ICTP The Abdus Salam International Centre for Theoretical Physics

Advanced Workshop on Physics of Atmospheric Neutrinos

Neutrino Oscillations in Dark Backgrounds

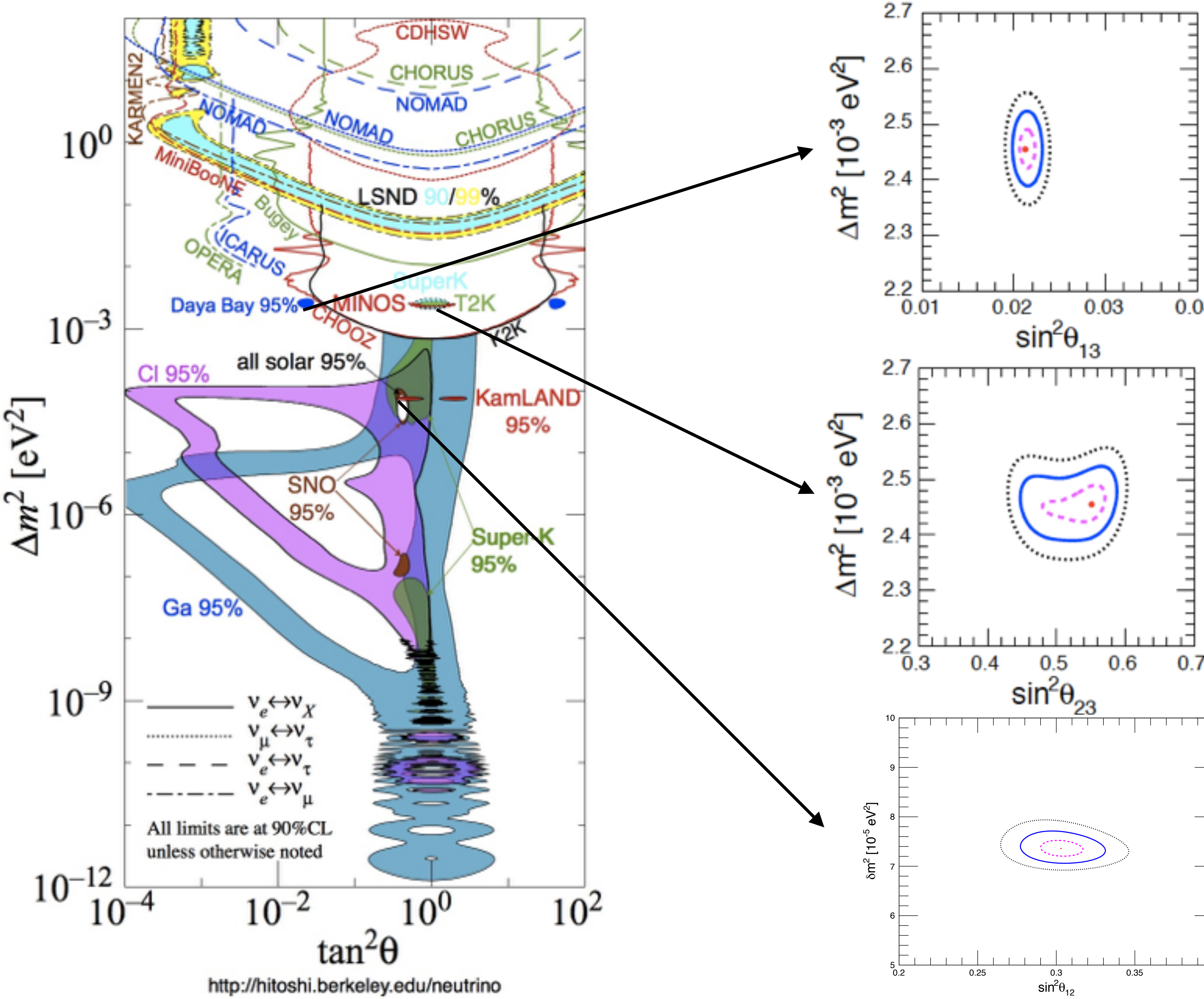
based on arXiv:1804.05117, with I. Shoemaker and L. Vecchi

FRANCESCO CAPOZZI

$\Delta p \cdot \Delta q \geq \frac{1}{2} \hbar$

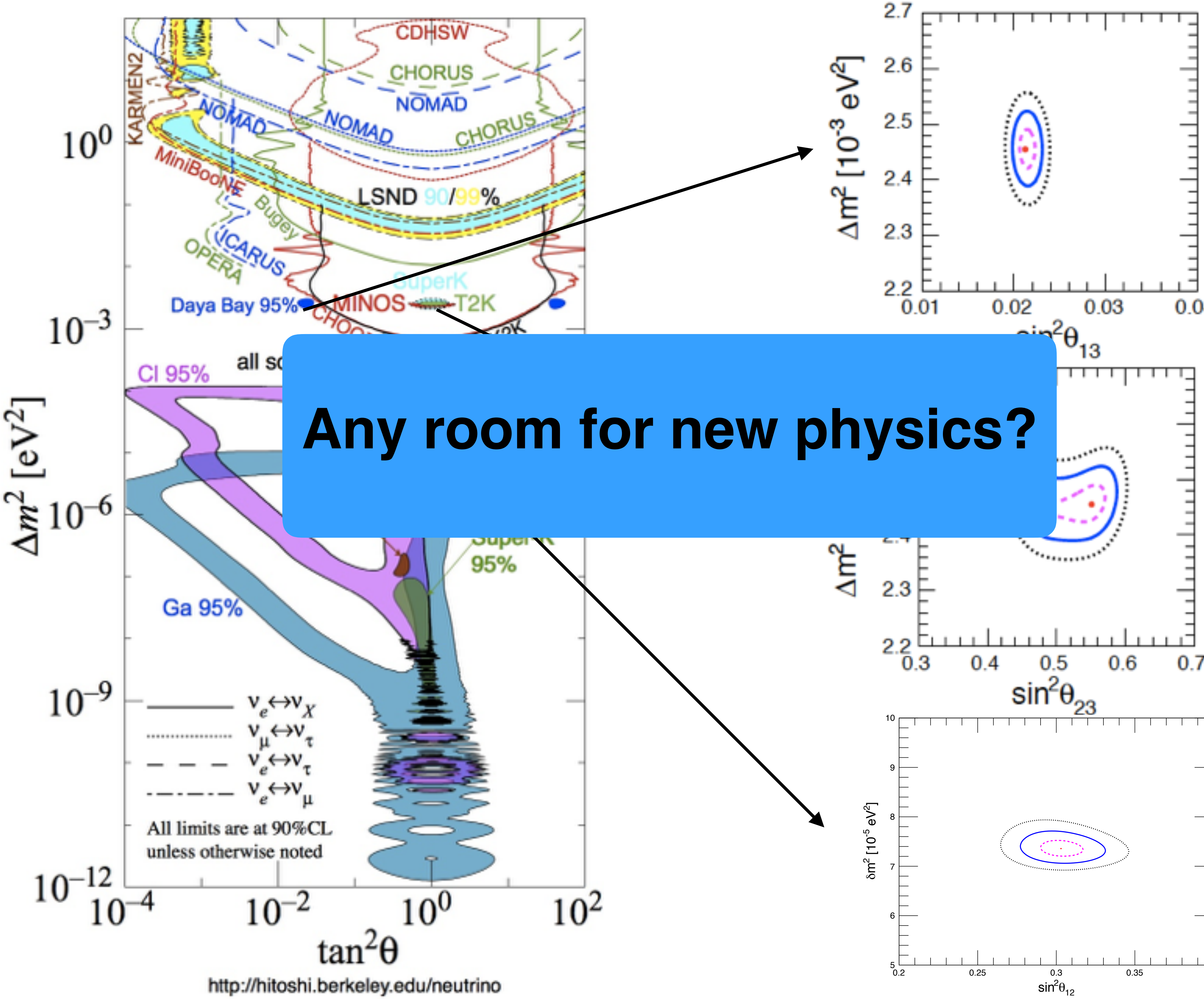
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Evidence for neutrino oscillations



Capozzi, *et al.*, arXiv:1804.09678

Evidence for neutrino oscillations

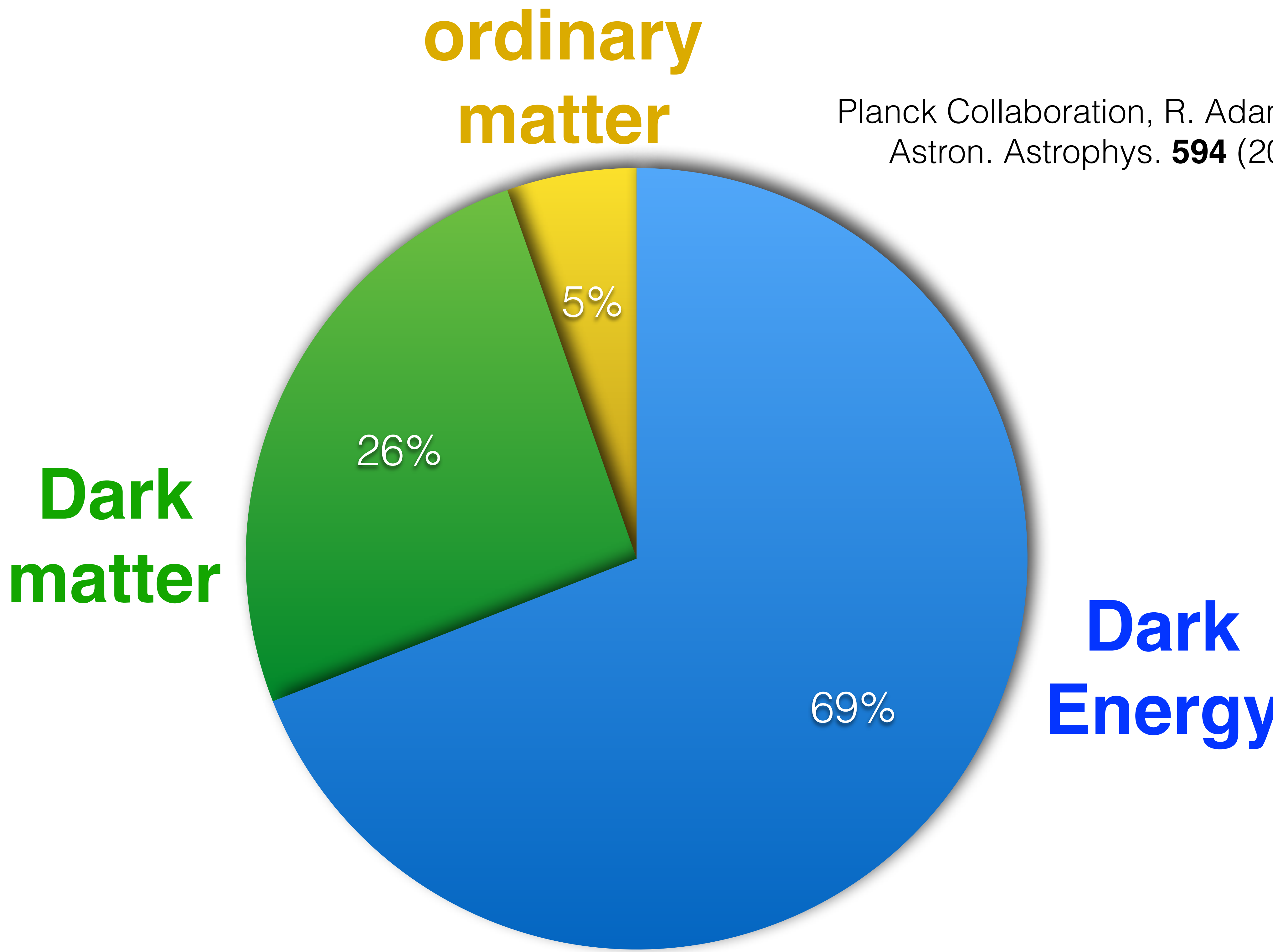


Any room for new physics?

Capozzi, *et al.*, arXiv:1804.09678

Evidence for dark sectors

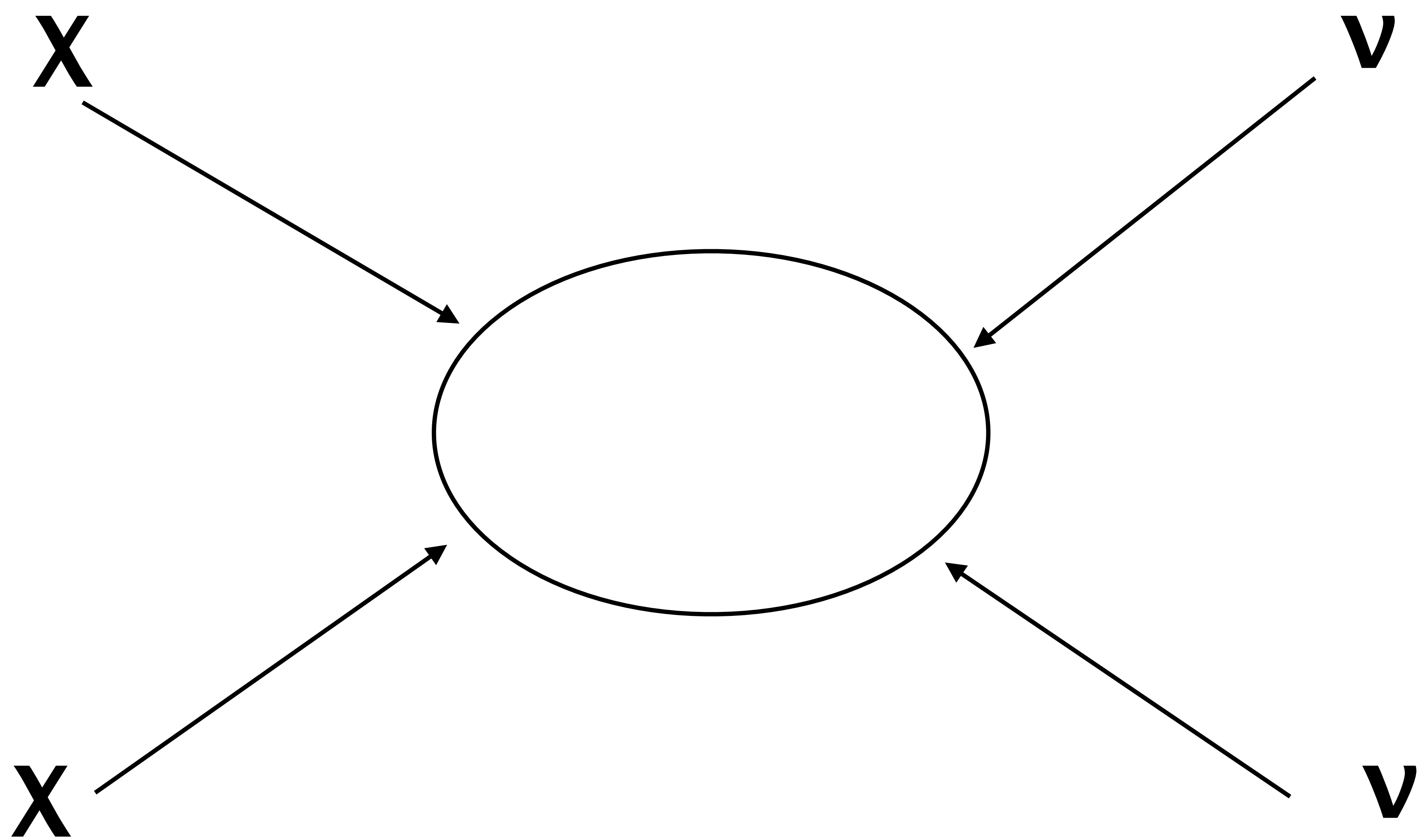
Planck Collaboration, R. Adam et al., Astron. Astrophys. **594** (2016)



Neutrino portals to Dark Sectors

Detecting dark sectors: neutrino portal

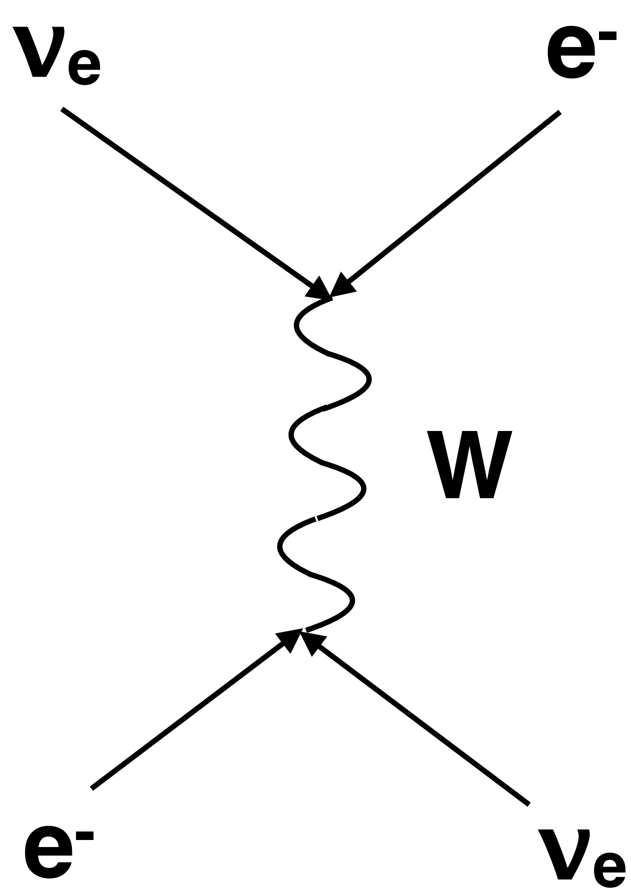
We assume dark sectors is coupled to neutrinos



<u>WHY NEUTRINO PORTAL?</u>

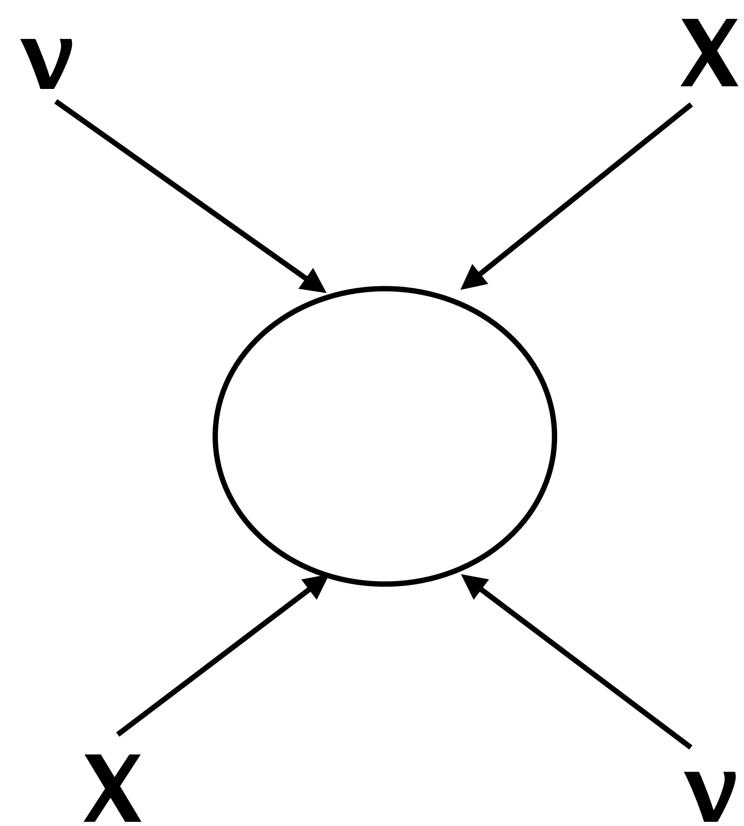
Detecting dark sectors: neutrino portal

Coherent forward scattering on a **Dark Background**



$V \sim G_F N_e$

$G_F \sim g_W^2/m_W^2$



$V_D \sim G_D N_D$

$G_D \sim g_D^2/m_D^2$

Secluded sectors (**g_D << 1**) are **observable only in neutrino oscillations** if m_D is small enough

Generic dark background

Neutrino propagation in a generic **Dark Background**

Vector Scalar Tensor

$$\mathcal{L} = N_\alpha^\dagger \bar{\sigma}^\mu [i\partial_\mu \delta_{\alpha\beta} + (V_\mu)_{\alpha\beta}] N_\beta + \left\{ \frac{1}{2} N_\alpha^\dagger \left[m_{\alpha\beta} + (F_{\mu\nu})_{\alpha\beta} \bar{\sigma}^{\mu\nu} \right] i\sigma_2 N_\beta^* + \mathrm{hc} \right\}$$

$$\nu_\alpha \xrightarrow{\quad \mathbf{V} \quad} \nu_\beta$$

$$\nu_\alpha \xrightarrow{\quad \mathbf{F} \quad} \bar{\nu}_\beta$$

m, V, F are generated by **exotic couplings** to the dark world

Neutrino mass from vector couplings

Assume V^μ is unpolarised for scales >> O(100) m

$$\langle V^0\rangle, \langle \mathbf{V}\rangle \approx 0, \quad \langle V^i V^j\rangle \approx \frac{\delta^{ij}}{3}\langle \mathbf{V}^2\rangle, \quad \langle \mathbf{V}^2\rangle \approx \text{const}$$

$$\langle E(\mathbf{p})\rangle = \begin{cases} |\mathbf{p}| + \frac{1}{3|\mathbf{p}|}\langle \hat{\mathbf{V}}^2\rangle + \cdots & |\mathbf{p}| \gg |\hat{\mathbf{V}}| \\ |\hat{\mathbf{V}}| + \frac{1}{3|\hat{\mathbf{V}}|}\mathbf{p}^2 + \cdots & |\mathbf{p}| \ll |\hat{\mathbf{V}}|, \end{cases}$$

See also:

R. Fardon, A. E. Nelson and N. Weiner, JCAP 0410 (2004) 005

H. Davoudiasl, G. Mohlabeng and M. Sullivan, 1803.00012

G. D'Amico, T. Hamill and N. Kaloper, 1804.01542

Effective hamiltonian

In the limit of small constant V, F

H_{SM} $\qquad$ H_D

$$H_{\text{eff}} = \begin{pmatrix} U\frac{mm^*}{2E}U^\dagger & 0 \\ 0 & U^*\frac{m^*m}{2E}U^T \end{pmatrix} + \begin{pmatrix} a(\hat{\mathbf{p}}) & b(\hat{\mathbf{p}}) \\ b^\dagger(\hat{\mathbf{p}}) & -a^*(\hat{\mathbf{p}}) \end{pmatrix}$$

$$a(\hat{\mathbf{p}}) = -V_0 + \hat{\mathbf{p}}\cdot\mathbf{V} \qquad b(\hat{\mathbf{p}}) = -4\sqrt{2}(\mathbf{E}+i\mathbf{B})\cdot\vec{\epsilon}(\hat{\mathbf{p}})$$

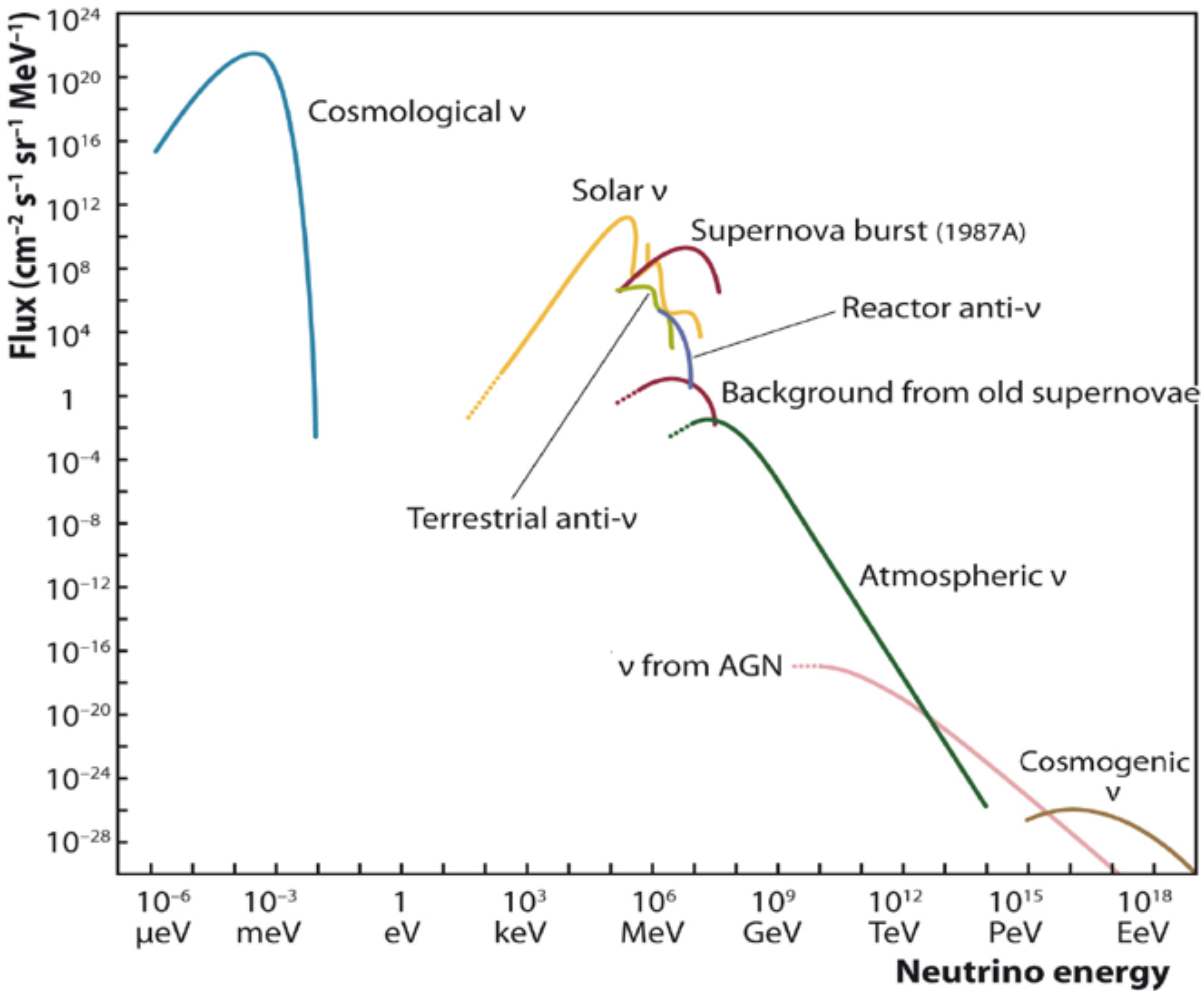
We further assume no dependence on **p**

$$a = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a_{\tau\tau} \end{pmatrix} \qquad b = \begin{pmatrix} 0 & b_{e\mu} & b_{e\tau} \\ -b_{e\mu} & 0 & b_{\mu\tau} \\ -b_{e\tau} & -b_{\mu\tau} & 0 \end{pmatrix}$$

Atmospheric neutrinos

The role of atmospheric neutrinos

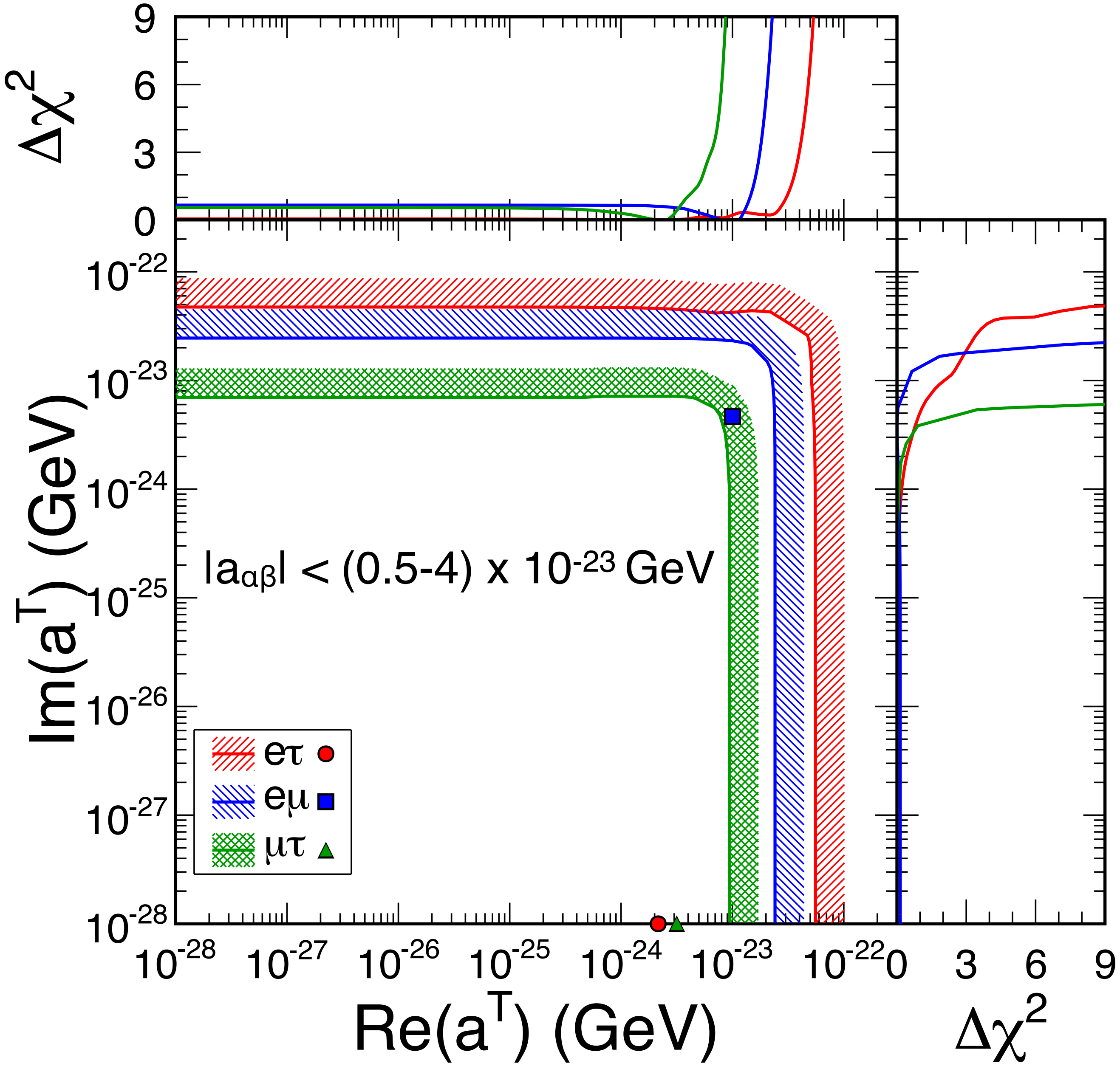
Atmospheric neutrinos are relatively well known with high energy



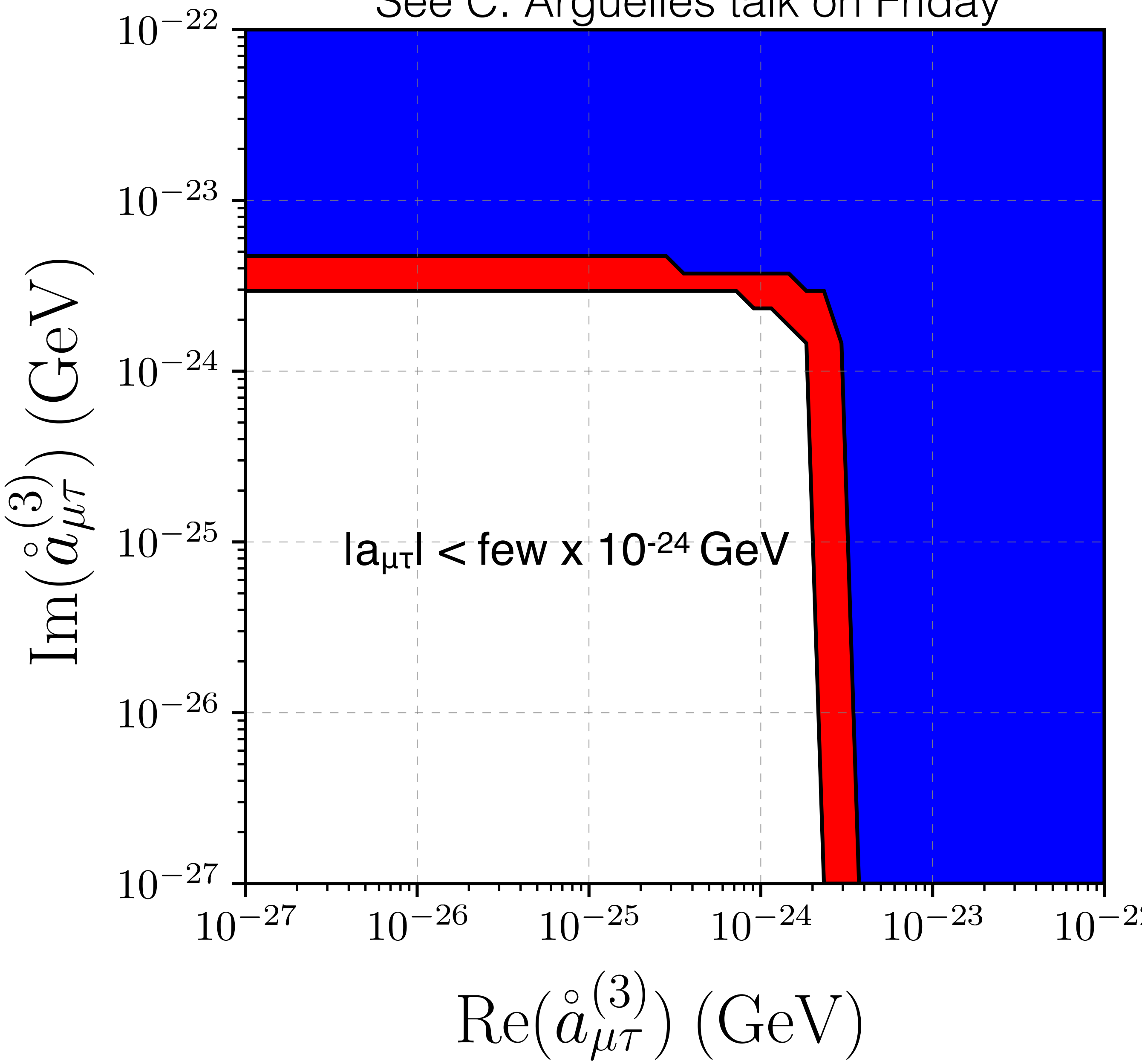
The role of atmospheric neutrinos

At large energy we can reach smaller H_D (H_{SM} <~ H_D)

SuperK - Phys. Rev. D 91, 052003 (2015)



IceCUBE - arXiv:1709.03434,
See C. Arguelles talk on Friday



The role of atmospheric neutrinos

Another regime occurs when $H_{SM} \ll H_D$

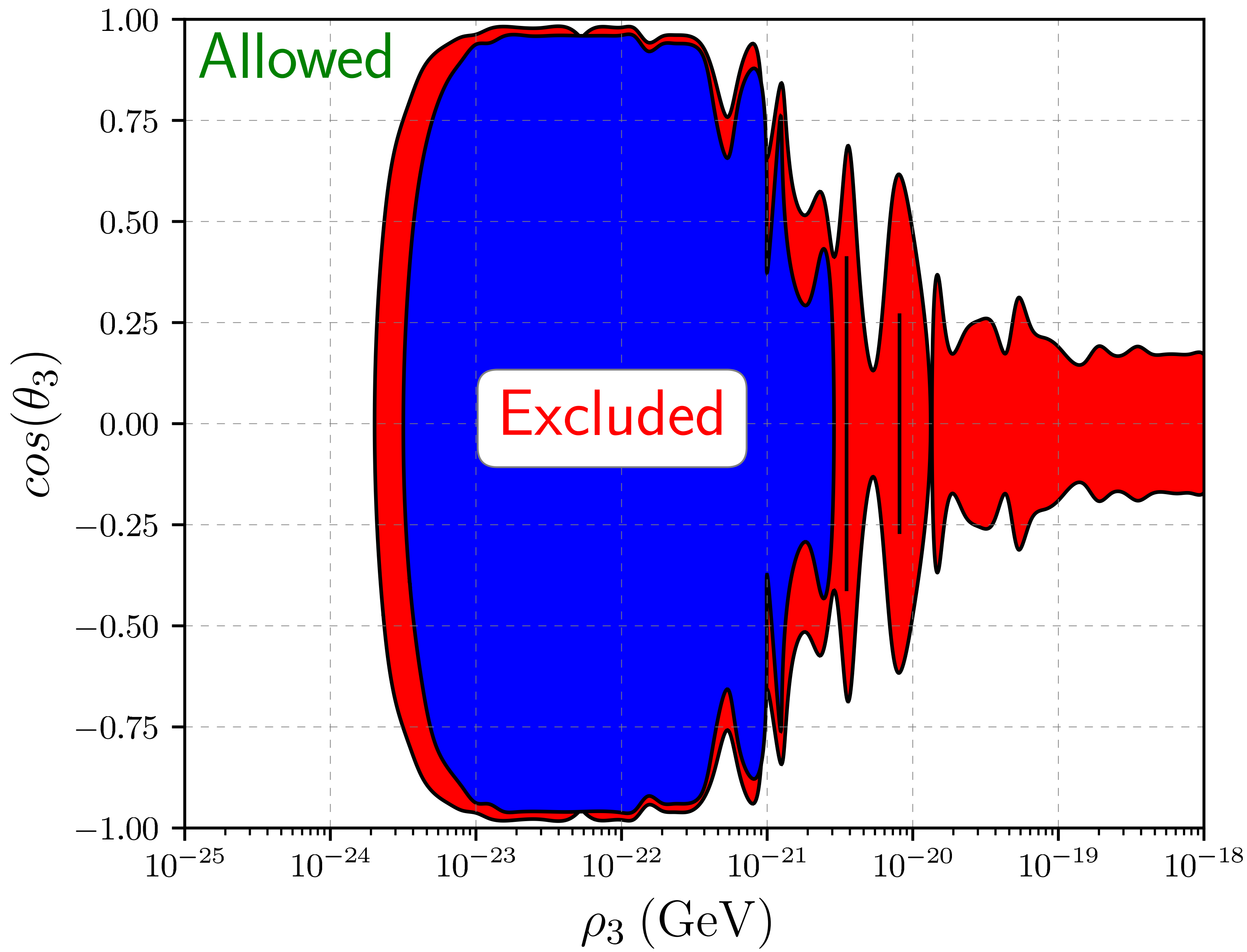
$$P(\alpha \to \beta) \propto \left(\frac{H_{D,\mathrm{off}}}{H_{D,\mathrm{diag}}} \right)^2$$

One cannot set a robust constraint on the magnitude of H_D

The role of atmospheric neutrinos

Another regime occurs when $H_{SM} << H_D$

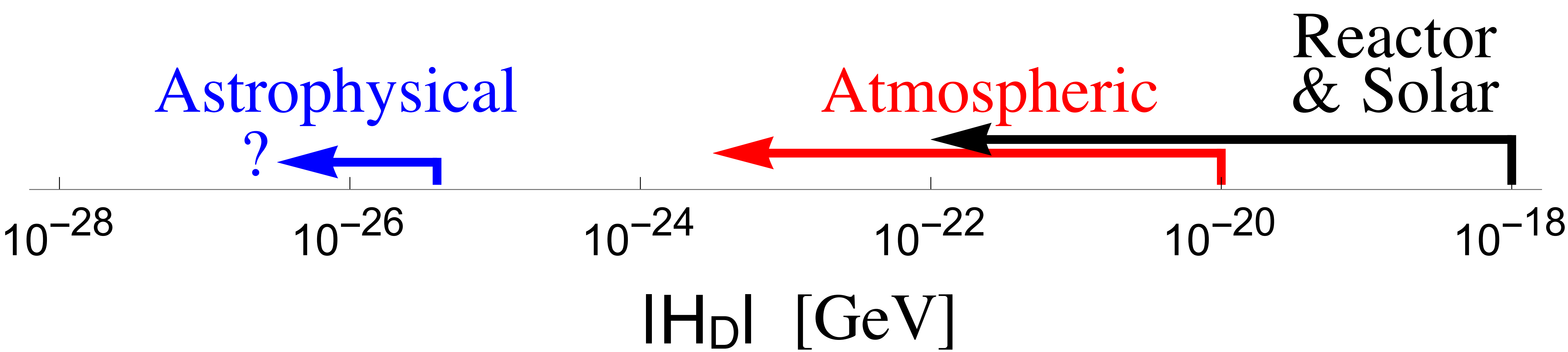
IceCUBE - arXiv:1709.03434, See C. Arguelles talk on Friday



One cannot set a robust constraint on the magnitude of H_D

The role of atmospheric neutrinos

For energies satisfying $H_D \gtrsim H_{SM}$ we can access the scale H_D

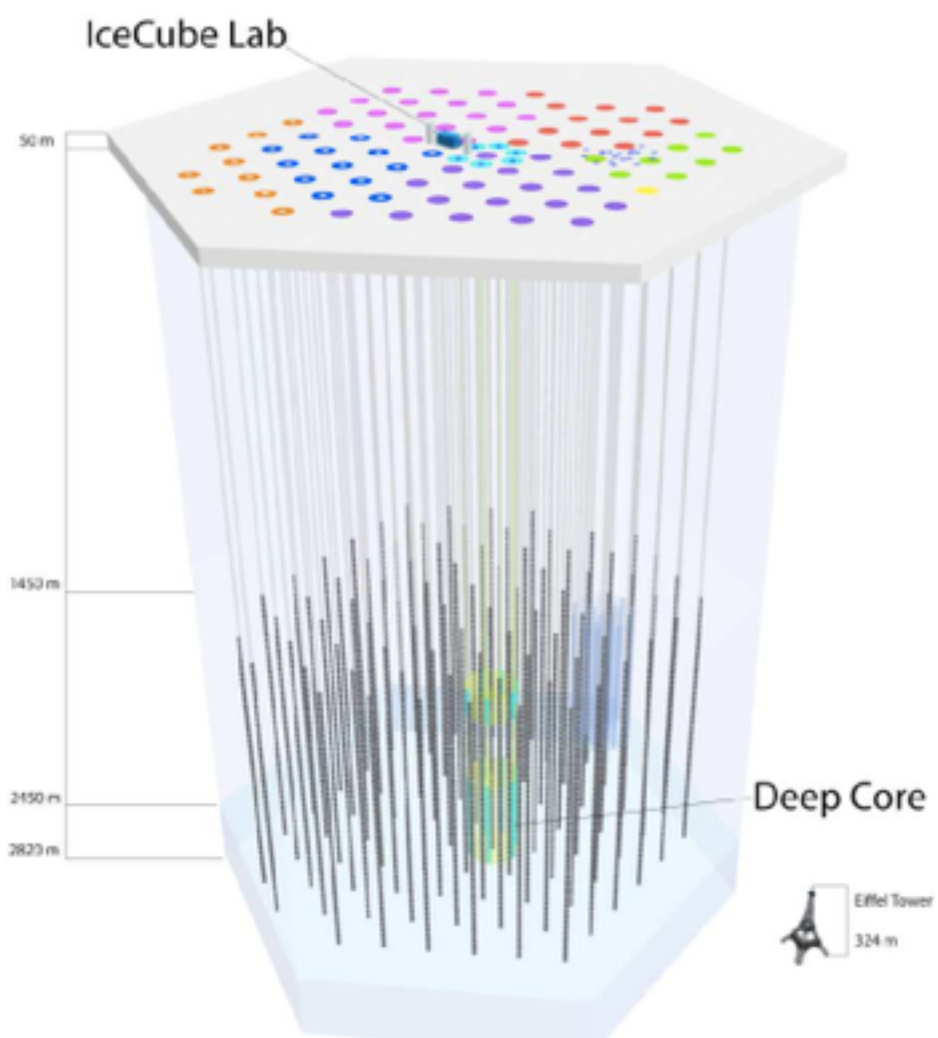


Atmospheric ν can fill the gap with Astrophysical ν

Future constraints from atmospheric ν

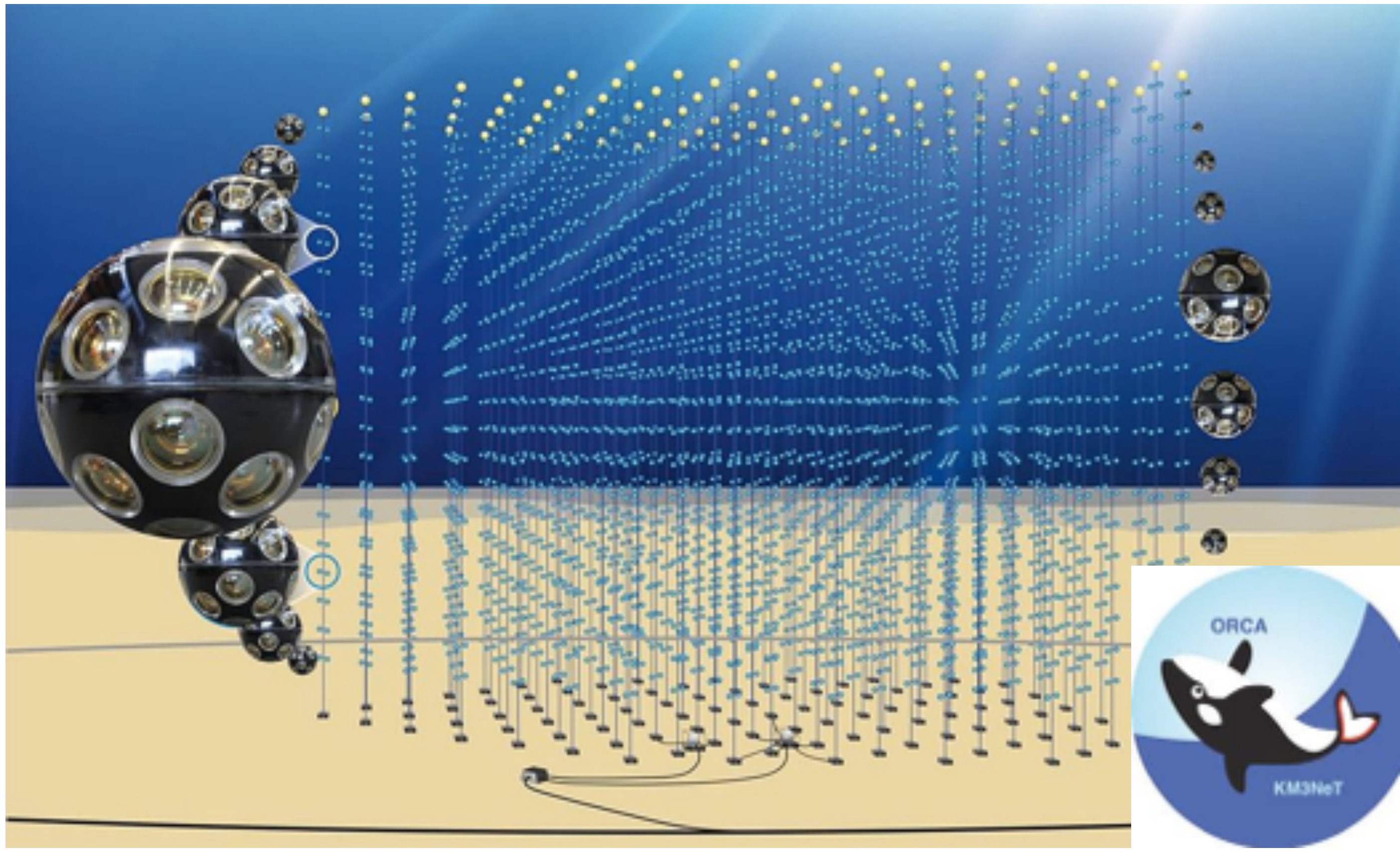
We consider two experiments

IceCube



Probes the regime
E > 400 GeV

ORCA / PINGU

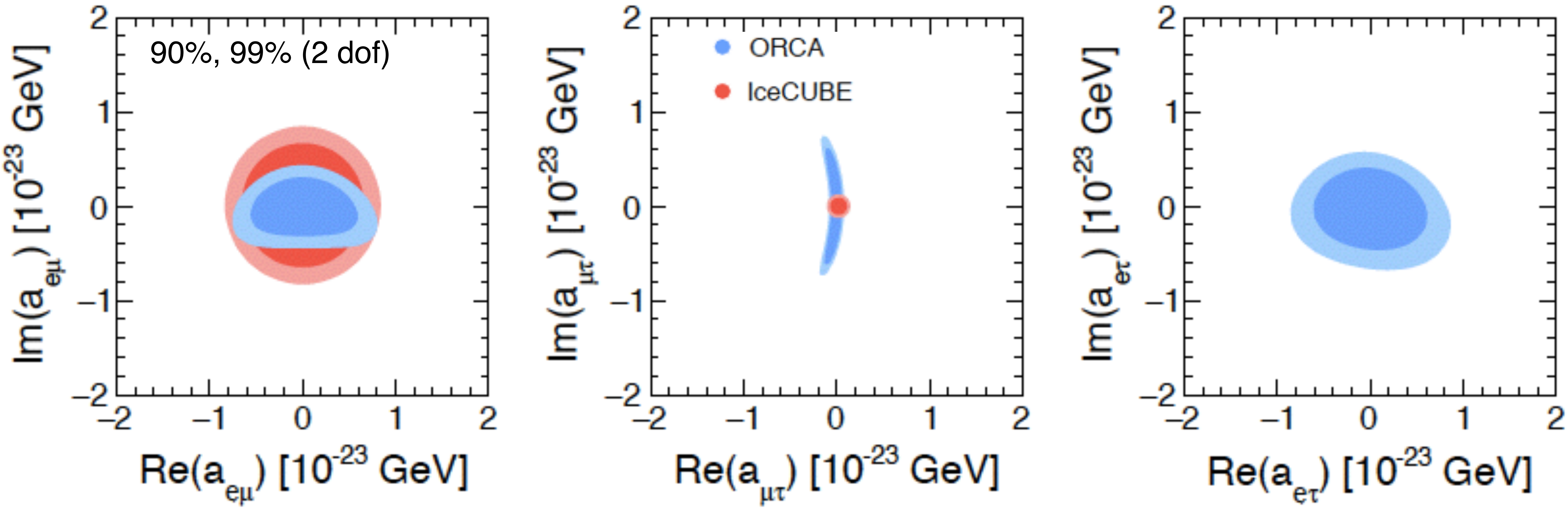


Probes the regime
E < 100 GeV

Future constraints from atmospheric ν

Constraints on $a_{\alpha\beta}$ from ORCA/IceCUBE (10 years)

Normal ordering

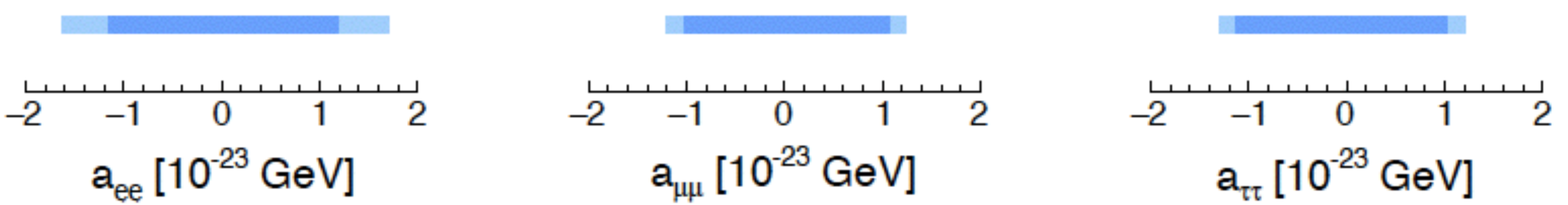


$|a_{e\mu}| <$ few 10^{-24} GeV $\quad |a_{\mu\tau}| < 10^{-24}$ GeV $\quad |a_{e\tau}| <$ few 10^{-24} GeV

Future constraints from atmospheric ν

Constraints on $a_{\alpha\alpha}$ from ORCA (10 years)

Normal ordering

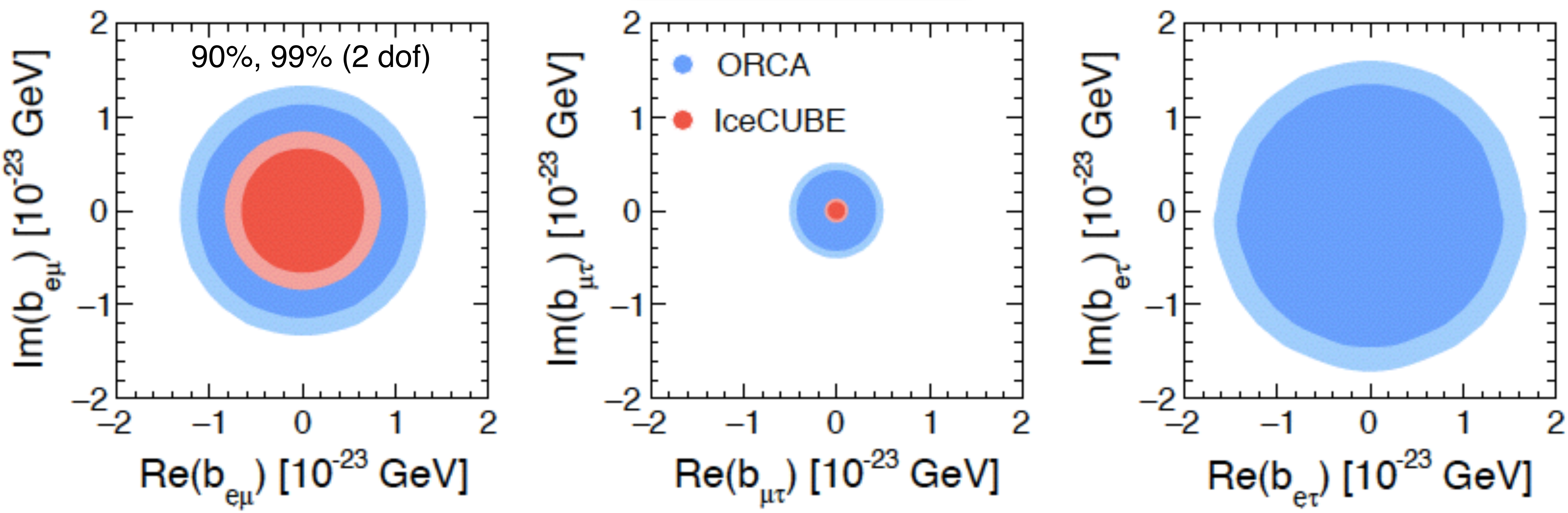


$|a_{\alpha\beta}| < 10^{-23}$ GeV

Future constraints from atmospheric ν

Constraints on $b_{\alpha\beta}$ from ORCA/IceCUBE (10 years)

Normal ordering



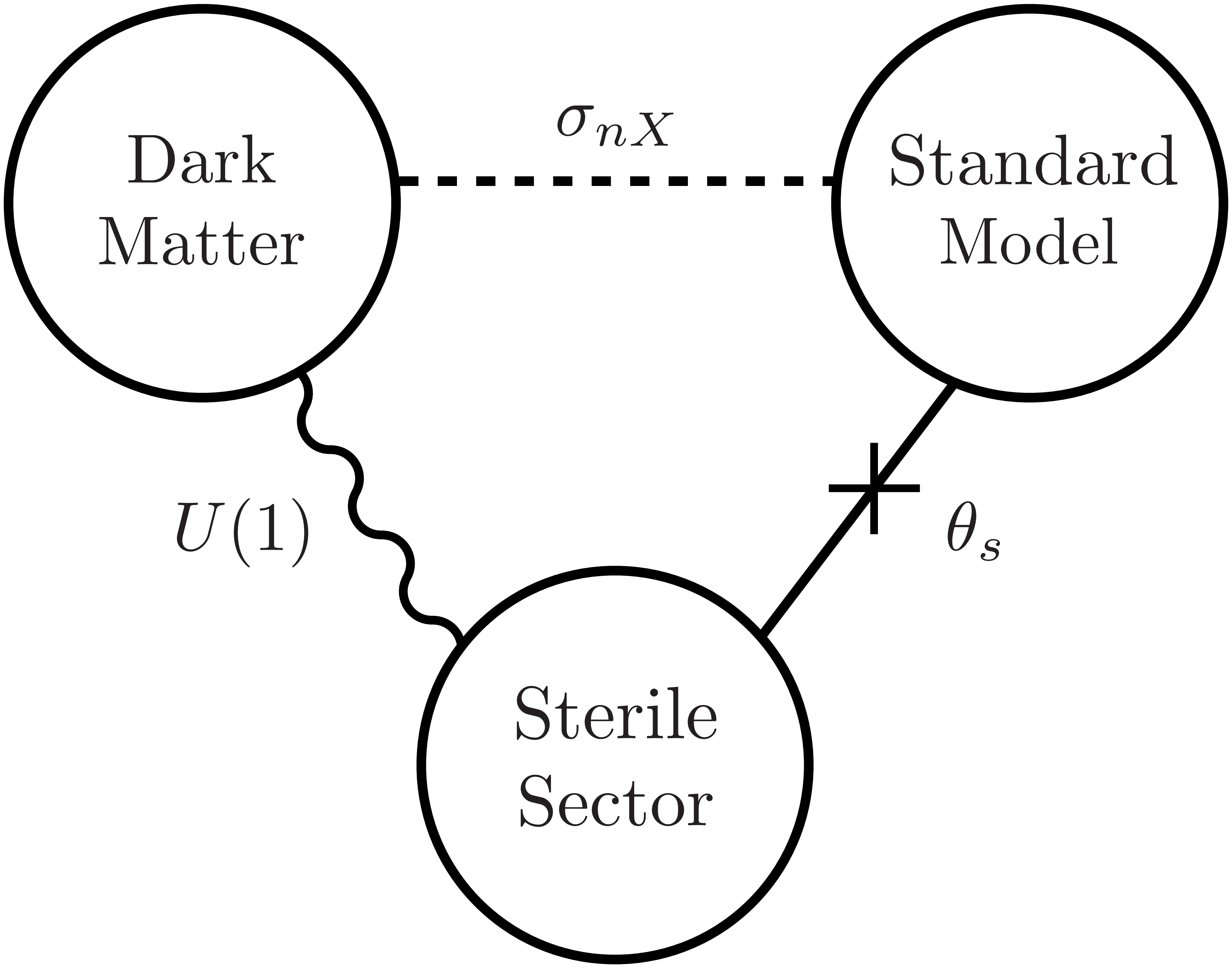
$|b_{e\mu}| <$ few 10^{-23} GeV

$|b_{\mu\tau}| < 10^{-24}$ GeV

$|b_{e\tau}| <$ few 10^{-23} GeV

Models

Vector V^μ

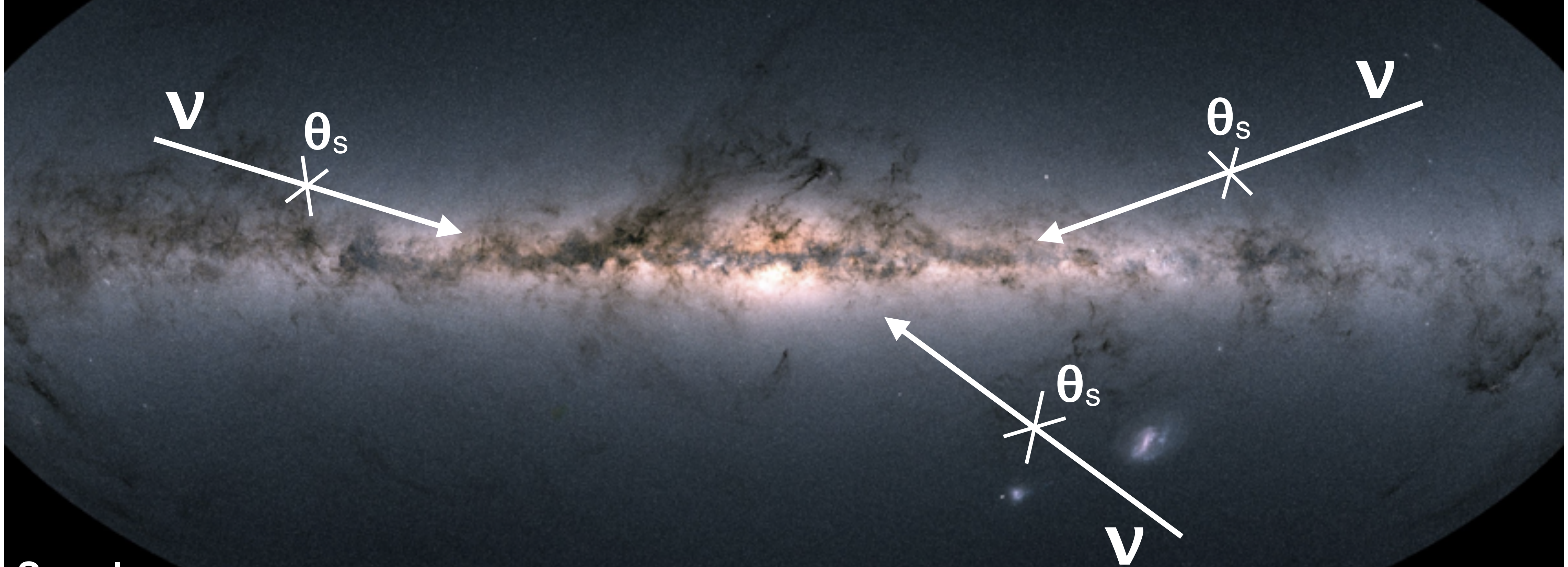


F. Capozzi, I. M. Shoemaker and L. Vecchi, JCAP 1707 (2017) 021

Vector V^μ

Neutrino oscillations in DM halo

$$V^\mu \sim 10^{-24}\ \text{GeV}\ \sin^2\theta_s \left(\frac{g_A\ \text{keV}}{m_A}\right)^2 \left(\frac{J^\mu m_{\rm DM}}{0.4\ \text{GeV/cm}^3}\right)\left(\frac{\text{keV}}{m_{\rm DM}}\right)$$

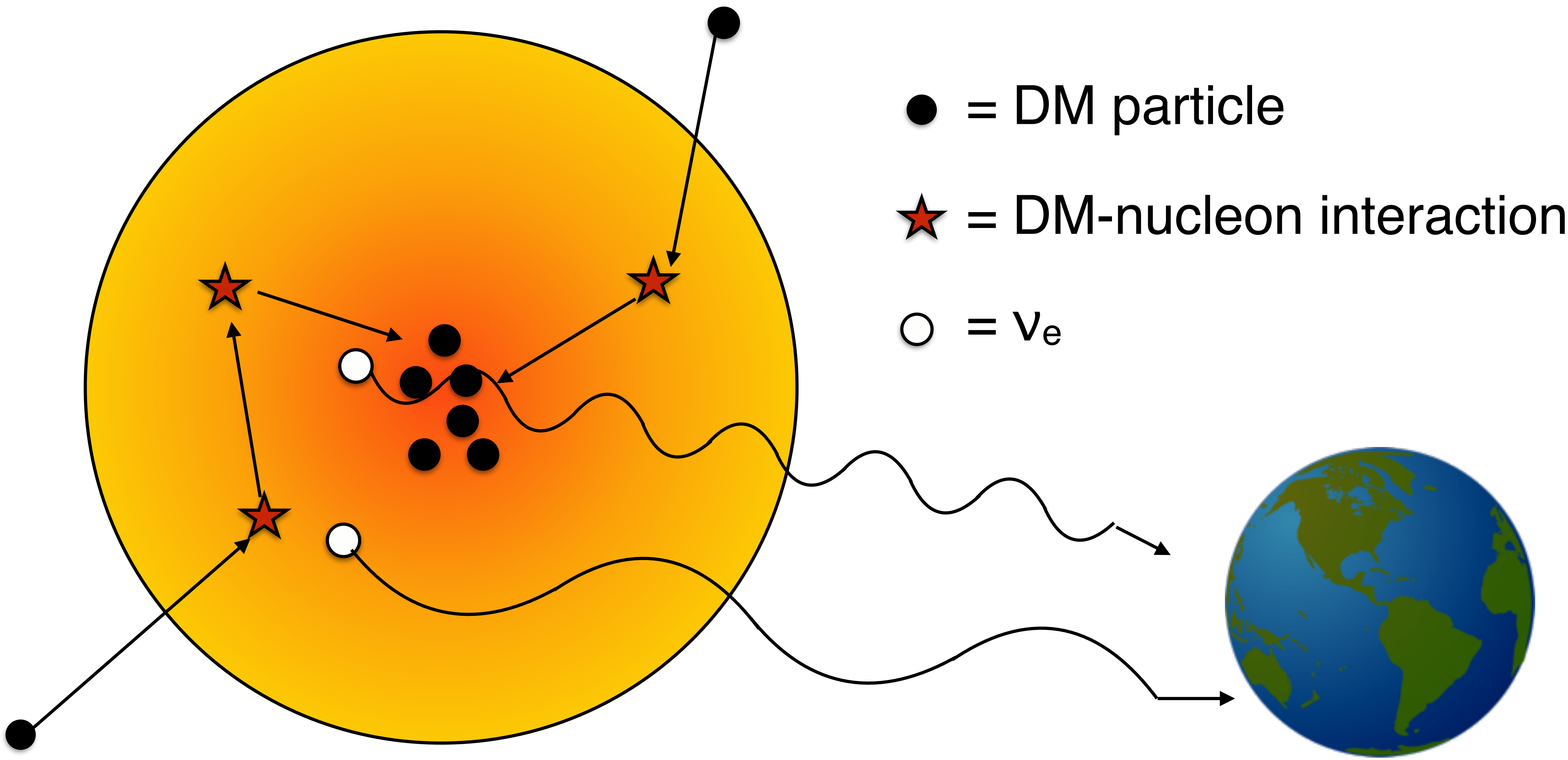


See also:

R. Horvat, Phys. Rev. D59 (1999) 123003
C. Lunardini and A. Yu. Smirnov, Nucl. Phys. B583 (2000) 260–290
O. G. Miranda, C. A. Moura and A. Parada, Phys. Lett. B744 (2015) 55–58
P. F. de Salas, R. A. Lineros and M. Tortola, Phys. Rev. D94 (2016) 123001
V. Brdar, J. Kopp, J. Liu, P. Prass and X.-P. Wang, Phys.Rev. D97 (2018) no.4, 043001

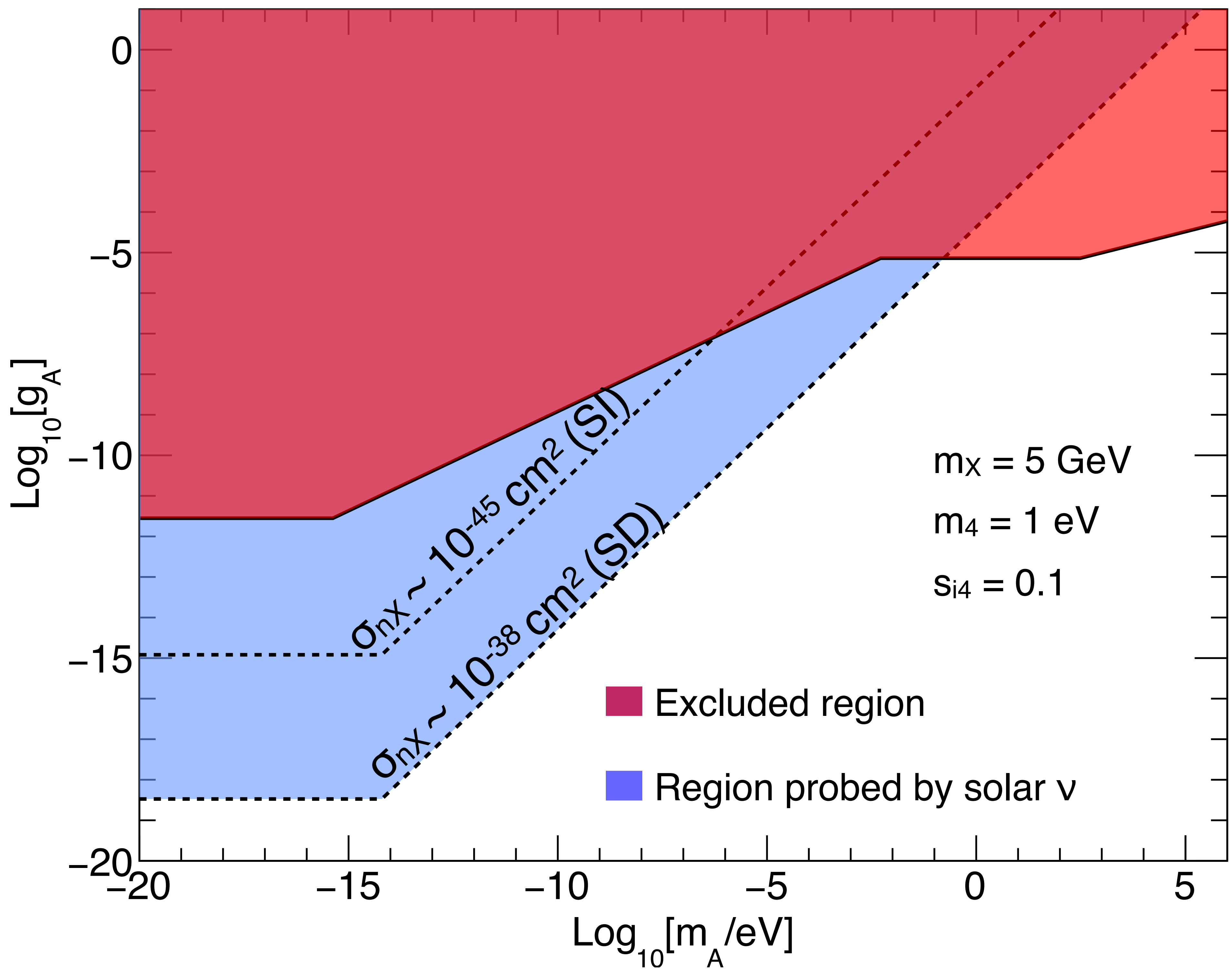
Vector V^{μ}

Neutrino oscillations in the Sun (assuming DM clustering)



F. Capozzi, I. M. Shoemaker and L. Vecchi, JCAP 1707 (2017) 021

Vector V^{μ}



F. Capozzi, I. M. Shoemaker and L. Vecchi, JCAP 1707 (2017) 021

Conclusions

Oscillation experiments can probe dark sectors even with very tiny couplings

Atmospheric neutrinos play an important role

ORCA/PINGU and IceCube have complimentary roles

Thank you

Ultra-light vector DM

Ultra-light vector A^μ coupled to sterile ν_s, with $\langle A \rangle = \frac{\sqrt{\rho_{DM}}}{m_A}$

$$V^\mu \sim 10^{-24}\ \mathrm{GeV}\ \sin^2\theta_s \left(\frac{g_A}{5\times 10^{-19}}\right)\left(\frac{10^{-6}\ \mathrm{eV}}{m_A}\right)\sqrt{\frac{\rho_{\mathrm{DM}}}{0.4\ \mathrm{GeV/cm^3}}}$$

Constraints:

Avoid DM-ν interaction reaching equilibrium.

We require $\Gamma(\nu_s \longrightarrow \nu_a + A) < H$ at $T = m_s$

$$g_A \lesssim \sqrt{\frac{8\pi m_s}{\sin^2\theta M_{\mathrm{Pl}}}} \simeq 6\times 10^{-13} \left(\frac{0.1}{\sin\theta}\right)\sqrt{\frac{m_s}{\mathrm{eV}}}$$

Ultra-light vector DM

Ultra-light vector A^μ coupled to sterile ν_s, with <A> = $\frac{\sqrt{\rho_{DM}}}{m_A}$

$$V^\mu \sim 10^{-24}\ \mathrm{GeV}\ \ \sin^2\theta_s \left(\frac{g_A}{5\times 10^{-19}}\right)\left(\frac{10^{-6}\ \mathrm{eV}}{m_A}\right)\sqrt{\frac{\rho_{\mathrm{DM}}}{0.4\ \mathrm{GeV/cm^3}}}$$

Constraints:

Avoid disappearance of $\bar{\nu}_e$ from SN1987A $\nu_a+\nu_s \longrightarrow \nu_s+\nu_s$

We require the optical depth to be less than unity

$$g_A \lesssim 2\times 10^{-7}\ \left(\frac{m_A}{10^{-5}\ \mathrm{eV}}\right)^{1/2}\ \left(\frac{0.1}{\sin\theta}\right)^{1/2}$$

Tensor coupling F

$F_{\mu\nu}$ induced by dipole interactions with a dark gauge boson A^{μ}
(suppressed vector coupling)

both charged under
dark radiation

$$\mathcal{L} \supset g_s \nu_s \Psi \Phi$$

$$F_{\mu\nu} \sim 10^{-24}\ \mathrm{GeV}\ \sin^2\theta_s \left(\frac{g_s}{10^{-1}}\right)^2 \left(\frac{g_A}{10^{-1}}\right) \left(\frac{100\ \mathrm{eV}\ m_s}{M^2}\right) \sqrt{\frac{\rho_{\mathrm{D,rad}}}{1\ \mathrm{eV/cm}^3}}$$

Constraints:

Avoid disappearance of ν_e from SN1987A
Assuming no relic abundance for Ψ,Φ: $g_s < 0.3$

Scalar coupling

Scalar field ϕ oscillating near its minimum (misalignment).
ϕ is coupled to ν_s

$$m_\nu \sim \sin^2\theta_s \; y \frac{\sqrt{\rho_\phi}}{m_\phi}$$

Requirements

$y/m_\phi \gtrsim 1$ eV
oscillation frequency $1/m_\phi \gtrsim$ few years.

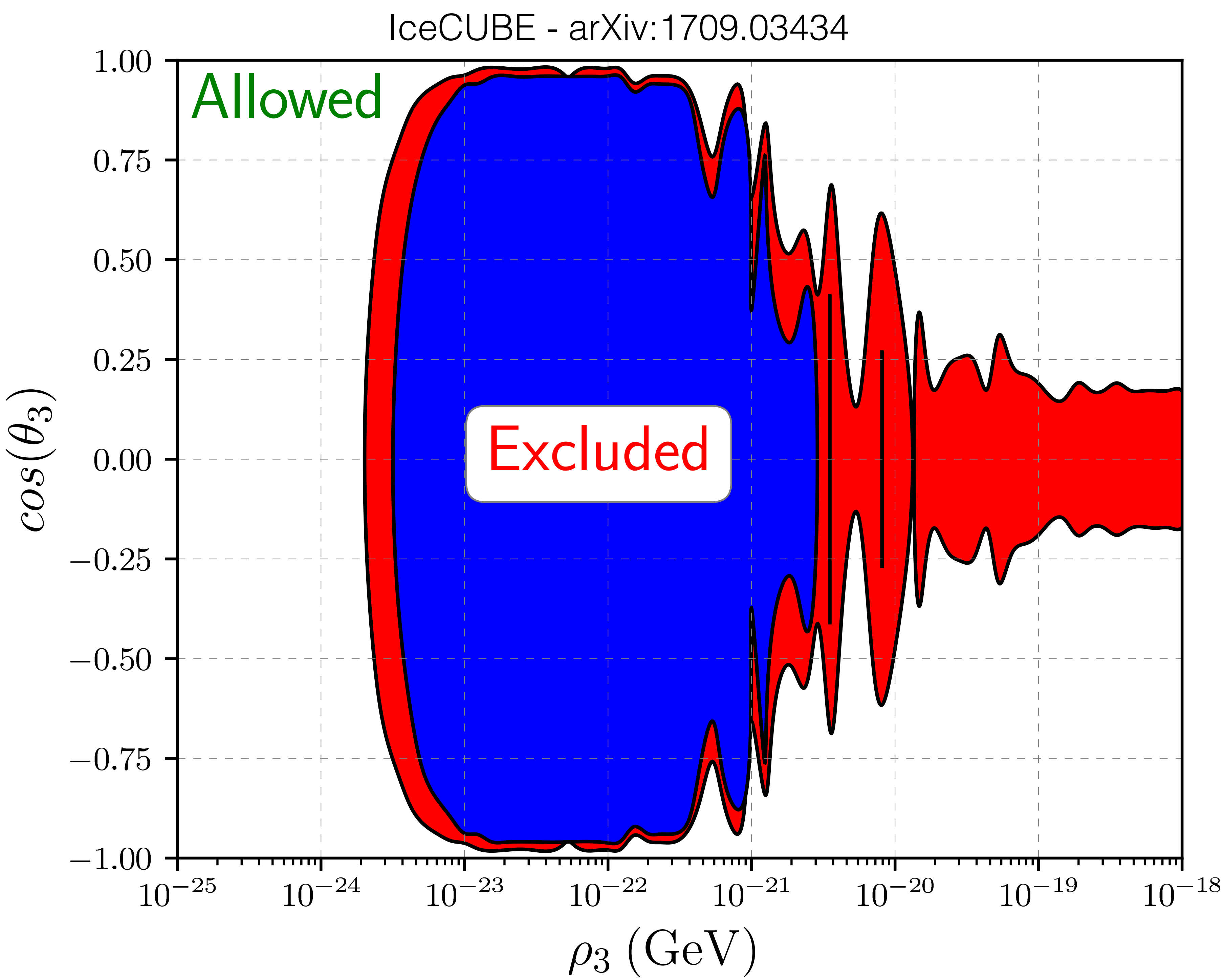
See:

A. Berlin, Phys. Rev. Lett. 117 (2016) 231801

V. Brdar, J. Kopp, J. Liu, P. Prass and X.-P. Wang, Phys.Rev. D97 (2018) no.4, 043001

G. Krnjaic, P. A.N. Machado, Lina Necib, Phys.Rev. D97 (2018) no.7, 075017

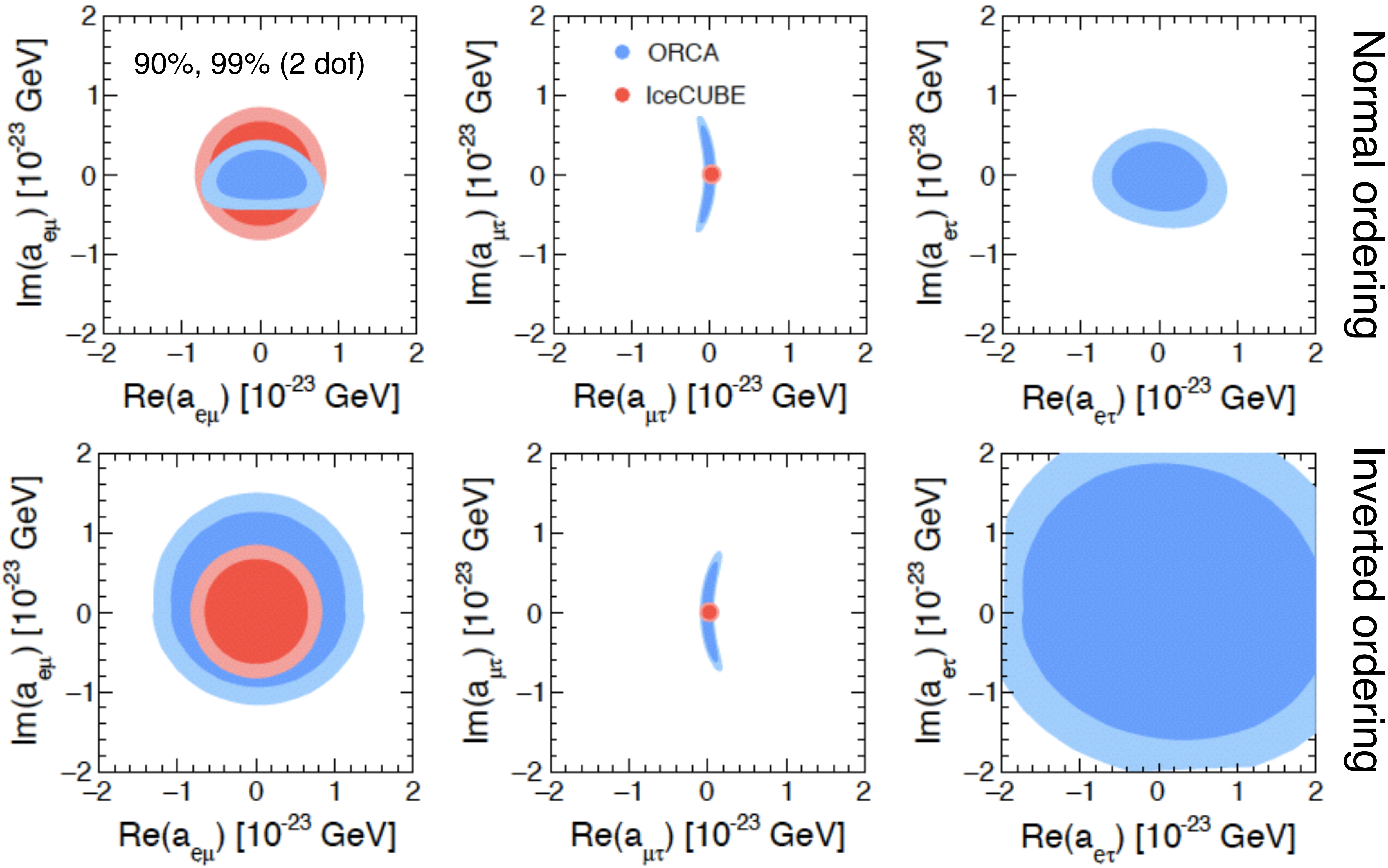
IceCUBE constraints on LV



$$\rho_3 = \sqrt{(a_{\mu\mu})^2 + \mathrm{Re}(a_{\mu\tau})^2 + \mathrm{Im}(a_{\mu\tau})^2} \qquad \cos\theta_3 = \frac{a_{\mu\mu}}{\rho_3}$$

Future constraints from atmospheric ν

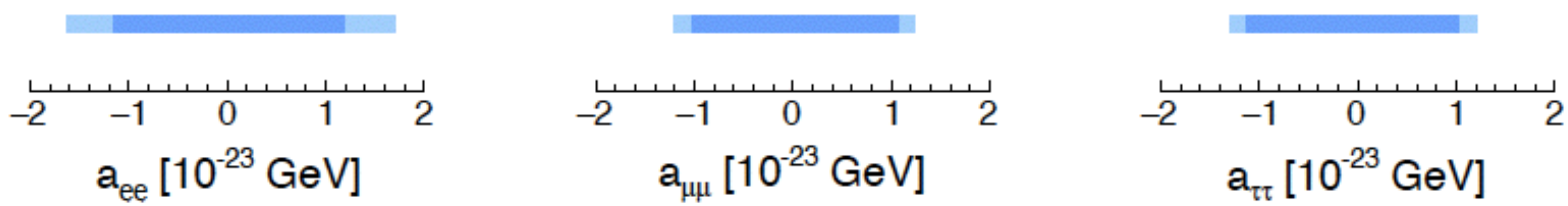
Constraints on $a_{\alpha\beta}$ from ORCA/IceCUBE (10 years)



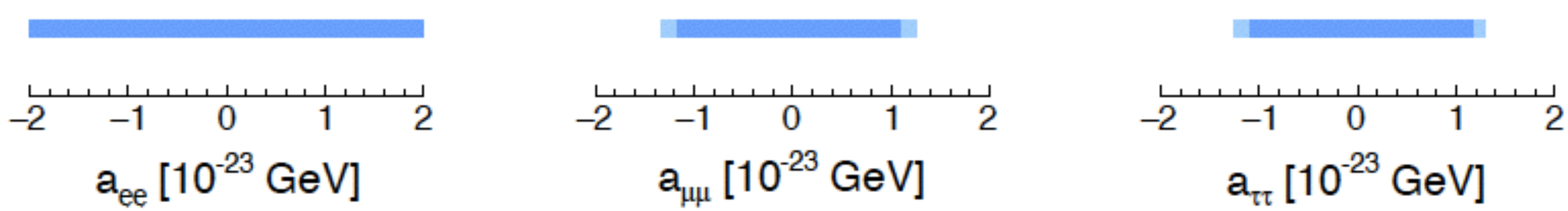
Future constraints from atmospheric ν

Constraints on $a_{\alpha\alpha}$ from ORCA (10 years)

Normal ordering

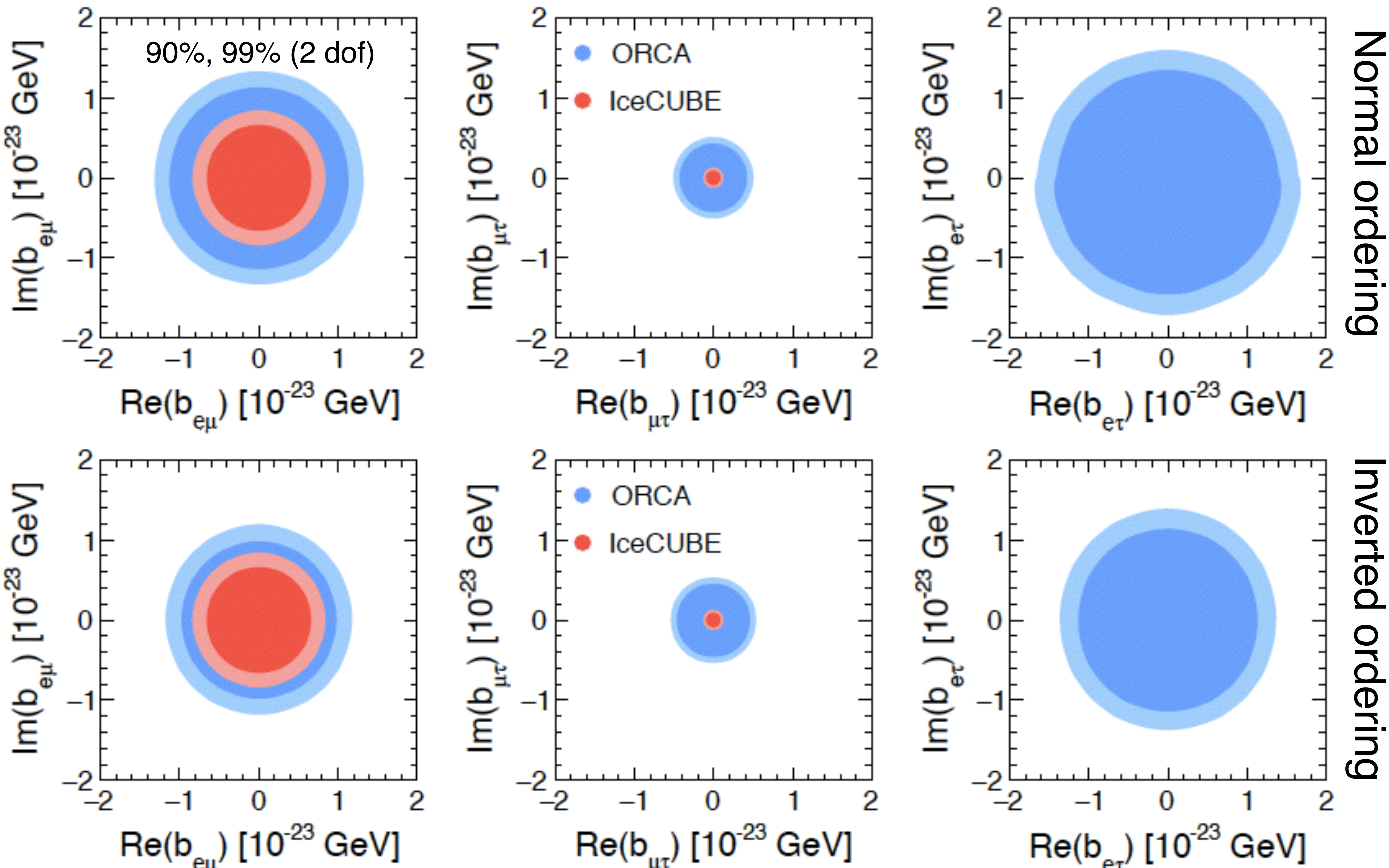


Inverted ordering



Future constraints from atmospheric ν

Constraints on $b_{\alpha\beta}$ from ORCA/IceCUBE (10 years)

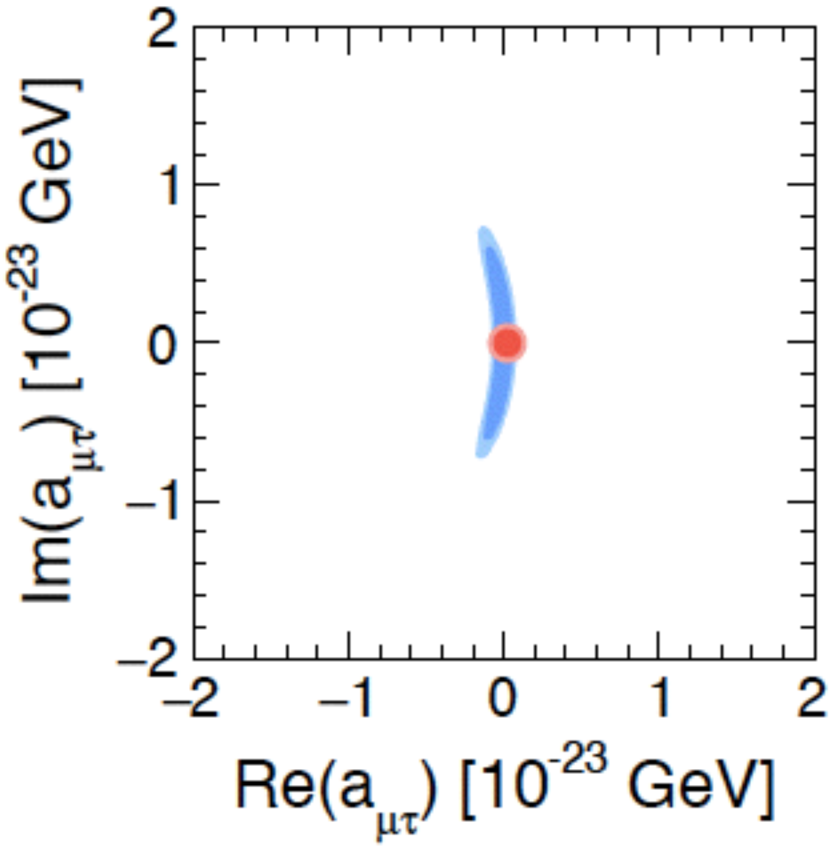


$a_{\mu\tau} \neq 0$

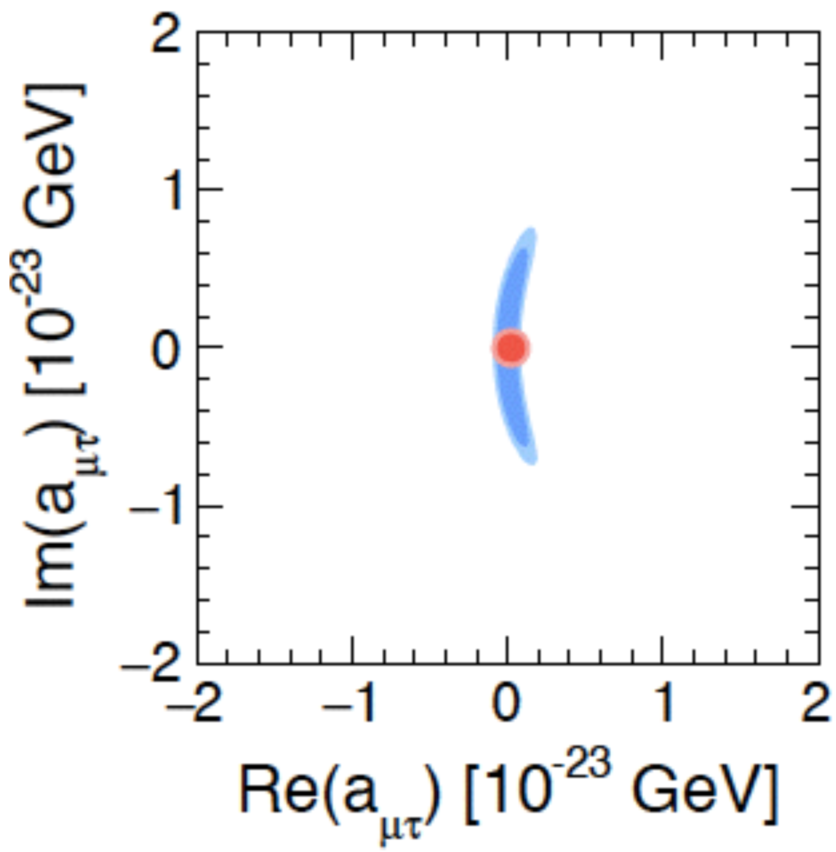
A partial cancellation between Re[$a_{\mu\tau}$] and Im[$a_{\mu\tau}$], may take place

$$P_{\mu\leftrightarrow\tau} - P^{(a=0)}_{\mu\leftrightarrow\tau} \propto \mathrm{Re}[a_{\mu\tau}] + \frac{2E}{\Delta m^2_{\rm atm}\sin 2\theta_{23}}\left[(\mathrm{Im}[a_{\mu\tau}])^2 - (1-2\cos(4\theta_{23}))(\mathrm{Re}[a_{\mu\tau}])^2\right] + \mathcal{O}(a^3),$$

Normal ordering



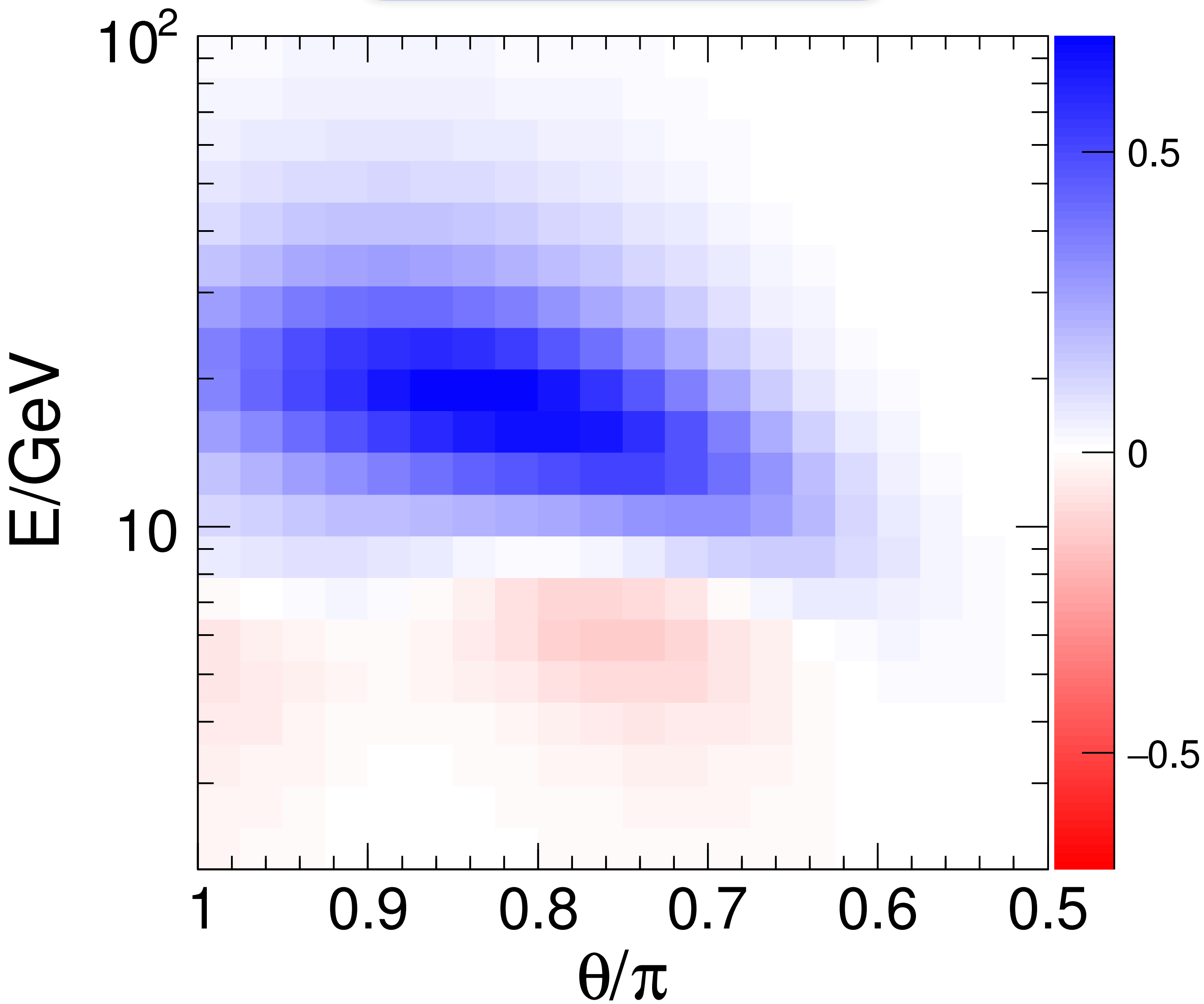
Inverted ordering



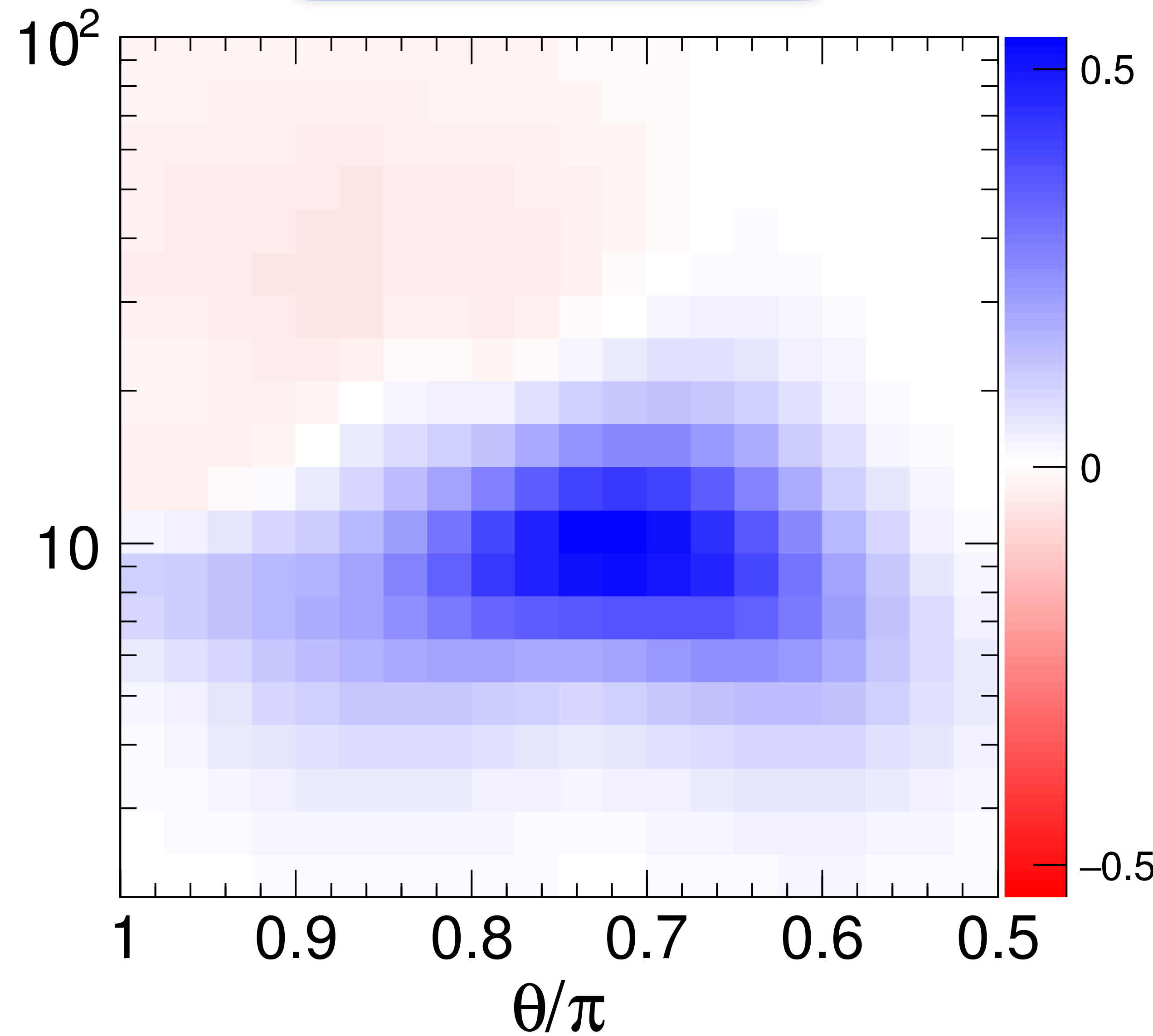
Event asymmetries

We calculate $(N-N_{SM})/\sqrt{N_{SM}}$, for ORCA and $\mathbf{a_{\mu\mu} = 10^{-23}}$

Track

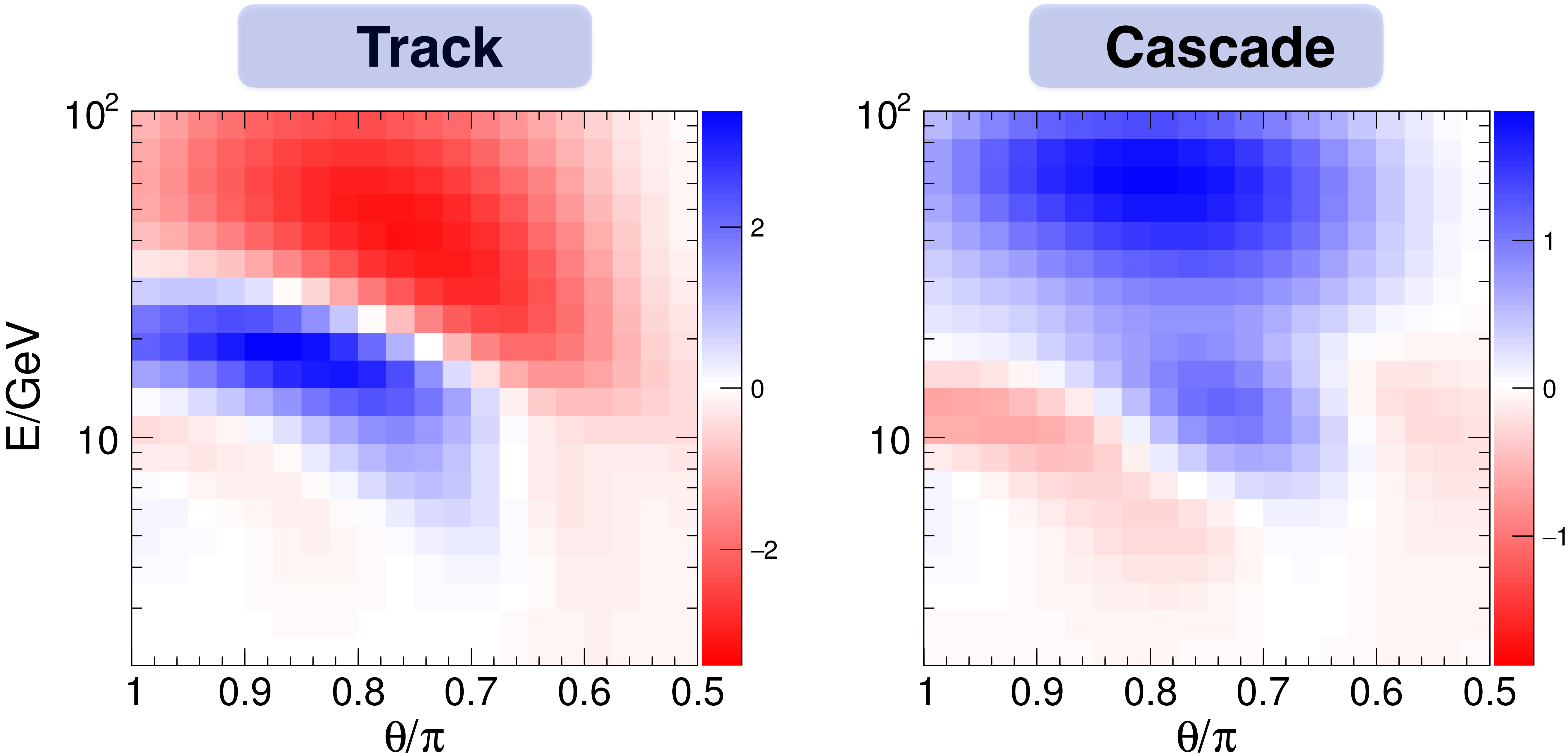


Cascade



Event asymmetries

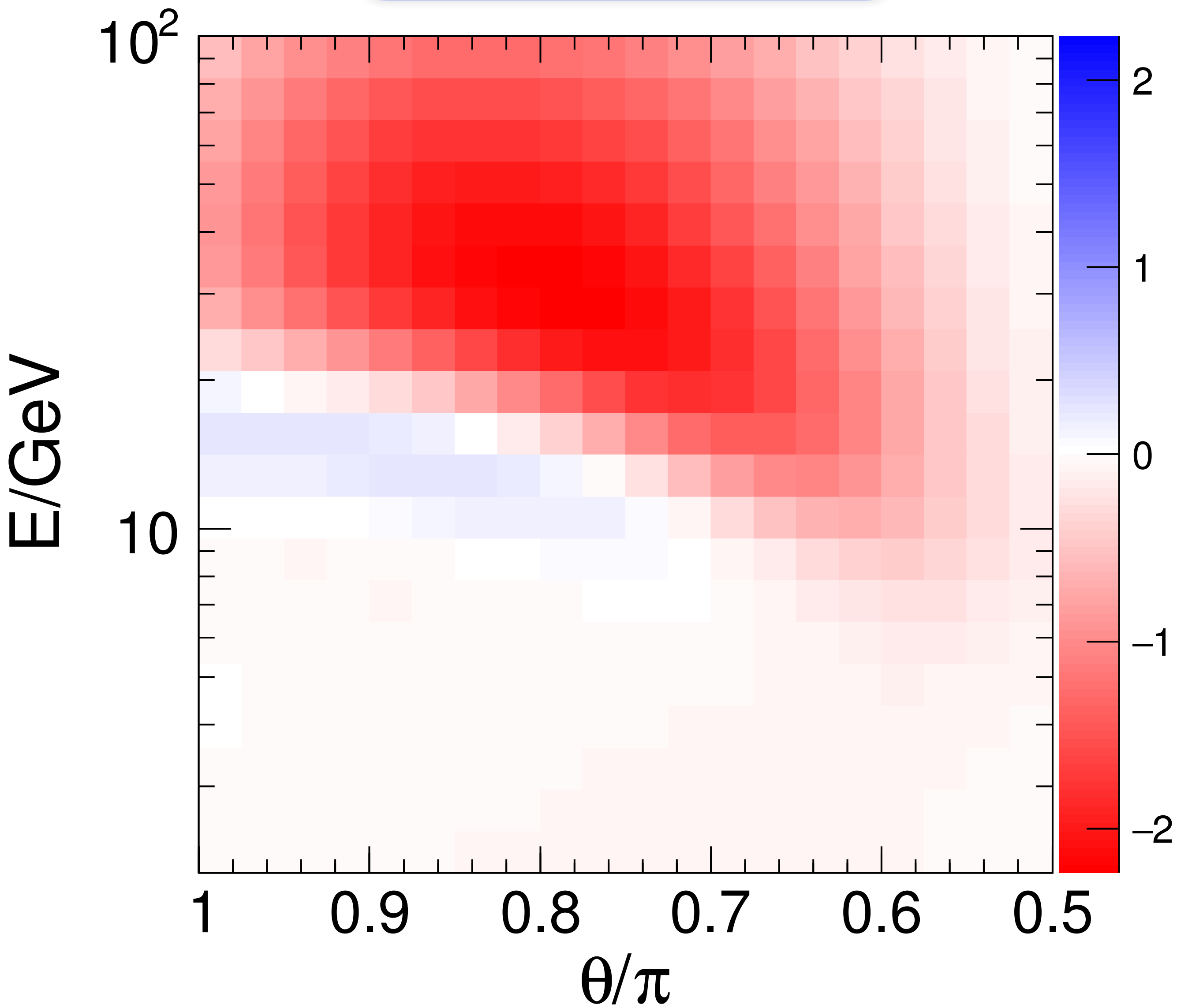
We calculate $(N-N_{SM})/\sqrt{N_{SM}}$, for ORCA and $\mathbf{a_{\mu\tau} = 10^{-23}}$



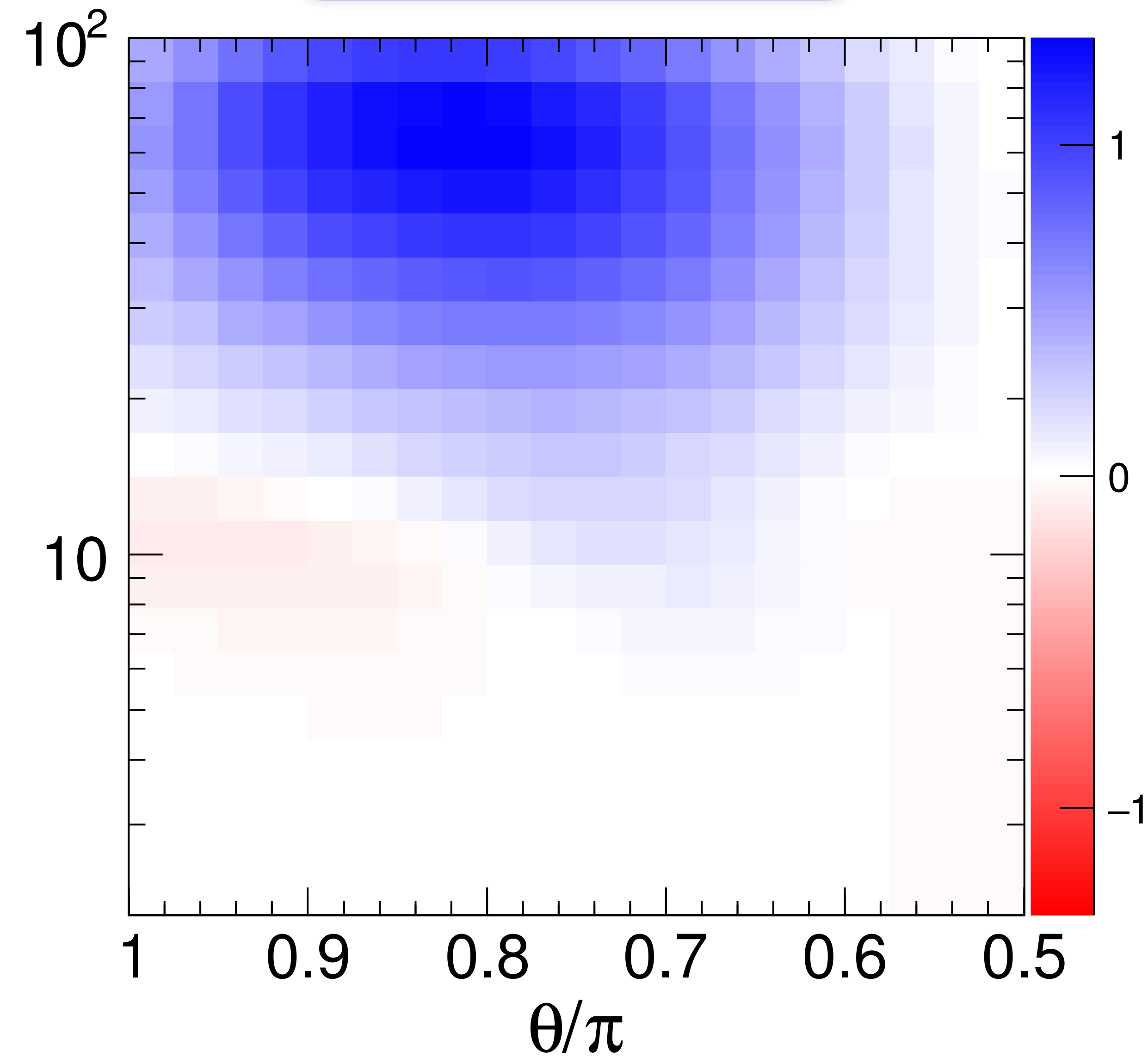
Event asymmetries

We calculate $(N-N_{SM})/\sqrt{N_{SM}}$, for ORCA and $\mathbf{b_{\mu\tau} = 10^{-23}}$

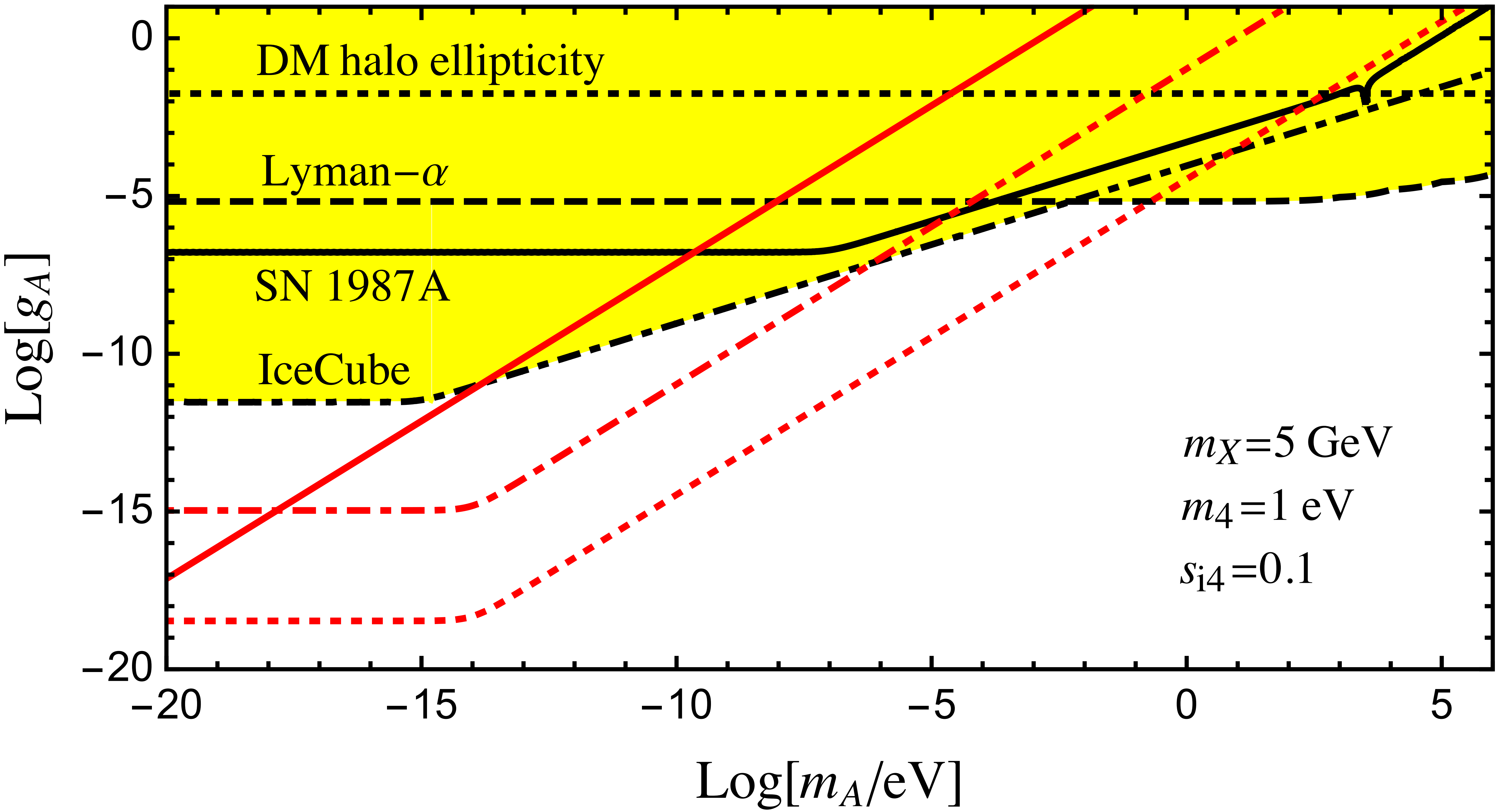
Track



Cascade



Vector V^μ



F. Capozzi, I. M. Shoemaker and L. Vecchi, JCAP 1707 (2017) 021