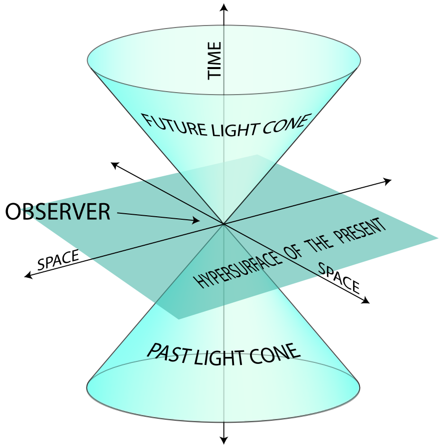
Sterile neutrino from micro to macro scales

Alexey Boyarsky
Lorentz Institute for Theoretical Physics

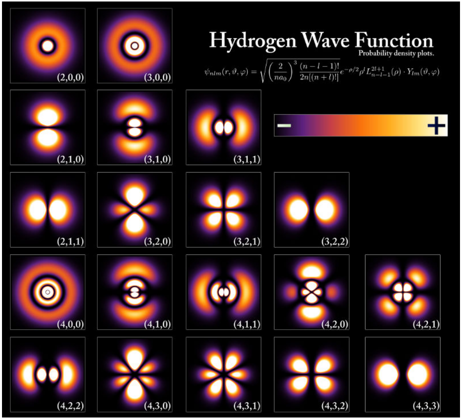
April 24, 2019

Scientific revolutions in XX century: relativity



https://www.wikipedia.org

- Relativity changed our basic notion of space and time
- Time is not **absolute** anymore
- There is a maximal speed – **speed of light**

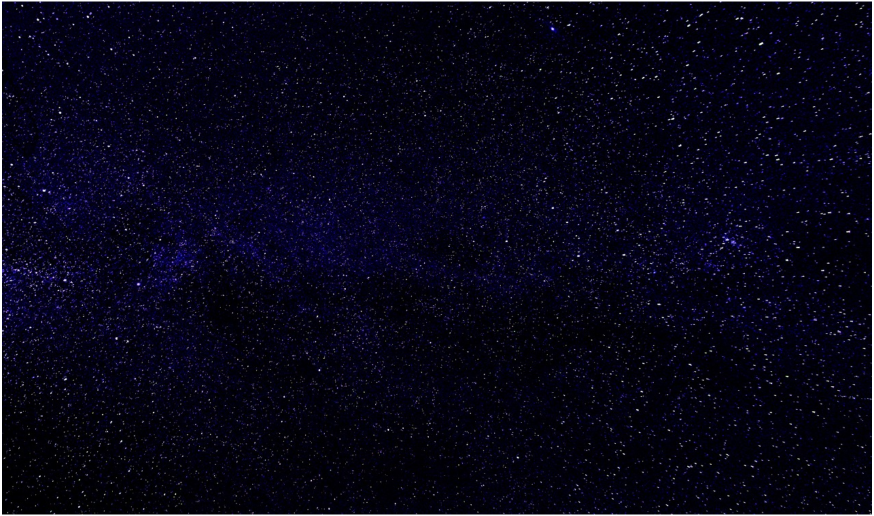


https://www.wikipedia.org

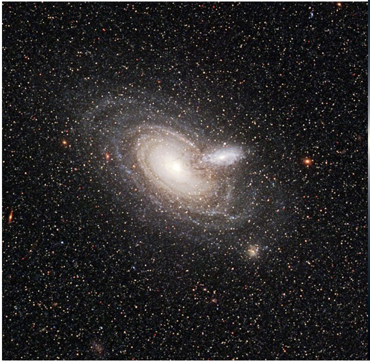
Quantum mechanics: attempts to explain atomic and nuclear physics

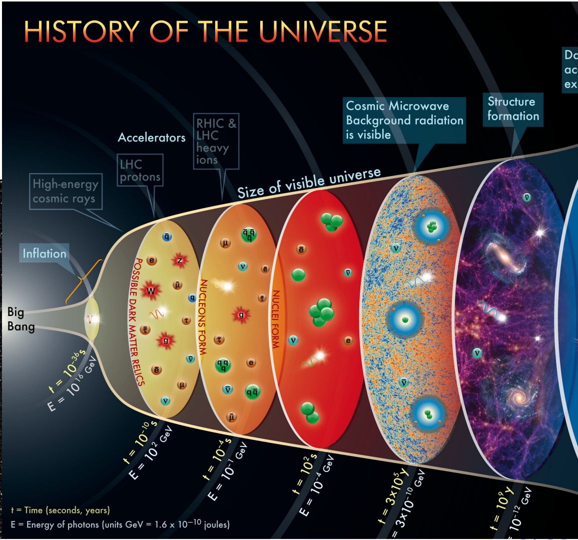
- State of the system: a **vector in the Hilbert space** $|\psi\rangle$ (rather than a point in the phase space (x, p))
- **Evolution:** operator acting on the Hilbert space $\hat{\mathcal{H}}$
$$i\hbar\frac{\partial}{\partial t}|\psi\rangle = \hat{\mathcal{H}}|\psi\rangle$$
- **Observables:**
$x(t) \to \langle\psi(t)|\,\hat{x}\,|\psi(t)\rangle$,
$p(t) \to \langle\psi(t)|\,\hat{p}\,|\psi(t)\rangle$

Scientific revolutions in XX century: Universe



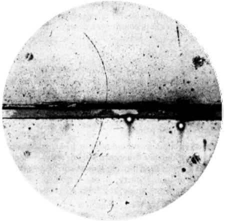
Scientific revolutions in XX century: Universe – some “stars” are galaxies

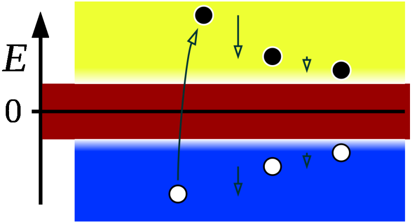




Relativistic quantum mechanics

- QM was developed for non-relativistic particles. A lot of effort was made to combine it with relativity and the **Pandora's box** was opened





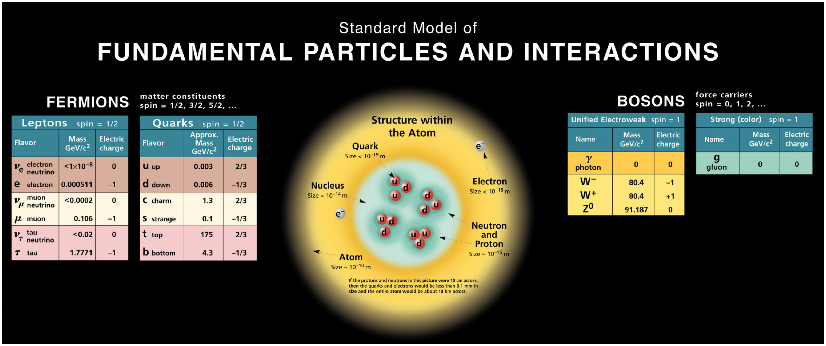
- Dirac equation

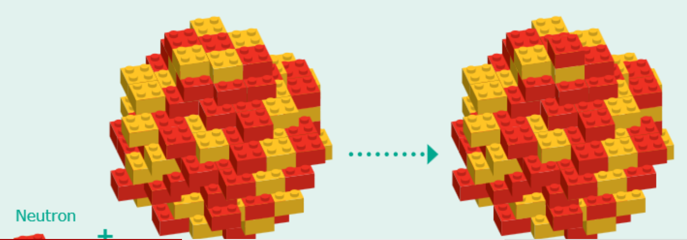
$$\left(i\gamma^\mu \frac{\partial}{\partial x^\mu} - m\right)\psi = 0$$

predicted antiparticles. The number of particles is not fixed

- We lost mathematicians and found phenomena we did not ask for

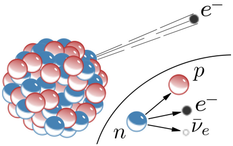
What are the fundamental constituents of nature?



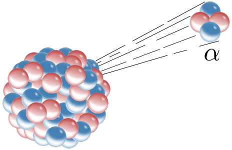


Early days of particle physics: 1930s – 1960s

- Two types of nuclear physics phenomena: α-**decay** and β-**decay**

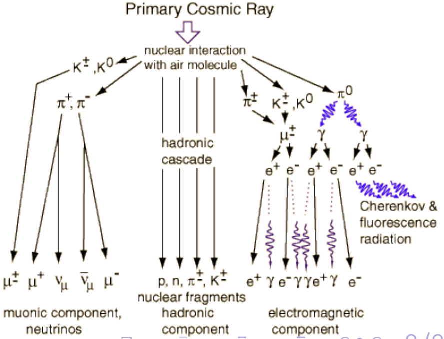


- β-decay
- **Weak** interactions

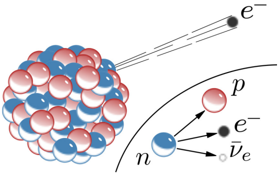


- α-decay
- **Strong** interactions

- Cosmic rays – first “accelerators”: many particles were first discovered in the cosmic rays
  - Discovery of positron **1932**
  - Discovery of muon **1936**
  - Discovery of pion **1947**



Fermi theory of weak interactions



- It was understood that β decay cannot be described by electrodynamics
- **Proposal of Fermi:** **β-decay is the decay of neutron inside a nucleus**

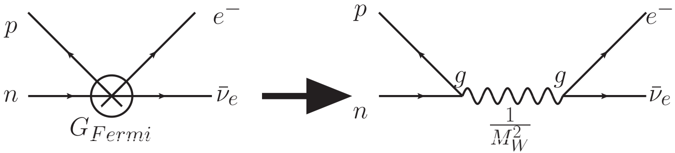
$$n \to p + e^- + \boldsymbol{\nu}$$

First theory of weak interactions

$$\mathcal{L}_{\text{Fermi}} = \frac{\boldsymbol{G_F}}{\sqrt{2}}[\bar{p}(x)\Gamma n(x)][\bar{e}(x)\Gamma \nu(x)]$$

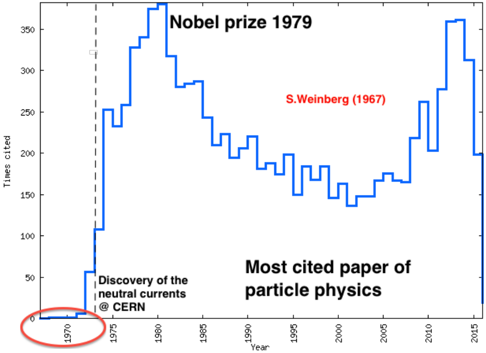
From β-decay to weak interactions. Fast forward

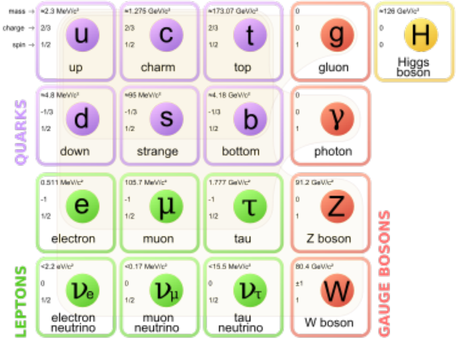
- Fermi theory predicted that if electron and neutrino collide at high energies, the probability of such a process can "exceed 1"
- **Prediction** of massive vector bosons — weak interaction is **mediated** by some particle (as all other interactions)



- Predictions of **neutral currents** [Glashow 1961]
- Building of electroweak theory. New gauge symmetries. Higgs mechanism [1964 – 1968]
- Proposals for **unification** of electromagnetic and weak forces ; [Weinberg 1967; Salam 1968]
- Discovery of neutral currents [1974]
- Discovery of Z and W bosons at LEP@CERN [1980s]

Standard Model of particle physics: 1967 → 2012



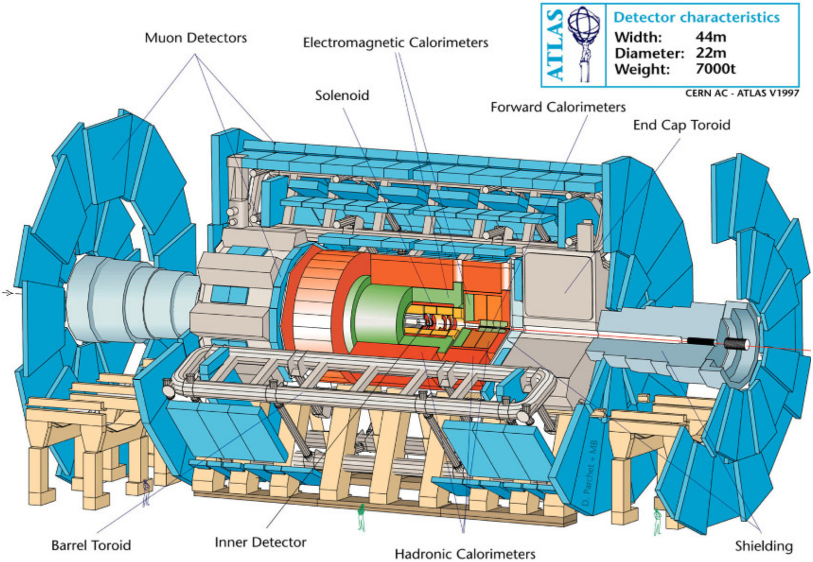


Higgs boson was predicted in **late 1960s**, but discovered in **2012**

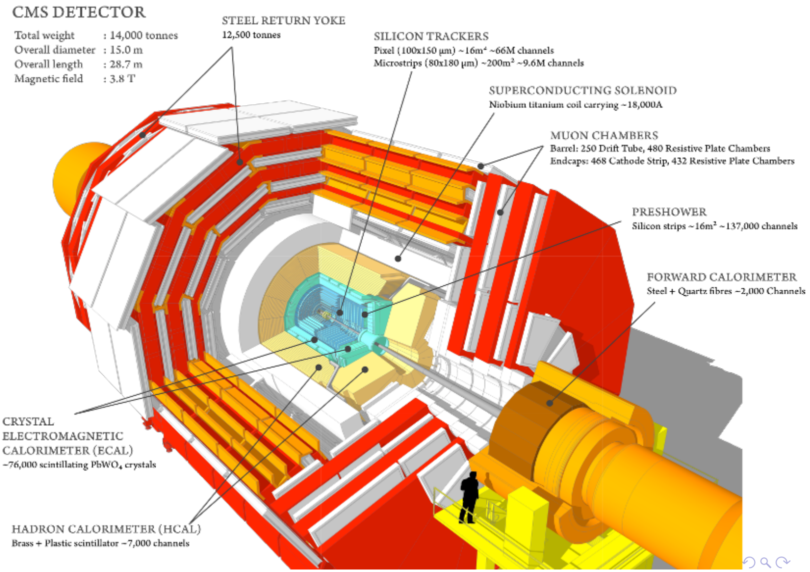
LHC at CERN


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

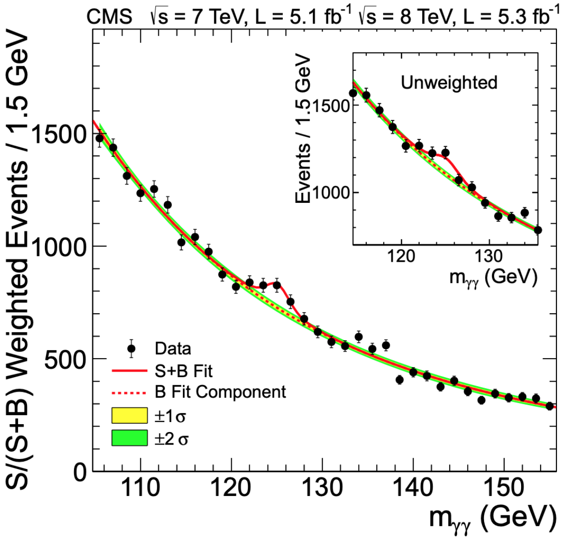
ATLAS experiment



CMS experiment



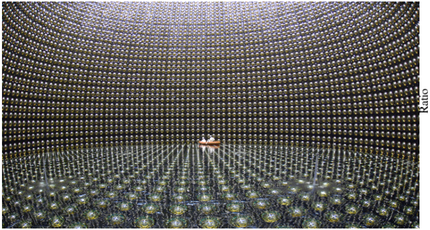
Higgs boson discovery: 2012

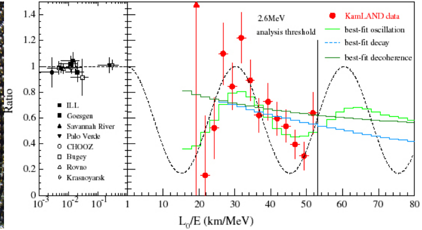


Yet we know with certainty that the Standard Model is **incomplete**!

1: Neutrino oscillations

Neutrino oscillations. Observed in the 1960s as solar neutrino deficit and checked by many experiments. Oscillations are possible only for massive neutrinos, but in SM neutrinos should be massless!





2: Matter-antimatter imbalance of the Universe

Baryonic asymmetry of the Universe. All around us consists of matter and there is no evidence of primordial antimatter. This contradicts the standard cosmological scenario that predicts symmetrical initial conditions. Not enough sources of asymmetry in SM to explain it

Sakharov's conditions on the Big Bang

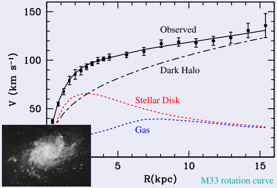
OLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

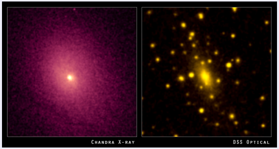
The theory of the expanding Universe, which presupposes a superdense initial state of tter, apparently excludes the possibility of macroscopic separation of matter from anti-tter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the iverse is asymmetrical with respect to the number of particles and antiparticles asymmetry). In particular, the absence of antibaryons and the proposed absence of ryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point t a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, propose in addition an approximate character for the baryon conservation law.

3: Dark Matter in the Universe

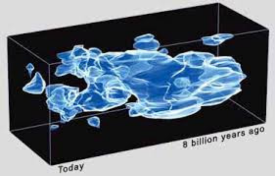
Astrophysical evidence:



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

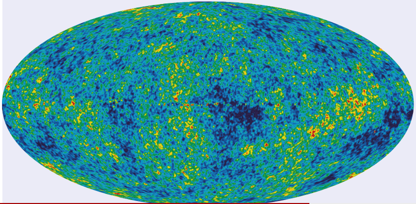


Expected:
$\text{mass}_{\text{cluster}} = \sum \text{mass}_{\text{galaxies}}$
Observed: 10^2 times more mass confining ionized gas

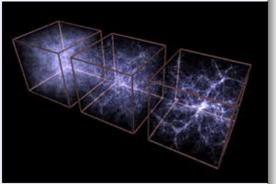


Lensing signal (direct mass measurement) **confirms** other observations

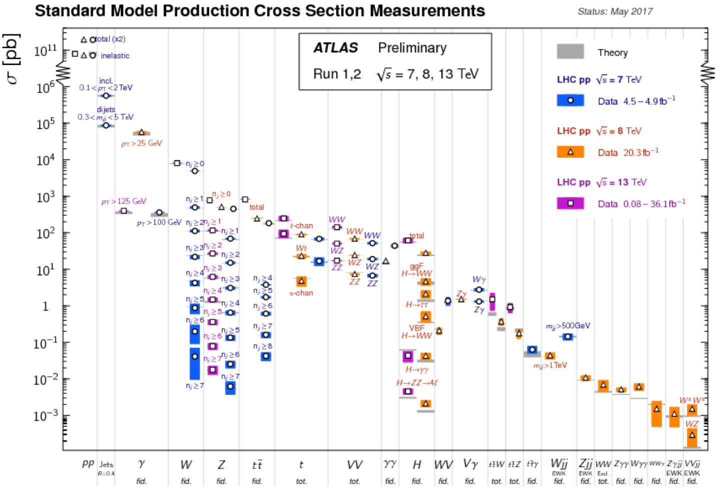
Cosmological evidence:



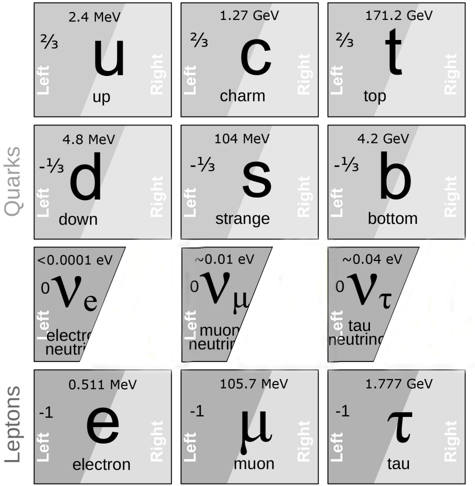
Jeans instability turned tiny density fluctuations into all visible structures



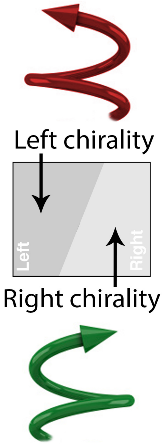
2012–2019



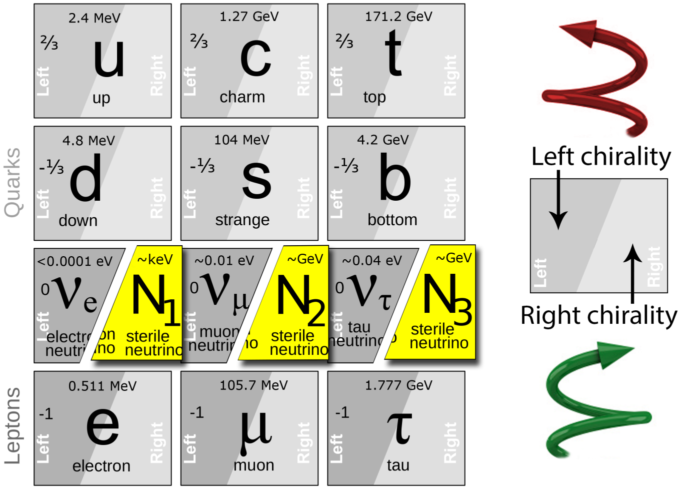
ATLAS collab., [1803.10800]



Quarks
Leptons
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
<0.0001 eV
0
ν_e
electr
neutri
~0.01 eV
0
ν_μ
muon
neutri
~0.04 eV
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



Left chirality
Left
Right
Right chirality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electron neutrino
~keV
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0
ν_μ
muon neutrino
~GeV
N_2
sterile neutrino
~0.04 eV
0
ν_τ
tau neutrino
~GeV
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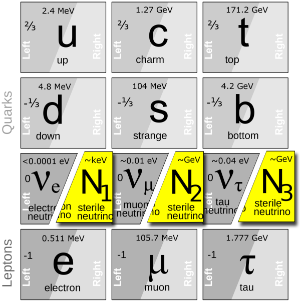
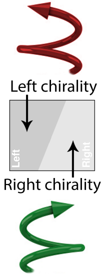
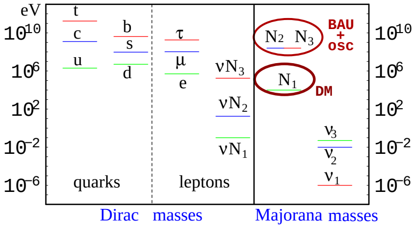
-1
μ
muon
1.777 GeV
-1
τ
tau
Left
Right
Left chirality
Right chirality

Neutrino minimal Standard Model (νMSM)



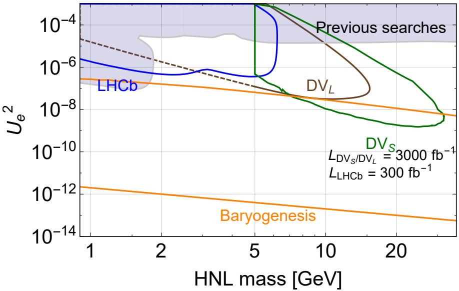


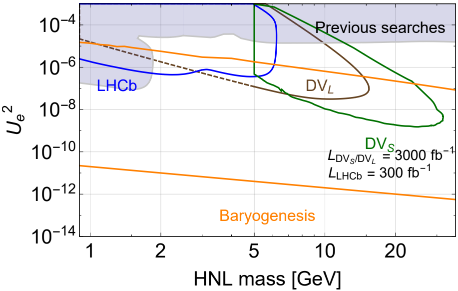


- **Neutrino oscillations:** particles N_2, N_3
- **Baryon asymmetry:** same particles N_2, N_3
  - masses $\mathcal{O}(100)$ MeV – $\mathcal{O}(80)$ GeV
- **Dark matter:** particle N_1
  - mass 1 – 50 keV
- **Inflation:** Higgs field coupled to gravity
  - Inflationary parameters for $M_{\text{Higgs}}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

- **Neutrino Minimal Standard Model (νMSM)**
- Masses of right-handed neutrinos as of other order of masses of other leptons
- Yukawas as those of electron or smaller
- Review: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]

Probing the baryogenesis at LHC





Boyarsky et al. [1902.04535]

New physics, yet no detection – what can we do?

- Explore the **Intensity Frontier** – look for rare events and feeble interactions
- Seek model-independent data in **cosmology** and **astrophysics**

These approaches and conventional accelerator experiments complement each other.

PLAN B: Finding superweakly interacting particles in lab

Proposal to Search for Heavy Neutral Leptons at the SPS

W. Bonivento (INFN, Cagliari & CERN) , A. Boyarsky (Leiden U.) , H. Dijkstra (CERN) , U. Egede (Imperial Coll., London) , M. Ferro-Luzzi, B. Goddard (CERN) , A. Golutvin (Imperial Coll., London) , D. Gorbunov (Moscow, INR) , R. Jacobsson, J. Panman (CERN) M. Patel (Imperial Coll., London) , O. Ruchayskiy (LPHE, Lausanne) , T. Ruf (CERN) , N. Serra (Zurich U.) , M. Shaposhnikov (LPHE, Lausanne) , D. Treille (CERN) Hide

Oct 7, 2013 - 21 pages

CERN-SPSC-2013-024, SPSC-EOI-010
e-Print: arXiv:1310.1762 [hep-ex] | PDF

Abstract (arXiv)
A new fixed-target experiment at the CERN SPS accelerator is proposed that will use decays of charm mesons to search for Heavy Neutral Leptons (HNLs), which are right-handed partners of the Standard Model neutrinos. The existence of such particles is strongly motivated by theory, as they can simultaneously explain the baryon asymmetry of the Universe, account for the pattern of neutrino masses and oscillations and provide a Dark Matter candidate. Cosmological constraints on the properties of HNLs now indicate that the

It took **8** years for an idea of a dedicated experiment to crystallize and get accepted by the community

SHiP : Search for Hidden particles

Search for rare particles becomes **official CERN theme**

It took then 1 year to create a collaboration

A facility to Search for Hidden Particles (SHiP) at the CERN SPS

SHiP Collaboration (M. Anelli *et al.*) Show all 235 authors

Apr 20, 2015 · 234 pages

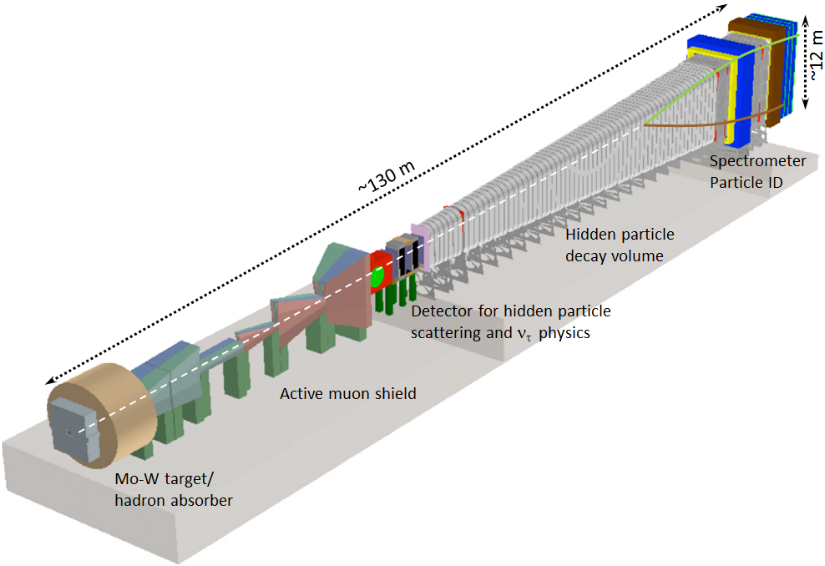
CERN-SPSC-2015-016, SPSC-P-350
e-Print: arXiv:1504.04956 [physics.ins-det] | PDF
Experiment: CERN-SPS-SHIP

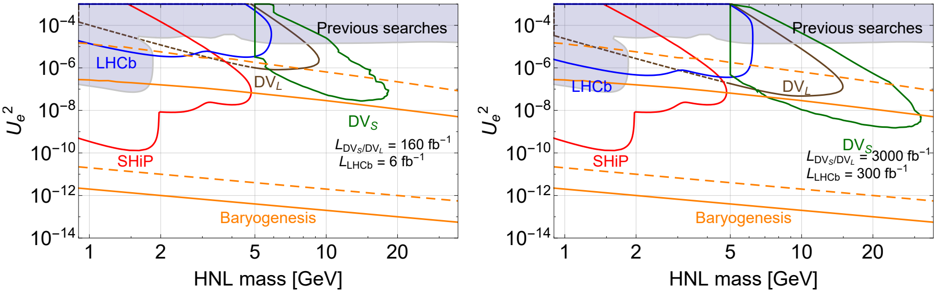
- About **250** members of the SHiP collaboration from **44** institutions worldwide
- SHiP is now an official CERN project

Timeline

- Approval by CERN **2019**
- Data taking **2024**

SHiP


~130 m
~12 m
Spectrometer
Particle ID
Hidden particle
decay volume
Detector for hidden particle
scattering and ν_τ physics
Active muon shield
Mo-W target/
hadron absorber

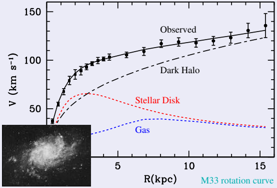


Previous searches
LHCb
DV_L
DV_S
SHiP
Baryogenesis
L_{DV_S/DV_L} = 160 fb^{-1}
L_{LHCb} = 6 fb^{-1}
L_{DV_S/DV_L} = 3000 fb^{-1}
L_{LHCb} = 300 fb^{-1}
U_e^2
HNL mass [GeV]

Dark Matter

Dark Matter

Astrophysical evidence:



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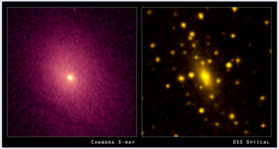

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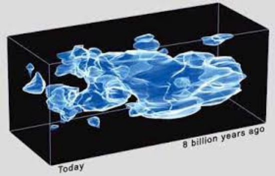

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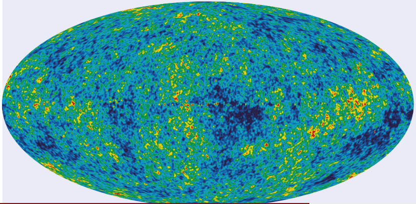
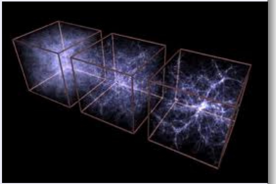
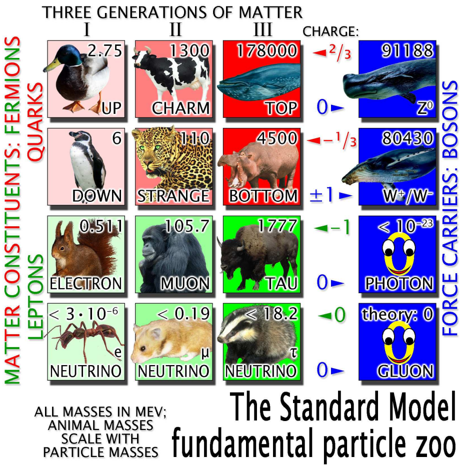


Jeans instability turned tiny density fluctuations into all visible structures



Neutrino dark matter

Neutrino seems to be a perfect dark matter candidate: neutral, long-lived, massive, abundantly produced in the early Universe



Cosmic neutrinos

- At early times the Universe is filled with a thermal bath of relativistic neutrinos that form Cosmic Neutrino Background (similar to CMB for photons):

$$f_\nu(p) = \frac{1}{1 + e^{E/T_\nu}} \tag{1}$$

- We know how neutrinos interact and we can compute their primordial number density (per flavour) $n_{\nu,0} \propto T_\nu^3(t_0) \sim T_\gamma^3(t_0)$

$$n_{\nu,0} = \int f_\nu(p) \frac{d^3p}{(2\pi)^3} \simeq 112 \mathrm{cm}^{-3} \tag{2}$$

- Massive neutrinos are now non-relativistic with energy density $\rho_{\nu,0} = \sum m_\nu n_{\nu,0}$
- To give correct dark matter abundance the neutrino masses should be $\sum m_\nu \sim 11\,\mathrm{eV}$

Tremaine-Gunn bound (1979)

- Fermionic particles are subject to Pauli exclusion principle and their phase-space density is bounded by density of degenerate Fermi gas:

$$\Pi_{deg} = \frac{m^4}{(2\pi\hbar)^3} \tag{3}$$

- If dark matter is made of fermions – **its mass is bounded from below**
- Indeed, a galaxy with mass M_{gal} and size R_{gal} has average matter density

$$\rho_{matter} = \frac{M_{gal}}{\frac{4\pi}{3}R_{gal}^3} \tag{4}$$

- It occupies the volume of velocity space with $|\boldsymbol{v}| < v_\infty$, where v_∞ is the **escape velocity** – velocity that is sufficient for a particle to break gravitational attraction of the galaxy and leave it

- Average phase-space density of any system of fermions should be lower than the phase-space density of degenerate gas

$$\frac{M_{gal}}{\underbrace{\frac{4\pi}{3}R_{gal}^3}_{\text{volume of space}}} \frac{1}{\underbrace{\frac{4\pi}{3}v_\infty^3}_{\text{volume of \textbf{velocity} space}}} \leq \frac{2{m_{\mathrm{DM}}}^4}{(2\pi\hbar)^3} \tag{5}$$

- Minimal mass for fermion dark matter $\sim 300 - 400\,\mathrm{eV}$
- If particles with such mass were **weakly interacting** (like neutrino) – they would **overclose the Universe**
  For $m_{\mathrm{DM}} = 300\mathrm{eV}$ one gets $\Omega_{\mathrm{DM}} h^2 \sim 3$ (wrong by a factor of 30!)

"Between friends"

In mid-80s

M. Davis, G. Efstathiou, C. Frenk, S. White, *et al.*
"*Clustering in a neutrino-dominated universe*"

argued that structure formation in the neutrino dominated Universe (with $m \sim 100\,\text{eV}$) would be incompatible with the observations:

http://www.adsabs.harvard.edu/abs/1983ApJ...274L...1W

Abstract

The nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution has been simulated. [. . .]
The conventional neutrino-dominated picture appears to be ruled out.

Neutrino dark matter

Massive Standard Model neutrinos cannot be simultaneously **astrophysical** and **cosmological** dark matter: to account for the missing mass in galaxies **and** to contribute to the cosmological expansion

Today this is confirmed by CMB, LSS and neutrino experimental data

Two generalizations of neutrino DM

- Dark matter cannot be both **light** and **weakly interacting** at the same time
- To satisfy **Tremaine-Gunn bound** the number density of any dark matter made of fermions should be **less** than that of neutrinos
- Neutrinos are light, therefore they decouple relativistic and their equilibrium number density is $\propto T^3$ at freeze-out

First alternative: WIMP

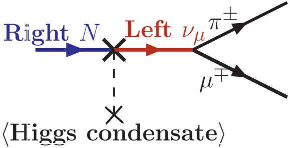
One can make dark matter **heavy** and therefore their number density is Boltzmann-suppressed ($n \propto e^{-m/T}$) at freeze-out

Second alternative: super-WIMP

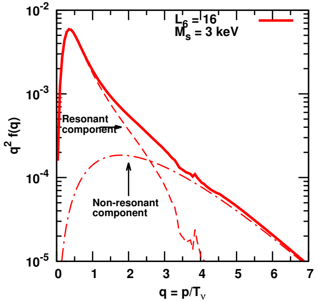
One can make dark matter interacting **super-weakly** so that their number density never reaches equilibrium value (e.g. sterile neutrino in νMSM)

- N interacts with the SM particles like neutrino, but the interaction strength is ϑG_F, where $\vartheta \ll 1$
- The $\vartheta \ll 1$ is so small that particles never enter thermal equilibrium. The interaction rate $\Gamma_N \approx \vartheta^2 G_F^2 T^5$ – similar to neutrino, but suppressed by ϑ^2

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \overline{N} i \partial N - y \bar{L} N H - \frac{M}{2} \overline{N}^c N + h.c. \tag{6}$$



Resonant production of sterile neutrino



- Maximal amount of DM produced resonantly (**MSW effect**):

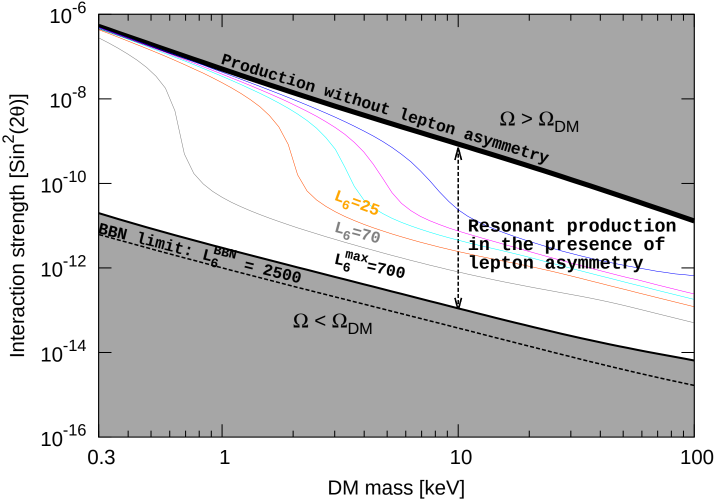
$$\Omega_{\text{resonant}} \propto M_{\text{DM}} \times \left| n_\nu - n_{\bar\nu} \right|$$

$$\Omega_{\text{non-res}} \propto \frac{M_{\text{DM}}}{94\ \text{eV}} \vartheta^2$$

- Colder (**resonant**) component with $\langle p \rangle \ll T_\nu$
- Warmer (**non-resonant**) component with $\langle p \rangle \sim 3\,T_\nu$

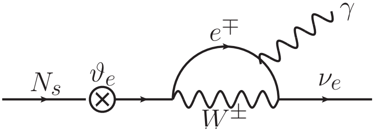
Shi & Fuller [astro-ph/9810076], Laine & Shaposhnikov [0804.4543]

Sterile neutrino DM production



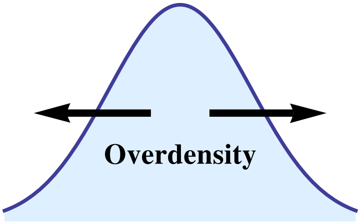
Properties of sterile neutrino dark matter

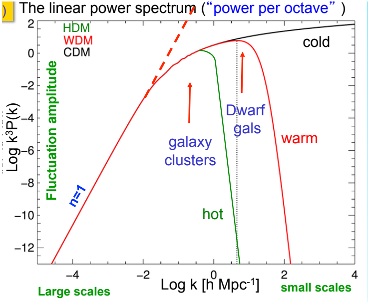
- Can be **light** (down to Tremaine-Gunn bound)
- Can be **decaying** (via small mixing with an active neutrino state)



The decay signal is proportional to $\int \rho_{\rm DM}(r)$

- Can be **warm** (born relativistic and cool down later)





Warm dark matter affects. . .

- **Matter power spectrum** of density fluctuations at scales **below the free-streaming**:

$$\mathbf{P(k)} = \left|\frac{\delta\rho_k}{\rho}\right|^2 = \int d^3\vec{r} e^{ik\cdot(\vec{x}-\vec{x}')}\left\langle \delta(\vec{x})\delta(\vec{x}')\right\rangle$$

- **Halo (subhalo) mass function** (decrease number of halos of small mass)

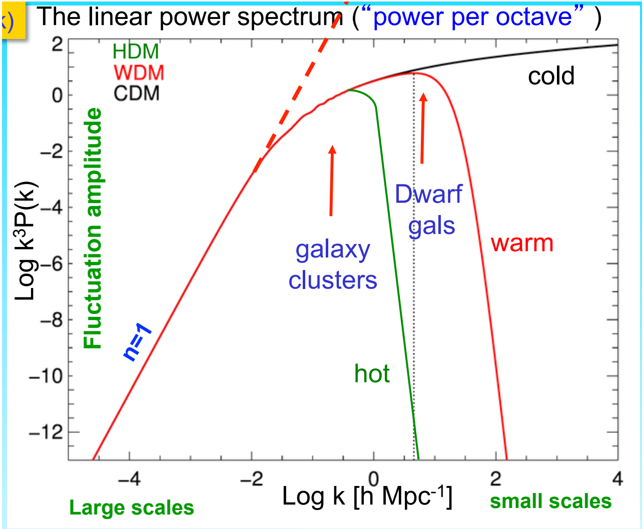
$$N(>M) = \int_M^\infty dM' \frac{dn(M')}{dM}$$

- Density profile (central **core** rather than **cusp**)

$$\rho(r) = \frac{\rho_0}{(r/r_0)^\alpha (1 + (r/r_0)^\beta)^\gamma}$$

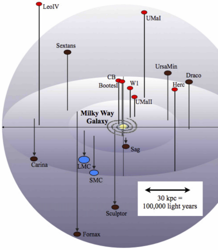
- Reionization, first stars, voids. . .

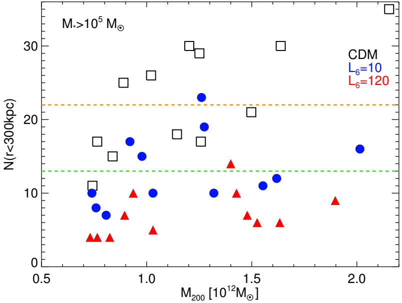
Suppression of power spectrum

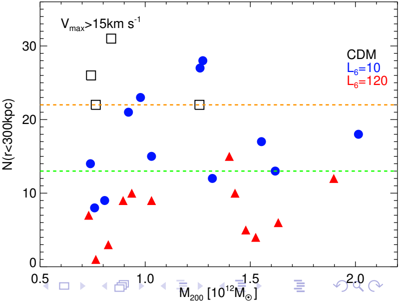


Satellite number and properties

- Warm dark matter erases substructures – compare number of dwarf galaxies inside the Milky Way with "predictions"
- **Simulations**: The answer depends **how** you "light up" satellites
- **Observations**: We do not know how typical Milky Way is





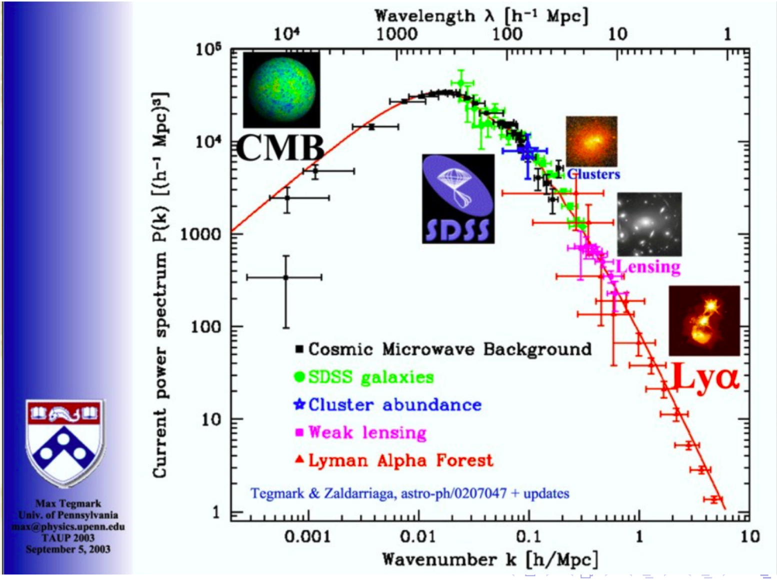


Current status of structure formation bounds from the Local Universe

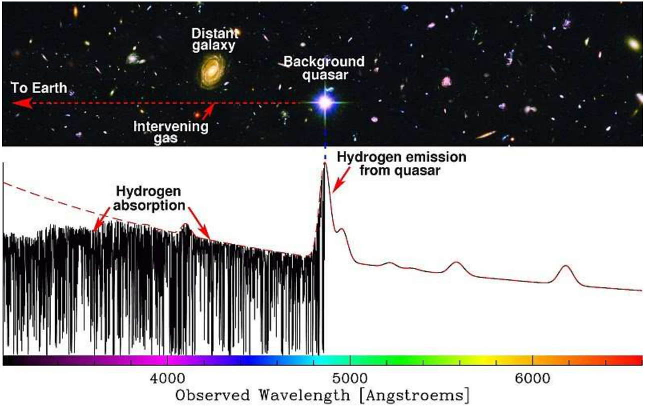
- Connection “dark structures” $\leftrightarrow$ “visible structures” depends on (yet unknown) way to implement baryonic feedback
- Simulation to simulation (or even halo-to-halo) scatter is quite large and affects the conclusions
- We do not know how typical is our Galaxy, our Local Group, etc

- You cannot “rule out” your warm dark matter model with these observations
- You can only **check** that your model **fits the data under “reasonable” assumptions about baryonic physics**

How to probe power spectrum

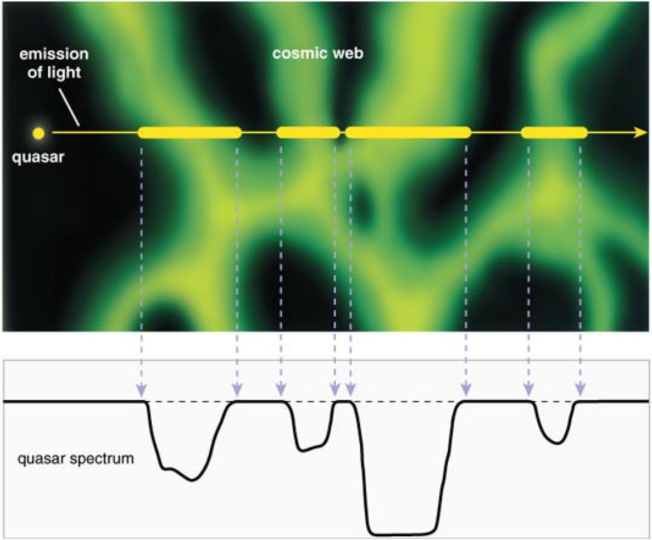


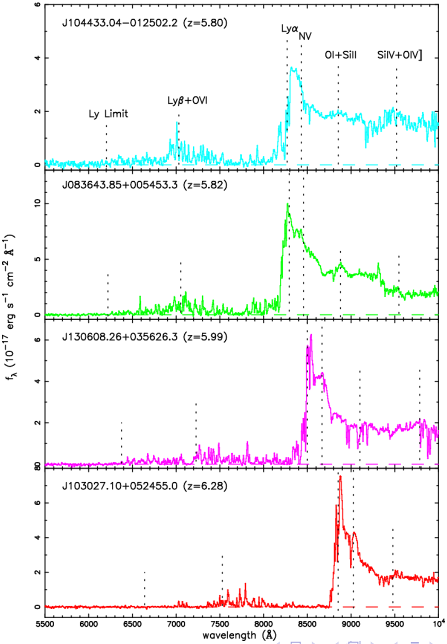
Lyman-α forest



- Neutral hydrogen absorption line at $\lambda = 1215.67\text{Å}$ (Ly-α absorption $1s \to 2p$)
- Absorption occurs at $\lambda = 1215.67\text{Å}$ in the **local reference frame** of hydrogen cloud
- Observer sees the **forest**: $\lambda = (1+z)1215.67\text{Å}$

Lyman-α forest





J104433.04−012502.2 (z=5.80)
Lyα
NV
OI+SiII
SiIV+OIV]
Lyβ+OVI
Ly Limit
J083643.85+005453.3 (z=5.82)
J130608.26+035626.3 (z=5.99)
J103027.10+052455.0 (z=6.28)
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
wavelength (Å)

Gunn-Peterson trough

Transmitted flux of the quasar is given by $F = e^{-\tau}$

$$\tau(z) \propto x_{HI} \tag{7}$$

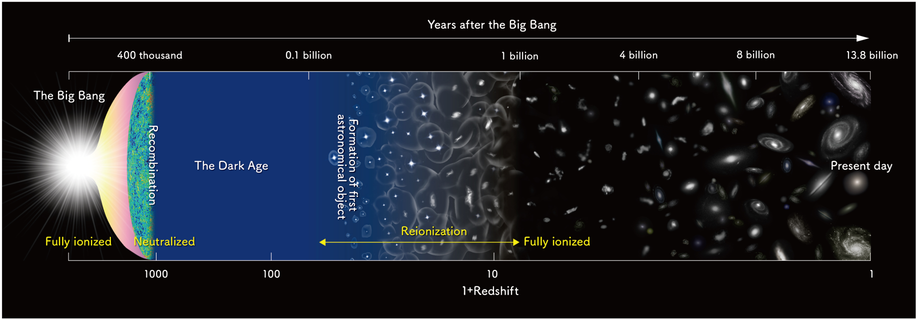
$$\tag{8}$$

According to Gunn-Peterson observations:

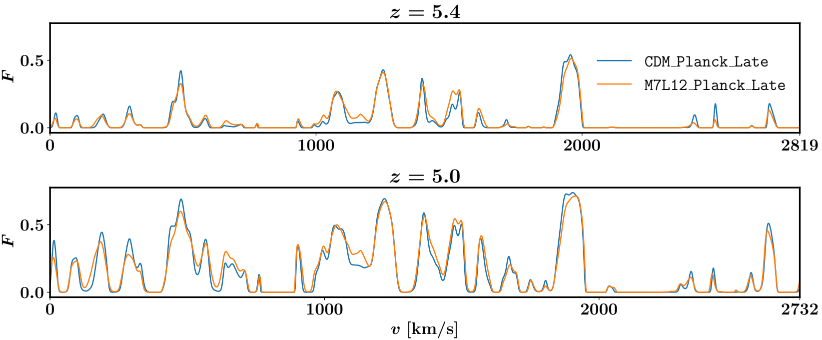
$$x_{HI} > 10^{-3} \text{ for } z \geq 6 \tag{9}$$

$$x_{HI} < 10^{-4} \text{ for } z \leq 5.5 \tag{10}$$

Scope of Lyman-α method



Lyman-α forest is visible only when the Universe is sufficiently ionized ($x_{HI} < 10^{-4}$), limiting the method to redshifts after reionization $z \lesssim 6$



$z = 5.4$
F
0.5
0.0
0
1000
2000
2819
CDM_Planck_Late
M7L12_Planck_Late
$z = 5.0$
F
0.5
0.0
0
1000
2000
2732
v [km/s]

Flux Power Spectrum

$$\delta_F \equiv \frac{F - \langle F \rangle}{\langle F \rangle} \tag{11}$$

$$\tilde{\delta}_F(k) = \frac{1}{V} \int_0^V dv\, e^{-ikv} \delta_F(v) \tag{12}$$

The FPS is defined by

$$\Delta_F^2(k) = \frac{V}{\pi} k \left\langle |\tilde{\delta}_F(k)|^2 \right\rangle \tag{13}$$

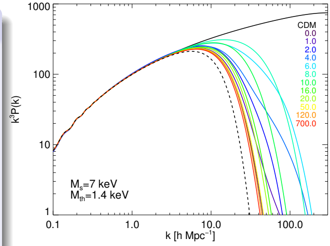
Suppression in the flux power spectrum (SDSS)

What we want to detect

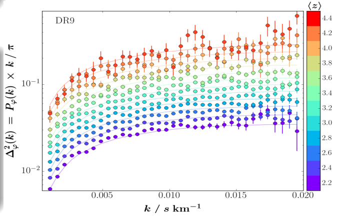
- CMB and large scale observations fix matter power spectrum at large scales
- Based on this we can predict the ΛCDM matter power spectrum at small scales
- WDM predicts suppression (cut-off) in the matter power spectrum as compared to the CDM

What we observe

- We observe **flux power spectrum** – projected along the line-of-sight power spectrum of neutral hydrogen absorption lines

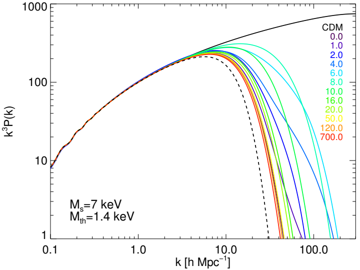


3D linear matter power spectra

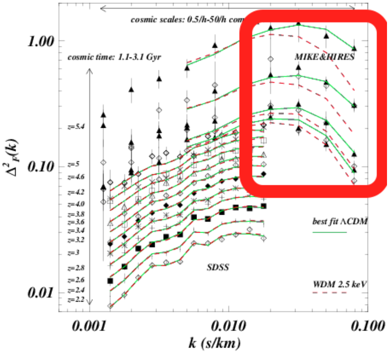


BOSS (SDSS-III) Ly-α [1512.01981]

High-resolution Ly-α forest



Warm dark matter predicts suppression (cut-off) in the flux power spectrum derived from the Lyman-α forest data



Lyman-α from HIRES data [1306.2314]

- HIRES flux power spectrum **exhibits suppression at small scales**
- Is this **warm dark matter?**

But we measure neutral hydrogen!

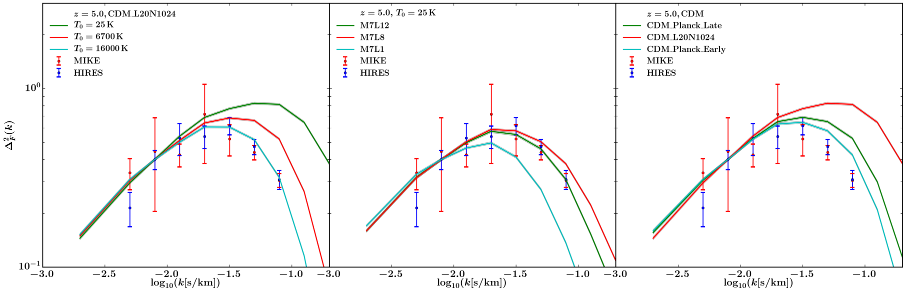
Lyman-α forest method is based on the underlying assumption

The distribution of neutral hydrogen follows the DM distribution

Baryonic effects

- Temperature at redshift z (Doppler broadening) – **increases hydrogen absorption line width**
- Pressure at earlier epochs (gas expands and then needs time to recollapse even if it cools)

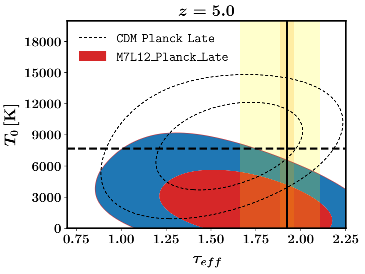
FPS effects: temperature, DM warmness, pressure



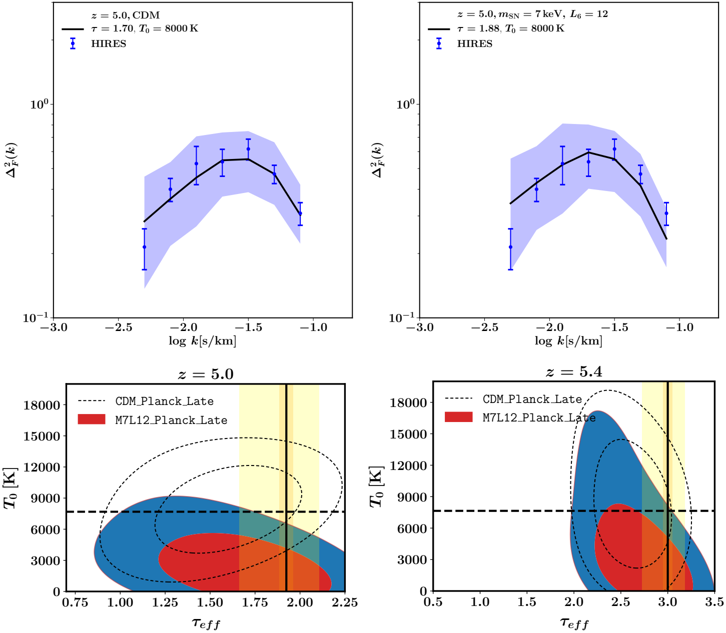
Can we explain shape of the flux power spectrum by the free-streaming of DM particles? [Garzilli, Boyarsky, Ruchayskiy (2015)]

Yes! We can

- The shape of the flux power spectrum can be explained by various DM models with non-zero free streaming
- Can be explained by:
  - resonantly produced sterile neutrinos with $M = 7\,\mathrm{keV}$ and $L_6 \sim 8 - 12$
- WDM evolution can fit the shape $P(k)$ at different redshifts



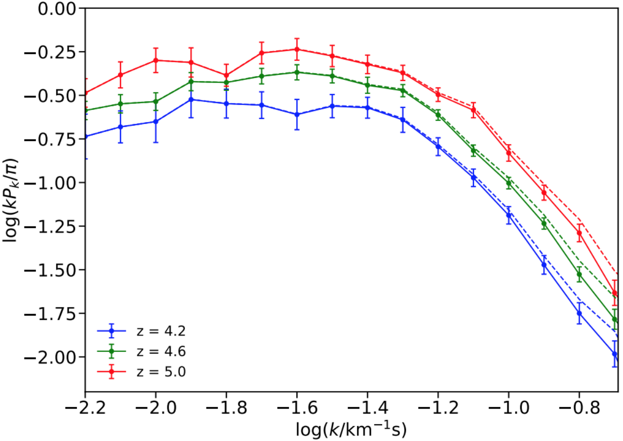
If the shape of the HIRES/MIKE flux power spectrum is explained by the DM free-streaming, one **predicts** IGM medium with $T_{IGM} \sim 2 - 5 \times 10^3$ K at $z \sim 5$



z = 5.0, CDM
τ = 1.70, T0 = 8000 K
HIRES
Δ²F(k)
log k[s/km]
z = 5.0, mSN = 7 keV, L6 = 12
τ = 1.88, T0 = 8000 K
HIRES
Δ²F(k)
log k[s/km]
z = 5.0
CDM_Planck_Late
M7L12_Planck_Late
T0 [K]
τeff
z = 5.4
CDM_Planck_Late
M7L12_Planck_Late
T0 [K]
τeff

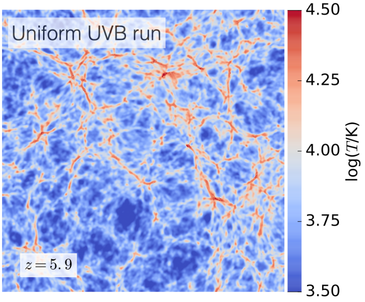
Lyman-α forest outlook I

- New data with more quasars and much smaller error bars is available: **Boera et al. [1809.06980]**



Lyman-α forest outlook II

- There is evidence for **"patchy" reionization** where properties of the gas can be **inhomogeneous**: gas starts ionizing in small bubbles that expand until the whole Universe is reionized



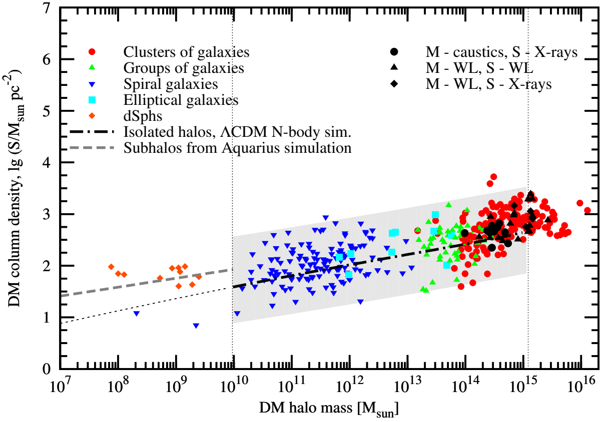
Lyman-α forest outlook III

- There is large uncertainty in the thermal history and even the mechanism of reionization
- To put **robust** constraints on dark matter we need to **"turn off"** the thermal effects and determine dark matter models that are **excluded with any thermal history**
- Such constraint is much weaker than present model-dependent bounds **[work in progress]**

Decaying Dark Matter

Signal from different DM-dominated objects

Boyarsky, Ruchayskiy et al. Phys. Rev. Lett. **97** (2006); Phys. Rev. Lett. **104** (2010)



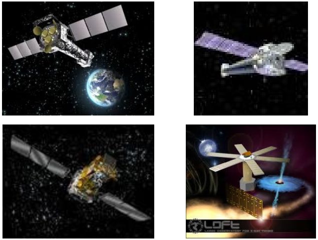
Signal:

$$\mathcal{S} = \int \rho_{dm}(r)dr$$

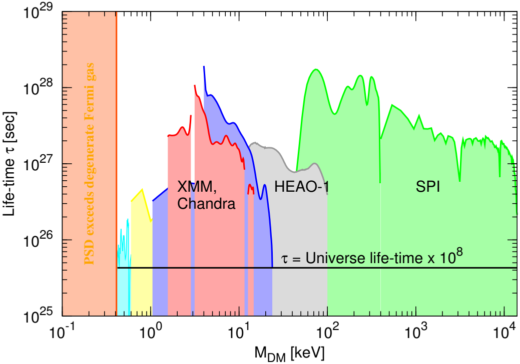
(Column density)

Search for Dark Matter decays in X-rays

See **"Next decade in sterile neutrino studies"** by Boyarsky et al. **[Physics of the Dark Universe, 1 (2013)]**



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



$$\text{Signal-to-noise} \propto \overbrace{\mathcal{S}_{\rm DM}}^{signal} \underbrace{\sqrt{t_{\rm exp}\cdot\Omega_{\rm fov}\cdot A_{\rm EFF}\cdot\Delta E}}_{signal-over-background}$$

All types of **individual** objects/observations have been tried: galaxies (LMC, Ursa Minor, Draco, Milky Way, M31, M33,. . .); galaxy clusters (Bullet cluster; Coma, Virgo, . . .)

Detection of An Unidentified Emission Line

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

Bulbul et al. 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

Boyarsky, Ruchayskiy et al. Phys. Rev. Lett. (2014) [1402.4119]

- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
- **Lifetime:** $\sim 10^{27} - 10^{28}$ sec (uncertainty: factor $\sim 3 - 5$)

Decaying dark matter?

Interpretations

There are 4 classes of interpretations

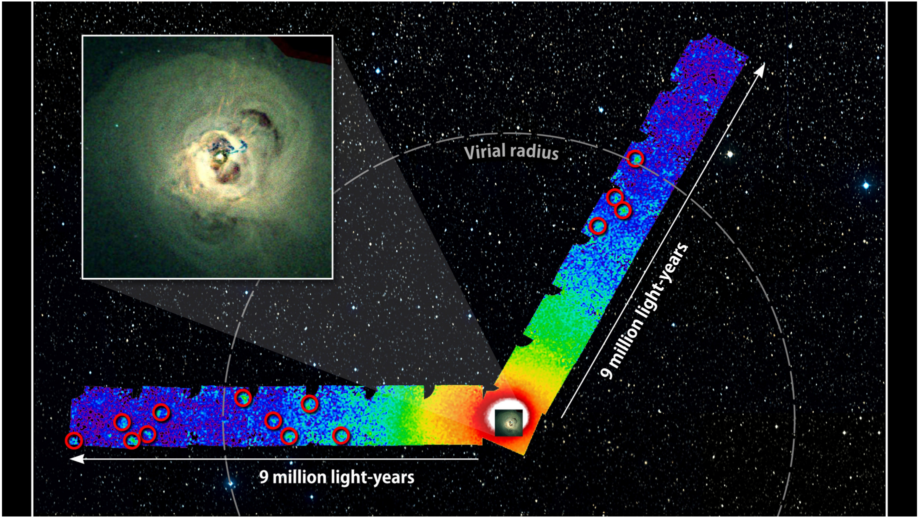
- Statistical fluctuation (there is nothing there at all!)
- Unknown astrophysical emission line (emission line of some chemical element)
- Instrumental feature (systematics) (We do not know our telescopes well enough)
- Dark matter decay line

Significance of the original signal

[Boyarsky, Ruchayskiy et al. Phys. Rev. Lett. (2014) [1402.4119]]		
M31 galaxy	$\Delta\chi^2 = 13.0$	3.2σ for 2 d.o.f.
Perseus cluster (MOS)	$\Delta\chi^2 = 9.1$	2.5σ for 2 d.o.f.
Perseus cluster (PN)	$\Delta\chi^2 = 8.0$	2.4σ for 2 d.o.f.
M31 + Perseus (MOS)	$\Delta\chi^2 = 25.9$	4.4σ for 3 d.o.f.
Global significance of detecting the same signal in 3 datasets: 4.8σ		
[Bulbul et al. ApJ (2014) [1402.2301]]		
73 clusters (XMM, MOS)	$\Delta\chi^2 = 22.8$	4.3σ for 2 d.o.f
73 clusters (XMM, PN)	$\Delta\chi^2 = 13.9$	3.3σ for 2 d.o.f
....		
Perseus center (XMM, MOS)	$\Delta\chi^2 = 12.8$	3.1σ for 2 d.o.f.
Perseus center (Chandra, ACIS-S)	$\Delta\chi^2 = 11.8$	3.0σ for 2 d.o.f.
Perseus center (Chandra, ACIS-I)	$\Delta\chi^2 = 6.2$	2.5σ for 1 d.o.f.

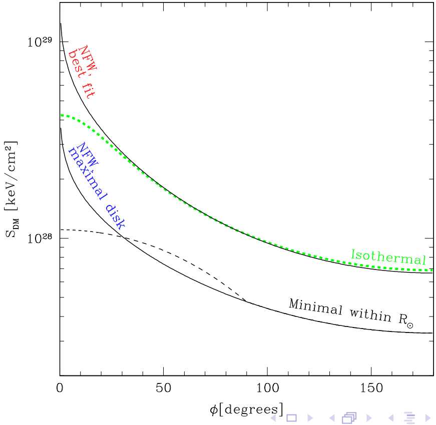
More detections followed!

Perseus galaxy cluster (0.5/0.2 Msec)



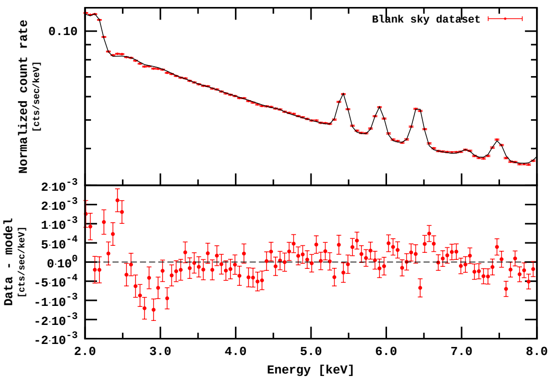
Signal from the Milky Way outskirts

- We are surrounded by the Milky Way halo on all sides
- Expect signal from any direction. Intensity drops with off-center angle
- Surface brightness profile of the Milky Way would be a “smoking gun”



Signal from the Milky Way outskirts?

Phys. Rev. Lett. (2014) [1402.4119]

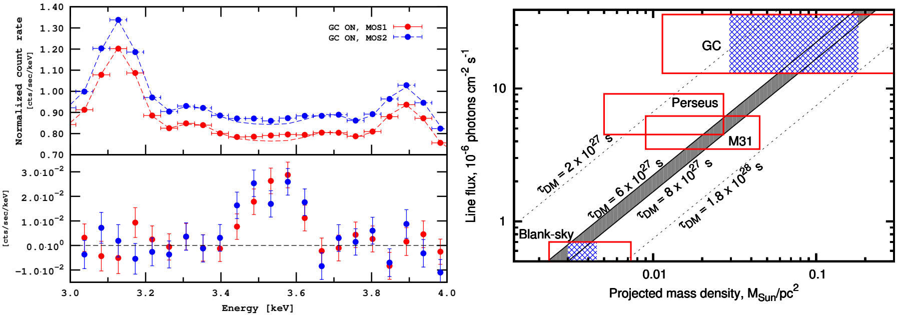


- No line is seen in 16 Msec observations of off-center Milky Way
- Confirmed by
  - [(Sekiya et al. [1504.02826])] with Suzaku
  - [(Figueroa-Feliciano et al. [1506.05519])] with XQC

Is this the end of the story?

Galactic center – a non-trivial consistency check

Boyarsky, O.R.+ Phys. Rev. Lett. 115, (2014)

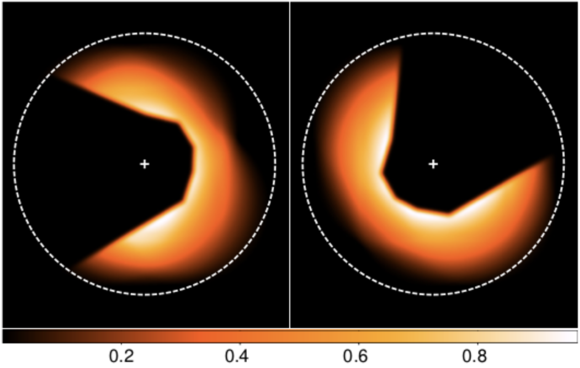


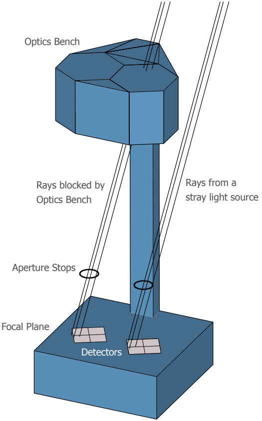
- $4\sigma+$ statistical significance
- Also in S. Riemer-Sorensen'14; Jeltema & Profumo'14

The observed signal fits into the predicted range

Another X-ray satellite: NuStar

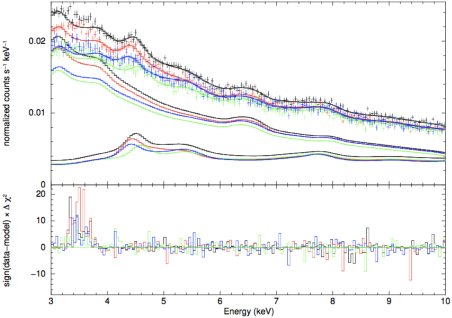
- Has small field of view, would not be competitive with XMM, Chandra or Suzaku
- **But!** NuStar has a specical **0-bounce photons** mode where FoV is 30 deg^2





Milky Way halo. Neronov & Malyshev [1607.07328]. Also Ng+ [1609.00667]

- The 3.5 keV is present in the 0-bounce spectrum of the Cosmos field and CDFS (total cleaned exposure 7.5 Msec)
- Combined detection has 11σ **significance**
- The spectrum of NuStar ends at 3 keV, so this is a lower edge of sensitivity band

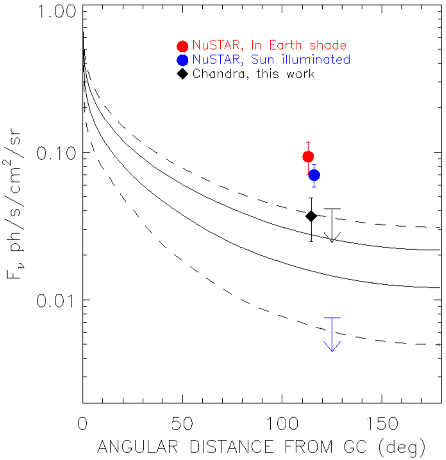


- The 3.5 keV line has been previously attributed to reflection of the sunlight on the telescope structure
- However, in the dataset when Earth shields satellite from the Sun the line is present with the same flux

Line in Chandra from the same region of the sky

Cappelluti+'17 [1701.07932]

- Combined 10 Msec of Chandra observation of COSMOS and CDFS fields (same as NuStar)
- 3σ detection of a line at ~ 3.5 keV
- Flux is compatible with NuStar
- If interpreted as dark matter decay – this is a signal from Galactic halo outskirts ($\sim 115^\circ$ off center)



Not systematics!

By now the 3.5 keV line has been observed with 4 existing X-ray telescopes, making the systematic (calibration uncertainty) origin of the line highly unlikely

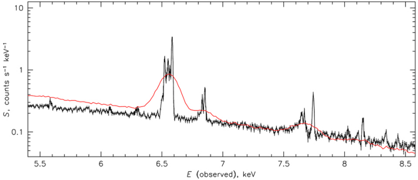
- Line is changing with redshift
- ACIS-I is a silicon CCD while the imagers of NuSTAR are two Cadmium-Zinc-Telluride detectors
- Chandra has mirrors made of Iridium (rather than Gold as XMM or Suzaku) – absorption edge origin becomes unlikely
- Different orbits of satellites – cosmic ray origin is unlikely
- Datasets accumulated over different periods (15yrs for Chandra vs. 3yrs for Nustar) – not related to, e.g. solar activity

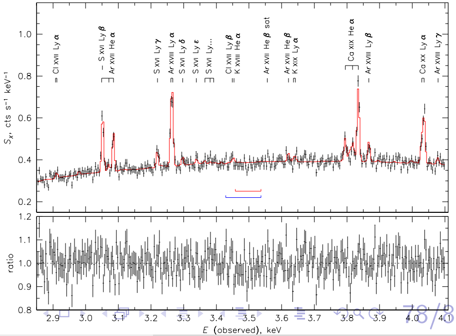
Is this a line from atomic transition(s)?

As argued by [Gu+; Carlson+; Jeltema & Profumo; Riemer-Sorensen; Phillips+]

Next step for 3.5 keV line: resolve the line

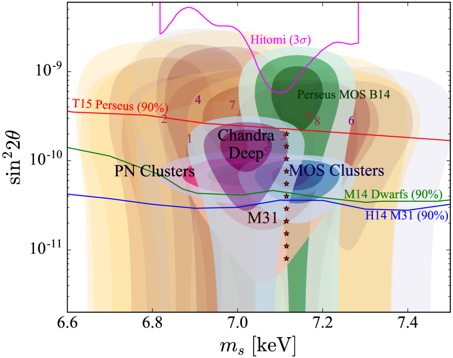
- A new microcalorimeter with a superb spectral resolution – Hitomi (Astro-H) was launched February 17, 2016
- During the first month of observations (calibration phase) it observed the central part of the Perseus galaxy cluster where strong line was detected by XMM & Suzaku
- Spectrometer of Hitomi is able to resolve atomic lines, measure their positions and widths (due to Doppler broadening)
-





What did we learn with existing Hitomi data?

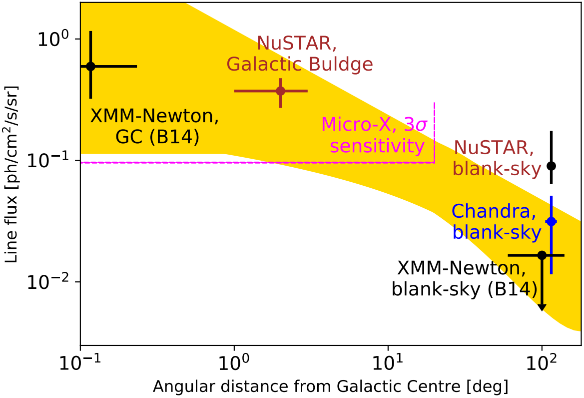
- Even the short observation of Hitomi showed **no nearby astrophysical lines** in Perseus cluster $\to$ 3.5 keV line is **not astrophysical** **[Hitomi collaboration, 1607.04487]**
- Astrophysical lines in the center are Doppler broadened with velocity $v_{th} \sim 10^2\,\mathrm{km/sec}$ (as measured by Hitomi collaboration)
- Decaying dark matter line broadening is determined by the virial velocity of the Perseus galaxy cluster, $v_{vir} \sim 10^3\,\mathrm{km/sec}$
- For XMM/Chandra/Suzaku/Nustar there was no difference – they resolution did not allow to distinguish broad from narrow lines
- Hitomi sensitivity to broad line is much weaker



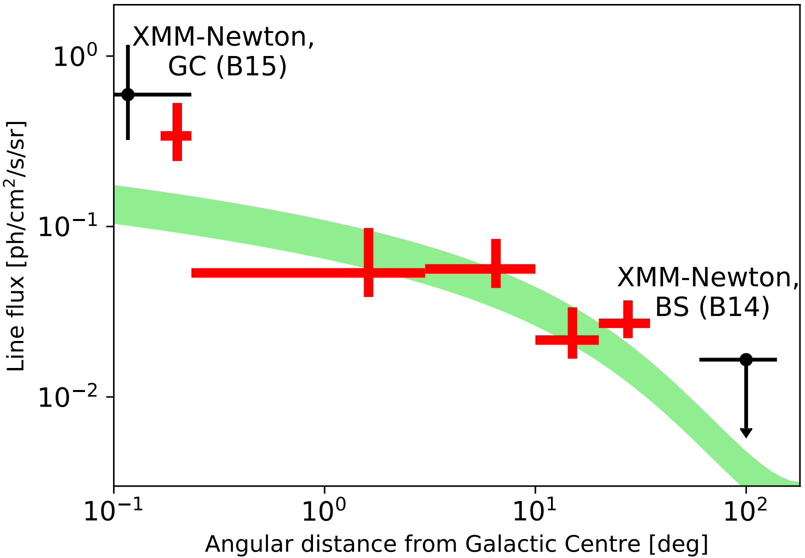
[1705.01837]

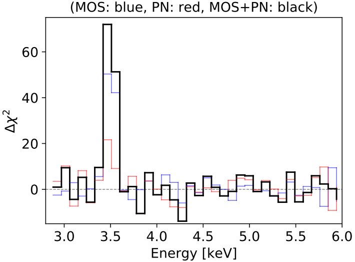
Surface brightness profile in the Milky Way

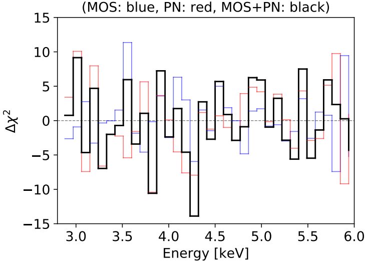
Boyarsky et al. (December 2018)



All detection in the Milky Way follow the same trend


XMM-Newton,
GC (B15)
XMM-Newton,
BS (B14)
10^0
10^{-1}
10^{-2}
Line flux [ph/cm^2/s/sr]
10^{-1}
10^0
10^1
10^2
Angular distance from Galactic Centre [deg]


(MOS: blue, PN: red, MOS+PN: black)
$\Delta\chi^2$
Energy [keV]


(MOS: blue, PN: red, MOS+PN: black)
$\Delta\chi^2$
Energy [keV]

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)

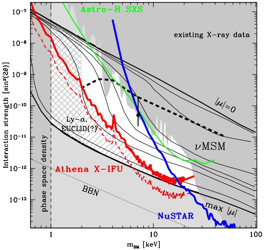
- Large ESA X-ray mission with X-ray spectrometer (X-IFU)
- Very large collecting area ($10\times$ that of XMM)
- Super spectral resolution

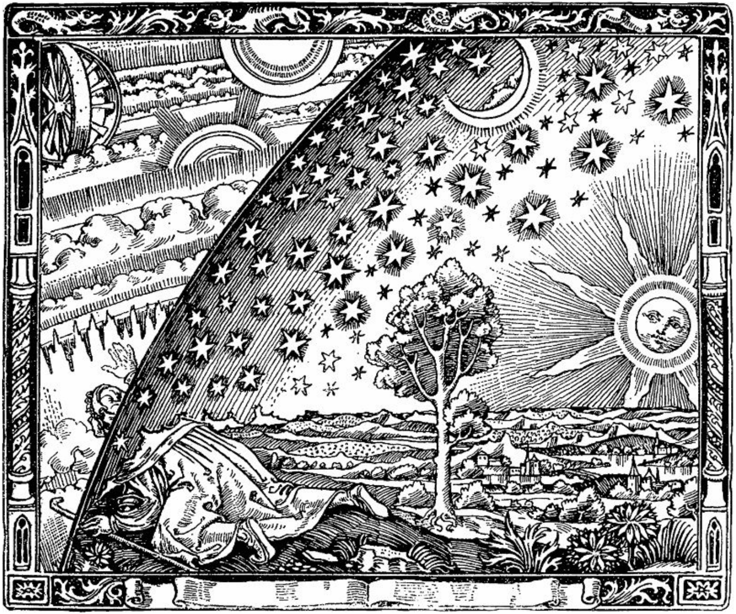
"Dark matter astronomy era" begins?

Spaceflight Now
@SpaceflightNow
Follow

JAXA, NASA approve replacement mission for Japan's failed Hitomi X-ray astronomy satellite. spaceflightnow.com/2017/07/06/jax …

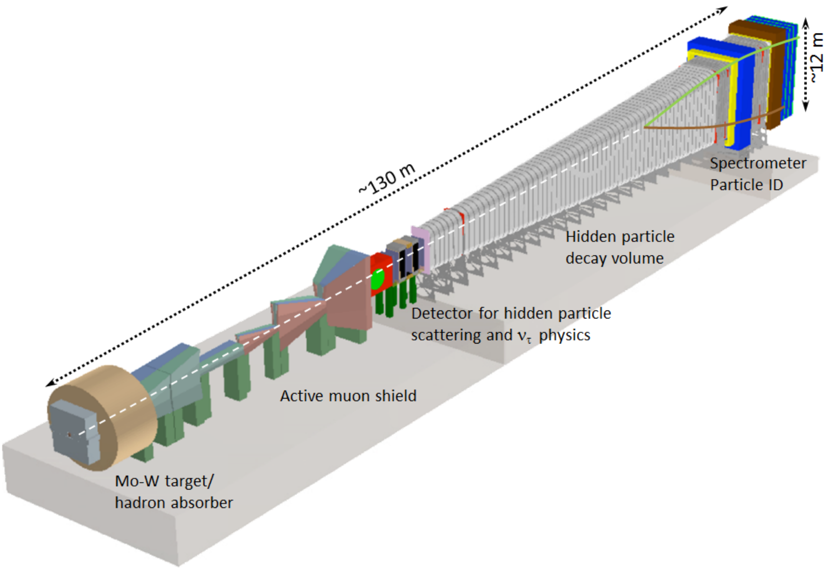
4:34 PM - 7 Jul 2017





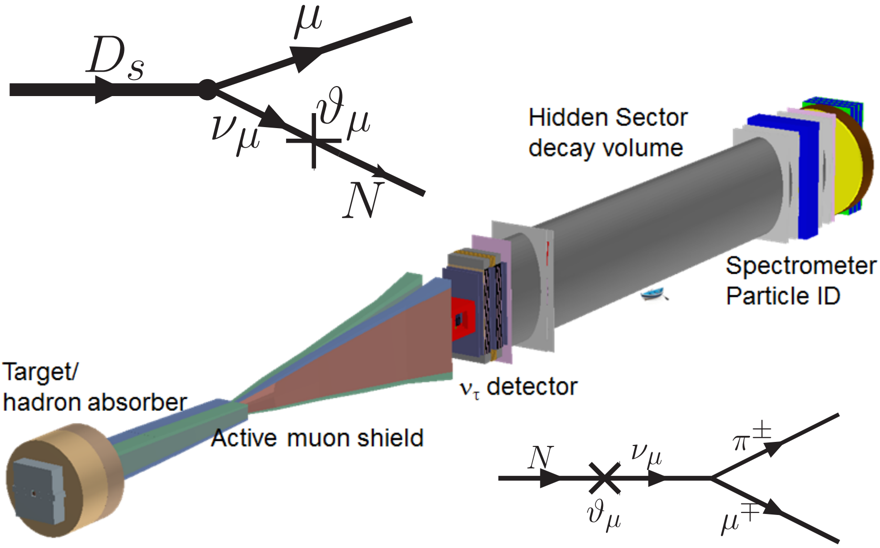
Backup slides

Searches for feebly interacting particles with SHiP



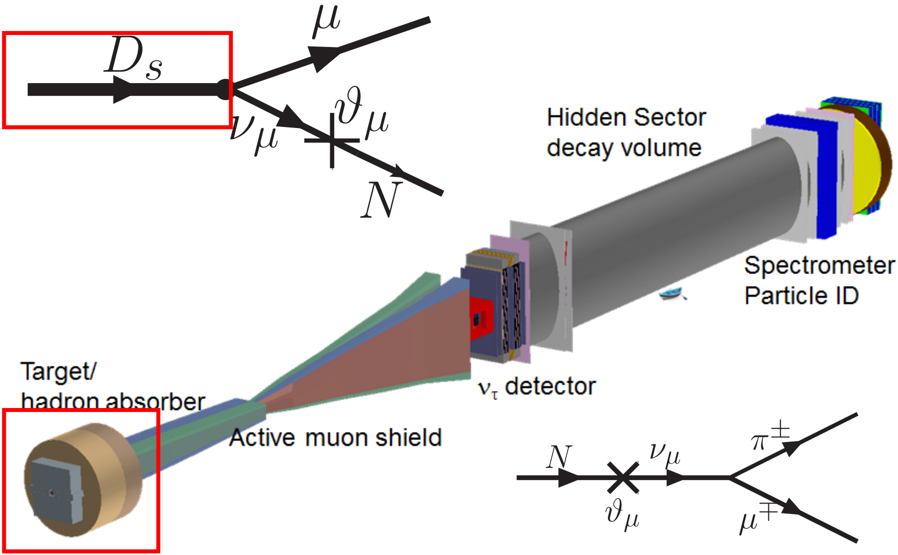
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



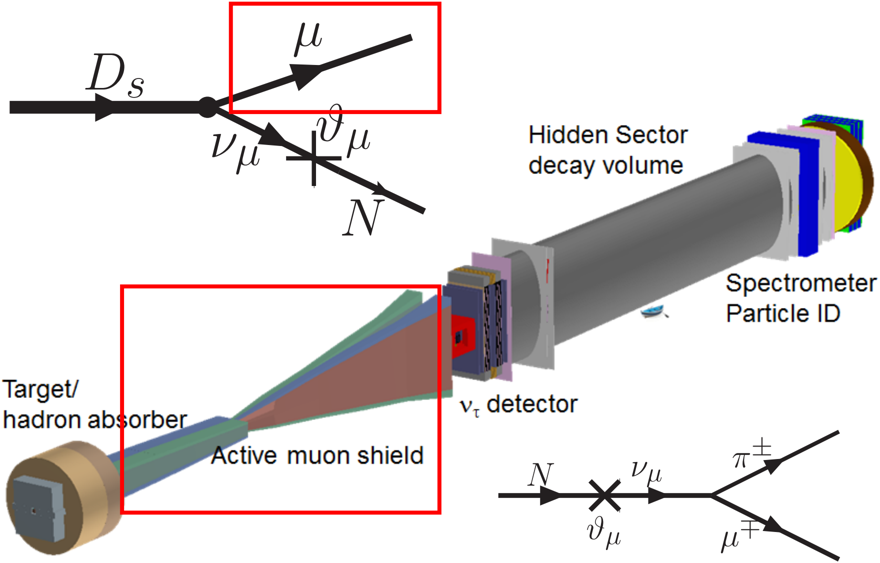
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



SHiP (*Search for Hidden Particles*) experiment

Step by step overview



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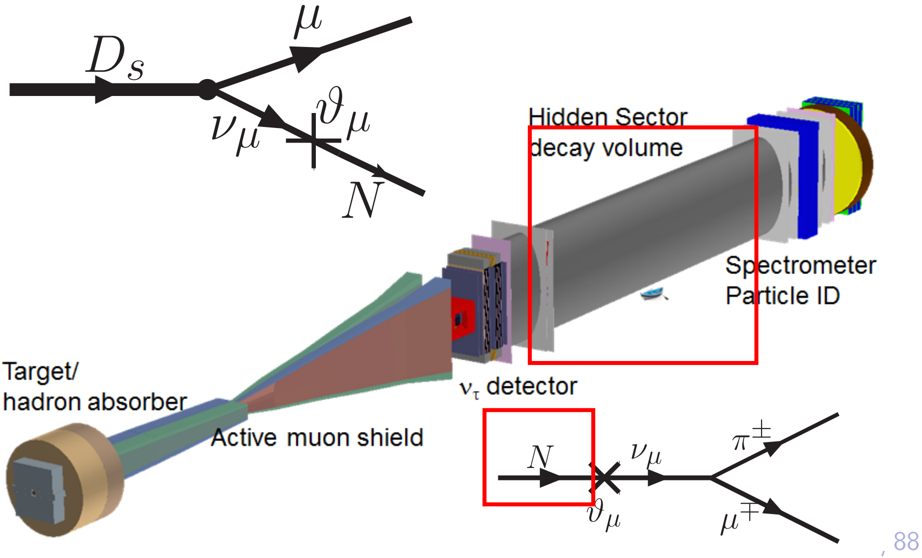
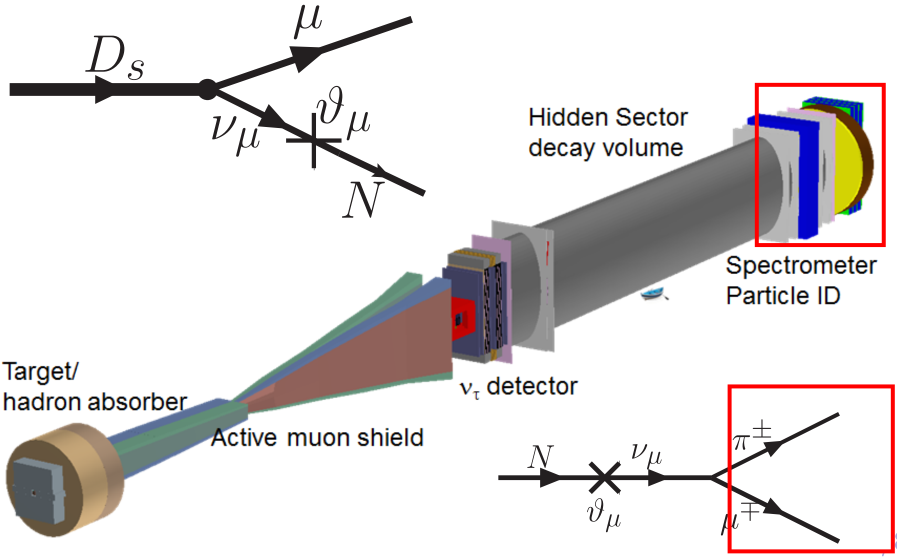
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



SHiP (*Search for Hidden Particles*) experiment

Step by step overview



SHiP : Search for Hidden particles

Search for rare particles becomes **official CERN theme**

It took then 1 year to create a collaboration

A facility to Search for Hidden Particles (SHiP) at the CERN SPS

SHiP Collaboration (M. Anelli *et al.*) Show all 235 authors

Apr 20, 2015 · 234 pages

CERN-SPSC-2015-016, SPSC-P-350
e-Print: arXiv:1504.04956 [physics.ins-det] | PDF
Experiment: CERN-SPS-SHIP

- About **250** members of the SHiP collaboration from **44** institutions worldwide
- SHiP is now an official CERN project

Timeline

- Approval by CERN **2019**
- Data taking **2024**