein frame



χ - canonically normalized scalar field in Einstein frame.

Cosmological inflation

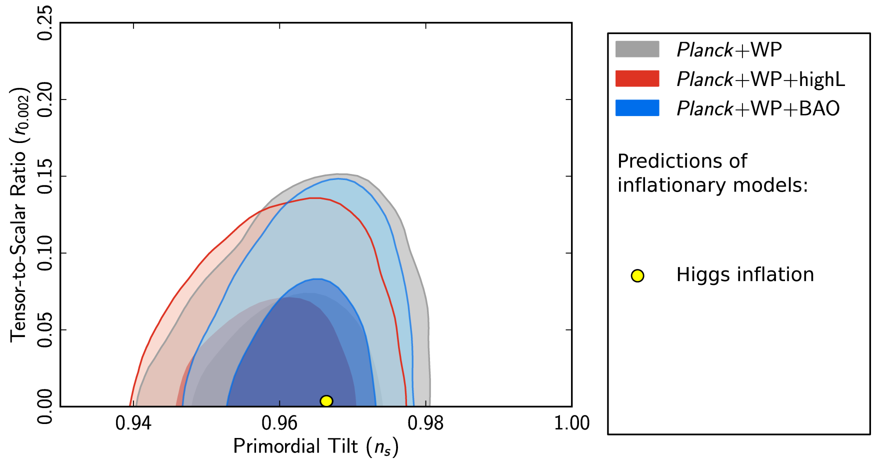
Stage 1: Higgs inflation, $h > \frac{M_P}{\sqrt{\xi}}$, slow roll of the Higgs field

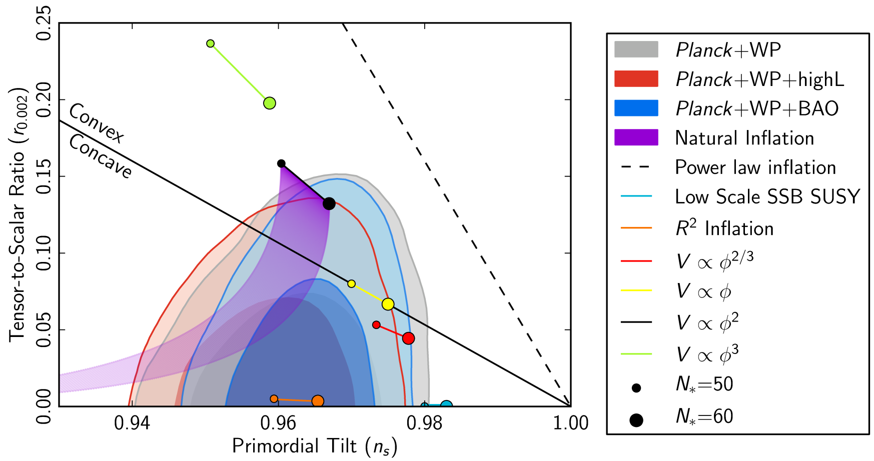


- Makes the Universe flat, homogeneous and isotropic
- Produces fluctuations leading to structure formation: clusters of galaxies, etc

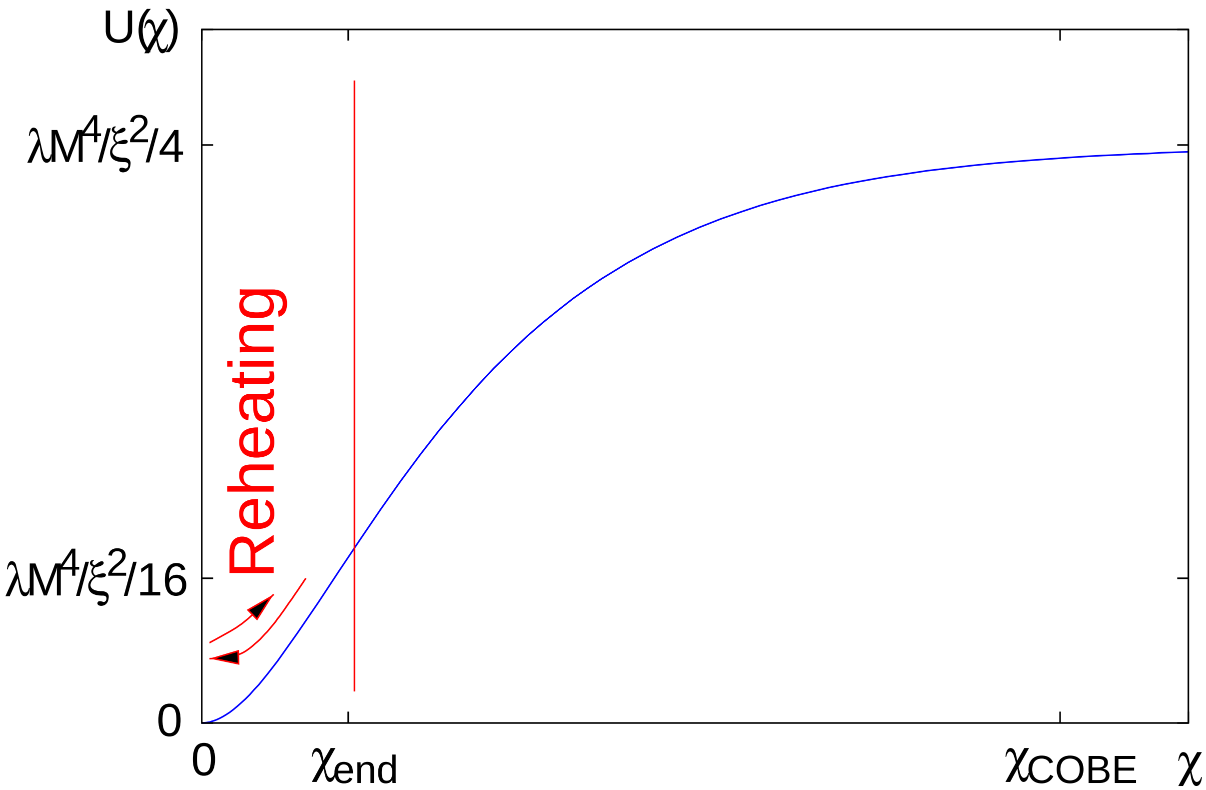
CMB parameters - spectrum and tensor modes, $\xi \gtrsim 1000$

$$n_s = 0.97, \quad r = 0.003$$





Stage 2: Big Bang, $\frac{M_P}{\xi} < h < \frac{M_P}{\sqrt{\xi}}$, Higgs field oscillations



- All particles of the Standard Model are produced
- Coherent Higgs field disappears
- The Universe is heated up to $T \propto M_P/\xi \sim 10^{14}$ GeV
- The universe is symmetric - no charge asymmetries

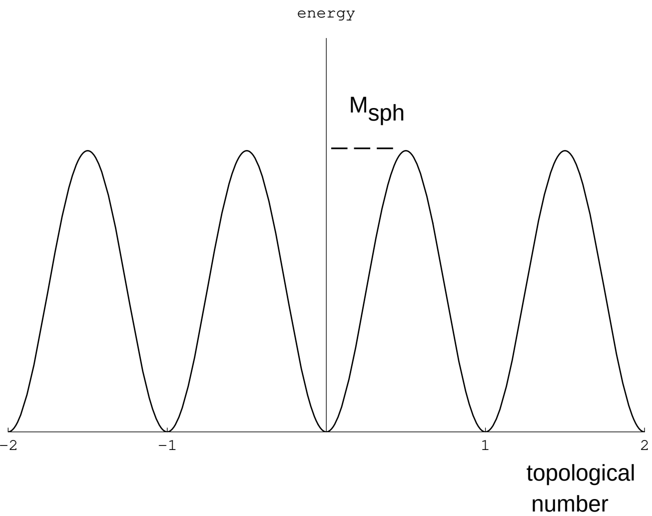
First great feature of the SM in cosmology

- Presence of the fundamental scalar field – Higgs boson, which can play a role of the inflaton and make the Universe flat, homogeneous and isotropic and produce quantum fluctuations necessary for structure formation. Hot Big Bang due to Higgs field oscillations. All this is possible because of the Higgs-gravity coupling : $\xi H^2 R$.

Two other great features of the SM in cosmology: Universe at the electroweak scale

Baryon number non-conservationists

The rate of B non-conservation exactly as we would like it to have for baryogenesis!



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

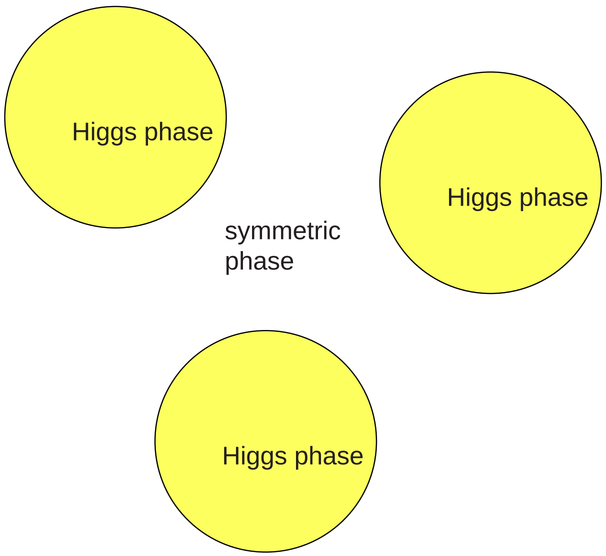
These reactions are in thermal equilibrium for

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

Electroweak phase transition

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

The universe is supercooled in the symmetric phase $\rightarrow$ 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.

Bubble wall baryogenesis

Cohen, Kaplan, Nelson

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

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

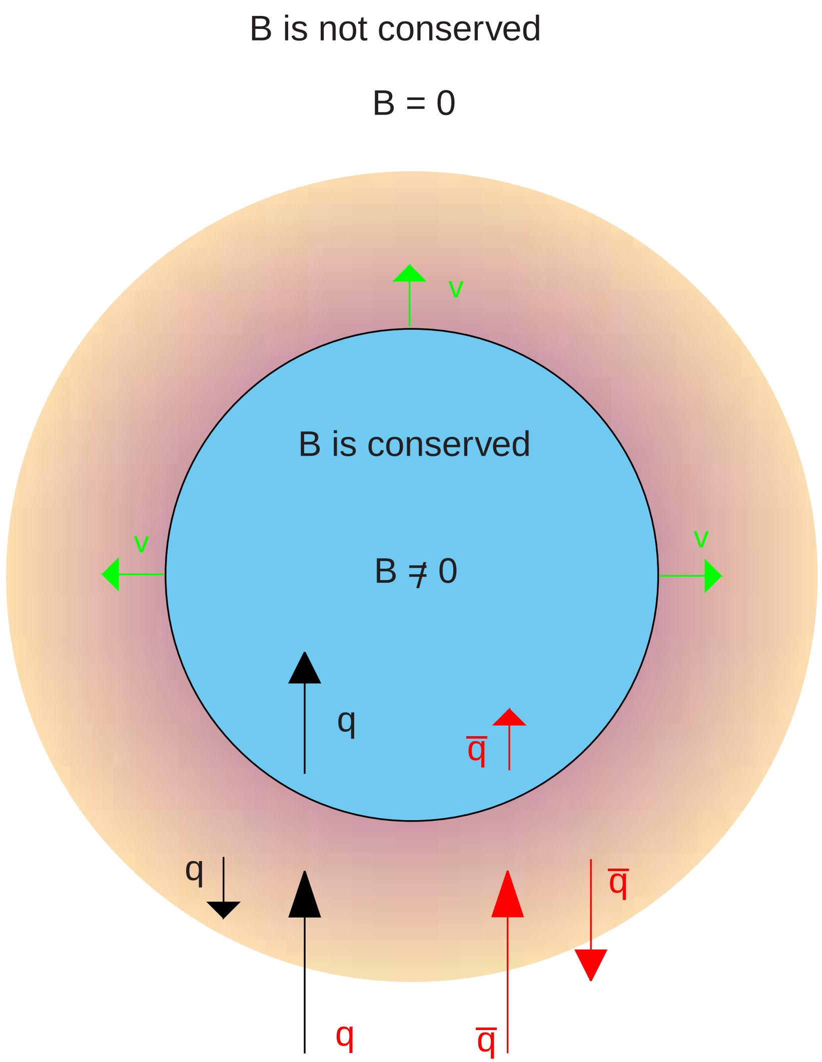
$\Downarrow$

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

$\Downarrow$

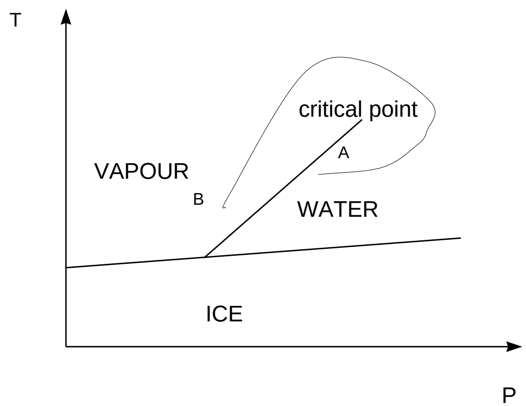
Baryon asymmetry of the Universe after EW phase transition.

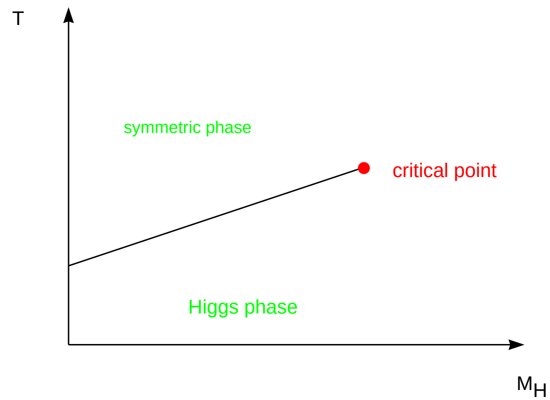
Mechanism



Phase transition in SM

Kajantie, Laine, Rummukainen, MS





Typical condensed matter phase diagram (pressure versus temperature)

No EW phase transition with 125 GeV Higgs boson!

Electroweak theory

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

$T = 109.2 \pm 0.8GeV,$

$M_H = 72.3 \pm 0.7GeV$

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

CP violation in the SM

MS; Farrar, MS; Gavela, Hernandez, Orloff, Pene, Quimbay; Huet, Sather

Relevant measure of CP violation: Jarlskog determinant

$$D \sim G_F^6 s_1^2 s_2 s_3 sin\delta m_t^4 m_b^4 m_c^2 m_s^2 \sim 10^{-20}$$

with possible amplifications due to finite temperature effects.

Too small to give the observed baryon asymmetry !

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Though SM works well in particle physics, it fails in cosmology and neutrino physics

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Neutrinos, baryogenesis and dark matter : window to physics beyond the Standard Model!

However, extensions of the SM are very far from being unique:

- Baryon asymmetry: there is just one number n_B/n_γ to explain: many scenarios were proposed.
- Dark matter, absent in the SM: plephora of different candidates, the masses of DM particles can be as small as $\mathcal{O}(10^{-22})$ eV (super-light scalar fields) or as large as $\mathcal{O}(10^{20})$ GeV (wimpzillas, Q-balls).
- Neutrino masses and oscillations: many mechanisms, even the scale of new physics explaining m_ν can vary from $\mathcal{O}(1)$ eV to $\mathcal{O}(10^{15})$ GeV.

Guiding principles

Requirement of “naturalness”? Naturalness = absence of quadratic divergencies in the Higgs mass.

Not unique:

- Low energy SUSY: compensation of bosonic loops by fermionic loops
- Composite Higgs boson - new strong interactions
- Large extra dimensions

All these require new physics right above the Fermi scale, which was expected to show up at the LHC...

Guiding principles

Requirement of simplicity and minimality? Ockham's razor principle: "Frustra fit per plura quod potest fieri per pauciora" or "entities must not be multiplied beyond necessity".

May be very constraining, but also not unique. Examples:

- NMSM: The New Minimal Standard Model, Davoudiasl, Kitano, Li, Murayama '05
- Sm*a*s*h: Standard Model–axion–seesaw–Higgs portal inflation, Ballesteros, Redondo, Ringwald, Tamarit '17
- νMSM: The Neutrino Minimal Standard Model, Asaka, M.S. '05
- ...

“Complete” theory 1: the NMSM

Davoudiasl, Kitano, Li, Murayama ’05

Particle content: SM + 2 Majorana neutrinos N_1, N_2 + 2 real scalars S_1, S_2

Role of $N_1,\ N_2$:“give” masses to neutrinos and produce baryon asymmetry of the Universe.

Role of S_1 : singlet scalar dark matter - WIMP. Symmetry $S_1 \to -S_1$ is required for stability. Minimal model of DM Burgess, Pospelov, ter Veldhuis.

Role of S_2 : inflaton. In fact, may not be needed, as inflation can be realised with the Higgs boson.

“Complete” theory 2: Sm*a*s*h

Ballesteros, Redondo, Ringwald, Tamarit ’17

Particle content: SM + 3 Majorana neutrinos N_1, N_2, N_3+ new quark Q + 1 complex scalar σ

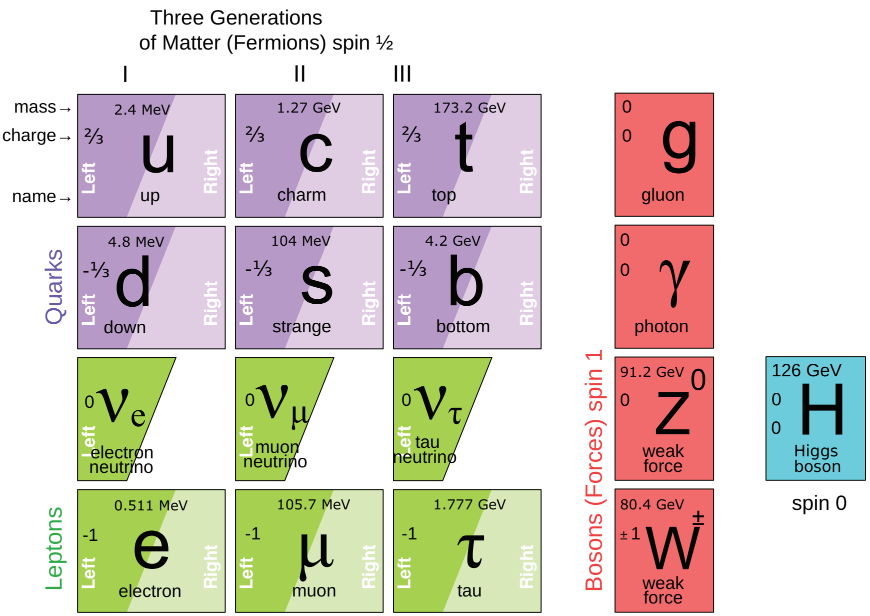
Role of σ: breaks lepton number and Peccei-Quinn (PQ) symmetry simultaneously. Leads to generation of Majorna masses of N_1, N_2, N_3. The complex phase of σ is the axion. Inflation : due to a scalar which is a mixture of the Higgs and σ

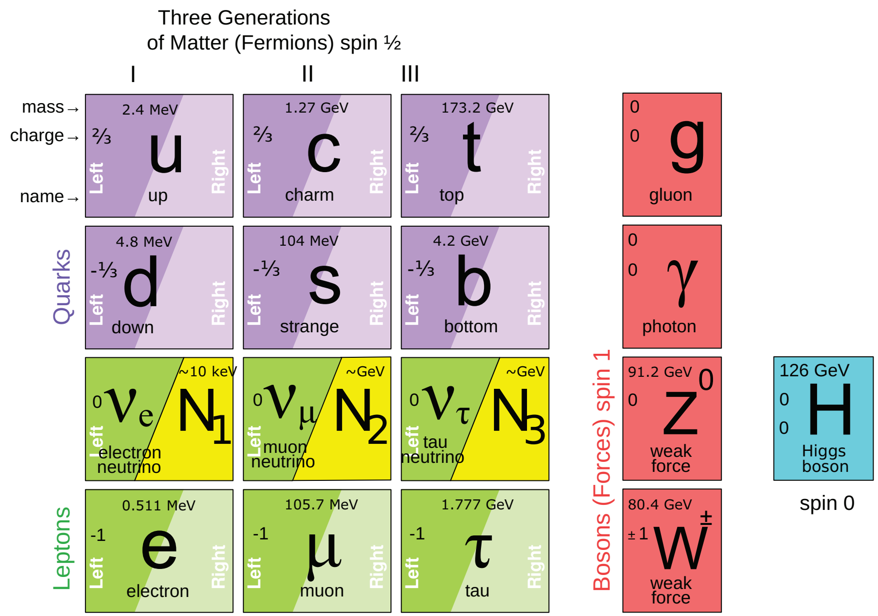
Role of $N_1,\ N_2,\ N_3$:“give” masses to neutrinos and produce baryon asymmetry of the Universe.

Role of Q : Allows to use PQ symmetry for strong CP-problem

Role of axion : dark matter

“Complete” theory 3: the νMSM





νMSM $\equiv$ Neutrino minimal Standard Model Asaka, M.S. ’05

$\equiv$ Minimal low scale see-saw model with 3 singlet fermions

Role of the Higgs boson: break the symmetry and inflate the Universe

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.

Parameter counting: the νMSM

Most general renormalizable Lagrangian

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

Extra coupling constants:

3 Majorana masses of new neutral fermions N_i,

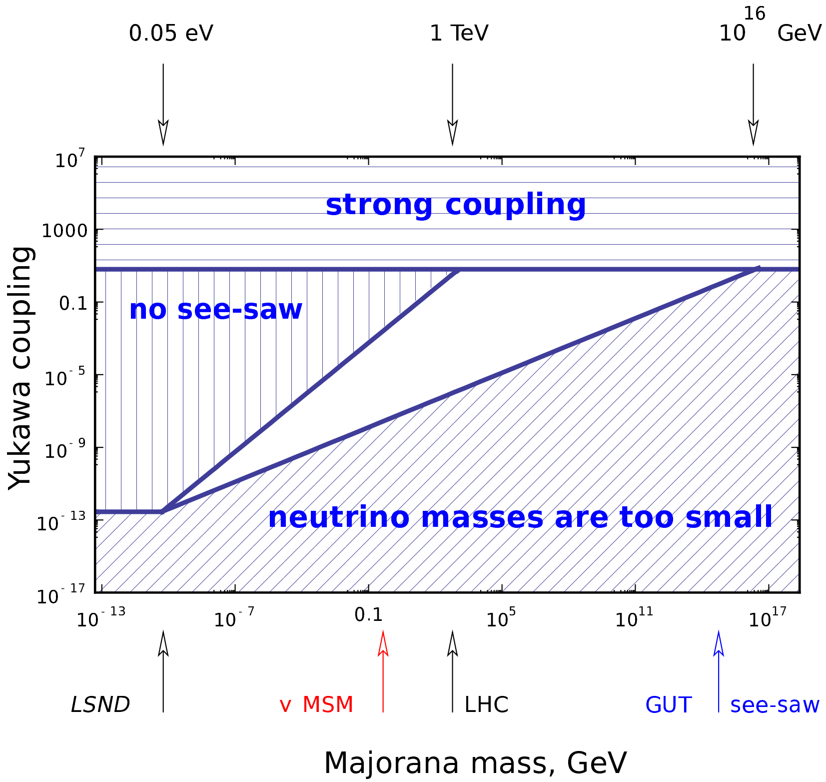
15 new Yukawa couplings in the leptonic sector

(3 Dirac neutrino masses, 6 mixing angles and 6 CP-violating phases),

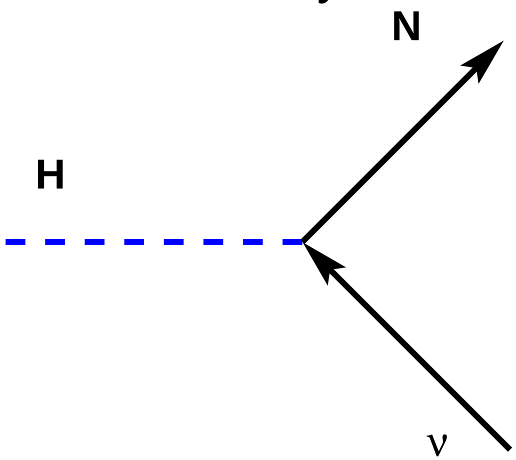
18 new parameters in total. The number of parameters is doubled in comparison with SM!

Neutrino masses and Yukawa couplings

Yukawa couplings: $Y^2 = Trace[F^\dagger F]$



Heavy neutral leptons interact with the Higgs boson via Yukawa interactions - exactly in the same way other fermions do:



$$F_{\alpha I}\,\bar{L}_\alpha N_I \tilde{H}$$

These interactions lead to

- active neutrino masses due to GeV scale see-saw
- creation of matter-antimatter asymmetry at temperatures $T \sim 100$ GeV
- to dark matter production at $T \sim 100$ MeV

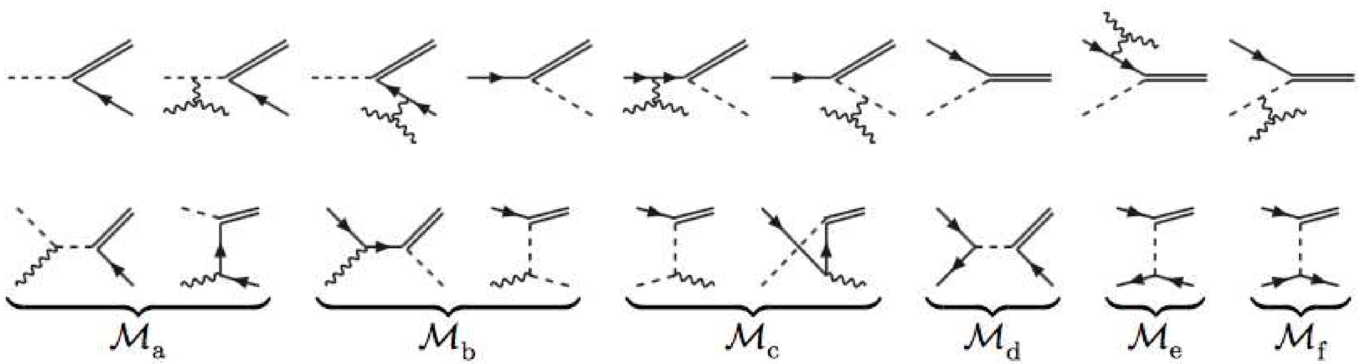
Baryogenesis

- Nothing essentially interesting happens between 10^3 GeV $< T < 10^{13}$ GeV: all SM elementary particles are nearly in thermal equilibrium.
- Heavy neutral leptons $N_{2,3}$ are out of equilibrium. They are created in interaction with the Higgs boson $H \leftrightarrow N\nu$, $t\bar{t} \leftrightarrow N\nu$, etc
- CP- violation in these reactions lead to lepton asymmetry of the Universe
- Electroweak baryon number violation due to SM sphalerons convert lepton asymmetry to baryon asymmetry of the Universe
- These processes freeze out at $T \simeq 140$ GeV

Baryon asymmetry

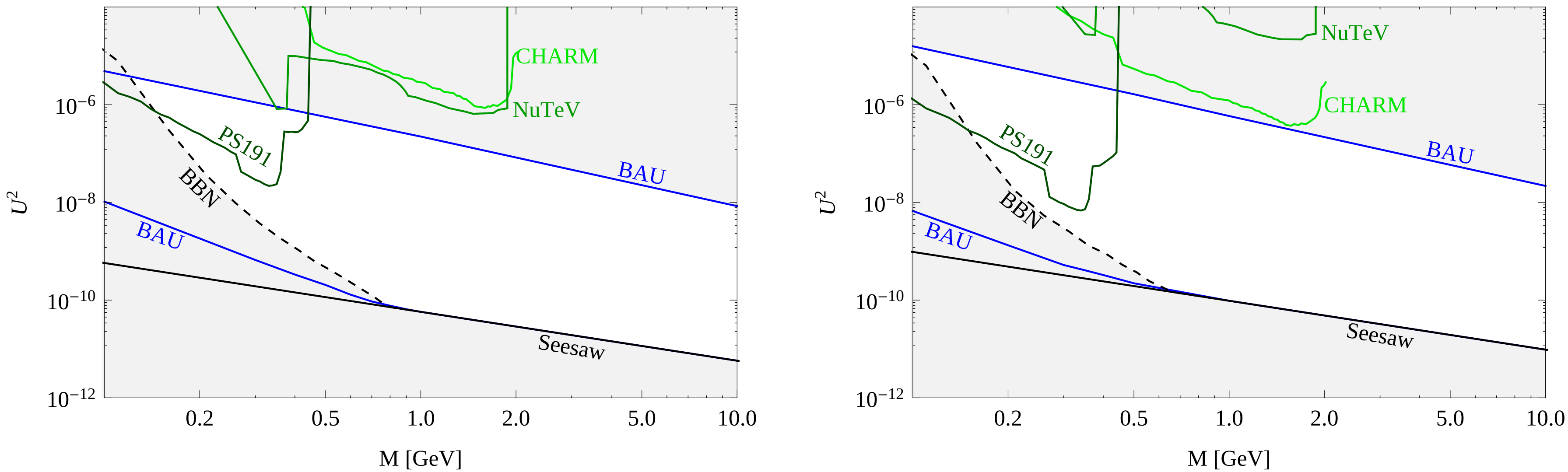
Creation of baryon asymmetry - a complicated process involving creation of HNLs in the early universe and their coherent CP-violating oscillations, interaction of HNLs with SM fermions, sphaleron processes with lepton and baryon number non-conservation

Akhmedov, Rubakov, Smirnov; Asaka, MS



Resummation, hard thermal loops, Landau-Pomeranchuk-Migdal effect, etc. Ghiglieri, Laine. How to describe these processes is still under debate, but the consensus is that it works and is testable.

Baryon asymmetry: HNLs $N_{2,3}$

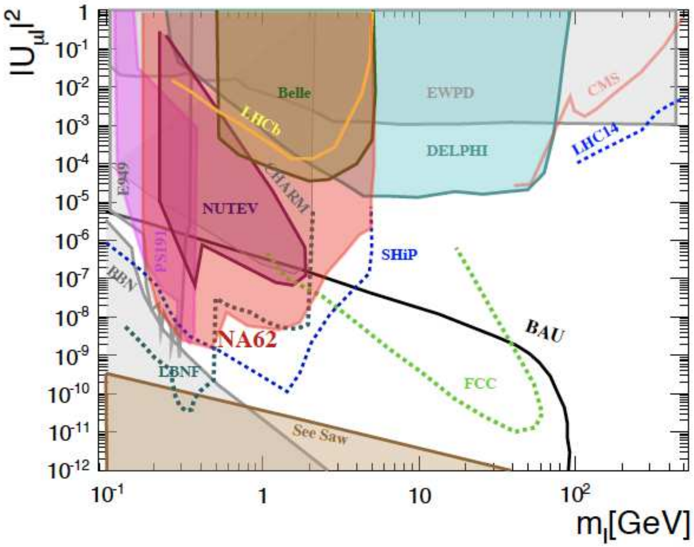


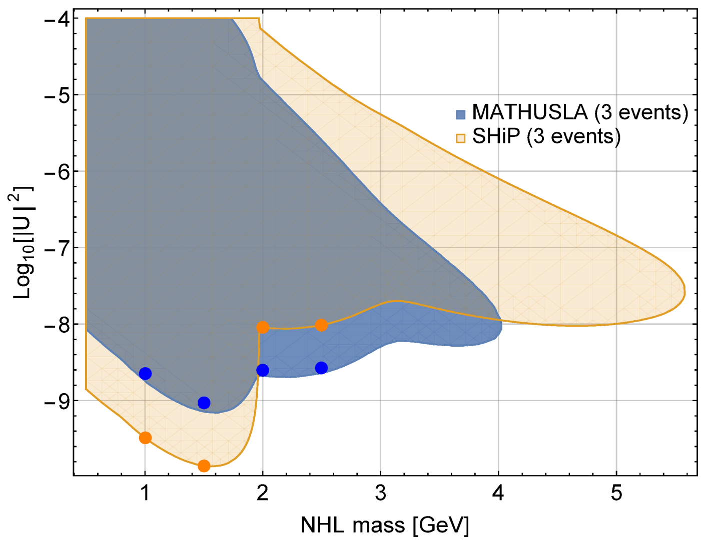
Constraints on U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS '12). Similar results: recent works by Abada, Arcadia, Domcke, Lucente ' 15, Hernández, Kekic, J. López-Pavón, Racker, J. Salvado '16,Drewes, Garbrech, Guetera, Klarić '16, Hambye, Teresi '17

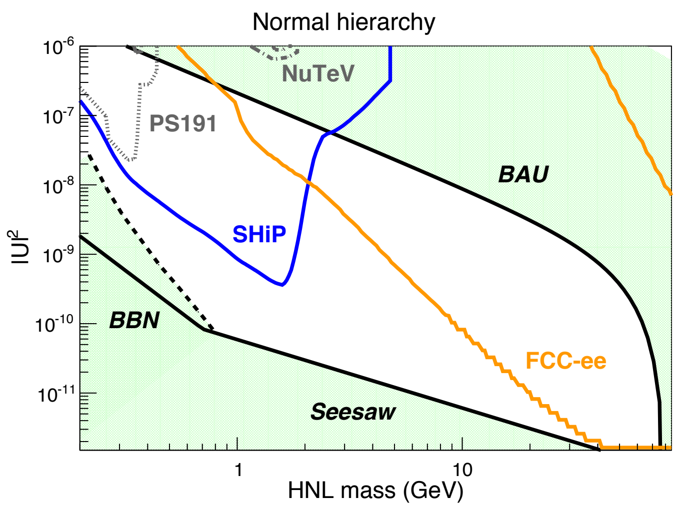
Experimental challenges:

- HNL production and decays are highly suppressed – dedicated experiments are needed:
  - Mass below ~ 5 GeV - Intensity frontier, CERN SPS: NA62 in beam dump mode, SHiP
  - Mass below ~ 5 GeV - Energy frontier, LHC: MATHUSLA
  - Mass above ~ 5 GeV - FCC in e^+e^- mode in Z-peak, LHC

Generic purpose experiments to search for all sorts of relatively light dark sector particles (dark photons, hidden scalars, etc).







FCC at 10^{13} Z^0 and decay length 0.01-500 cm

Dark Matter candidate: N_1

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

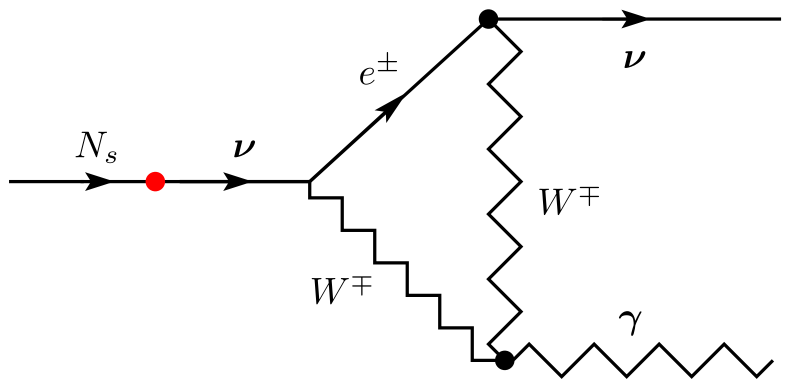
Subdominant radiative decay channel: $N \rightarrow \nu\gamma$.

Photon energy:

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

Radiative decay width:

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

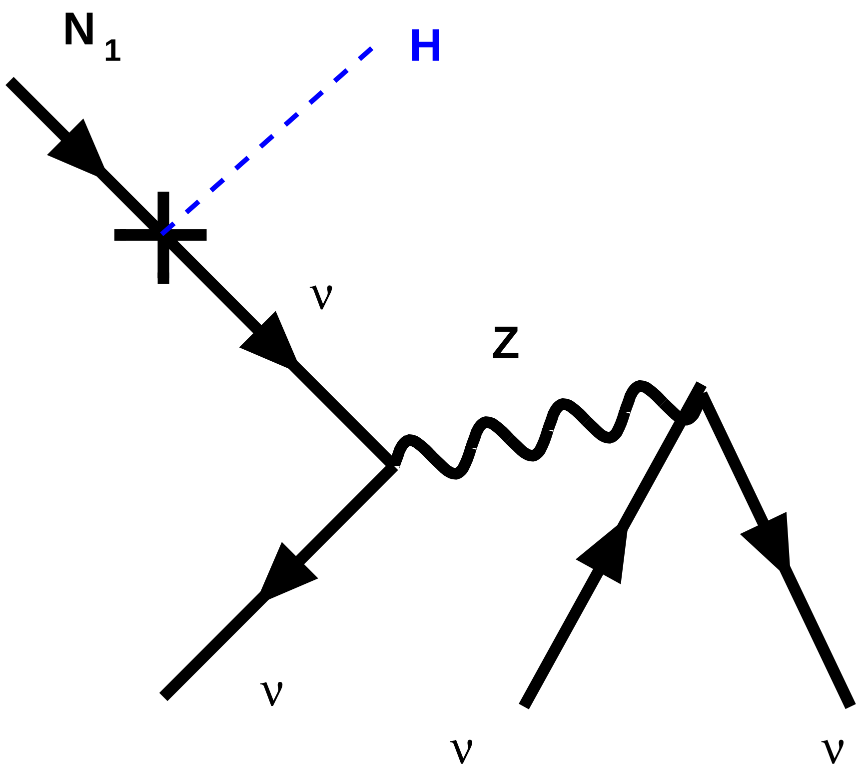


N_1 decays radiatively, $N_1 \rightarrow \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes!

Dark matter production

Production temperature of Dark matter HNL via processes like $l\bar{l} \to \nu N_1$:

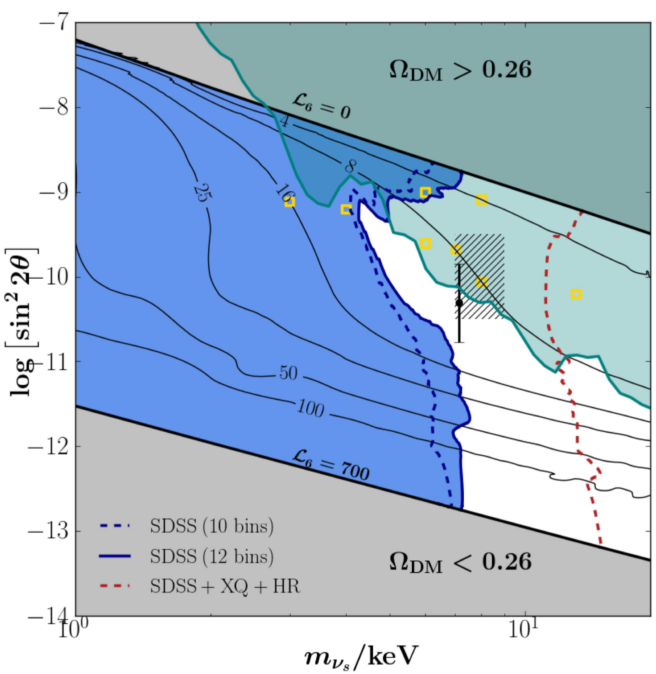
$$T \sim 130 \left(\frac{M_I}{1 \text{ keV}} \right)^{1/3} \text{MeV}$$

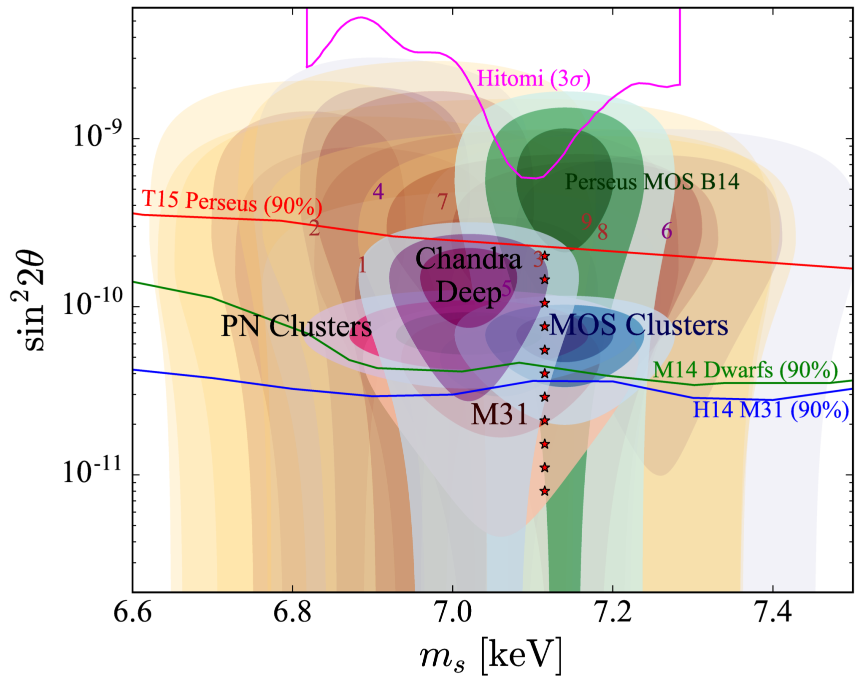


Status of sterile neutrino dark matter N_1

Decaying DM: $N_1 \to \gamma\nu$

3.5 keV line: E. Bulbul et al, Boyarsky et al





1706.03118, Baur et al.

1705.01837 Abazajian

Future of decaying dark matter searches in X-rays

Another Hitomi (around 2020)

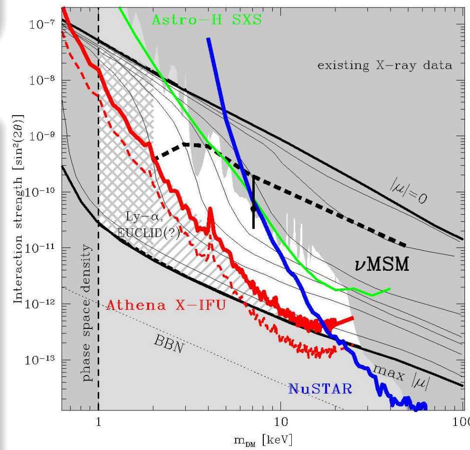
It is planned to send a replacement of the Hitomi satellite

Microcalorimeter on sounding rocket (2019)

- Flying time $\sim 10^2$ sec. Pointed at GC only
- Can determine line's position and width

Athena+ (around 2028)

- Large ESA X-ray mission with X-ray spectrometer (X-IFU)
- Very large collecting area ($10\times$ that of XMM)
- Super spectral resolution



Conclusions

The Standard Model is in great shape.

The SM Higgs field can play an important role in cosmology:

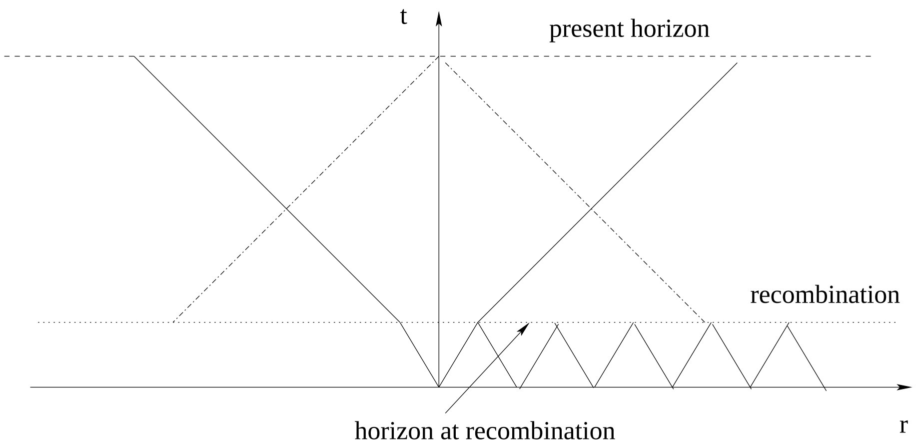
- It can make the Universe flat, homogeneous and isotropic
- Quantum fluctuations of the Higgs field can lead to structure formation
- Coherent oscillations of the Higgs field can make the Hot Big Bang and produce all the matter in the Universe
- Real and virtual Higgs boson can play a crucial role in baryogenesis leading to charge asymmetric Universe
- Dark Matter production may come about as an effect of mixing between neutrinos and heavy neutral leptons, induced by the Higgs field

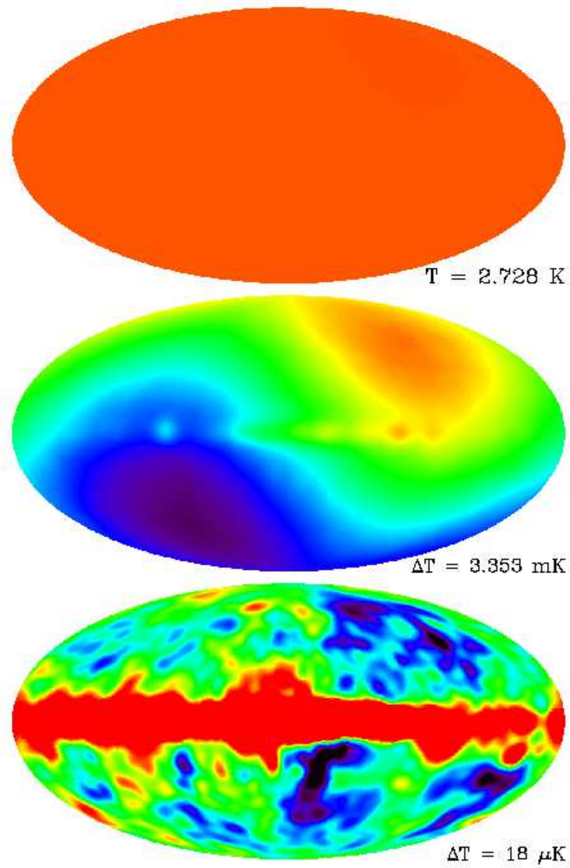
A number of new experiments is needed to reveal the “secret” couplings of the Higgs boson

Backup slides

Important cosmological problems:

Horizon problem: Why the universe is so uniform and isotropic?





Expected fluctuations at $\boldsymbol{\theta \sim 1^o}$:

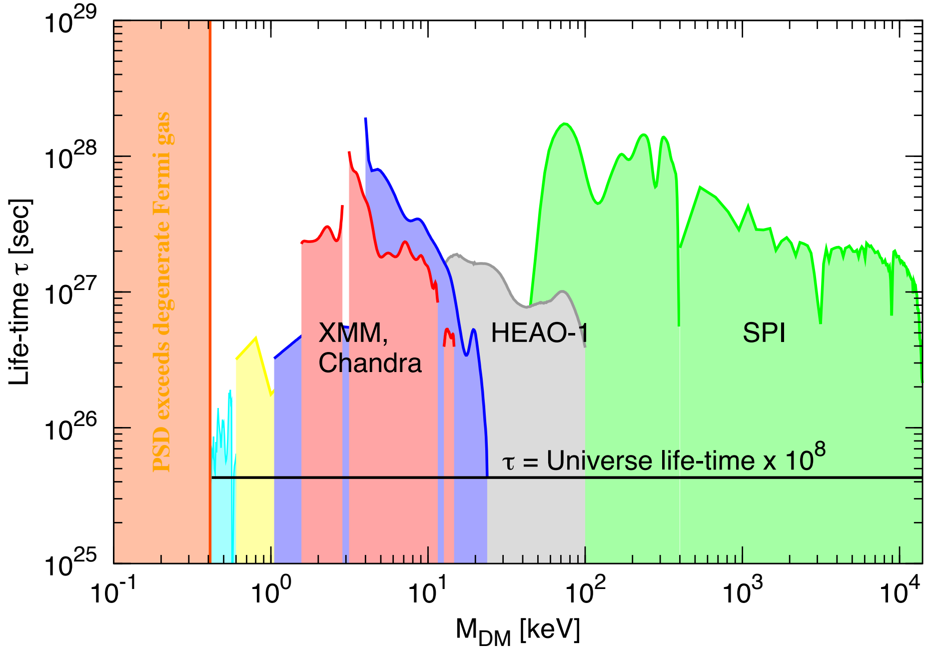
$\boldsymbol{\delta T/T \sim 1}$.

Observed fluctuations: $\boldsymbol{\delta T/T \sim 1O^{-5}}$

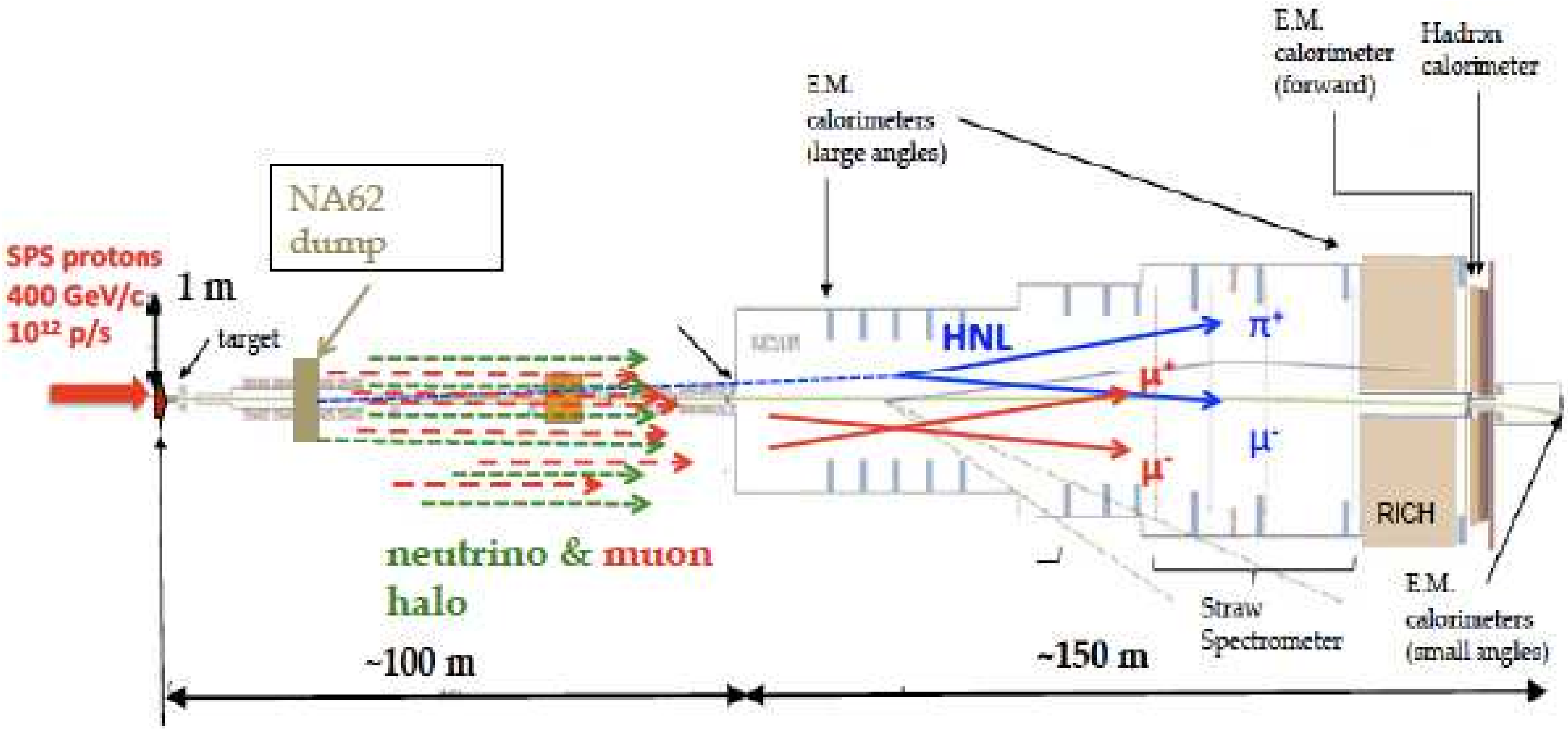
Flatness problem: Why $\boldsymbol{\Omega_M + \Omega_\Lambda + \Omega_{\mathrm{rad}}}$ is so close to 1 now and was immensely close to 1 in the past?

All this requires enormous fine-tuning of initial conditions (at the Planck scale?) if the Universe was dominated by matter or radiation all the time!

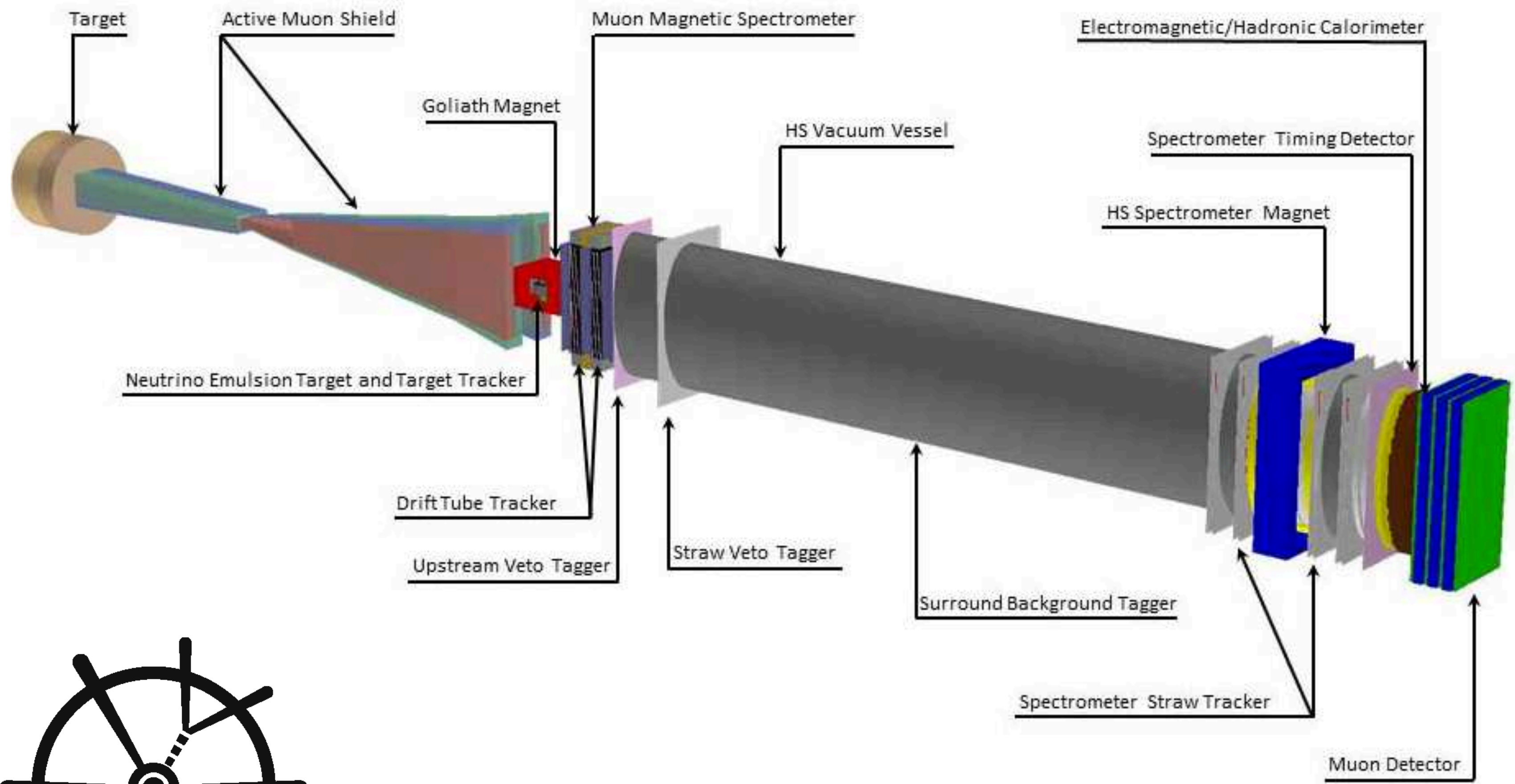
Available X-ray satellites:
Suzaku, XMM-Newton, Chandra,
INTEGRAL, NuStar



NA62



SPS protons
400 GeV/c
10^{12} p/s
1 m
target
NA62
dump
neutrino & muon
halo
~100 m
E.M.
calorimeters
(large angles)
HNL
π^+
μ^+
μ^-
μ^-
E.M.
calorimeter
(forward)
Hadron
calorimeter
RICH
Straw
Spectrometer
~150 m
E.M.
calorimeters
(small angles)



SHiP
Search for Hidden Particles

MATHUSLA

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles