# Search for Hidden Particles with SPS

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# Structure of the Standard Models

In the past the structure of the Standard Model was giving us hints where to expect new physics

We were searching for the particles without which our explanation of all the previous experiments would become inconsistent

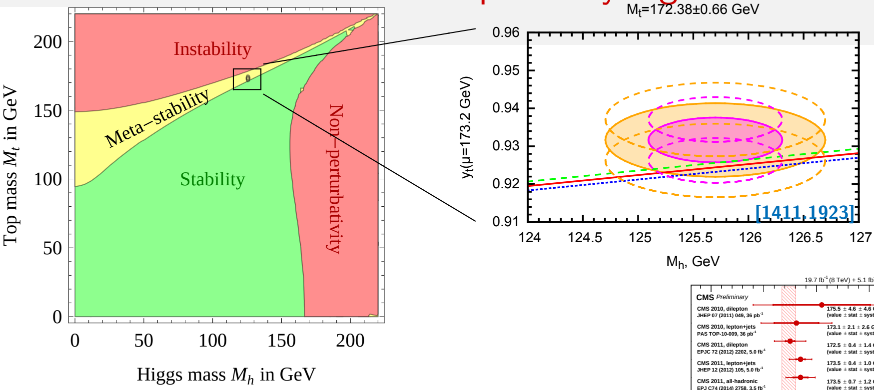
- We knew that something shall be found at energies below $E < G_{\text{Fermi}}^{-1/2}$
- Without the top quark the Standard Model would be **non-unitary**
- Without the Higgs boson the Standard Model would be **non-unitary**

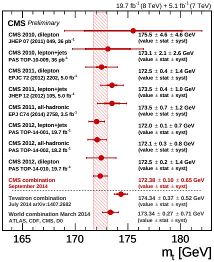
### Higgs boson

Higgs boson was the last predicted but unseen particle

- **Did century long quest come to its end?**
- **Where do we need to look for something else?**

# Standard Model is consistent up to very high scales




"It is expected that the difference between the MC mass definition and the formal pole mass of the top quark is up to the order of 1 GeV" (from *First combination of Tevatron and LHC measurements of the top-quark mass* [1403.4427]

**Bezrukov et al. "Higgs boson mass and new physics" [1205.2893]**

**Degrassi et al. [1205.6497], Buttazzo et al. [1307.3536]**

# Should we believe that new particles exist?

# Physics **Beyond** the Standard Model

### Neutrino masses and oscillations

What makes neutrinos disappear and then re-appear in a different form? Why they have mass?

- Neutrino oscillations do not tell us what is the scale of new physics
- It can be **anywhere** between sub-eV and $10^{15}$ GeV (like $M_W < G_F^{-1/2}$)

### Baryon asymmetry of the Universe

what had created tiny matter-antimatter disbalance in the early Universe?

- Particles as light as 1 MeV or as heavy as $10^{12}$ GeV can be responsible for this

### Dark matter

What is the most prevalent kind of matter in our Universe?

- Physics at high scales ($10^{12}$ GeV for axions), at intermediate scales (TeVs for WIMPs) or at low scales (keV-ish sterile neutrino, physics below electroweak scale) can be responsible for this

# Question about the evolution of the Universe as a whole

### Cosmological inflation:

What was driving the accelerated expansion of the universe during the early stages of its evolution? (possibly Higgs field)

### Dark Energy:

What drives the accelerated expansion of the universe now (possibly this is just $\Lambda$-term)

### Deep theoretical questions

- Strong CP problem
- Why Planck scale $10^{19}$ GeV is much higher than the electroweak scale (100 GeV)?
- What is the theory of quantum gravity?

(Fundamental questions, but it is possible to be agnostic about them for quantitative description of what was observed so far)

# Unsolved problems mean that **new particles should exist**

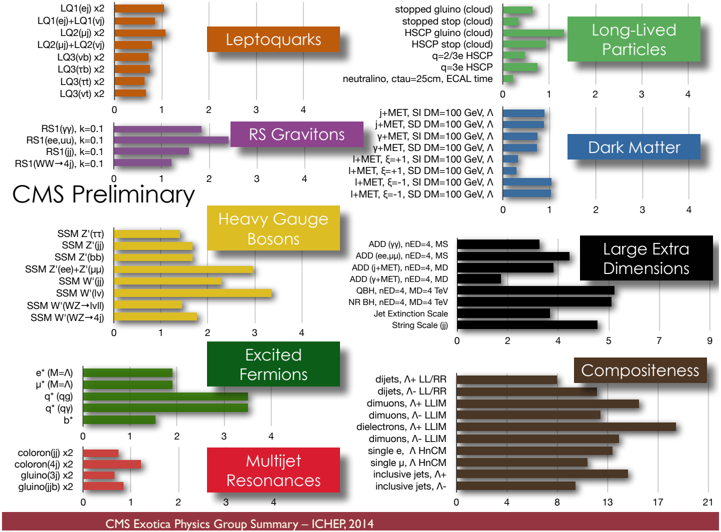
We did not detect them because

they are **heavy**

**OR**

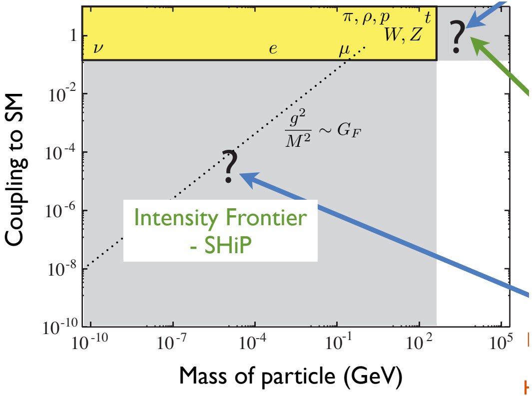
they are light but
**very weakly interacting**

# Heavy particles: active LHC searches




Probed scale $\ll 10^{19}$ GeV

# Intensity frontier searches for feebly interacting particles




Intensity frontier has been paid much less attention in the recent years:

- PS 191 (early 1980s)
- CHARM: 1980s
- NuTeV: 1990s
- DONUT: late 1990s – early 2000

**Two possibilities exist**

- Standard Model plus some light particles is valid up to very high energies. No new physics between Fermi and Planck scale
- There is a wider theory with a new energy scale (SUSY scale, GUT scale, extra dimensions, new strong dynamics, etc) but there are light particles in the spectrum

# Complimentarity of energy & intensity frontier searches

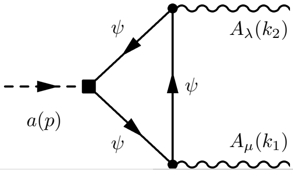
Why some of the new particles can be light?

Example: **axion**

- Heavy fermions $\Psi$ interact with a heavy scalar $\Phi = |\Phi|^{i\theta}$
- The theory possesses U(1) symmetry **spontaneously broken** at high energies $E \sim g_{\phi\gamma\gamma} \gg \mathrm{TeV}$
- Spontaneously broken symmetry leaves behind a **Goldstone boson** $\phi$
- if the symmetry was not exact these (pseudo)-Goldstone bosons will be massive. But generically light

Heavy fermions in the loops induce interactions between light particles:

$$\mathcal{L}_{\text{axion}} = \frac{\phi}{g_{\phi\gamma\gamma}} F\tilde{F}$$



# Why some SUSY particles can be light?

## Gravitino

- Superpartner of graviton $\Rightarrow$ Massless at tree level
- Roughly speaking

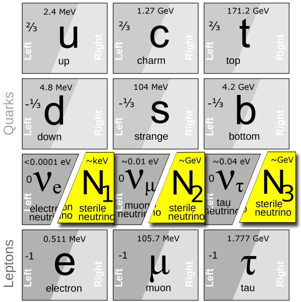
$$m_{\text{gravitino}} = \frac{(\text{SUSY breaking scale})^2}{M_{\text{Planck}}} \ll \text{Other SUSY particles}$$

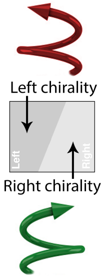
## Sgoldstino

- spontaneous SUSY breakin $\Rightarrow$ the existence of spin 1/2 Goldstone particle **goldstino**
- Superpartner to goldstino – **Sgoldstino**
- Massless at tree level
- Mass via loop corrections

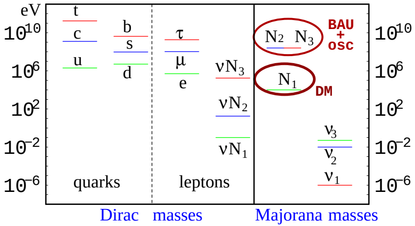
# No new particles heavier than electroweak scale

## All BSM puzzles are resolved with the particles lighter than EW scale




- **Neutrino oscillations:** particles $N_2$, $N_3$
- **Baryon asymmetry:** same particles $N_2$, $N_3$
  - masses $\mathcal{O}(100)$ MeV – $\mathcal{O}(80)$ GeV
- **Dark matter:** particle $N_1$
  - mass $1 - 50$ keV
- **Inflation:** Higgs field coupled to gravity
  - Inflationary parameters for $M_{\text{Higgs}} \sim 126$ GeV in perfect agreement with observations




**Neutrino Minimal Standard Model ($\nu$MSM)**

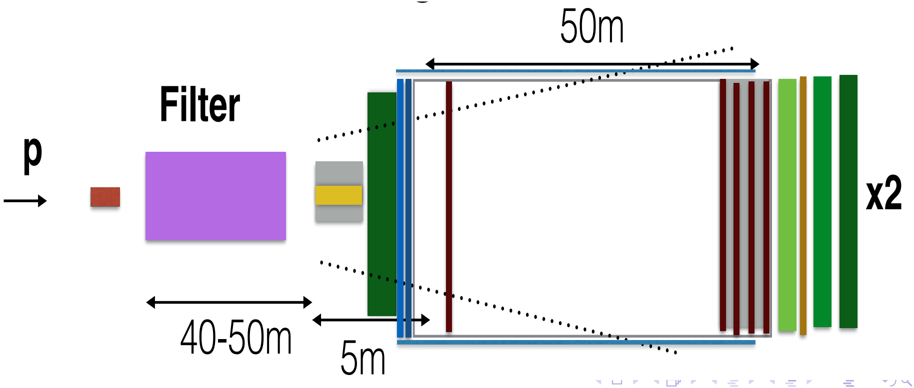
Masses of right-handed neutrinos as of other order of masses of other leptons

Yukawas as those of electron or smaller

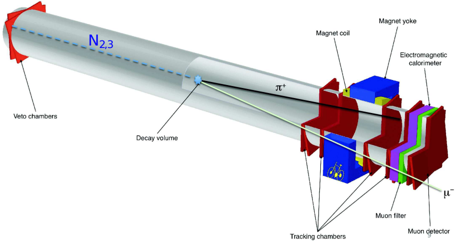
# SHiP (*Search for Hidden Particles*) experiment

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

- Take the highest Energy/Intensity proton beam of the world
- . . . dump it into a target . . .
- . . . followed by the closest, longest and widest possible and technically feasible decay tunnel!



# SHiP detector




- Aim: background free detector
- Any event would mean new particles

| Generic decay modes | Final states | Models tested |
|---|---|---|
| meson and lepton | $\pi l$, $Kl$, $\rho l$, $l = (e, \mu, \nu)$ | $\nu$ portal, HNL, SUSY neutralino |
| two leptons | $e^+e^-$, $\mu^+\mu^-$ | V, S and A portals, SUSY s-goldstino |
| two mesons | $\pi^+\pi^-$, $K^+K^-$ | V, S and A portals, SUSY s-goldstino |
| 3 body | $l^+l^-\nu$ | HNL, SUSY neutralino |

- Can probe: neutrino, vector, scalar portals; axions; light SUSY particles
- Has designated $\nu_\tau$ programme (For the first time there will be a high intensity neutrino flux with all three species of neutrinos and antineutrinos!)

# SHiP collaboration

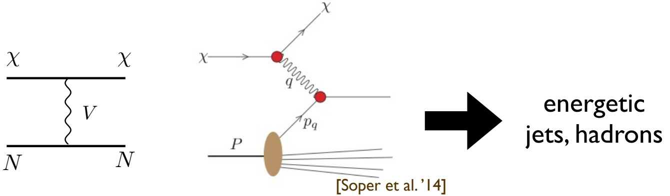
- SHiP collaboration has been **officially created yesterday in CERN**
- Technical proposal & physics case papers to be submitted to the SPS committee at the end of March 2015
- The designa and the science programme are not final yet!

  ... Considering the large cost and complexity of the required beam infrastructure as well as the significant associated beam intensity, such a project should be designed as a general purpose beam dump facility with the broadest possible physics programme, including maximum reach in the investigation of the hidden sector

  (from SPS response to the SHiP's expression of interest **[1310.1762]**)
- Interested groups and interested people are welcome to join!
- SHiP Physics case mailing list: `ship-theory@cern.ch`

# More physics with beam dump: Light dark matter

- Light (below $\sim$ GeV) dark matter particles: fermions that couple to "dark photon" mesons $\to V' \to \chi\chi$
- Not probed with direct detection experiments
- Detection via **scattering events** in the detector



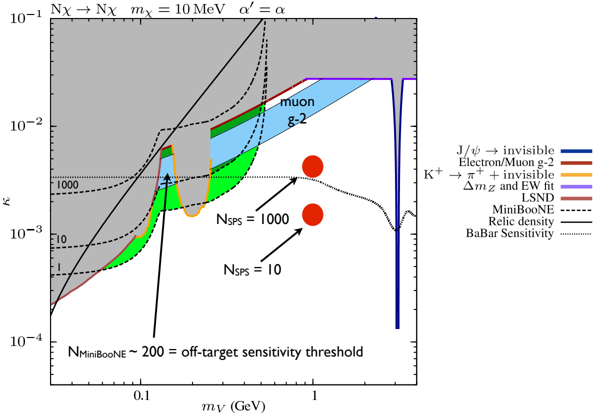

$\chi-$nucleon elastic    deep inelastic

- sub-GeV dark matter can be searched at neutrino experiments
  - at proton beam dumps — **dedicated MiniBooNe run [1211.2258]**
  - electron beam dumps — **Letter for Intent for JLab [1406.3028]**

**For more details see B.Batell talk at 2nd SHiP meeting**

# Can SPS do better?

## Oh, yes!



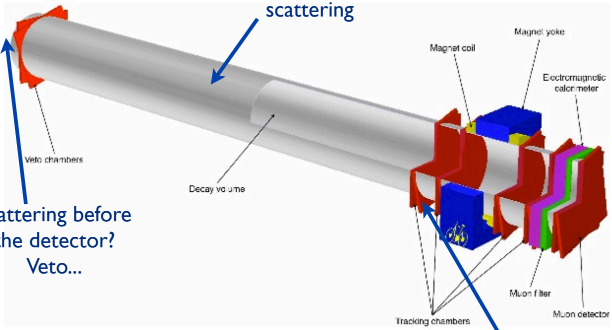

**Courtesy of Adam Ritz. Red dots (unpublished): estimate of SPS sensitivity.**

Assumes that detector is 40 ton (e.g. LAr TPC)

# How?

work in progress. . . Everyone is welcome to contribute!

Decay volume is evacuated, so no scattering




Scattering before the detector? Veto...

Looks difficult...
Can a dedicated analysis be done?

Scatter in the tracking chambers, or ECAL?

**Alternative: Put here dedicated detector???**

- We are discussing this right now!
- Ideas (and people) are welcome

**Slide from B. Batell's talk at 2nd SHiP meeting**

# Possible signal of the keV-scale dark matter

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

ESRA BULBUL[1,2], MAXIM MARKEVITCH[2], ADAM FOSTER[1], RANDALL K. SMITH[1] MICHAEL LOEWENSTEIN[2], AND SCOTT W. RANDALL[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.
*Submitted to ApJ, 2014 February 10*

**ApJ (2014) [1402.2301]**

**An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster**

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

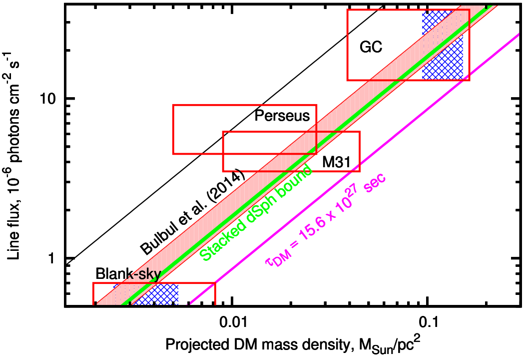
**PRL (2014) [1402.4119]**

**Energy:** 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
**Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor $\sim 3$)
**Possible origin:** decay $\text{DM} \to \gamma + \nu$ (fermion) or $\text{DM} \to \gamma + \gamma$ (boson)

# Many models could provide such a signal

The 3.5 keV X-ray line from decaying **gravitino** dark matter. **Axino** dark matter in light of an anomalous X-ray line. The Quest for an Intermediate-Scale Accidental **Axion** and Further **ALPs**. keV Photon Emission from Light **Nonthermal Dark Matter**. X-ray lines from R-parity violating decays of keV **sparticles**. Neutrino masses, leptogenesis, and **sterile neutrino** dark matter. A Dark Matter Progenitor: **Light Vector Boson Decay** into (Sterile) Neutrinos. A 3.55 keV Photon Line and its Morphology from a 3.55 keV ALP Line. 7 keV Dark Matter as X-ray Line Signal in Radiative Neutrino Model. X-ray line signal from decaying **axino** warm dark matter. The 3.5 keV X-ray line signal from **decaying moduli** with low cutoff scale. X-ray line signal from 7 keV **axino** dark matter decay. Can a **millicharged dark matter** particle emit an observable gamma-ray line?. Effective field theory and keV lines from dark matter. Resonantly-Produced 7 keV **Sterile Neutrino Dark Matter** Models and the Properties of Milky Way Satellites. Cluster X-ray line at $3.5\,\mathrm{keV}$ from axion-like dark matter. Axion Hilltop Inflation in Supergravity. A 3.55 keV hint for decaying axion-like particle dark matter. The 7 keV axion dark matter and the X-ray line signal. An X-Ray Line from **eXciting Dark Matter**. 7 keV **sterile neutrino dark matter** from split flavor mechanism. **FImP** Miracle of Sterile Neutrino Dark Matter by Scale Invariance. **Non-abelian Dark Matter** Solutions for Galactic Gamma-ray Excess and Perseus 3.5 keV X-ray Line. 3.5 keV X-ray Line Signal from Dark Matter Decay in **Local** $U(1)_{B-L}$ **Extension of Zee-Babu Model**. **SIMPle** Dark Matter: Self-Interactions and keV Lines. Exploring X-Ray Lines as **Scotogenic** Signals. **Hidden axion dark matter** decaying through mixing with QCD axion ...

# What's next?




- XMM-Newton's time allocation committee has just granted us 1.4 Mega-seconds (PI: A. Boyarsky)
- This is 10% of the XMM's annual observational budget!

. . . the panel recognised that a detection of the 3.5 keV line in Draco would be a spectacular discovery. Even the non-detection represents an important result since it will rule out the dark matter origin of the 3.5 keV line detected by several teams earlier this year. Overall, the panel felt that this observation can and will trigger a lot of discussion on this topic. . .

# Next generation of X-ray missions

from ASTRO-H Space X-ray Observatory White Paper

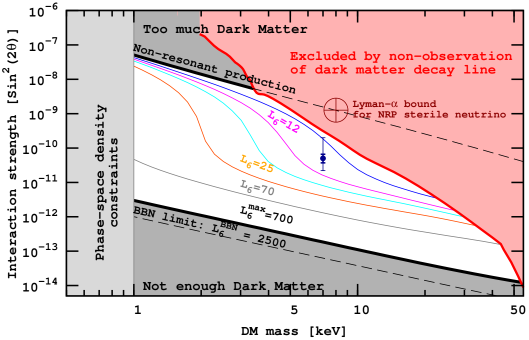
Clusters of Galaxies and Related Science **[1412.1176]**

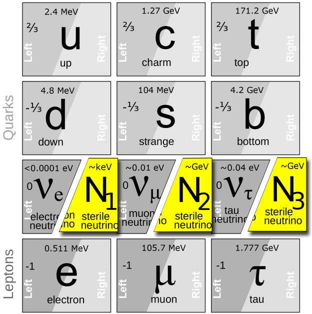
## 9 A Spectroscopic Search for Dark Matter

### Overview

X-ray spectroscopic observations provide a unique probe of direct signatures of dark matter, such as a line of a hypothetical sterile neutrino in the $\sim$ keV mass range. In the event that any candidate emissio is detected in the $1-10$ keV energy band, *ASTRO-H* SXS will offer the first opportunity to resolve its and distinguish it from plasma lines and instrumental effects. The significance of dark matter identificatio be improved crucially if the line is detected from multiple sources with distinguishable differences in red and velocity dispersions. Plausible targets include nearby galaxy clusters, the Milky Way Galaxy, and spheroidal galaxies, many of which will be observed by SXS for other purposes. [16]

# Sterile neutrino and 3.5 keV line




- **Atmospheric** and **Solar** neutrino mass splitting $\Rightarrow$ need two sterile neutrino
- Are they Dark matter? $\Rightarrow$ No way! Very short lifetime
- Third sterile neutrino ($N_1$)? $\Rightarrow$ Yes! Great dark matter particle!
  (its exact properties depend on two other sterile neutrinos $N_2, N_3$)
- SHiP can search these other two particles ($N_2, N_3$)

# Conclusions

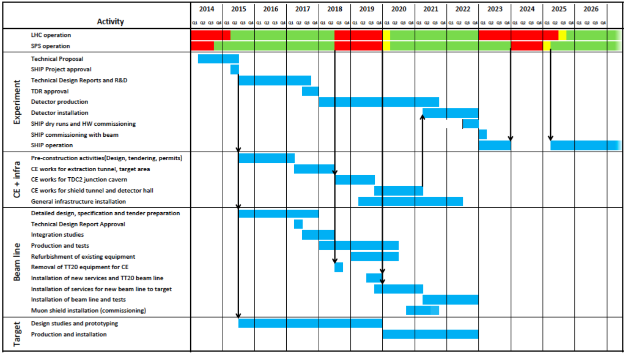
- Intensity frontier is an underexplored possibility to discover new particles, complimentary to LHC-like experiments
- SPS is the highest energy/intensity proton beam in the world
  90% of the SPS protons are not used!
- Such experiments may be the future of particle physics for some time
- Experiments like SHiP are capable to discover new particles expected from various phenomenological and theoretical directions
- Design and the science programme of a generic beam-dump experiment with the SPS beam is not final yet. We discuss it right now
  - $\Rightarrow$ there are many things that can be done
  - $\Rightarrow$ people are welcome to join!
- SHiP-like experiment has capability not only to constrain many interesting models, but also directly experimentally resolve three major BSM phenomena: neutrino masses, dark matter, origin of matte-antimatter asymmetry

# The end

Thank you for your attention

# Timeframe

## *Next steps: schedule of the SHIP facility*




***A few milestones:***

- ✓ ***Form SHIP collaboration*** → ***15th December at 5 pm***
- ✓ *Technical proposal* → *2015* *Plan to submit TP by March 31*

***We expect CERN to decide on the strategy for the SHIP beam within a year after TP submission !***

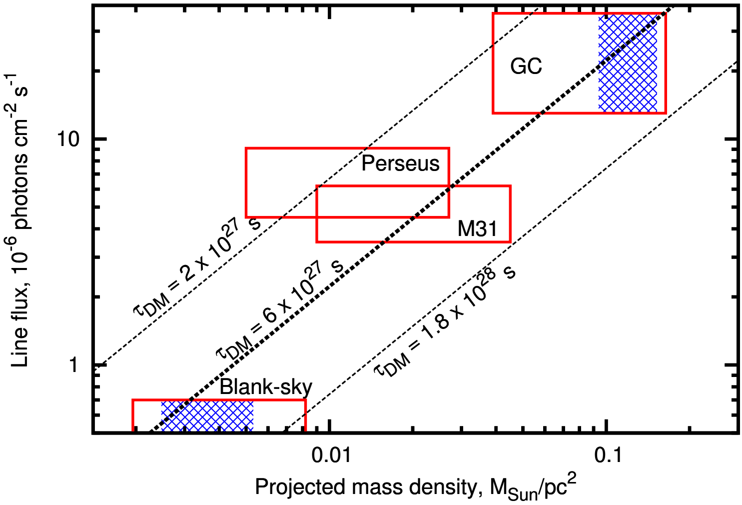
- ✓ *Technical Design Report* → *2018*
- ✓ *Construction and installation* → *2018 – 2022*
- ✓ *Data taking and analysis of* $2{\times}10^{20}$ *pot* → *2023 - 2027*

# Current status

- Several other groups confirmed the existence of the line in the Perseus cluster [1411.0050] Milky Way center [1405.7943,1408.1699,1411.1758]
- Interpretation as Potassium emission line? (K XVIII ion has transitions at 3.47 keV and 3.51 keV)
  - Impossible to give simultaneous explanation for Milky Way, Andromeda galaxy and Persesus cluster at the same time
- Non-observation from the outskirts of galaxy clusters (our original work, [1408.4115])
  - Does not contradict to DM interpretation: DM distribution is sharply peaked in the center
- Dwarf spheroidal galaxies? Perfect targets: dark, dense. Not enough sensitivity with the current data [1408.3531]
- $\Rightarrow$ Need more data!!

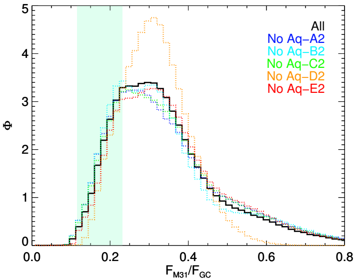
# Current status

## Signal from different object is consistent with **dark matter** interpretation

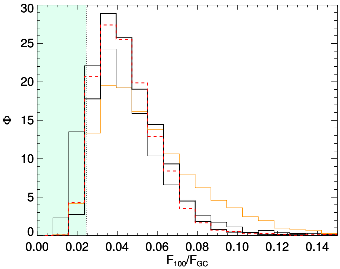



[1408.2503]

# Comparison of signal between the objects




The probability distribution function for the M31/GC flux ratio.




The probability distribution function for the Milky Way center/outskirts flux ratio.

**1411.0311**

# Physics with neutrinos

For the first time there will be a high intensity neutrino flux with all three species of neutrinos and antineutrinos!

## $\nu_\tau$ physics with SHiP

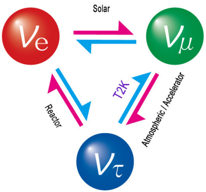
- Previous observation of $\nu_\tau$ charged current interactions
  - 9 events by DONUT not distinguishing among $\tau^+$ and $\tau^-$ creation
  - 4 events by OPERA observing $\tau^-$ as the result on $\nu_\mu \to \nu_\tau$ neutrino oscillation
- With SHiP it will be possible
  - First detection of $\bar{\nu}_\tau$
  - Cross-section measurements (separate for $\nu_\tau$ and $\bar{\nu}_\tau$)

## Not only $\nu_\tau$: what could be done with $\nu_\mu$

- Structure functions ($F_2$, $R$ and $F_3$) measurements
- Charm physics from neutrinos and anti-neutrinos charged-currents interaction
- ...much more (see SHiP physics paper)

# Neutrino masses and oscillations

What makes neutrinos disappear and then re-appear in a different form? Why they have mass?

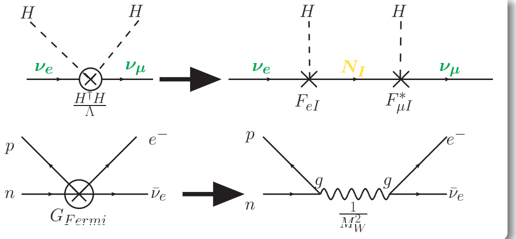



Neutrino oscillation between three generations

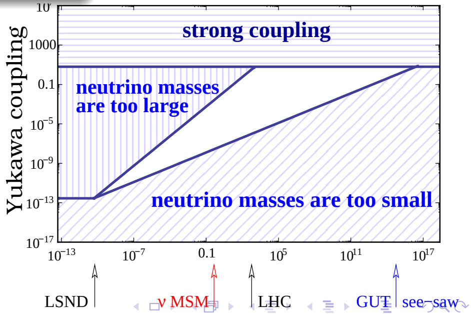
- Neutrino flavour oscillations tells us that there are quadratic mixings between different sorts of neutrino $\bar{\nu}^c_\alpha \nu_\beta$
  $\Rightarrow$ neutrino is massive!
- Neutrino is a part of the left SU(2)-doublet $L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$
- Neutrino mixing term is **operator of dimension 5**:

$$\bar{\nu}^c_\alpha \nu_\beta \to \frac{(\bar{L}^c_\alpha \cdot H)(L_\beta \cdot H)}{\Lambda} \qquad \Lambda \sim \frac{\langle H \rangle^2}{m_{\rm atm}} \sim 10^{15}\,\mathrm{GeV}$$

# Neutrino oscillations scale




**New particle!** Scale $\Lambda \sim \frac{|F_{\alpha I}|^2 \langle H \rangle^2}{m_{\text{atm}}}$

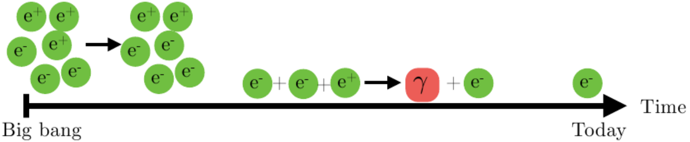



- Neutrino oscillations do not tell us what is the scale of new physics
- It can be **anywhere** between sub-eV and $10^{15}$ GeV (like $M_W < G_F^{-1/2}$)

# Baryon asymmetry of the Universe

what had created tiny matter-antimatter disbalance in the early Universe?

- Particle physics applied to the whole Universe was very successful in explanation of primordial abundance of elements, prediction of CMB, etc.
- We live in the era of precision cosmology!

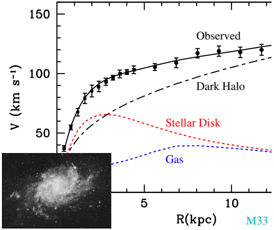



- Since Dirac we know: physics is symmetric if one interchanges particles and antiparticles
- Thermal equilibrium "does not remember" its history
- **Sakharov conditions:** violation of Baryon number; violation of CP; deviation from thermal equilibrium
- Even neutrinos are in equilibrium in the dense primordial plasma; there is no phase transition in the Standard Model with the current Higgs mass

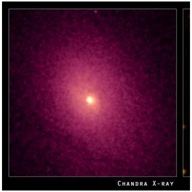
$\Rightarrow$ **we need new particles**

# Dark matter

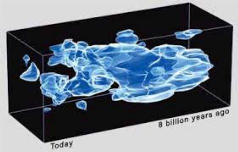
## What is the most prevalent kind of matter in our Universe?



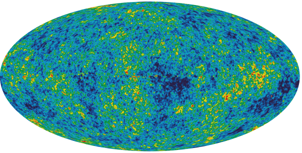

**Expected:** $v(R) \propto \frac{1}{\sqrt{R}}$
**Observed:** $v(R) \approx \text{const}$



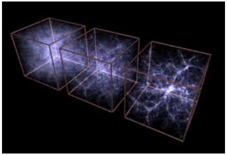

**Expected:**
$\text{mass}_{\text{cluster}} = \sum \text{mass}_{\text{galaxies}}$
**Observed:** $10^2$ times more mass confining ionized gas




**Lensing signal** (direct mass measurement) **confirms** other observations



Jeans instability turned tiny density fluctuations into all visible structures



Neutrinos (the only neutral, stable particles) cannot be dark matter

⇒ **need new particle**!

# Portals

For details see talk by Misha Shaposhnikov at 2nd SHiP meeting

Dimension $\text{GeV}^2$, Vector portal:

new particles are Abelian fields, $A'_\mu$ with the field strength $F'_{\mu\nu}$, that couple to the hypercharge field $F_Y^{\mu\nu}$ via

$$\mathcal{L}_{\text{Vector portal}} = \epsilon F'_{\mu\nu} F_Y^{\mu\nu}$$

Dimension $\text{GeV}^2$, Scalar portal:

new particles are neutral singlet scalars, $S_i$ that couple the Higgs field:

$$\mathcal{L}_{\text{Scalar portal}} = (\lambda_i S_i^2 + g_i S_i)(H^\dagger H)$$

Dimension $\text{GeV}^{\frac{5}{2}}$, Neutrino portal:

the singlet operators $(\bar{L} \cdot \tilde{H})$ couple to new neutral singlet fermions $N_I$