High Energy neutrinos from Dark Matter decay

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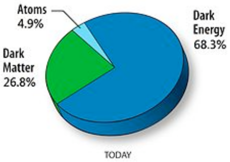
Contents

Universe is flat: $\Omega_{\rm tot} \approx 1$ *(inflation)* and multi-component

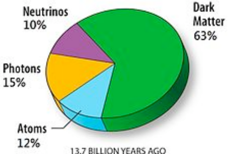
- $\Omega_B \simeq 0.05$ observable matter
- $\Omega_D \simeq 0.25$ dark matter $\rightarrow$ $\Omega_M = \Omega_D + \Omega_B \simeq 0.3$
- $\Omega_\Lambda \simeq 0.70$ dark energy/cosmological term

Matter – DE *coincidence:* $\Omega_M/\Omega_\Lambda \simeq 3/7$, $\rho_\Lambda = \text{Const.}$, $\rho_M \propto a^{-3}$
$\rho_M/\rho_\Lambda \propto a^{-3} \sim 1$ – *just Today?* Antrophic explanation

Baryon and DM *Fine Tuning:* $\Omega_B/\Omega_D \simeq 1/5$, $\rho_B \propto a^{-3}$, $\rho_D \propto a^{-3}$
$\rho_B/\rho_D = \mathrm{const.} \sim 1$ *True if DM is stable !*



TODAY



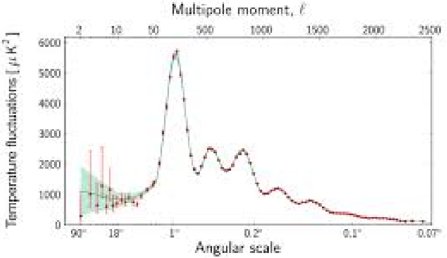
13.7 BILLION YEARS AGO

Baryons are stable:
$\tau_p > 10^{33}$ yr *vs.* $t_u \simeq 10^{10}$ yr

But are we sure that DM is table ?

if DM (or some its fraction) is unstable:
$\rho_D \propto a^{-3} e^{-t/\tau_D}$ with $\tau_D \geq t_u$

Precision Cosmology *CMB, LSS, etc. ....*



$$\theta_* = (1.0415 \pm 0.0006) \times 10^{-2}$$

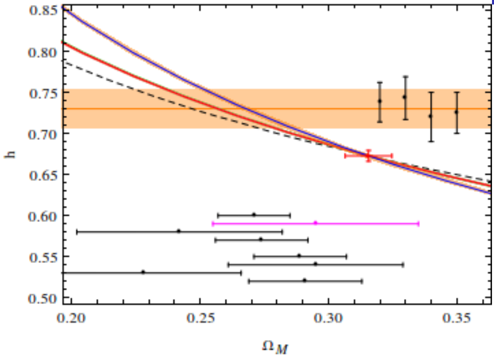
$H_0 = (67.27 \pm 0.66)\ \mathrm{km/s \cdot Mpc^{-1}}$, inflation $n_s = 0.965 \pm 0.005$

$\Omega_B h^2 = 0.02225 \pm 0.00016$, $\Omega_D h^2 = 0.1198 \pm 0.0015$

$\Omega_M = \Omega_B + \Omega_D \simeq 0.3156 \pm 0.0091$
$\rightarrow$ $\Omega_\Lambda = 1 - \Omega_M = 0.6844 \pm 0.0091$ from $\Omega_{\mathrm{tot}} = 1$
$\sigma_8 = 0.831 \pm 0.013$

But direct measurement: $H_0 = 73.24 \pm 1.74$ Riess et al., 2016

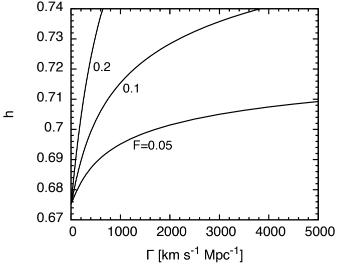
Anatomy of Planck results and DDM

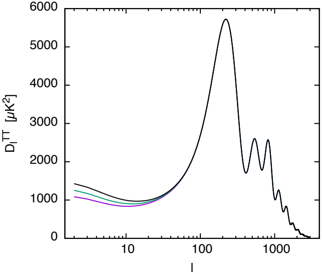


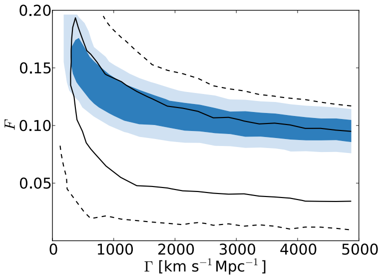
$\theta_* = (1.0415 \pm 0.0006) \times 10^{-2}$ fixed by Planck data (red curve)

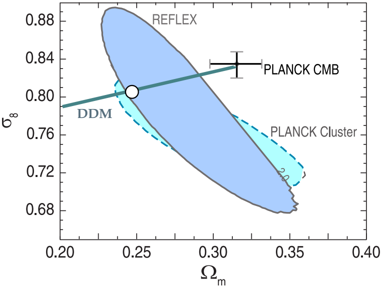
ρ_B and ρ_D at CMB epoch fixed from Planck data, if DM is stable, imply $\Omega_B h^2 = 0.02225 \pm 0.00016, \quad \Omega_D h^2 = 0.1198 \pm 0.0015$
and thus $\quad \Omega_M h^2 = 0.1420 \pm 0.0016$ (blue curve)
But if a fraction of DM decays, $F = \frac{\omega_{DDM}}{\omega_{SDM}+\Omega_{DDM}}$, today we have less DM than at recombination and blue curve moves down

DDM lifetime vs H_0: ZB, Dolgov, Tkachev, PRD 92, 061303 (2015)









DDM fraction ∼ 5 % mitigate Planck results both with H_0 and σ_8

Scenarios of decay

- DM decays in light (massless) species (but not photons)

$$X \to LL$$

then $F \sim 0.05$ if $\tau_D < t_u$, or $\tau_D > 2 \times 10^{11}$ if $F = 1$

light decay products need some time to redshift their energies

- Dark matter has two (or more) massive components, $M_1 = M$ and $M_2 = M + \delta M$, X_2 decaying into X_1 and a light (massless) L

$$X_2 \to X_1 + L$$

light L takes a tiny energy, X_1 promptly redshifts its kinetic energy

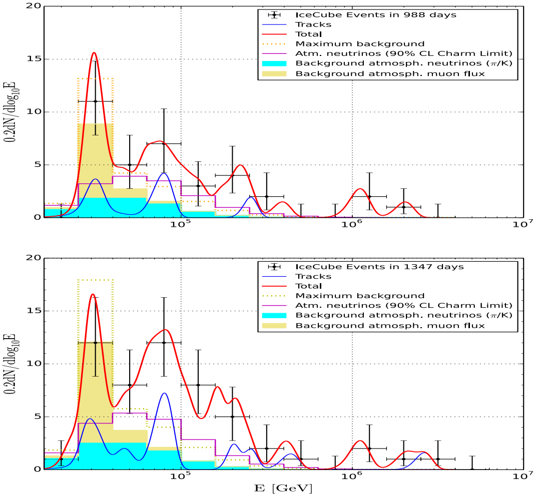
$$E_1 = \frac{M_2^2 + M_1^2}{2M_2} \approx M + \frac{Mv^2}{2}, \quad \epsilon_L = \frac{M_2^2 - M_1^2}{2M_2} \approx Mv^2, \qquad v^2 \approx \delta = \frac{\delta M}{M} \ll 1$$

In this case decay can be pretty late, $\tau_D \sim t_u$

$$\rho_{in} \propto M_1 + M_2 = 2M + \delta M, \qquad \rho_{fin} \propto 2M_1 = 2M \qquad \to F = \frac{\delta}{2+\delta}$$

IceCube HESE: spectral densities for 988 and 1347 days

$$\frac{dN_i(E)}{dE} = \frac{\exp\left[-(E-E_i)^2/2\sigma_i^2\right]}{\sigma_i\sqrt{2\pi}} \qquad \sigma_i/E_i = 0.1 - 0.15$$



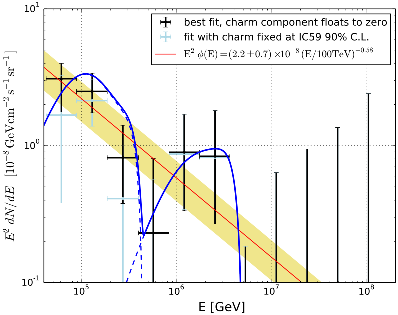
Discovery of astrophysical/cosmological HE neutrinos

Excess at higher energies: $E > 30$ TeV.

Not atmospheric neutrinos, nor cosmogenic (GZK) neutrinos !

Spectrum ends at few PeV ? Deficit between 400 TeV – 1 PeV ?

Can explain 750 GeV diphoton events ?



Origin is unknown: astrophysical (cosmic rays) with $\gamma \simeq 2.6$?

or cosmological (DDM or else) with spectral features ?

Independent indication: upgoing HE passing muons (but $\gamma \simeq 2.1$)

then problem with Glashow resonance

Let us concentrate on DDM

Can one explain all these feature
(provided they are indeed true)

Our proposal

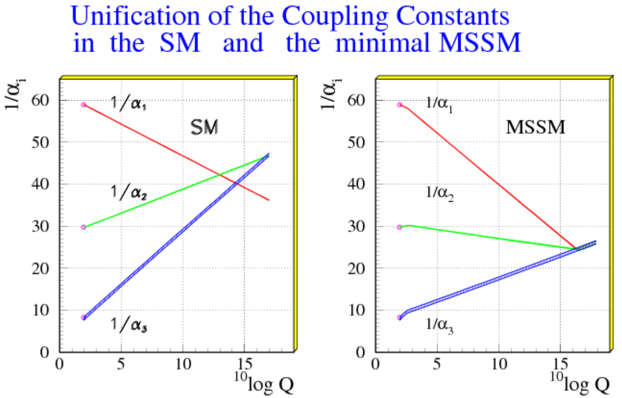
1. Heavy dark matter ($M \sim$ few PeV) belongs to hidden gauge sector
2. It decays ($\tau_{\rm dec} \sim t_U$), mostly in invisible channel but producing, with proper branching ratios, also ordinary neutrinos (and not too much photons)

How to get necessary necessary mass scales, lifetime, oscillation probabilities and bumpy energy spectrum of neutrinos ?

Let us do it in a best possible way,
without many ad hoc assumptions !

SUSY + GUT = LOVE ... in our world

- GUT: $SU(3) \times SU(2) \times U(1) \to SU(5)$



(coupling crossing → $M_{\rm SUSY} < 10$ TeV)

Hierarchy (and doublet-triplet splitting) problems – 28 orders – between $M^2_{\rm Higgs} \sim (100~{\rm GeV})^2$ and $M^2_{GUT} \sim (10^{16}~{\rm GeV})^2$

Two worlds: SUSY + GUT + GUT$'$ = LOVE

At $M_G \sim 10^{16}$ GeV $SU(5)$ breaks down to $SU(3) \times SU(2) \times U(1)$.
At $M_S \sim$ TeV SUSY is broken.
Below TeV scale the theory is just the normal (one Higgs) SM.
$SU(2) \times U(1)$ breaks spontaneously at $M_Z \simeq 100$ GeV.
$SU(3)$ IR prisoned at $\Lambda \simeq 200$ MeV

Proton decay: $\tau_p \sim \frac{M_5^4}{\alpha_G^2 m_p^5} \sim 10^{30}$ Gyr

Now imagine that Dark sector is also described by same physics:

Two identical SUSY gauge factors: $SU(5) \times SU(5)'$
Identical Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
– Discrete symmetry $SU(5) \leftrightarrow SU(5)'$.

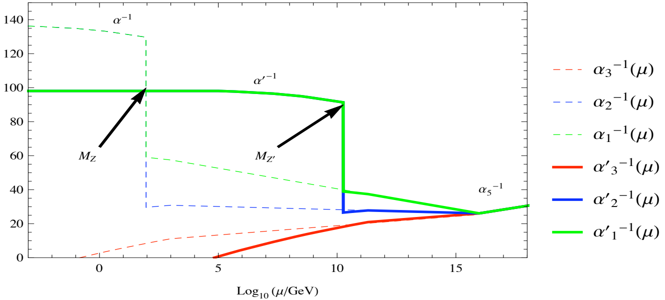
Both $SU(5)$ or $SU(5)'$ breaks to SM and SM$'$ at $M_G \sim 10^{16}$ GeV

But then in parallel sector SUSY is broken at $M_S' \sim 10^{11}$ GeV.

This induces SUSY breaking in our sector at $M_S \sim \frac{M_S'^2}{M_{Pl}} \sim 1$ TeV, transmitted by gravity.

Two worlds: SUSY + GUT + GUT′ = LOVE

Running of gauge constants of $SU(5)$ and $SU(5)'$



Our sector: SUSY broken at $M_S \sim 1$ TeV.
$SU(2) \times U(1)$ breaks at $v \simeq 100$ GeV, $SU(3)$ has $\Lambda \simeq 200$ MeV

Shadow sector: SUSY breaking $M'_S \sim 10^{11}$ GeV
$SU(2)' \times U(1)'$ breaks at $V \sim 10^{11}$ GeV, $SU(3)'$ has $\Lambda' \sim 100$ TeV
And miracles begin! proton masses: $m_p \simeq 1$ GeV, $m'_p \sim 1$ PeV

proton lifetimes: $\tau_p \sim \frac{M_G^4}{\alpha_G^2 m_p^5} \sim 10^{30}$ Gyr $\tau_p \sim \frac{M_G^4}{\alpha_G^2 m'^5_p} \sim 10$ Gyr

Quark-lepton masses in shadow sector

$$Y^e_{ij} l_i e^c_j h_1 + Y^d_{ij} q_i d^c h_1 + Y^u_{ij} q_i u^c_j h_2$$

$$Y^e_{ij} L_i E^c_j H_1 + Y^d_{ij} Q_i D^c H_1 + Y^u_{ij} Q_i U^c_j H_2$$

Fermion masses scale as $\propto V/v \simeq M'_Z/M_Z$ ...
But RG running must be taken into account:

$$m_e = Y_e R_e \eta_e v_1, \quad m_d = Y_d R_d \eta_d v_1, \quad m_u = Y_u R_u \eta_u v_2 B^3_t$$
$$M_E = Y_e R_E \eta_E V_1, \; M_D = Y_d R_D \eta_D V_1, \; M_U = Y_u R_U \eta_U V_2 B^3_T$$

RG in Susy SM: $R_e \eta_e \approx 1.5, \;\; R_d \eta_d, R_u \eta_u \approx 8.5, \;\; B_t \approx 0.7 \; (Y_t \sim 1)$

RG in Susy SM′: $R_E \eta_E \approx 1.1, \; R_d \eta_d, R_u \eta_u \approx 1.3, \; B_T \simeq 1$

Our matter: we have $v \simeq 100$ GeV; $m_e = 0.5$ MeV,
$m_u \approx 3$ MeV, $m_d \approx 5$ MeV ($\mu = 2$ GeV) – $m_{u,d} \ll \Lambda$.

Shadow matter: For $V \sim 10^{10}$ GeV,
shadow electron mass $M_E \simeq 0.5$ PeV, lightest quark masses $M_D \simeq 1$ PeV, $M_U \simeq 2$ PeV – $M_{U,D} \gg \Lambda'$

Hadron masses in shadow sector

Our sector:

Pions ($\pi^0, \pi^\pm$) are PGB's: $m_\pi \simeq \frac{m_q^{1/2}\langle \bar{q}q\rangle^{1/2}}{f_\pi} \sim (m_q \Lambda^3)^{1/2}$

lightest (stable) baryon: proton with $m_p \simeq 1$ GeV.

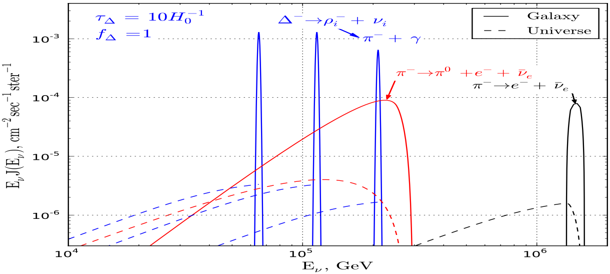
But in SUSY $SU(5)$ it decays: $\tau_p \sim \frac{M_5^4}{\alpha_G^2 m_p^5} \sim 10^{30}$ Gyr

Shadow: $M_E = 0.5$ PeV, $M_D = 1.1$ PeV, $M_U = 1.9$ PeV

Shadow quark is similar to our heavy quark sector (b, c). Pions (lightest pseudoscalars) are not PGB's:
$M_D^0 \simeq 2.2$ PeV, $M^\pm \simeq 3$ PeV, $M_U^0 \simeq 3.8$ PeV,

lightest (stable) shadow baryon is $\Delta \sim DDD$ (spin 3/2) with $M_\Delta \simeq 3.3$ GeV.
in Susy $SU(5)$ it decays: $\tau_\Delta \sim \frac{M_G^4}{\alpha_G^2 M_\Delta^2 \Lambda'^3} \sim 10 - 100$ Gyr,
$\Delta_{(DDD)} \to \rho^-(D\overline{U}) + \nu'_x \qquad (M_\rho \simeq 3.1 \text{ PeV}),$
producing monoenergetic shadow neutrinos with
$E_x = \frac{1}{2} M_\Delta \left(1 - \frac{M_\rho^2}{M_\Delta^2}\right) \simeq 200$ TeV – Miracle No. 1 !

Shadow neutrino spectrum from Δ-baryon decay



$\rho^-(D\overline{U})$ meson as well as its excited states can be produced, with masses say $3.1, 3.2, 3.25$ PeV, producing monoenergetic neutrinos ν'_x

$$E_{xi} = \frac{1}{2} M_\Delta \left(1 - \frac{M_{\rho i}^2}{M_\Delta^2}\right) \simeq 200, 100, 60 \text{ TeV}$$

ρ_i bearing energies $E_{\rho i} = \frac{1}{2} M_\Delta \left(1 + \frac{M_{\rho i}^2}{M_\Delta^2}\right) \simeq 3.3$ PeV. They all decay into

$\rho^-(D\overline{U}) \to \pi^-(D\overline{U}) + \gamma'$ (pseudoscalar bound state is ligtest!)
Pion decays: 2-body$\pi^- \to E + \bar\nu_e$ and 3-body $\pi^- \to \pi_D^0 + E + \bar\nu_e$,
with comparable branchings $\frac{\Gamma_2}{\Gamma_3} \simeq 5 \left(\frac{F_\pi}{1 \text{ PeV}}\right)^2$ ($F_\pi \sim \Lambda' \sim 100$ TeV)
– Miracle No. 2!

Neutrino masses, active-sterile mixing

Neutrino masses from Planck scale operators Akhmedov, ZB, Senjanovic, 1992

$$\frac{Y\chi}{M_{Pl}^2}\,\bar{5}\bar{5}h_5h_5+\frac{Y\chi}{M_{Pl}^2}\,\bar{5}'\bar{5}'H_5H_5+\frac{Z}{M_{Pl}}\,\bar{5}\bar{5}'h_5H_5$$

2-nd operator generates shadow neutrino Majorana masses

$M'_\nu=\frac{Y\chi V^2}{M}=Y\chi_{15}V_{10}^2\times 10^3$ keV

3-rd operator generates mixing (Dirac) masses between active and shadow neutrinos

$m_D=\frac{Z v V}{M}=ZV_{10}\times 1$ keV ... and active-sterile mixing:

$\Theta=\frac{m_D}{M'_\nu}=\frac{ZvM_{Pl}}{YV\chi}\sim(Z/Y)(V_{10}/\chi_{15})\times 10^{-4}$.

This "seesaw" induces Majorana mass terms of ordinary neutrinos

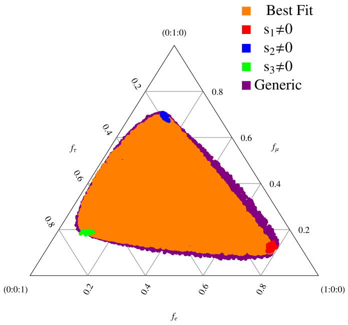
$m_\nu=\frac{m_D^2}{M'_\nu}=\frac{Z^2v^2}{Y\chi}=(Z^2/Y)\times 10^{-2}$ eV.

Oscillation probability $\sim 10^{-8}-10^{-10}$ suits for transmission of right amount of shadow neutrino flux to ordinary VHE neutrinos

– Miracle No. 3 !

What about flavor composition ?

Wide spectrum of "flavor" possibilities.



A generic prediction is that flavor content should be energy dependent, generically different for lower energy neutrinos (from $\Delta^- \to \rho_i + \nu'_x$ decay, ν'_x being a superposition of $\nu'_e, \nu'_\mu, \nu'_\tau$) and higher energy neutrinos (from shadow pion decays $\pi^- \to e^- + \bar{\nu}'_e$ and $\pi^- \to \pi^0 + e^- + \bar{\nu}'_e$)

Cfr. flavor composition in standard three neutrino case

$$\nu_\alpha = V_{\alpha i}\nu_i, \qquad \alpha = e,\mu,\tau, \qquad i = 1,2,3$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix} = \begin{pmatrix} |V_{e1}|^2 & |V_{\mu 1}|^2 & |V_{\tau 1}|^2 \\ |V_{e2}|^2 & |V_{\mu 2}|^2 & |V_{\tau 2}|^2 \\ |V_{e3}|^2 & |V_{\mu 3}|^2 & |V_{\tau 3}|^2 \end{pmatrix} \begin{pmatrix} \tilde{f}_e \\ \tilde{f}_\mu \\ \tilde{f}_\tau \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} f_e \\ f_\mu \\ f_\tau \end{pmatrix} = \begin{pmatrix} |V_{e1}|^2 & |V_{e2}|^2 & |V_{e3}|^2 \\ |V_{\mu 1}|^2 & |V_{\mu 2}|^2 & |V_{\mu 3}|^2 \\ |V_{\tau 1}|^2 & |V_{\tau 2}|^2 & |V_{\tau 3}|^2 \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} f_e \\ f_\mu \\ f_\tau \end{pmatrix} = \begin{pmatrix} P_{ee}(=0.55) & P_{e\mu}(=0.24) & P_{e\tau}(=0.21) \\ P_{\mu e}(=0.24) & P_{\mu\mu}(=0.38) & P_{\mu\tau}(=0.38) \\ P_{\tau e}(=0.21) & P_{\tau\mu}(=0.38) & P_{\tau\tau}(=0.41) \end{pmatrix} \begin{pmatrix} \tilde{f}_e \\ \tilde{f}_\mu \\ \tilde{f}_\tau \end{pmatrix} \tag{4}$$

Uncertainties in neutrino mixing parameters

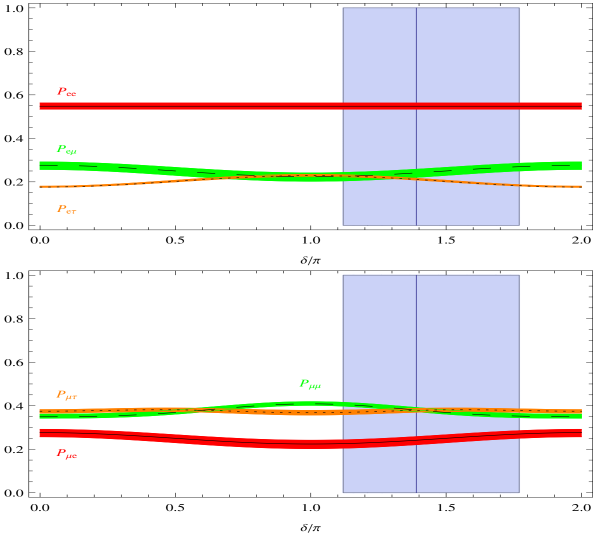
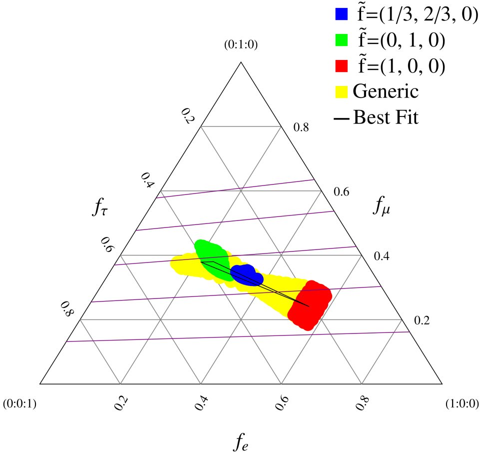


Figura: Flavor composition obtained from initial ν_e and ν_μ

Flavor triangle in standard case



Initial composition in mass eigenstates

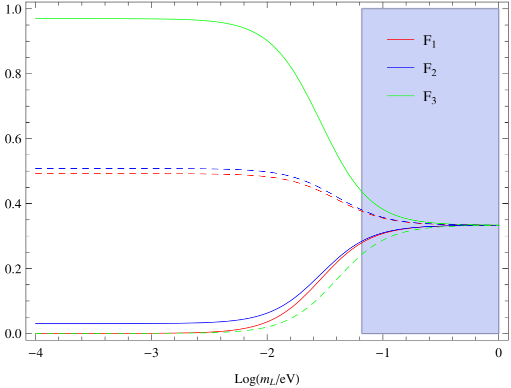
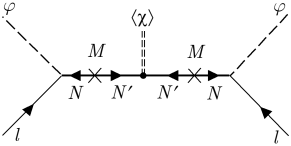


Figura: Fractions $F_{1,2,3}$ as functions of the lightest neutrino mass ($M_L = m_1$ in NH model and $M_L = m_3$ in IH model. The shaded are is excluded by cosmological limit on the sum of neutrino masses, $m_1 + m_2 + m_3 < 0.32$ eV.

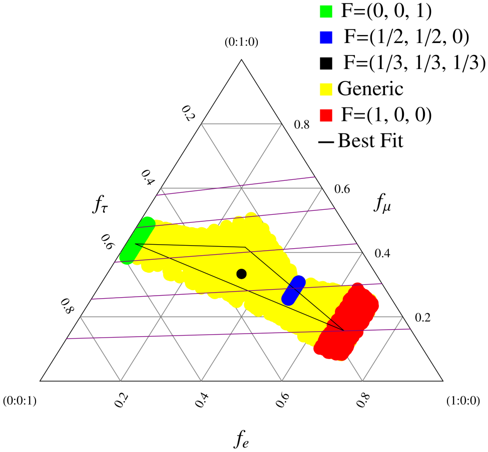
IC neutrinos via majoron/smajoron portal



Effective operator $\frac{\chi}{M} ll\phi\phi$, χ scalar with $B-L=2$, ϕ ordinary Higgs

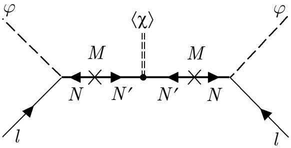
$\langle\chi\rangle = \frac{f+h}{\sqrt{2}} e^{i\beta/f}$ induces neutrino masses $m_\nu \sim fv^2/M^2 \leq 0.1$ eV
Goldstone β (majoron) and Higgs h (smajoron) modes both have diagonal couplings with neutrino mass eigenstates, $g_i = m_i/f$
not inducing neutrino decay – decays $\nu_i \to \nu_j + \gamma$ exist but extremely suppressed.
Therefore, if one could produce IC neutrinos via smajoron portal, one would have $f_1 : f_2 : f_3 = m_1^2 : m_2^2 : m_3^2$.

Cases of the neutrino NO and IO



How to produce smajorons

Introduce a shadow gauge sector with $SU(3)' \times SU(2)' \times U(1)'$ and generate shadow neutrino masses via effective operators $\frac{\chi}{M} l' l' \phi' \phi'$



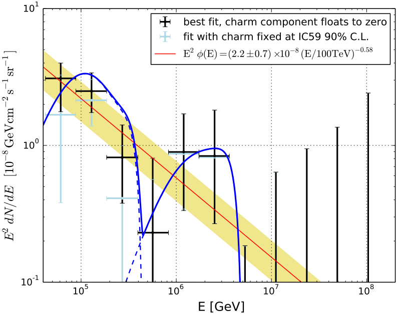
but with shadow Higgs ϕ' having VEV $v' \ll 100$ GeV, so that $m'_\nu \sim f v'/M^2 \sim 1$ PeV. Then two things happen:

- heavier shadow neutrinos become unstable: $\nu'_i \to \nu'_j + \gamma'$ decay occurs with $\tau_D \sim t_u$
- Smajoron gets tiny non-diagonal couplings which induce also $\nu'_i \to \nu'_j + h$ decays with branchings $\ll 1$.

The game is done.

As a result ...

Taking three shadow neutrinos with $\sim$ PeV masses, e.g. with $M_3 - M_2 \sim 0.5$ PeV and $M_3 - M_1 \sim 4$ PeV, the chain of decays $\nu_3' \to n_2'$, $\nu_3' \to \nu_1'$ and $\nu_2' \to \nu_1'$ with liftimes $\sim t_u$ can reproduce a bumpy spectrum as



which will have well defined initial mass eigenstate compositions: $(0,0,1)$ for NO and $(1/2,1/2,0)$ for IO cases for mass hierarchies with wee-defined (energy independent) predictions for IceCube neutrino flavor content

Conclusions

Situation with HE neutrinos is still so unclear that I would not dare to make any conclusion apart of appreciating that the discovery of IceCube is very important and can be a road towards understanding of new physics (or astrophysics)

It is still premature to insist of understanding the origin, spectral features and flavor composition of IceCube neutrinos, everyone can do his game – and hopefully the best theoretically consistent picture can be achieved in future. Let us play these games within well-defined rules, not constructing models with exotic names but many ad hoc assumptions and arbitrary tuned parameters – which is easy but not instructive.

Thanks !