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Sterile Neutrinos

Hiding from the Universe

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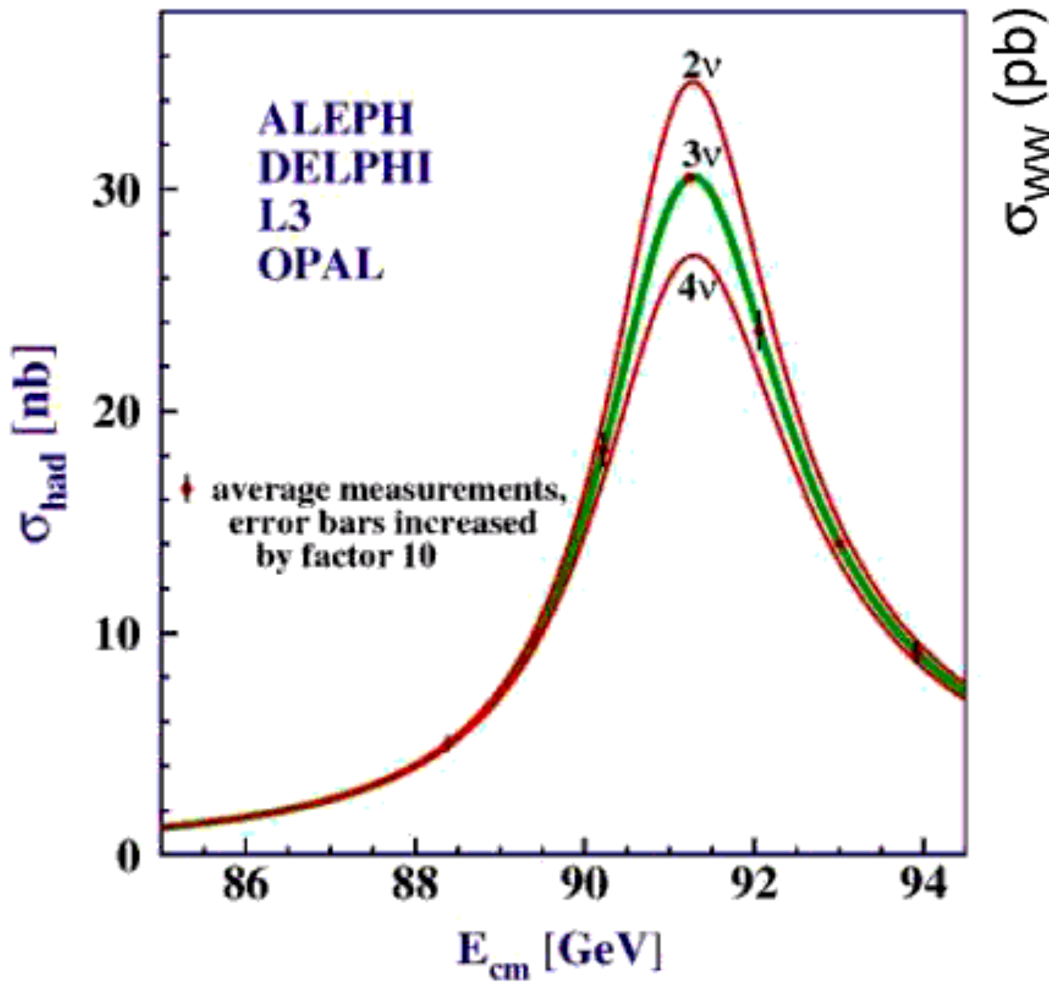
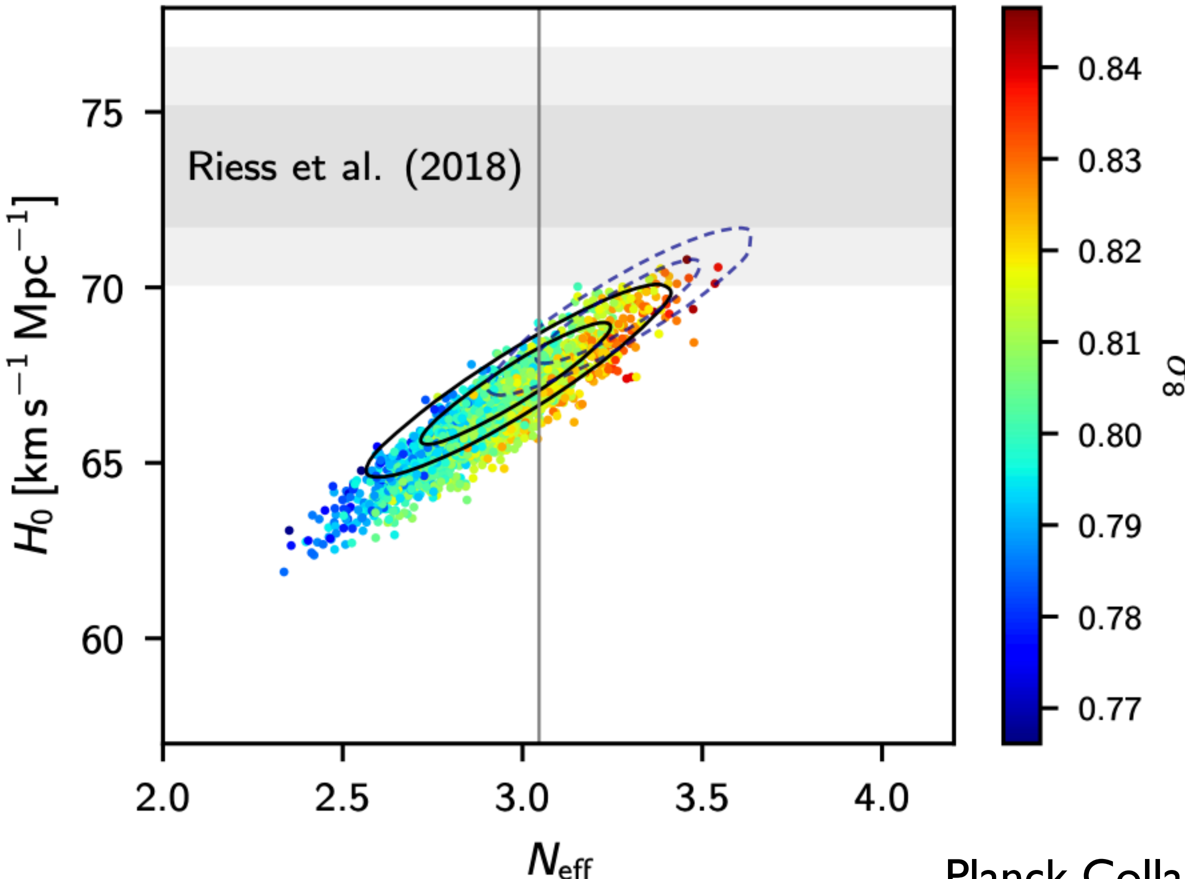
How many neutrinos?
How heavy?
New interactions?

Number of neutrinos



LEP data strongly constraints the number of light active neutrinos to be 3

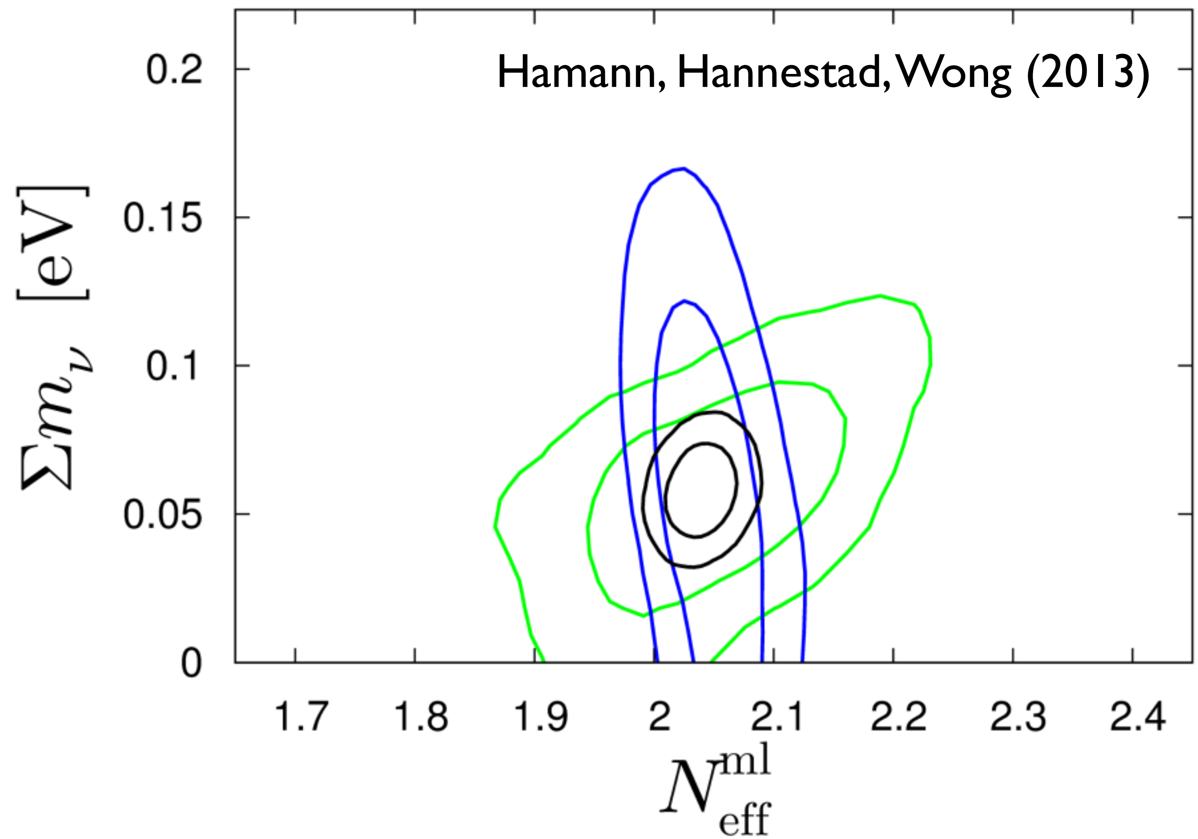
Planck bound on N_{eff}



Planck Collaboration (2018)

One full standard extra neutrino is strongly disfavored

Future measurements of Neff

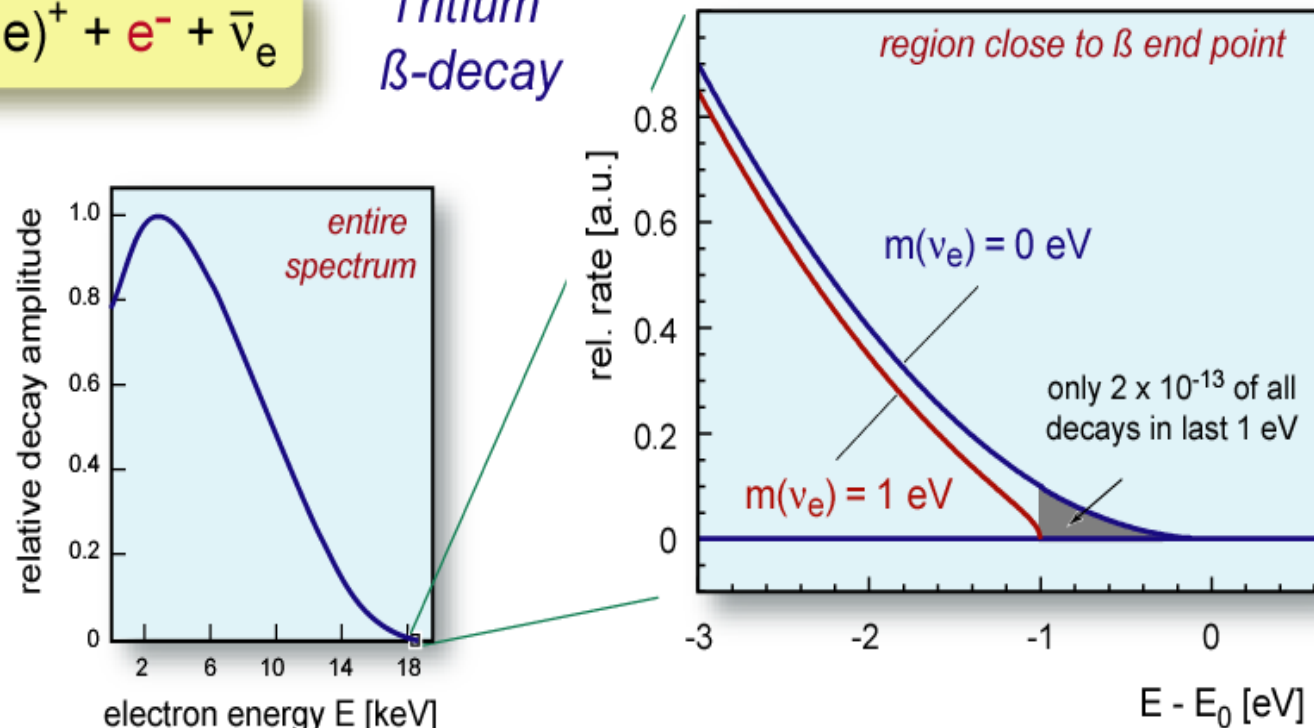


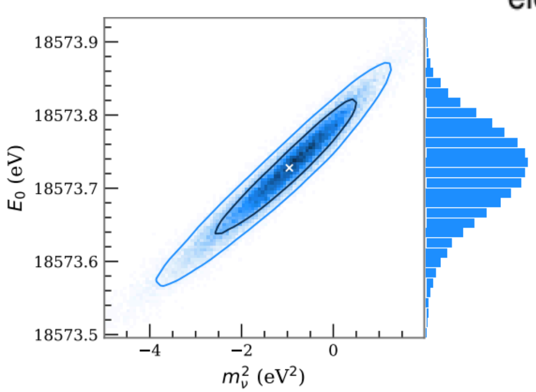
CMB-S4, EUCLID, etc. will measure Neff at level of 0.1
This is a crucial number and rules out a fermion that is hidden using relative cooling

How heavy are neutrinos?

$T_2 \rightarrow (T\,{}^3He)^+ + e^- + \bar{\nu}_e$

Tritium ß-decay



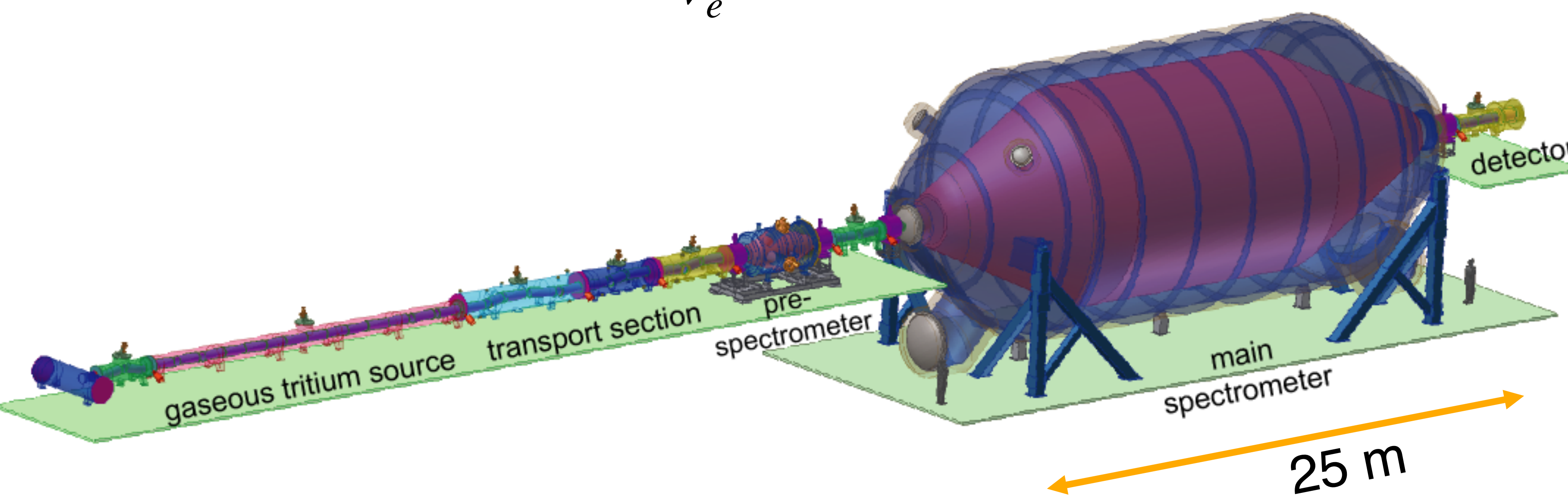


Mnu_e < 1.1 eV => Sum of masses < 3eV (Katrin 2019)
Factor of 2 better than previous result by Mainz

Future prospects

KATRIN will probe sum of neutrino masses down to 0.2 eV

$$\sigma(m_{\nu_e}) \sim 0.2 \text{ eV}$$



Neutrino mass in cosmology

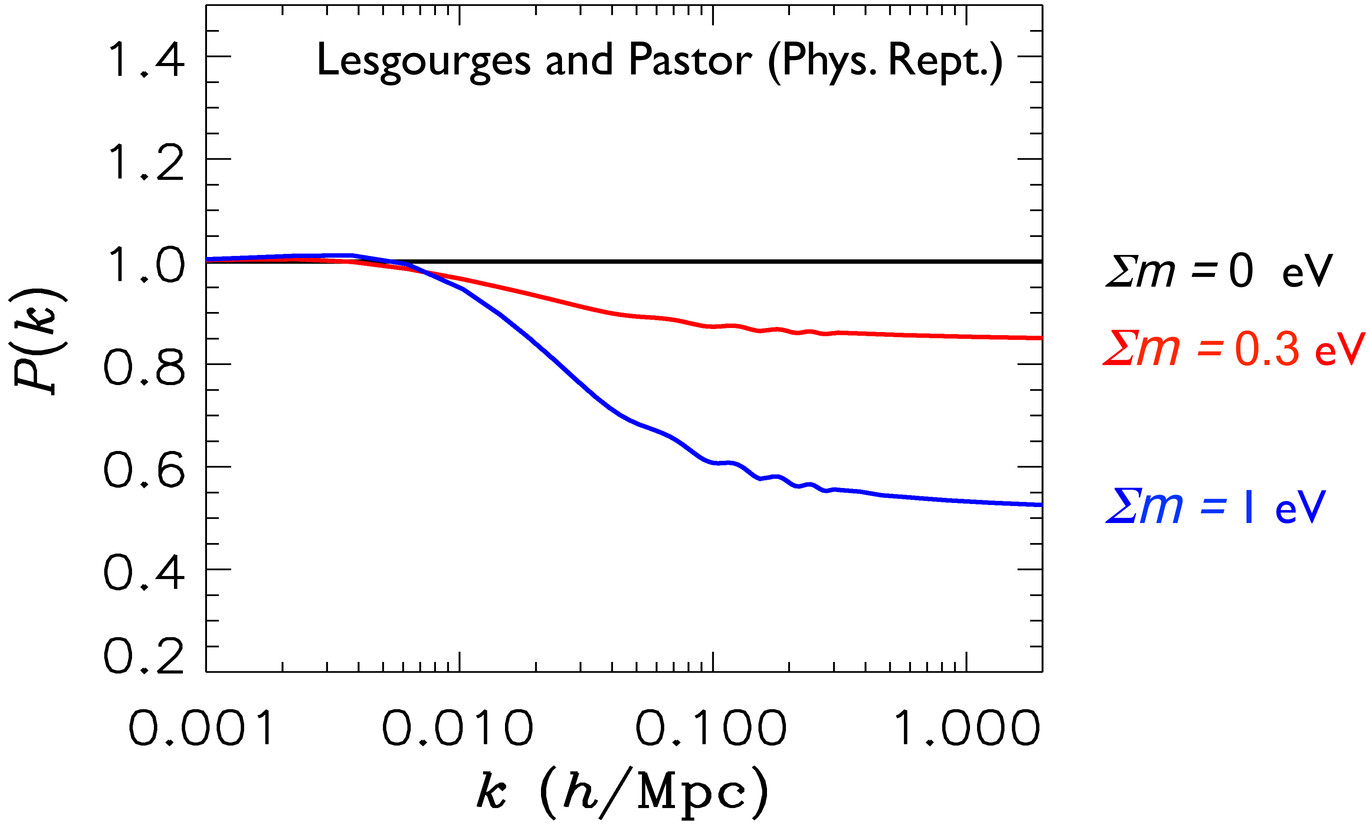
Cosmological structures form due to continued collapse of matter. However, at length-scales smaller than the free-streaming length of any abundant free-streaming species, there is damping of this structure formation.

$$d_{\mathrm{FS}} \sim 1\ \mathrm{Gpc}\ m_{\mathrm{eV}}^{-1}$$

This affects the small length scales (galaxies) and the impact is proportional to the total energy density in this free-streaming species

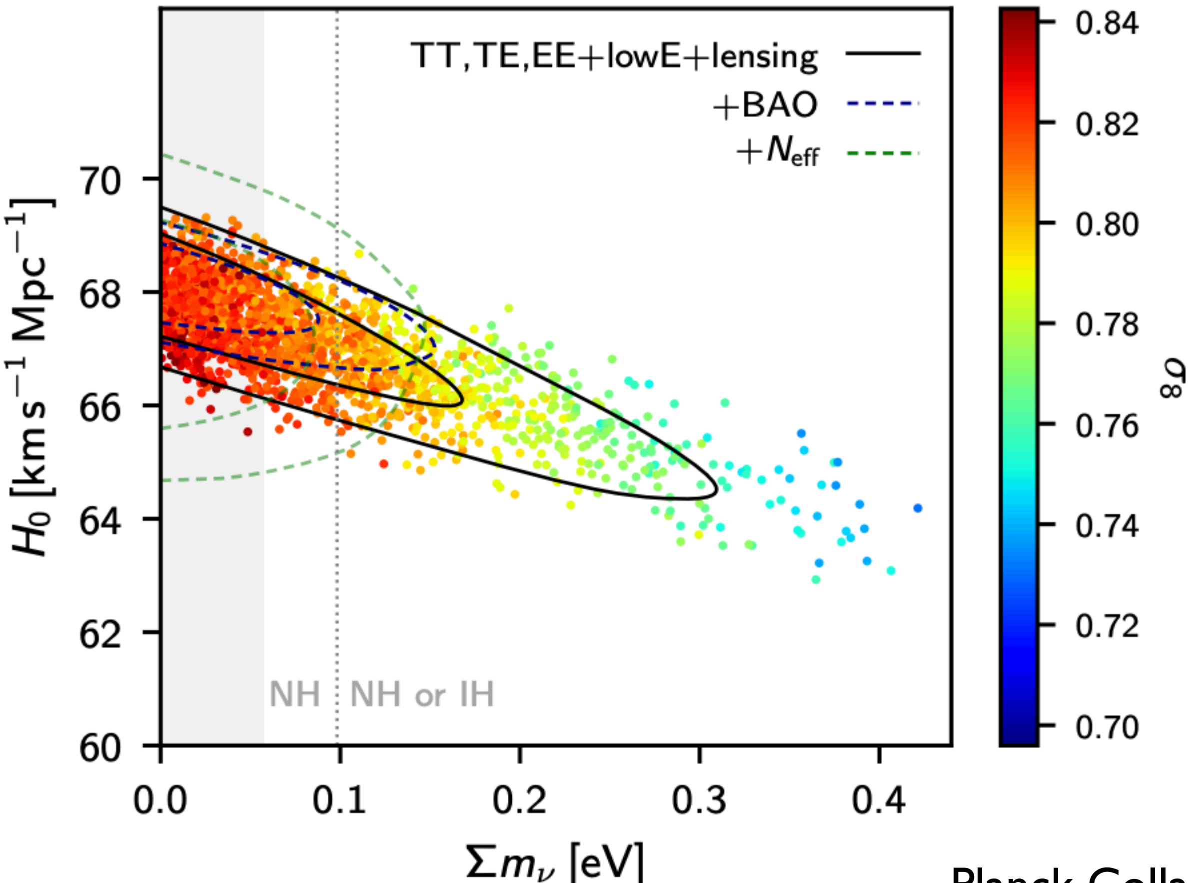
$$\frac{\Delta P}{P_{m=0}}(k >> k_{FS}) \sim -8\,\frac{\rho_\nu}{\rho_{TOT}}$$

Suppression of power



$$\frac{\Delta P}{P_{m=0}}(k >> k_{FS}) \sim -8\frac{\rho_\nu}{\rho_{TOT}}$$

Mass bound from Planck



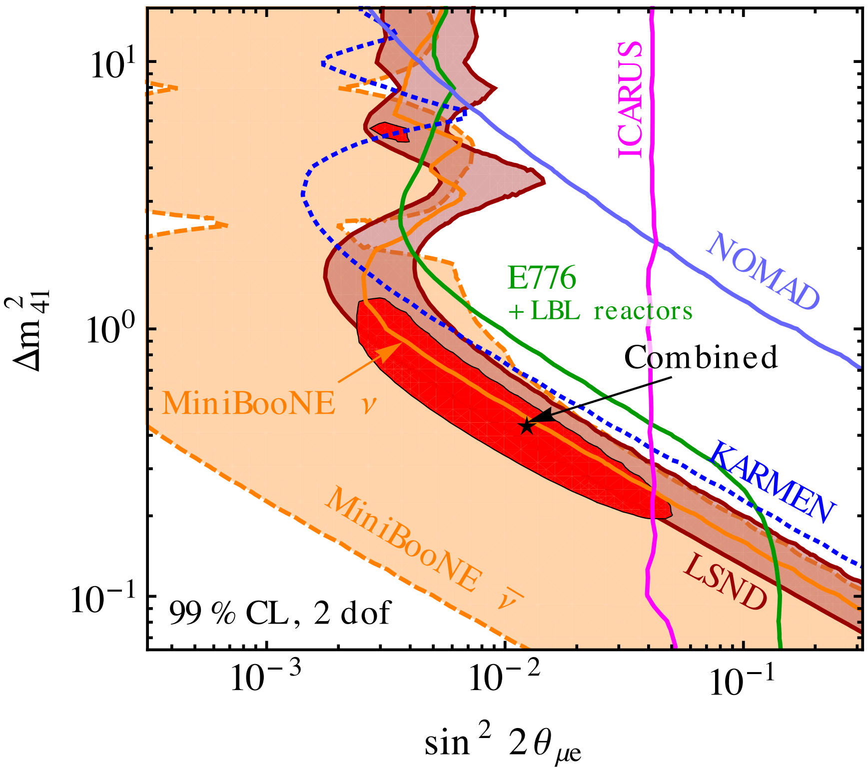
Planck Collaboration (2018)

Sum of Masses ~ 1 eV is strongly disfavored

Why sterile neutrinos ?

- Generic extensions of SM
- Seesaw mechanism
- Baryogenesis via Leptogenesis
- Dark Matter (keV)
- X-ray lines (keV)
- Pulsar kicks (keV)
- Neutrino oscillations (eV)

Sterile neutrinos at 1eV



Global fit give no consistent hint for sterile neutrino if appearance and disappearance are both taken

Only appearance is sort of ok..

Machado, Kopp, Maltoni, Schwetz

Also,

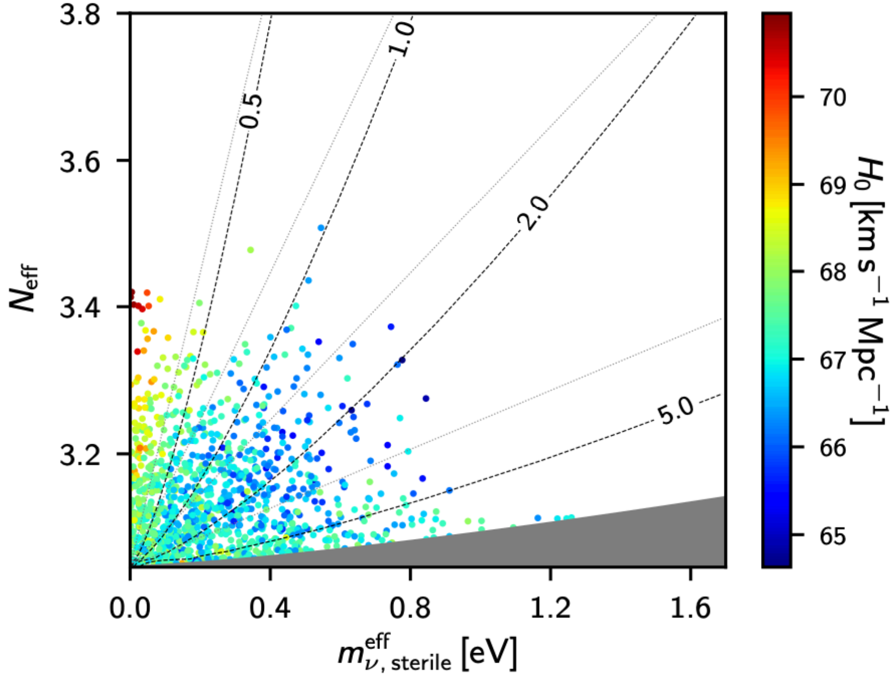
Palazzo;

Giunti, Laveder, et al;

Conrad et al., …

If one takes these neutrino oscillation anomalies seriously, one needs 1 or 2 sterile neutrinos with large mixings

Strong bounds from CMB+LSS



Oscillation-friendly neutrinos are in strong tension with PLANCK alone

Planck Collaboration (2018)

$$\left.\begin{aligned} N_{eff} &< 3.29, \\ m^{eff}_{\nu,\,sterile} &< 0.65\ \text{eV}, \end{aligned}\right\}\ 95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE +lensing+BAO,}$$

Compare to
Planck Collaboration (2015)

$$\left.\begin{aligned} N_{eff} &< 3.80 \\ m^{eff}_{\nu,\,sterile} &< 0.42\,\text{eV} \end{aligned}\right\}\ (95\%;\ \text{CMB+BAO for}\ m^{thermal}_{sterile} < 10\,\text{eV})\,.$$

Related to change in Optical Depth and depends on prior on m

Ways to avoid the constraint

- Large lepton asymmetry
  - Foot and Volkas (1995)
- Majorons
  - Babu and Rothstein (1992), Bento and Berezhiani (2001),
- Very low reheating temperature
  - Gelmini, Palomarez-Ruiz, Pascoli (2004)
- Dilution by decay of exotic heavy particles
  - Fuller, Kishimoto, Kusenko (2011), Ho and Scherrer (2012), …
- ...

The not-so-sterile neutrino

$$\mathcal{L} = e_\nu \overline{\nu_s} \gamma_\mu \nu_s A'_\mu$$

Add to SM a sterile neutrino that has some gauge interaction via a new light gauge boson A.

Initially sterile and active sectors in equilibrium, and decouple at T > 100 GeV.

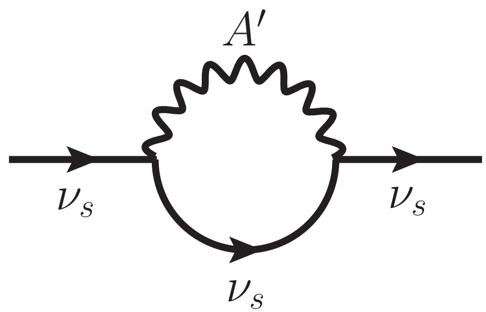
Because of energy injection into photons, $T_s = \left(\frac{g_*(T_\gamma)}{g_*(\mathrm{TeV})} \right)^{1/3} T_\gamma$

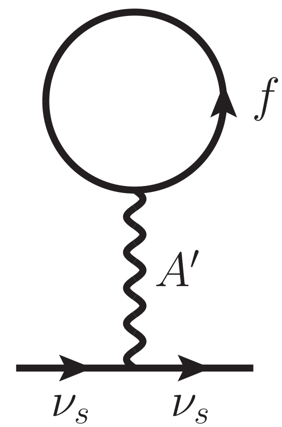
Leads to extra N_eff ~ 0.2 not ruled out by any data yet but discoverable soon

What about oscillations?

Hansen, Hannestad, Tram (PRL, Editors Sugestion, 2014)
Dasgupta and Kopp (PRL, Editors Sugestion, 2014)

Thermal masses

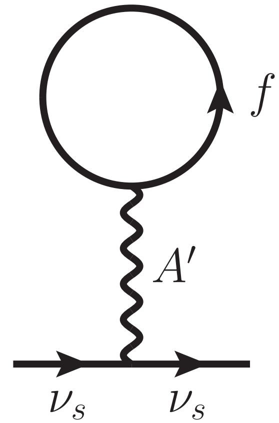




Sterile neutrinos acquire a "thermal mass" due to their interactions with virtual/real gauge bosons which can be quite large at high-T.

They are not produced by oscillations if this mass exceeds the active-sterile neutrino oscillation frequency.

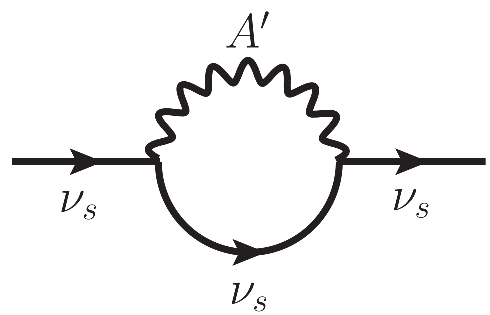
Thermal masses



$$V_{\rm eff}^{\rm tadpole} \simeq \frac{2\pi\alpha_\chi}{M^2}(n_f - n_{\bar{f}})$$

Usual MSW term. We could assume an asymmetry in sterile neutrinos. Let's not.

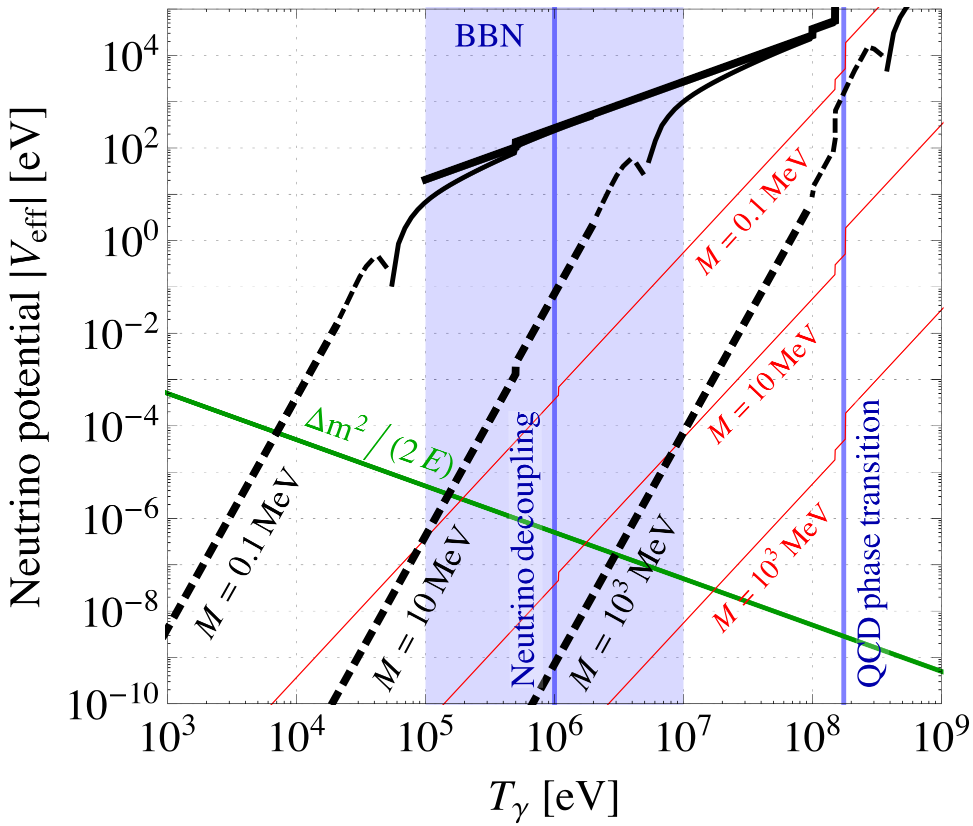
Thermal masses



$$V_{\rm eff}^{\rm bubble} \simeq \begin{cases} -\dfrac{28\pi^3\alpha_\chi E T_s^4}{45M^4} & \text{for } T_s, E \ll M \\ \\ +\dfrac{\pi\alpha_\chi T_s^2}{2E} & \text{for } T_s, E \gg M \end{cases}$$

Purely thermal contribution. Exists even with no asymmetry.

Thermal MSW potential



If M < 10 MeV the thermal potential can be large

Dasgupta and Kopp (2014)

MSW suppression

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos 2\theta_0 + \frac{2E}{\Delta m^2} V_{\text{eff}}\right)^2 + \sin^2 2\theta_0}$$

$$|V_{\text{eff}}| \gg \left| \frac{\Delta m^2}{2E} \right|$$

No production by oscillations. Also thermalization rate is similarly suppressed.

N_{eff} is increased by ~0.5 due to sterile neutrinos at BBN (much less at CMB)

Dasgupta and Kopp (2014)

Some comments

- Detailed dynamics should consider MSW resonances
- Adiabaticity effects
- Non-forward scattering processes
- Sterile neutrino decoupling is slightly earlier than 1 MeV due to mixing angle suppression
- Tails of the thermal distribution
- $V << T$, so relativistic approximation holds

Full QKE

$$\dot{\mathbf{P}} = \mathbf{V} \times \mathbf{P} - D(P_x \mathbf{x} + P_y \mathbf{y}) + \dot{P}_0 \mathbf{z} \ ,$$

$$\dot{P}_0 = \Gamma \left[\frac{f_{\rm eq}}{f_0} - \frac{1}{2}(P_0 + P_z) \right]$$

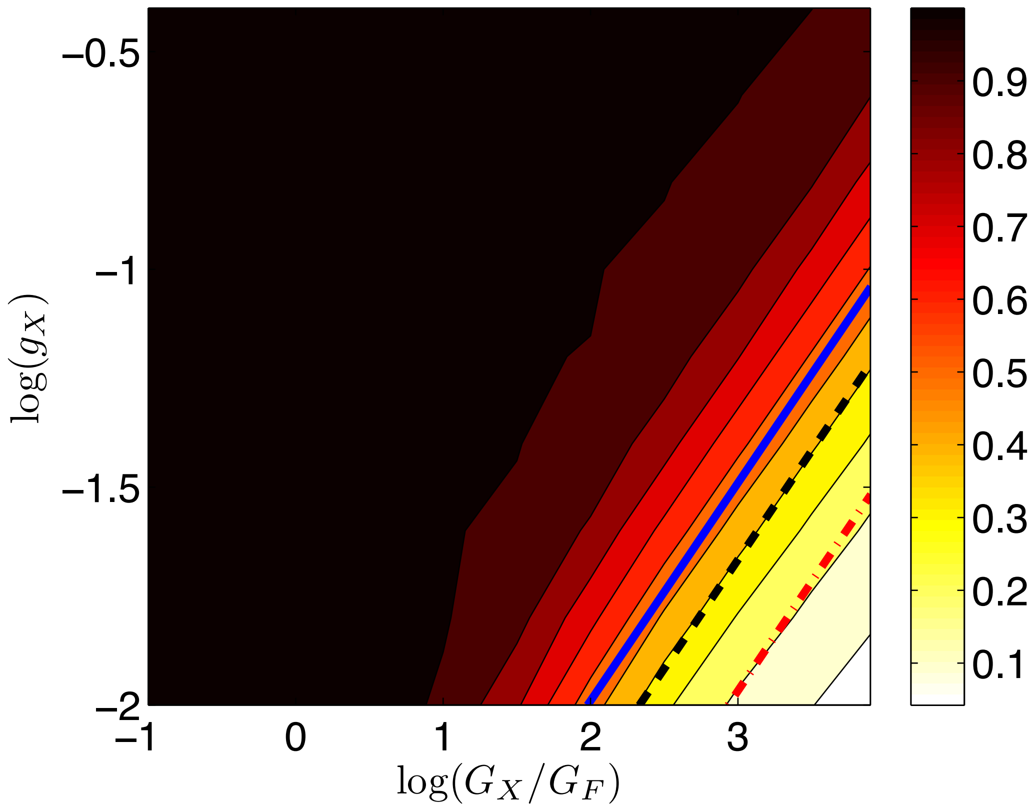
Besides oscillations, scattering processes also taken into account. The scattering rate is

$$\Gamma = C_a G_F^2 x T^5$$

$$D = \frac{1}{2}\Gamma \ .$$

Hansen, Hannestad, Tram (2014)

Fractional dofs from QKE



For ~100 MeV boson
One can easily suppress
N_eff to below 0.5

Hansen, Hannestad, Tram (2014)

On an unrelated note ...

Small scale problems with CDM?

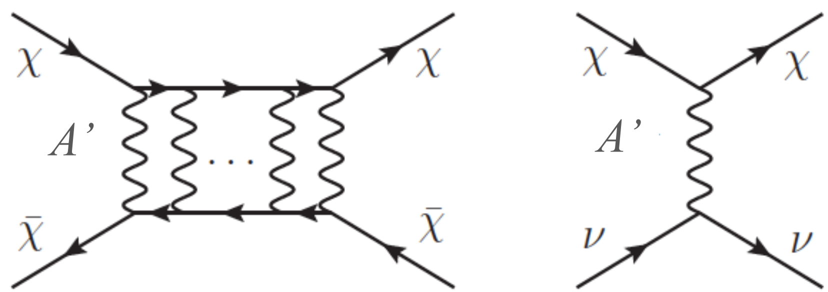
- Baryonic effects (Reionization, SN Feedback,…, Tidal stripping…)
  - DM core creation + Tidal stripping (TBTF)
  - Faint galaxies + Reionization (only MSP)
- Yukawa interactions of DM (can't solve MSP)
- DM-neutrino interactions (strong constraints)
- …

A DM-Neutrino connection

$$\mathcal{L} = e_\chi \overline{\chi} \gamma_\mu \chi A'_\mu + e_\nu \overline{\nu_s} \gamma_\mu \nu_s A'_\mu$$

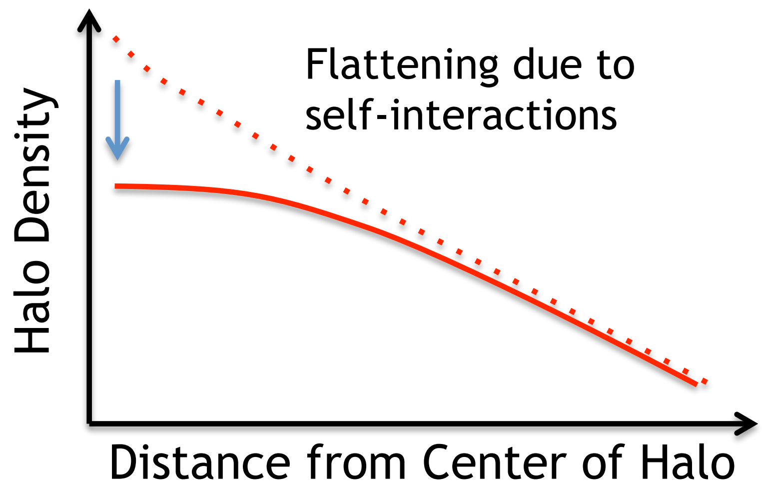
Assume that the new force couples to DM as well (coupling is taken to be same)

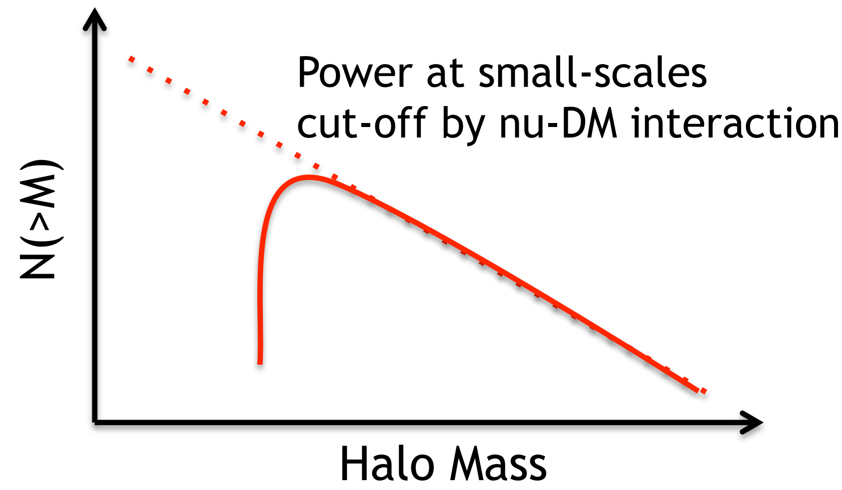
No new parameters are introduced.



Two new processes are automatically expected

A neutrino-tempered DM





Core-Cusp problem solved using self-interactions. TBTF is also solved.

Missing Satellites solved using DM interactions with neutrinos, that leads to late kinetic decoupling

Van den Aarssen, Bringmann, Pfrommer (2012); Dasgupta and Kopp (2014)

Smoothening DM cusps

Dwarf-sized halos do not have cusps due to DM-DM interactions mediated by A'.

What one needs is then DM-DM scattering cross section at the level of 0.1 cm^2 / g for velocities of dwarf galaxies (10 km/s).

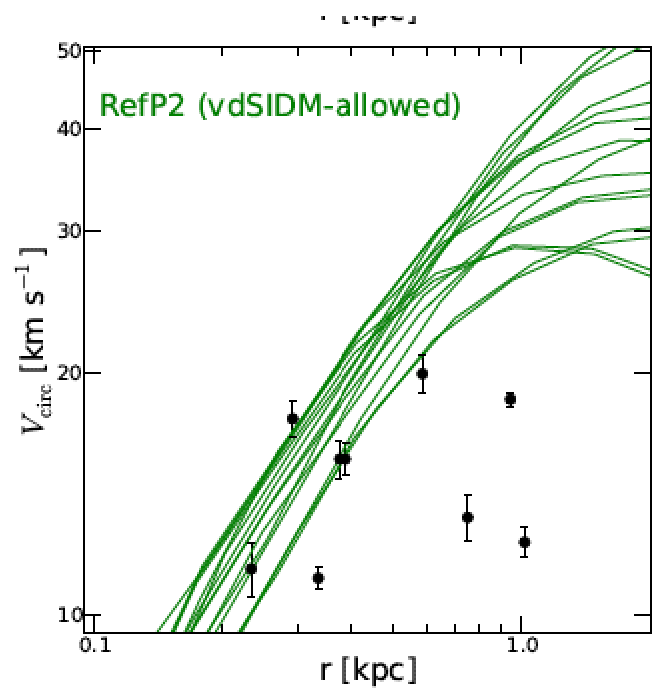
Feng, Kaplinghat, Tu, Yu (2009); Loeb and Weiner (2011)

This is easily achieved by having a light mediator A' that enhances the cross section.

Addressing the TBTF problem

Dwarf-sized subhalos inside MW do not have cusps due to DM-DM interactions mediated by A'.

What one needs is then DM-DM scattering cross section at the level of 0.1 cm^2 / g for velocities of dwarf galaxies (10 km/s). This is the same condition as that for solving the core-cusp problem.



Zavala, Vogelsberger, Loeb (2012)

Explaining the missing satellites

The sterile neutrino-DM scattering keeps DM in kinetic equilibrium until somewhat later ($T_\chi/m_\chi\ n_\nu\ \sigma_{\nu\chi}$) ~ H

This erases structure at the smallest scales, and the smallest (dwarf) halos never form.

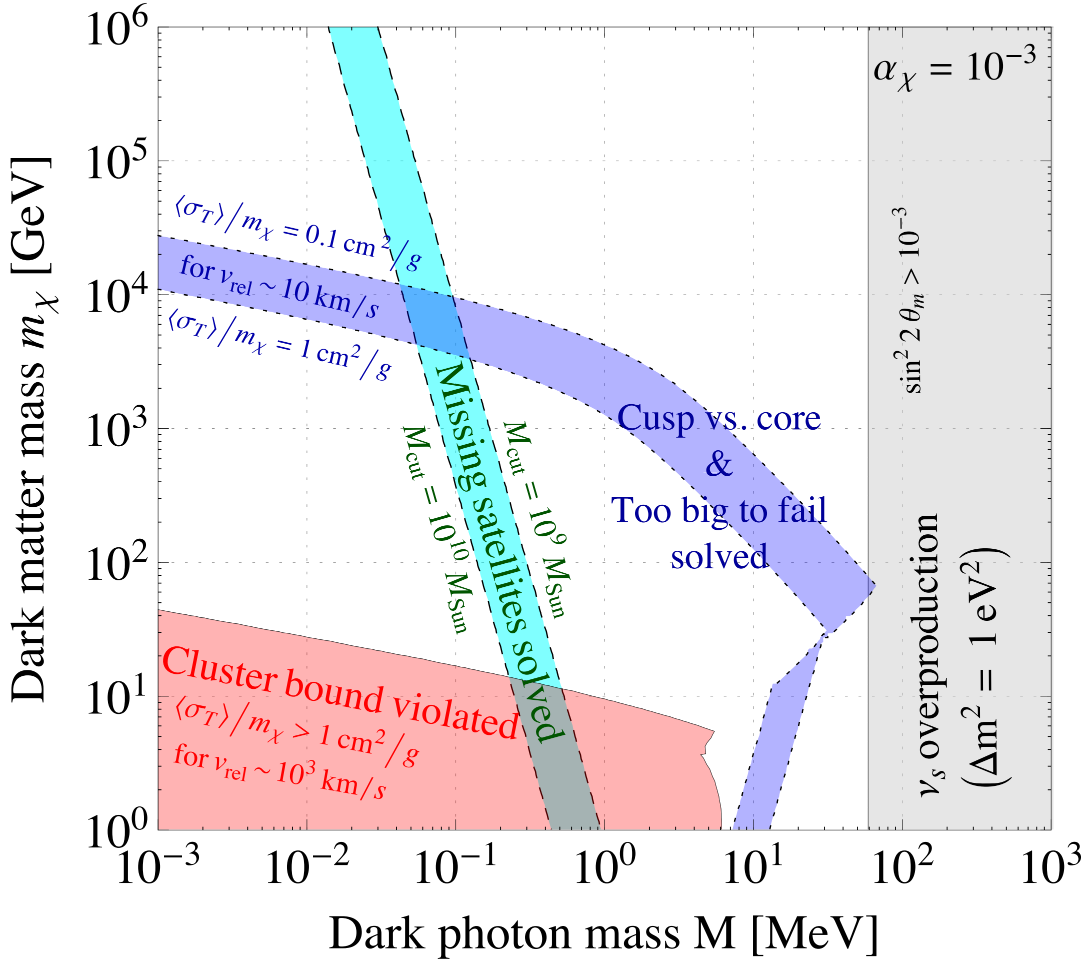
Boehm, Fayet, Schaeffer (2000); Loeb and Zaldarriaga (2005)

What one needs is then M_cut ~ 10^9 solar masses or so.

$$\frac{M_{\rm cut}}{M_{\rm Sun}} \simeq 3.2\times 10^{13}\,\alpha_\chi^{\frac{3}{2}}\left(\frac{T_s}{T_\gamma}\right)_{\rm kd}^{\frac{9}{2}}\left(\frac{\rm TeV}{m_\chi}\right)^{\frac{3}{4}}\left(\frac{\rm MeV}{M}\right)^3 .$$

One needs a spin-1 mediator for this to work. Scalars lead to a m/E suppressed effect.

DM-Neutrino concordance

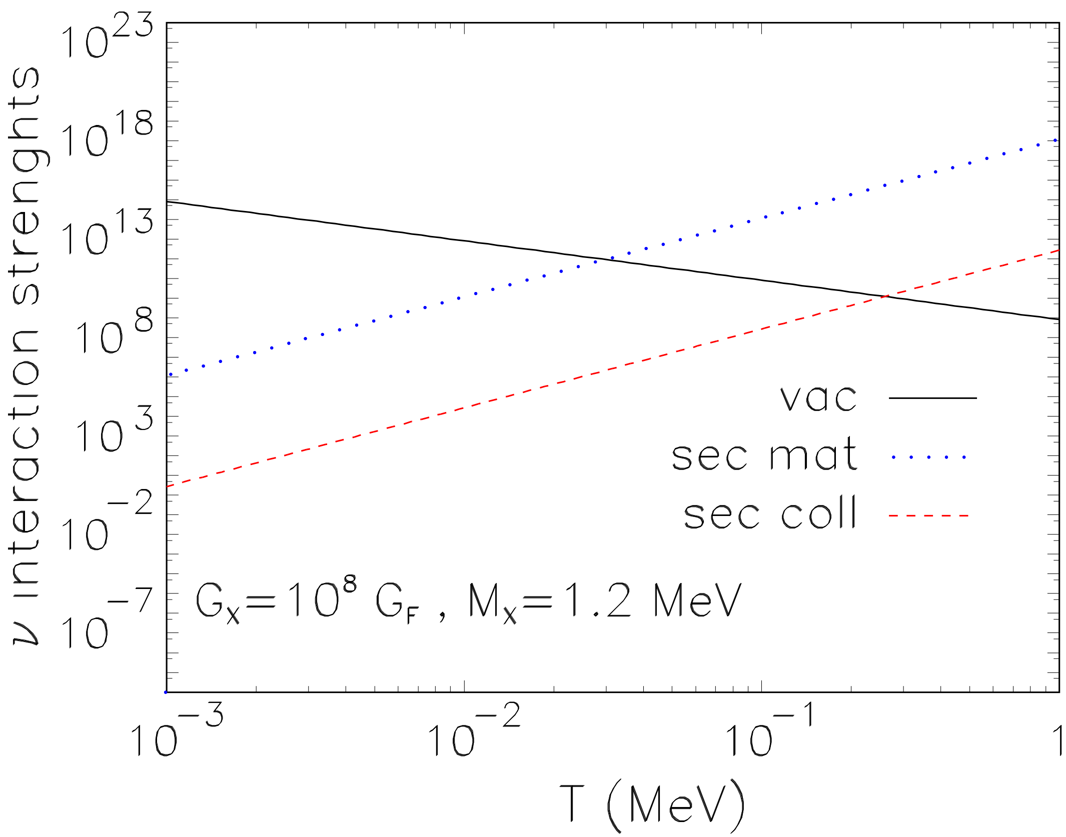


One can explain N_{eff}, Neutrino Oscillations, and All 3 DM problems, simultaneously

Dasgupta and Kopp (2014), see also Bringmann, Hasenkamp, Kersten (2014)

Post-BBN thermalization

Mirizzi, Mangano, Pisanti, Saviano (2014)



$$\nu_1 \nu_4 \leftrightarrow \nu_4 \nu_4$$

$$\nu_1 \overline{\nu}_4 \leftrightarrow \nu_4 \overline{\nu}_4$$

For ~1 MeV boson,
one equilibrates sterile
and active neutrinos through
collisional decoherence

In some cases tension with
mass bounds ☹

Collisional sterile neutrinos?

The suppression of power on occurs at scales smaller than those over which the neutrinos can transport energy

$$\lambda_s^2 = (\lambda_s^{\rm coll})^2 + (\lambda_s^{\rm fs})^2$$

$$(\lambda_s^{\rm coll})^2 \simeq \int_0^{t_s^{\rm dec}} dt \, \frac{\langle v_s \rangle^2}{a^2(t)} \frac{1}{n_s \langle \sigma v \rangle_s}$$ Diffusion

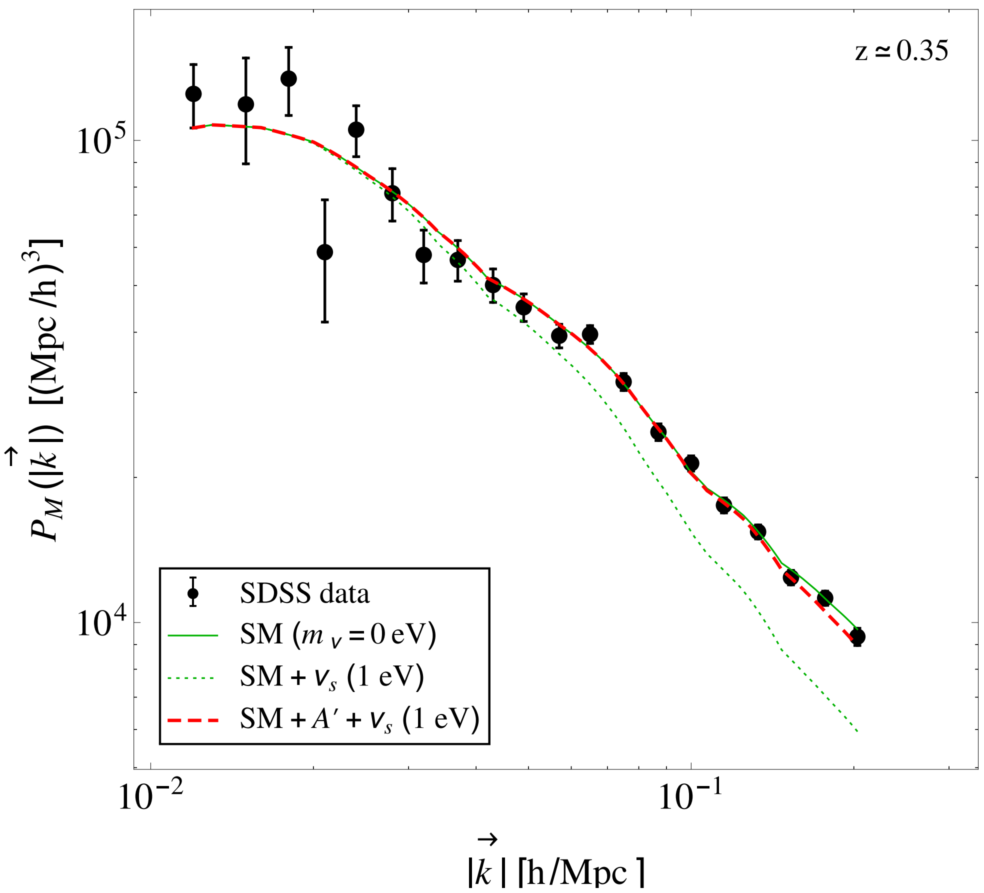
$$\lambda_s^{\rm fs} = \int_{t^{\rm dec}}^{t_0} dt \, \frac{\langle v_s(t) \rangle}{a(t)}$$ Free-stream

Without interactions: $$k_s^{\text{no self-int.}} \simeq 0.018 \sqrt{\frac{m}{\rm eV}} \, h/{\rm Mpc}$$

With interactions for eV sterile: $$k_s \equiv 2\pi/\lambda_s \simeq 0.085 \; h/{\rm Mpc} \, .$$

A factor of 5 larger k where smearing becomes important. So constraints avoided.

SDSS constraint on neutrino mass



1 eV neutrinos are strongly constrained by SDSS data, but not if they are "collisional"

Chu, Dasgupta, and Kopp (2015)

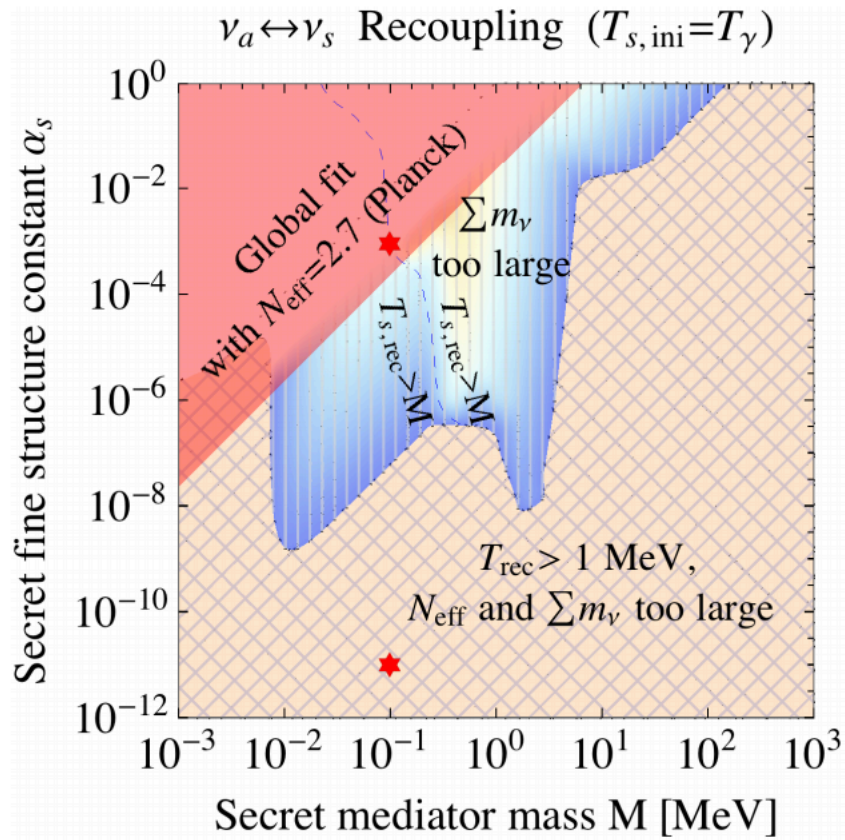
Hidden interactions are dead

There is NO region in parameter space of coupling and mediator mass where an eV sterile does not violate the mass bound

Cherry, Shoemaker, Friedland (2016)

The collisional sterile makes active neutrinos NOT freestream via mixing, and CMB forbids it

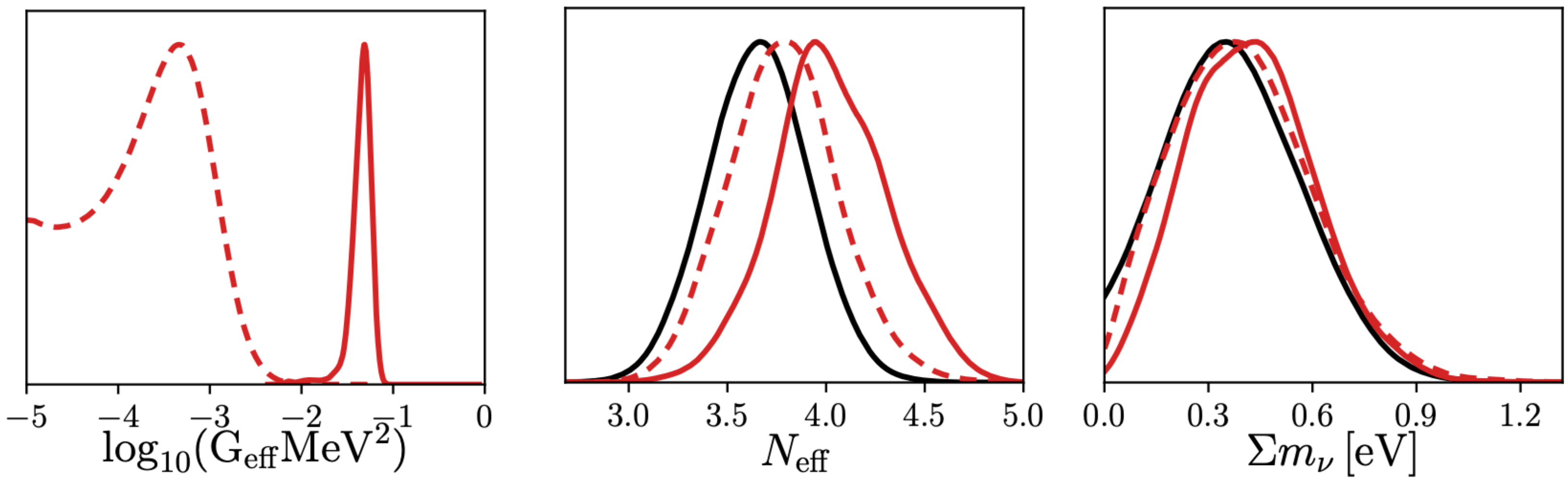
Forastieri, Lattanzi, Mangano, Mirizzi, Natali, Saviano (2017)
Archidiacono & Hannestad (2013)



Chu, Dasgupta, Dentler, Kopp, Saviano (2018): ugly loopholes!

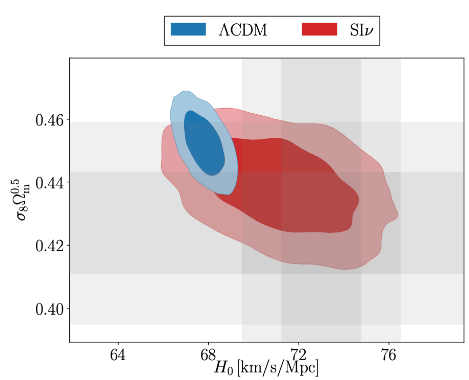
Lot of related work … cited in the paper
See e.g., Tang (2015), Song, Gonzales-Garcia, Salvado (2018), …

Long live hidden interactions …



Kreich, Cyr-Racine, Dore (2019)

This is largely driven by latest polarization data and the Hubble tension. The overall fit is statistically better than base LambdaCDM.



See also
Oldengott, Rampf, Tram, Wong (2017)
Lancaster, Cyr-Racine, Knox, Pan (2018)

Initial milder hints:
Cyr-Racine Sigurdson (2013)
Archidiacono, Hannestad (2013)

New avatars: Coupled to ultralight DM

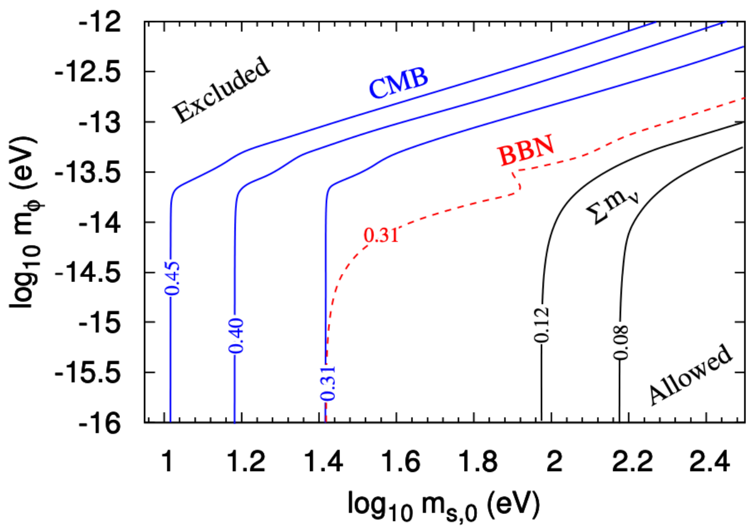
Farzan (2019): Couples to Neutrino Gives Time-Dep Mass

$$\lambda \phi \nu_s^T c \nu_s + \text{H.c.} \qquad m_{eff} = \lambda \frac{\sqrt{2\rho_\phi}}{m_\phi} \cos(m_\phi t)$$

In early Universe the mass is too large to be produced by oscillations. Later, can even decay.

Cline (2019):

$$\frac{1}{2}\lambda \bar{\nu}_s \phi \nu_s \qquad m_{\text{eff}} = m_{ss} + \lambda\phi$$



Few eV sterile, with order 1 mixing is still viable, if it couples to an ultralight scalar (instead of A')

The "sterile neutrino" is not dead, just hiding

Take Away

Secret interactions can hide sterile neutrinos in cosmology. This is not only viable but can be done simply and has other testable observable signatures.