Sterile Neutrinos as Dark Matter

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Particle physics

neutrinos have mass → new particles

Cosmology

unknown Dark Matter particle

Astrophysics

unknown supernova physics

Common explanation?

Neutrino Masses

Neutrino masses suggests the existence of right-handed degrees of freedom, the sterile neutrinos

$$\nu_e,\ \nu_\mu,\ \nu_\tau,\ N_1,\ N_2,\ N_3,\ \ldots.$$

The SM Lagrangian extended to include the new states

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a i \partial\!\!\!/ N_a - y_{\alpha a} \varepsilon^{ij} H_i (\bar{L}_\alpha)_j N_a - \frac{M_a}{2} \bar{N}_a^c N_a + h.c.$$

What is *M*?

Seesaw mechanism

New mass-mixing matrix

$$\widetilde{M} = \begin{pmatrix} 0 & D_{3\times n} \\ D^{T}_{3\times n} & M_{n\times n} \end{pmatrix}$$

Eigenvalues separate into two groups:

$$m_\nu \sim \frac{D^2}{M} \quad \text{and} \quad M$$

The smallness of active neutrino masses can be due to

large D large M	or	small D small M

Majorana masses

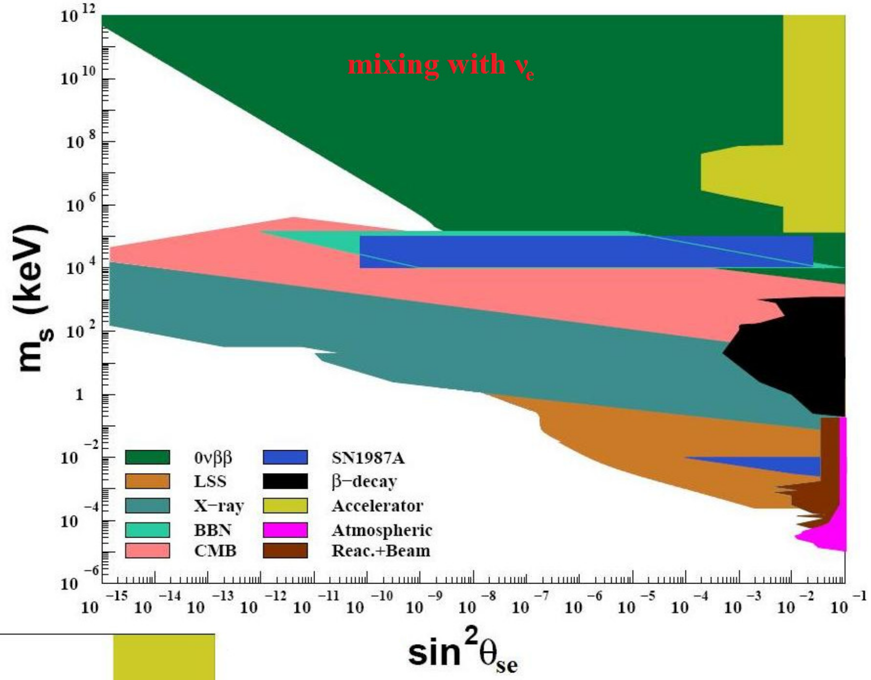
$D_{\alpha a} = y_{\alpha a} \langle H \rangle$

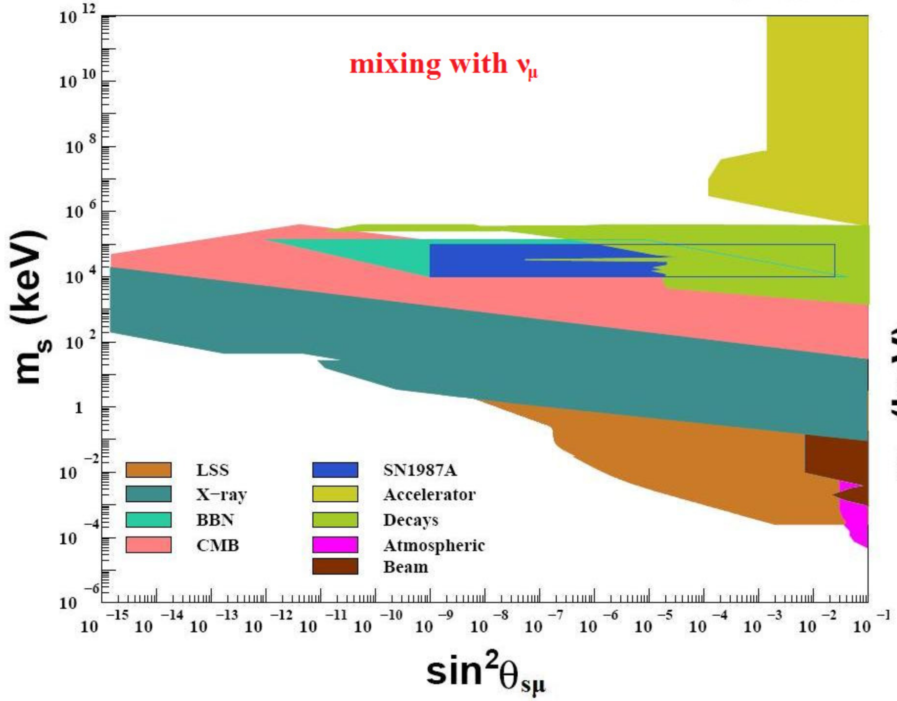
Theory of Yukawa couplings unknown.

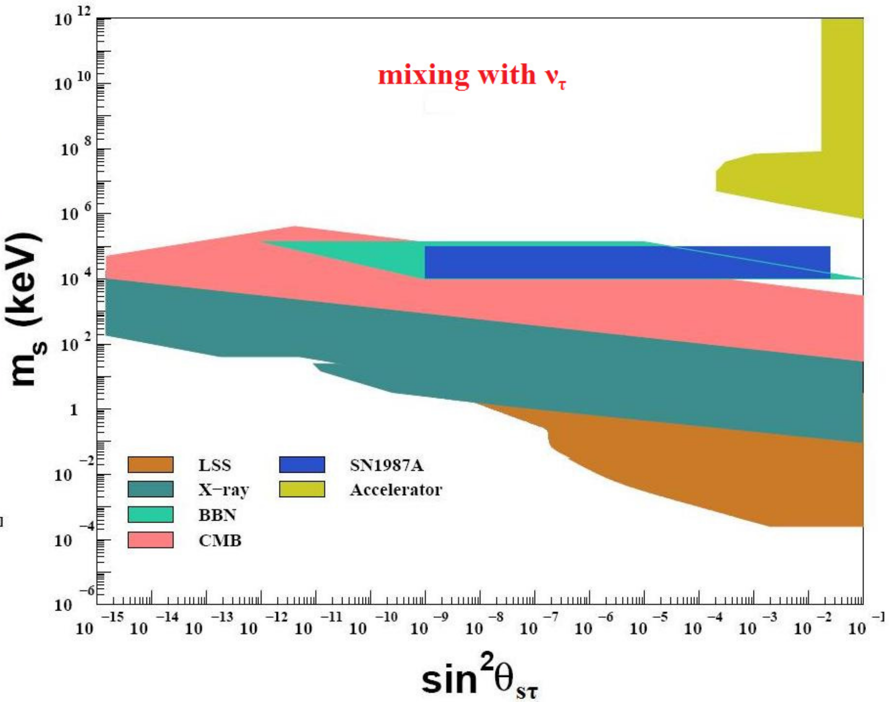
They can be $y \ll 1$ or $y \sim 1$

⇨ *M* can be anything

Consider all allowed values for sterile neutrino masses







Majorana masses

Some may be small, some may be large:

- If $M \gg M_W$, sterile neutrinos are practically unobservable.
- If $M < M_W$, sterile neutrinos can take part in a lot of observable phenomena ➔ study phenomenology.

Sterile-neutrino Dark Matter

A sterile neutrino
of a few keV
can be
Dark Matter

Interesting candidate:

- Light and stable
- Warm Dark Matter candidate

It may also play a role in:

- Pulsar Kicks [Kusenko, Segre]
- Star Formation [Biermann, Kusenko; Stasielak et al.]

Sterile-Neutrino Dark Matter

Production mechanisms.

Small-scale galactic structure. Limits.

Detection and Bounds.

Astrophysical role of keV sterile neutrinos.

Production Mechanisms

Sterile neutrinos can be produced in the early universe via:

- Oscillations, @ $T_{prod} \sim 150$ MeV
  - Off-resonance [Dodelson, Widrow]; almost thermal spectrum.
  - On-resonance, if lepton asymmetry large [Fuller, Shi]; non-thermal spectrum →"Cool DM"

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- Decays of heavy bosons
  - inflaton decays [Shaposhnikov, Tkachev]
  - Higgs decays at the electroweak scale [Kusenko, KP]

Sterile neutrino production via decays

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N} i \partial\!\!\!/ N - y H \bar{L} N - \frac{M}{2} \bar{N}^c N + h.c.$$

In the SM, fermion masses arise via the Higgs mechanism. Can the Majorana masses of sterile neutrinos arise in the same way?

Sterile neutrino production via decays

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{N} i \partial\!\!\!/ N + \frac{1}{2}(\partial S)^2 - y H \bar{L} N - \frac{f}{2} S \bar{N}^c N - V(H,S) + h.c.$$

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The Majorana masses arise after SSB

$$M = f\langle S \rangle$$

Sterile neutrinos are produced by *S* decays

$S \rightarrow N\,N$

The features of the model

I. Ω_N: No dependence on the mixing angle.

The features of the model

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DM particle mass and production scale are correlated.

$$\begin{aligned} m_{\rm N} &= f\langle S\rangle \\ T_{\rm prod} &\sim m_{\rm S} \sim \langle S\rangle \;\Rightarrow\; \Omega_{\rm N} \sim 0.2\left(\frac{f}{10^{-8}}\right)^3\left(\frac{\langle S\rangle}{m_{\rm S}}\right)\left(\frac{33}{\xi}\right) \\ \Gamma_{\rm S\to N\,N} &= \frac{f^2 m_{\rm S}}{16\pi} \end{aligned}$$

The result is

$$\begin{aligned} m_N &\sim \text{few keV} \\ \langle S\rangle &\sim 10^2\ \text{GeV} \end{aligned}$$

Implications for
- Electroweak phase transition.
- Small-scale structure properties of sterile neutrino DM.

The features of the model

I. Ω_N: No dependence on the mixing angle.
DM particle mass and production scale are correlated.

II. Simple extension of the Higgs sector, with a real singlet field, that has been studied for

- Baryon Asymmetry of the Universe (1st order phase trans.)
- Dark Matter (scalar)
- LHC signatures

The extended Higgs sector

$$V(H,S) = -\mu_H^2|H|^2 + \lambda_H|H|^4 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + 2\lambda_{HS}|H|^2 S^2 + \frac{1}{6}\alpha S^3 + \omega|H|^2 S$$

If *SNN* coupling <u>not</u> included

- No Z_2 symmetry
  - 1^{st} order phase transition possible → BAU
  - S boson unstable → no DM candidate
  - LHC signatures
- Z_2 symmetry imposed
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[Profumo, Ramsey-Musolf, G. Shaughnessy (2007); Barger et al. (2008)]

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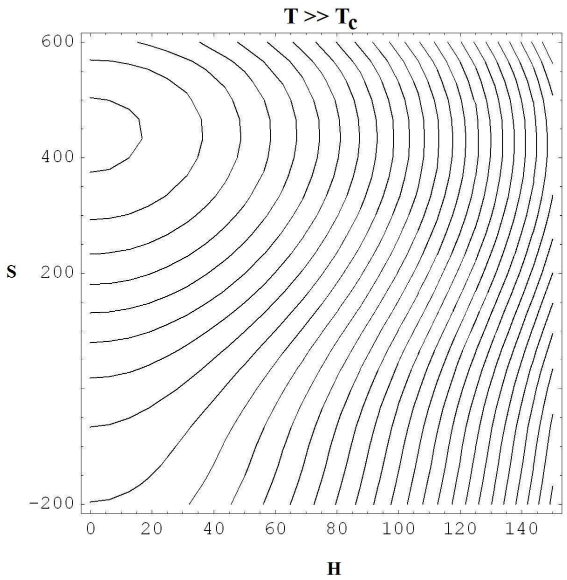
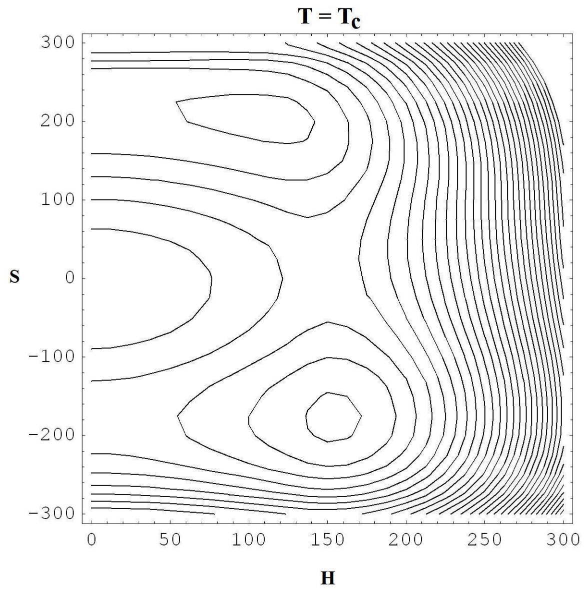
If *SNN* coupling included

- **No Z_2 symmetry**
  - **1^{st} order phase transition possible → BAU**
  - **S boson unstable → sterile neutrinos can be DM**
  - **LHC signatures**

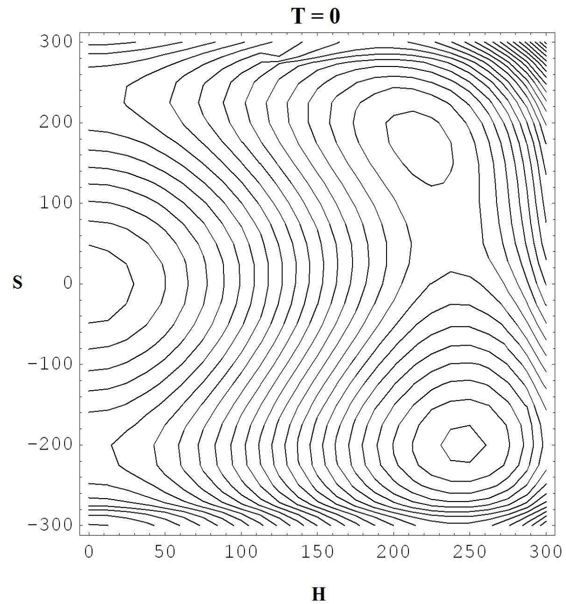
The Electroweak Phase Transition



$$S \neq 0, H = 0$$



2nd order PT to $H \neq 0$



1st order PT to the true vacuum

[KP, Kusenko (2008)]

The features of the model

I. Ω_N: No dependence on the mixing angle.
   DM particle mass and production scale are correlated.

II. Simple extension of the Higgs sector, with a real singlet field, that provides for BAU, DM and LHC signatures.

III. Sterile-neutrino DM produced is colder than DM produced via oscillations, and thus has different small-scale structure properties.

Thermal content of DM sterile neutrinos

Producing the right amount of DM fixes the coupling of sterile neutrinos to the Higgs sector

$$f \sim 10^{-8}$$

This is very weak coupling and sterile neutrinos are produced and remain always out of equilibrium.

At the EW scale all of the SM degrees of freedom are thermally coupled to the universe. As they decouple, they release entropy, which reheats the universe but not the out-of-equilibrium species, e.g. sterile neutrinos.

Sterile neutrinos are diluted and redshifted.

Dilution

$$\xi = \frac{g_*(T_{\rm prod})}{g_*(T_{\rm today})} = \frac{110}{3.36} \simeq 33$$

$$\left.\frac{\langle p_{\rm N}\rangle}{3.15T}\right|_{\rm T_{prod}} = 0.8$$

Redshift

$$\Downarrow$$

$$\left.\frac{\langle p_{\rm N}\rangle}{3.15T}\right|_{\rm T_{today}} = \frac{0.8}{\xi^{\frac{1}{3}}} \simeq 0.2$$

Chilling

Dilution

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Redshift

⇩

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chilled dark matter

This weakens the small-scale structure limits [Kusenko (2006)]

Structure Formation and DM thermal velocities

DM consists of collisionless particles: clustering properties depend only on the primordial thermal content of DM.

CDM: "Bottom-up" formation, small-scale structure favored.

WDM: structure erased below some scale due to free-streaming out of potential wells.

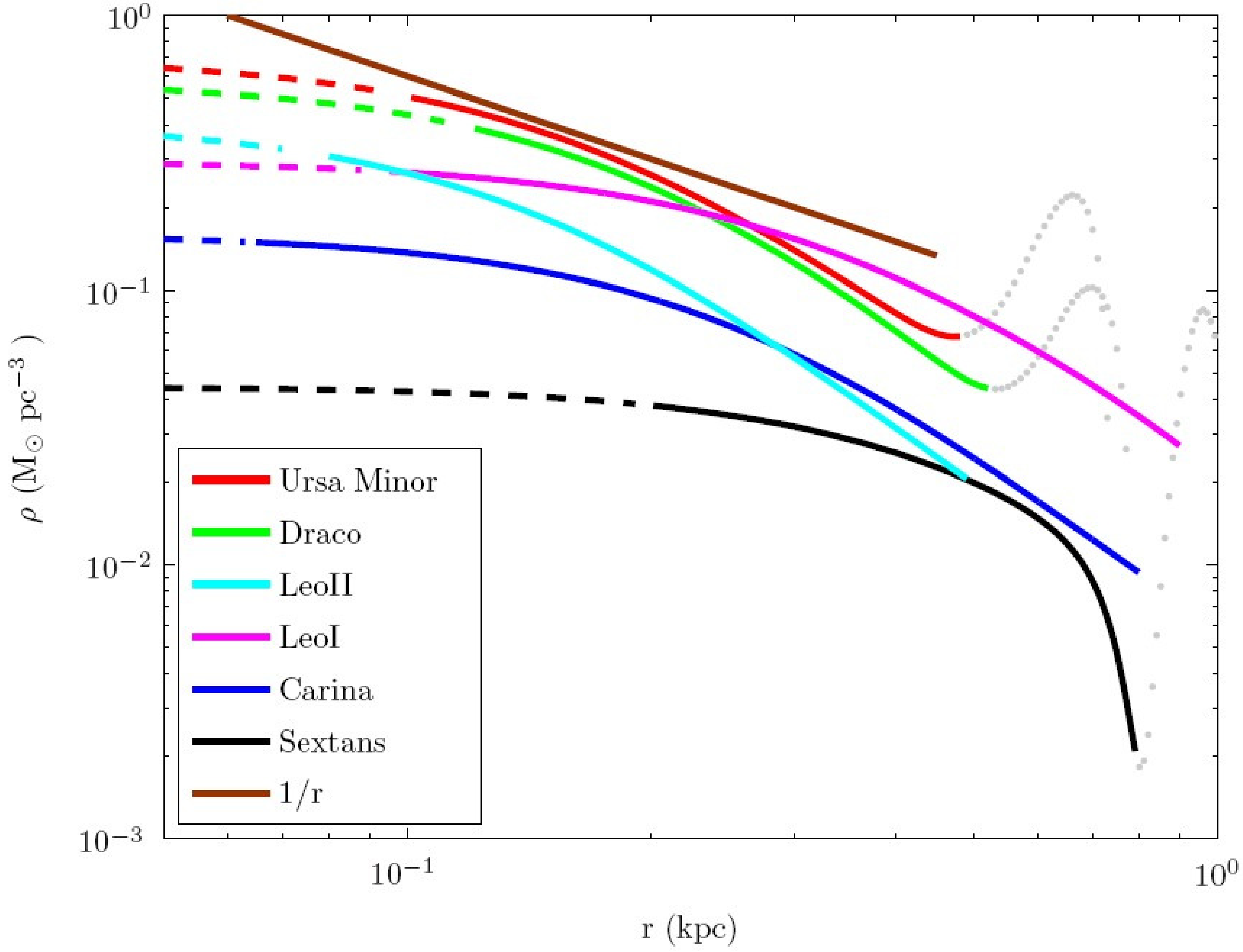
At large scales, CDM and WDM reproduce observed structure equally well.

At small scales, some CDM predictions do not match observations.

CDM problems

- Overprediction of satellite galaxies [Klypin; Moore]
- Galactic density profiles: central cusps rather than cores [Gilmore, Wyse; Strigari et al.]
- No pure-disk galaxies predicted [Governato et al.; Kormendy et al.]
- Overprediction of halos in low-density voids [Peebles]
- The angular momentum problem: gas condenses early and looses too much angular momentum [Dolgov]

Galactic density profiles of six Dwarf Spheroidal Galaxies



[Gilmore et al. (2007)]

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Possible solutions

- Simulations and observations improve, discrepancies go away.
- Gastrophysics: complicated astrophysical solutions for individual problems
  - Star formation suppressed in small halos
  - Central velocities underestimated
  - Baryonic feedback
- Warm Dark Matter
  - Suppression of structure at small scales
  - Smaller merger rate

How warm can WDM be?

Need high-resolution simulations for different WDM candidates, a formidable task.

⇩

Shortcut: employ quantities that are both calculable and observable.

Compare DM candidates with observations, or different DM candidates among themselves. Obtain limits.

Free-streaming length, Phase-space density

Free-streaming length

Cutoff scale of the power spectrum of density perturbations

$$\lambda_{\rm FS} \simeq 13\,{\rm kpc}\,\sqrt{1+z}\,\frac{1}{\xi^{\frac{1}{3}}}\left(\frac{\langle p^{-2}\rangle^{-\frac{1}{2}}}{1.61\,T}\right)_{\rm T_{prod}}\left(\frac{\rm keV}{m_{\rm DM}}\right)\left(\frac{0.2}{\Omega_{\rm DM}}\right)^{\frac{1}{2}}$$

[Boyanovsky (2008)]

$\lambda > \lambda_{\rm FS}$: perturbations begin to grow

$\lambda < \lambda_{\rm FS}$: perturbations are damped

- For CDM, λ_{FS}=0 and there is no small-scale suppression.
- For WDM, suppression depends on mass, primordial momentum distribution and the chilling effect.
- Currently not directly observable. Useful for comparing different DM candidates among themselves.

Phase-space density

$$Q \equiv \varrho \Big/ \left\langle \frac{p^2}{m^2} \right\rangle^{\frac{3}{2}}$$

[Dalcanton, Hogan (2001); Boyanovsky, Vega, Sanchez (2008)]

- Encodes thermal content of DM.
- Calculable for DM models; observable from galactic structure (Dwarf Spheroidal Galaxies).
- Liouville invariant, until epoch of gravitational clustering.
- Can only decrease due to gravitational interactions, which reflects the entropy increase:

$$Q_{\rm obs} < Q_{\rm prim} \quad \Rightarrow \text{ Limits!}$$

Phase-space density

$$Q \equiv \varrho \Big/ \left\langle \frac{p^2}{m^2} \right\rangle^{\frac{3}{2}}$$

$$Q_{\rm obs} < Q_{\rm prim}$$

- Primordial Q sets an upper limit on the density of DM in halos. For CDM, $Q_{\rm prim}^{\rm CDM} = \infty$ and no such limit exists $\Rightarrow$ central cusps

- Observable Q limits p/m

  i.e. how relativistic DM particles could have been at production. This results in a lower limit in mass.

$$Q_{\rm obs} \sim 10^{-5} - 10^{-4}\, \frac{M_\odot/\,{\rm pc}^3}{({\rm km/s})^3}$$

[Gilmore, Wyse]

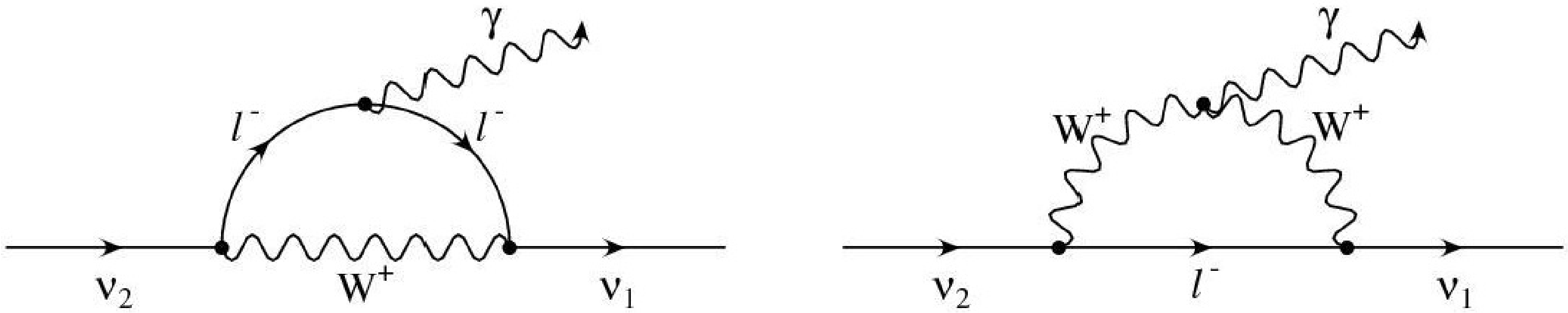
Dark Matters

sterile neutrino production mechanism	Free-streaming length $\lambda_{\rm fs}$	Phase-space density $Q_{\rm prim}\ \left(\frac{M_\odot/\,{\rm pc}^3}{({\rm km/s})^3}\right)$	sterile neutrino lower mass limit $m_{\rm min}$
Warm DM off-resonance oscillations	$7\ {\rm kpc}\ \left(\frac{\rm keV}{m}\right)$	$2.2\cdot 10^{-5}\ \left(\frac{m}{\rm keV}\right)^3$	$0.76\ {\rm keV}\left[\frac{Q_{\rm obs}}{10^{-5}\,\frac{M_\odot/\,{\rm pc}^3}{({\rm km/s})^3}}\right]^{\frac{1}{3}}$
Cool DM resonant oscillations	$1.7\ {\rm kpc}\ \left(\frac{\rm keV}{m}\right)$	$3.7\cdot 10^{-3}\ \left(\frac{m}{\rm keV}\right)^4$	$0.23\ {\rm keV}\left[\frac{Q_{\rm obs}}{10^{-5}\,\frac{M_\odot/\,{\rm pc}^3}{({\rm km/s})^3}}\right]^{\frac{1}{4}}$
Chilled DM Decays at the electroweak scale	$2\ {\rm kpc}\ \left(\frac{\rm keV}{m}\right)$	$2.4\cdot 10^{-4}\ \left(\frac{m}{\rm keV}\right)^3$	$0.35\ {\rm keV}\left[\frac{Q_{\rm obs}}{10^{-5}\,\frac{M_\odot/\,{\rm pc}^3}{({\rm km/s})^3}}\right]^{\frac{1}{3}}$

[Boyanovsky, Vega, Sanchez (2008); Boyanovsky (2008); KP (2008)]

Detection

- Sterile neutrinos with $m_N \sim$ keV have lifetime larger than the age of the universe, but they do decay into a lighter neutrino state and a photon.



- Decay rate very small, but large lumps of dark matter emit some X-rays. [Abazajian, Fuller, Tucker; Dolgov, Hansen; Shaposhnikov et al.]

- Photon energy is $m_N/2$: detection with X-ray telescopes

Star Formation

Molecular Hydrogen is a very important cooling agent and necessary for star formation.

$$H + H \quad \rightarrow \quad H_2 + \gamma$$ -slow process!

In the presence of ions the following reactions are faster

$$H + H^+ \quad \rightarrow \quad H_2^+ + \gamma$$
$$H + H_2^+ \quad \rightarrow \quad H^+ + H_2$$

The X-ray photons produced by DM sterile neutrino decays ionize H. H^+ catalyzes the formation of H_2.

[Biermann, Kusenko; Stasielak, Biermann, Kusenko]

Astrophysical Hints

Where else can sterile neutrinos be important?

Supernovae!

Pulsar Kicks

Pulsars have very large velocities v ~ 250 - 500 km/s.

99% of the gravitational energy, $\sim 10^{53}$ erg is emitted in neutrinos.

1% asymmetry in neutrino emission can explain pulsar velocities.

Active neutrinos are produced asymmetrically in the presence of magnetic field

$$p + e^- \rightleftharpoons n + \nu_e \qquad n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

but asymmetry is washed out as they escape from supernova.

If a more weakly-interacting particle, a sterile neutrino, is produced in the same processes, asymmetry in production will be asymmetry in emission and result in a pulsar kick.

[Kusenko, Segre]

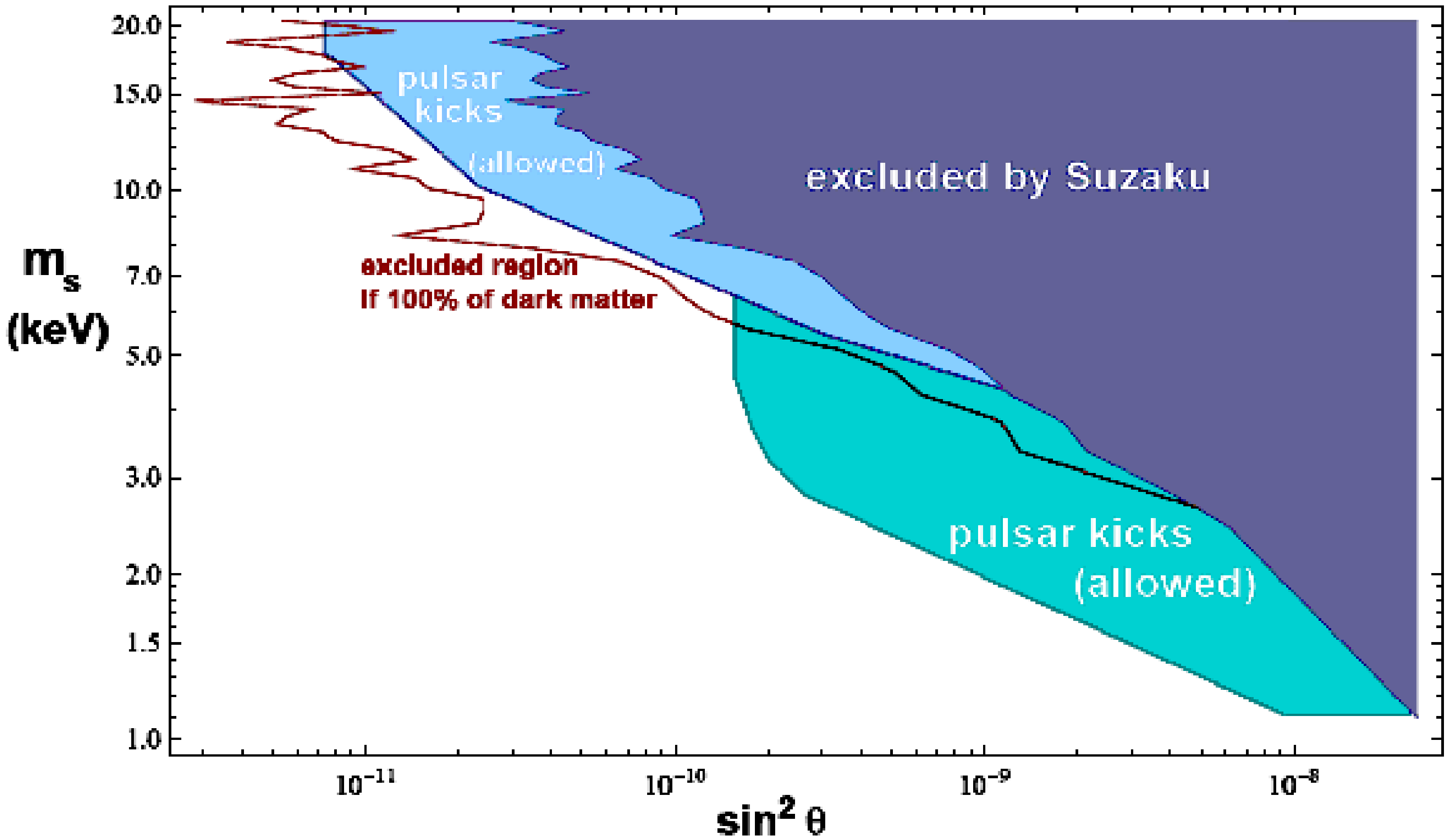
Observational Bounds

Given the various possible productions mechanisms, observational bounds correspond to two different questions:

I. Can a sterile neutrino of a given mass and mixing angle exist, independently of what fraction of dark matter it forms? (based on the oscillation production channel)

II. Can sterile neutrinos constitute all of the dark matter, independently of what mechanism they were produced by?

Suzaku X-ray observations (Ursa Minor) and pulsar kick parameter space



[Loewenstein, Biermann, Kusenko (2009)]

Happy Note

Mike Loewenstein and Alex Kusenko are analyzing a *candidate line!* (Chandra observation of Willman 1).

The line is consistent with 100% of dark matter abundance, and within the region of parameters favored by the pulsar kicks.

Conclusions

Sterile neutrinos are introduced to explain the observed neutrino masses. These particles can be of great cosmological and astrophysical significance.

If one of them is light, $m_s \sim$ keV, it can be the dark matter. Different production mechanisms result in "colder" or "warmer" DM.

The same particle can explain the large velocities of pulsars and facilitate star formation.