Cosmology and neutrino experiments discovered something new.

New experiments will test minimal theories and search for the unseen effects that they suggest: $\theta_{13}, \quad CP, \quad m_{\nu}, \quad n - 1, \quad r, \quad CDM$...

What else could these experiments discover?
New light particles are not the best probe of heavy particles: high energy is SU(2) invariant and it is easier to deal with. Being light, they are sensitive to light particles, are not the best probe of heavy particles: high energy is SU(2) invariant and

\[ \ell \text{ (true for known light particles: } \gamma, \Omega, \Lambda) \].

Presumably a light particle is stable enough for affecting cosmology, astro.

Presumably lightness follows from some deep principle.

Any light new particle would be a key discovery:

Colliders search for new heavy particles. Better if they have fundamental im-
portance for theory or cosmology or astro or ... E.g. neutralino: SUSY + CDM

which can be searched for with cosmology, astrophysics, experiments, and
it is easier to deal with. Being light, they are sensitive to light particles,
Which spin?

...But so far the idea remained sterile...

...e.g., lower Gallium rates...).

...in the standard `emergency exit', from anomalies (solar, atmospheric, solar, cosmic, Gaia, LSND, neutrinos are the standard 'emergency exit'. From anomalies (solar, atmospheric, solar, Cosmic, LSND).

Adding neutral fermions is the simplest extension of the massive \( \nu \) scenario.

\[ \frac{\nu}{\nu} \quad \frac{\text{graviton/axion}}{\nu} \quad \frac{\text{photino/axion}}{\nu} \]

Merging with existing light particles does not need couplings: coupling.

Merging with existing light particles does not need couplings. Adding neutral fermions is the simplest extension of the massive scenario.

\[ \begin{aligned}
\text{I}/2, \text{Goldstino} & \quad \text{I}/2, \text{Goldstino} \\
\text{I}/2, \text{MSSM} & \quad \text{I}/2, \text{MSSM} \\
\text{0, \text{Goldstino}} & \quad \text{0, \text{Goldstino}} \\
\text{0, \text{MSSM}} & \quad \text{0, \text{MSSM}}
\end{aligned} \]

Which spin?

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\text{I}/2, \text{MSSM} & \quad \text{0, \text{Goldstino}} \\
\text{0, \text{MSSM}} & \quad \text{0, \text{MSSM}}
\end{aligned} \]

...interact with new light particles in different ways, according to their spin...
Why should $\nu$s be light?

$m_\nu \sim \frac{\text{MeV}}{\text{Planck mass}}$.

Flavor symmetries of $\nu$, such as $\nu^- - \nu^-$, could act at low energy.

Taken to the extreme suggests 'mirror matter': a sector identical to the SM.

Maybe for the same reason why $\nu$s are light:

Chiral symmetry (new gauge group).

A plethora of candidates from SUSY, extra dimensions, strings, M-theory (Axino, Brannino, Composite, Dilatino, Extra-d $\nu^L$, Familino, Goldstino, ...).

Many other model-dependent mechanisms can be introduced.

Why $\nu$s is not massless (eV-scale masses and mixings)?

Why $\nu$s is not very heavy (Planck or Fermi scale)?

Theory does not help: too many answers = no answer.

These would be main questions, if $\nu$s were found. Now main issue is searching.
In general these hold as estimates, valid up to fine-tunings or up to specific structures. No particular implications. Better to perform 360° searches.

$\left( \begin{array}{ccc} m_{RR} & m_{LR} & m_{LL} \\ m_{LR} & m_{LL} & m_{LR} \\ m_{LL} & m_{LR} & m_{RR} \end{array} \right)^R \sim m$

where

Dominant $m_{LL}$:

\[ m_{LL} \sim 4 \sqrt{m_{\text{active}}} \]

Small $m_{LR}$:

\[ m_{LR} \sim m_{\text{active}} \]

Small $m_{RR}$:

\[ m_{RR} \sim \theta \]

Good taste allows to guess some patterns:

because the theorists worked a lot, but flavour remains not understood.

$360° > \theta > 0 \quad \infty > m_{s} \quad \infty > m_{u} \quad \infty > m_{s}$

for the number of $s$ with masses $m_{s}$ and mixings $s$ are not very restrictive

**Predictions**
$S$ vs signals of $I$
Neutrino mixing is described by 3 extra parameters: convenient mixing angles and a vector $\nu$ that tells which active $\nu$ mixes with $\nu_s$. Add 1 $\nu_s$. Neutrino mixing now corresponds to $\nu_s$.

Usual bounds on $\nu_s$ from sun or atm correspond to $\nu_s$.

**Mixing with a mass eigenstate**

Mixing with a flavoured eigenstate

$\nu_s$ mixes with a neutrino of mixed flavour $\nu_s$.

$\nu_i = \nu_1$ or $\nu_2$ or $\nu_3$

Two of them known: $m_2^\text{sun, atm}$

$\nu_s$ oscillates at 3 different $m_2$.

$\nu_1 \cdot \nu^c_1 = 0$

6 representative cases:
Solar neutrinos

Usual analysis: $e^{-} + q_1 \rightarrow e^{-} + q_2$; gives $\Delta m^2 = 0$ dominantly affected with $\nu_1$.

Critical energy $E \sim \frac{G e N_e}{2 m_\nu^2}$

Averaged vacuum oscillations

But things can be qualitatively different:

Such energy-independent $\nu$ is obtained for $\nu_2$ mixing with large $\Delta m^2$.

Sub-MeV effects sub-MeV $\nu_1$.

Adiabatic MSW resonance

Sun emits $\nu_1 (\propto \cos^2 \theta_{sun})$, $\nu_2$.

$1 - \frac{2}{\sin^2 2\theta} \propto (\nu_{e} \leftrightarrow \nu_{\mu})_p$

Averaged probability of solar neutrinos

Energy of solar neutrinos in MeV

Flux in cm$^{-2}$ s$^{-1}$

Survival probability

0 % 20 % 40 % 60 % 80 % 100 %

0.1

0.5

$\Delta m^2$ Sun emits only $\nu_2$

$\theta_{sun} = (\nu_{e} \leftrightarrow \nu_{\mu})_p$

Solar neutrinos
The active/active effects fully included assuming normal hierarchy and $\frac{1}{2} \theta_3 = 0$ are

$$\text{Status of } \nu_s^L/\nu_1^L$$
\[ \text{Mton WC: } AE_{\text{S}} \gtrsim 0.005. \]

Borexino seasonal at 2%
Borexino day/night at 2%
Measure rate at 2%

Gallium experiments are crucial.

\[ \tan \theta < \tan \theta_{\text{sun}} < m_{2}^{41} \gtrsim m_{2}^{17} \]

\[ \tan \theta > 1 \]

distorted MSW triangle at

\[ \text{vs/ν}: \text{solar neutrinos} \]
Interacting $\nu$s reduce free-streaming (CMB, peaks, shifted, clusterings)

**LSS sensitive to $m^2$ (i.e. $\tau < \frac{m}{\sqrt{2}}$)**

**But can/will improve ($\frac{10}{2}$)**

$\frac{N_{\nu}}{N_{\text{CMB}}} \approx 3 \pm 2$

Deuterium and CMB now depleted.

Before BBN if $\Delta m^2 \gtrsim 10^{-8} \text{eV}^2$.

He affected by $\nu$, depleted.

$\frac{N_{\text{He}}}{N_{\nu}} = 2.7 \pm 0.7$

BBN: He

$N_{\text{He}}$: $N_{\text{He}} = 4$ disfavored?

$LSS$ observables: redundant?

$LSS$ comparable with CDM, that $n$. Compatibility with minimal cosmology with minimal $\Lambda$CDM.

Below $\nu$, $\Delta m^2 \gtrsim 10^{-5} \text{eV}^2$ has produced before $T^\nu$ decoupling ($\approx \text{MeV}$).

$\nu/s$ Cosmology
$\tan^2 \theta_s = 10^{-2} \Delta m_{14}^2$ in eV$^2$

Reduction of supernova rate will be the main observable.

Need a exp/th compromise: $\tilde{\nu} \neq \nu$ profile, $\tan \theta_s < 1$ (but peculiar $\nu_e$ profile).

MSW resonance mostly for $\nu_e$'s.

Supernovae collapse: core collapse supernovae.

$\nu_s/\nu_l$
Search non-standard sterile signals in atm data.

Atmospheric experiments SK, K2K, MACRO better at smaller $\tan^2 \theta_S$. Chooz, Bugey, all other SBL.

Chooz, Bugey, all other SBL, Biloc, double-CHOOZ.

$\nu_s/\nu_t$: terrestrial exp's.
Results similar to $\nu_s/\nu$ with one qualitative difference: if $\nu_e$ is negligibly involved in sterile mixing cosmology becomes the main probe.
Other probes are potentially sensitive down to much smaller $\Delta m^2$. But...

Relic supernovae $\bar{\nu}_e$: initial flux uncertain. Energy spectrum unaffected.

Neutrino astrophysics at high energy: initial flux, energy spectrum unknown. Expected flavour composition: $\Phi_e / \Phi_\mu = r = 1$.

But $r < 1$ if some $\mu$ cannot decay. But different spectra.

$\nu_s$ negligibly affect $\Phi_\mu / \Phi_\tau$ ($\nu_{1,2,3}$ contain roughly equal amounts of $\mu$ and $\tau$).

$\nu_s$ can modify $\Phi_e / \Phi_\mu, \tau$, but hard to measure $\Phi_e$. Could be (?) reconstructed from the shower rate, proportional to $\text{CC}_e + \text{NC}_{e,\mu,\tau}$.

Direct detection of CMB neutrinos: sensitive to $\nu / \nu_s$ oscillations after BBN, i.e. $\Delta m^2 \lesssim 10^{-8} \text{eV}^2$. Rate well known and ridiculously small: see you at Nu2040 (unless extra interaction could make $\nu$ clustered enough).
Signals vs ∞
The minimal model predicts, in terms of the radius $R$, a tower of sterile neutrinos $\nu_R$ with $\nu_\ell$ in the extra dimensions.
Reduced $N_{\text{Free Stream}}$ from new low-energy interactions: test with CMB/LS. Anomalously complicating from mixing with extra-d $\nu^R$ or with 4d pseudo-Dirac.

Anomalous $\nu$ and $\nu$ from mixing with extra-d $\nu^R$ or with 4d pseudo-Dirac: different patterns. Main vs searches seem suggesting is always easier than doing.

If explodes tomorrow, theoretical errors would dominate. Test if the next supernova otherwise.

Also DoubleChooz, Minon WC, Monolith-ino... Measure better low energy solar $\nu$s. Could manifest only there.

Large scale structures + CMB test $\nu$s with small abundancy and $m \sim 10^eV^s$.

Minimal subset: test $N_{\text{He}}^4 = 4$ and measure $N_{\text{CMB}}$.

Today none discriminates 3 from 4 (extra vs) from 3 + 4/7 (extra spin 0).

Astronomer/cosmo $\nu$ exps can probe different patterns. Main vs searches seem (suggesting is always easier than doing).
FAQ:

1) Relate $\tilde{n}$ to $V$
2) What is $\nu_2/\nu_1$ level crossing?
3) How computations are done?
4) How fits are done?
5) Relate $N_t$ to true observables
6) LSND?

Other questions are at the asker’s risk
\[
\begin{pmatrix}
\cos^s \theta \\
\sin^s \theta \\
\end{pmatrix}
\begin{pmatrix}
\sin^s \theta \\
\cos^s \theta \\
\end{pmatrix}
\begin{pmatrix}
u_n \\
\nu_n \\
\end{pmatrix}

= \Lambda
\]

\[
\varepsilon_\theta \alpha u + \varepsilon_\theta \beta u + \varepsilon_\theta \gamma u = \varepsilon_\eta \omega u + \varepsilon_\eta \theta u + \varepsilon_\eta \phi u = \varepsilon \cdot u
\]
Level crossings in the sun and in a SN
How to compute

(3) When changes in a not very sharp way the rotation angle is given by
\[ \tan \phi = \frac{\partial \rho}{\partial \rho - 1} \]

(2) When changes in a sharp way \( \rho \) is a rotation with angle \( \phi = 90^\circ \) in the plane. If levels \( \rho \) and \( \rho' \) cross, \( \rho' \) is a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way \( \rho \) changes in a sharp way

(1) When density is constant, this allows to analytically average over fast oscillations. Give small imaginary parts to oscillation phases.

Compute oscillations using the matrix density in the mass eigenstate bases. Numerical analyses are orders of magnitude more demanding than usual fits. Compute oscillations using the matrix density in the mass eigenstate bases. Numerical analyses are orders of magnitude more demanding than usual fits. Compute oscillations using the matrix density in the mass eigenstate bases. Numerical analyses are orders of magnitude more demanding than usual fits.
Include uncertainties on active parameters in Gaussian approximation:

(How to fit)
Cosmological observables parameterized in terms of "effective number of neutrinos"
Full computation confirms estimates: 3+1 implies non-standard cosmology.