Astrophysical Insights into Pseudo-Dirac Neutrinos with IceCube Observations

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Based on *arXiv: 2406.06476 [astro-ph.HE]*
with

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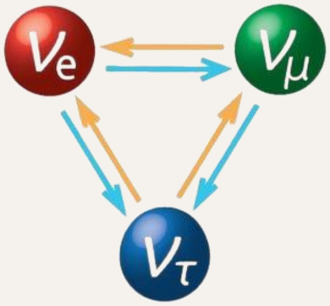
Neutrino Oscillations

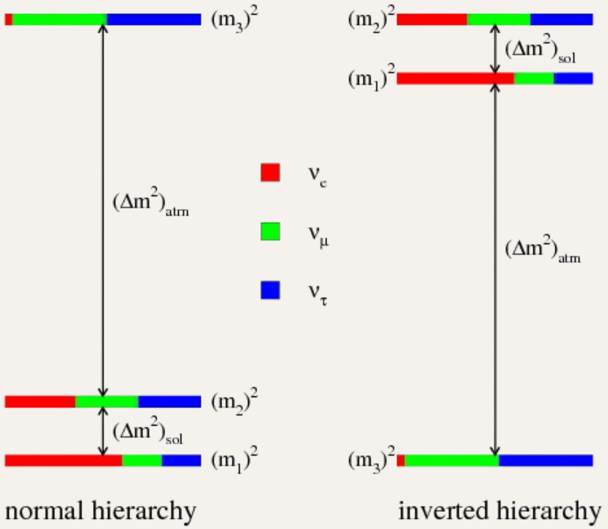
- Neutrinos interact only via weak interactions
- There are three active neutrino flavors
- Neutrinos are massive and change their flavor during a distant travel



Flavor transition probability

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$L_{osc} \propto E/\Delta m^2$$



Neutrino Masses

- Only neutrinos may have Majorana masses

active

- In the basis of weak eigenstates $\Psi_L = \begin{pmatrix} \nu_{\alpha L} \\ \bar{\nu}_{\alpha L} \end{pmatrix}; \qquad \bar{\nu}_{\alpha L} = \nu^C_{\alpha R}$ ← (sterile)

  neutrino mass term $L_{mass} = \frac{1}{2}\Psi^t_L C M \Psi_L$

  with generic Majorana mass matrix $M = \begin{pmatrix} M_L & M_D \\ M_D & M_R \end{pmatrix}$

Three possibilities:

1. **Dirac limit:** $M_L, M_R = 0 \rightarrow$ no lepton number violation
2. **Majorana limit:** $M_L, M_R \gg M_D \rightarrow$ explicit lepton number violation
3. **Pseudo-Dirac (pD) limit:** $M_L, M_R \ll M_D \rightarrow$ soft lepton number violation

$\rightarrow$ Neutrino oscillation between an active state and a sterile state

$$|\tan 2\theta| = \left|\frac{2M_D}{M_L - M_R}\right| \gg 1 \Rightarrow \theta \sim \pi/4$$

Active and sterile states: $\nu_A = \frac{-i}{\sqrt{2}}(\nu_L - \bar{\nu}_L), \quad \nu_S = \frac{1}{\sqrt{2}}(\nu_L + \bar{\nu}_L)$

Pseudo-Dirac Neutrino Oscillations

- Three pairs of quasi-degenerate states, separated by tiny $\delta m^2 \ll \Delta m^2_{\rm sol}, \Delta m^2_{\rm atm}$

$$\left\{\begin{array}{l} \nu^{\alpha L} = \frac{1}{\sqrt{2}} U^{\alpha j}_{\rm PMNS}(\nu_{js} + i\nu_{ja}), \\ m^2_{ks,ka} = m^2_k \pm \delta^2_{mk}/2 \end{array}\right\} \Rightarrow$$

maximal mixing

- Mass matrix can be diagonalized by

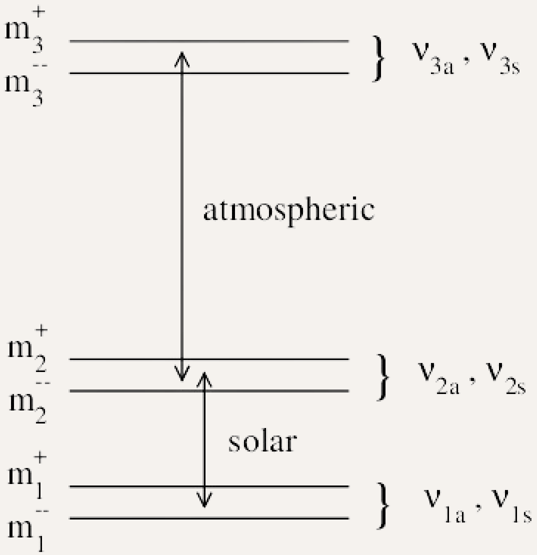
$$V = \begin{pmatrix} U_{PMNS} & 0 \\ 0 & U_R \end{pmatrix} \cdot \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} I_3 & iI_3 \\ \phi & -i\phi \end{pmatrix}$$

- Active flavor transition probabilities

$$P_{\alpha\beta} = \frac{1}{4} \left| \sum_{j=1}^{3} U_{\beta j} \left\{ \exp\left(i \frac{\delta m^2_{js} t}{2E}\right) + \exp\left(i \frac{\delta m^2_{ja} t}{2E}\right) \right\} U^*_{\alpha j} \right|^2$$

$$P_{\alpha\beta} = \sum_{i=1,2,3} |U_{\alpha i}|^2 |U_{\beta i}|^2 \cos^2\left(\frac{\delta m^2_i L}{4E_\nu}\right); \quad \alpha = e, \mu, \tau$$

(For astrophysical neutrinos)



Kobayashi, Lim, PRD 2001

Bounds on Pseudo-Dirac Neutrinos

- Atmospheric Neutrinos : $\delta m^2 < 10^{-4}\ eV^2$ Beacom, Bell, et al., PRL 2004
- Solar Neutrinos : $\delta m^2 < 10^{-12}\ eV^2$ de Gouvea, Huang, Jenkins, PRD 2009
- *SN1987A* : Excluded $2.55 \times 10^{-20}\ eV^2 < \delta m^2 < 3.0 \times 10^{-20}\ eV^2$ Soler, Gonzalez, Sen, PRD 2021

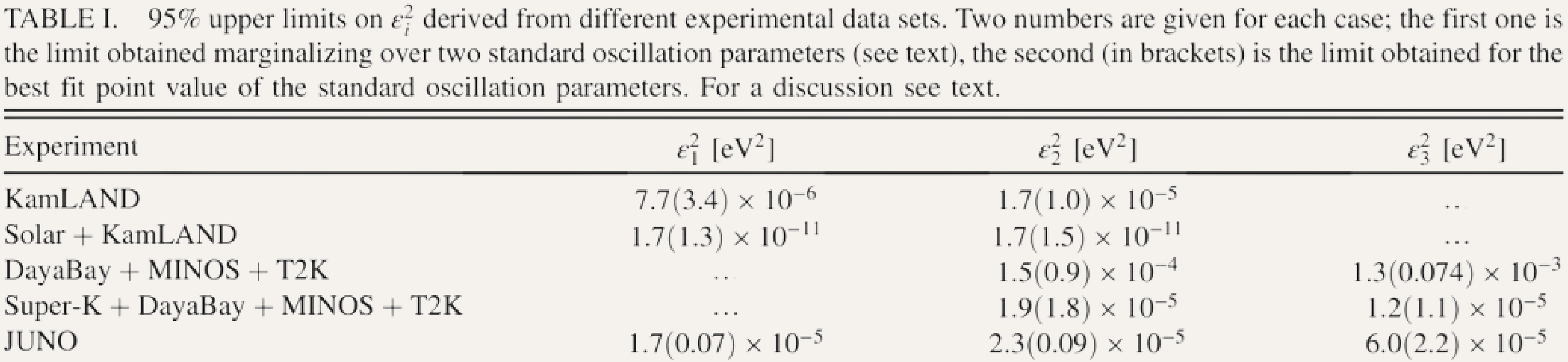
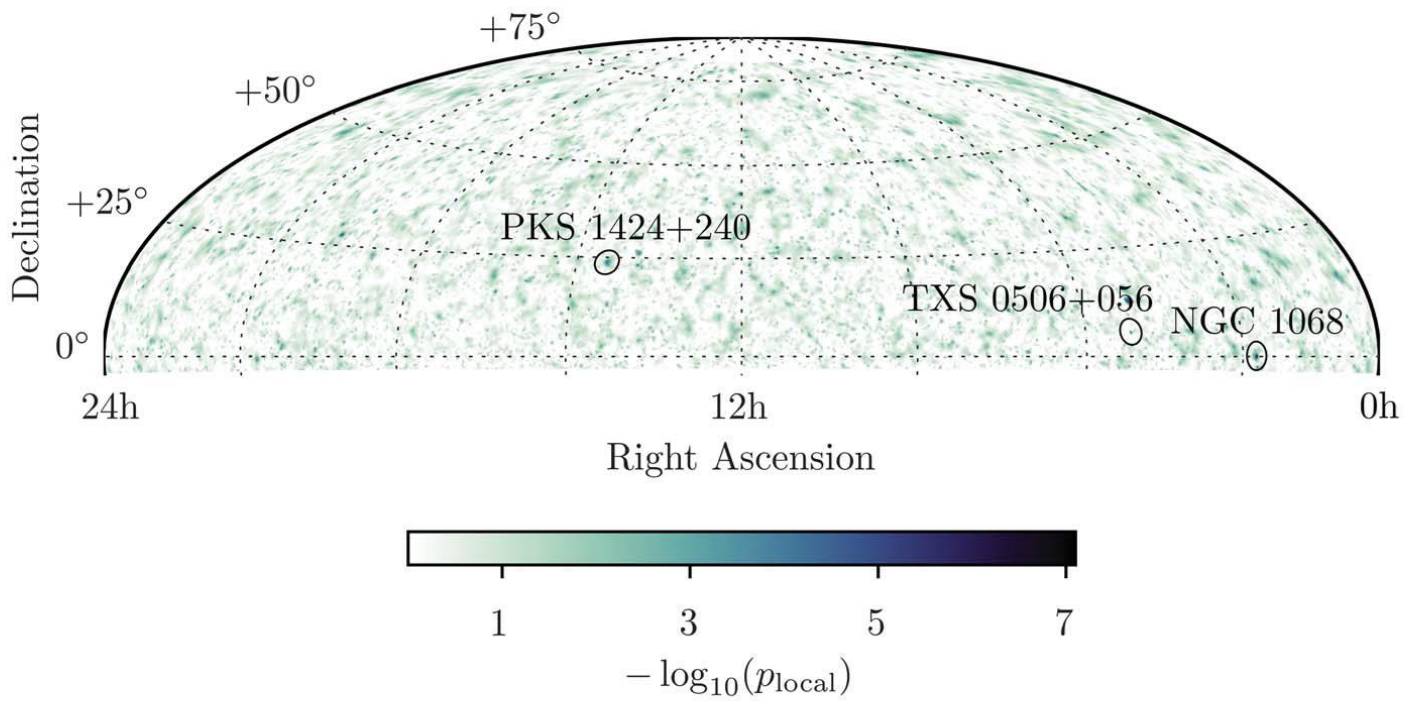


TABLE I. 95% upper limits on ε_i^2 derived from different experimental data sets. Two numbers are given for each case; the first one is the limit obtained marginalizing over two standard oscillation parameters (see text), the second (in brackets) is the limit obtained for the best fit point value of the standard oscillation parameters. For a discussion see text.

Experiment	ε_1^2 [eV^2]	ε_2^2 [eV^2]	ε_3^2 [eV^2]
KamLAND	$7.7(3.4) \times 10^{-6}$	$1.7(1.0) \times 10^{-5}$	..
Solar + KamLAND	$1.7(1.3) \times 10^{-11}$	$1.7(1.5) \times 10^{-11}$	...
DayaBay + MINOS + T2K	..	$1.5(0.9) \times 10^{-4}$	$1.3(0.074) \times 10^{-3}$
Super-K + DayaBay + MINOS + T2K	...	$1.9(1.8) \times 10^{-5}$	$1.2(1.1) \times 10^{-5}$
JUNO	$1.7(0.07) \times 10^{-5}$	$2.3(0.09) \times 10^{-5}$	$6.0(2.2) \times 10^{-5}$

Anamiati, Fonseca, Hirsch, PRD 2018

Searches for Point-like Neutrino Sources at IceCube

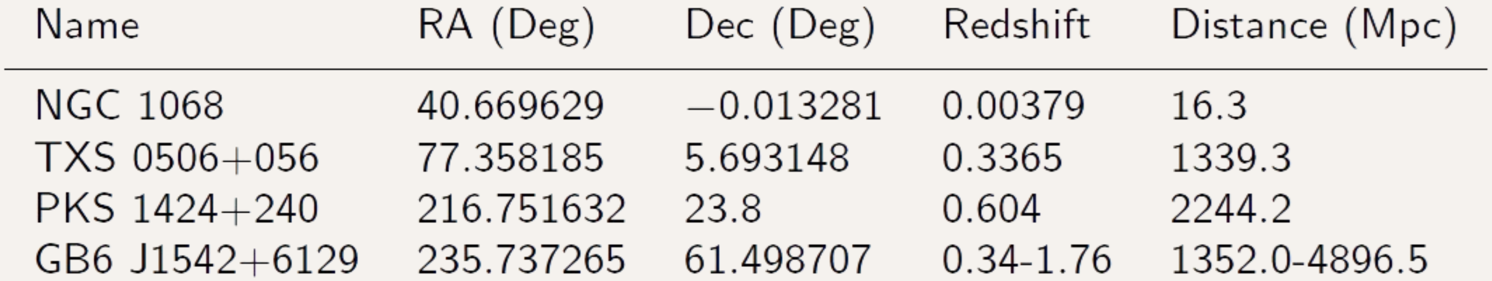


IceCube Collaboration, 2022

High Energy Astrophysical Neutrino Data from IceCube

- ➔ IceCube has performed several all-sky searches for point-like neutrino sources using track-like events induced by ν_μ and $\bar{\nu}_\mu$.
- ➔ PSTracks event selection : IceCube public data from its IC86 configuration
  - ◆ Designed for point-source studies that benefit from the good angular resolution of tracks $(< 1^o)$
  - ◆ Can tolerate larger atmospheric background contributions compared to diffuse neutrino analyses.
- ➔ Cumulative excess of events has been observed, mostly determined by four sources with significance of 3.3σ (Abbasi, et al., 2021)

Point sources detected by IceCube with high significance



Name	RA (Deg)	Dec (Deg)	Redshift	Distance (Mpc)
NGC 1068	40.669629	−0.013281	0.00379	16.3
TXS 0506+056	77.358185	5.693148	0.3365	1339.3
PKS 1424+240	216.751632	23.8	0.604	2244.2
GB6 J1542+6129	235.737265	61.498707	0.34-1.76	1352.0-4896.5

Oscillation Probabilities for NGC 1068

Assuming : $\delta m_1^2 = \delta m_2^2 = \delta m_3^2 \equiv \delta m^2$

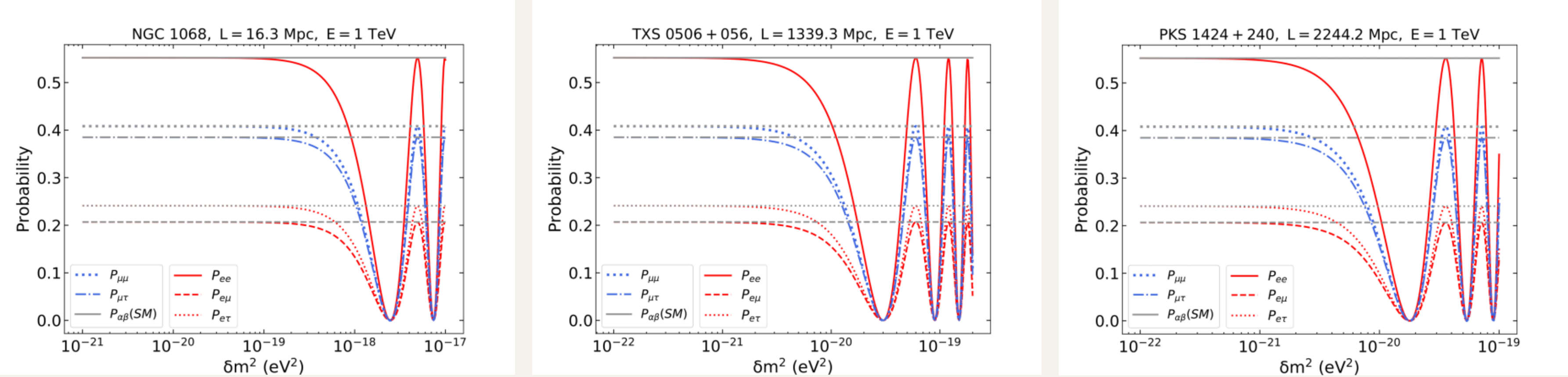


Figure: Active flavor oscillation probabilities in the pseudo-Dirac scenario.

- Smallest values of active-sterile mass splittings δm_i^2 can be probed:
    - for PKS 1424+240 with longest distance observed among all three sources

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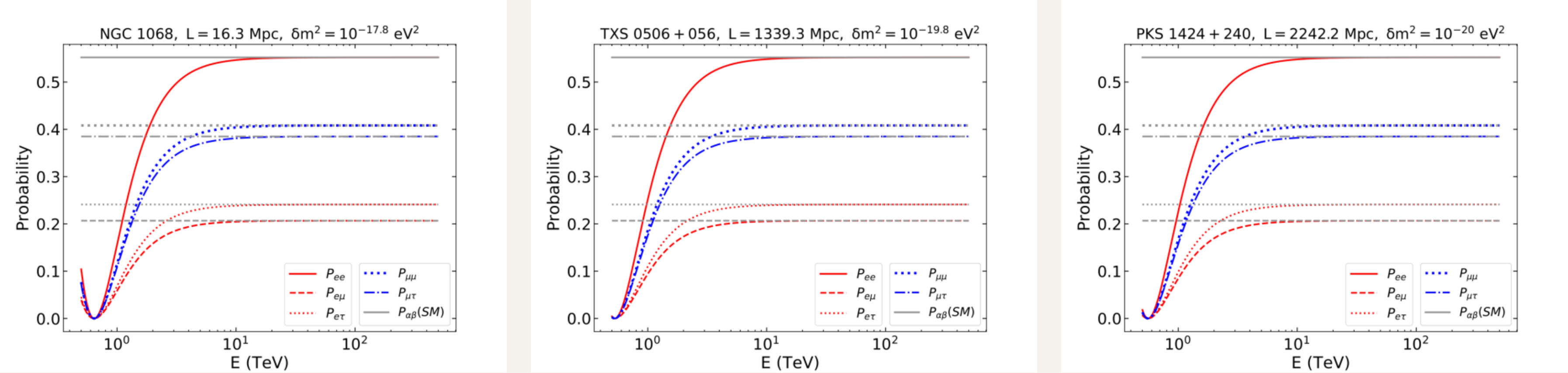


Figure: Active flavor oscillation probabilities in the pseudo-Dirac scenario.

- Smallest values of active-sterile mass splittings δm_i^2 can be probed:
  - for PKS 1424+240 with longest distance observed among all three sources
  - with lower energy neutrinos

Source Flux and Event Distributions

- Typical pion-decay neutrino flux from astrophysical sources: $\Phi^0_{\nu_\mu} \approx \Phi^0_{\bar{\nu}_\mu} \approx \Phi^0_{\nu_e} = \phi^0 \left(\frac{E_\nu}{1\ \mathrm{TeV}}\right)^{-\gamma}$
- Source flux at the detector: $\Phi^{\mathrm{src}}_{\nu_\mu} = \Phi^0_{\nu_\mu} P_{\mu\mu} + \Phi^0_{\nu_e} P_{e\mu} = x P_{ee} \Phi^0_{\nu_e} + (1-x) P_{e\mu} \phi^0_{\nu_\mu}$

$$(x = 1/3 \text{ for } \pi - \text{decay})$$

- Events from the source:

$$n_s = T \int d\Omega \int_{E_1}^{E_2} dE_\nu\, A^{\mathrm{eff}}_\nu(E_\nu, \Omega)\, \Phi^{\mathrm{src}}_{\nu_\mu}(E_\nu; \delta m_i^2, \phi^0, \gamma) + \text{antineutrinos}$$

- Events from atmospheric and astrophysical backgrounds:

$$n_b = T \int d\Omega \int_{E_1}^{E_2} dE_\nu\, A^{\mathrm{eff}}_\nu(E_\nu, \Omega) \left[\phi^{\mathrm{atm}}_{\nu_\mu}(E_\nu, \Omega) + \phi^{\mathrm{ast}}_{\nu_\mu}(E_\nu, \Omega)\right] + \text{antineutrinos}$$

$\phi^{atm}_{\nu_\mu}$ → Conventional & prompt atmospheric background (Honda et al., 2015; Reno and Enberg, 2008)

$\phi^{ast}_{\nu_\mu}$ → Diffuse astrophysical background (IceCube collaboration, 2020)

Statistical Analysis

- Probability density for a neutrino with energy E_j from an astrophysical point source with flux Φ^{src} and corresponding signal events $n_{s,k}$ is

$$P(E_j|\phi^{\mathrm{src}}) = \frac{\sum_k M(E_j, E_k^*) n_{s,k}}{\sum_k n_{s,k}} \;;$$

$M(E_j, E_k) \longrightarrow$ energy migration matrix provided by the IceCube Collaboration

- Source probability density for the j-th ν event drawn from a Gaussian profile

$$\mathcal{S}_j(\vec{x}_j, \vec{x}_s, E_j, \phi^{\mathrm{src}}) = \frac{1}{2\pi\sigma_j^2} e^{-\frac{|\vec{x}_j - \vec{x}_s|^2}{2\sigma_j^2}} P(E_j|\phi^{\mathrm{src}})$$

- Background probability density for the j-th ν event $\mathcal{B}_j = \frac{P(E_j|\phi^{\mathrm{atm}} + \phi^{\mathrm{ast}})}{\Delta\Omega_s}$
- Likelihood function $\mathcal{L}(\vec{x}_s; \hat{\theta}) = \prod_{j=1}^{N} \left[\frac{n_s}{N}\mathcal{S}_j + \left(1 - \frac{n_s}{N}\right)\mathcal{B}_j\right], \hat{\theta} = \{\phi^0, \gamma, \delta m_i^2\}$
- Test Statistic $TS = -2\left[\log \mathcal{L}(\vec{x}_s; \hat{\theta}_0) - \log \mathcal{L}(\vec{x}_s; \hat{\theta})\right]$ Braun et al. 2008

Results

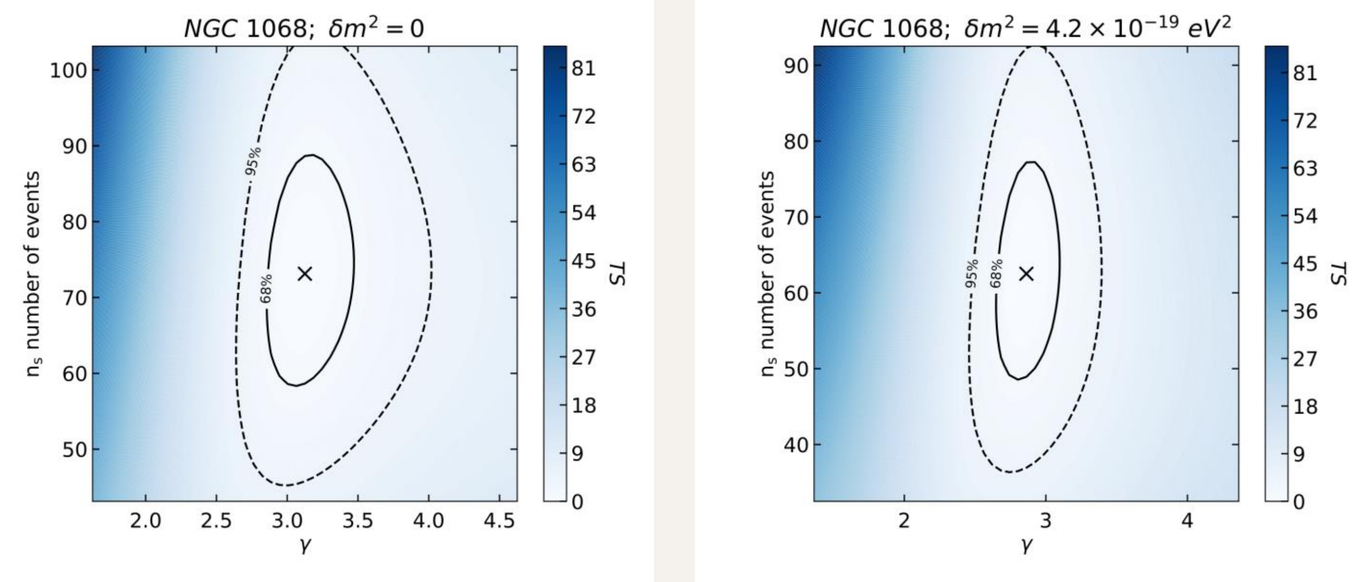
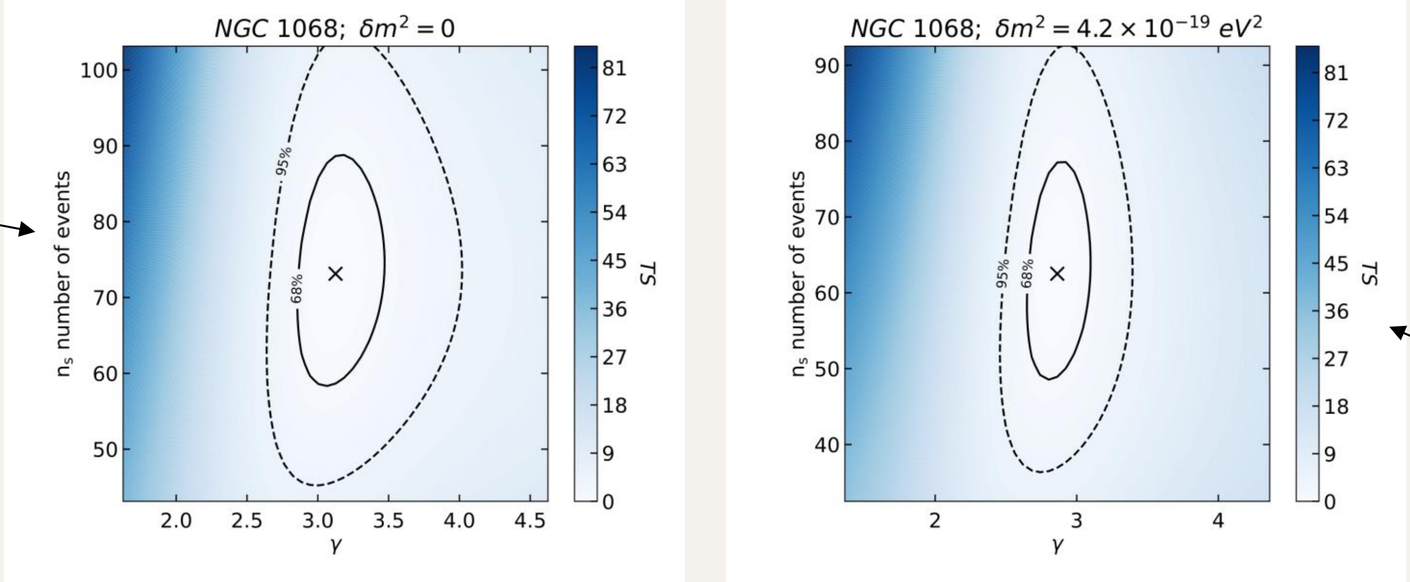


Figure: Left panel: SM case (all $\delta m^2 = 0$), compatible with IceCube Collaboration results (2022). Right panel: pseudo-Dirac case (all $\delta m^2 = 4.2 \times 10^{-19}\ eV^2$). The energy range here is 1-100 TeV. The color bar represents Test Statistic.

Results



Good agreement with with IceCube Collaboration's published results for NGC 1068

No. of events decreased, lower spectral index

Figure: Left panel: SM case (all $\delta m^2 = 0$), compatible with IceCube Collaboration results (2022). Right panel: pseudo-Dirac case (all $\delta m^2 = 4.2 \times 10^{-19}\ eV^2$). The energy range here is 1-100 TeV. The color bar represents Test Statistic.

Event Distributions with pseudo-Dirac Neutrinos

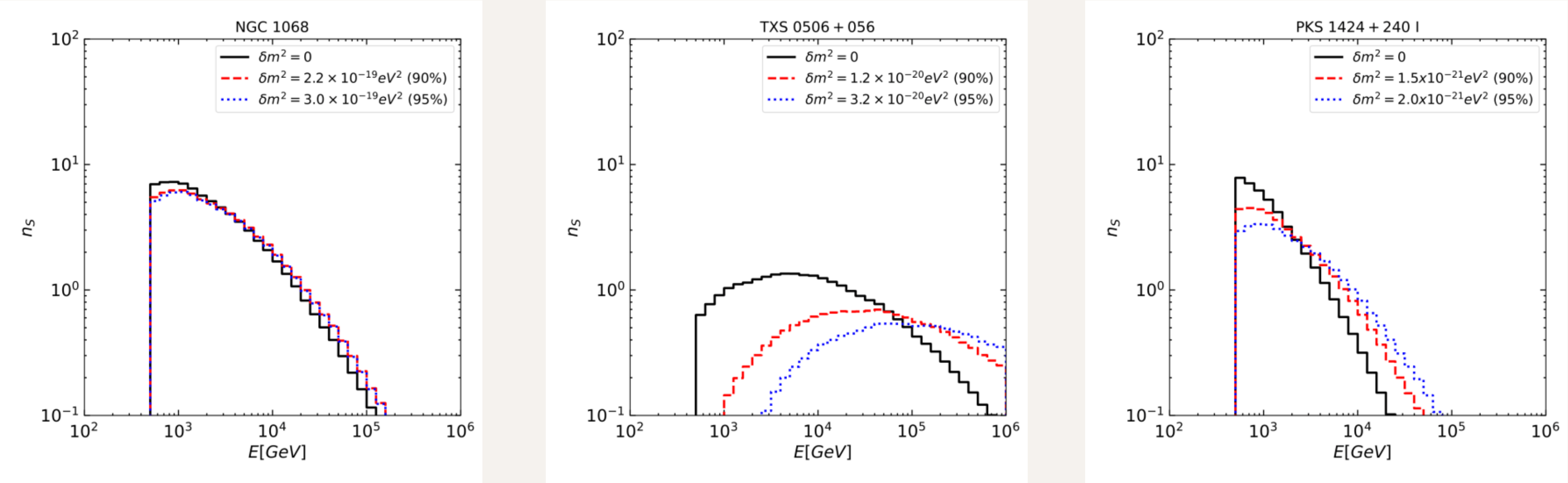
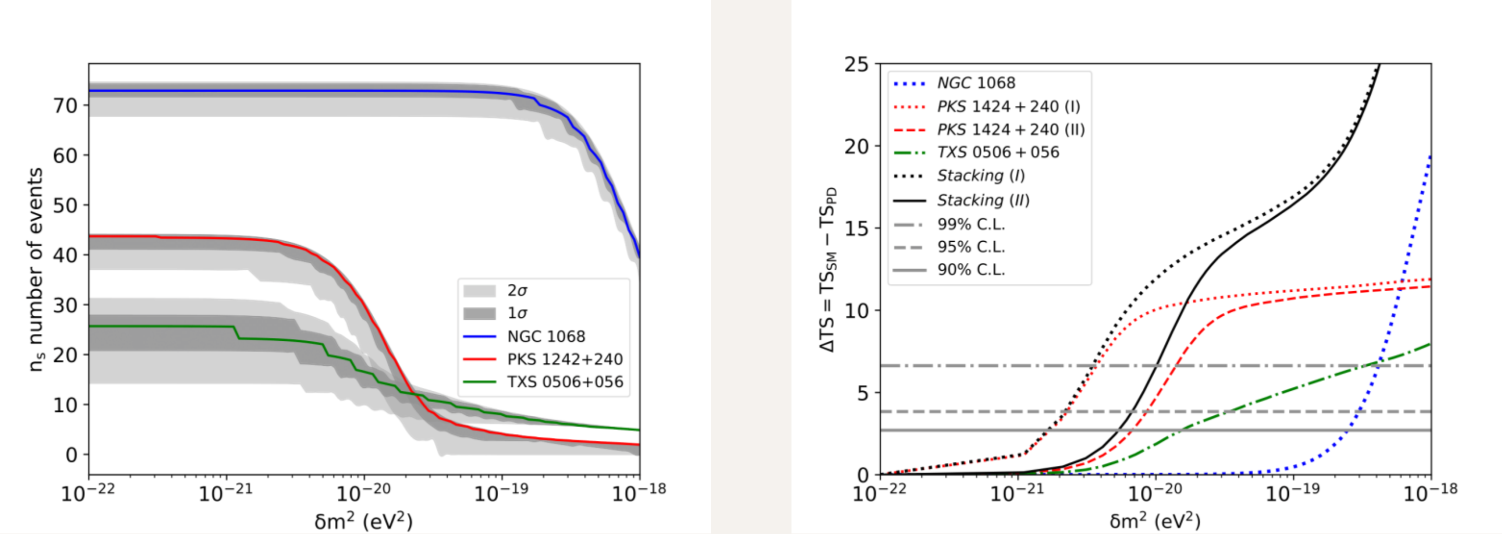


Figure: Event distributions generated for the energy-range 0.5 TeV - 1 PeV for all the sources. The $\hat{\gamma}$ obtained for these fits are 3.1 (3.0) for NGC 1068, 2.4 (2.0) for TXS 0506+056, 3.7 (3.3) for PKS 1424+240 for SM (90% CL constraint on pD).

- In pD scenario, fast oscillations at lower energies get averaged out to a lower value compared to the standard oscillations.
- Changes the flux reaching the earth, lower in normalization and harder in index compared to the standard case.

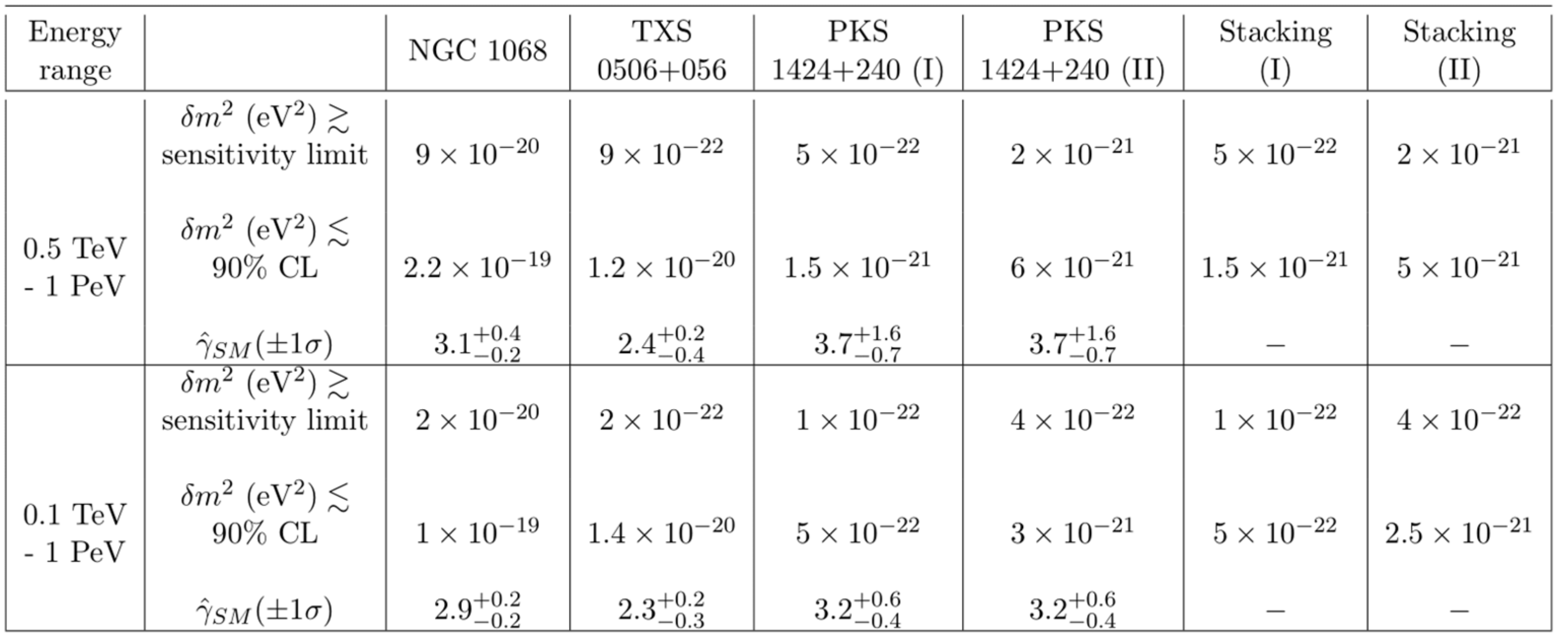
Constraints on pseudo-Dirac neutrinos

$$\Delta TS = TS^{SM} - TS^{pD}$$



- Number of signal events decreases with increasing δm^2 as more active neutrinos convert to sterile neutrinos.
- We constrain the pseudo-Dirac neutrino mass-squared-difference $\delta m^2 \lesssim 1.5 \times 10^{-21}\ eV^2$ at 90% CL performing a stacking analysis.

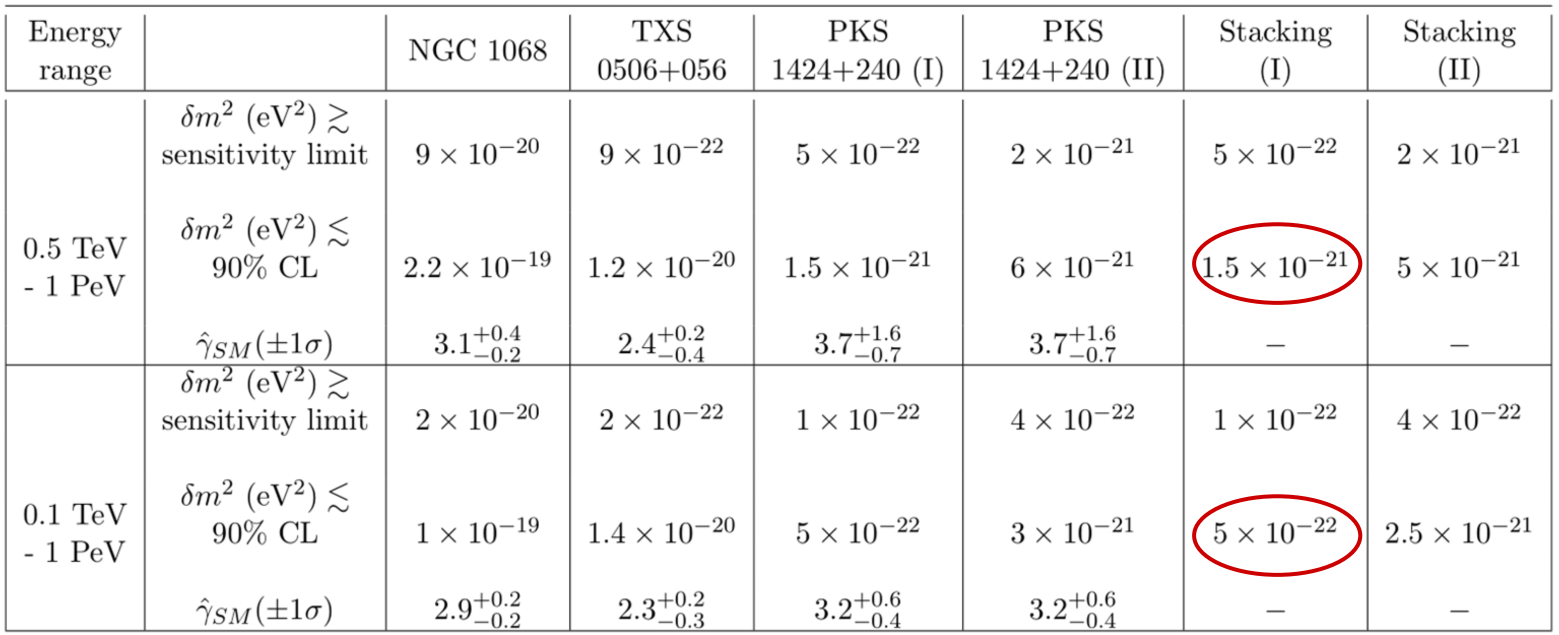
Summary



Energy range		NGC 1068	TXS 0506+056	PKS 1424+240 (I)	PKS 1424+240 (II)	Stacking (I)	Stacking (II)
0.5 TeV - 1 PeV	δm^2 (eV^2) $\gtrsim$ sensitivity limit	9×10^{-20}	9×10^{-22}	5×10^{-22}	2×10^{-21}	5×10^{-22}	2×10^{-21}
	δm^2 (eV^2) $\lesssim$ 90% CL	2.2×10^{-19}	1.2×10^{-20}	1.5×10^{-21}	6×10^{-21}	1.5×10^{-21}	5×10^{-21}
	$\hat{\gamma}_{SM}(\pm 1\sigma)$	$3.1^{+0.4}_{-0.2}$	$2.4^{+0.2}_{-0.4}$	$3.7^{+1.6}_{-0.7}$	$3.7^{+1.6}_{-0.7}$	–	–
0.1 TeV - 1 PeV	δm^2 (eV^2) $\gtrsim$ sensitivity limit	2×10^{-20}	2×10^{-22}	1×10^{-22}	4×10^{-22}	1×10^{-22}	4×10^{-22}
	δm^2 (eV^2) $\lesssim$ 90% CL	1×10^{-19}	1.4×10^{-20}	5×10^{-22}	3×10^{-21}	5×10^{-22}	2.5×10^{-21}
	$\hat{\gamma}_{SM}(\pm 1\sigma)$	$2.9^{+0.2}_{-0.2}$	$2.3^{+0.2}_{-0.3}$	$3.2^{+0.6}_{-0.4}$	$3.2^{+0.6}_{-0.4}$	–	–

Results of the analysis performed for all sources and the stacking analysis are given in terms of constraints on δm^2 with 90% CL and γ with 1σ error.

Summary



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Summary

- We searched for pseudo-Dirac neutrinos from the most significant three astrophysical point sources in the PSTrack events coming from the IC86 configuration of IceCube.
- *We performed a more general analysis than the previous studies, kept the spectral index as free parameter.*
- *For NGC 1068,* $\delta m^2 \lesssim 2.2 \times 10^{-19}\ eV^2\ (1.0 \times 10^{-19}\ eV^2)$ *at 90% C.L. for the analysis in the 0.5 TeV - 1 PeV (0.1 TeV - 1 PeV) energy range. a stronger constraint than the one obtained by Rink & Sen 2022, which kept the power-law index of the source flux fixed.*
- The most stringent constraint is for PKS 1424+240 where $\delta m^2 \lesssim 1.5 \times 10^{-21}\ eV^2\ (6.0 \times 10^{-21}\ eV^2)$ at 90% C.L. for $z = 0.64\ (0.16)$ for 0.5 TeV - 1 PeV energy range. More stringent constraint for 0.1 TeV - 1 PeV energy range.
- *Finally, we found constraints on* $\delta m^2 \lesssim (1.5 - 5.0) \times 10^{-21}\ eV^2$ *at 90% C.L. from a stacking analysis, where the constraint is dominated by PKS 1424+240.*

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Thanks!

Backup slides

Event Distributions with pseudo-Dirac Neutrinos

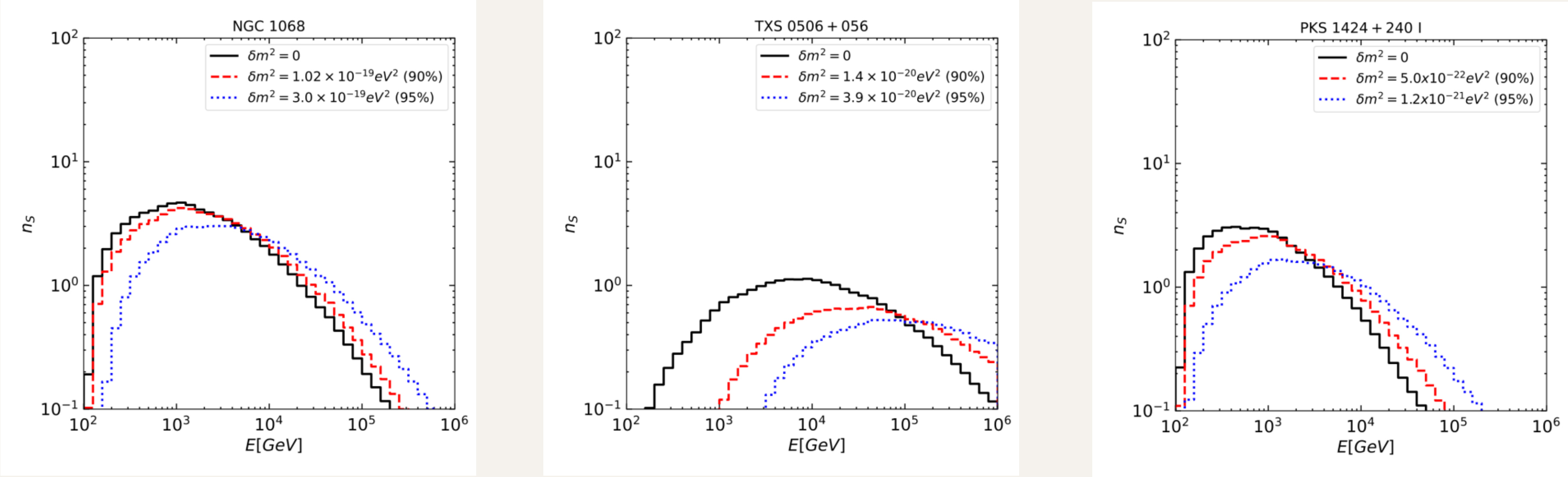
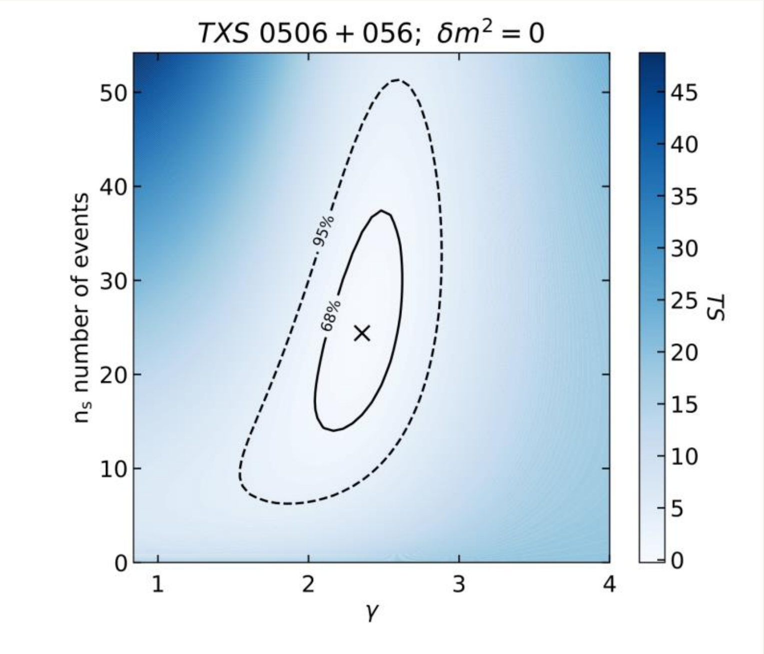
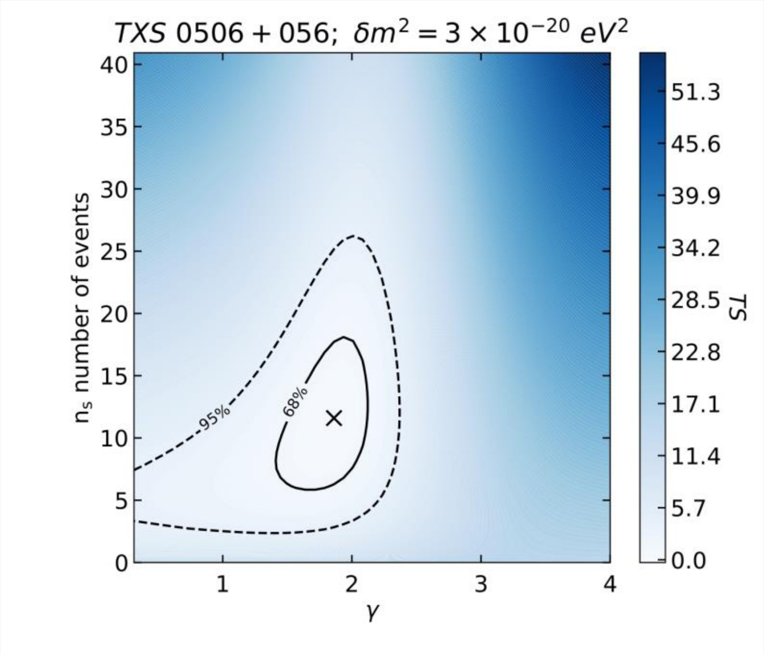


Figure: Expected events from different sources **0.1 TeV - 1 PeV**

Backup slides





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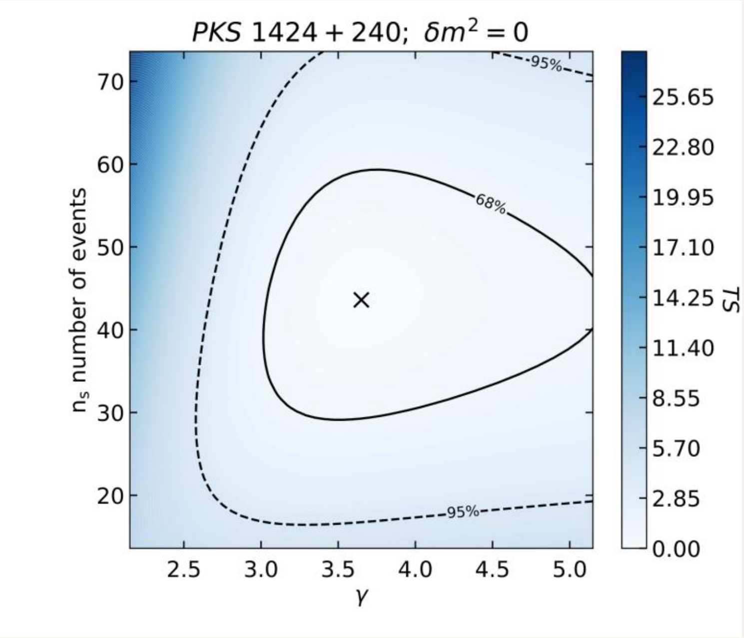

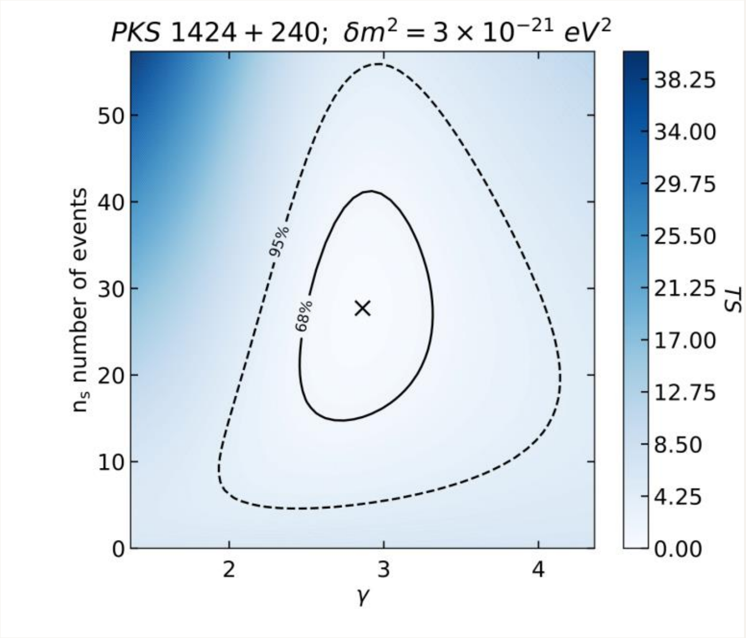

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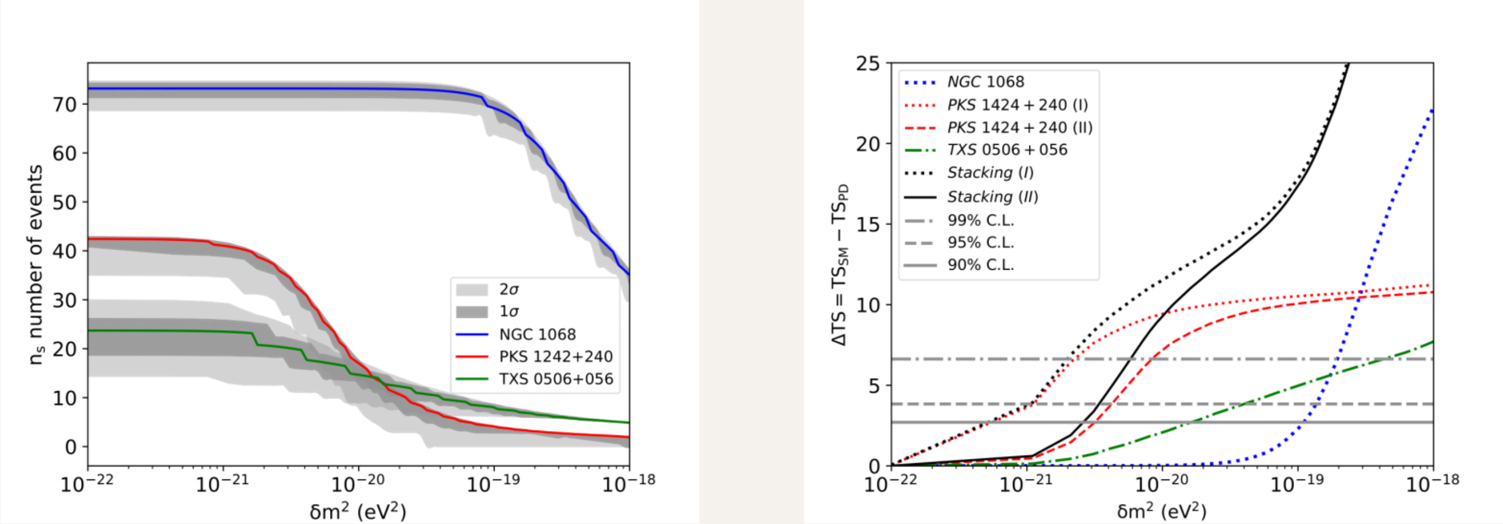

Figure: Constraints on δm^2 in the energy-range **0.1 TeV - 1 PeV**.