Massive and supermassive neutrinos as dark matter

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Talk based on:

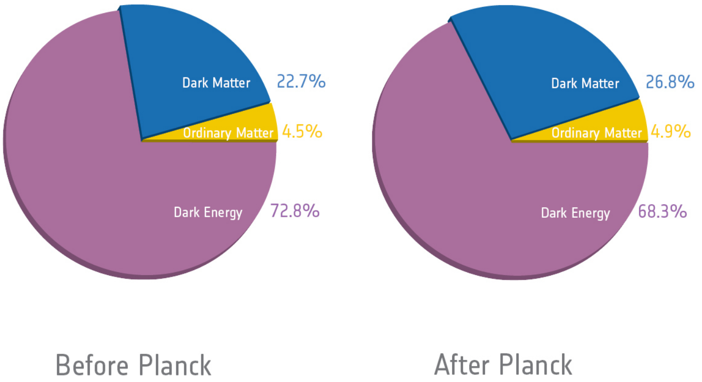
P. Di Bari, P.O.L. and S. Palomares-Ruiz (IFIC Valencia): 1606.06238

Outline of the talk

I. Neutrinos as dark matter?
II. The cold DM right-handed neutrino mixing scenario
III. Dark matter decays
IV. Leptogenesis
V. Possible signatures at IceCube
VI. Summary and conclusions

I. Neutrinos as dark matter?

Energy content of the Universe



(Copyright: ESA and the Planck Collaboration.)

$\rightarrow$ **26.8%** dark matter.

What do we know about dark matter?

Dark matter particles must be

- **'dark':** electrically neutral (or extremely weakly charged),
- **'cold' or 'warm':** non-relativistic (or not ultrarelativistic) at freeze-out $\rightarrow$ masses either $\gtrsim \mathrm{keV}$ or non-thermal production (e.g. axions: can be almost massless, but still cold),
- **stable at cosmological timescales**: decay is allowed, but lifetime must be long,
- **produced in the early Universe with the correct abundance**.

Neutrinos as dark matter?

Light active neutrinos as dark matter?

- ✓ **'dark'**: Have only weak interactions,
- ✗ **'cold' or 'warm':** eV-scale neutrinos are **hot** at freeze-out $\rightarrow$ can only be a small part of dark matter,
- ✓ **stable at cosmological timescales**: All light neutrinos are stable at cosmological time scales. Lightest neutrino is absolutely stable.
- ✗ **produced in the early Universe with the correct abundance**: Abundance too small.

$\rightarrow$ **Light ($\lesssim \mathrm{eV}$) neutrinos are excluded** as main component of dark matter.

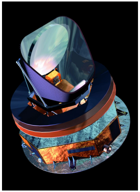
But still, neutrinos are a (small) part of dark matter. $\rightarrow$ How much?

Contribution of light (thermal) neutrinos to dark matter

$$\Omega_\nu h_0^2 \approx \frac{\sum_\nu m_\nu}{94\,\mathrm{eV}}$$

Bounds from cosmology: Bounds on the sum of the three active neutrino masses:

$$\begin{aligned}
\sum m_\nu &< 0.72 \text{ eV} \quad \textit{Planck}\text{ TT+lowP,}\\
\sum m_\nu &< 0.21 \text{ eV} \quad \textit{Planck}\text{ TT+lowP+BAO,}\\
\sum m_\nu &< 0.49 \text{ eV} \quad \textit{Planck}\text{ TT, TE, EE+lowP,}\\
\sum m_\nu &< 0.17 \text{ eV} \quad \textit{Planck}\text{ TT, TE, EE+lowP+BAO.}
\end{aligned}$$



(Planck Collaboration [1502.01589]).

Dependent on which data taken into account. In any case bound stronger than current direct neutrino mass bounds.

$$\rightarrow \sum_\nu m_\nu \lesssim \mathcal{O}(\mathrm{eV}) \Rightarrow \Omega_\nu h_0^2 \lesssim 0.01 < \frac{1}{10}\Omega_{\mathrm{DM}} h_0^2.$$

Light neutrinos comprise less than 10% of dark matter!

What about heavier neutrinos as dark matter?

Most prominent model: νMSM (Asaka, Blanchet, Shaposhnikov)[1]

- SM + three right-handed neutrinos, type-I seesaw mechanism for neutrino masses,
- heavy neutrino mass spectrum: **one keV** neutrino, two $\lesssim 100\,\mathrm{GeV}$ neutrinos, **main decay mode of keV neutrino: decay into three light neutrinos: strong phase space suppression** $\rightarrow$ **long lifetime** $\rightarrow$ warm dark matter,
- baryogenesis via leptogenesis (requires $M_{2,3} \lesssim 100\,\mathrm{GeV}$), Dirac neutrino Yukawa couplings are small,

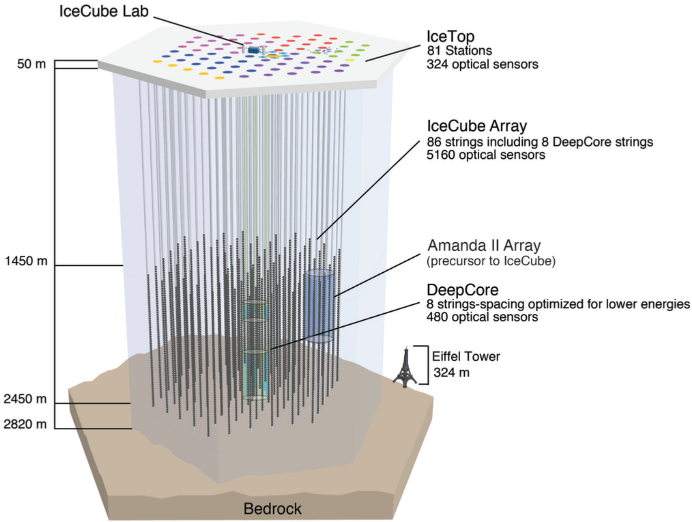
$$m_\nu \sim \frac{m_D^2}{M_R} = \frac{y^2 v^2}{M_R} \Rightarrow y \sim \frac{\sqrt{m_\nu M_R}}{v} \sim \frac{\sqrt{0.1\,\mathrm{eV} \times 100\,\mathrm{GeV}}}{100\,\mathrm{GeV}} = 10^{-6}.$$

- dark energy = cosmological constant.

$\rightarrow$ **Consistent with all observations!**

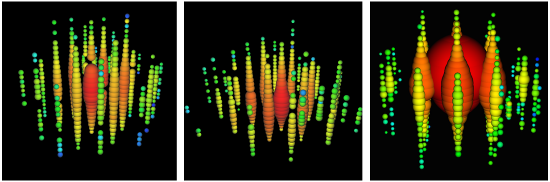
[1] hep-ph/0503065, hep-ph/0505013.

New neutrino physics? - High energy neutrinos at IceCube



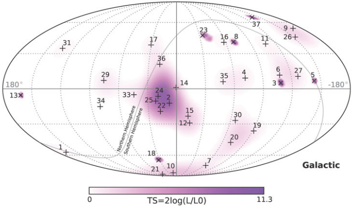
(Graphics: IceCube Collaboration.)

New neutrino physics? - High energy neutrinos at IceCube



Three events with energy deposited in the detector of >1 PeV.

Of astrophysical origin? Still unknown. **IceCube high-energy data do not fit to a single astrophysical power-law flux.**

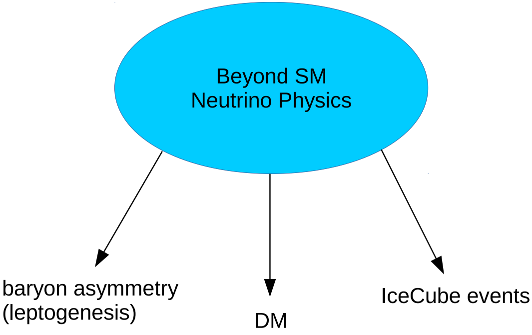


(Graphics: IceCube Collaboration.)

IceCube high-energy signal - decaying dark matter?

Idea that a part of the high-energy neutrino spectrum recorded by IceCube originates from decaying dark matter rather than astrophysical sources (*e.g.* blazars).[2]

Can we combine such ideas also with leptogenesis?



[2]See *e.g.* Esmaili, Serpico 1308.1105.

Heavy neutrinos as decaying dark matter?

Idea of Anisimov and Di Bari:[3]

- Type-I seesaw mechanism with one (almost) decoupled right-handed neutrino (tiny or vanishing Yukawa-coupling to Higgs).
- In contrast to νMSM: all neutrinos are heavy ($>$electroweak scale).
- Production in early Universe via mixing with the other RH neutrinos (resonance conversion via MSW effect), small mixing enough to create sufficient abundance.
- Decay rate small due to extremely tiny Yukawa-coupling. $\rightarrow$ Stable on cosmological timescales.

In our recent paper:

- Showed that this scenario is compatible with leptogenesis,
- investigated possible signatures at IceCube.

[3] A. Anisimov and P. Di Bari 0812.5085 [hep-ph].

II. The cold DM right-handed neutrino mixing scenario

The cold DM right-handed neutrino mixing scenario

Mass terms with three right-handed neutrinos:

$$\mathcal{L}_M = -\overline{\nu_L} m_D N_R - \frac{1}{2}\overline{N_R^c} M_R N_R + \mathrm{H.c.}$$

Flavour basis: m_D non-diagonal, M_R diagonal.

$$m_D = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ \times & \times & 0 \end{pmatrix}, \quad M_R = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix}.$$

Dark matter candidate, e.g. N_3, decoupled (Yukawa couplings vanish). $\Rightarrow$ m_D has rank 2. $\Rightarrow$ m_ν has rank 2. **Lightest neutrino is massless!**

How small must Yukawa-coupling of DM right-handed neutrino be?

Yukawa coupling to Higgs and active neutrinos:

$$-h_{\mathrm{DM}} \overline{\nu_L} \phi N_{\mathrm{DM}} + \mathrm{H.c.}$$

Two-body decay: Lifetime

$$\tau_{\mathrm{DM}} = \frac{4\pi}{h_{\mathrm{DM}}^2 M_{\mathrm{DM}}} \simeq 0.87\, h_{\mathrm{DM}}^{-2}\, 10^{-23} \left(\frac{\mathrm{GeV}}{M_{\mathrm{DM}}}\right) s.$$

For cosmological stability ($\tau \gtrsim 10^{28}\,\mathrm{s}$):

$$h_{\mathrm{DM}} \lesssim 3 \times 10^{-26} \sqrt{\frac{\mathrm{GeV}}{M_{\mathrm{DM}}}}.$$

$\Rightarrow$ Yukawa coupling must be extremely tiny.

Cosmological stability of DM

... Yukawa coupling must be extremely tiny. $\Rightarrow$ 2 problems:

- Correct abundance of dark matter can never be produced by production via the Yukawa coupling from a thermal bath in the early Universe.
- Small Yukawa coupling asks for symmetry justification.

Approach of the νMSM: Make Yukawa couplings small, but large enough to allow production of the correct abundance. If DM neutrino mass of $\mathcal{O}(\mathrm{keV})$, the main decay mode is

$$N_{\mathrm{DM}} \to 3\nu,$$

which has $\Gamma \propto M_{\mathrm{DM}}^5$ and therefore is strongly suppressed by the smallness of the DM neutrino mass ($\sim$keV). $\Rightarrow$ Decay rate small, though Yukawa couplings are not tiny (but small).

Cosmological stability of DM

Alternative: Add new interactions: Dimension-5 operator

$$\frac{\lambda_{IJ}}{\Lambda}(\phi^\dagger\phi)\overline{N_I^c}N_J.$$

In general non-diagonal in flavour basis. Contribution to RH-neutrino mass term negligible compared to mass term already existing (if Λ very large). Tiny mixing induced by this operator leads to

- Long (but not infinite) lifetime of dark matter neutrino,
- production in the early Universe by resonant conversion via MSW effect: Conversion of other heavy neutrinos to N_{DM}. Turns out that conversion of only a small amount of neutrinos is **sufficient to generate the correct DM abundance.**

Symmetry justification via Higgs portal interactions

$\mathbb{Z}_2$ symmetry under which all fields apart from N_{DM} transform trivially:

$$\mathbb{Z}_2 : \quad N_{\mathrm{DM}} \to -N_{\mathrm{DM}}.$$

$\Rightarrow$ N_{DM} completely decoupled. No Yukawa interactions:

$$m_D = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ \times & \times & 0 \end{pmatrix}, \quad M_R = \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & M_{\mathrm{DM}} \end{pmatrix}.$$

Spontaneous breaking of $\mathbb{Z}_2$ by a heavy scalar singlet χ in

$$-\frac{1}{2}\chi\,\overline{N_R^c} Y N_R + \mathrm{H.c.}$$

VEV of χ at GUT-scale would lead to too large mixing, dark matter would be too unstable!

Symmetry justification via Higgs portal interactions

Idea for way out: Start from $\mathbb{Z}_2$-symmetric scalar potential, right-handed neutrino mass term and right-handed neutrino Yukawa interactions.

Soft breaking of $\mathbb{Z}_2$ in the scalar sector only:

$$\mu\chi\phi^\dagger\phi \qquad (\text{“Higgs-portal”}).$$

$\Rightarrow$ At dimension-4, Yukawa-interactions still $\mathbb{Z}_2$-invariant. **Explicit $\mathbb{Z}_2$-breaking appears at dimension-5:**

$$\frac{\mu}{M_\chi^2}\phi^\dagger\phi\lambda_{IJ}\overline{N_I^c}N_J.$$

If soft breaking is very weak,

$$\Lambda \equiv \frac{M_\chi^2}{\mu}$$

may be much larger than $M_\chi \sim m_{\mathrm{Planck}}$.

Symmetry justification via Higgs portal interactions

$$\frac{\mu}{M_\chi^2}\phi^\dagger\phi\lambda_{IJ}\overline{N_I^c}N_J.$$

Example:

$$M_\chi \sim m_{\mathrm{Pl}},\ \mu \sim M_{\mathrm{GUT}} \Rightarrow \Lambda \sim \frac{m_{\mathrm{Pl}}^2}{M_{\mathrm{GUT}}} \sim 10^{22}\,\mathrm{GeV}.$$

Remark: Soft breaking also induces negligible spontaneous breaking due to

$$V(\chi,\phi=v) = \frac{1}{2}M_\chi^2\chi^2 + \mu v^2\chi + \dots$$

$$\Rightarrow \langle\chi\rangle = -\frac{\mu v^2}{M_\chi^2} \sim 10^{-18}\,\mathrm{GeV}.$$

Symmetry justification via Higgs portal interactions

Summary:

- Exact $\mathbb{Z}_2$-symmetry in RH-neutrino mass term (dim. 3) and Yukawa-interactions (dim. 4): No RH neutrino mixing, dark matter decoupled. $\rightarrow$ Exactly stable, not produced in the early Universe.
- Spontaneous breaking of $\mathbb{Z}_2$ in dim.-4 interactions with VEV of χ at GUT-scale: DM by far too instable.
- Way out: Explicit breaking of $\mathbb{Z}_2$ in Higgs-portal interaction only $\Rightarrow$ Explicit breaking at dimension 5 in Yukawa interactions. Enough to produce cosmologically stable DM in the early Universe.
- $\mathbb{Z}_2$ then automatically broken also spontaneously at negligible scale.

Estimation of $N_{\rm DM}$ abundance

For simplicity: Consider mixing of $N_{\rm DM}$ with only one other right-handed neutrino, which we call N_S (source RH neutrino). Has Yukawa-coupling to leptons

$$-\overline{\nu_{\alpha L}} h_{\alpha S} \phi (N_S)_R + \mathrm{H.c.}$$

'Total coupling'

$$h_S^2 \equiv \sum_\alpha |h_{\alpha S}|^2.$$

Hamiltonian in early Universe (at temperature T, $\tilde{\Lambda} = \frac{\Lambda}{\lambda_{\mathrm{DM},S}}$):

$$H = \begin{pmatrix} E_{\rm DM} & \frac{T^2}{12\tilde{\Lambda}} \\ \frac{T^2}{12\tilde{\Lambda}} & E_S + \frac{T^2}{8E_S} h_S^2 \end{pmatrix}$$

Estimation of $N_{\rm DM}$ abundance

$\rightarrow$ MSW resonance at resonance temperature

$$T_{\rm res} = \frac{2\sqrt{M_{\rm DM}^2 - M_S^2}}{h_S}$$

Resonance occurs only for $M_{\rm DM} > M_{\rm S}$. At $T_{\rm res}$ a small fraction of $N_{\rm S}$ is (highly) non-adiabatically converted into $N_{\rm DM}$.

Adiabaticity parameter at resonance temperature:

$$\gamma_{\rm res} \simeq 0.4 \frac{m_{\rm Pl}}{\tilde{\Lambda}^2} \frac{\sqrt{M_{\rm DM}^2 - M_{\rm S}^2}}{\sqrt{g^*_{\rm res}} h_S^3}.$$

$$\left.\frac{N_{N_{\rm DM}}}{N_{N_S}}\right|_{\rm res} \approx \frac{\pi}{2}\gamma_{\rm res},$$

$$\underbrace{\Omega_{\rm DM} h^2}_{0.1193 \pm 0.0014} \simeq 1.7 \times 10^6 \gamma_{\rm res} \left(\frac{M_{\rm DM}}{\rm GeV}\right).$$

III. Dark matter decays

Dark matter decays

Mixing of N_S and N_{DM} via

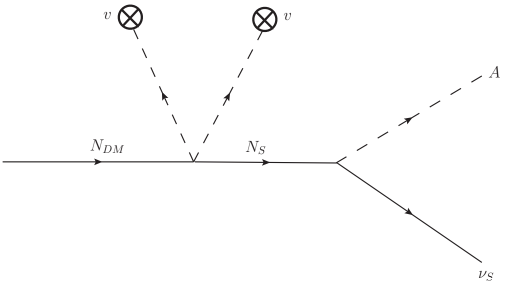
$$\frac{\lambda_{IJ}}{\Lambda}(\phi^\dagger \phi)\overline{N_I^c} N_J$$

is the source of N_{DM}-decay:

Three decay modes:

- 2-body decay,
- 3-body decay,
- 4-body decay.

Dark matter decays: Two-body decay

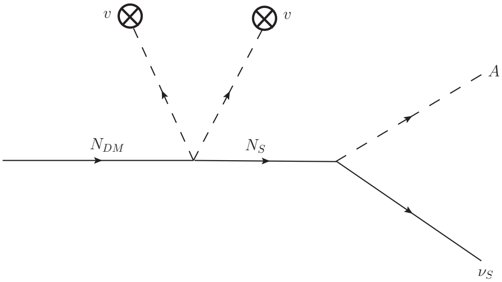


$$\tau_{\mathrm{DM}\to\mathrm{S}\to A+\nu_{\mathrm{S}}} \simeq \frac{2.4\times 10^{-9}\,\mathrm{s}}{z_{\mathrm{res}}^5}\left(\frac{M_{\mathrm{DM}}}{\mathrm{GeV}}\right)^3 \frac{M_{\mathrm{DM}}/M_{\mathrm{S}}}{(1+M_{\mathrm{S}}/M_{\mathrm{DM}})^2} \propto M_{\mathrm{DM}}^3.$$

$(A = H, Z.)$

$$z_{\mathrm{res}} = \frac{M_{\mathrm{DM}}}{T_{\mathrm{res}}} = \frac{h_S}{2\sqrt{1-\frac{M_S^2}{M_{\mathrm{DM}}^2}}}.$$

Dark matter decays: Two-body decay

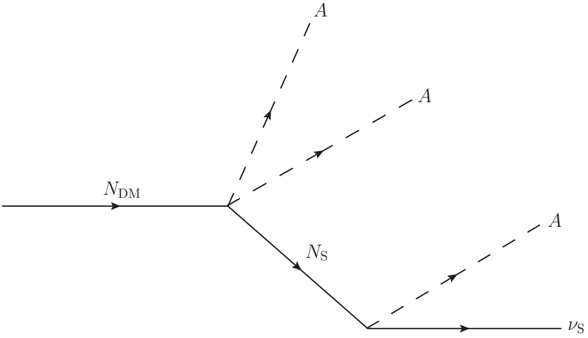


$(A = H, Z.)$

$$\tau_{\mathrm{DM}\to\mathrm{S}\to A+\nu_{\mathrm{S}}} \propto M_{\mathrm{DM}}^3.$$

IceCube: $\tau_{\mathrm{DM}} \gtrsim 10^{28}\,\mathrm{s} \Rightarrow$ Lower bound on M_{DM}.

Dark matter decays: Four-body decay

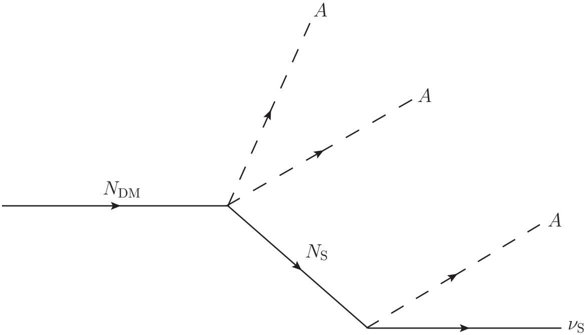


$(A = H, Z.)$

$$\tau_{\mathrm{DM}\to 3\,A+\nu_{\mathrm{S}}} \simeq \frac{0.1\,\mathrm{s}}{\alpha_{\mathrm{S}}} \left(\frac{\mathrm{GeV}}{M_{\mathrm{DM}}}\right)^4 \left(\frac{M_{\mathrm{DM}}}{M_{\mathrm{S}}}\right) \left(\frac{\widetilde{\Lambda}}{\mathrm{GeV}}\right)^2 \propto M_{\mathrm{DM}}^{-4}.$$

$\alpha_S = v^2 h_S^2 / (M_S \sqrt{\Delta m_{\mathrm{sol}}^2})$.

Dark matter decays: Four-body decay

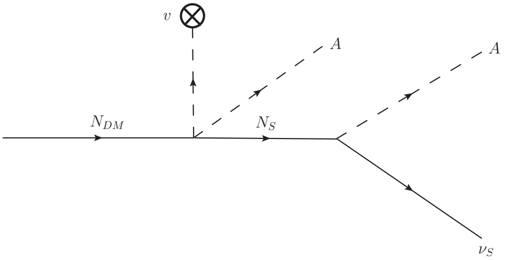


$(A = H, Z.)$

$$\tau_{\mathrm{DM}\to 3\,A+\nu_{\mathrm{S}}} \propto M_{\mathrm{DM}}^{-4}.$$

IceCube: $\tau_{\mathrm{DM}} \gtrsim 10^{28}\,\mathrm{s} \Rightarrow$ Upper bound on M_{DM}.

Dark matter decays: Three-body decay



Estimate decay rate of three-body decay: 4-body $\rightarrow$ 3-body:

$$|\mathcal{M}|^2_{\text{3-body}} = (2v)^2 |\mathcal{M}|^2_{\text{4-body}}$$

Phase space integral:

$$\int d\phi_n \rightarrow \int d\phi_{n+1} = \int d\phi_n \int \underbrace{\frac{d^3p'}{(2\pi)^3 2E'}}_{\frac{1}{16\pi^3} \times 4\pi \int \frac{dp \cdot p^2}{E}} \sim \frac{M^2_{\mathrm{DM}}}{4\pi^2} \int d\phi_n .$$

Dark matter decays: Three-body decay

Estimate decay rate of three-body decay:

$$|\mathcal{M}|^2_{\text{3-body}} = (2v)^2 |\mathcal{M}|^2_{\text{4-body}}$$

$$\int d\phi_4 \sim \frac{M_{\mathrm{DM}}^2}{4\pi^2} \int d\phi_3 .$$

$$\Rightarrow \frac{\Gamma_4}{\Gamma_3} = \frac{\int d\phi_4 |\mathcal{M}|^2_{\text{4-body}}}{\int d\phi_3 |\mathcal{M}|^2_{\text{3-body}}} \sim \frac{1}{16\pi^2} \frac{M_{\mathrm{DM}}^2}{v^2} = \left(\frac{M_{\mathrm{DM}}}{4\pi v} \right)^2 .$$

$\Rightarrow$ **4-body decay dominates if $M_{\mathrm{DM}} \gg 4\pi v \approx 2\,\mathrm{TeV}$.**

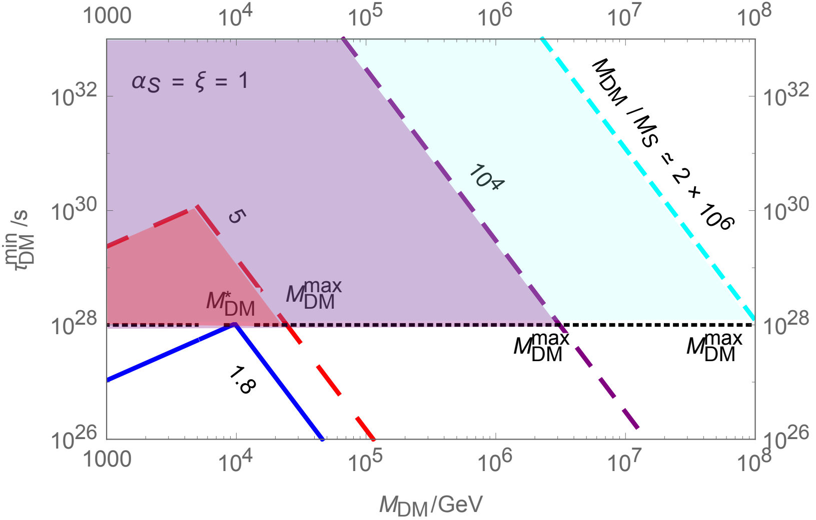
Bounds on DM lifetime $\rightarrow$ Windows for M_{DM}

- 2-body decay: Lower bound on M_{DM}.
- 4-body decay: Upper bound on M_{DM}.

$\Rightarrow$ for given M_{DM}/M_S, Λ chosen such that DM abundance correct: **Window of allowed values for M_{DM}.** Example: Initial vanishing N_{S} abundance: No N_S after inflation, all N_S produced by Yukawa-interactions from thermal bath. Most interesting case: At resonance N_S not yet in thermal equilibrium.

$\rightarrow$ **Window opens up for $M_{\mathrm{DM}} \gtrsim 9.3\,\mathrm{TeV}$.**

Bounds on DM lifetime → Windows for M_{DM}



IV. Leptogenesis

Leptogenesis

Dark matter production: Need MSW effect: Leads to requirement

$$M_{\mathrm{DM}} > M_S.$$

Dark matter stability constraints lead to

$$\delta_{\mathrm{DM}} \equiv \frac{M_{\mathrm{DM}} - M_S}{M_S} > 10^{-2}$$

Numerically checked that leptogenesis works for

$$\delta_{\mathrm{lep}} \equiv \frac{M_2 - M_1}{M_1} \lesssim 10^{-5}.$$

$\Rightarrow$ Dark matter neutrino is the **heaviest neutrino.** The other two neutrinos enable leptogenesis.

$$M_S < M_{\mathrm{DM}} < \mathcal{O}(1 - 1000\,\mathrm{TeV}).$$

$\Rightarrow$ Leptogenesis happens at the TeV to PeV scale!

V. Possible signatures at IceCube

Possible signatures at IceCube

Dark matter neutrino instable: Signatures from neutrino decays.

- Flavour ratio at source determined by model $\rightarrow$ Constraints on flavour ratios of high-energy neutrinos in IceCube.
- Flux of neutrinos from dark matter decays contributes to IceCube high-energy neutrino spectrum.

Hard and soft neutrinos from dark matter decays

Hardest component of neutrinos from two-body decays: Through mixing with N_S. Energy up to $M_{\mathrm{DM}}/2$.

Neutrinos: hard or soft.

- $N_{\mathrm{DM}} \to N_{\mathrm{S}} \to \ell^{\pm} W^{\mp} \to \ell^{\pm} \ell^{\mp} \nu$
- $N_{\mathrm{DM}} \to N_{\mathrm{S}} \to Z\nu \to \nu\nu\nu$
- $N_{\mathrm{DM}} \to N_{\mathrm{S}} \to H\nu \to \bar{b}b\nu \to \ldots \nu\nu$

Hard neutrinos come directly from the vertex with the N_S. $\Rightarrow$ Contribute to the high-energy end of the spectrum, preserve information about the flavour structure of the interaction (*i.e. Dirac mass matrix*). **Extremely challenging to measure!**

Why so challenging to measure?

Depending on the type of interaction (CC, NC) and on the flavour of the incoming neutrino, the **deposited energy in the detector might be quite different from the actual ν energy.**

Only highest-energy neutrinos preserve information about the flavour structure. $\rightarrow$ **Huge statistics needed to identify flavour composition experimentally!**

Extremely challenging, but nevertheless interesting, since IceCube observations could easily rule out our model.

Flavour ratio at the source

Two-body decay proceeds via mixing with N_S.

$$\Rightarrow \Gamma_{\mathrm{DM}} \propto \Gamma_{\mathrm{N_S}} \propto (m_D^\dagger m_D)_{ii}.$$

(i = index of N_S.)

$\Rightarrow$ Flavour ratio at source:

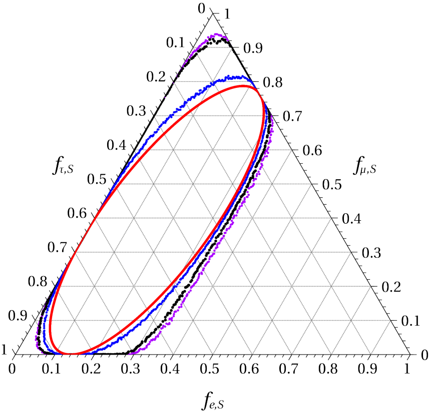
$$f_{\alpha,S} = \frac{|m_{D_{\alpha i}}|^2}{\sum_\beta |m_{D\beta i}|^2}$$

One can show that in our model, irrespective of the neutrino masses,

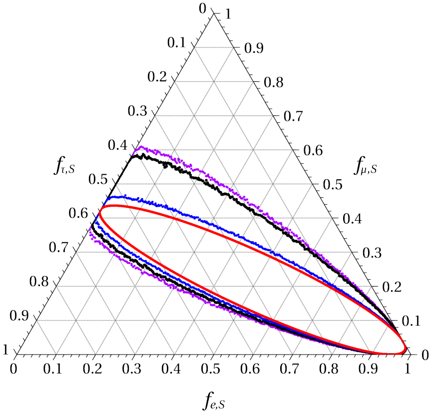
$$f_{\alpha,S} \leq 1 - |U_{\alpha 1}|^2.$$

Flavour ratio at the source

$$f_{e,\mathrm{S}} \lesssim 0.36, \quad f_{\mu,\mathrm{S}} \lesssim 0.95, \quad f_{\tau,\mathrm{S}} \lesssim 0.94 \qquad \text{(NH)},$$
$$f_{e,\mathrm{S}} \lesssim 0.98, \quad f_{\mu,\mathrm{S}} \lesssim 0.62, \quad f_{\tau,\mathrm{S}} \lesssim 0.65 \qquad \text{(IH)} .$$



(NH)



(IH)

Flavour composition at Earth

Coherence length of neutrinos is **smaller** than galactic scales.

$\Rightarrow$ Neutrino states which arrive at Earth from distant galactic or even extragalactic sources are

incoherent superpositions of mass eigenstates.

$\Rightarrow$ Probability to find a neutrino of flavour α at Earth if flavour β was produced at a distant source:

$$P_{\alpha\beta} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2.$$

$\Rightarrow$ Flavour composition at Earth:

$$f_{\alpha,\oplus} = \sum_\beta P_{\alpha\beta} f_{\beta,S}.$$

Flavour composition at Earth

$$f_{\alpha,\oplus} = \sum_{\beta} P_{\alpha\beta} f_{\beta,S}.$$

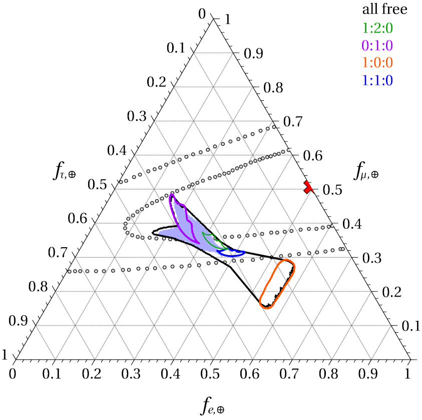
Strong constraint only for normal hierarchy and only in the electron component:

$$f_{e,\oplus} \approx \frac{1}{5} + \frac{f_{e,S}}{3}.$$

Compare this with expected signal for

- pion decay: $f_{e,S} : f_{\mu,S} : f_{\tau,S} = 1 : 2 : 0$,
- muon only: $f_{e,S} : f_{\mu,S} : f_{\tau,S} = 0 : 1 : 0$,
- neutron decay: $f_{e,S} : f_{\mu,S} : f_{\tau,S} = 1 : 0 : 0$,
- electron + muon: $f_{e,S} : f_{\mu,S} : f_{\tau,S} = 1 : 1 : 0$.

Flavour ratio at Earth



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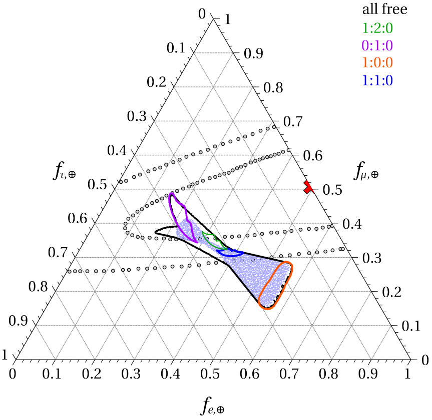


(IH)

Dark matter flux and event spectrum

For 2 representative cases for DM mass and lifetime: Computed flux and event spectrum from 2-body decays.

DM signal alone does not provide good fit to entire IceCube datasample.

$\Rightarrow$ Also consider an astrophysical contribution with a power-law flux.

Flux from DM decays has two contributions: galactic and extragalactic.

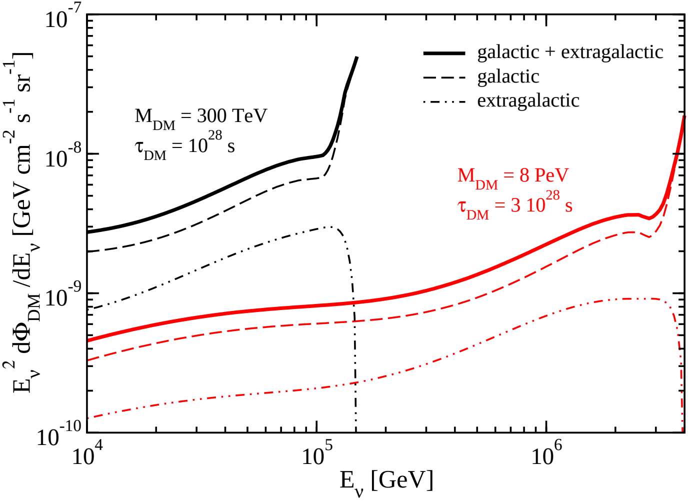
- Extragalactic flux: Nearly isotropic flux of neutrinos and antineutrinos.
- Galactic flux: Not isotropic because sun not in center of galaxy.

Ingredients for flux computation:

- Energy spectrum $\frac{dN_\nu}{dE_\nu}$: From literature (results up to 200 TeV scaled up to PeV scale).[4]
- Dark matter profile of the galaxy: Assume generalized Navarro-Frenk-White profile $\rho(r)$. Estimated flux less sensitive to particular form of $\rho(r)$ than in case of dark matter annihilations (there flux $\propto \rho^2$).

[4] See Cirelli et *al.*, 1012.4515.

Neutrino flux for $M_{\mathrm{DM}} = 300\,\mathrm{TeV}$ and $M_{\mathrm{DM}} = 8\,\mathrm{PeV}$



Event spectra

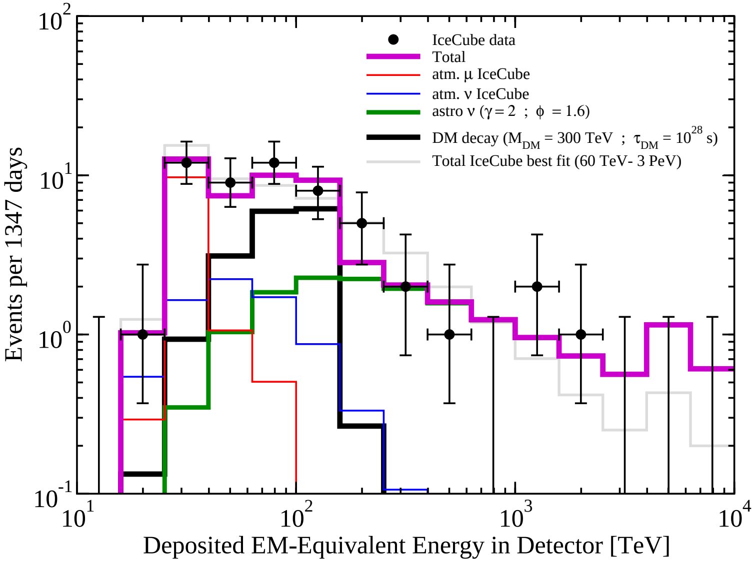
DM signal alone does not provide good fit to entire IceCube datasample.

$\Rightarrow$ Also consider an astrophysical contribution with a power-law flux (assumed flavour ratio at Earth 1:1:1).

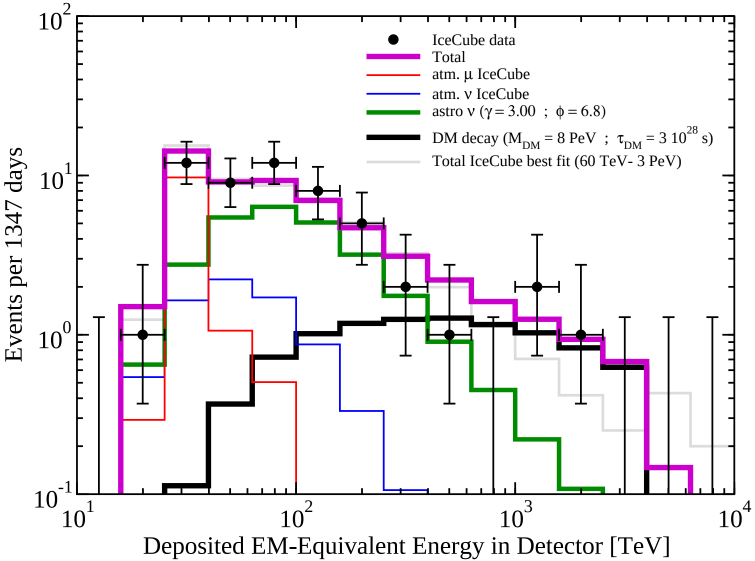
$$\frac{d\Phi_a}{dE_\nu} = \phi \left(\frac{E_\nu}{100\,\mathrm{TeV}} \right)^{-\gamma} .$$

$\phi =$ flux normalization in units of $10^{-18}\,\mathrm{GeV}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$.

IceCube event spectrum for $M_{\mathrm{DM}} = 300\,\mathrm{TeV}$



IceCube event spectrum for $M_{\mathrm{DM}} = 8\,\mathrm{PeV}$



VI. Summary and Conclusions

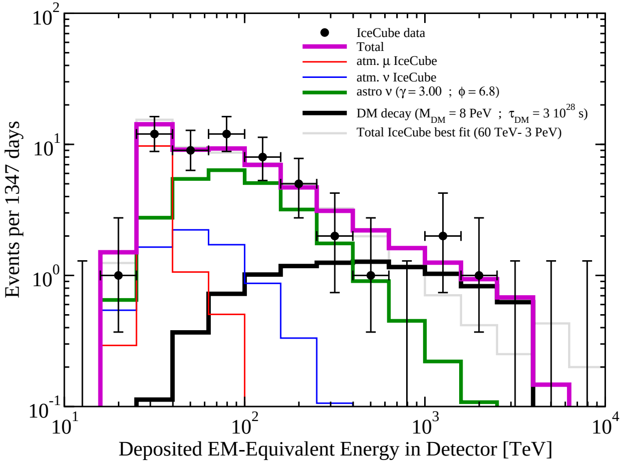
Summary

- Light (keV), heavy (TeV) and superheavy (PeV) neutrinos can be good candidates for dark matter.
- Tried to build a model like the νMSM with heavier neutrinos (to potentially explain a part of the IceCube high-energy neutrino spectrum).
- Main concept: Type-I seesaw with one decoupled right-handed neutrino.
- Production of dark matter: Mixing with source right-handed neutrino (MSW resonance).
- Yukawa-couplings tiny: Dark matter stable at cosmological scales.
- Small enough Yukawas justifiable in a framework with soft breaking of a $\mathbb{Z}_2$ in Higgs portal interactions.

Conclusions

- Dark matter right-handed neutrino almost decoupled $\Rightarrow$ Lightest neutrino almost massless.
- Two main decay modes: 2-body decay (lower bound on $M_{\rm DM}$) and 4-body decay (upper bound on $M_{\rm DM}$).
- Allowed window for $M_{\rm DM}$ in the TeV to PeV range.
- Successful leptogenesis possible, if dark matter is the heaviest neutrino. The other two must be degenerate to degree $\delta_{\rm lep} \lesssim 10^{-5}$.
- Signatures at IceCube:
  - Flavour ratios at Earth. Hard neutrinos keep information on Dirac Yukawa structure. Challenging to measure, but the signature of our model $f_{e,\oplus} < 1/3$ (for NO) is an interesting prediction.
  - Event energy spectrum: Additional component to (necessary) astrophysical flux. Can fit IceCube data with "Dark matter decay + astrophysical power-law flux." Examples: Either ~ 100 TeV dark matter + power-law $\gamma = 2$ or PeV dark matter + power-law $\gamma = 3$.
- Main interesting feature of our model: Only one new interaction (Higgs portal) responsible for dark matter production and decay.

Thank you for your attention!



Backup slides

Hard and soft components of the neutrino flux