# Searching for signatures of Pseudo-Dirac neutrinos in IceCube data from Astrophysical sources

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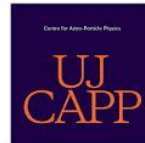University of Johannesburg, South Africa

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Based on *arXiv: 2406.06476 [astro-ph.HE]*
with
**Soebur Razzaque** (CAPP, University of Johannesburg)
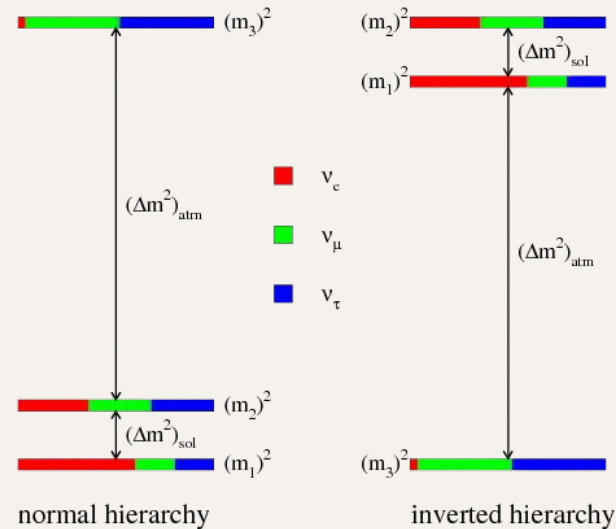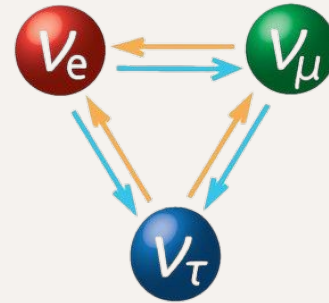**Salvador Miranda** (IFSC, USP, University of São Paulo)

# 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

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

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



normal hierarchy          inverted hierarchy

# Neutrino Masses

- Only neutrinos may have Majorana masses

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

  active

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

  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

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

*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 $\delta m^2 \ll \Delta m^2_{\text{sol}}, \Delta m^2_{\text{atm}}$

$$\left\{ \begin{array}{l} \nu^{\alpha L} = \frac{1}{\sqrt{2}} U^{\alpha j}_{\text{PMNS}}(\nu_{js} + i\nu_{ja}), \\ m^2_{ks,ka} = m^2_k \pm \delta^2_{mk}/2 \end{array} \right\}$$ ⮕ maximal mixing
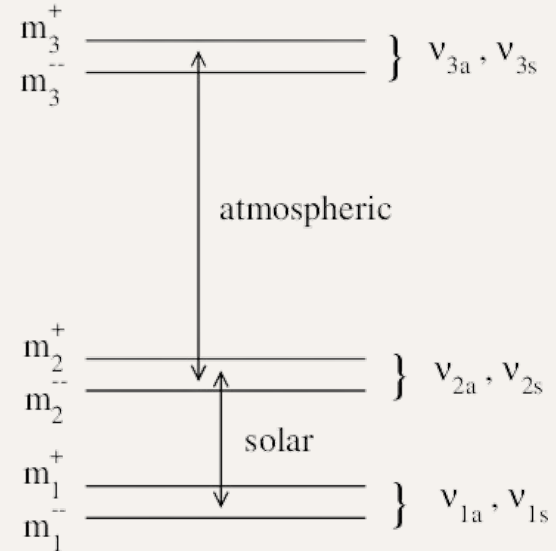
- Mass matrix can be diagonalized by

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

- Active flavor transition probabilities

Kobayashi, Lim, PRD 2001

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

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

$m^+_3$ ___ $m^{--}_3$ ___ } $\nu_{3a}, \nu_{3s}$

atmospheric

$m^+_2$ ___ $m^{--}_2$ ___ } $\nu_{2a}, \nu_{2s}$

solar

$m^+_1$ ___ $m^{--}_1$ ___ } $\nu_{1a}, \nu_{1s}$

# 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 $\epsilon_i^2$ 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 | $\epsilon_1^2$ [eV$^2$] | $\epsilon_2^2$ [eV$^2$] | $\epsilon_3^2$ [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
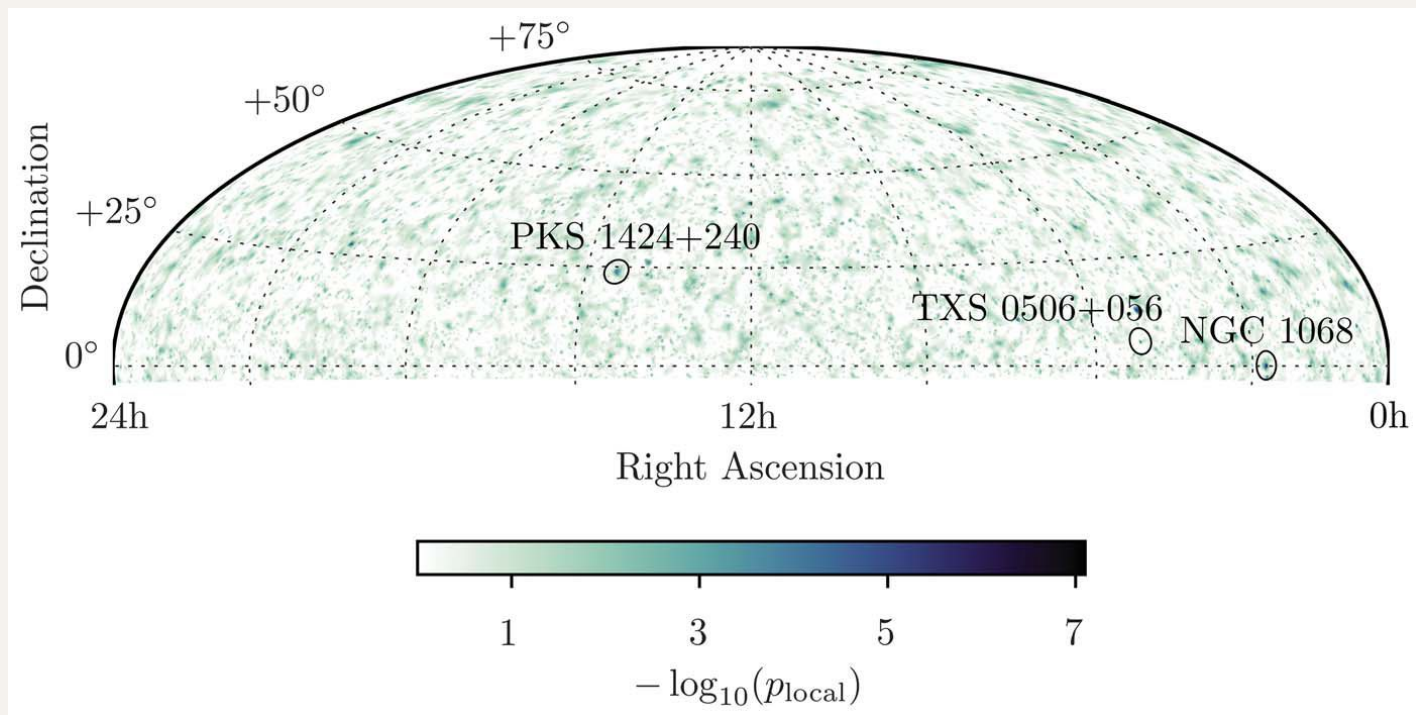
# High Energy Astrophysical Neutrino Data from IceCube

➔ IceCube has performed several all-sky searches for point-like neutrino sources using track-like events induced by $\nu_\mu$ 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 $3.3_\sigma$  (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

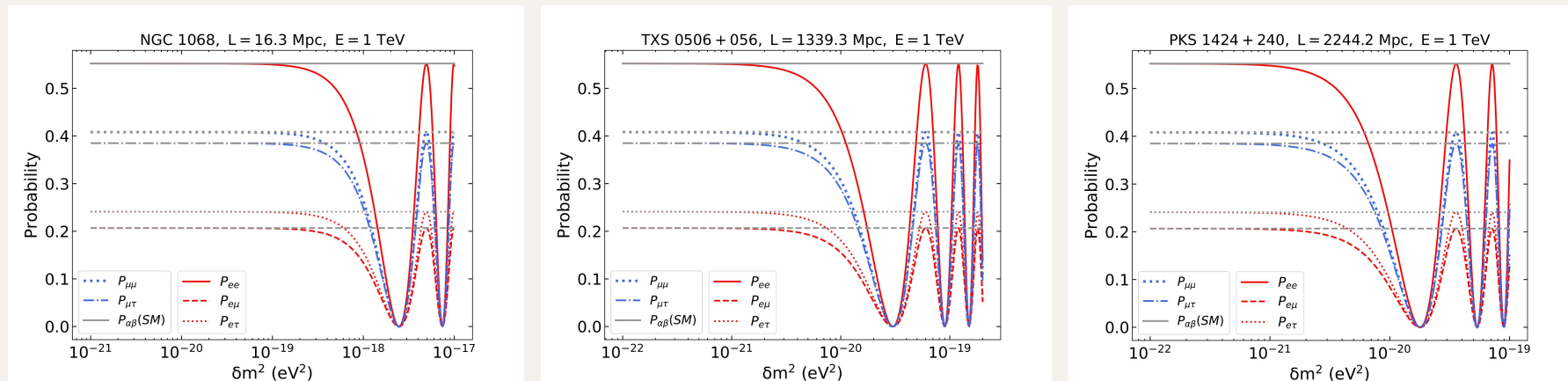Assuming : $\delta m_1^2 = \delta m_2^2 = \delta m_3^2 \equiv \delta m^2$



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

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

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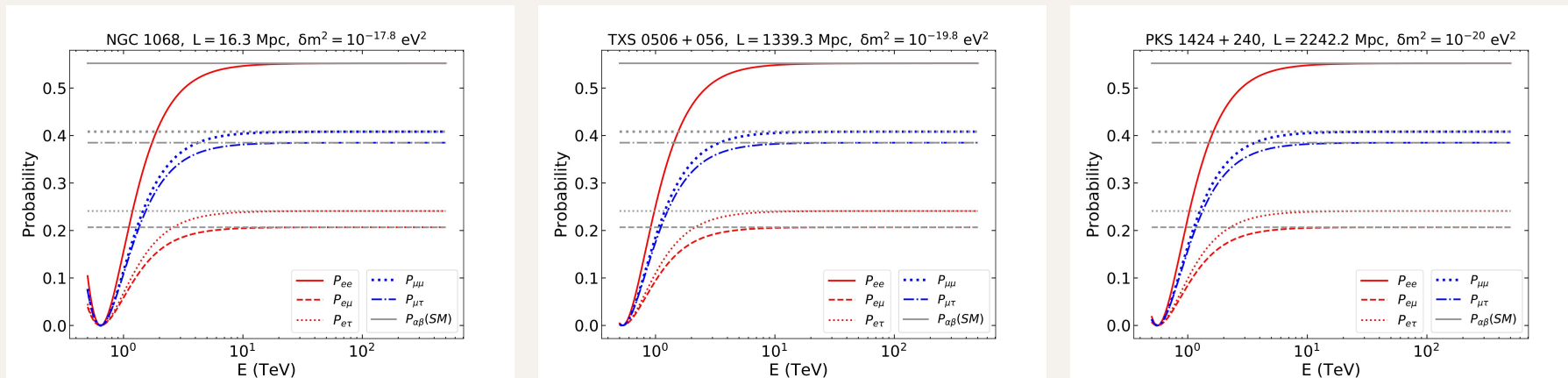Assuming : $\delta m_1^2 = \delta m_2^2 = \delta m_3^2 \equiv \delta m^2$



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

- Smallest values of active-sterile mass splittings $\delta m_i^2$ 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: $\Phi^0_{\nu_\mu} \approx \Phi^0_{\bar{\nu}_\mu} \approx \Phi^0_{\nu_e} = \phi^0 \left( \frac{E_\nu}{1\,\text{TeV}} \right)^{-\gamma}$

- Source flux at the detector: $\Phi^{\text{src}}_{\nu_\mu} = \Phi^0_{\nu_\mu} P_{\mu\mu} + \Phi^0_{\nu_e} P_{e\mu} = x P_{ee} \Phi^0_{\nu_e} + (1-x) P_{e\mu} \phi^0_{\nu_\mu}$

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

- **Events from the source:**

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

- **Events from atmospheric and astrophysical backgrounds:**

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

$\phi^{atm}_{\nu_\mu}$ → 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 $\Phi^{\mathrm{src}}$ and corresponding signal events $n_{s,k}$ is

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

provided by the IceCube Collaboration

- Source probability density for the j-th $\nu$ 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 $\nu$ 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 $TS = -2 \left[ \log \mathcal{L}(\vec{x}_s; \hat{\theta}_0) - \log \mathcal{L}(\vec{x}_s; \hat{\theta}) \right]$
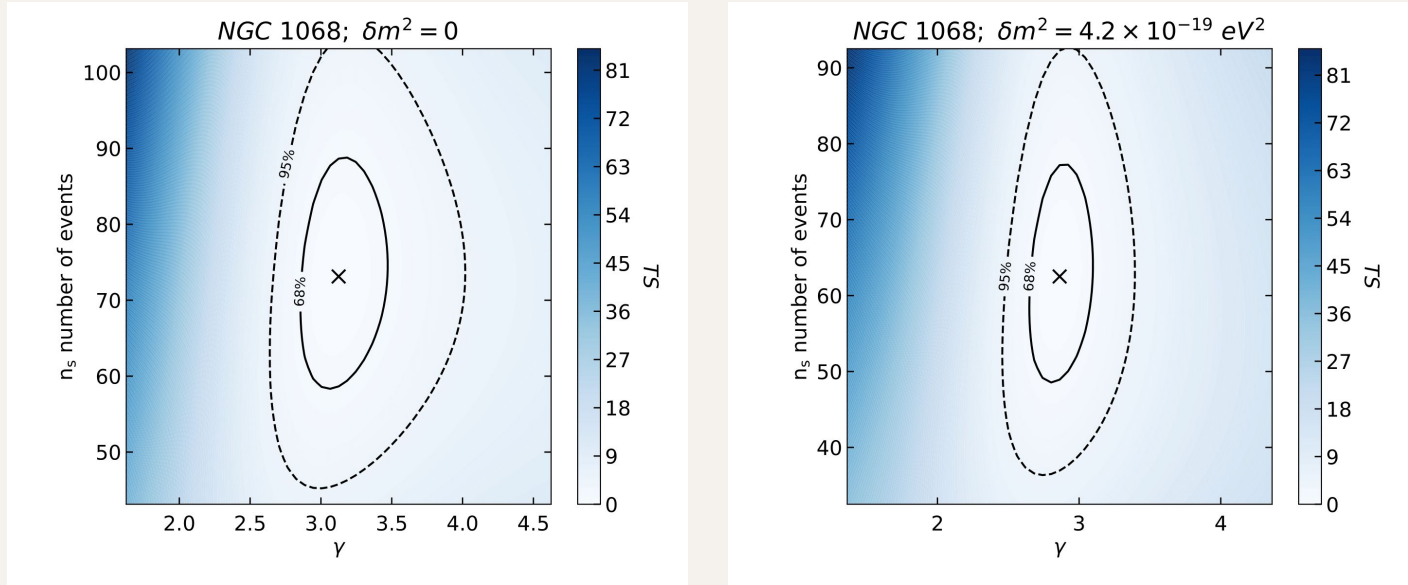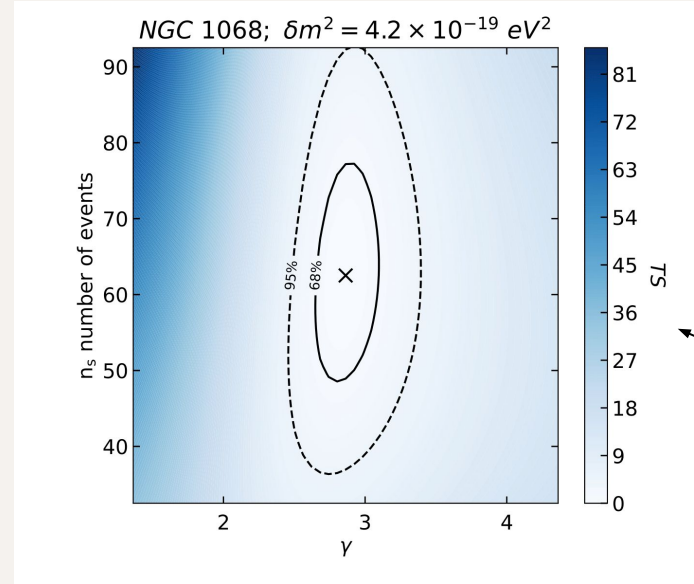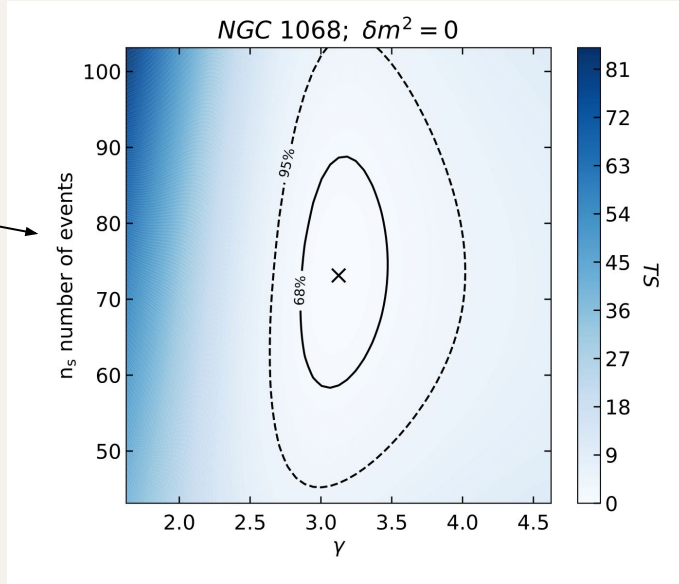
Braun et al. 2008

# 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.

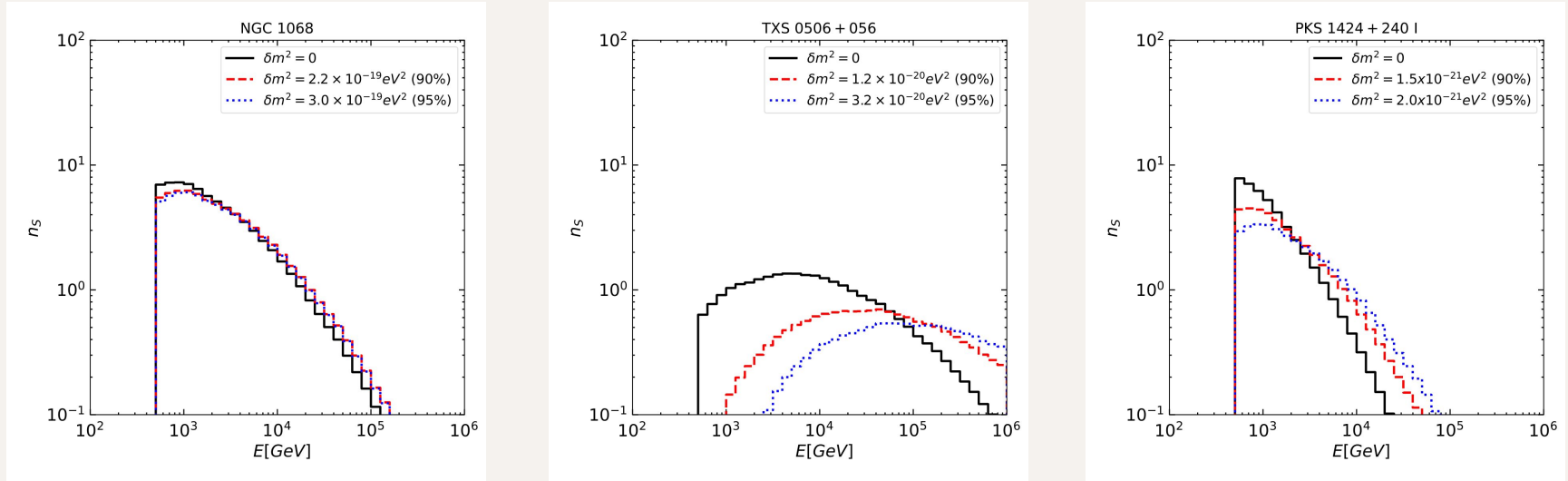# Event Distributions with pseudo-Dirac Neutrinos



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

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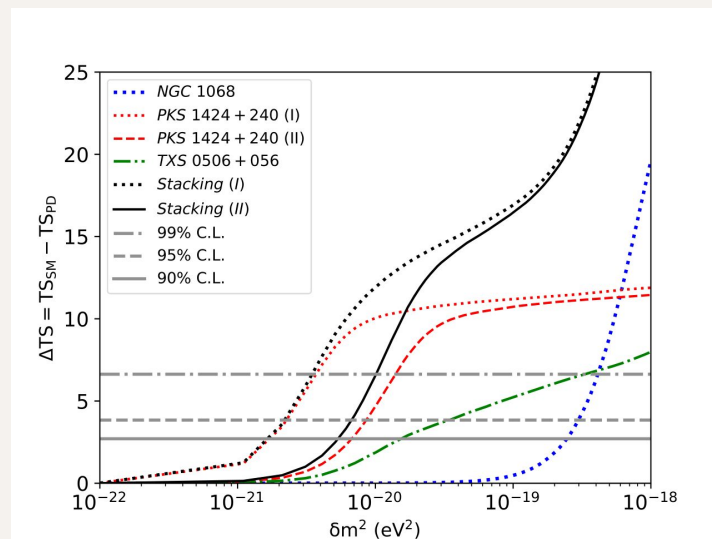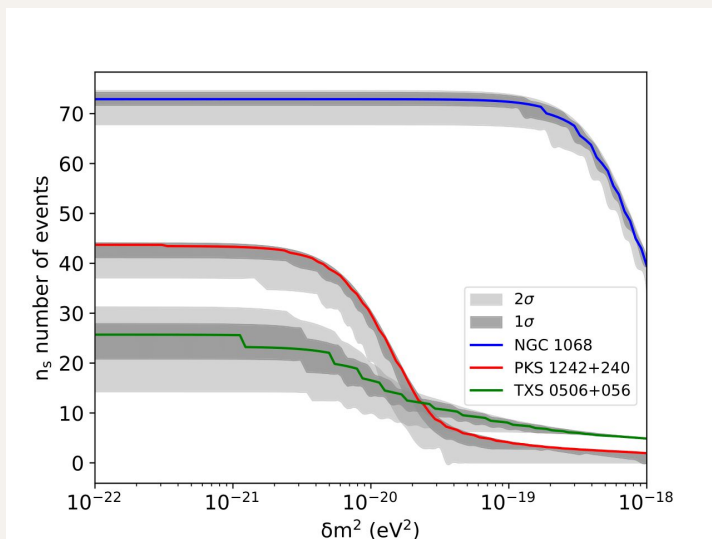


- Number of signal events decreases with increasing $\delta m^2$ as more active neutrinos convert to sterile neutrinos.
- We constrain the pseudo-Dirac neutrino mass-squared-difference $\delta m^2 \lesssim 1.5 \times 10^{-21} \ eV^2$ at 90% CL performing a stacking analysis.

# 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 | $\delta m^2$ (eV$^2$) $\gtrsim$ sensitivity limit | $9 \times 10^{-20}$ | $9 \times 10^{-22}$ | $5 \times 10^{-22}$ | $2 \times 10^{-21}$ | $5 \times 10^{-22}$ | $2 \times 10^{-21}$ |
| | $\delta m^2$ (eV$^2$) $\lesssim$ 90% CL | $2.2 \times 10^{-19}$ | $1.2 \times 10^{-20}$ | $1.5 \times 10^{-21}$ | $6 \times 10^{-21}$ | $1.5 \times 10^{-21}$ | $5 \times 10^{-21}$ |
| | $\hat{\gamma}_{SM} (\pm 1\sigma)$ | $3.1^{+0.4}_{-0.2}$ | $2.4^{+0.2}_{-0.4}$ | $3.7^{+1.6}_{-0.7}$ | $3.7^{+1.6}_{-0.7}$ | $-$ | $-$ |
| 0.1 TeV - 1 PeV | $\delta m^2$ (eV$^2$) $\gtrsim$ sensitivity limit | $2 \times 10^{-20}$ | $2 \times 10^{-22}$ | $1 \times 10^{-22}$ | $4 \times 10^{-22}$ | $1 \times 10^{-22}$ | $4 \times 10^{-22}$ |
| | $\delta m^2$ (eV$^2$) $\lesssim$ 90% CL | $1 \times 10^{-19}$ | $1.4 \times 10^{-20}$ | $5 \times 10^{-22}$ | $3 \times 10^{-21}$ | $5 \times 10^{-22}$ | $2.5 \times 10^{-21}$ |
| | $\hat{\gamma}_{SM} (\pm 1\sigma)$ | $2.9^{+0.2}_{-0.2}$ | $2.3^{+0.2}_{-0.3}$ | $3.2^{+0.6}_{-0.4}$ | $3.2^{+0.6}_{-0.4}$ | $-$ | $-$ |

Results of the analysis performed for all sources and the stacking analysis are given in terms of constraints on $\delta m^2$ with 90% CL and $\gamma$ with $1\sigma$ error.

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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!**

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# Backup slides

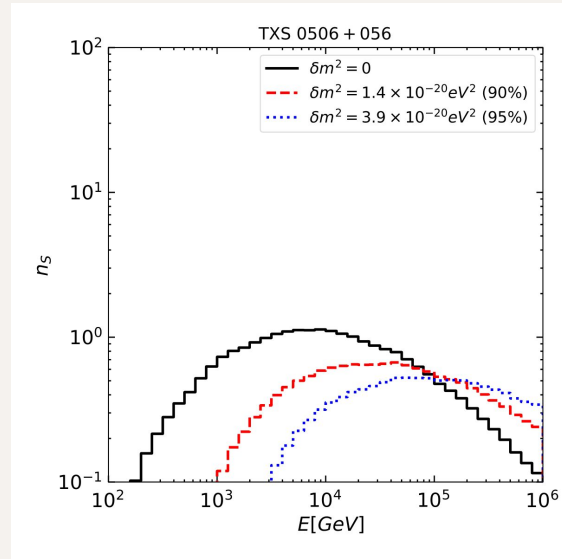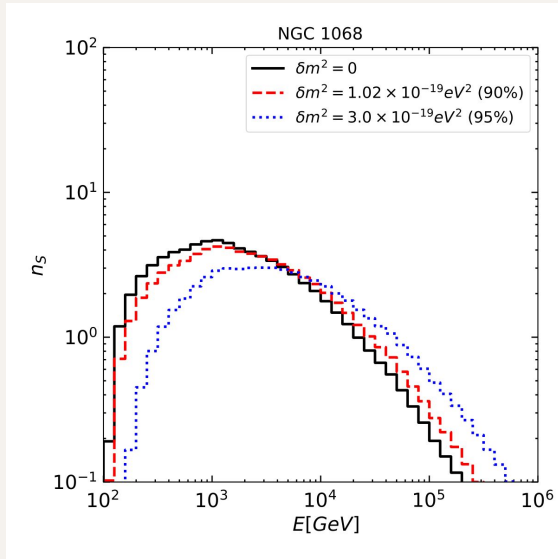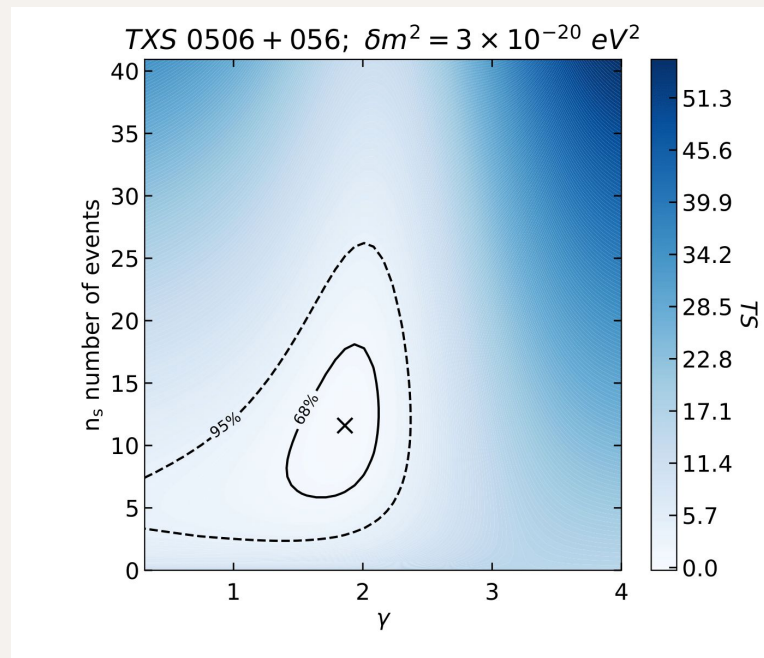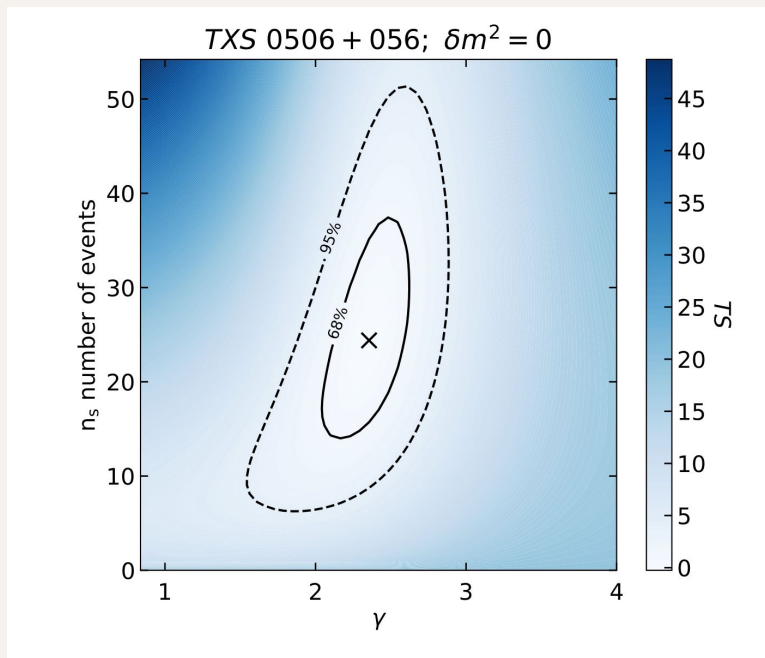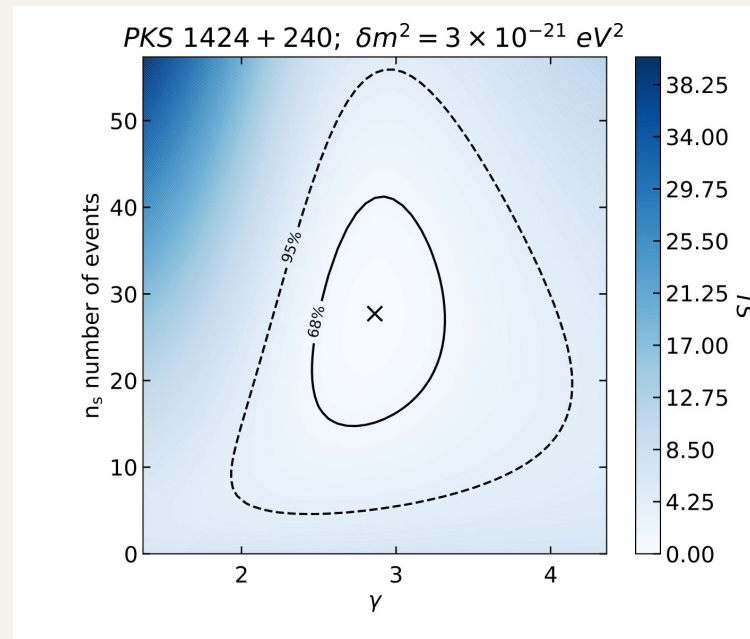## Event Distributions with pseudo-Dirac Neutrinos
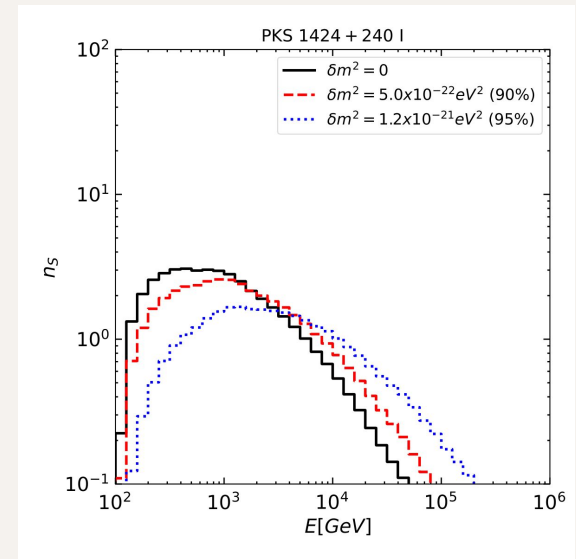


Figure: Expected events from different sources **0.1 TeV - 1 PeV**

# Backup slides

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PKS 1424 + 240; $\delta m^2 = 0$

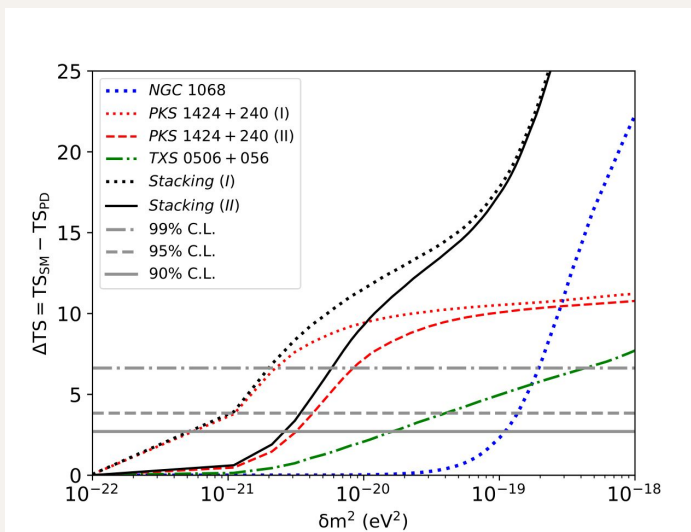PKS 1424 + 240; $\delta m^2 = 3 \times 10^{-21} \ eV^2$
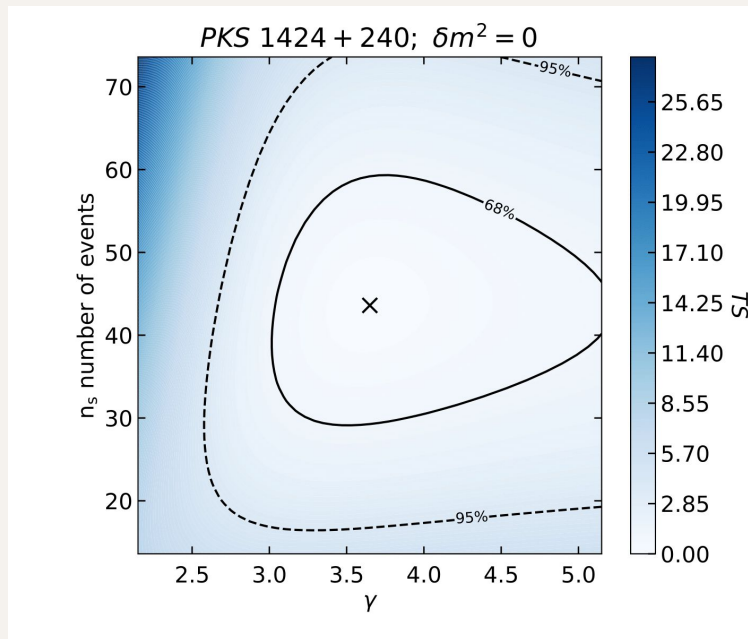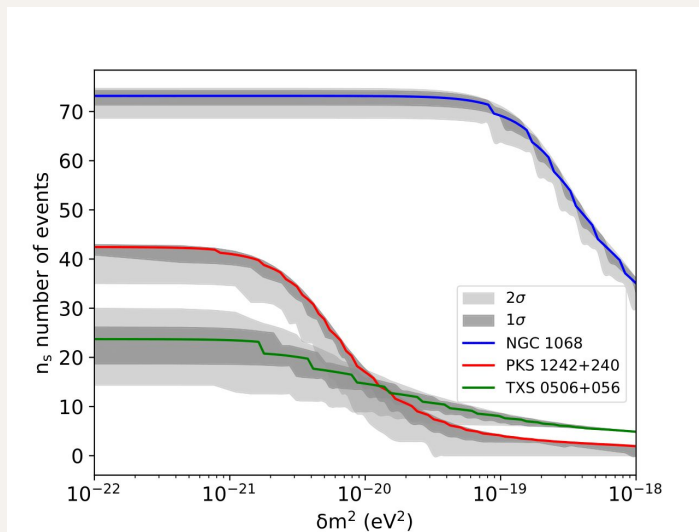
# Backup slides



**Figure:** Constraints on $\delta m^2$ in the energy-range **0.1 TeV - 1 PeV**.