What can particle physics learn from dark matter cosmological observations?

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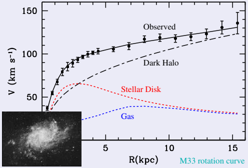
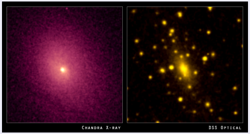
Dark Matter

Astrophysical evidence:

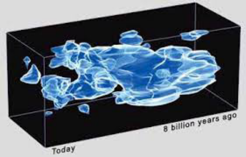


Expected: $v(R) \propto \frac{1}{\sqrt{R}}$

Observed: $v(R) \approx$ const

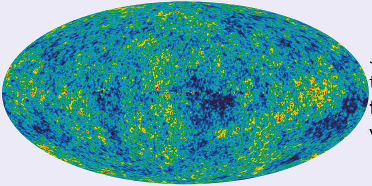


Expected:
$m_{\text{cluster}} = \sum m_{\text{galaxies}}$
Observed: 10^2 times more mass is confining the ionized gas

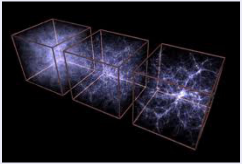


Lensing signal (direct mass measurement) **confirms** other observations

Cosmological evidence:



Jeans instability turned tiny density fluctuations into all visible structures



Cosmological standard model

In the concordance model dark matter is

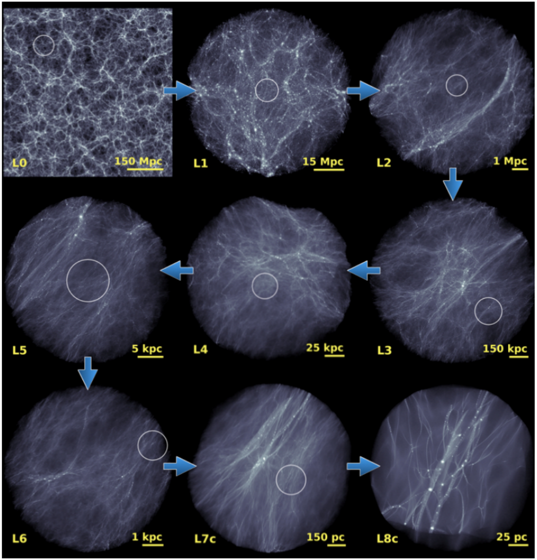
- cold
- stable
- collisionless

Each of these assumptions can turn out to be wrong!

Astrophysics is the key!

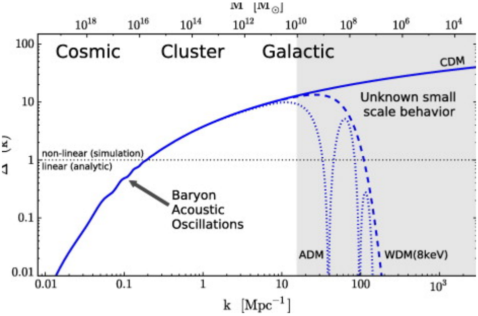
- Only astrophysics can confirm these assumptions
- What shall we do if tomorrow CDM is ruled out?

Cold dark matter – self-similar structure formation

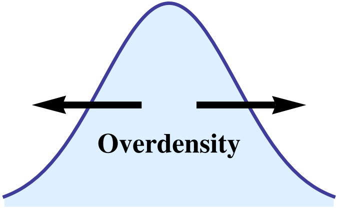


CDM vs. non-CDM

- Example: WDM. Particles are born relativistic ⇒ they do not cluster
- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities

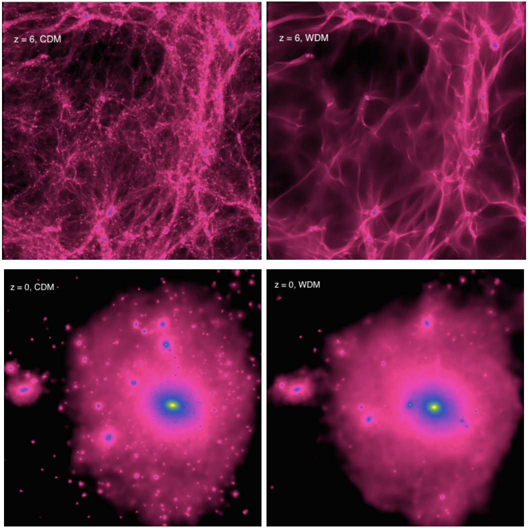


[Kuhlen et al. (2012)]



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

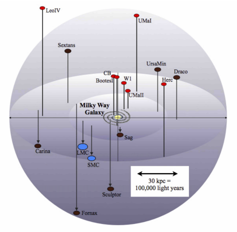
What is "warm dark matter" observationally?



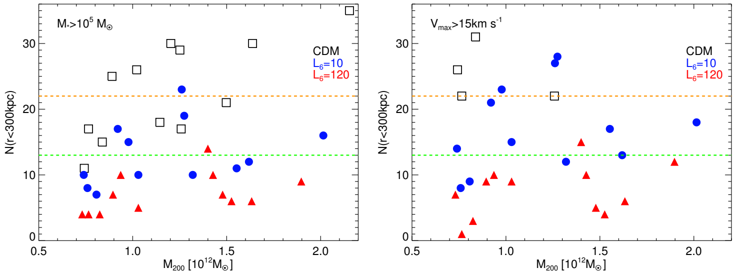
Warm dark matter:

- Same structures as in **CDM** Universe at scales of Mpc and above ⇒ no signatures in CMB or galaxy counts
- Decreasing number of small galaxies around Milky Way
- Decreasing number of small satellite galaxies **within** Milky Way halo
- **Can help** with "too big to fail" or "missing satellites" problems

Satellite number and properties



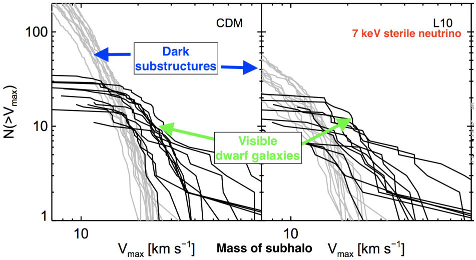
- Warm dark matter erases substructures – compare number of dwarf galaxies inside the Milky Way with "predictions"
- **Simulations**: The answer depends **how** you "light up" satellites
- **Observations**: We do not know how typical Milky Way is

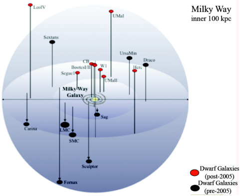


Lovell, Boyarsky+ [1611.00010]

Counting satellites

Boyarsky, Ruchayskiy with Lovell et al. [1611.00010]





The same number of luminous satellites, but different number of **dark** satellites

- Warm dark matter erases substructures – compare number of dwarf galaxies inside the Milky Way with "predictions"
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Counting satellites

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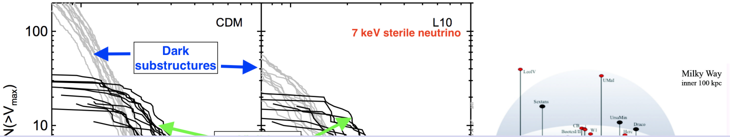

- The way out is to detect **dark substructures** directly
- This can be done via strong gravitational lensing

The same number of luminous satellites, but different number of **dark** satellites

- Warm dark matter erases substructures – compare number of dwarf galaxies inside the Milky Way with “predictions”
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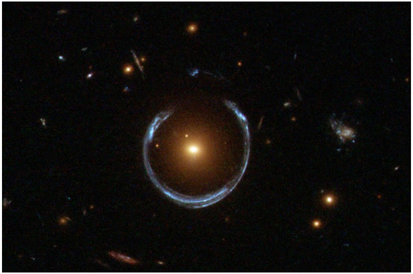
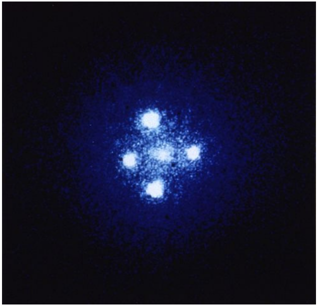
Way 1: Strong gravitational lensing

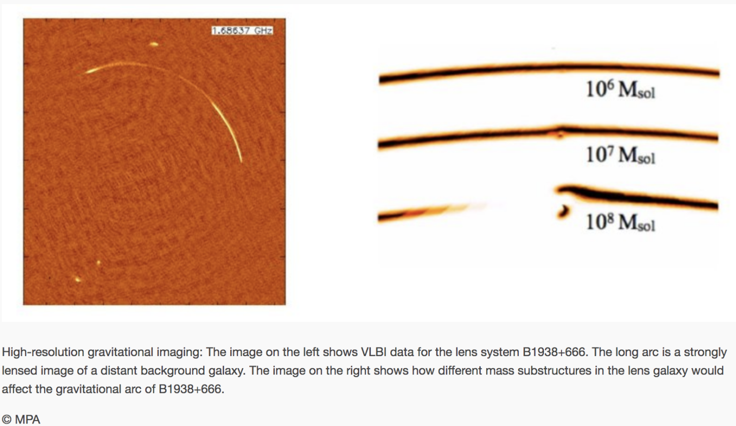


Einstein ring: large red galaxy lenses distant blue galaxy (almost on the line-of-sight).



Einstein cross: 4 images of a distant quasar

Dark substructures detection via arcs



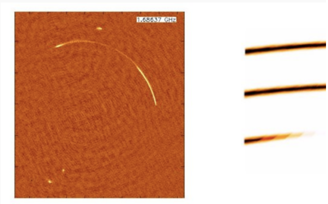
High-resolution gravitational imaging: The image on the left shows VLBI data for the lens system B1938+666. The long arc is a strongly lensed image of a distant background galaxy. The image on the right shows how different mass substructures in the lens galaxy would affect the gravitational arc of B1938+666.

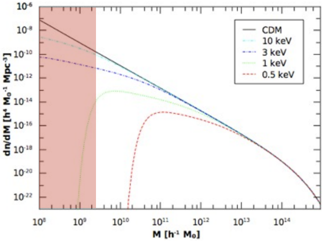
© MPA

S. Vegetti

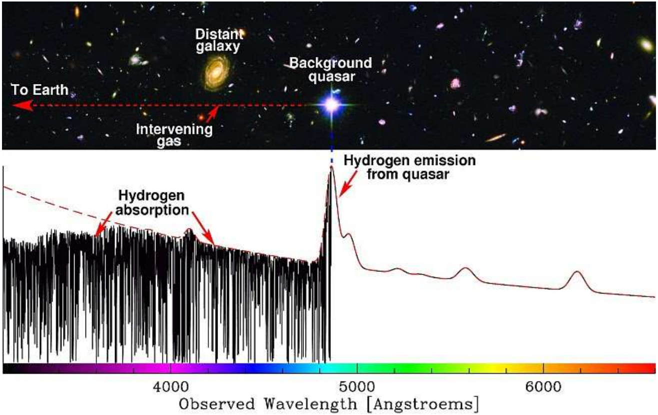
Ruling out cold or warm dark matter

- Current detection limits $M_{sub} \sim 10^9 M_\odot$
- Future surveys (more lenses/arcs) will bring the detection limits $M_{sub} \sim 10^6 M_\odot$
- If no substructures of this size will be found $\Rightarrow$ **CDM is ruled out!** Strong impact on direct detection experiments, axion DM searches, etc
- If such substructures are found – WDM strongly disfavoured, no sterile neutrino DM...





Way2: Lyman-α forest



- Neutral hydrogen absorption line at $\lambda = 1215.67\text{Å}$

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

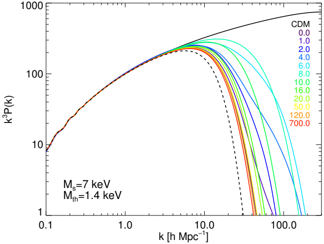
Suppression in the flux power spectrum (SDSS)

What we want to detect

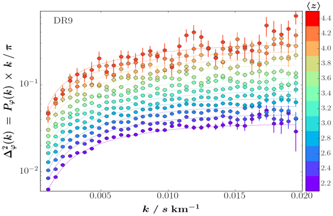
- CMB and large scale observations fix matter power spectrum at large scales
- Based on this we can predict the ΛCDM matter power spectrum at small scales
- WDM predicts suppression (cut-off) in the matter power spectrum as compared to the CDM

What we observe

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

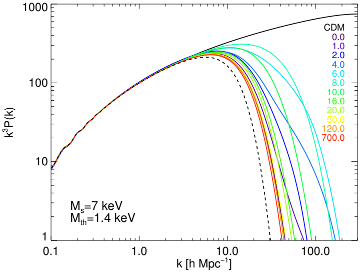


3D linear matter power spectra

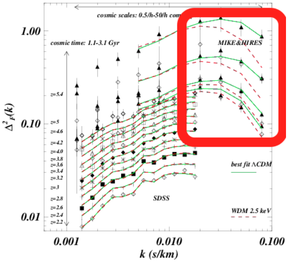


BOSS (SDSS-III) Ly-α [1512.01981]

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

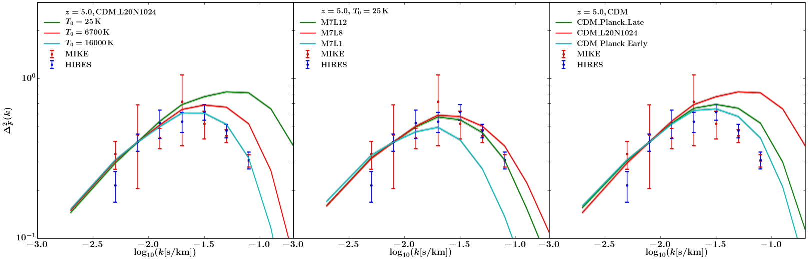
The distribution of neutral hydrogen follows the DM distribution

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)

Temperature? Pressure? WDM?

Garzilli, Magalich, Theuns, Frenk, Weniger, Ruchayskiy, Boyarsky [1809.06585]

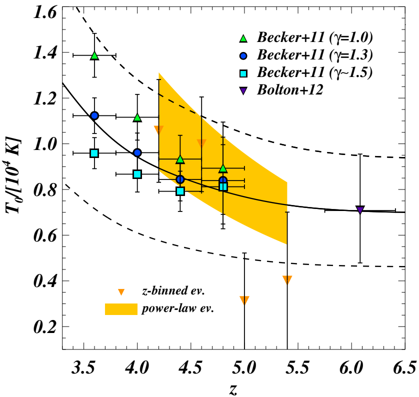


Temperature **WDM** **Pressure**

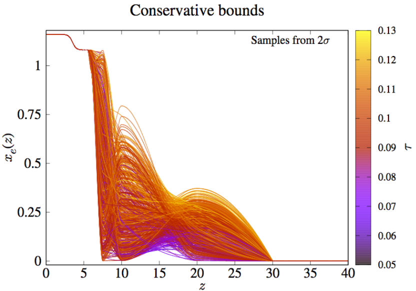
- CDM with the IGM temperature $\sim 10^4$ K is able to explain the MIKE/HIRES flux power spectrum
- Different thermal histories (onset/intensity of reionization) are able to explain power spectra
- ...and so can WDM with a reasonable thermal history

What is known about the IGM thermal history?

Current measurements of IGM temperature



[1306.2314]

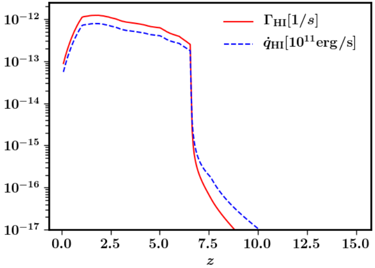


[1708.04913]

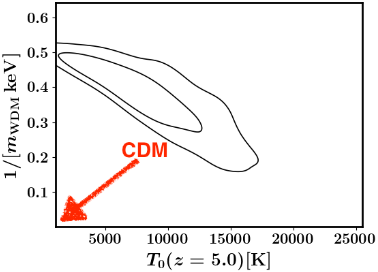
- There are many measurements at $z < 5$
- There is a single measurement **above** $z = 6$
- History of reionization at higher redshifts is poorly constrained

Warm dark matter may have been discovered

Garzilli, Boyarsky, Ruchaiskiy,. . . 2015, 2018, 2019



[Onorbe et al. 2016]



[Garzilli et al. [1912.09397]]

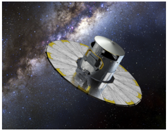
- Universe reionizes late
- CDM is ruled out for such reionization scenario (even if instantaneous temperature is varied)

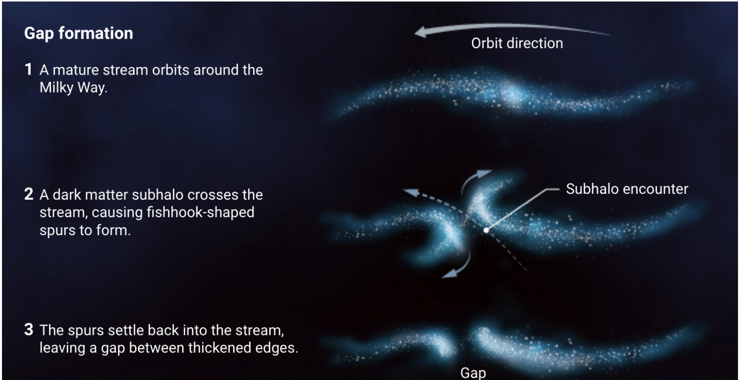
WDM effects and thermal effects have different redshift dependence. More data are on the way, we can distinguish between them!

Way 3: Stellar stream gaps

E.Hand, Science (2018)

- Thanks to Gaia we know much better the structure of the Milky Way
- In particular many **stellar streams** – distrupted dwarf galaxies – have been discovered





Gap formation

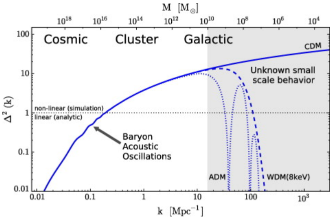
1 A mature stream orbits around the Milky Way.

2 A dark matter subhalo crosses the stream, causing fishhook-shaped spurs to form.

3 The spurs settle back into the stream, leaving a gap between thickened edges.

What does this mean for particle physics?

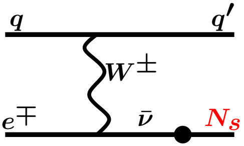
- If one of these methods shows convincing deviation from CDM – what does this mean for particle physics?
- How can particle physics help to identify a microscopic model beyound "non-CDM"?

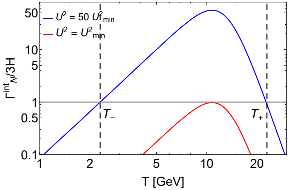


Light new physics

- Although this is not a theorem, but **generically** deviations from CDM would strongly suggest that **new light physics exists**
- This can mean that
  1. Dark matter particles are **light**.
  2. Mediators with the "**dark sector**" are light (mediators)
  3. Both!

Example 1: HNL – "naturally warm" DM. I





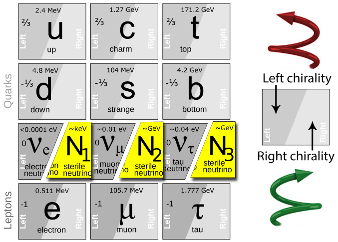
- Heavy neutral lepton (HNL) – part of the **neutrino portal**
- In the early Universe mixing angle is **temperature dependent**
- Produced via freeze-in

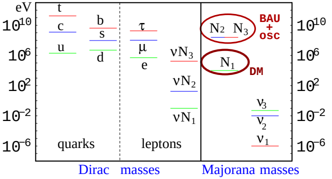
  [Dodelson & Widrow'93; Shi & Fuller'98; Abazajian et al.'00; Asaka, Laine, Shaposhnikov'06-08]
- Production is effective at temperatures

$$T_{max} = 150\,\mathrm{MeV}\left(\frac{M_{dm}}{\mathrm{keV}}\right)^{1/3}$$

- ...and average momentum $p \sim T_{max} \gg M_{dm}$ – **warm dark matter**
- Production is sensitive to the presence of lepton asymmetry in the primordial plasma (MSW-like effect)

HNL DM as a part of full model





Heavy neutral leptons can explain . . .

- . . . **neutrino oscillations**

  Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79; Mohapatra & Senjanovic'80; Schechter & Valle'80

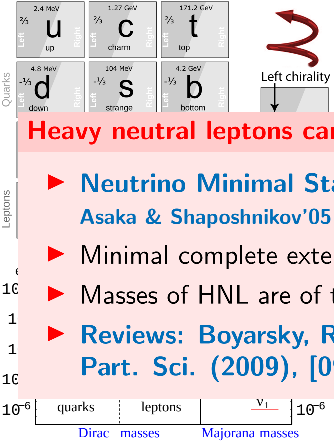
- . . . **Baryon asymmetry**

  Fukugita & Yanagida'86; Akhmedov, Smirnov & Rubakov'98; Pilaftsis & Underwood'04-05; Shaposhnikov+'05–

- . . . **Dark matter**

  Dodelson & Widrow'93; Shi & Fuller'99; Dolgov & Hansen'00; Abazajian+; Asaka, Shaposhnikov, Laine'06 –

HNL DM as a part of full model



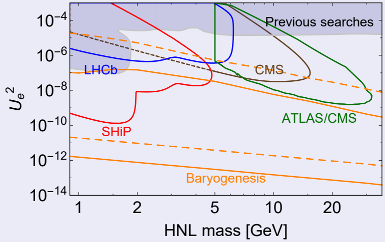
Heavy neutral leptons can explain . . .

- neutrino oscillations

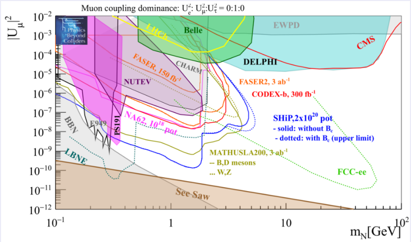
Heavy neutral leptons can explain all of it

- **Neutrino Minimal Standard Model (νMSM)**
  Asaka & Shaposhnikov'05 + . . . hundreds of subsequent works
- Minimal complete extension of the Standard Model
- Masses of HNL are of the order of masses of other leptons
- **Reviews: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]**

HNLs are part of the search program of all major particle physics experiments



LHC searches (Boiarska+ [1902.04535])

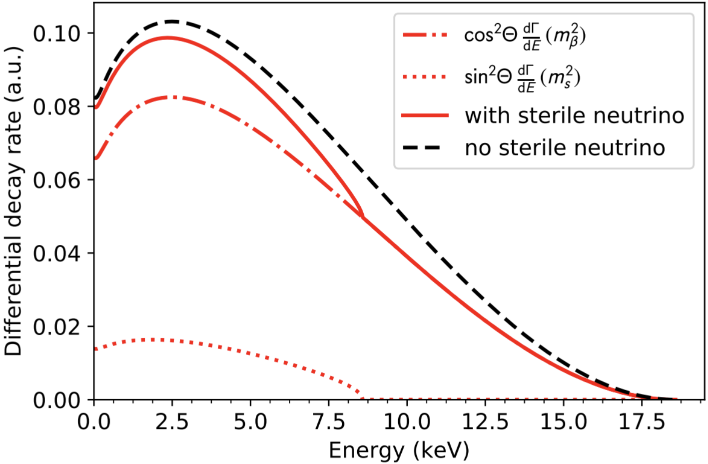


Beyond LHC (PBC report [1901.09966])

• • •

Signature of keV sterile neutrino detection

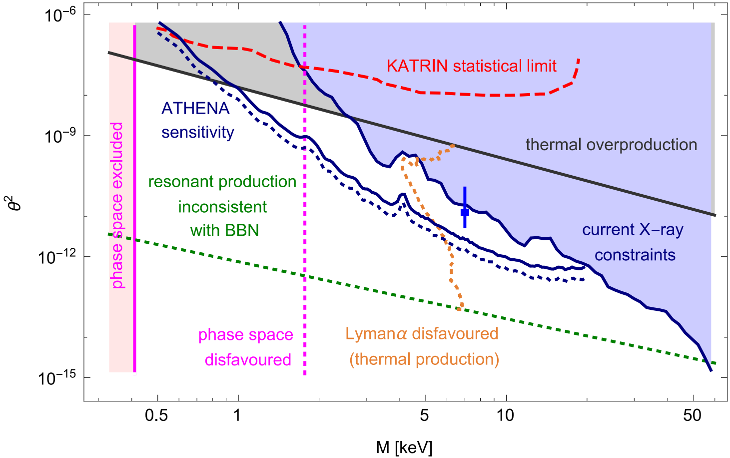
Detection idea: look for a **reaction** T $\to^3$ He $+ e^- + N$



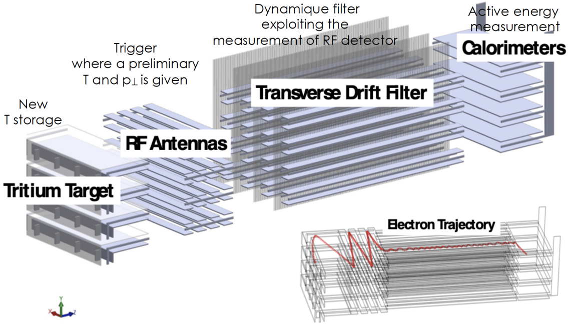
Searching for sterile neutrinos in lab. . .

. . . in the grand scheme of things

Boyarsky, Drewes, Lasserre, Mertens, Ruchayskiy [1807.07938]



PTOLEMY experiment



Goals:

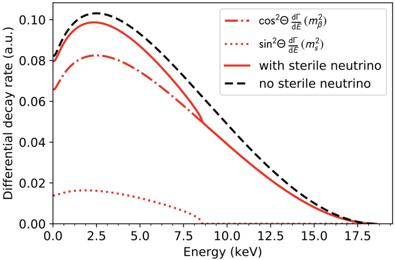
1. Detect CNB
2. Accurate measurement of m_ν (anyway necessary before detecting CNB)
3. eV and/or keV sterile neutrino detection (?)

Key challenges:

1. Statistics: extreme amount of tritium
2. Systematics: extreme energy resolution is required
3. Extreme background rates from the target

Signature of keV sterile neutrino detection

- **Detection idea**: look for a **reaction** T $\to^3$ He $+ e^- + N$
- **Signature**: **[1810.06711]**



- **Main problem**: large background from the regular tritium decay
- **Solution**: more statistics – one has $N_T \sim 10^{25}$, taking 10% of them we can resolve the signal to noise ratio

$$\boxed{\frac{S}{N} \sim \frac{1}{\sqrt{N_T}} \sim 10^{-12}} \qquad (1)$$

- See, however **[Boyarsky, Cheianov, Cheipesh (to appear)]**

Constraining sterile neutrino

- Constraining sterile neutrino in the lab is more than challenging
- Fortunately, sterile neutrino has a number of distinct astrophysical/cosmological signatures that can be used to explore its properties
- Together with laboratory searches for heavier sterile neutrinos this may allow to explore parameter space of the minimal sterile neutrino model

Feebly interacting particles and dark matter

Cosmological mass bound on weakly interacting particles

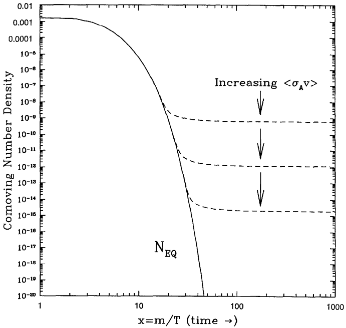
- Original idea of Weakly Interacting Massive Particles (**WIMP** dark matter) goes back to 1977
- **Lee & Weinberg (Phys. Rev. Lett. 1977)**

  "Cosmological lower bound on heavy-neutrino masses"
- **Vysotskii, Dolgov, Zel'dovich (JETP Lett. 1977)**

  "Cosmological limits on the masses of neutral leptons"

- Assume a new **weakly** interacting stable particle (called "heavy neutrino" in the original paper)
- These particles were in **thermal equilibrium** in the early Universe
- They keep the equilibrium number density via annihilation $\chi + \bar{\chi} \leftrightarrow \mathrm{SM} + \mathrm{SM}$
- As Universe expands — DM density drops and annihilation rate decreases
- At some moment **annihilation rate** is not enough to maintain the equilibrium number density $\Rightarrow$ **freeze out**
- WIMP "remembers" density of the Universe at the time of **freeze-out**

Example: light dark matter and light mediators



- The weaker you interact the larger is your number density

$$\Omega_\chi h^2 \sim \frac{3 \cdot 10^{-27}\,\mathrm{cm}^3/\mathrm{sec}}{\langle \sigma_{ann} v \rangle} \qquad (2)$$

- Annihilation cross-section depends on the interaction strength and on the number of final states

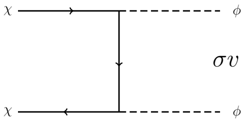
$$\langle \sigma_{ann} v \rangle \sim G_F^2 \; m_\chi^2 \; N_{\text{channels}} \qquad (3)$$

For mass $m_\chi \sim \mathcal{O}(1)$ GeV annihilation into the SM channels leads to a **too small** cross-section $\Rightarrow$ **too large** DM abundance

Lee & Weinberg took G_F as an interaction strength and got the lower bound $m_\chi > 5$ GeV

Light WIMP $\Rightarrow$ extra light states

- Light DM requires more **light** states to annihilate into (scalars, vectors, ...)
- **or** light mediators to increase the annihilation cross-section



$\sigma v \propto g_\chi^4$

$(m_\phi < m_\chi)$

Examples:

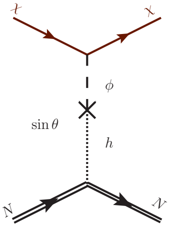
- Light scalar ϕ (scalar portal mediator)

$$\mathcal{L}_{\mathsf{DM}-\phi} = \bar{\chi}\Big(g_\chi + \gamma_5 g'_\chi\Big)\phi\chi$$

- Light vector portal A_μ

$$\mathcal{L}_{\mathsf{DM}-A'} = \bar{\chi}\gamma^\mu A'_\mu\Big(g_\chi + \gamma_5 g'_\chi\Big)\chi$$

- χ – dark matter particle, heavier than (dark) scalar or vector



Light WIMP: extra final states or stronger interaction

Light Dark matter requires

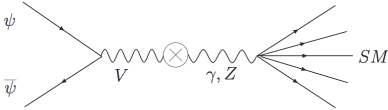
$\langle \sigma_{ann} v \rangle \sim G_F^2 m_\chi^2 N_{\text{channels}}$

- more **light** states to annihilate to
- increasing the interaction strength to above G_F

- To increase annihilation rate we need a new **light** mediator $m_{\text{mediator}} \ll m_W$ with a sizeable coupling to the SM sector

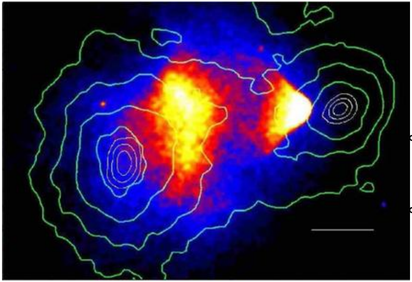
$$G_F \to G_F^{\text{mediator}} = \frac{4\pi\tilde{\alpha}}{m^2_{\text{mediator}}} \qquad (4$$

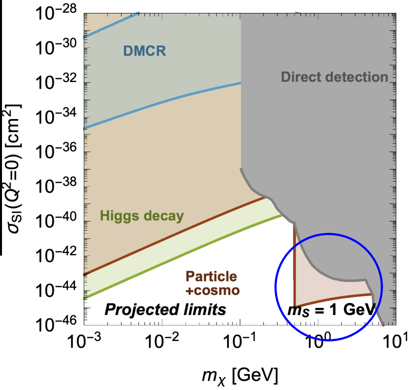
- Different mediators are possible: scalars, vectors, pseudoscalars, fermions, etc
- If dark matter is **lighter** than mediator – LDM annihilates into SM states via off-shell mediator



- Light DM can stay in kinetic equilibrium till low temperatures and in this way suppress the small scale structures **[hep-ph/0612238]**

Scalar portal to light dark matter





[1909.08632], see also **[1512.04119]**

- **Bullet cluster** – "Cosmic collider"
- Leads to the self-interaction bound $\sigma/m < 1\,\mathrm{cm}^2/\mathrm{g}$
- Currently we observe ~ 70 of such merger clusters **[1610.05327]**

non-CDM means new physics

- Thanks to the influx of cosmological data we may learn within the next decade whether dark matter is really
  1. cold (alternatively: warm)
  2. collisionless (alternative: self-interacting)
  3. stable (alternatively: decaying)
- Cosmology can provide unambiguous evidence for/against any of these properties but can tell **little** about particular nature
- non-CDM dark matter likely implies new light (and thus **feebly interacting**) particles
- Particle physics can either discover dark matter particle **or** discover a framework into which we can embed these particles

The synergy of particle physics and cosmology is our way forward if feebly interacting particles exist!