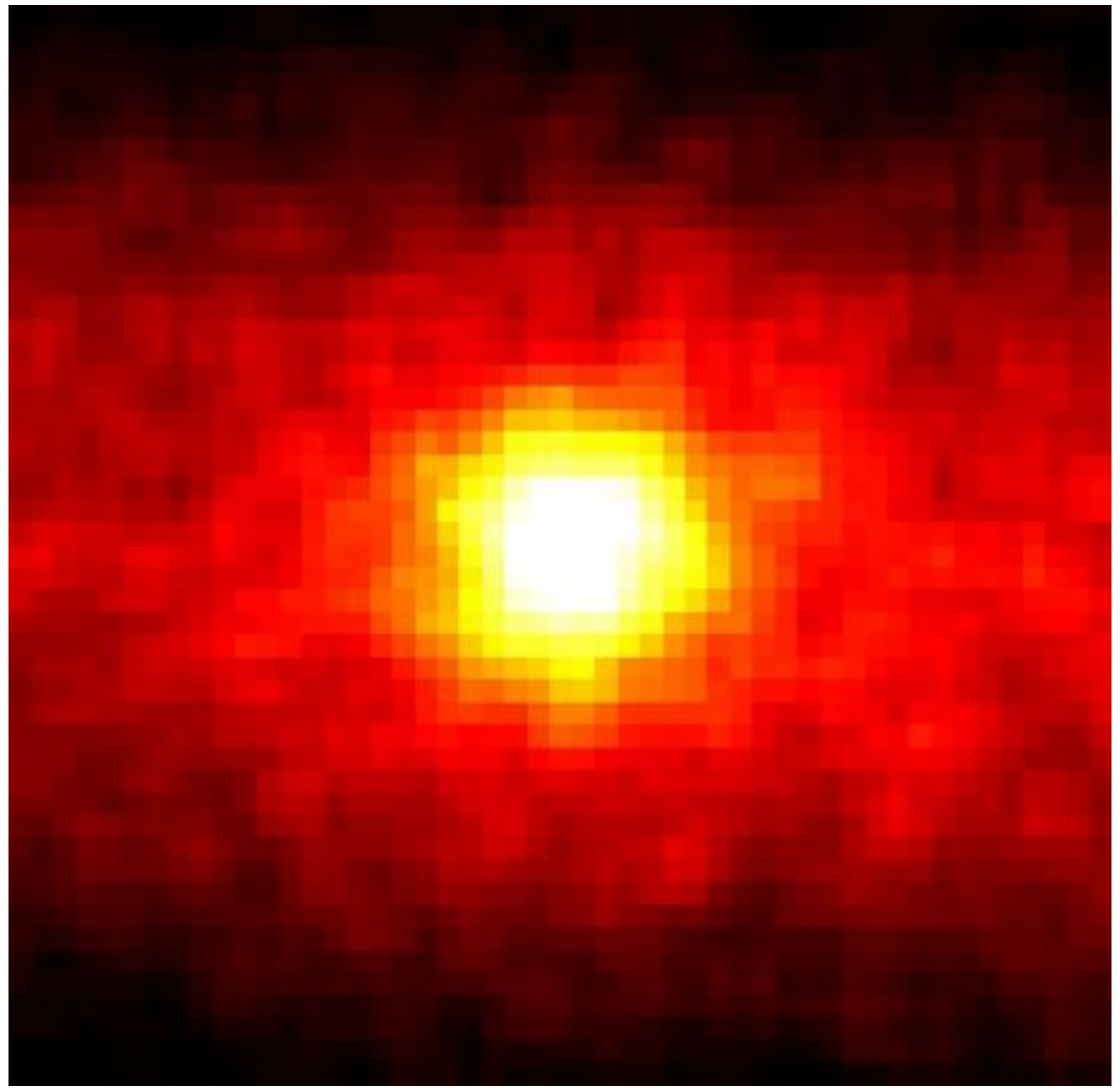
Neutrino astronomy with dark matter - neutrino interactions

Subhendu Rakshit

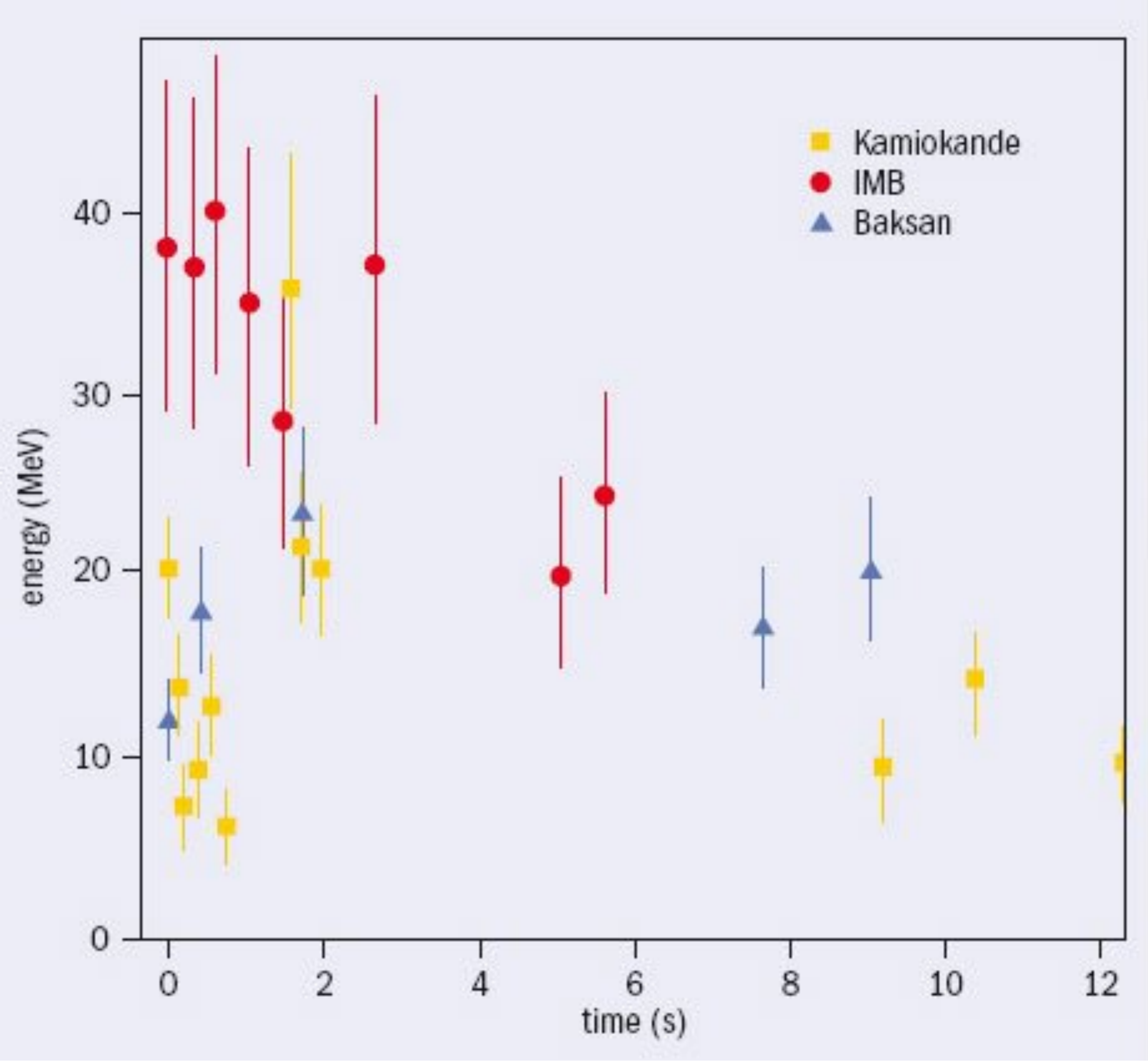
IIT Indore

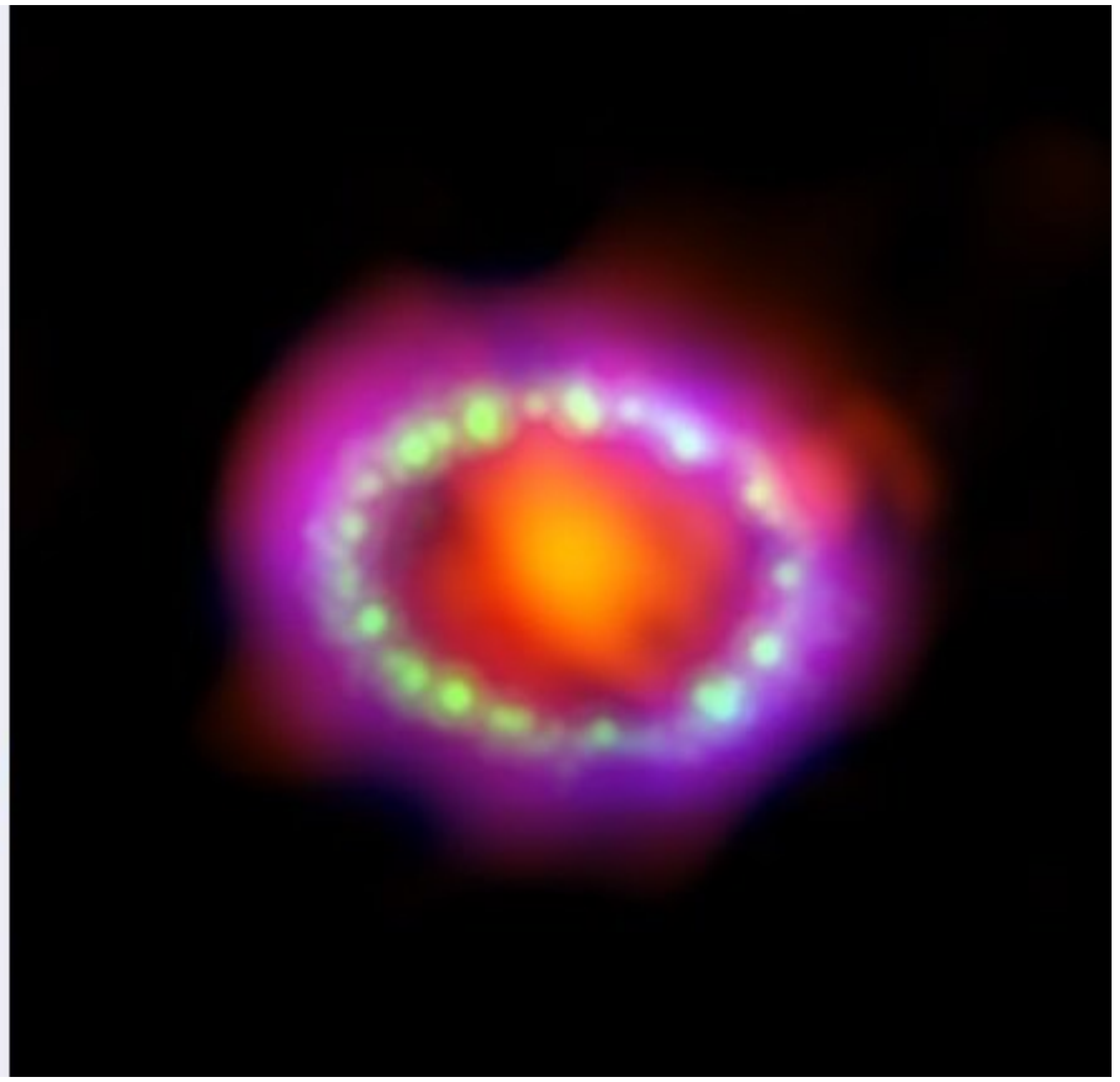
Neutrino astronomy — Earlier Successes



Credit: SuperK

Neutrino-graph of the Sun





Credit: Hubble

Neutrinos received from supernova 1987A

A History of Neutrino Astronomy in Antarctica

1988 — Telescope in the Ice Envisioned

2000 — AMANDA Completed

2001 — Atmospheric Neutrinos Detected

2011 — IceCube Completed

2013 — Astrophysical Neutrinos Discovered

2018 — First Source TXS 0506+056 Identified

2021 — Glashow Resonance Neutrino Identified

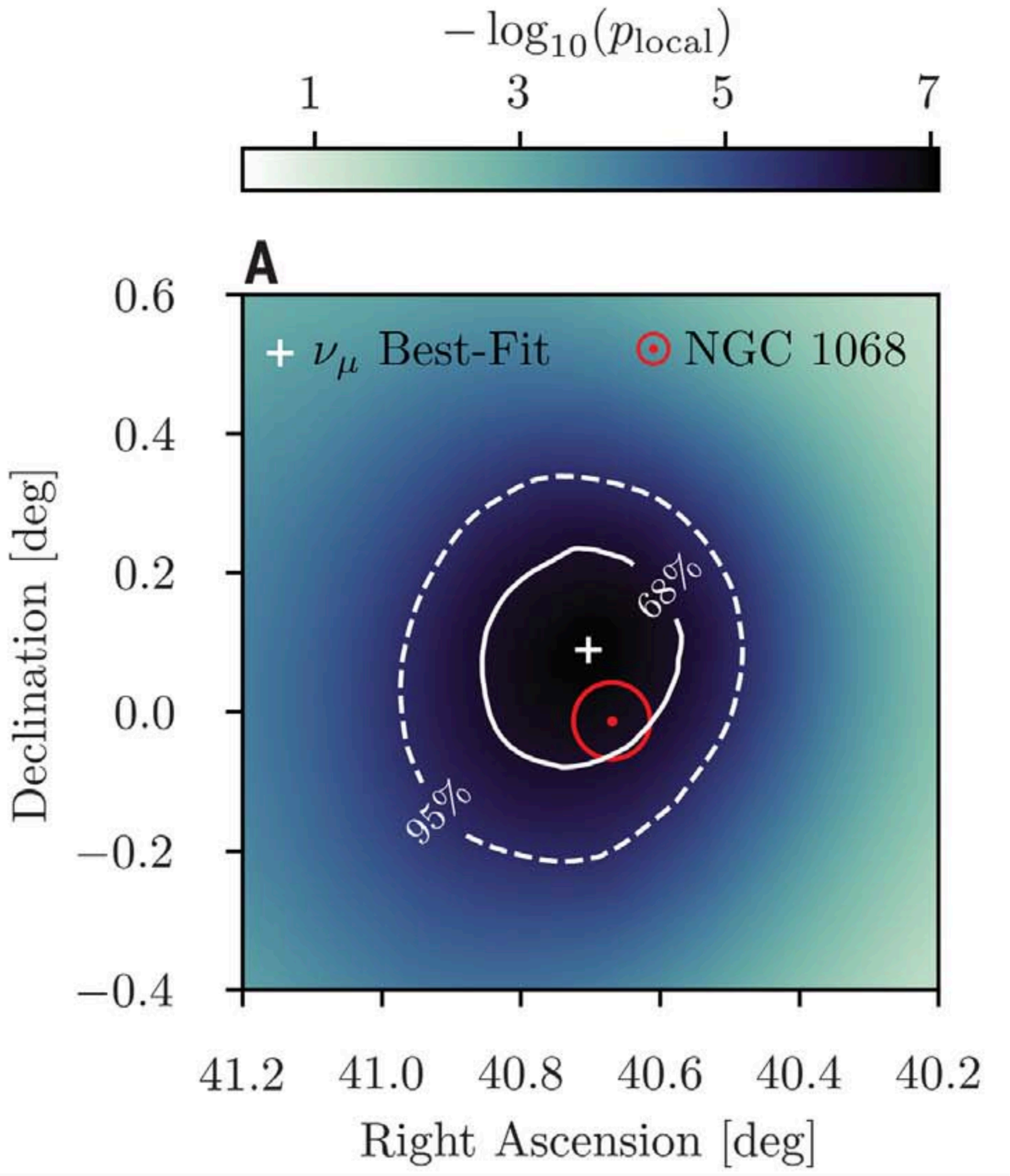
2022 — Second Source NGC 1068 Identified

2023 — Third Source Milky Way Identified

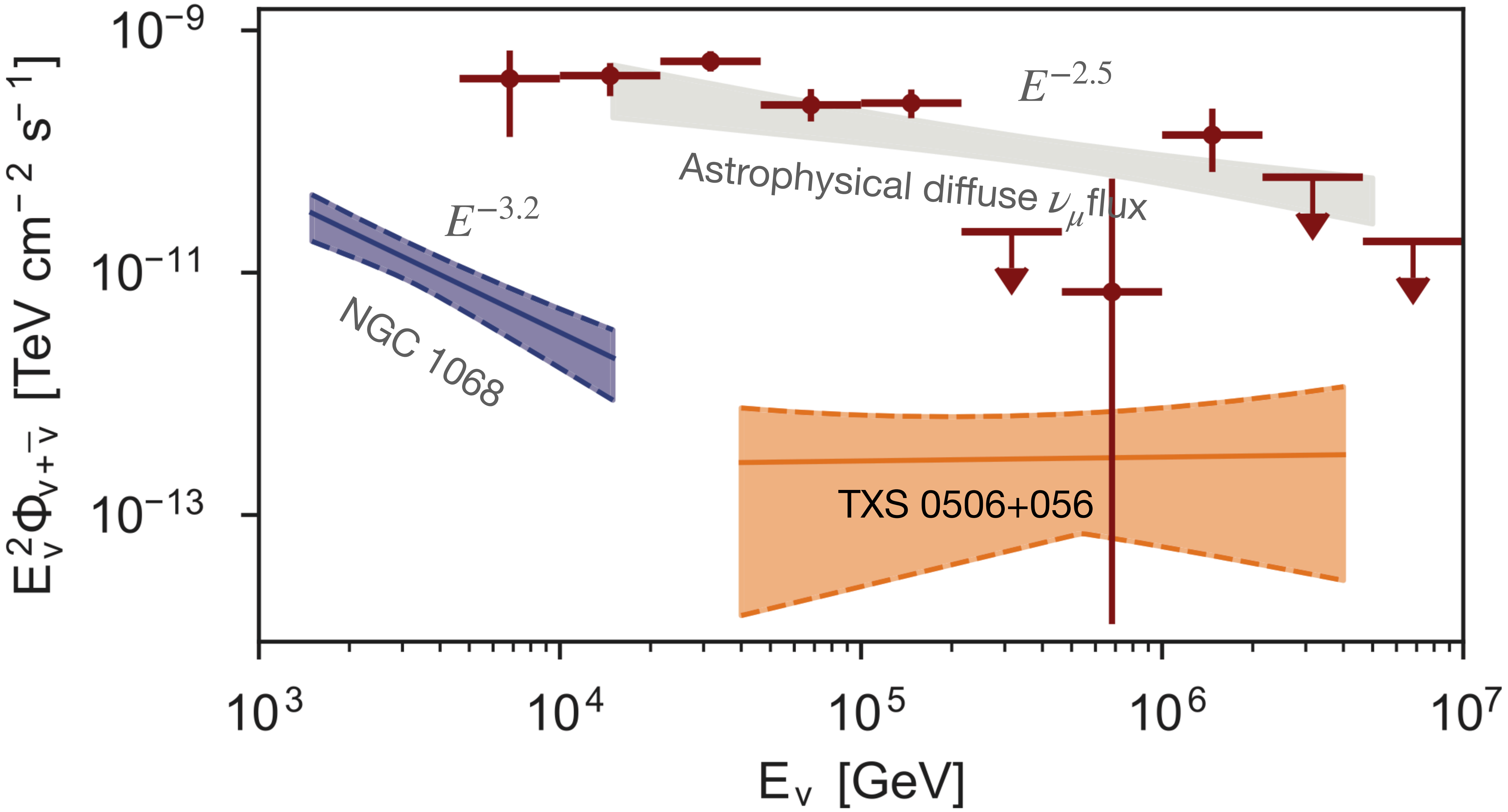
The IceCube Collaboration found an excess of 79^{+22}_{-20} neutrinos over the background associated with NGC 1068 at a statistical significance of 4.2σ.

Radio-quiet AGNs, including NGC 1068, and other low-luminosity AGNs, which are more abundant than blazars and radio-loud AGNs, might help explain the amount of all cosmic neutrinos observed by the IceCube Neutrino Observatory

NGC 1068 is a radio quite AGN at a distance of 46 million light-years. Neutrinos can escape.



IceCube Collaboration, Science **378** (2022) 538



Interactions of astrophysical neutrinos with dark matter: a model building perspective

Sujata Pandey, Siddhartha Karmakar and Subhendu Rakshit

JHEP01 (2019) 095

An encyclopedia of neutrino interactions with ultralight scalar DM

Astronomy with energy dependent flavour ratios of extragalactic neutrinos

Siddhartha Karmakar, Sujata Pandey and Subhendu Rakshit

JHEP10 (2021) 004

ν-DM interactions lead to energy dependent flavour ratios at neutrino telescopes

Motivation for ultralight DM

ΛCDM fits cosmological observations very well. The CDM paradigm emerges from the large scale observations, and describes structure formation through gravitational clustering.

- Cusp Core Problem → CDM prefers cusp $\rho(r) \propto 1/r$, but observations indicate core

- Missing satellites → For CDM, MilkyWay size galaxies DM halo should have many sub-halos, leading to too many satellite galaxies, which are not observed

Motivation for ultralight DM

Review: E. Ferreira, Astron.Astrophys.Rev. 29 (2021) 7

de Brogli wavelength of DM ~ size of a galaxy $\Longrightarrow$ $\lambda = \dfrac{h}{m_{\rm DM} v} \sim 1\,{\rm kpc}$

$v \sim 220\,{\rm km/s} \Longrightarrow$ $\boxed{m_{\rm DM} \sim 10^{-22}\,{\rm eV/c^2}}$

Small masses of bosons leads to the formation of BE condensate on galactic scales.

Wave nature of DM $\Longrightarrow$ non-CDM behaviour at galactic scale.

But CDM-like behaviour on larger scales retaining the success of CDM.

At small scales, the quantum pressure forbids over-production of sub-halos.

Ultralight/Fuzzy DM solitonic core in presence of a SMBH

FDM halos are comprised of a central core that is a stationary, minimum-energy solution of the Schrödinger-Poisson equation, sometimes called a "soliton," surrounded by an envelope that resembles a CDM halo.

Hui, Ostriker, Tremaine, Witten, PRD95(2017)043541

$$\rho(r) = \rho_0 \exp(-r/a)$$

E.Y. Davies and P. Mocz, MNRAS 492 (2020) 5721

$$a = \frac{1}{G M_{\rm BH} m_{\rm DM}^2} \qquad \rho_0 = \frac{M_{\rm sol}}{8\pi a^3}$$

The observations of Lyman-α forest, etc. exclude DM masses lower than $m_{\rm DM} \lesssim 10^{-22}$ eV.

Ultralight scalar DM of masses $m_{\rm DM} > 10^{-22}$ eV are viable in the presence of DM self-interactions.

Feel for numbers

Neutrinos can be produced in the corona around ~$10 - 40R_s$, where $R_s = 2GM_{\rm BH}$

For $M_{\rm BH} \sim 10^5 M_\odot$, $R_s \sim 5 \times 10^{-8}$ pc,

neutrino emission takes place around 10^{-7}pc from the centre, where DM density is uniform.

With $m_{\rm DM} \sim 3 \times 10^{-17}$ eV, $a \sim 10^{-6}$pc, where the core meets its edge. $\Longrightarrow$ Sharp fall in DM density can induce non-adiabaticity

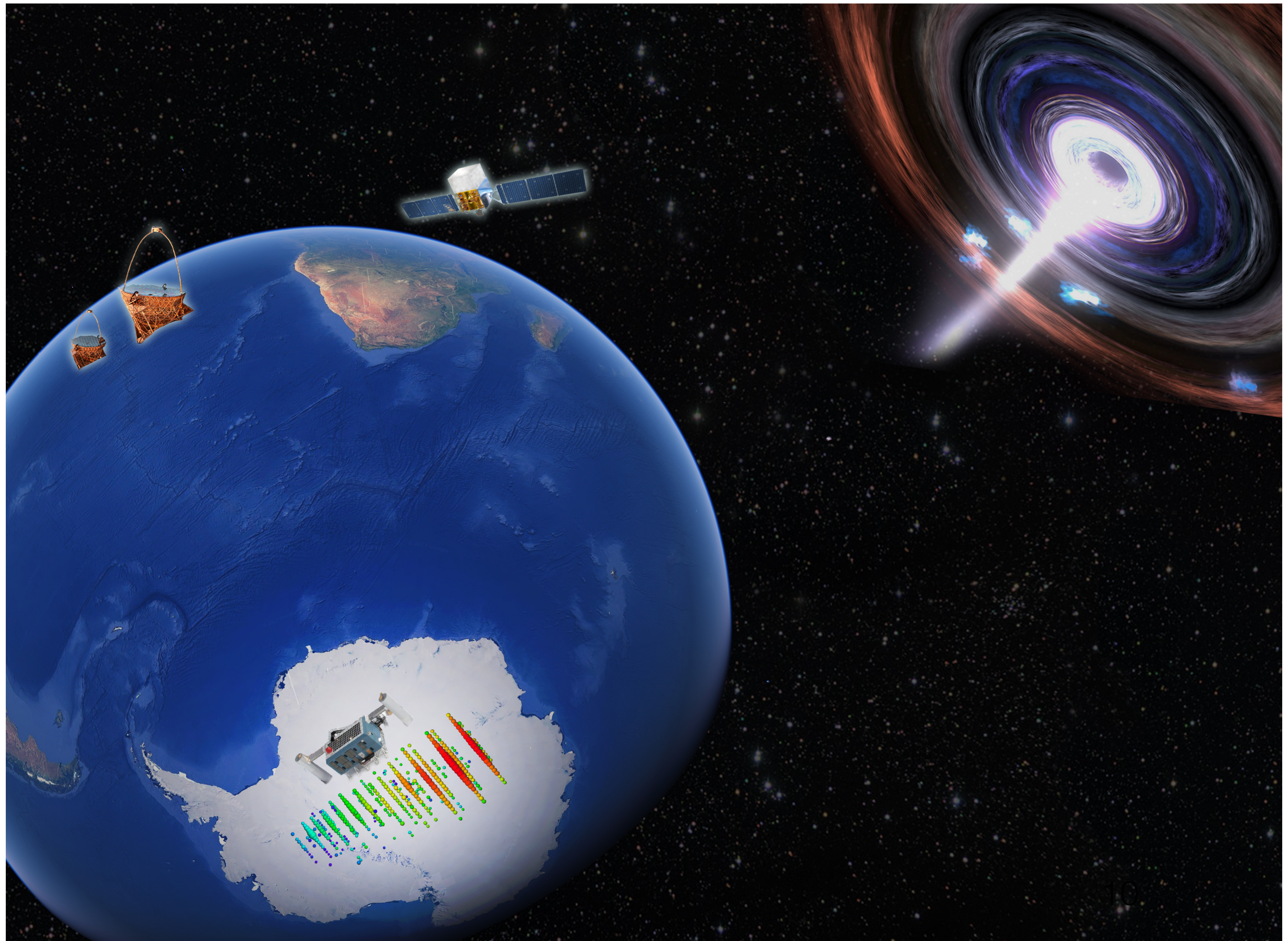
$\Longrightarrow$ Enables us to do neutrino astronomy by determining the shape of the core

Propagation of neutrinos from astrophysical sources

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\,\mathrm{Re} \sum_{k>j} U^\star_{\alpha k} U_{\beta k} U_{\alpha j} U^\star_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

$$\overline{P}_{\nu_\alpha \to \nu_\beta} = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2$$

For astrophysical distance the oscillatory term gets averaged out



$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$ Source

Neutrinos oscillate

$$f^D_\beta = P_{\alpha\beta} f^S_\alpha$$

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$ IceCube

Energy independent in the standard scenario

$$P_{\alpha\beta} = |U^D_{\beta i}|^2|U^S_{\alpha i}|^2 - P^c_{ij}(|U^D_{\beta i}|^2 - |U^D_{\beta j}|^2)(|U^S_{\alpha i}|^2 - |U^S_{\alpha j}|^2) - P^c_{ik}P^c_{kj}(|U^D_{\beta k}|^2 - |U^D_{\beta j}|^2)(|U^S_{\alpha i}|^2 - |U^S_{\alpha k}|^2)$$

$\longrightarrow$ ν-osc probability

$$P^c_{ij} = \frac{\exp\left(-\frac{\pi}{2}\gamma^R_{ij}F_{ij}\right) - \exp\left(-\frac{\pi}{2}\gamma^R_{ij}\frac{F_{ij}}{\sin^2\theta_{ij}}\right)}{1-\exp\left(-\frac{\pi}{2}\gamma^R_{ij}\frac{F_{ij}}{\sin^2\theta_{ij}}\right)}$$

$\longrightarrow$ Jumping probability

$$\gamma^R_{ij} = \frac{\Delta m^2_{ij}\sin^2 2\theta_{ij}}{2E(1+z)\cos 2\theta_{ij}\,|\mathrm{d}\ln\rho/\mathrm{d}r|_R}$$

$\longrightarrow$ Non-adiabaticity $\Longrightarrow$ $\gamma^R_{ij} \lesssim 1$

$\gamma_{ij} \sim 0$ corresponds to extreme non-adiabaticity.

$$\rho(r) = \rho_0 \exp(-r/a)$$

$$|\mathrm{d}\ln\rho/\mathrm{d}r|_R = 1/a$$

$$F_{ij} = \frac{4}{\pi}\,\mathrm{Im}\int_0^i db\frac{(b^2+1)^{1/2}}{(b\tan 2\theta_{ij}+1)} = \begin{cases} 1-\tan^2\theta_{ij}, & \text{if } \theta_{ij} \leqslant \pi/4 \\ 1-\cot^2\theta_{ij}, & \text{if } \theta_{ij} > \pi/4 \end{cases}$$

Motivation for ν-DM interactions

Relieves Hubble tension! S. Ghosh, R. Khatri, T. Roy, PRD102 (2020) 123544

Negates the phase shift introduced by the free-streaming neutrinos

in the photon temperature transfer function pushing H_0 to higher values.

Due to the ν-DM interactions, neutrinos scatter and cannot free-stream,

effectively generating a negative phase-shift wrt ΛCDM.

ν-DM interaction: Constraints on thermal relic DM!

- **Relic density should not exceed the observed limit:**

$$\langle \sigma v \rangle \geq 3 \times 10^{-26} \text{cm}^3\ \text{s}^{-1}$$

- **Collisional damping:** $\nu - \text{DM}$ scattering tends to erase small scale density perturbations, thereby disrupting large scale structure formation.

$$\sigma_{\text{el}} \lesssim 10^{-48} \times \left(\frac{m_{\text{DM}}}{\text{MeV}}\right) \left(\frac{T_0}{2.35 \times 10^{-4}\text{eV}}\right)^2 \text{cm}^2$$

- **Constraints from BBN:** In standard cosmology the decoupling temperature of neutrinos from the rest of the SM particles is $T_{\text{dec}} \sim 2.3\ \text{MeV}$ and the effective number of neutrinos $N_{\text{eff}} = 3.045$. $\nu - \text{DM}$ scattering below this T_{dec} transfers entropy from DM to the ν sector, changing the effective number of d.o.f. in thermal equilibrium with the νs. This alters N_{eff} significantly unless $m_{\text{DM}} \geq 10\ \text{MeV}$.

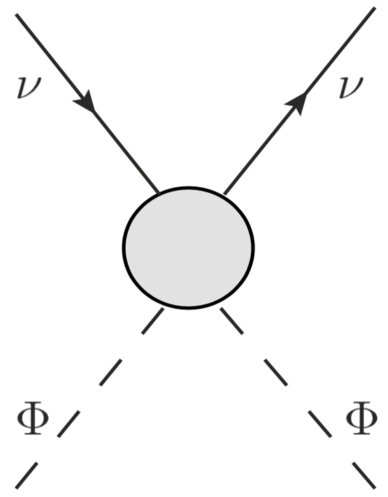
No appreciable suppression with thermal relics!

For BEC DM, the large number density pays off!

ν-DM effective interactions

S. Pandey, S. Karmakar and S. Rakshit, JHEP 1901(2019) 095

Topology I



Favoured if satisfies 1% flux suppression criteria!

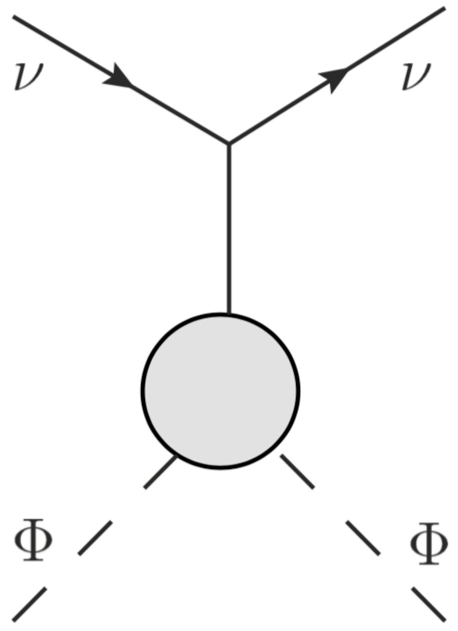
Topology	Interaction	Constraints	Remarks
I 1	$\frac{c_l^{(1)}}{\Lambda^2}(\bar{\nu} i \partial\!\!\!/ \nu)(\Phi^*\Phi)$	$c_l^{(1)}/\Lambda^2 \lesssim 8.8\times10^{-3}\,\text{GeV}^{-2}$, $c_e^{(1)}/\Lambda^2 \lesssim 1.0\times10^{-4}\,\text{GeV}^{-2}$, $c_\mu^{(1)}/\Lambda^2 \lesssim 6.0\times10^{-3}\,\text{GeV}^{-2}$, $c_\tau^{(1)}/\Lambda^2 \lesssim 6.2\times10^{-3}\,\text{GeV}^{-2}$	disfavoured
I 2	$\frac{c_l^{(2)}}{\Lambda^2}(\bar{\nu}\gamma^\mu\nu)(\Phi^*\partial_\mu\Phi - \Phi\partial_\mu\Phi^*)$	$c_l^{(2)}/\Lambda^2 \lesssim 1.8\times10^{-2}\,\text{GeV}^{-2}$, $c_e^{(2)}/\Lambda^2 \lesssim 2.6\times10^{-5}\,\text{GeV}^{-2}$, $c_\mu^{(1)}/\Lambda^2 \lesssim 1.2\times10^{-2}\,\text{GeV}^{-2}$, $c_\tau^{(1)}/\Lambda^2 \lesssim 1.3\times10^{-3}\,\text{GeV}^{-2}$	disfavoured
I 3	$\frac{c_l^{(3)}}{\Lambda}\bar{\nu^c}\nu\,\Phi^\star\Phi$	$c_l^{(3)}/\Lambda \leq 0.5\,\text{GeV}^{-1}$	favoured[a]
I 4	$\frac{c_l^{(4)}}{\Lambda^3}(\bar{\nu^c}\sigma^{\mu\nu}\nu)(\partial_\mu\Phi^*\partial_\nu\Phi - \partial_\nu\Phi^*\partial_\mu\Phi)$	$c_l^{(4)}/\Lambda^3 \lesssim 2.0\times10^{-3}\,\text{GeV}^{-3}$	disfavoured
I 5	$\frac{c_l^{(5)}}{\Lambda^3}\partial^\mu(\bar{\nu^c}\nu)\partial_\mu(\Phi^*\Phi)$	$c_l^{(5)}/\Lambda^3 \lesssim 7.5\times10^{-4}\,\text{GeV}^{-3}$	disfavoured
I 6	$\frac{c_l^{(6)}}{\Lambda^4}(\bar{\nu}\partial^\mu\gamma^\nu\nu)(\partial_\mu\Phi^*\partial_\nu\Phi - \partial_\nu\Phi^*\partial_\mu\Phi)$	$c_l^{(6)}/\Lambda^4 \lesssim 2.5\times10^{-5}\,\text{GeV}^{-4}$, $c_e^{(6)}/\Lambda^4 \lesssim 1.2\times10^{-6}\,\text{GeV}^{-4}$, $c_\mu^{(6)}/\Lambda^4 \sim c_\tau^{(6)}/\Lambda^4 \lesssim 10^{-5}\,\text{GeV}^{-4}$	disfavoured

$Z \to inv$, LEP monophoton+$\not{E}_T$, $Z \to \mu^+\mu^-$, $Z \to \tau^+\tau^-$ and $(g-2)_{e,\mu}$.

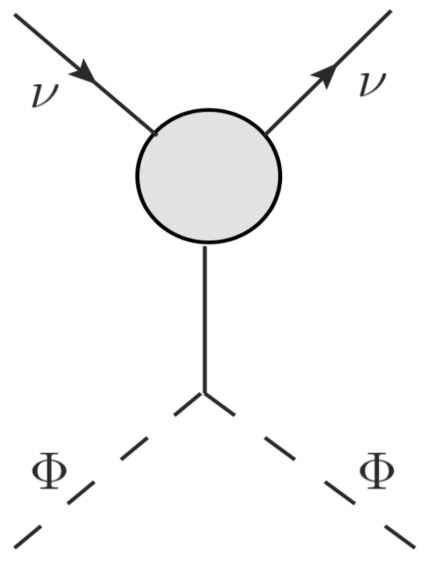
ν-DM effective interactions

S. Pandey, S. Karmakar and S. Rakshit,
JHEP 1901(2019) 095

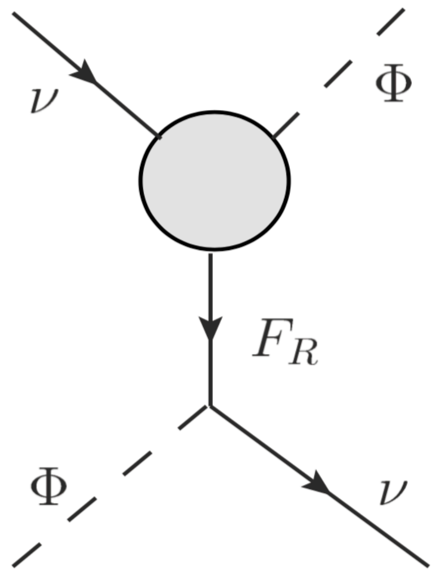
Topology II



Topology III



Topology IV



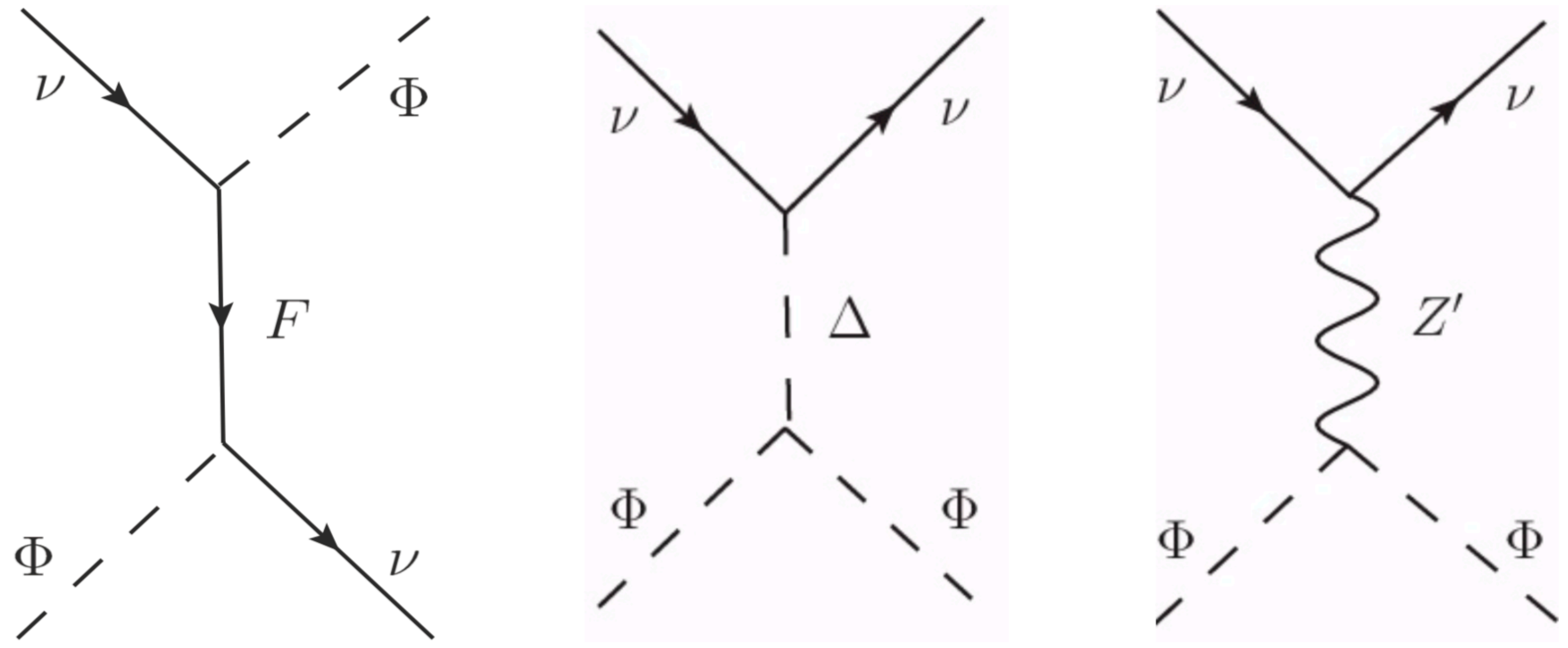
II 1	$\frac{c_l^{(7)}}{\Lambda^2}(\partial^\mu\Phi^*\partial^\nu\Phi - \partial^\nu\Phi^*\partial^\mu\Phi)Z'_{\mu\nu} + f_i\bar{\nu}_i\gamma^\mu P_L\nu_i Z'_\mu$	$f_l c_l^{(7)}/\Lambda^2 \lesssim 4.2\times10^{-2}\,\mathrm{GeV}^{-2}$, $f_e c_e^{(7)}/\Lambda^2 \lesssim 1.9\times10^{-5}\,\mathrm{GeV}^{-2}$, $f_\mu c_\mu^{(7)}/\Lambda^2 \sim f_\tau c_\tau^{(7)}/\Lambda^2 \lesssim 8.1\times10^{-3}\,\mathrm{GeV}^{-2}$, $[f_e, f_\mu, f_\tau] \lesssim [10^{-5}, 10^{-6}, 0.02]$ for $m_{Z'} \sim 10\,\mathrm{MeV}$	disfavoured
II 2	$\frac{c_l^{(8)}}{\Lambda}\partial^\mu\|\Phi\|^2\partial_\mu\Delta + f_l\bar{\nu^c}\nu\Delta$	$m_\nu \sim f_l v_\Delta \lesssim 0.1\,\mathrm{eV}$, $m_\Delta \gtrsim 150\,\mathrm{GeV}$	disfavoured
III	$C_1(\Phi^*\partial_\mu\Phi - \Phi\partial_\mu\Phi^*)Z'^\mu + \frac{c_l^{(9)}}{\Lambda}(\bar{\nu^c}\sigma_{\mu\nu}P_L\nu)Z'^{\mu\nu}$	$c_l^{(9)}/\Lambda \lesssim 3.8\times10^{-3}\,\mathrm{GeV}^{-1}$ for $m_{Z'} \sim 10\,\mathrm{MeV}$	favoured[b]
IV	$\frac{c_l^{(10)}}{\Lambda^2}\bar{L}F_R\Phi\|H\|^2 + C_L\bar{L}F_R\Phi$	See fermionic case for renormalisable interactions	disfavoured

$Z \to inv$, LEP monophoton+$\not{E}_T$, $Z \to \mu^+\mu^-$, $Z \to \tau^+\tau^-$ and $(g-2)_{e,\mu}$.

[b]Favoured if $0.08\,\mathrm{eV} \lesssim m_{\mathrm{DM}} \lesssim 0.5\,\mathrm{eV}$ for $m_{Z'} \sim 10\,\mathrm{MeV}$ and $E_\nu \sim 1$ PeV

ν-DM renormalisable interactions

S. Pandey, S. Karmakar and S. Rakshit,
JHEP 1901(2019) 095



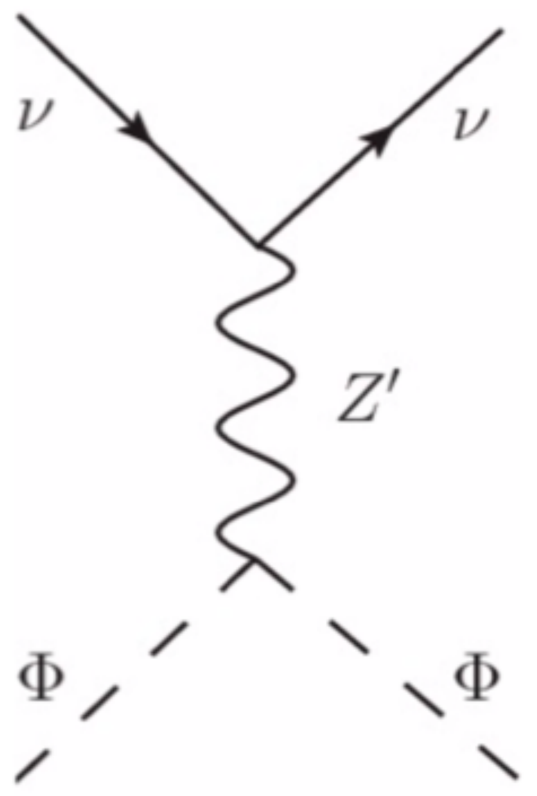
Mediator	Interaction	Constraints	Remarks
Fermion	$(C_L \bar{L} F_R + C_R \bar{l}_R F_L)\Phi + h.c.$	$m_F \gtrsim 100\,\text{GeV},\ m_{\text{DM}} \gtrsim 10^{-21}\,\text{eV}$, $C_L C_R \lesssim \{2.5, 0.5\} \times 10^{-5}$ for e and μ	disfavoured
Scalar	$f_l \bar{L}^c L \Delta + g_\Delta \Phi^* \Phi \lvert\Delta\rvert^2$	$m_\nu \sim f_l v_\Delta \lesssim 0.1\,\text{eV},\ g_\Delta \sim v_\Delta^2 / m_{\text{DM}}^2$	disfavoured
Vector	$f_l' \bar{L} \gamma^\mu P_L L Z_\mu' + i g' (\Phi^* \partial^\mu \Phi - \Phi \partial^\mu \Phi^*) Z_\mu'$	$[f_e, f_\mu, f_\tau] \lesssim [10^{-5}, 10^{-6}, 0.02]$ for $m_{Z'} \sim 10\,\text{MeV}$	favoured only for ν_τ

$Z \to inv$, LEP monophoton$+\not{E}_T$, $Z \to \mu^+\mu^-$, $Z \to \tau^+\tau^-$ and $(g-2)_{e,\mu}$.

ν-oscillation with ν-DM interactions

S.Karmakar, S.Pandey and SR, JHEP 10 (2021) 004

$$\mathcal{L} \supset ig'(\phi^* \partial_\mu \phi - \phi\, \partial_\mu \phi^*) Z'^\mu + f \bar{\nu}_\tau \gamma_\mu \nu_\tau Z'^\mu$$



Long-range forces:

Joshipura, Mohanty, PLB 584(2004)103

Agarwalla, Bustamante, PRL122(2019)061103

$U(1)_\tau$

$$V_{\tau\tau} = \frac{G'_F}{m_{\rm DM}} \rho(r) \qquad G'_F = g' f / m^2_{Z'}$$

Non-adiabatic flavour transitions help!

$$H_{\rm eff} = \frac{1}{2E(1+z)} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{12} & 0 \\ 0 & 0 & \Delta m^2_{32} \end{pmatrix} U^\dagger - \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & V_{\tau\tau}(r) \end{pmatrix}$$

Only $V_{\tau\tau} \neq 0$

For large E the first term vanishes

ν-$\bar{\nu}$-ϕ-ϕ^* ⟶ Constrained from corresponding charged lepton interactions

For vector mediated ν-DM interactions:

$\epsilon_{ee} \lesssim 10^{-38}\,\mathrm{eV}^{-2}$ ⟶ Avoids anomalous energy loss in sun

$\epsilon_{\mu\mu} \lesssim 1.5 \times 10^{-26}\,\mathrm{eV}^{-2}$ ⟶ Z' search at LHC

$\epsilon_{\mu\tau} \lesssim 10^{-31}\,\mathrm{eV}^{-2}$ ⟶ flavour violating charged lepton decays

$\epsilon_{\mu e} \lesssim 10^{-40}\,\mathrm{eV}^{-2}$ ⟶ flavour violating charged lepton decays

$\epsilon_{\tau e} \lesssim 4 \times 10^{-32}\,\mathrm{eV}^{-2}$ ⟶ flavour violating charged lepton decays

$\epsilon_{\tau\tau} \leqslant 1.3 \times 10^{-20}\,\mathrm{eV}^{-2}$ ⟶ partial Z decay width

For refs. see S.Karmakar, S.Pandey and SR, JHEP 10 (2021) 004

$$\theta_{12} = 33.8^\circ,\ \theta_{23} = 48.6^\circ,\ \theta_{13} = 8.6^\circ,\ \delta_{\rm CP} = 1.22\pi\ \text{rad}$$

$$\Delta m^2_{32} = m^2_3 - m^2_2 = 2.53 \times 10^{-3}\,\text{eV}^2$$

$$\Delta m^2_{21} = m^2_2 - m^2_1 = 7.39 \times 10^{-5}\,\text{eV}^2$$

JHEP 01 (2019) 106
http://www.nu-fit.org/

$$\sin 2\theta^M_{13} = \Delta m^2_{31} \sin 2\theta_{13} / \left[(2E(1+z)V_{\tau\tau} - \Delta m^2_{31} \cos 2\theta_{13})^2 + (\Delta m^2_{31} \sin 2\theta_{13})^2 \right]^{1/2}$$

Very large E leads to vanishing mixing angles

$$2E^R_{ij}(1+z)V_{\tau\tau} = \Delta m^2_{ij} \cos 2\theta_{ij}$$ $\longrightarrow$ Resonance condition

θ_{23} lies in the 2nd octant $\implies$ resonance condition is satisfied for $V_{\tau\tau} < 0$ for $ij = 32$

θ_{13} lies in the 1st octant $\implies$ resonance condition is satisfied for $V_{\tau\tau} > 0$ for $ij = 31$

At $E = 1$ PeV

for $V_{\tau\tau} > 0, \gamma_{31} \sim 1$ is obtained for $a \sim 10^{-3}$ pc.

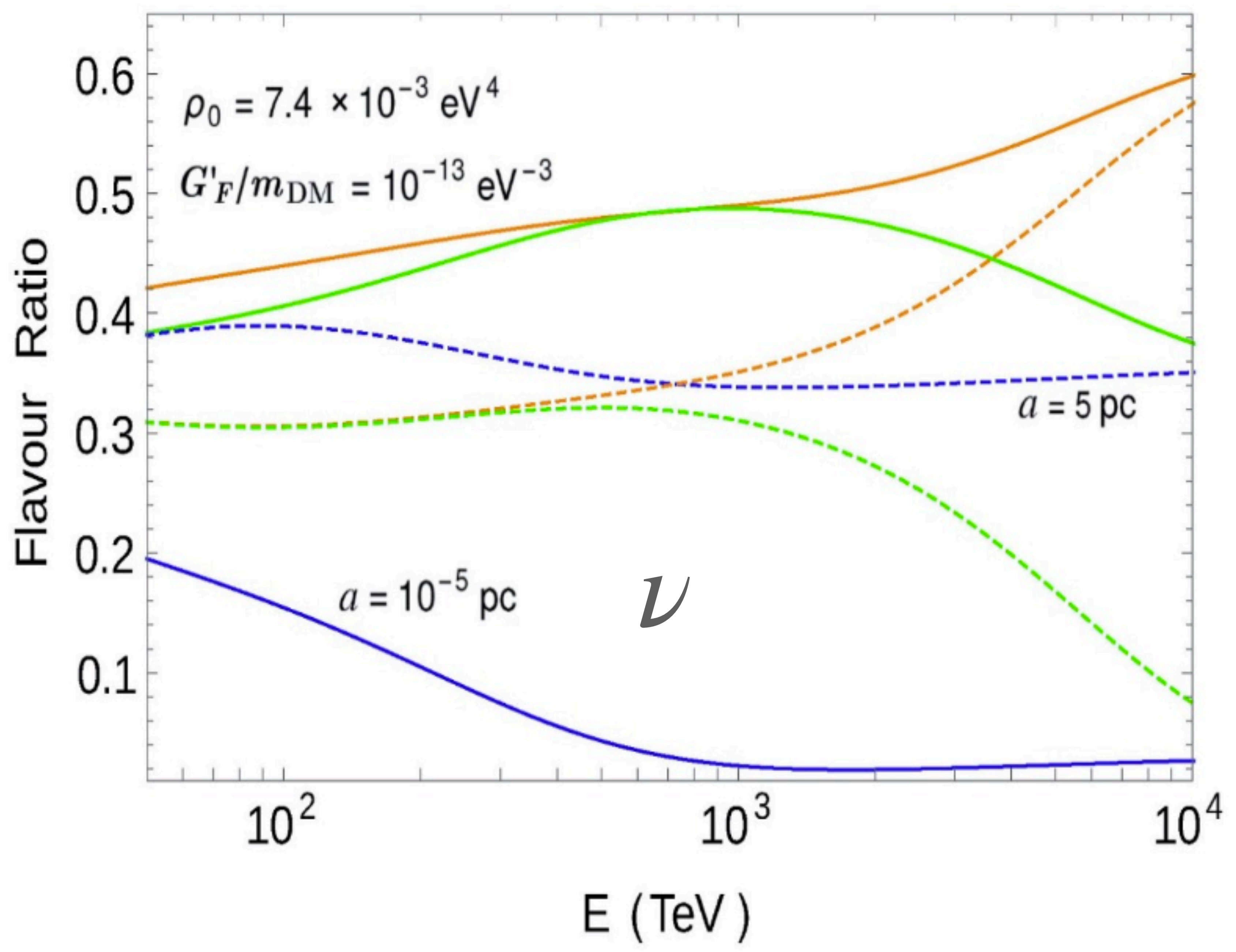
for $V_{\tau\tau} < 0, \gamma_{32} \sim 1$ is obtained for $a \sim 10^{-5}$ pc.

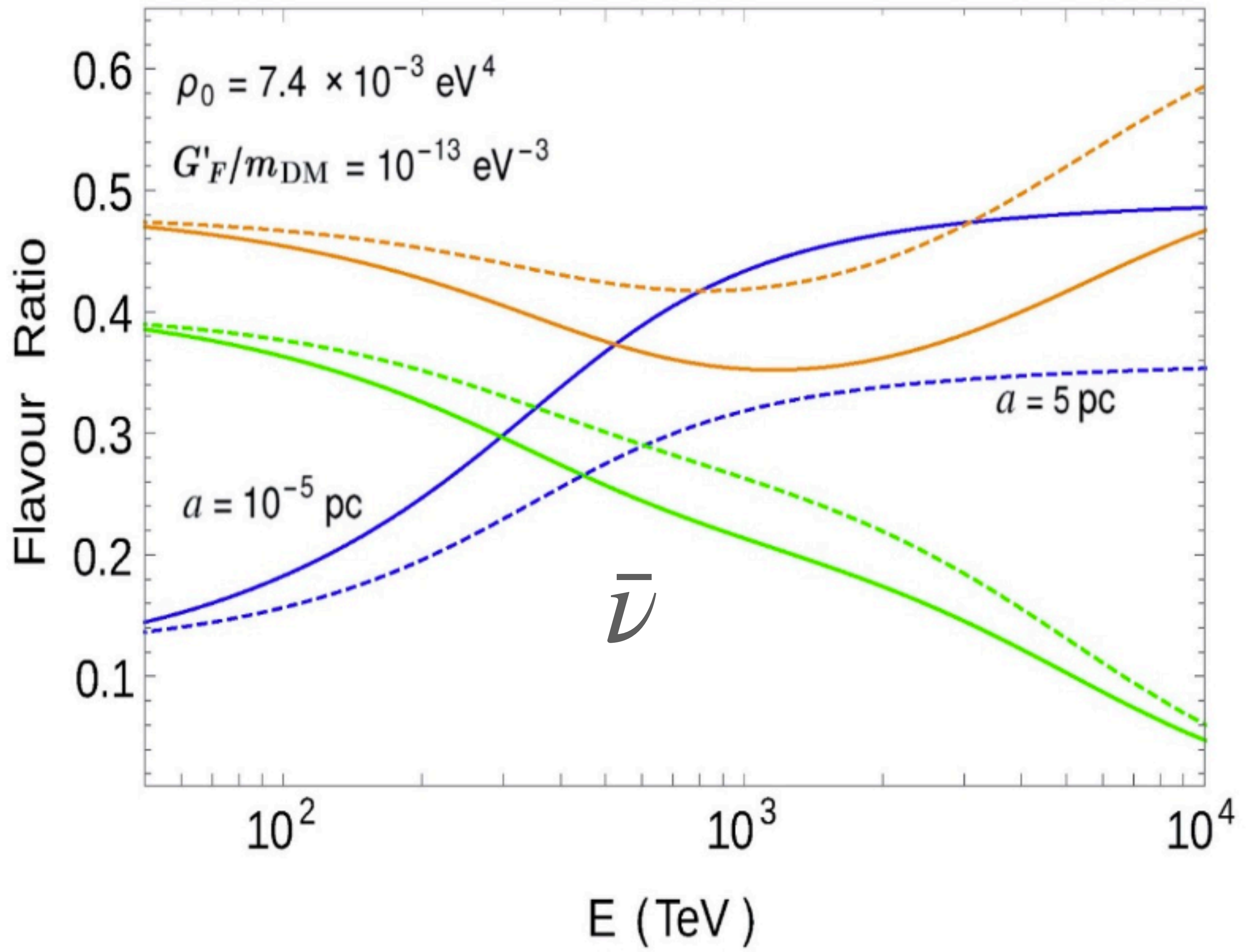
$$\gamma_{ij}^R = \frac{\Delta m_{ij}^2 \sin^2 2\theta_{ij}}{2E(1+z)\cos 2\theta_{ij}\, |\mathrm{d}\ln\rho/\mathrm{d}r|_R}$$

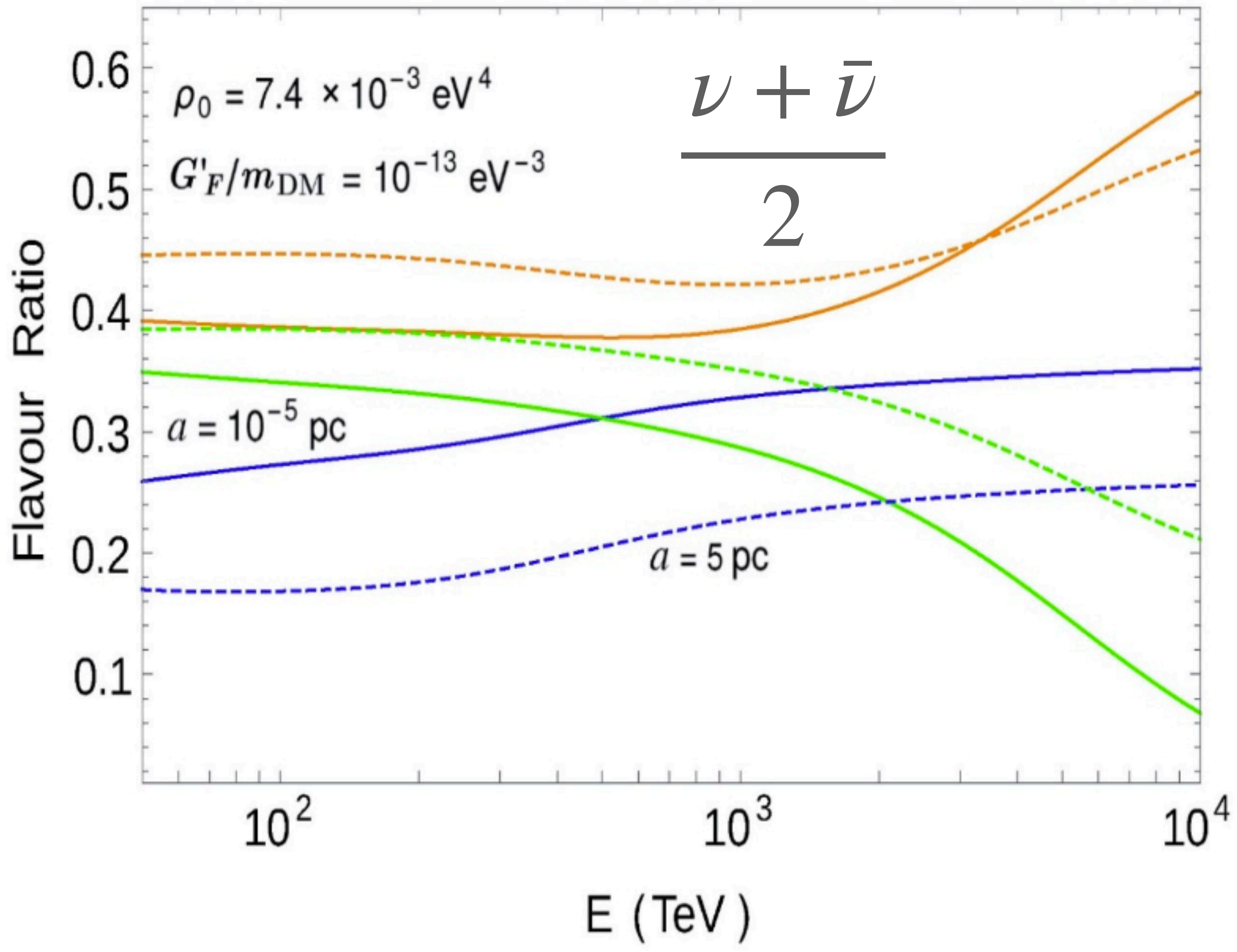
For lower energies, non-adiabaticity is achieved for lower values of a.

We take $V_{\tau\tau} > 0$ for neutrinos and $V_{\tau\tau} < 0$ for anti-neutrinos

Depending on the various parameters at different energies, adiabatic or non-adiabatic flavour transitions are possible.







Energy dependence of flavour ratios

Source at $z = 2$

{blue, orange, green} $\longrightarrow \{e, \mu, \tau\}$

solid: non-adiabatic ($a = 10^{-5}$pc)

dashed: adiabatic ($a = 5$pc)

Neutrino flavour distinction at IceCube

Track to shower ratio

$$\frac{N_{\rm track}}{N_{\rm shower}} = \frac{0.8A_\mu f_\mu^D + 0.13A_\tau f_\tau^D}{A_e f_e^D + 0.2A_\mu f_\mu^D + 0.87A_\tau f_\tau^D}$$

Track to shower ratio A_l is the effective area for detecting ν_l

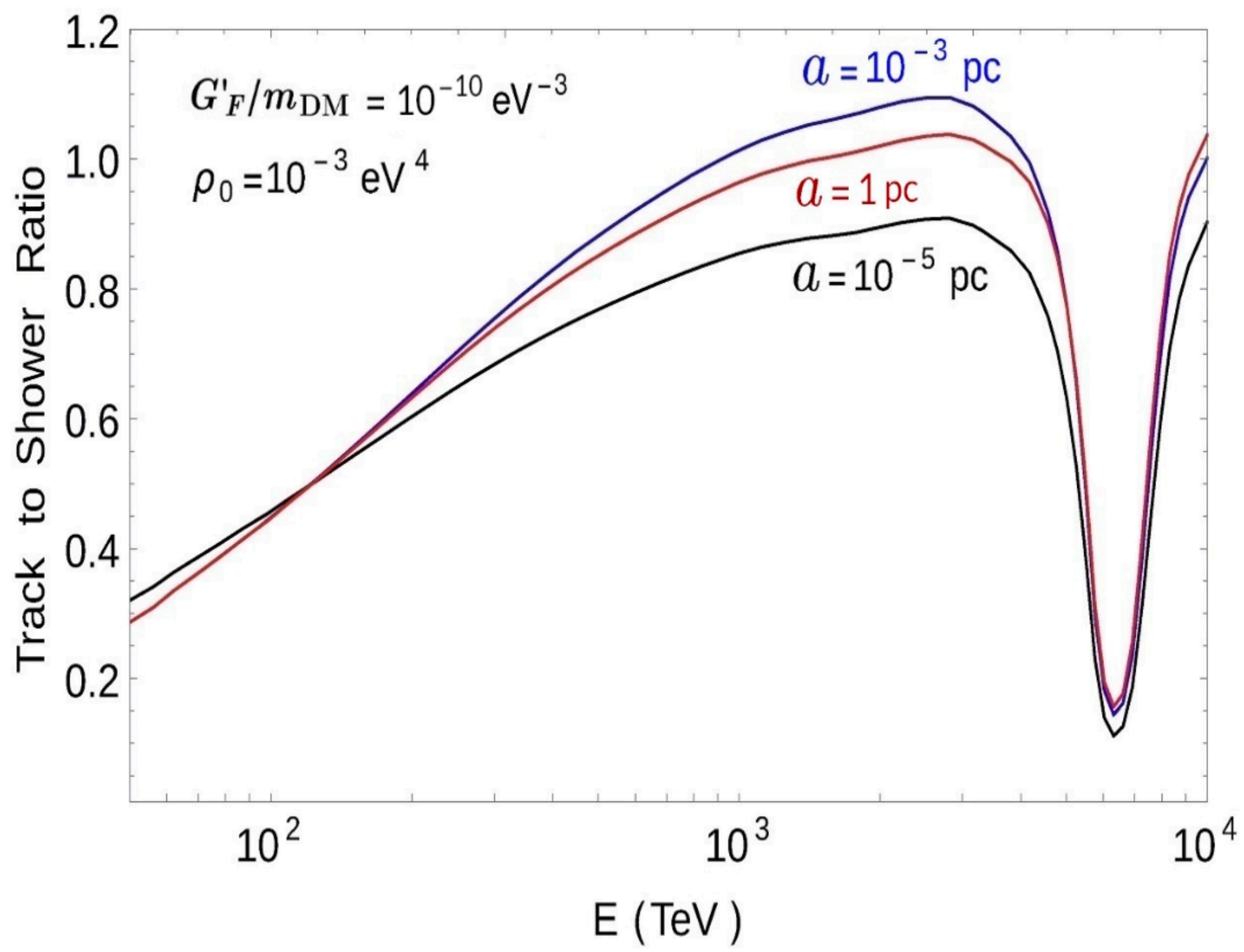
Probabilities of obtaining a track from a ν_μ or ν_τ are 0.8 and 0.13 respectively

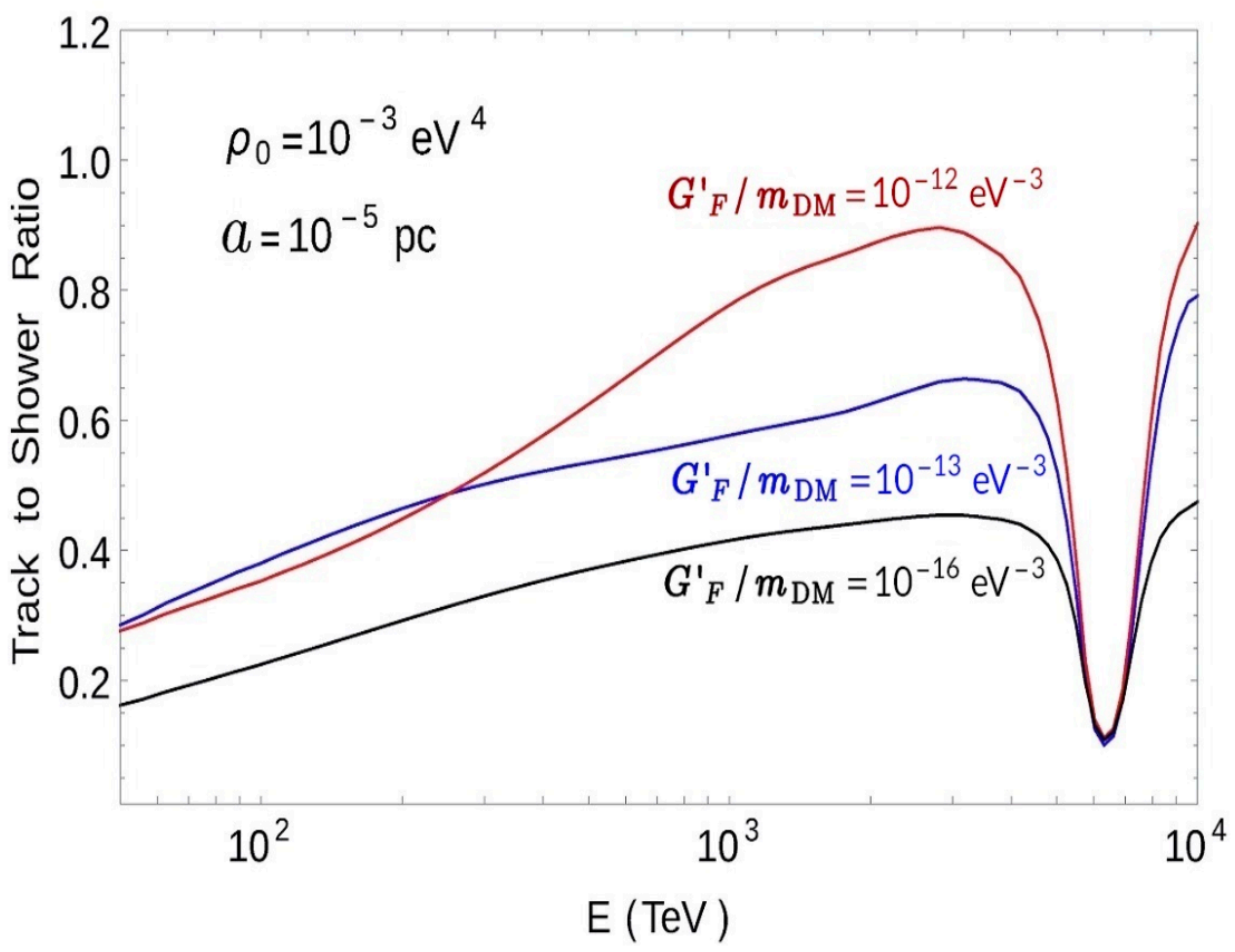
For E > 1 PeV, ν_τ produces distinguishable signatures: double-bang / lollipop

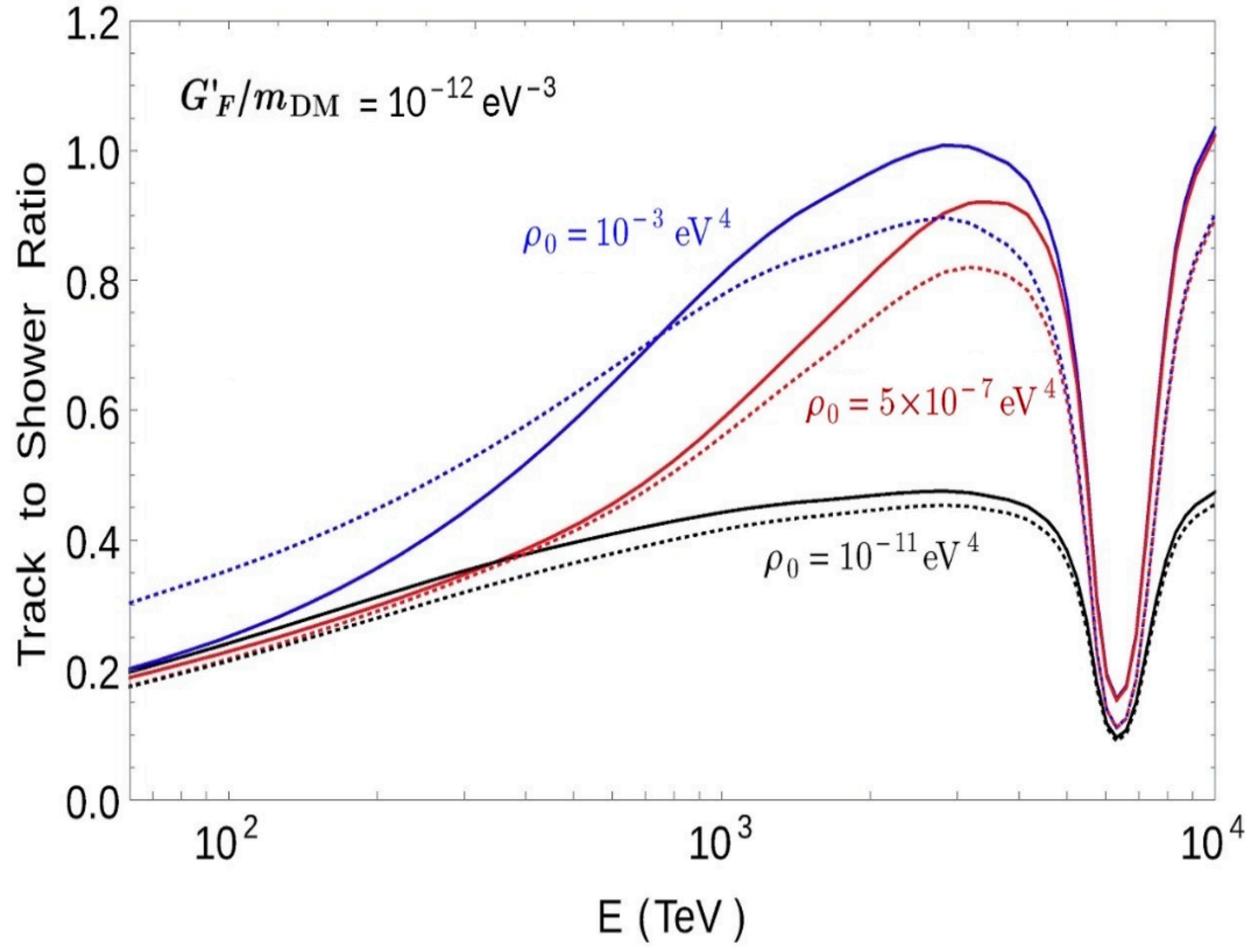
Can we distinguish between the electromagnetic shower from ν_e vs. hadronic shower from ν_τ?

Difficult at lower energies ⟶ Pion and neutron echos help in TeV-PeV range!

Li, Bustamante, Beacom, PRL122(2019)151101







Sensitivity of parameters: $\{a, \rho_0, G'_F/m_{\mathrm{DM}}\}$

Source at $z = 2$

(left) solid: adiabatic ($a = 1$pc)

(left) dotted: non-adiabatic ($a = 10^{-5}$pc)

Outlook

- At present one integrates over energy to plot the flavour ratio. Consistent with 1:1:1. Poor statistics although
- As the statistics improves, the energy dependence of the detected flavour ratio would turn out to be a nice tool
- In addition to the neutrino spectrum, the energy dependence of the flavour ratio can help in neutrino astronomy
- By 2040, one expects that the flavour composition of the astrophysical sources would be revealed to within 6% (JCAP04(2021)054)
- Quite a few experiments are lined up!