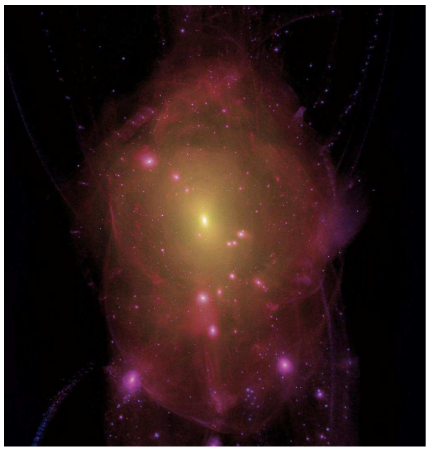
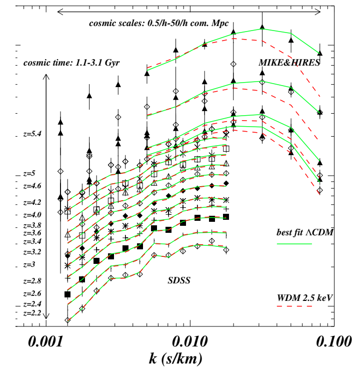
SUPER-WEAKLY INTERACTING DARK MATTER



Oleg RUCHAYSKIY



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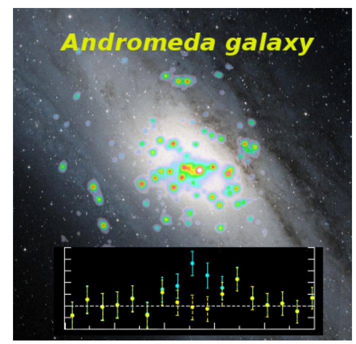
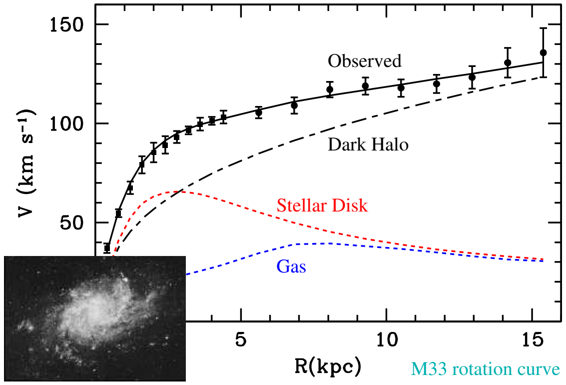
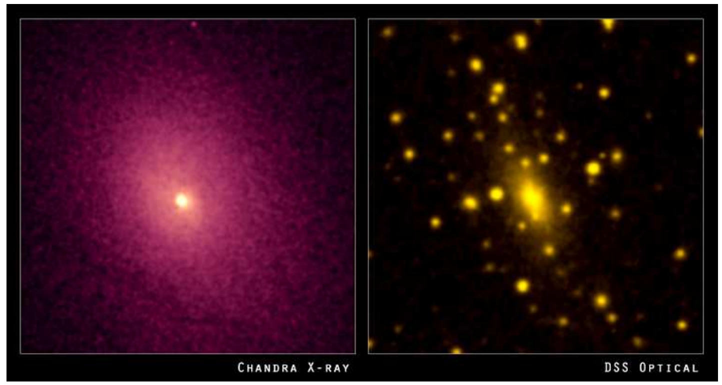


September 07, 2015

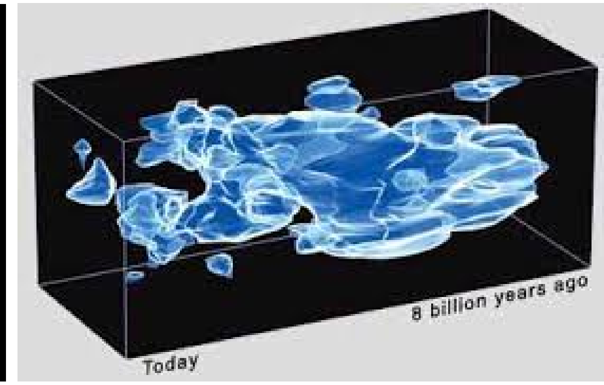
Massive neutral particles fill the Universe



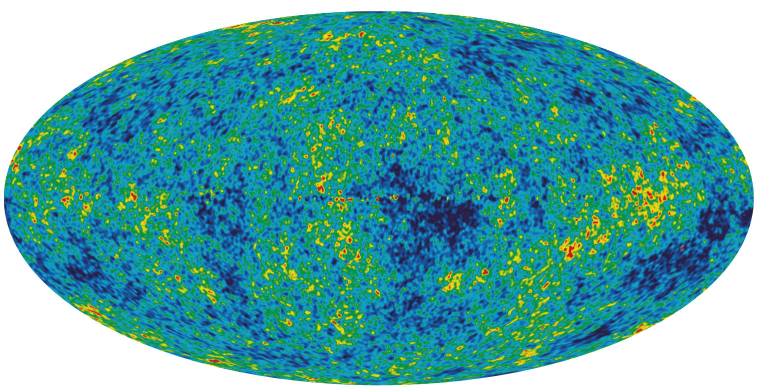
Expected: $v(R) \propto \frac{1}{\sqrt{R}}$
Observed: $v(R) \approx \text{const}$



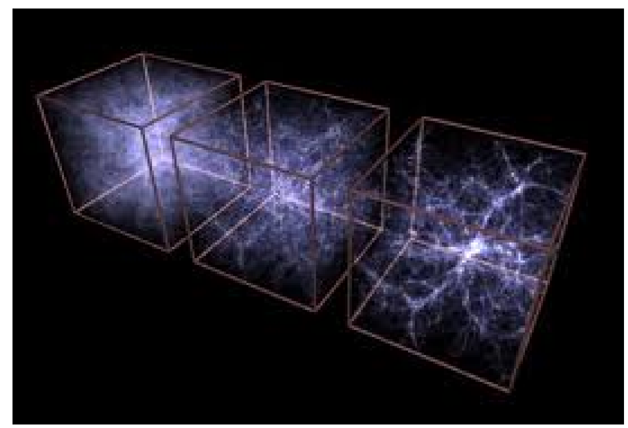
Expected:
$\text{mass}_{\text{cluster}} = \sum \text{mass}_{\text{galaxies}}$
Observed: 10^2 times more mass confining ionized gas



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



Jeans instability turned tiny density fluctuations into all visible structures



Is this neutrino Dark Matter?

- In 1979 when S. Tremaine and J. Gunn published in Phys. Rev. Lett. a paper *"Dynamical Role of Light Neutral Leptons in Cosmology"*
  - The smaller is the mass of Dark matter particle, the larger is the number of particles in an object with the mass M_{gal}
  - Average phase-space density of **any fermionic** DM should be **smaller** than density of **degenerate Fermi gas**

⇒ If dark matter is made of fermions – its mass is bounded from below:

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

Our paper [0808.3902]

- Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the **lower bound** on the fermionic DM mass

$$\boxed{m_{\text{DM}} \gtrsim 300 - 400\ \text{eV}}$$

Is this neutrino Dark Matter?

- **However**, if you compute contribution to DM density from massive active neutrinos ($m_\nu \lesssim$ MeV), you get

$$\Omega_{\nu\,\mathrm{DM}} h^2 = \sum m_\nu \int \frac{d^3k}{(2\pi)^3} \frac{1}{e^{\frac{k}{T}} + 1} = \boxed{\frac{\sum m_\nu[\mathrm{eV}]}{94\ \mathrm{eV}}}$$

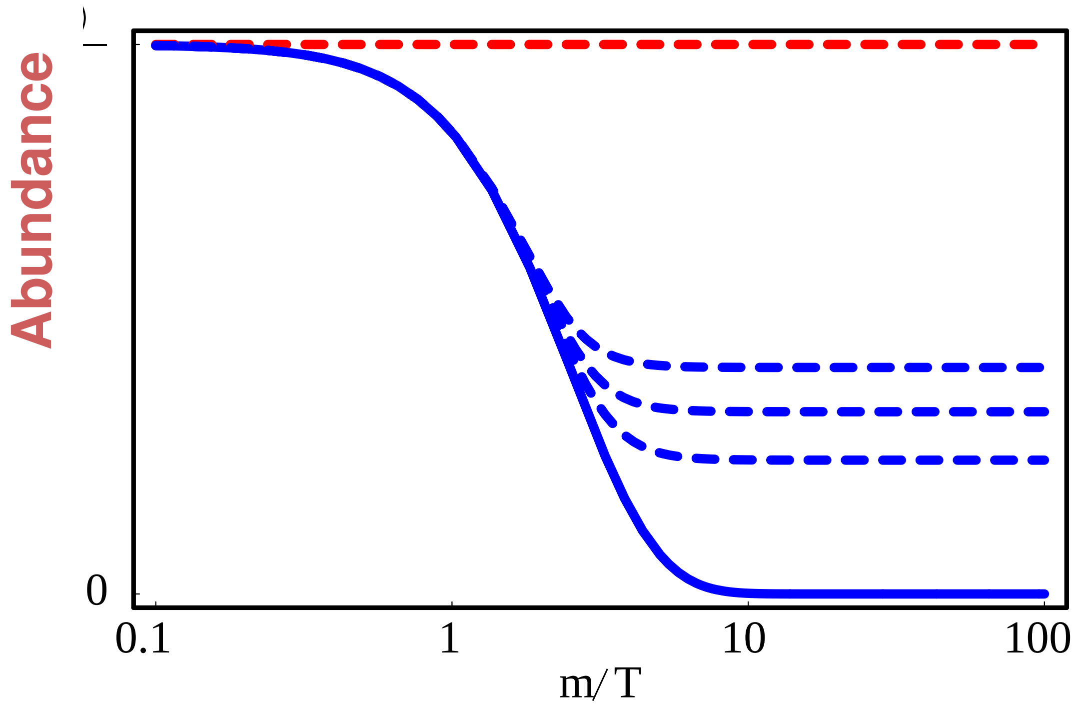
- Using minimal mass of 300 eV you get $\Omega_{\mathrm{DM}} h^2 \sim 3$ (**wrong by about a factor of 30!**)

- Sum of masses to have the correct abundance $\boxed{\sum m_\nu \approx 11\ \mathrm{eV}}$

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

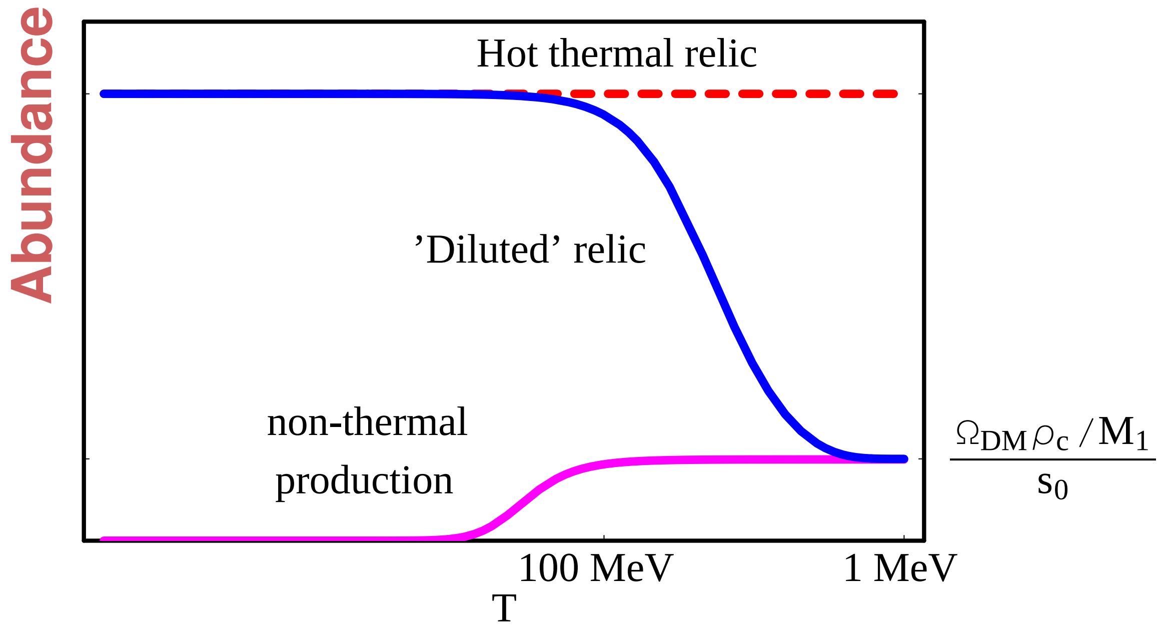
Thermal production in the early Universe



- particles that decouple/are produced relativistic with $T_{\text{dec}} > m$ – universal abundance — **thermal relics** (Depends only on $g_*(T_{\text{dec}})$)

- particles that decouple with $T_{\text{dec}} < m$ (WIMPs)

Non-thermal production



- abundance is too high **unless** $M_{\text{DM}} = 11$ eV
- need **entropy dilution** (some other particles decay after DM decouples and heats up all plasma apart from DM)

- If interaction strength is too low – particles **never enter thermal equilibrium**
- The concentration of these particles gradually builds up
- Non-equilibrium processes can "remember" something about the history of the Universe

Two generalizations of neutrino DM:

Dark matter cannot be both **light** and **weakly interacting** at the same time

Two classes of alternatives:

Light yet **super-weakly** interacting

– **Can be light** (down to Tremaine-Gunn bound)

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

– **Can be decaying** (stability is not required)

Heavy and therefore weakly interacting — **WIMP**

Large part of this conference is about WIMP DM. I shall not speak about it

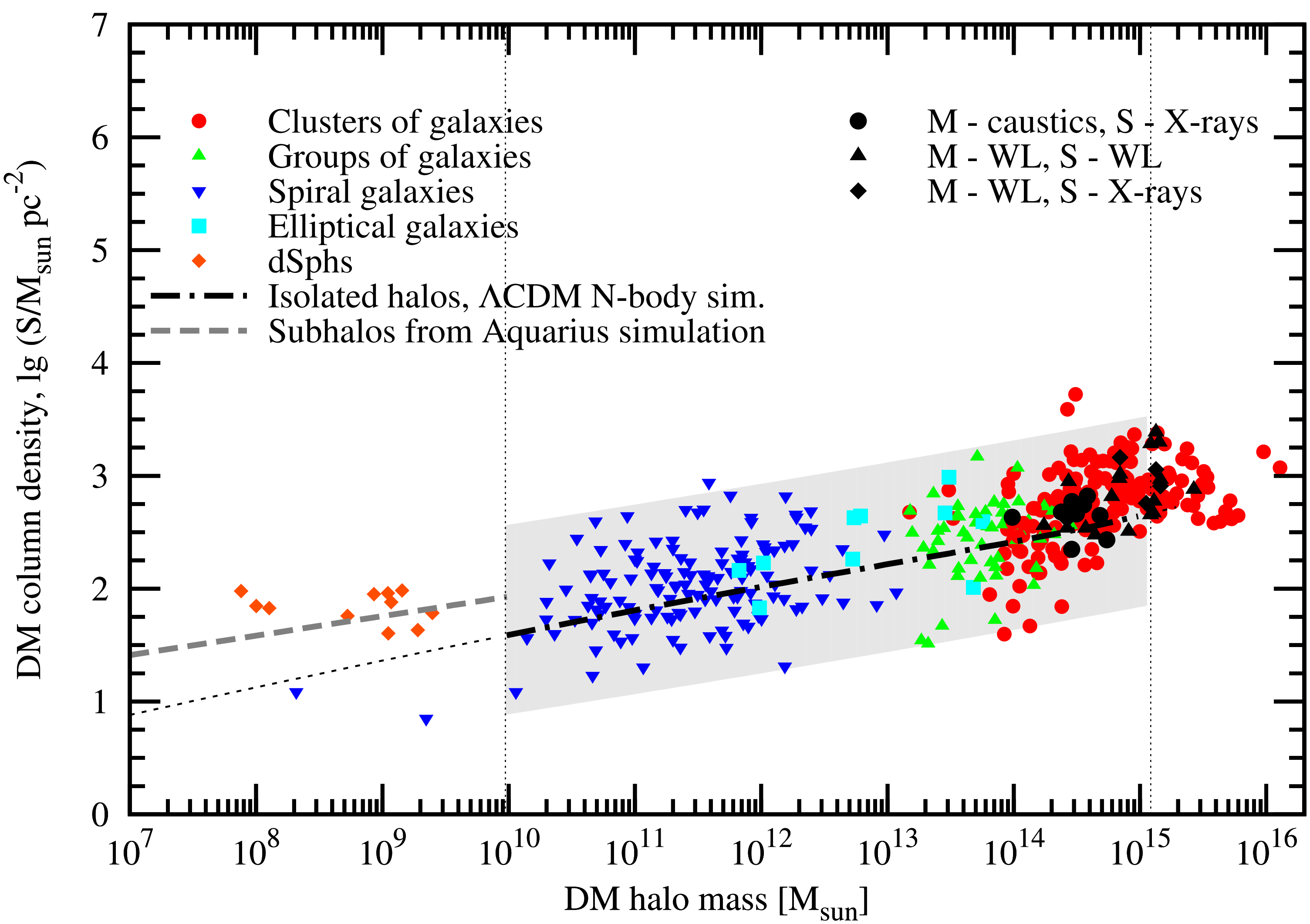
SEARCHING FOR DECAYING DARK MATTER

Decaying dark matter signal

- Two-body decay into two massless particles (DM $\to \gamma + \gamma$ or DM $\to \gamma + \nu$) $\Rightarrow$ narrow decay line
$$E_\gamma = \frac{1}{2} m_{\text{DM}} c^2$$
- The width of the decay line is determined by **Doppler broadening**
- Typical virial velocities:
  - A dwarf satellite galaxy: $\sim 30\,\mathrm{km/sec}$
  - Milky Way or Andromeda-like galaxy: $\sim 200\,\mathrm{km/sec}$
  - Typical velocity in the galaxy cluster $\sim 1500\,\mathrm{km/sec}$
- Very characteristic signal: narrow line in all DM-dominated objects with $\dfrac{\Delta E}{E_\gamma} \sim \dfrac{v_{\text{vir}}}{c} \sim 10^{-4} \div 10^{-2}$

Signal from different DM-dominated objects

Decay signal is proportional to this



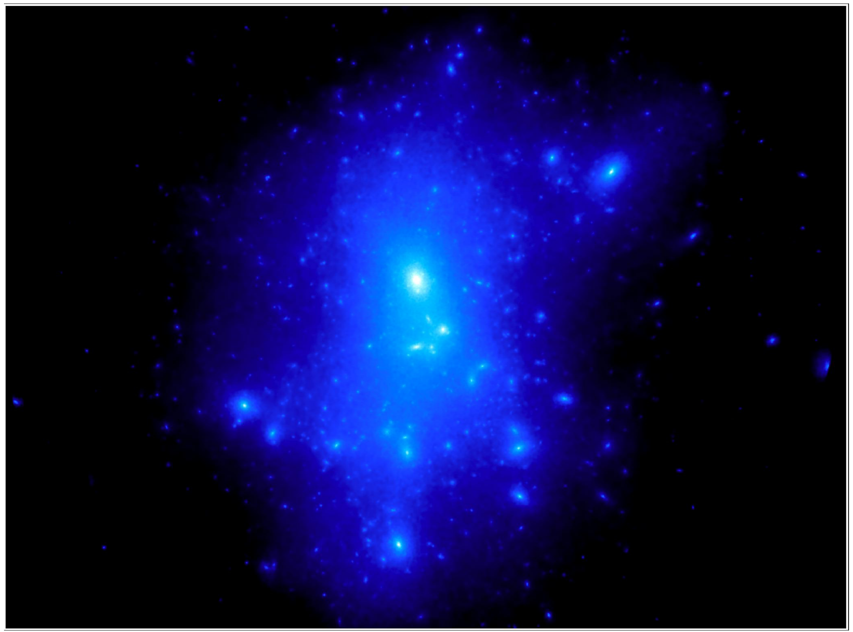
Boyarsky, Neronov, **O.R.** Shaposhnikov, Tkachev PRL'06

Boyarsky, Neronov, **O.R.** Tkachev PRL'09

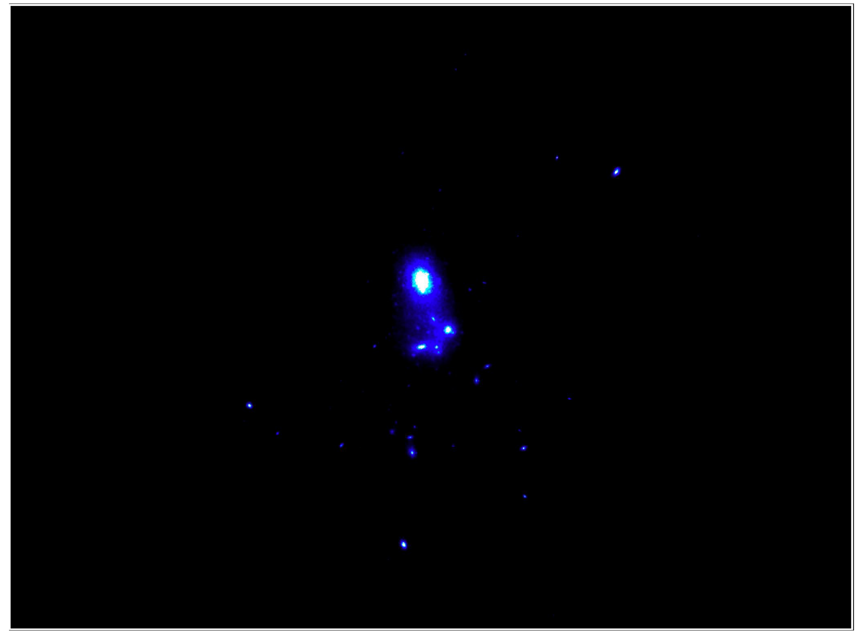
Milky Way satellites

Galaxy clusters

Why nearby objects?



DM **decay** signal from a galaxy



DM **annihilation** signal from a galaxy

For decaying dark matter astrophysical search is (almost) "**direct detection**" as any candidate line can be unambiguously checked (confirmed or ruled out) as DM decay line

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

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]

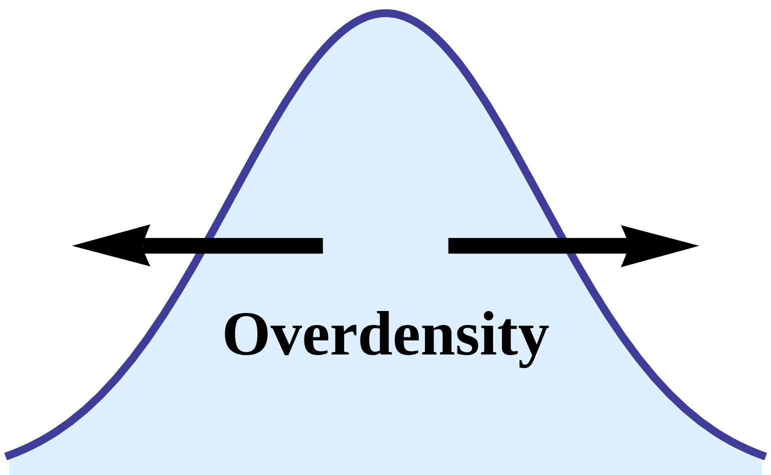
- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
- **Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor ~ 3)
- **Possible origin:** decay DM $\to \gamma + \nu$ (fermion) or DM $\to \gamma + \gamma$ (boson)

Talk by Jeroen Franse on Wednesday

Warm Dark Matter?

Warm dark matter

- Particles are born relativistic $\Rightarrow$ they do not cluster
- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities

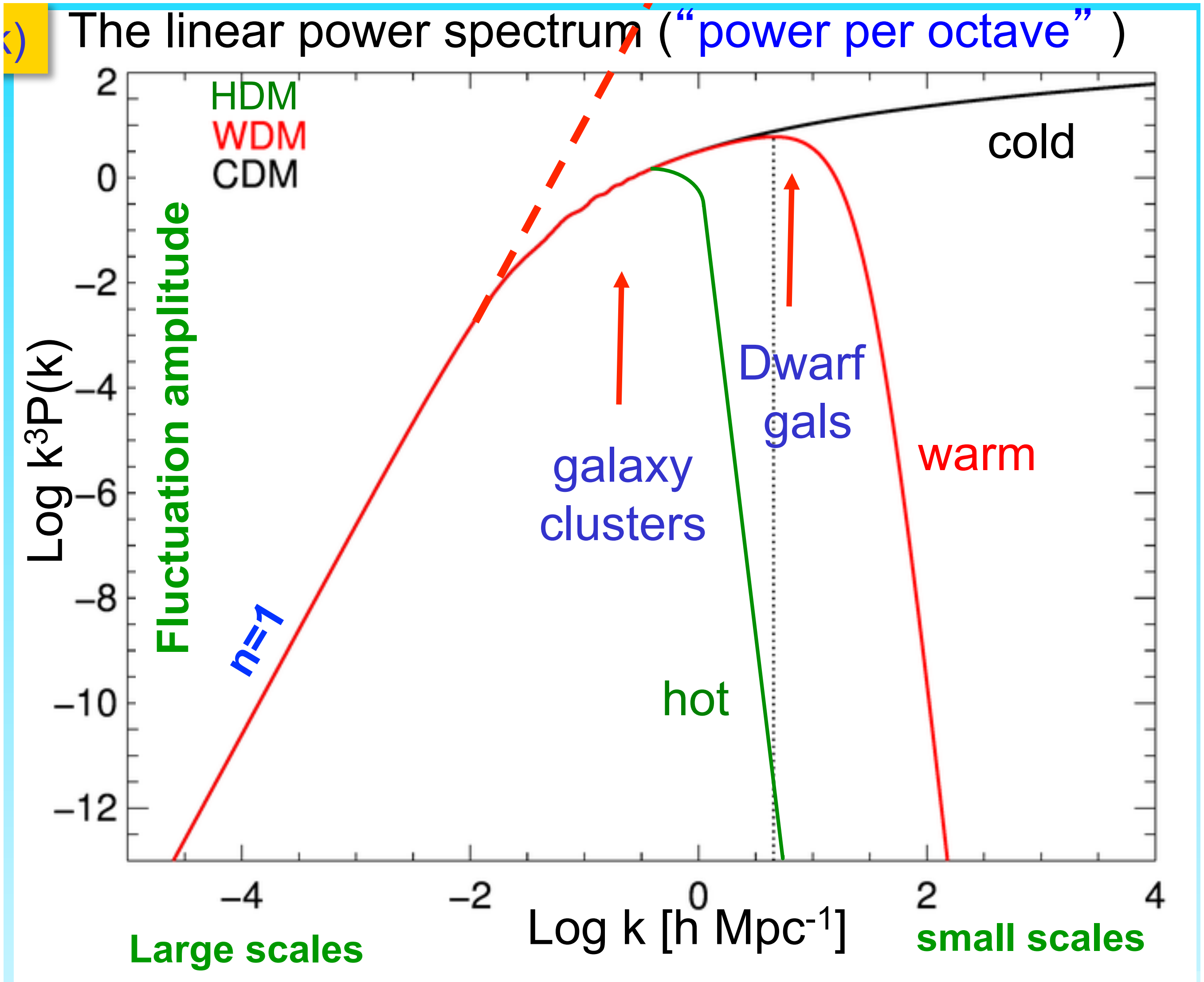


– Free-streaming scale:

$$\lambda_{FS}^{co} = \int_0^t \frac{v(t')dt'}{a(t')} = 1\ \mathrm{Mpc}\left(\frac{\mathrm{keV}}{M_{\mathrm{sterile}}}\right)$$

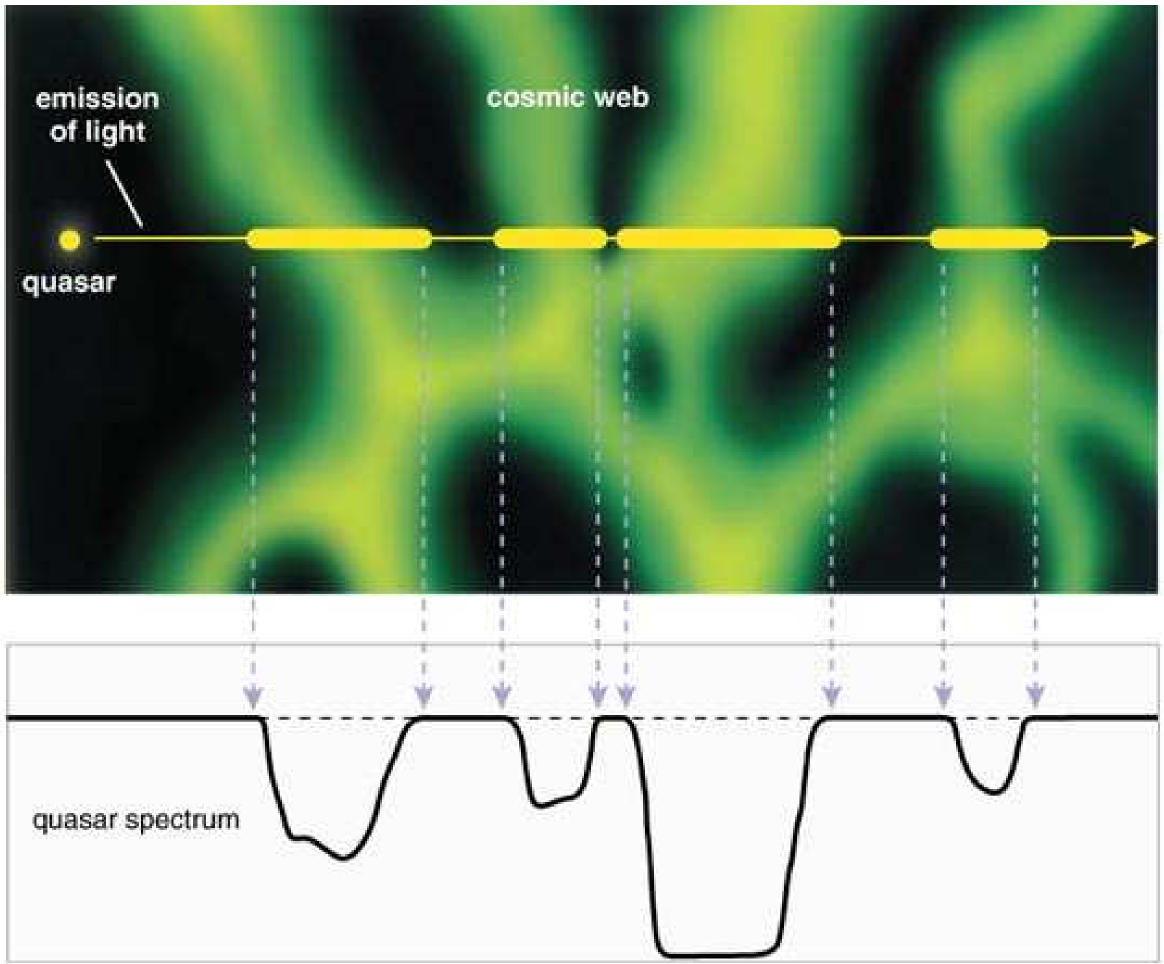
– Particle velocities means that warm dark matter has effective **pressure** that prevents small structure from collapsing

Suppression of power spectrum

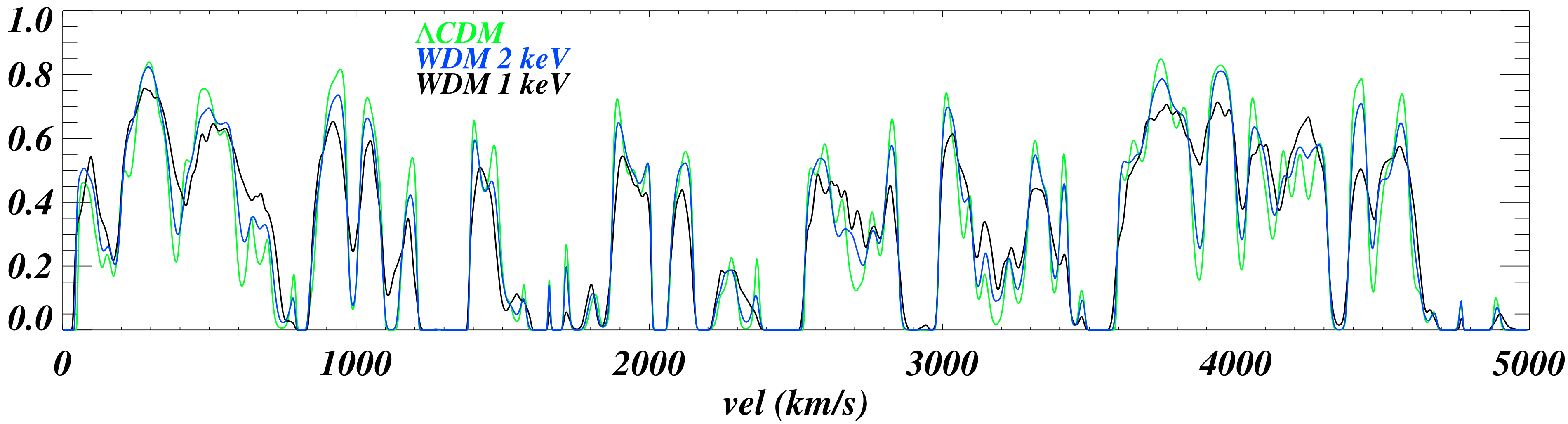


$$k^3 P(k) \sim |\delta_k|^2$$

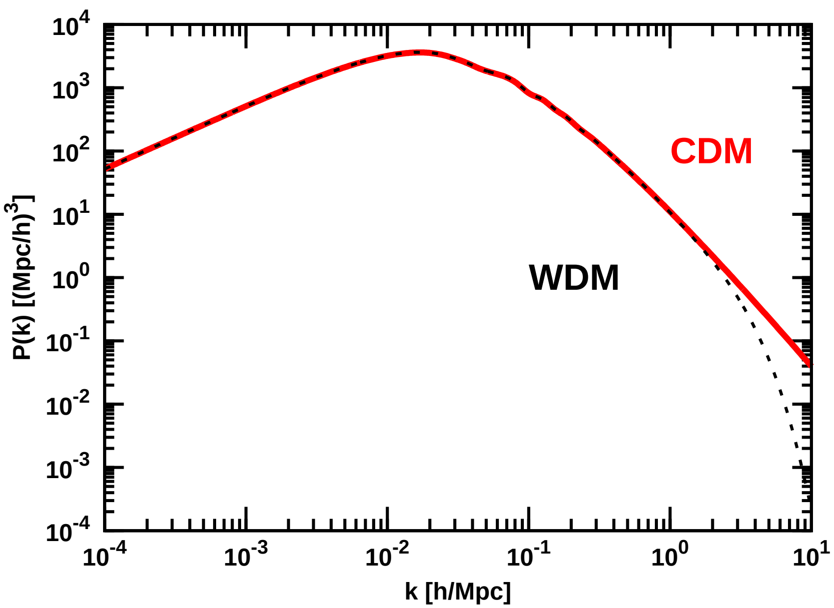
Lyman-α forest and power spectrum



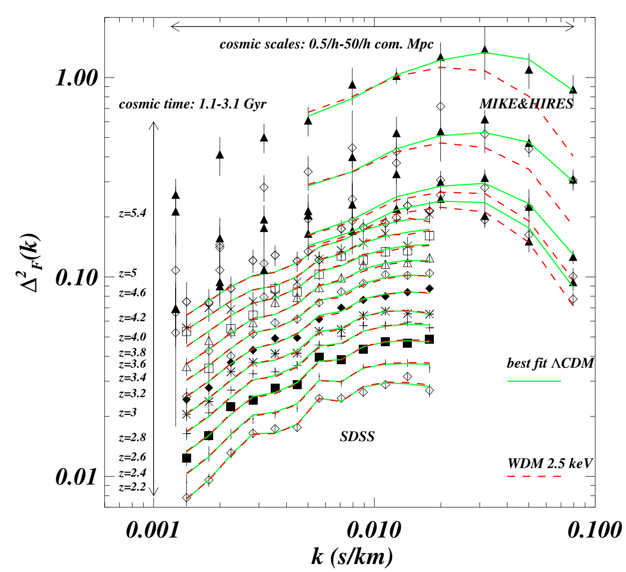
Lyman-α forest and power spectrum



Viel et al.'13

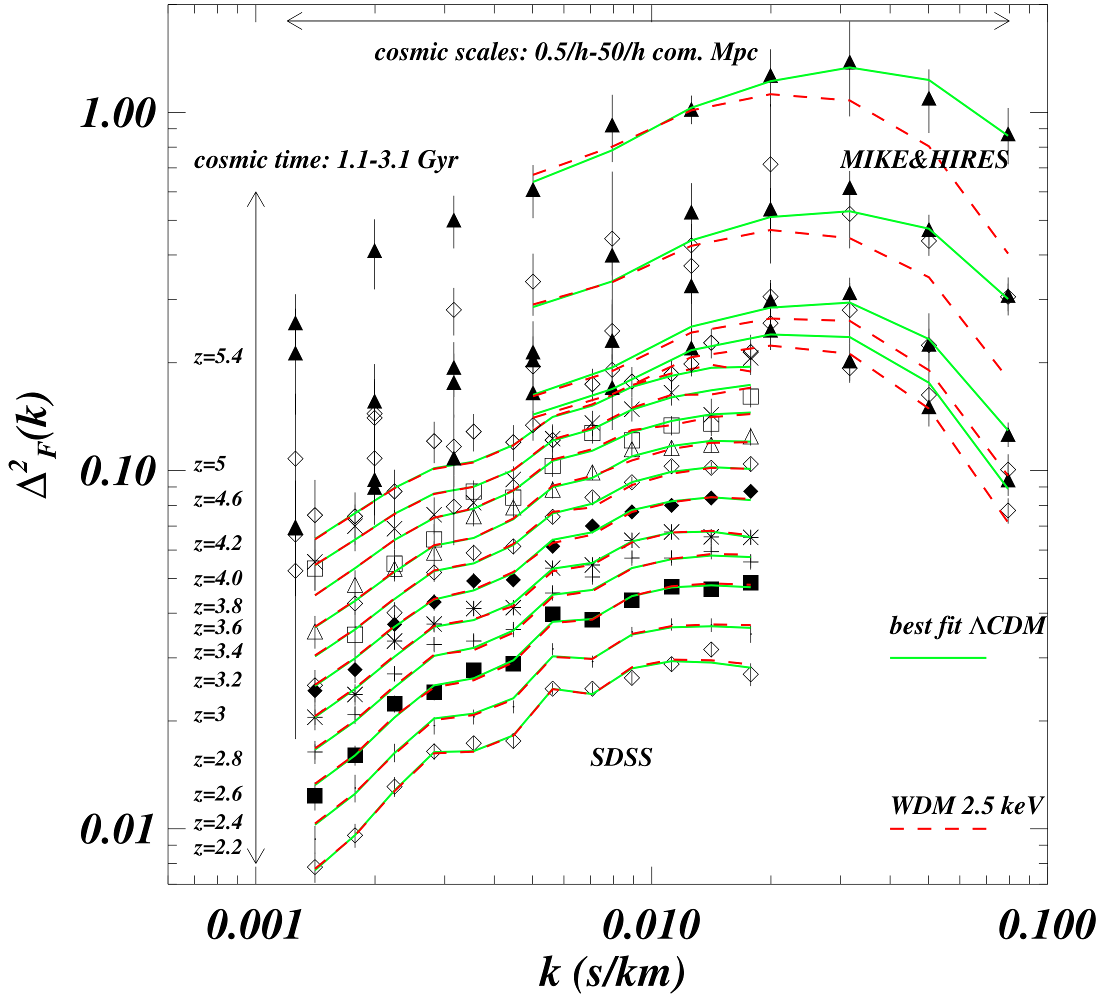


⟹



Lyman-α forest data

Viel et al. [1306.2314]



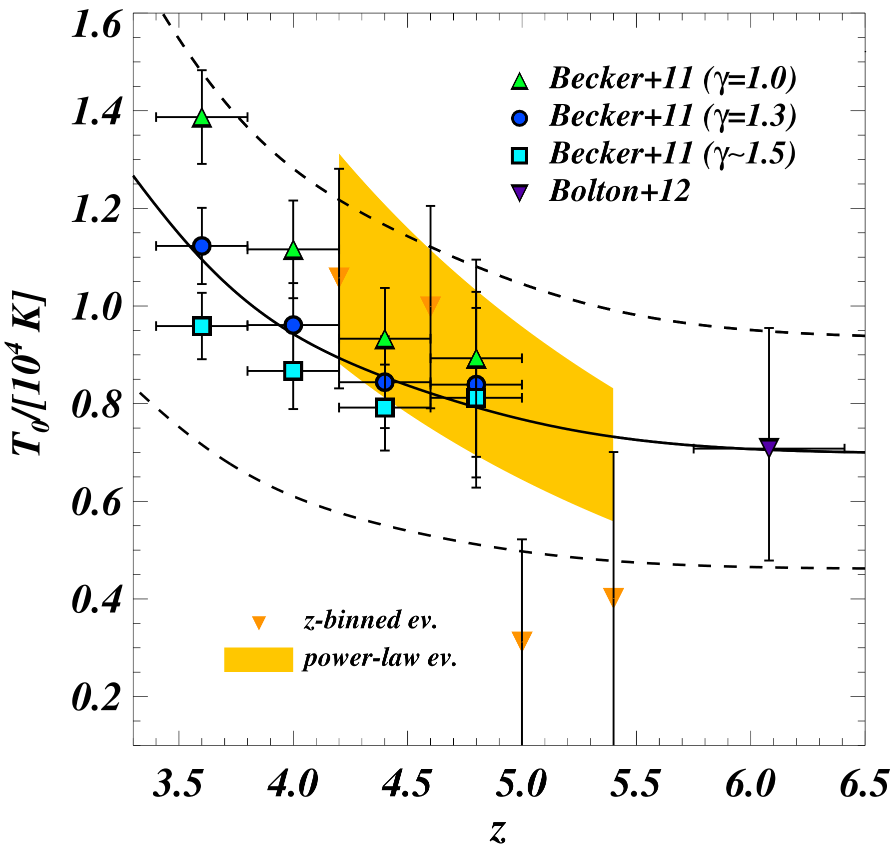
Suppression in the flux power spectrum may be due to

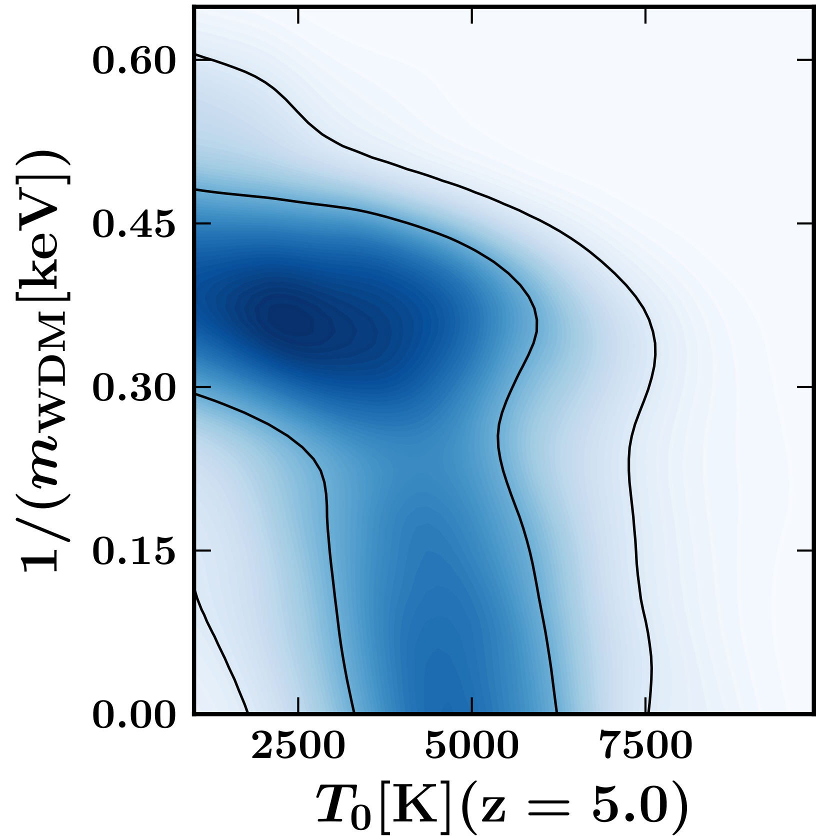
- Thermal effects (Jeans broadening)
- Doppler broadening
- WDM

Large scales: no suppression CDM-like spectrum

Small scales: suppression in the power spectrum! WDM?!

Warm dark matter + cold IGM





Data prefers cold IGM medium around redshift $z = 5$ $\Rightarrow$ power spectrum suppression is due to **something else**?

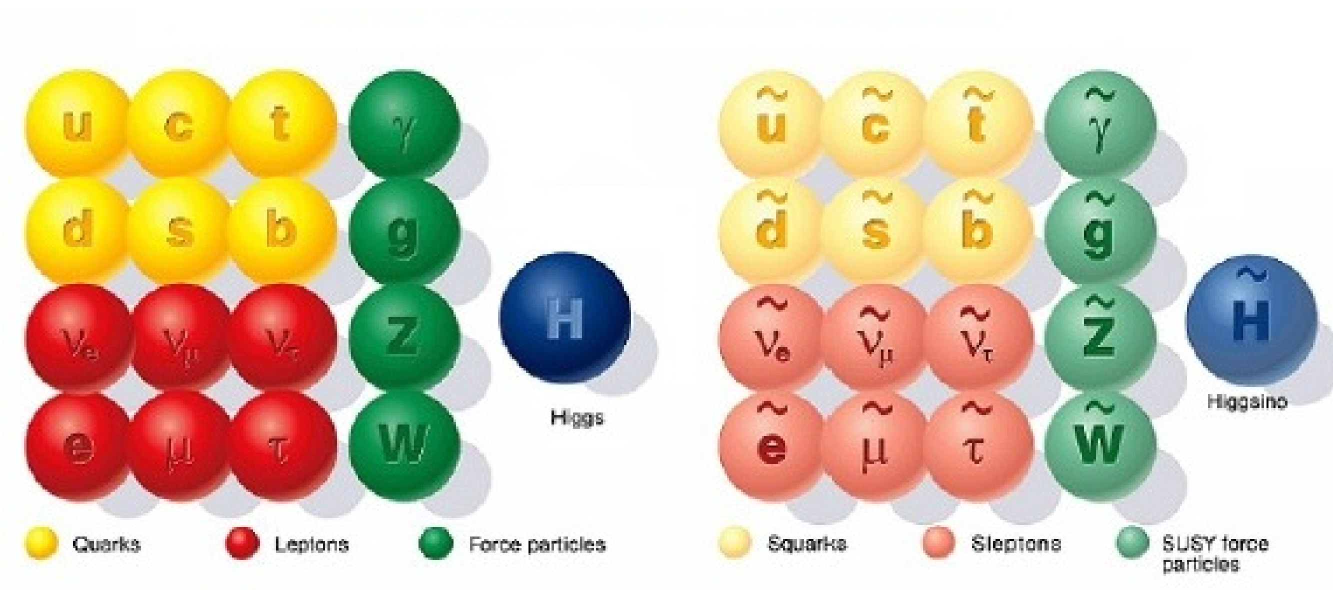
A. Garzilli et al. [1509.***]**

To WIMP or not to WIMP?

Common (mis)conception

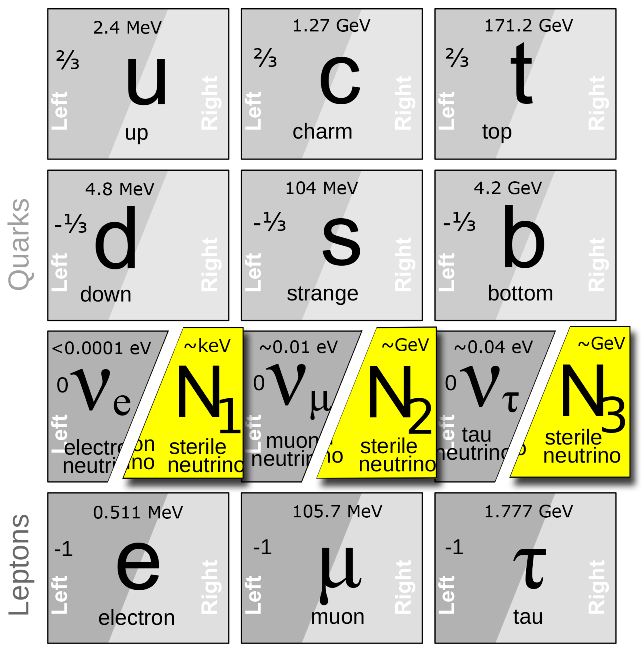
I hear often that:
WIMP is the simplest imaginable model. Any kind of **super-WIMP** is some extra (non-minimal) construction on top of that

- Weakly interacting particle should have a symmetry that protects it from decay
- A WIMP-predicting particle physics model looks like that



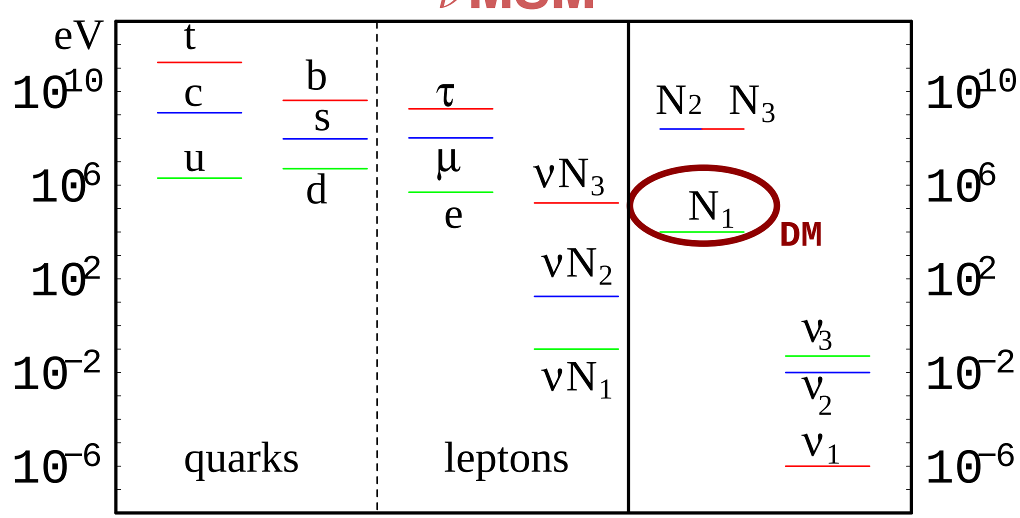
WIMP is the simplest imaginable model? Any **super-WIMP** is some extra (non-minimal) construction on top of that? Really?

- A super-WIMP-predicting particle physics model looks like that



Neutrino Minimal Standard Model

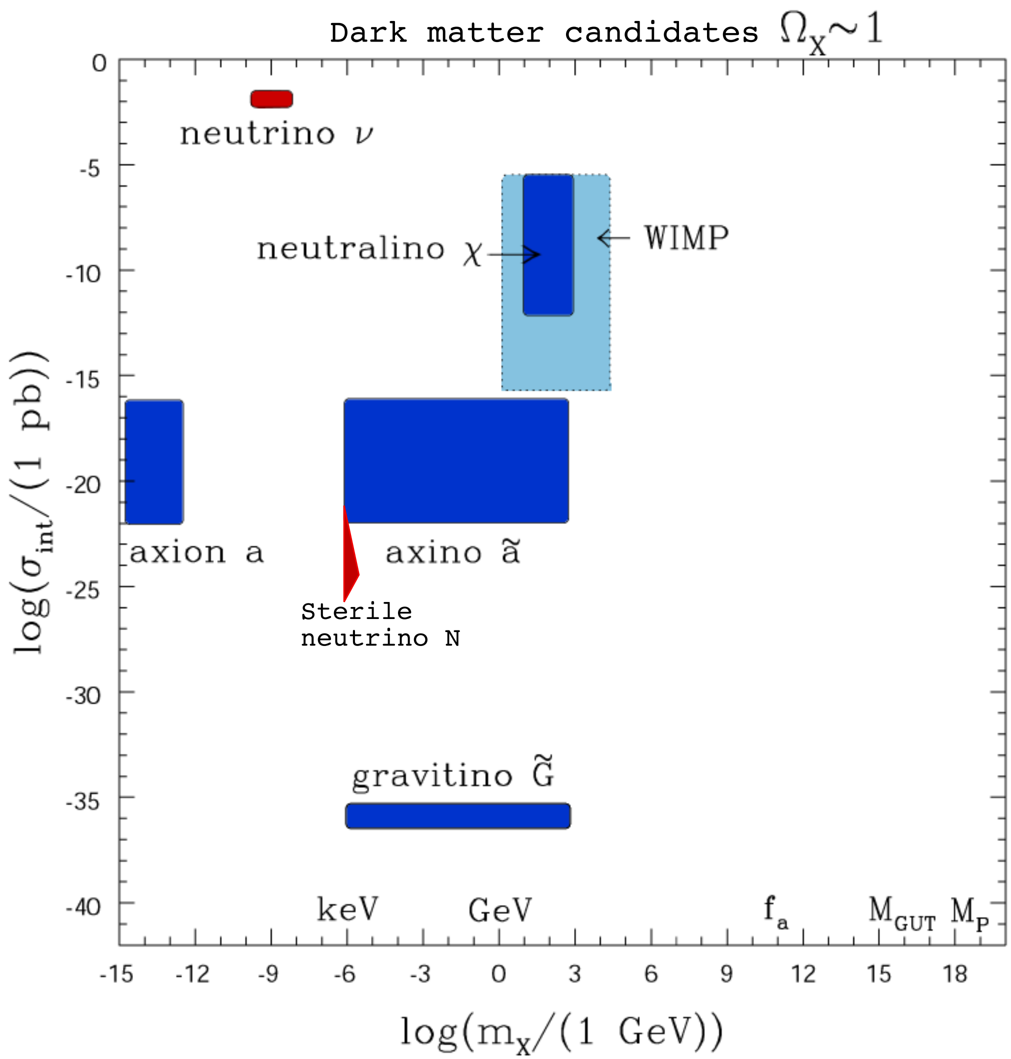
νMSM



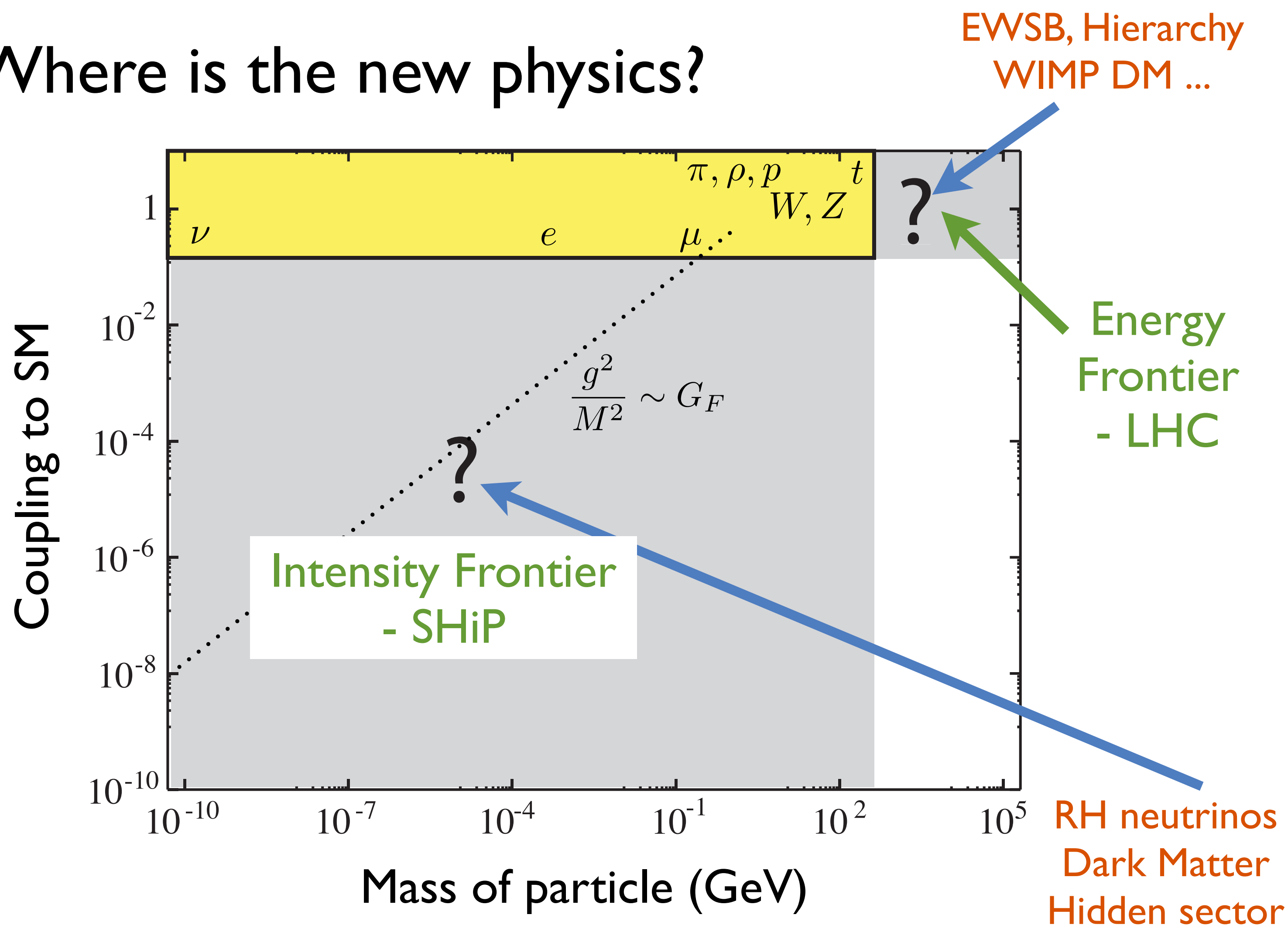
Boyarsky, Ruchayskiy, Shaposhnikov
Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]

And there are many of them...

L.Roszkowski



Where is the new physics?



Talk by Marilisa De Serio about SHiP on Thursday

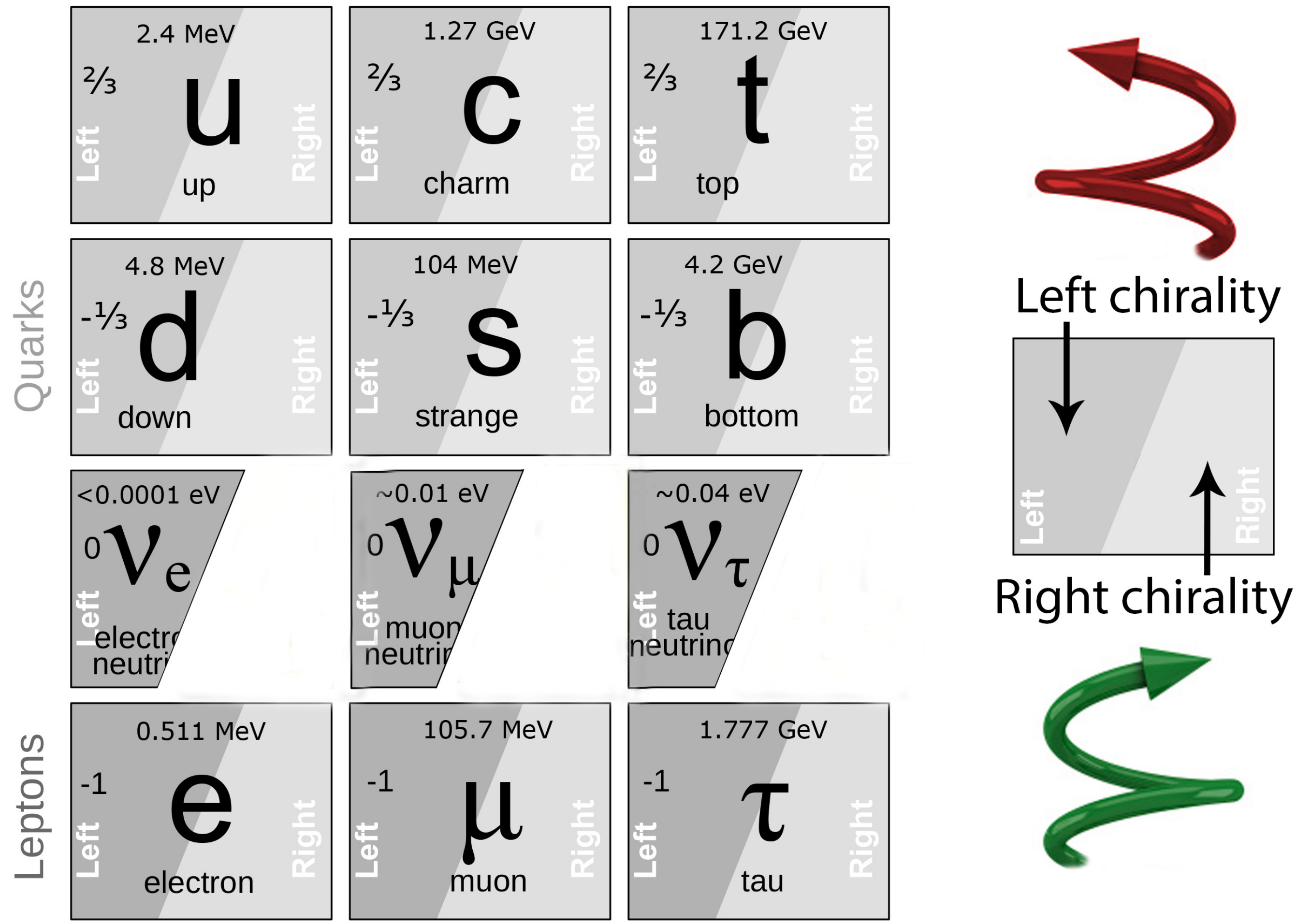
Conclusion

- Super-WIMP dark matter is a part of the paradigme about **feebly interacting** (*rather than heavy*) new physics.
- Super-WIMPs can be **light** (*e.g. keV scales*); can **decay** (*rather than annihilate*) and can be **warm** (*erasing primordial density perturbations*)
- Current status of warm dark matter searches: missing information about state of IGM at $z \sim 5$ can drastically change the situation: rule out WDM as an astrophysically interesting scenario **or confirm existence of warm dark matter**
- The searches for decaying dark matter are ongoing. Stay tuned!
- All the data looks consistent with a ~ 7 keV sterile neutrino produced in the model like νMSM

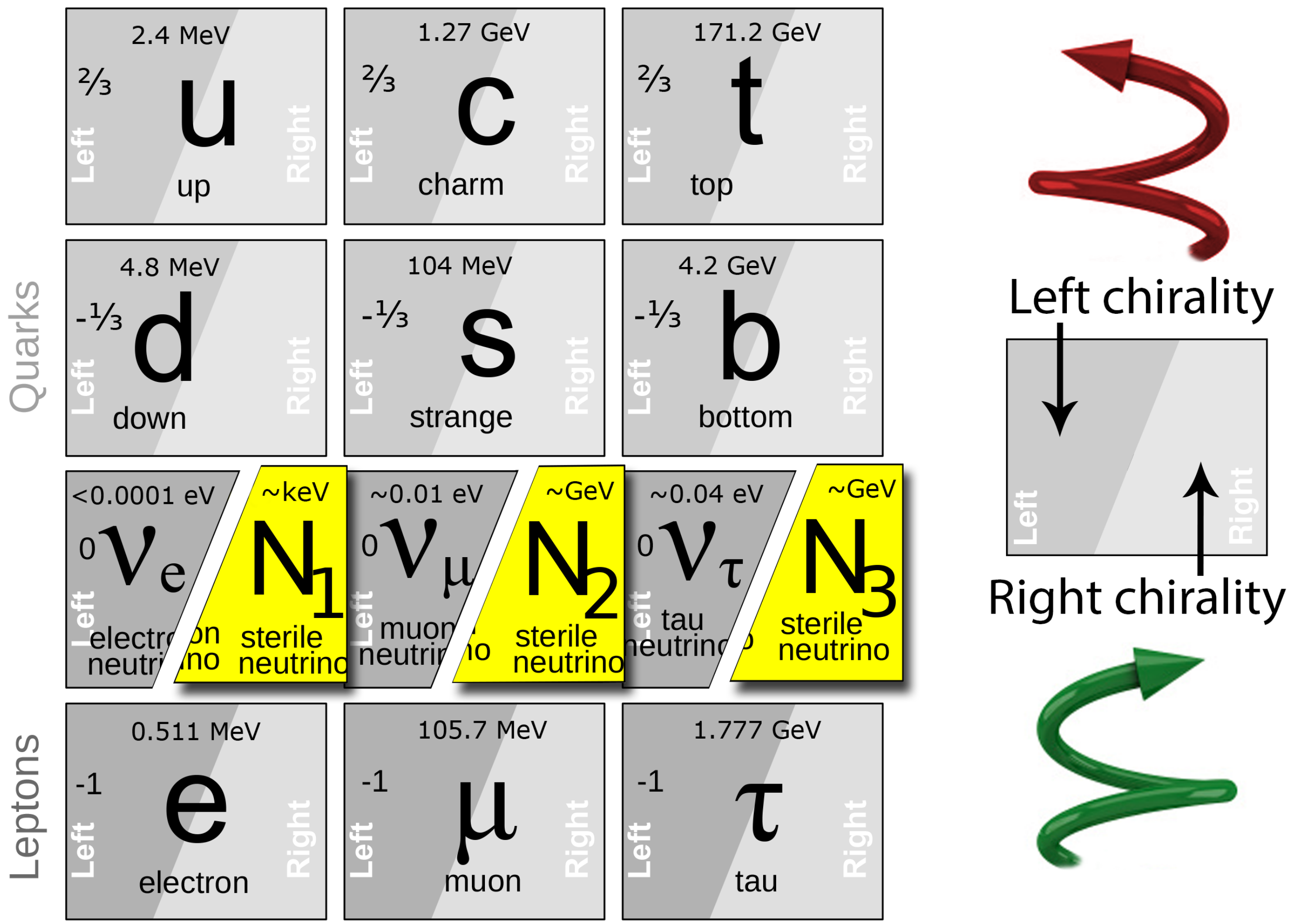
THANK YOU FOR YOUR ATTENTION!

STERILE NEUTRINO DARK MATTER

Oscillations ⇒ new particles!

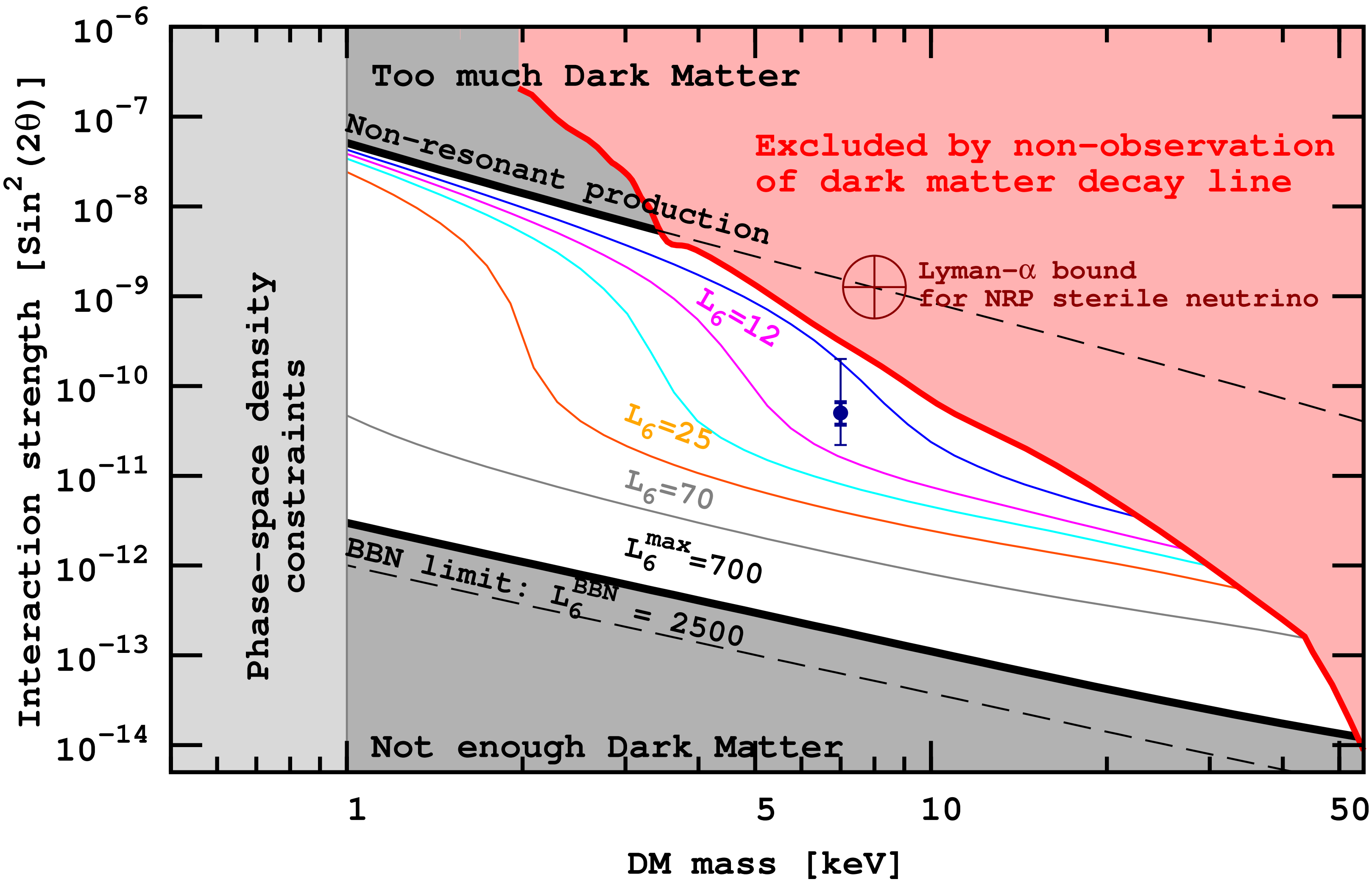


Oscillations ⇒ new particles!



Right components of neutrinos?!

Sterile neutrino and 3.5 keV line



from PRL (2014)

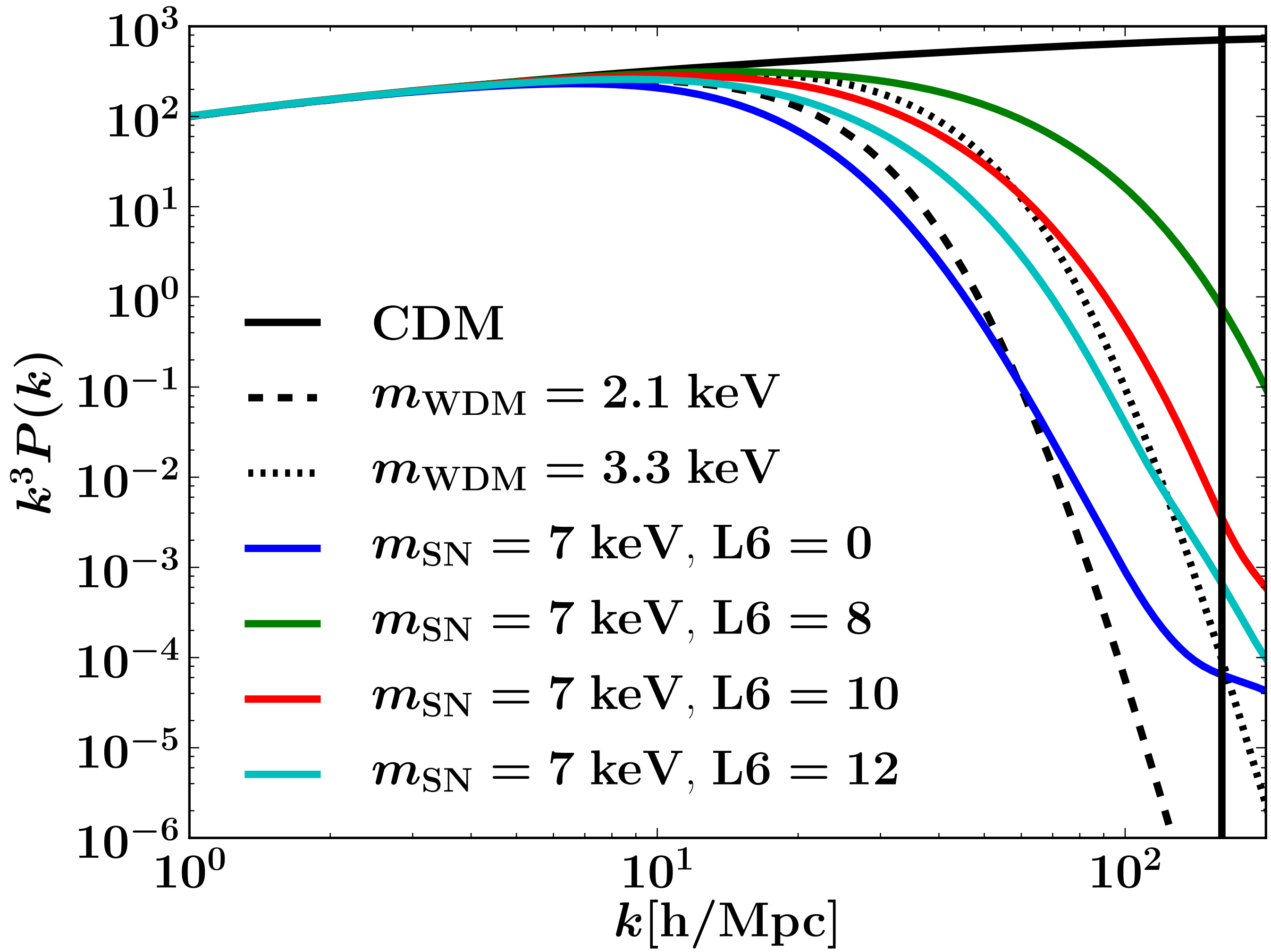
Ly-α bounds: Viel, Lesgourgues et al.'05-'06

Ly-α in resonan case: Boyarsky, Lesgourgues, O.R. Viel '08

X-rays: '05-'14 Boyarsky, Ruchayskiy et al. Abazajian et al. Hansen et al. Watson et al. Kusenko, Lowenstein

Production: Laine & Shaposhnikov'08

7 keV sterile neutrino and Lyman-α forest



SHiP: Search for Hidden particles

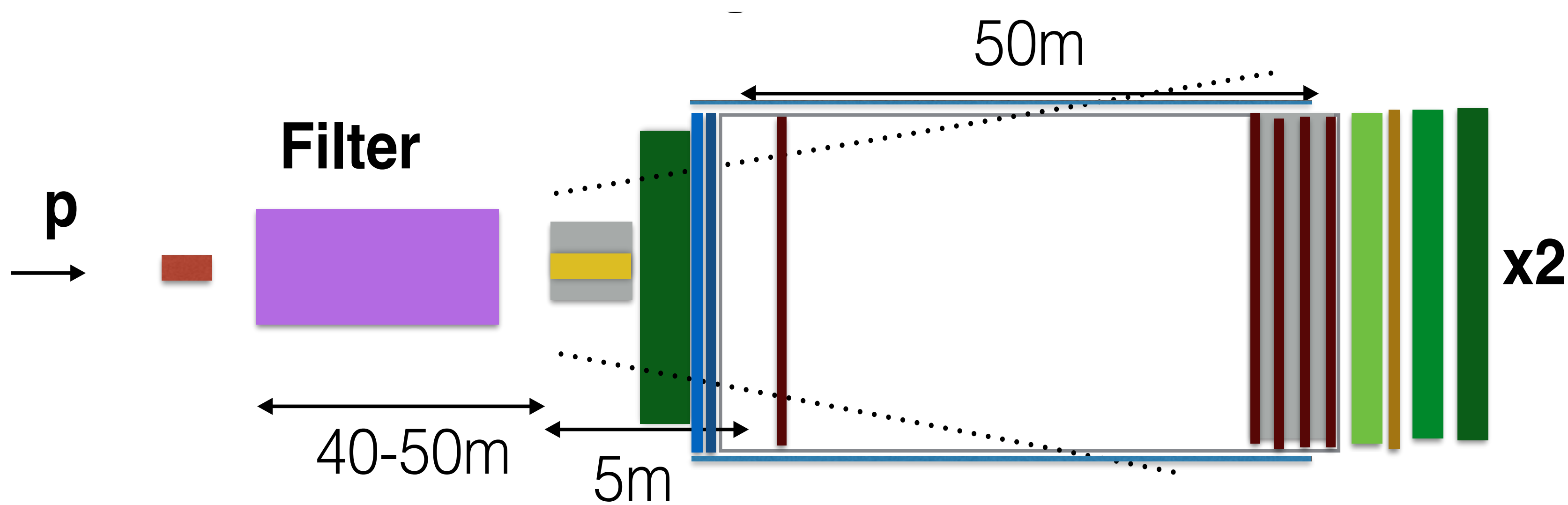
[1310.176]

– Take the highest Energy/Intensity proton beam of the world . . .

– . . . dump it into a target . . .

– . . . followed by the closest, longest and widest possible decay tunnel

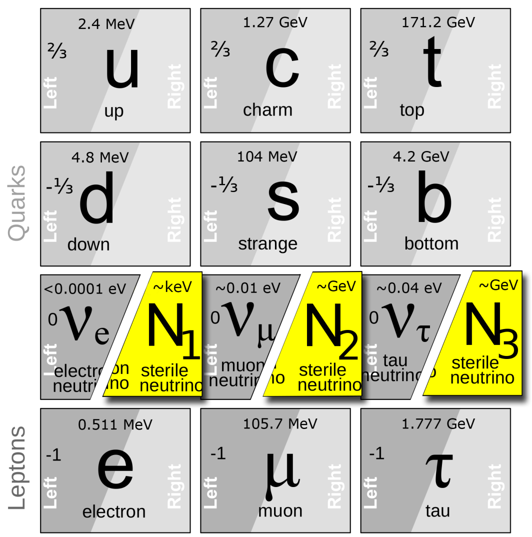
– Any signal within a detector – decay of new particle

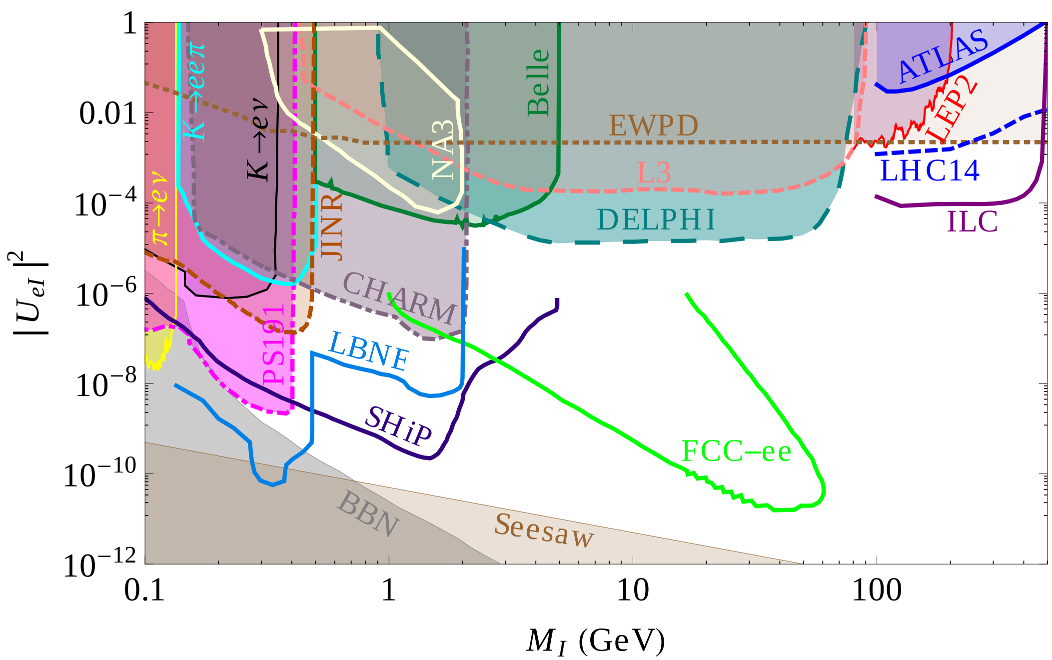


1504.04956 : Technical proposal

1504.04855 : physics case

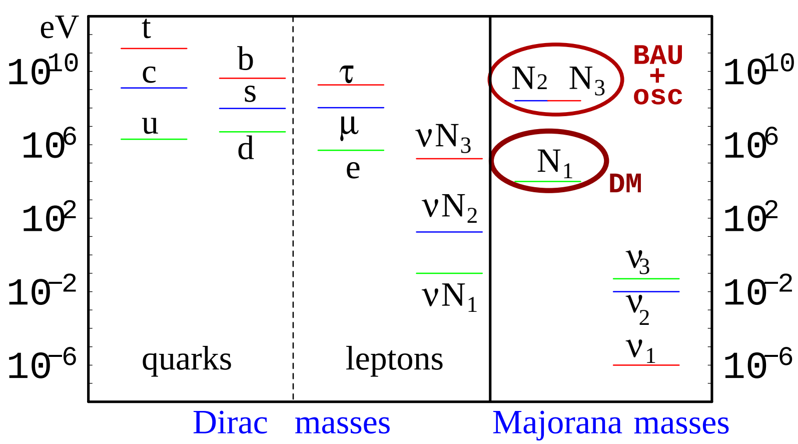
SHiP: Search for Hidden Particles





1504.04956 : Technical proposal

1504.04855 : physics case



- Particle N_1 with the mass 7 keV is the dark matter
- Particles N_2 and N_3 with $\mathcal{O}(1)$ GeV mass are discovered by SHiP
- Their properties (mass/interaction strength) are related