Cutoff for Cosmic-ray Neutrino and Collider Signature with a Neutrino Portal Interaction

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Based on paper to appear in arXiv.
Partially based on arXiv:1706.07028

05/21/2018 @ 20th ISVHECRI,

Contents

1. Introduction

2. A Neutrino Portal Interaction

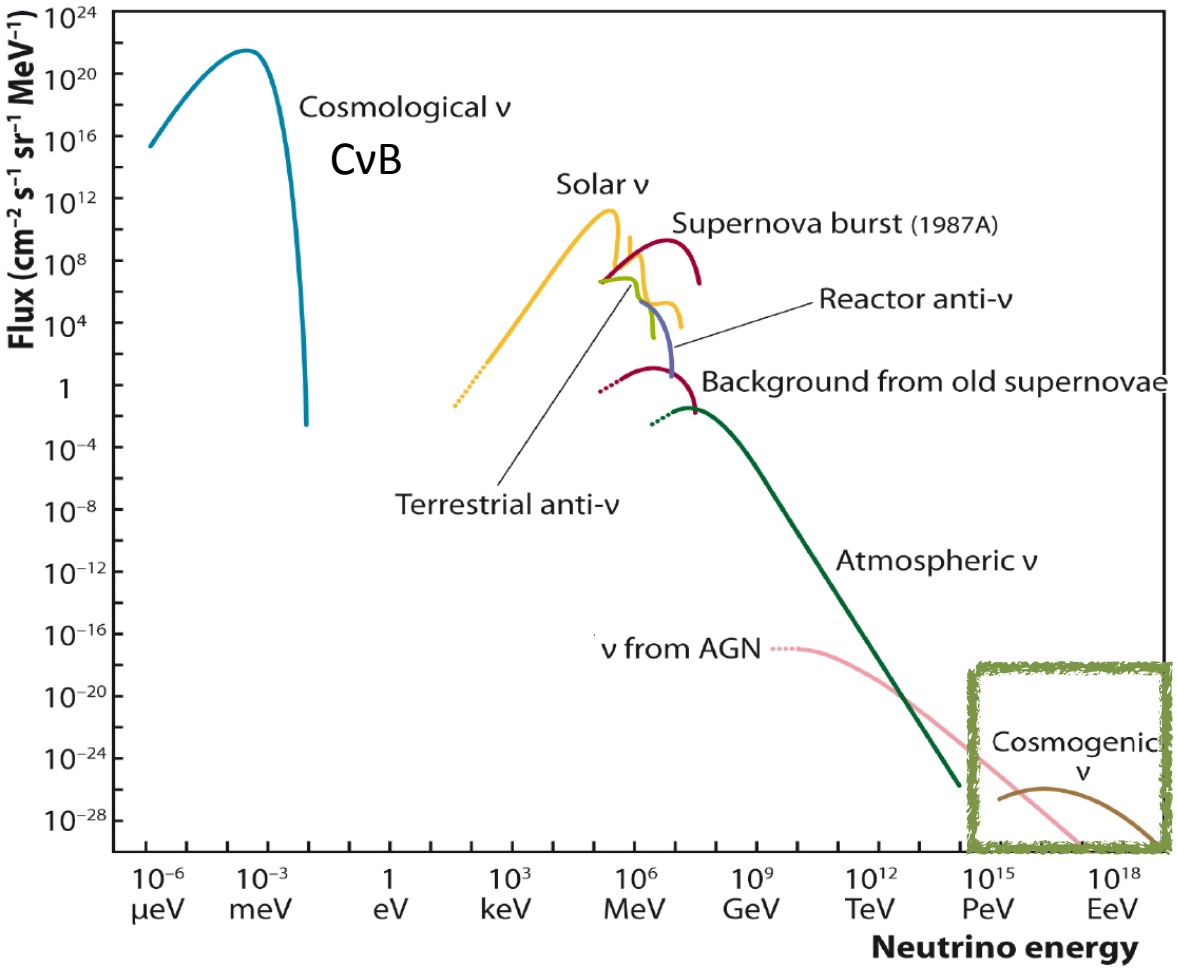
3. Collider Signature

4. Highly Boosted Dark Matter

5. Summary

1. Introduction

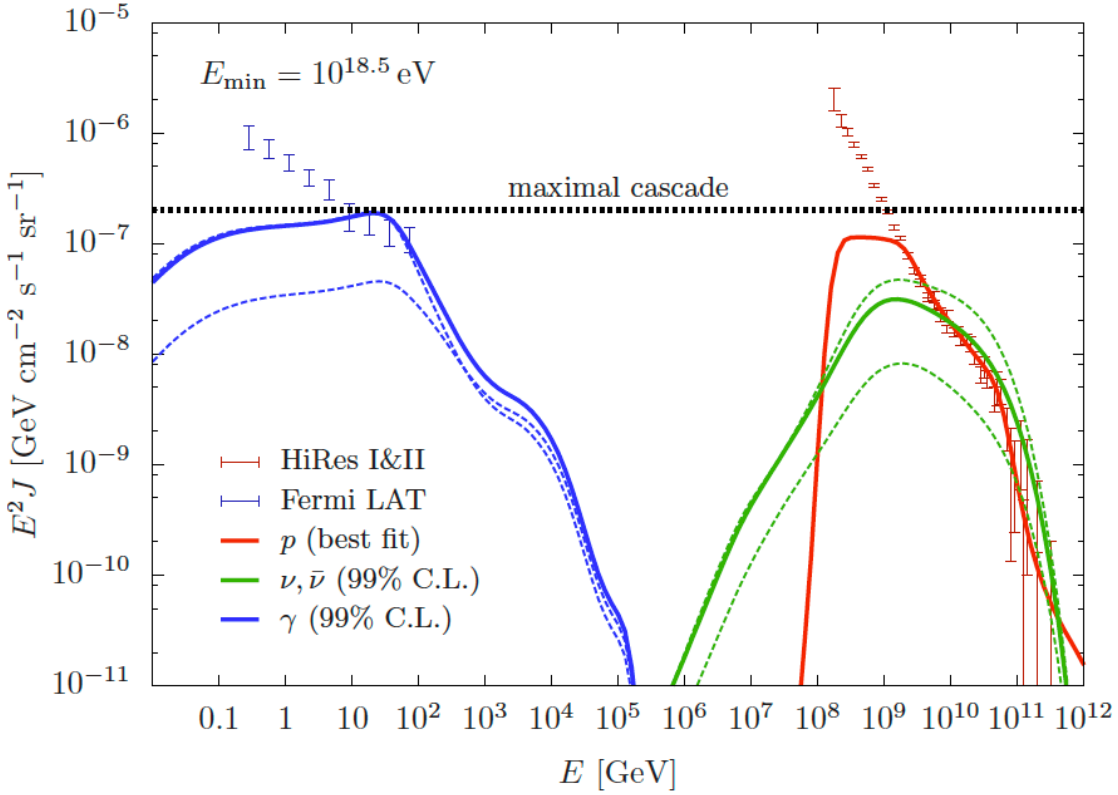
SM Neutrinos are produced from various phenomena,
and believed to be possible to propagate across the Universe.



Katz, Spiering, 1111.0507

Photo-Pion Production

$$p^{\mathrm{UHE}}\gamma^{\mathrm{CMB}} \rightarrow p\pi^0, n\pi^+ \qquad E_p > 10^{11}\,\mathrm{GeV}$$



HIRes Data for UHECR

Simulated Protons

Cosmogenic Neutrinos

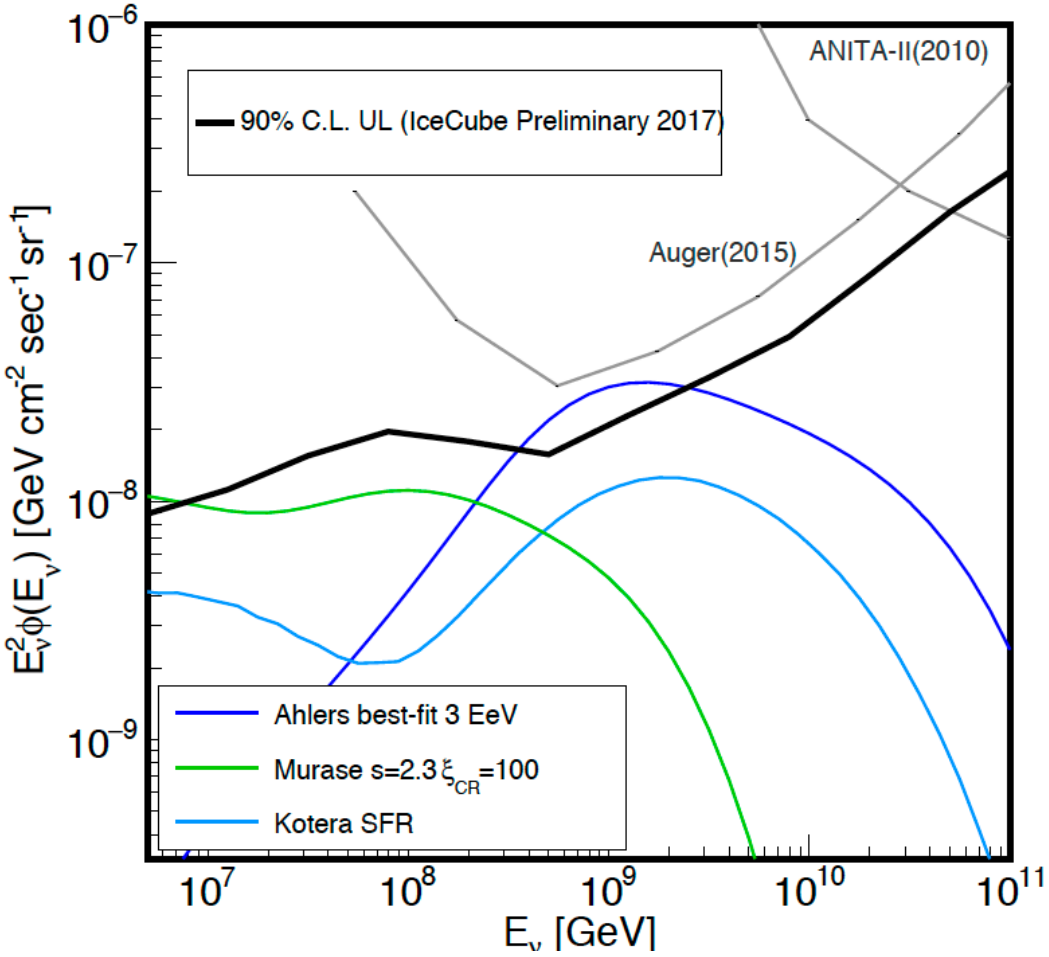
EeV Neutrinos predicted by the observed cut-off

M. Ahlers, et al,1005.2620

$$\pi^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$$: cosmogenic neutrinos

A “guaranteed” High energy neutrino flux.

Current Status



No event until now, some models are in tension with the non observation.

A hint to new physics?

Yoshida, Ishihara, 1710.01191 (Proceeding)

Why new physics explanation?

Neutrino sector:

*Origin of neutrino mass needs explanation.

*Right-handed neutrino may exist,
which can explain neutrino mass in various ways.

Yanagida, 1979; Gell-Mann et al., 1979; Minkowski, 1977; Mohapatra and Valle 1986; Malinsky et al., 2005; Ma, 0601225; etc

*Right-handed neutrino can couple to dark sector for dark matter : Neutrino Portal Dark Matter.

Kaplan et al., 0901.4117; Falkowski et al., 0908.1790; Bertoni et al., 1412.3113, etc

The Universe may be opaque for cosmogenic neutrino due to the interaction to dark sector.

What I will talk about

arXiv:1806.XXXX, arXiv:1706.07028

- Neutrino portal interaction:

  Dark sector for dark matter is connected with SM through right-handed neutrino.

- Cosmogenic neutrino flux gets suppressed

$$\nu\ /\overline{\nu}\ + \nu^{\mathrm{C}\nu\mathrm{B}} \rightarrow \text{Dark sector particles+...}$$

- Testable in colliders.
- Highly boosted dark matter is produced.

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2. A Dirac Neutrino Portal Interaction

SM (neutrino) sector

Dark Sector

Lepton number: ν_i, ν_{Ri}, ϕ_i are 1, ψ has 0.

At lepton number symmetric limit:

$$\delta\mathcal{L}_{\rm int} = -\sum_{i=e,\mu,\tau}\left(y_{Ri}H\overline{\nu}_{Ri}\hat{P}_L L_i + \tilde{y}_i\overline{\nu}_{Ri}\hat{P}_R\psi\phi_i\right) + \text{h.c.}$$

$$\delta\mathcal{L}_{\rm mass} = -\sum_{i=e,\mu,\tau}\left(m^2_{\phi ij}\phi^*_i\phi_j + \underbrace{M_{Rij}\overline{\nu}_{Ri}\nu_{Rj}}_{\text{Dirac mass}} + \frac{1}{2}M_\psi\overline{\psi}\psi\right) + \text{h.c.},$$

(and potential for scalars.)

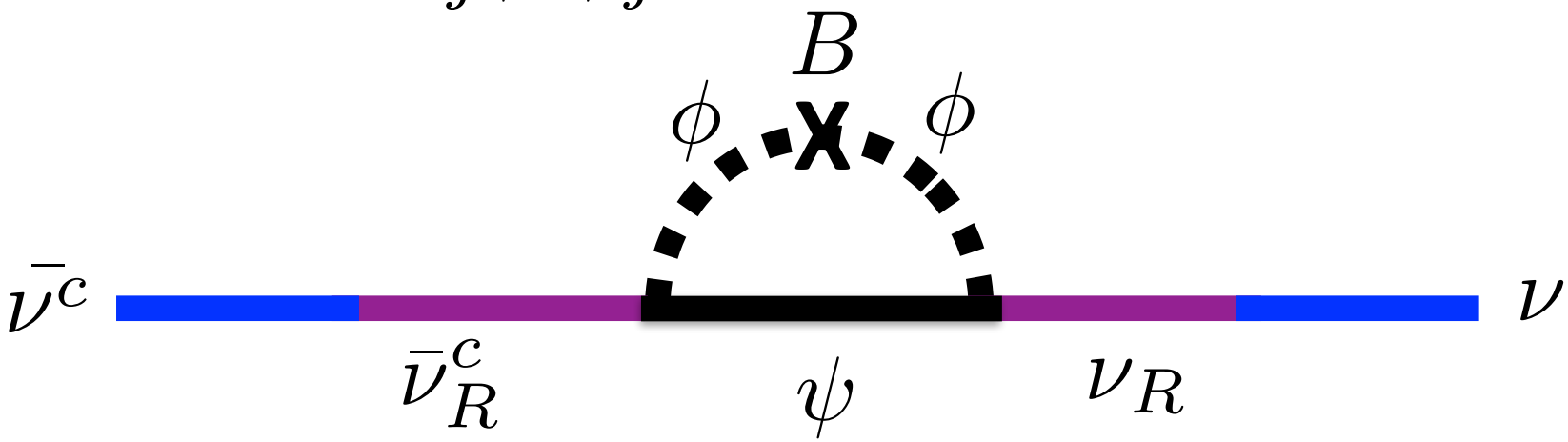
This model and similar model explain dark matter:

Kaplan et al., 0901.4117; Bertoni et al., 1412.3113; Escudero et al., 1607.02373 etc

Neutrino mass and Dark Matter

Soft breaking term of lepton number:

$$\delta\mathcal{L} = B_{ij}\phi_i\phi_j + \text{h.c.} \qquad U(1)_{\text{Lepton}} \to Z_2$$

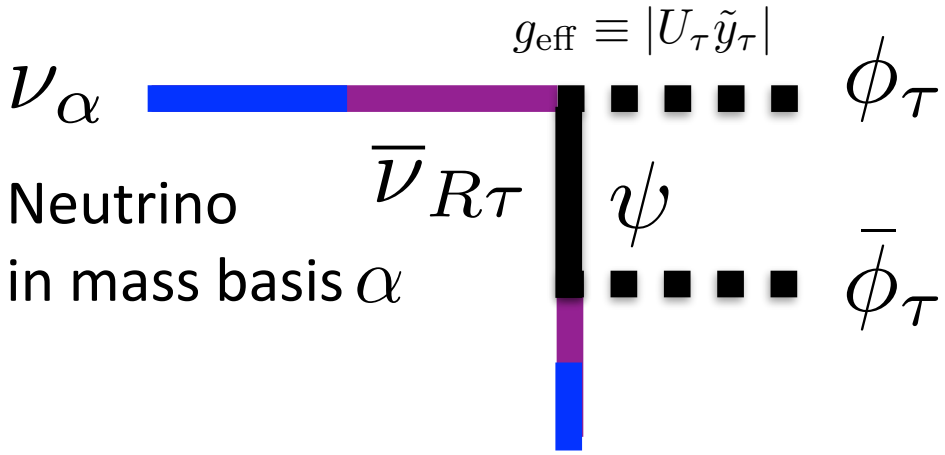


Alternatively, one can take inverse seesaw mechanism by introducing majorana mass term of right-handed neutrinos.
Mohapatra and Valle, 1986; Malinsky et al, 2005;
The following discussion does not change.

Lightest lepton number odd (even) scalar (fermion) becomes stable:
lightest of ψ, ϕ_i can be dark matter.

Suppression for CRNeutrino flux

For simplicity, focus on tau portal interaction and neglect the e and μ portals.
(The experimental constraints are severer for e and μ portals)



$$\left(\xrightarrow{\text{decay}} \text{dark sector particles} \right)$$
$$\left(\xrightarrow{\text{decay}} \text{dark sector particles} \right)$$

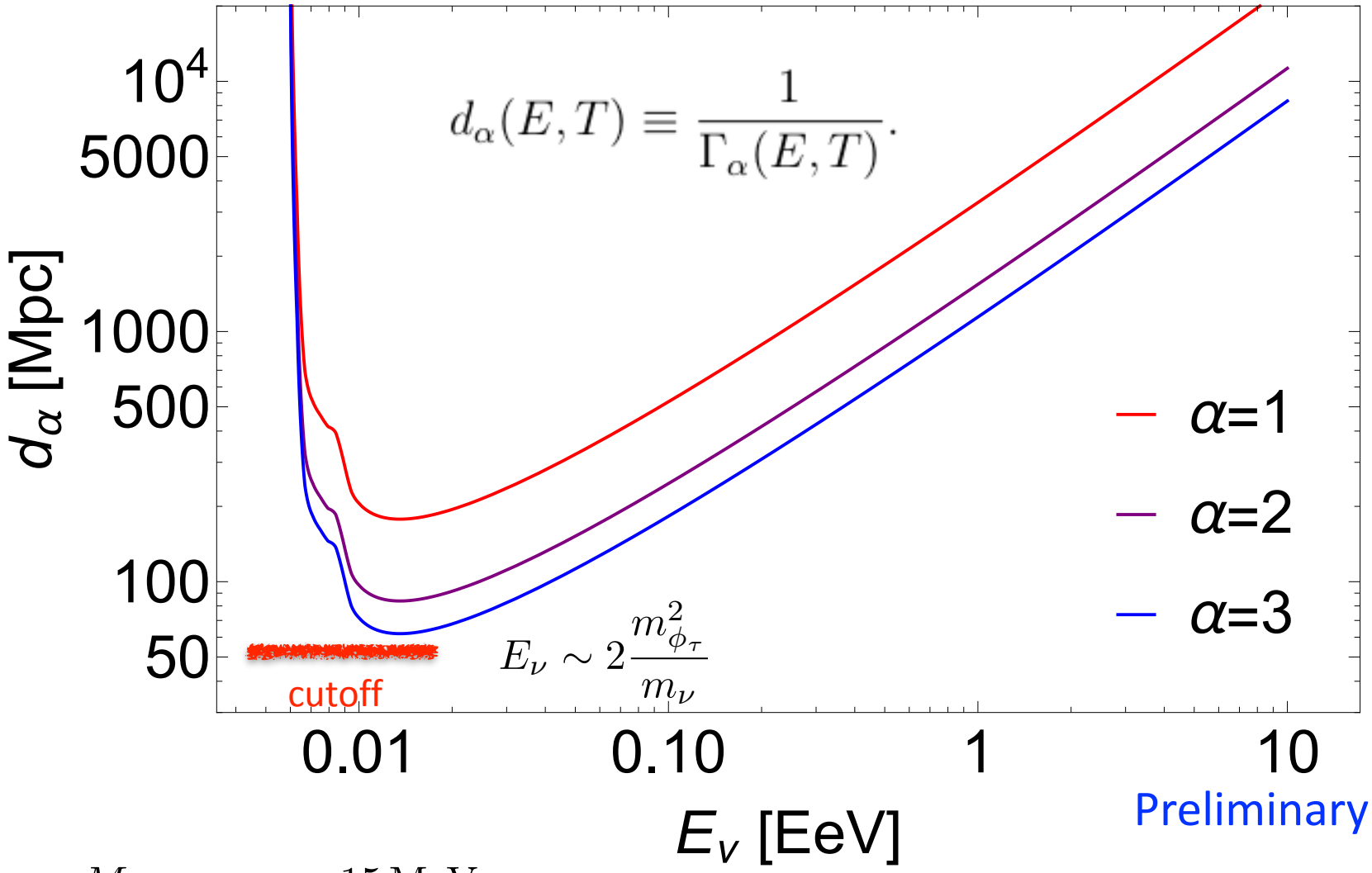
$$E_{\rm cm} \simeq \sqrt{2E_\nu m_\nu} \gtrsim 2m_{\phi_\tau}$$

Interaction rate:

$$\Gamma_\alpha(E_\nu, T_\nu) = \langle \sigma_\alpha v_{\rm rel} n_{\rm C\nu B} \rangle$$

$\nu_\alpha + \nu_{\rm C\nu B} \to 2\psi$ channel, etc. also included

Mean Free Path for Neutrinos



$M_\psi \simeq m_{\phi_\tau} = 15\,\mathrm{MeV}$

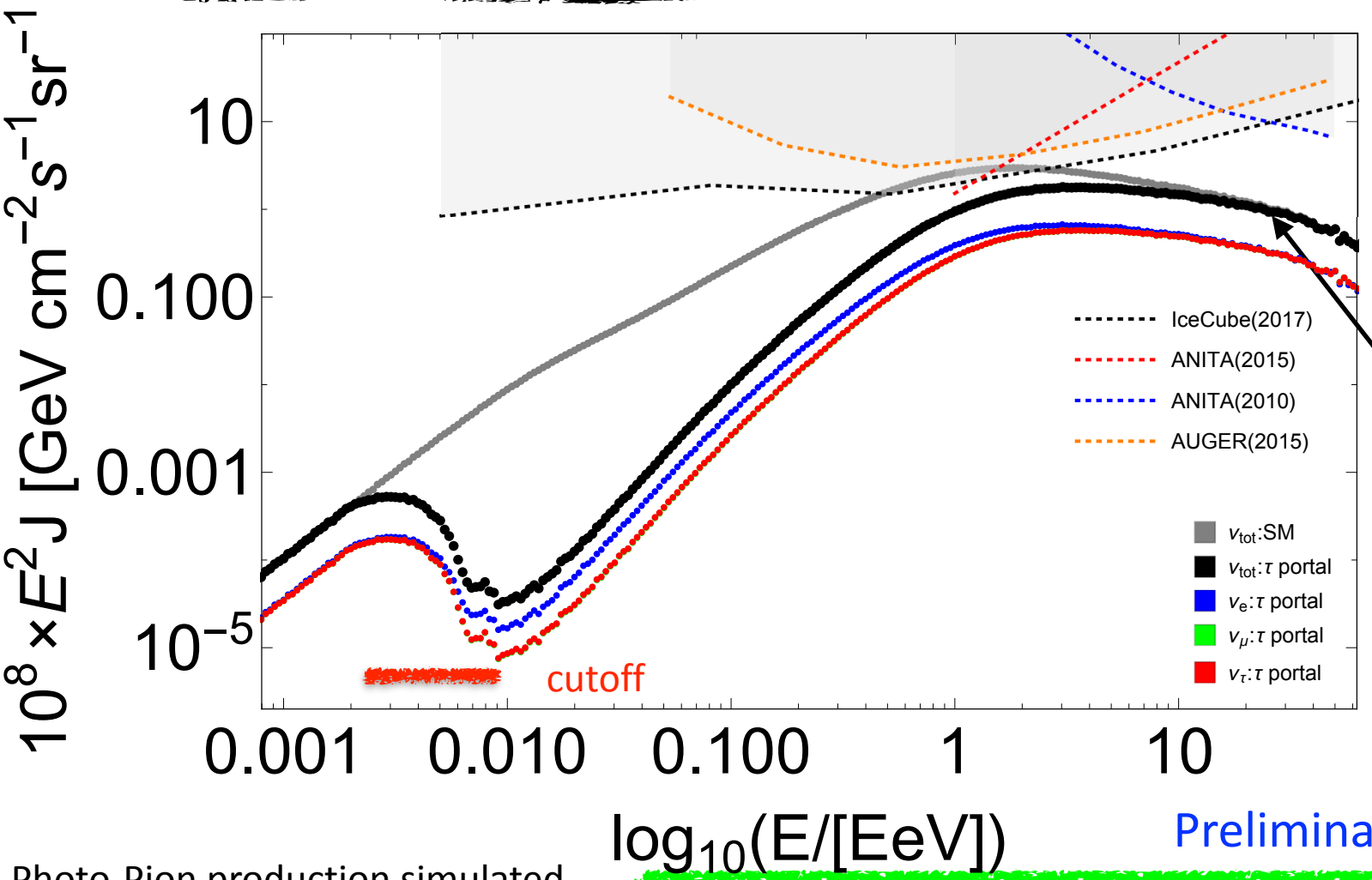
$g_{\mathrm{eff}} = 0.4$

normal mass ordering for neutrino

$\delta_{13} = -\pi/2 \qquad m_{\nu\mathrm{lightest}} = 0.05\,\mathrm{eV}$

Hereafter we will use the parameter set.

Cosmogenic Neutrino flux: $g_{\rm eff} = 0.4$



Neutrinos Reach the Earth

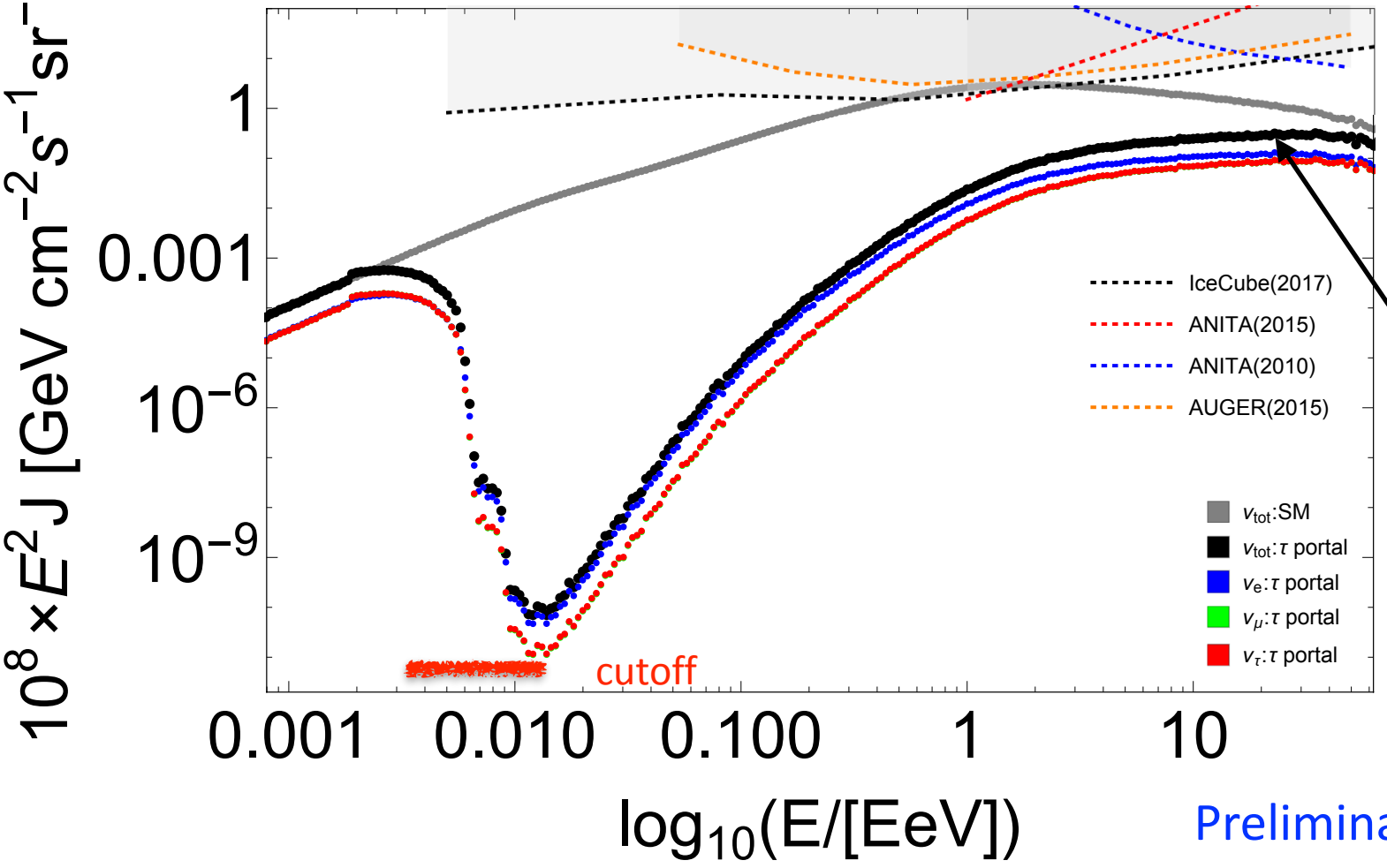
Preliminary

Photo-Pion production simulated from CRPropa 3 Alves Batista et al., 1603.07142;

Survivability:

$$R_\alpha(E_{\rm now}, z_s) = e^{-\int_0^{z_s} dz \left|\frac{dt}{dz}\right| \Gamma_\alpha(E_{\rm now}(1+z), T_\nu(1+z))}$$

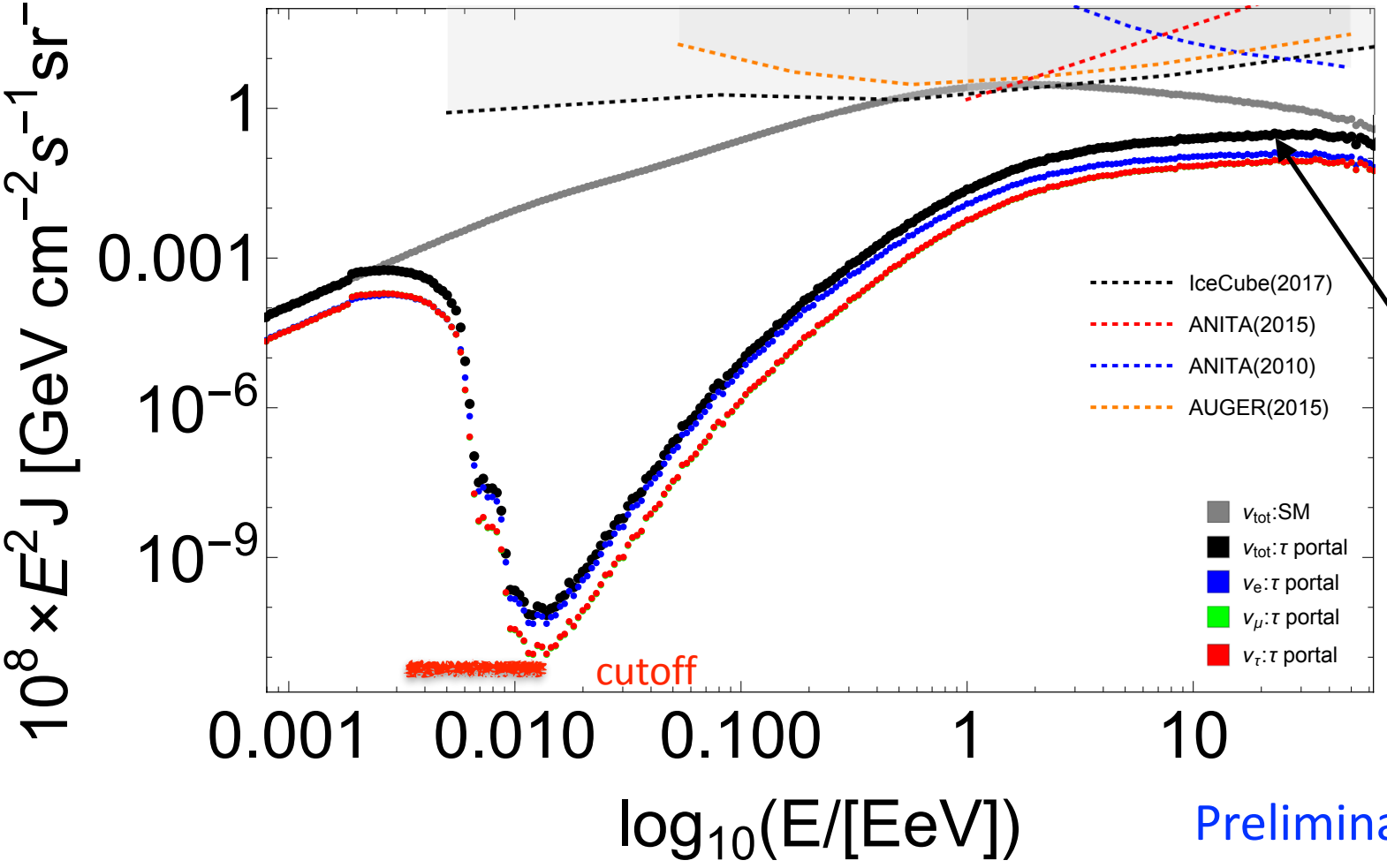
Cosmogenic Neutrino flux: $g_{\rm eff} = 1$



Neutrinos Reach the Earth

Preliminary

Cosmogenic Neutrino flux: $g_{\rm eff} = 1$



Neutrinos Reach the Earth

Preliminary

Neutrino flux can be suppressed above PeVs.

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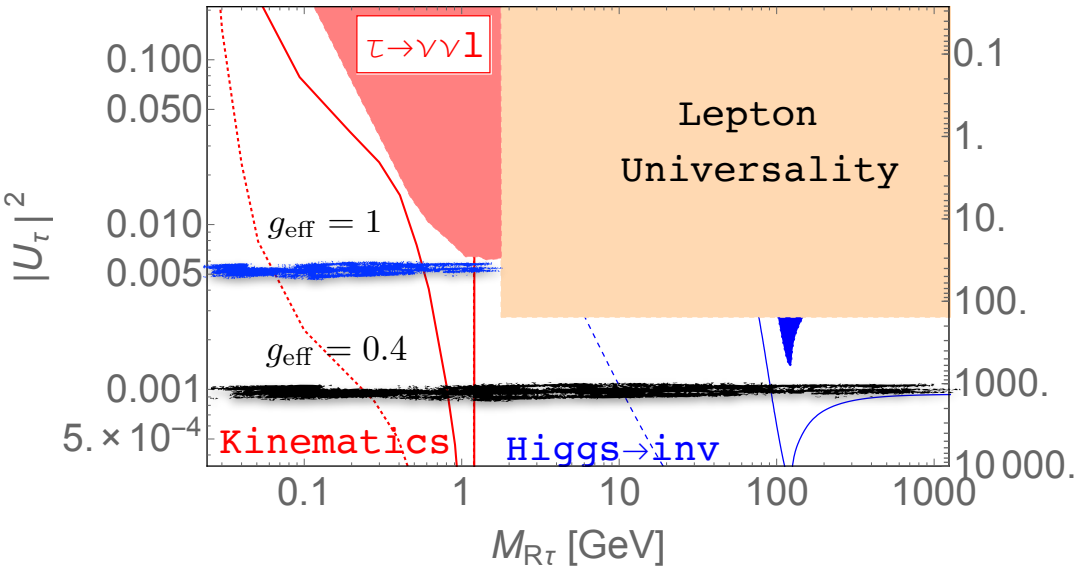
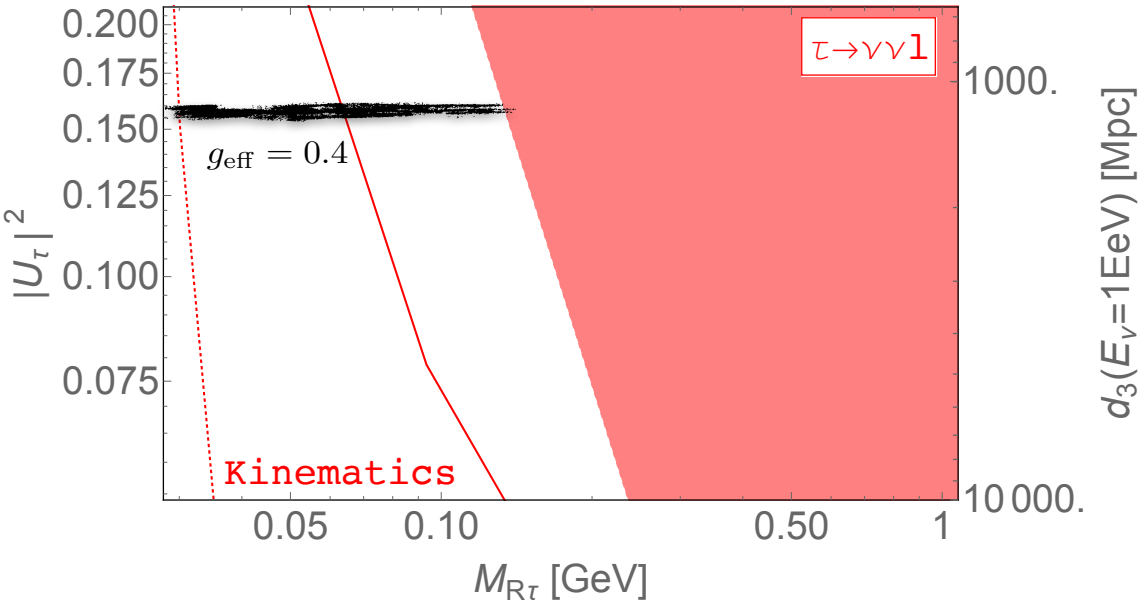
3. Collider Signature

Assumption:

$$M_{R\tau} > m_{\phi_\tau} + M_\psi$$

$$\tilde{y}_\tau = 4\pi$$



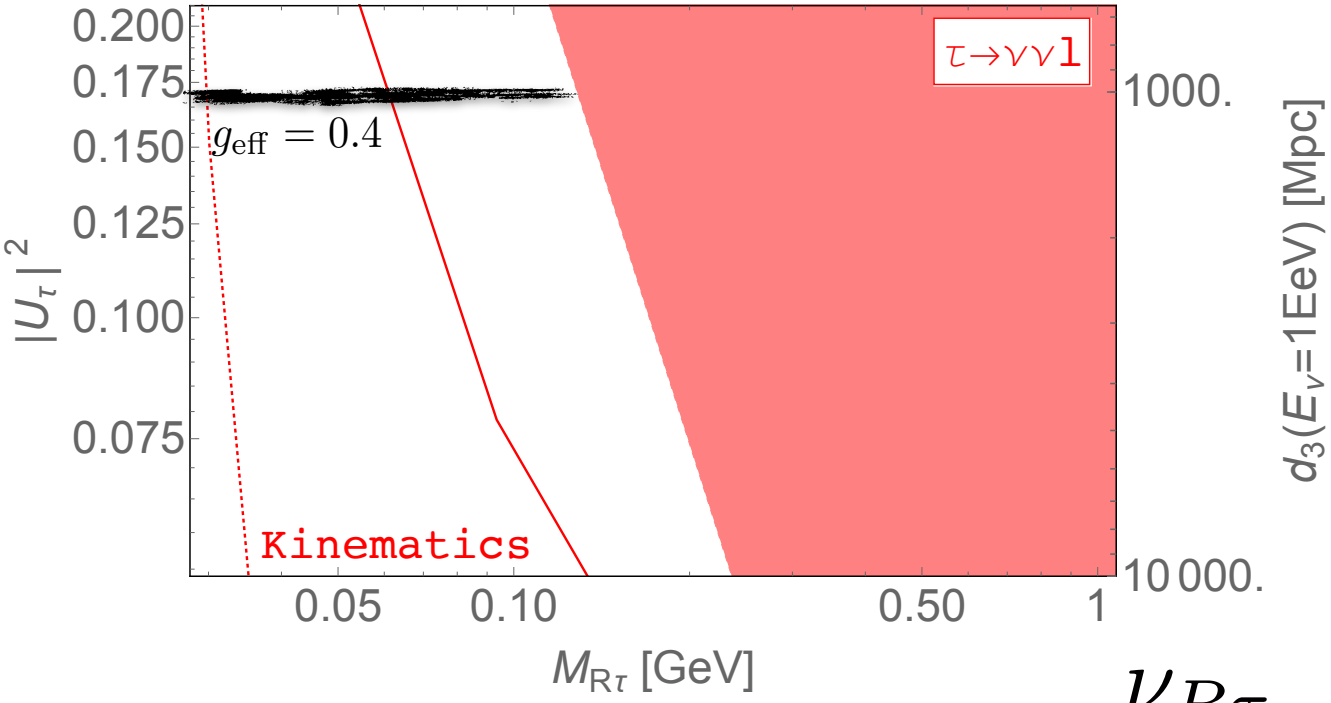


Preliminary

$$\tilde{y}_\tau = 1$$

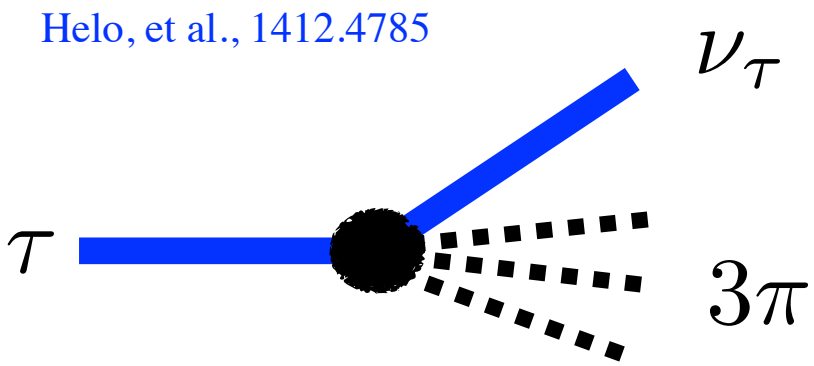
Kinematics of Tau Lepton Decay

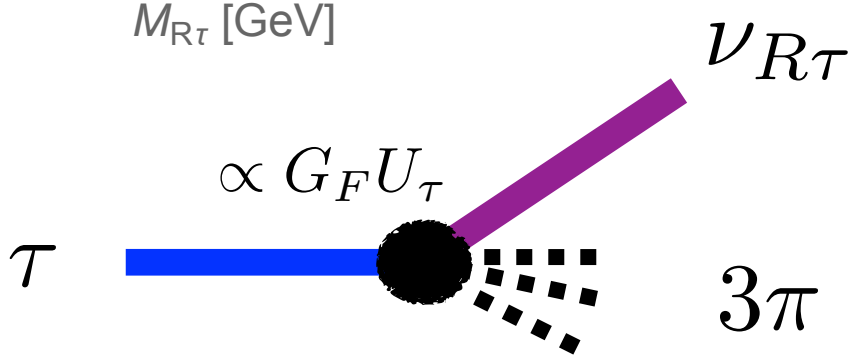
$\tilde{y}_\tau = 1$



Kobach, Dobbs, 1105.3019

Helo, et al., 1412.4785

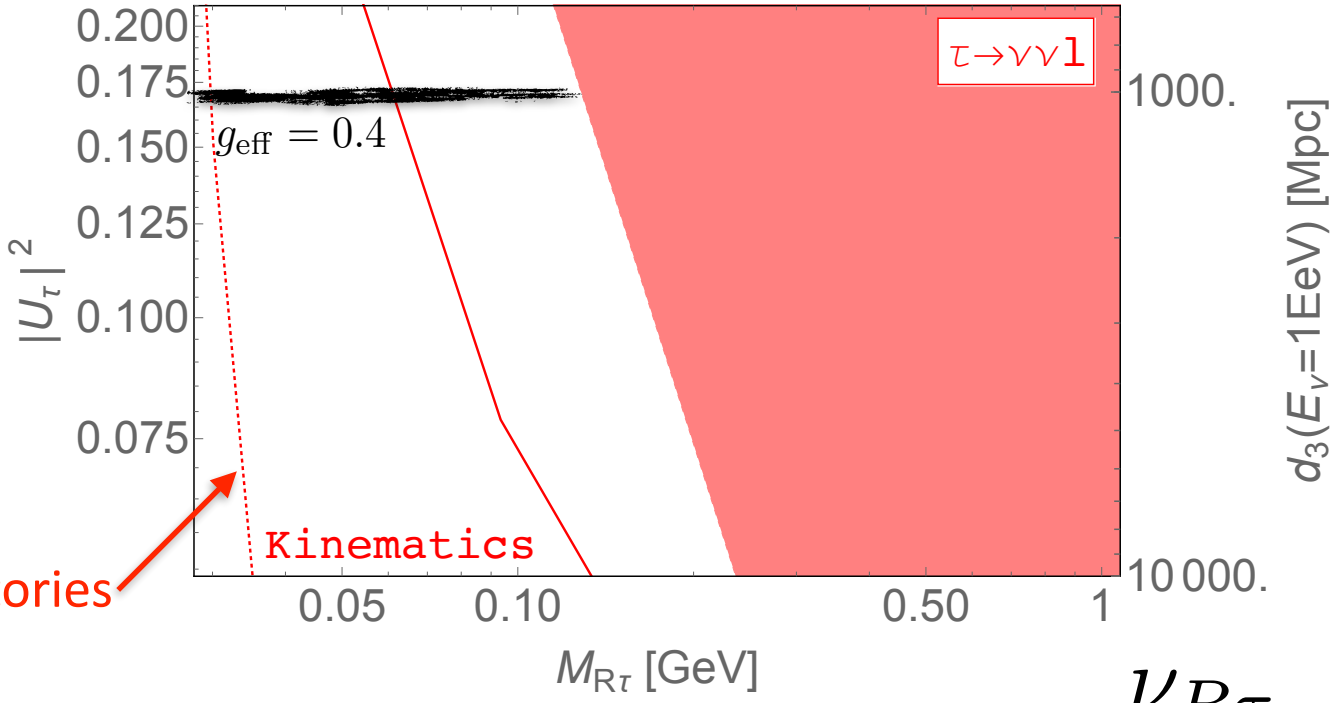




When $M_{R\tau} \lesssim m_\tau$, the latter introduces a non-trivial kinematical distribution for pions.

Kinematics of Tau Lepton Decay

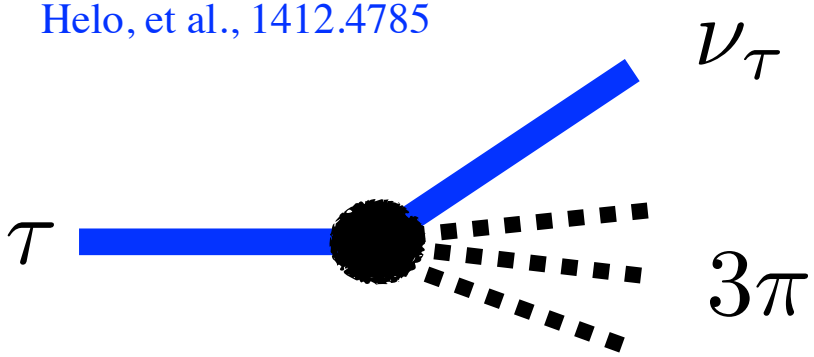
$\tilde{y}_\tau = 1$

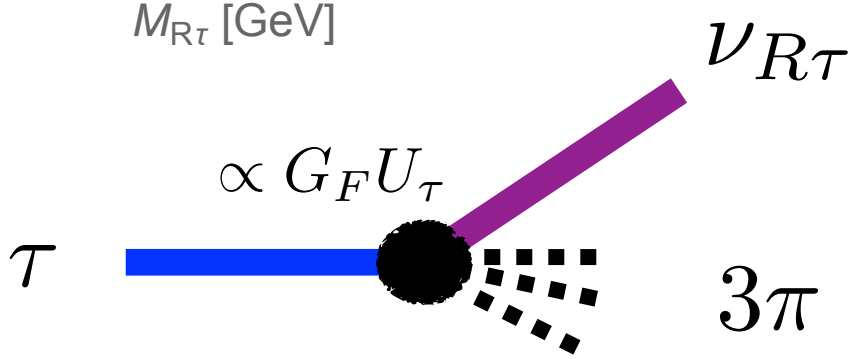


Kobach, Dobbs, 1105.3019

Future reach for B-factories

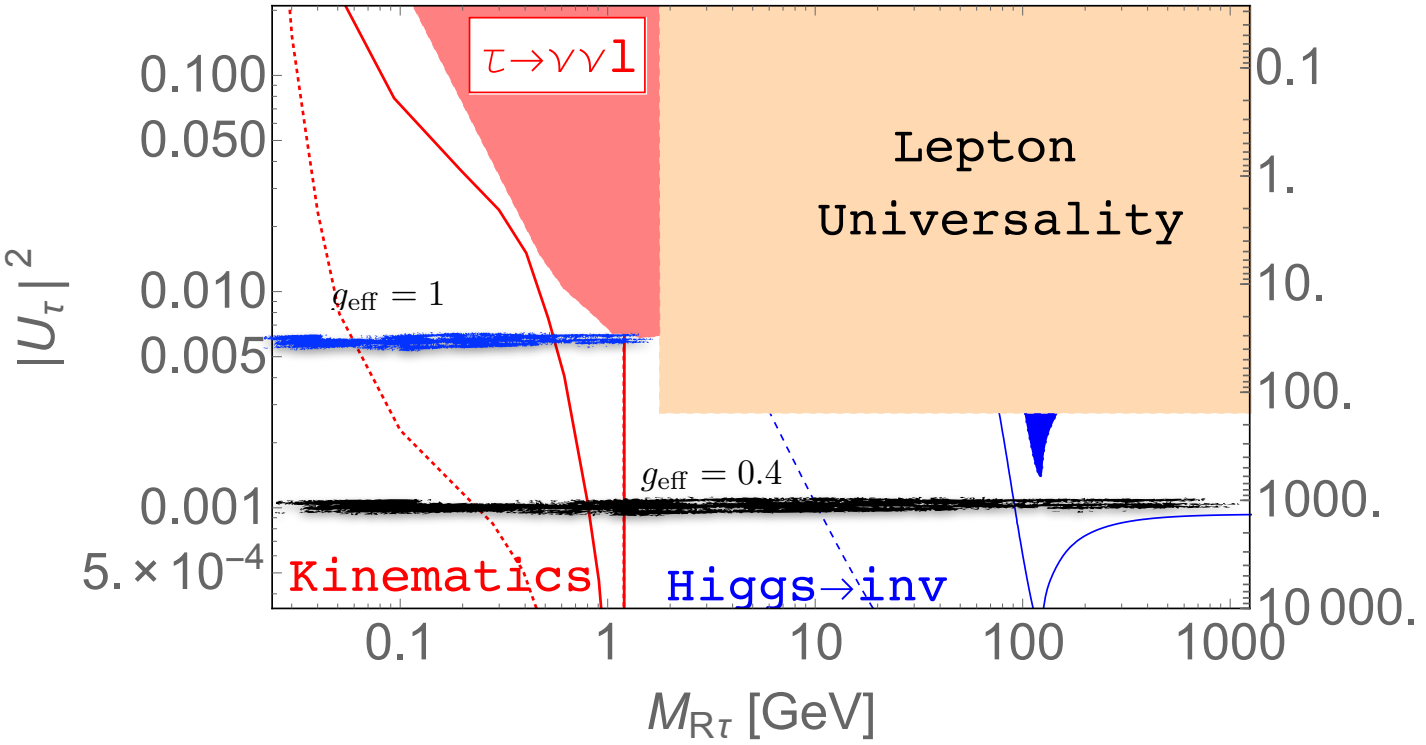
Helo, et al., 1412.4785





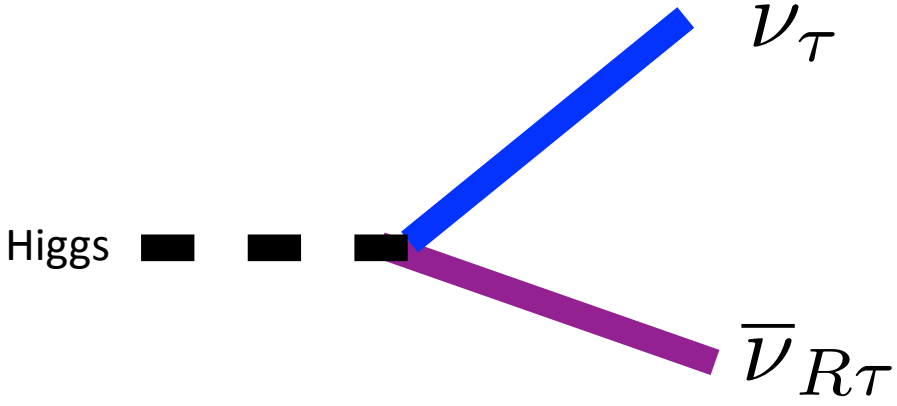
When $M_{R\tau} \lesssim m_\tau$, the latter introduces a non-trivial kinematical distribution for pions.

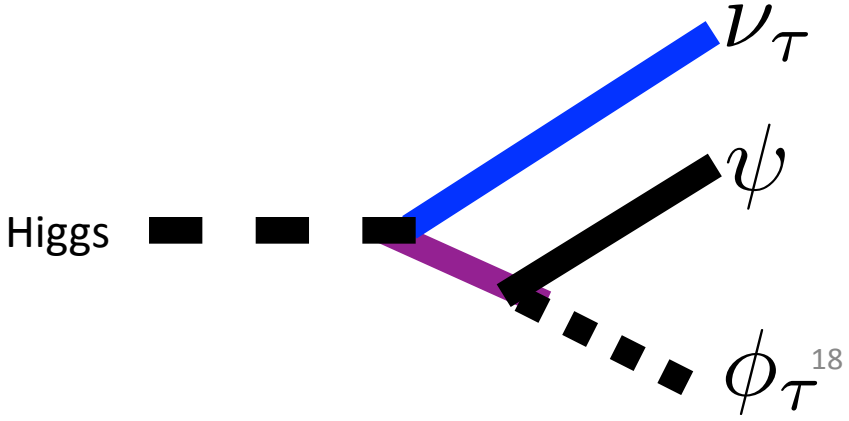
Higgs Invisible Decay



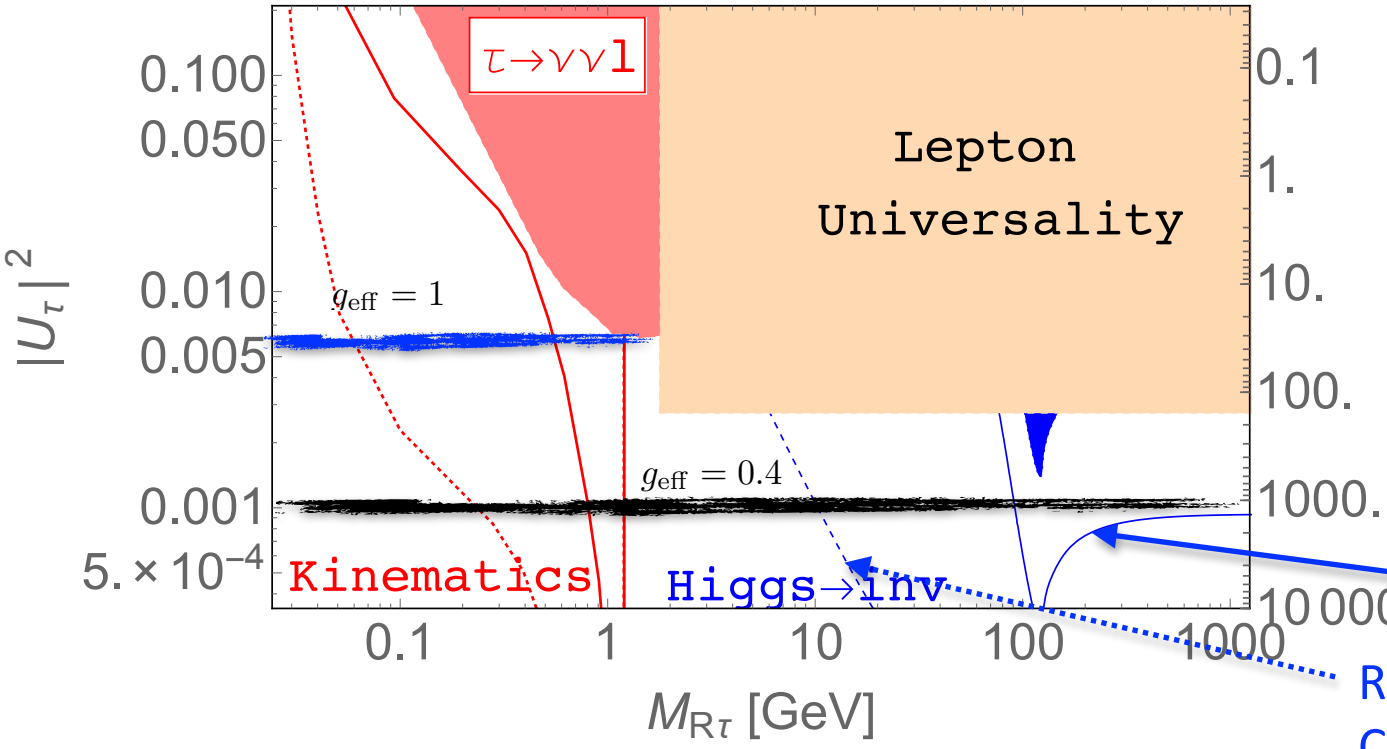
$$\tilde{y}_\tau = 4\pi$$

(Upper bound c.f. pions)





Higgs Invisible Decay



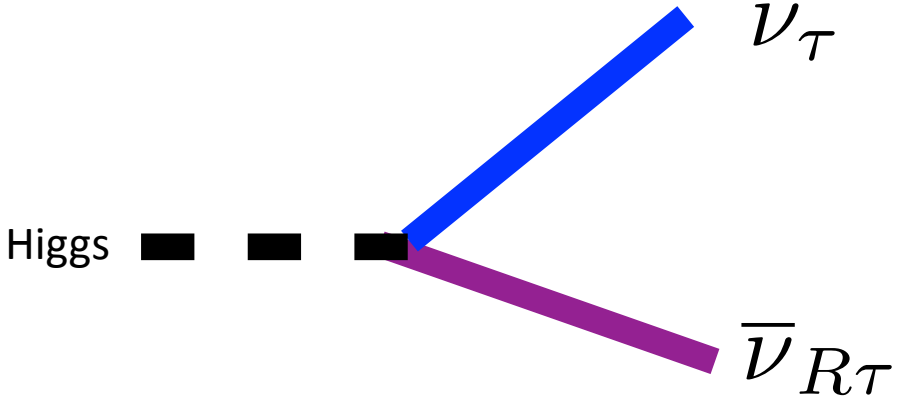
$\tilde{y}_\tau = 4\pi$

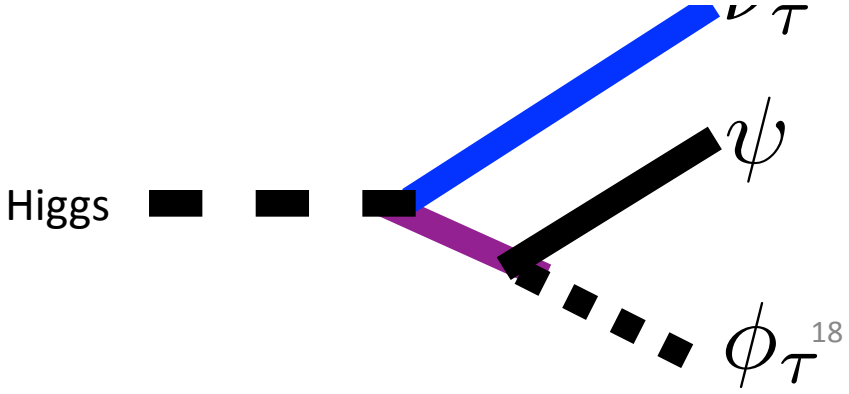
(Upper bound c.f. pions)

$\lambda_3(E_\nu=1\mathrm{EeV})$ [Mpc]

Future reach of LHC

Reach of CEPC,FCC-ee, ILC, etc.





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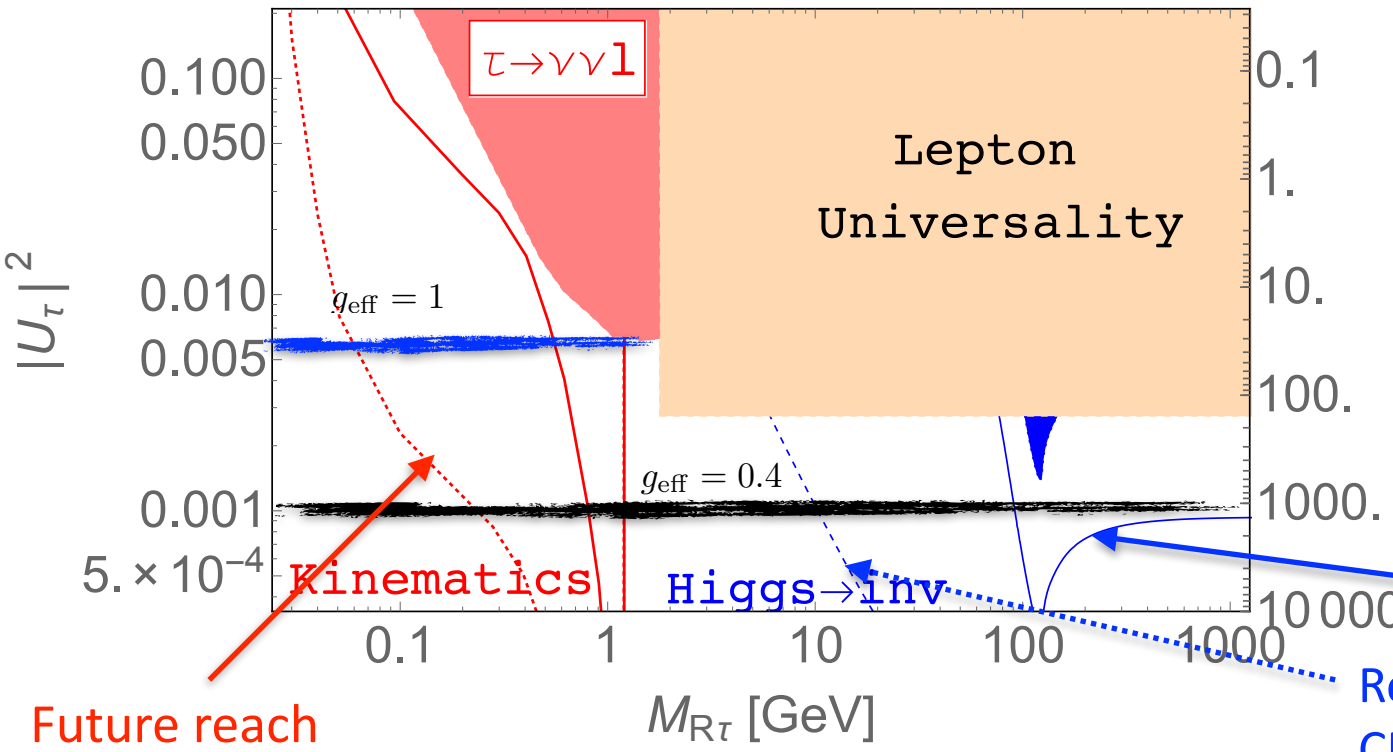


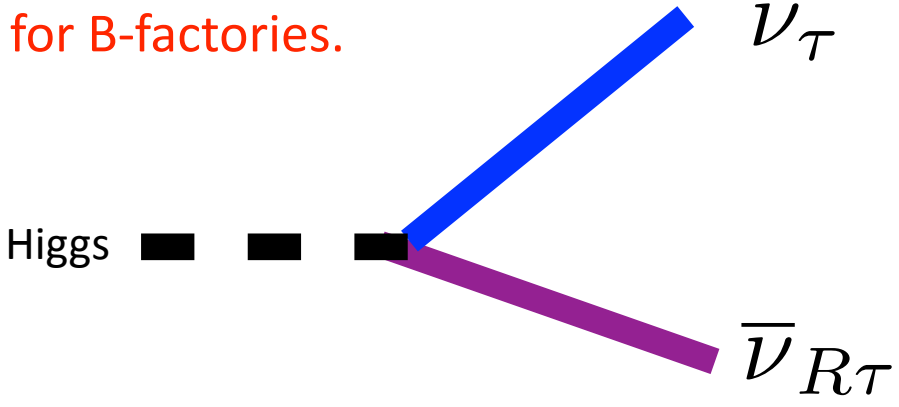
$\tilde{y}_\tau = 4\pi$

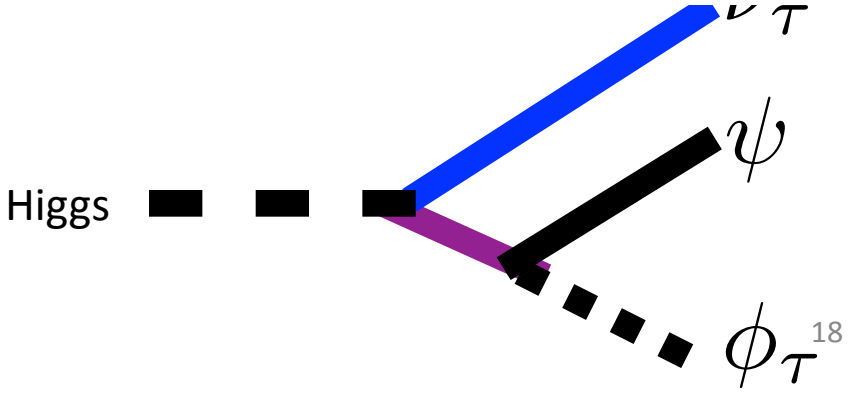
(Upper bound c.f. pions)

Future reach of LHC

Reach of CEPC,FCC-ee, ILC, etc.

Future reach for B-factories.



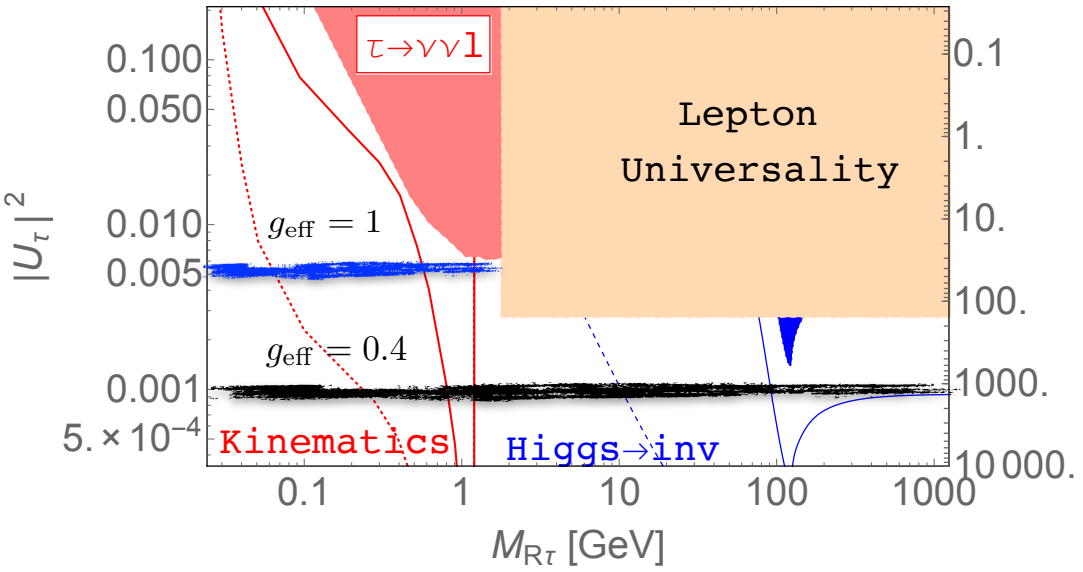


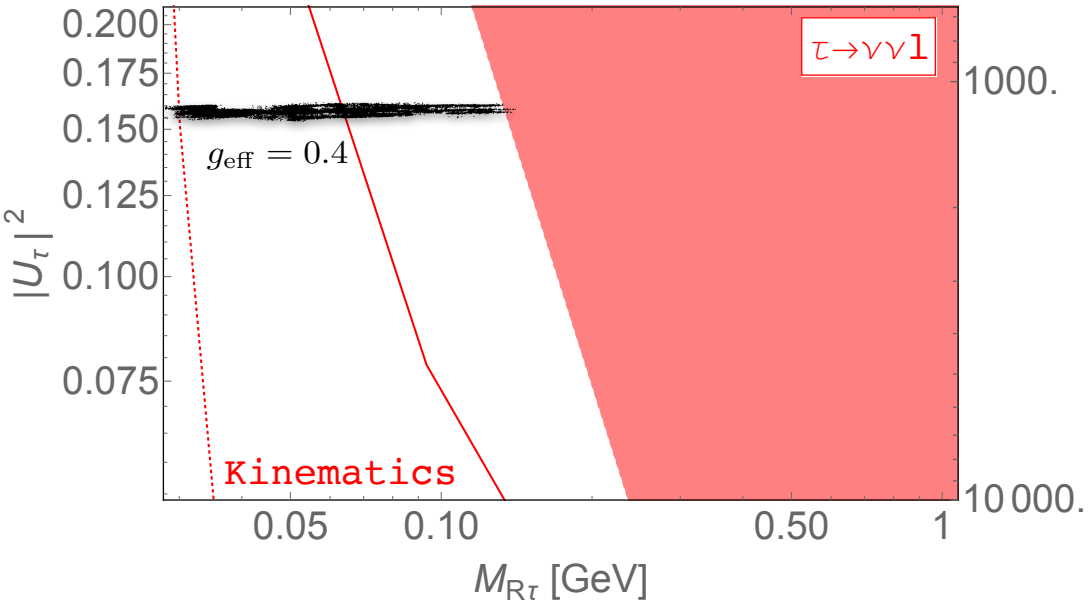
Testability

Assumption:

$$M_{R\tau} > m_{\phi_\tau} + M_\psi$$

$$\tilde{y}_\tau = 4\pi$$





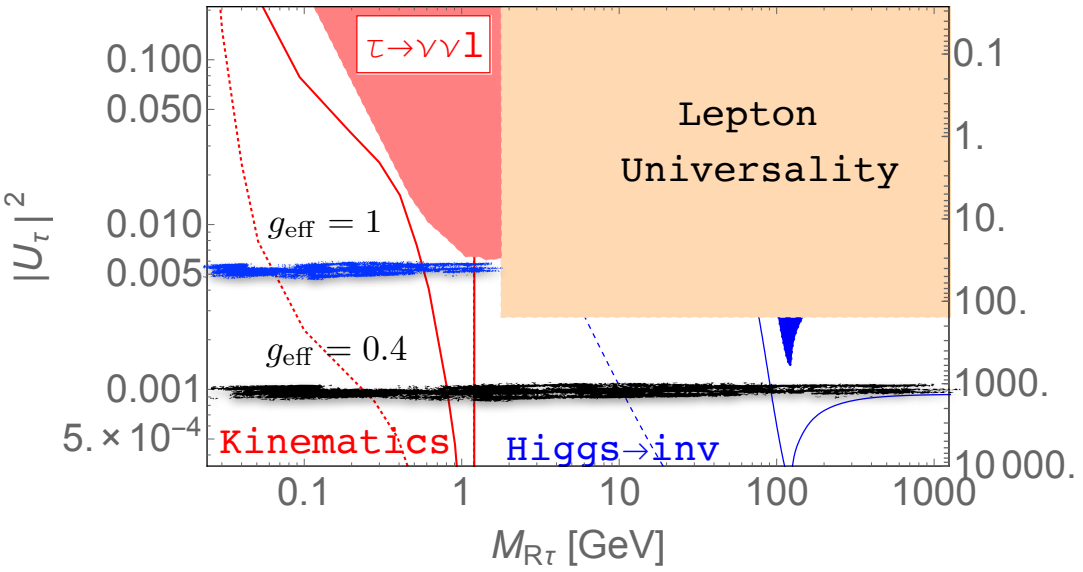
$$\tilde{y}_\tau = 1$$

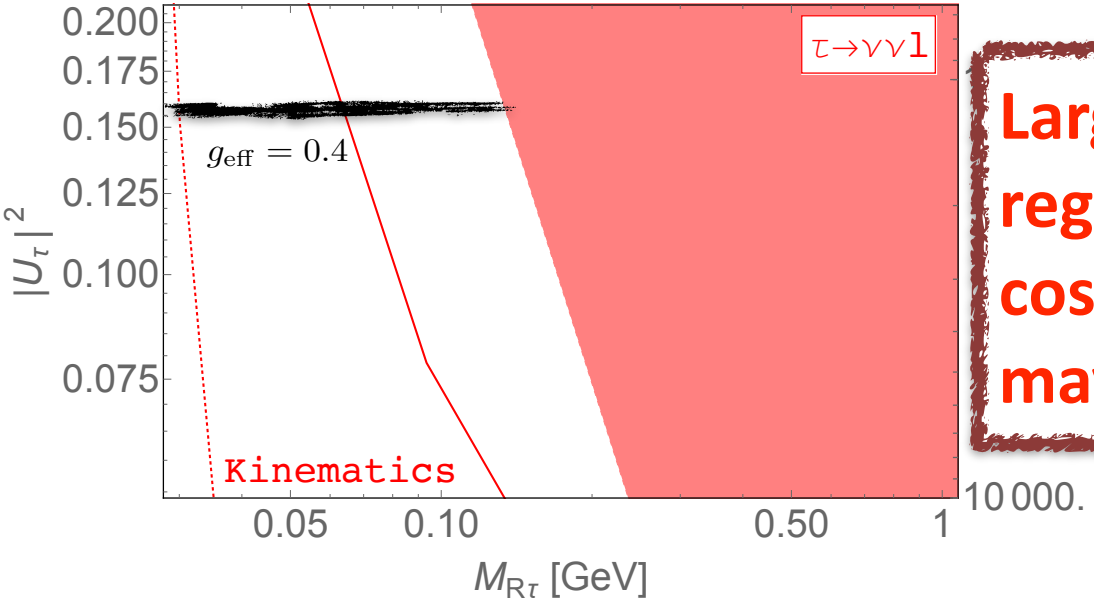
Testability

Assumption:

$$M_{R\tau} > m_{\phi_\tau} + M_\psi$$

$$\tilde{y}_\tau = 4\pi$$





Large fraction of the viable region, affecting the cosmogenic neutrino flux, may be tested in future.

$$y_\tau = 1$$

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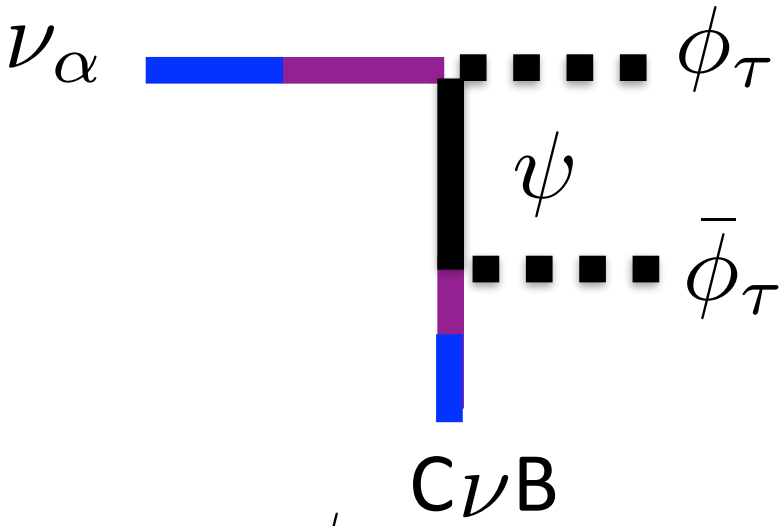
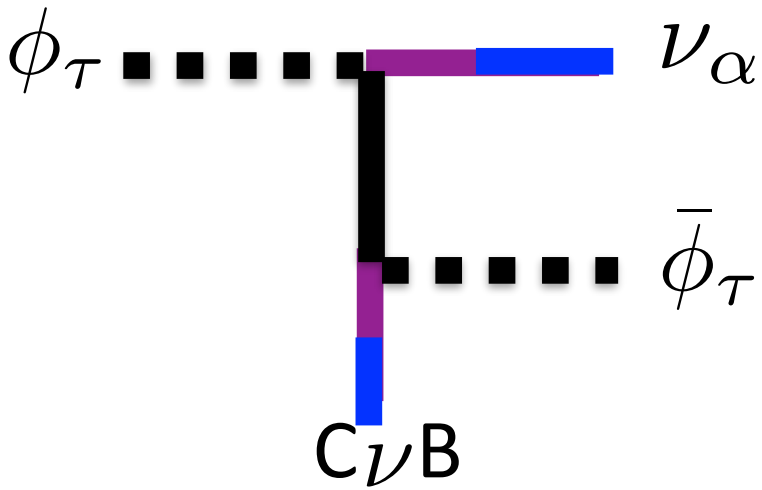


The cosmogenic neutrino energies are transferred the lightest particles in the dark sector: **Dark Matter**.

Highly boosted dark matter is produced

Consider that ϕ_τ is the dark matter. The small-scale structure discrepancy may be relaxed for $g_{\rm eff} = O(0.1), m_{\rm DM} = O(10)\mathrm{MeV}$.

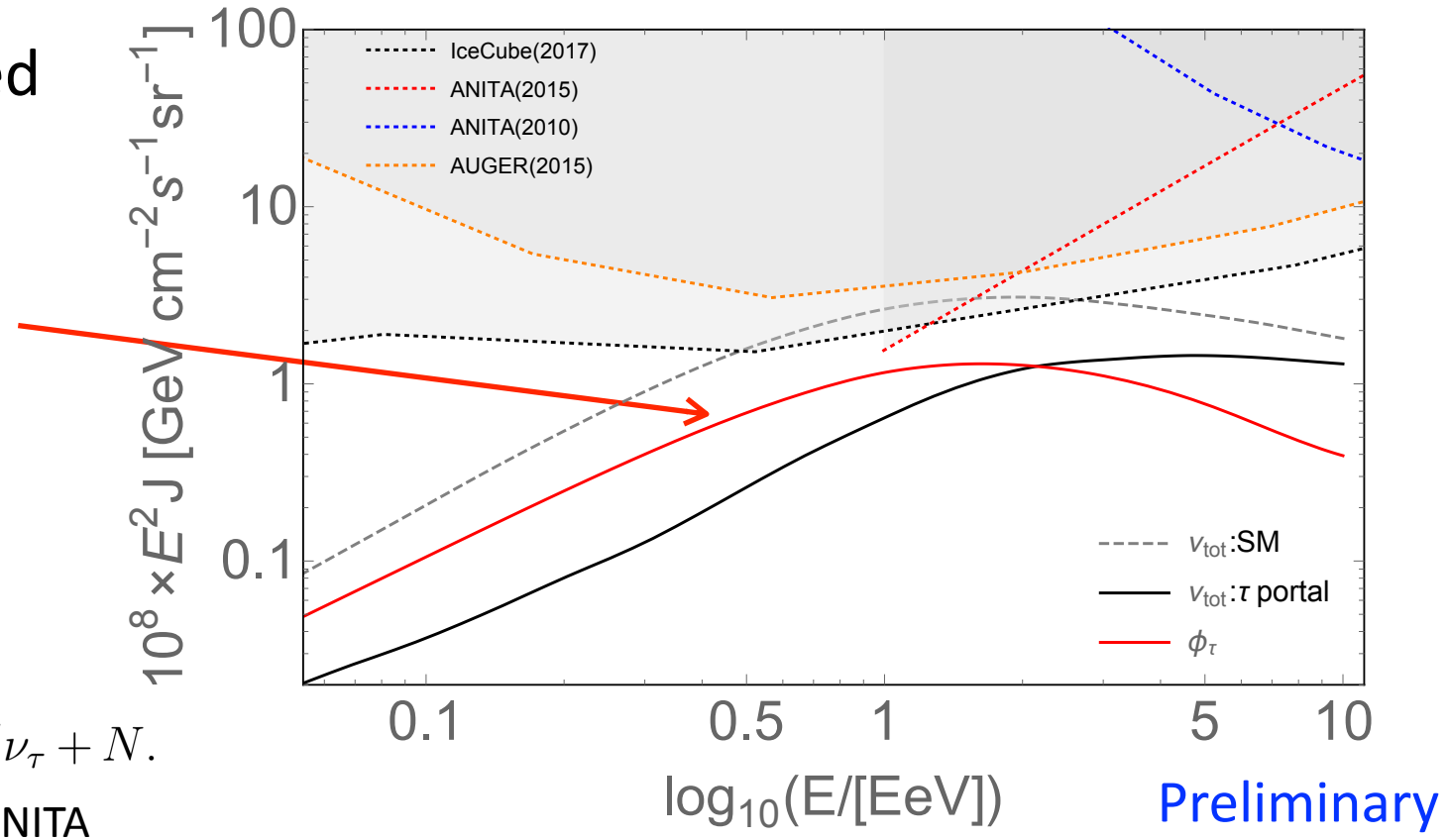
(c.f. Ref. Wilkinson, 1401.7597; Bertoni, et al. 1412.3113)



Dark matter loses energy by scattering with CνB.

Assumption: $\nu_{R\tau} \gtrsim O(100)\mathrm{MeV} \quad M_\psi \simeq m_{\phi_\tau} = 15\,\mathrm{MeV} \quad g_{\mathrm{eff}} = 0.5$

Highly boosted dark matter reaching the Earth.



$\phi_\tau + N \to \psi + \tau/\nu_\tau + N.$

may be tested in ANITA experiments.

c.f. Ref. Cherry et al, 1802.01611

Might be already observed as the ANITA upward going showers.

Gorham et al. 1803.05088;

Equations:

$$\frac{\partial}{\partial t} J_{\nu\alpha}(E_\nu) \simeq H(z) \frac{\partial}{\partial E_\nu}(E_\nu J_{\nu\alpha}) - \Gamma_\alpha J_{\nu\alpha} + J_{\mathrm{source}} + \int dE_{\phi_\tau} \frac{d\sigma_{\phi_\tau \alpha}}{dE_\nu} v_{\mathrm{rel}} n_{\mathrm{C}\nu\mathrm{B}} J_{\phi_\tau}(E_{\phi_\tau}),$$

$$\frac{\partial}{\partial t} J_{\phi_\tau}(E_{\phi_\tau}) \simeq H(z) \frac{\partial}{\partial E_{\phi_\tau}}(E_{\phi_\tau} J_{\phi_\tau}) - \Gamma_{\phi_\tau} J_{\phi_\tau} + \int dE_\nu \sum_\alpha \frac{d\sigma_\alpha}{dE_{\phi_\tau}} v_{\mathrm{rel}} n_{\mathrm{C}\nu\mathrm{B}} J_{\nu\alpha}(E_\nu)$$

$$+ \int d\tilde{E}_{\phi_\tau} \sum_\alpha \frac{d\sigma_{\phi_\tau \alpha}}{dE_{\phi_\tau}} v_{\mathrm{rel}} n_{\mathrm{C}\nu\mathrm{B}} J_{\phi_\tau}(\tilde{E}_{\phi_\tau}),$$

Summary

arXiv:1806.XXXX, arXiv:1706.07028

- Dirac neutrino portal interaction:

  Dark sector for dark matter is connected with SM only through dirac right-handed neutrino.

- Cosmogenic neutrino flux gets suppressed

$$\nu\ /\overline{\nu}\ + \nu^{\mathrm{C}\nu\mathrm{B}} \rightarrow$$ Dark sector particles+...

- Testable in future colliders.
- Boosted dark matter may be tested
- in ANITA experiment.

Backup Slides

Energy-loss rate for Highly boosted dark matter

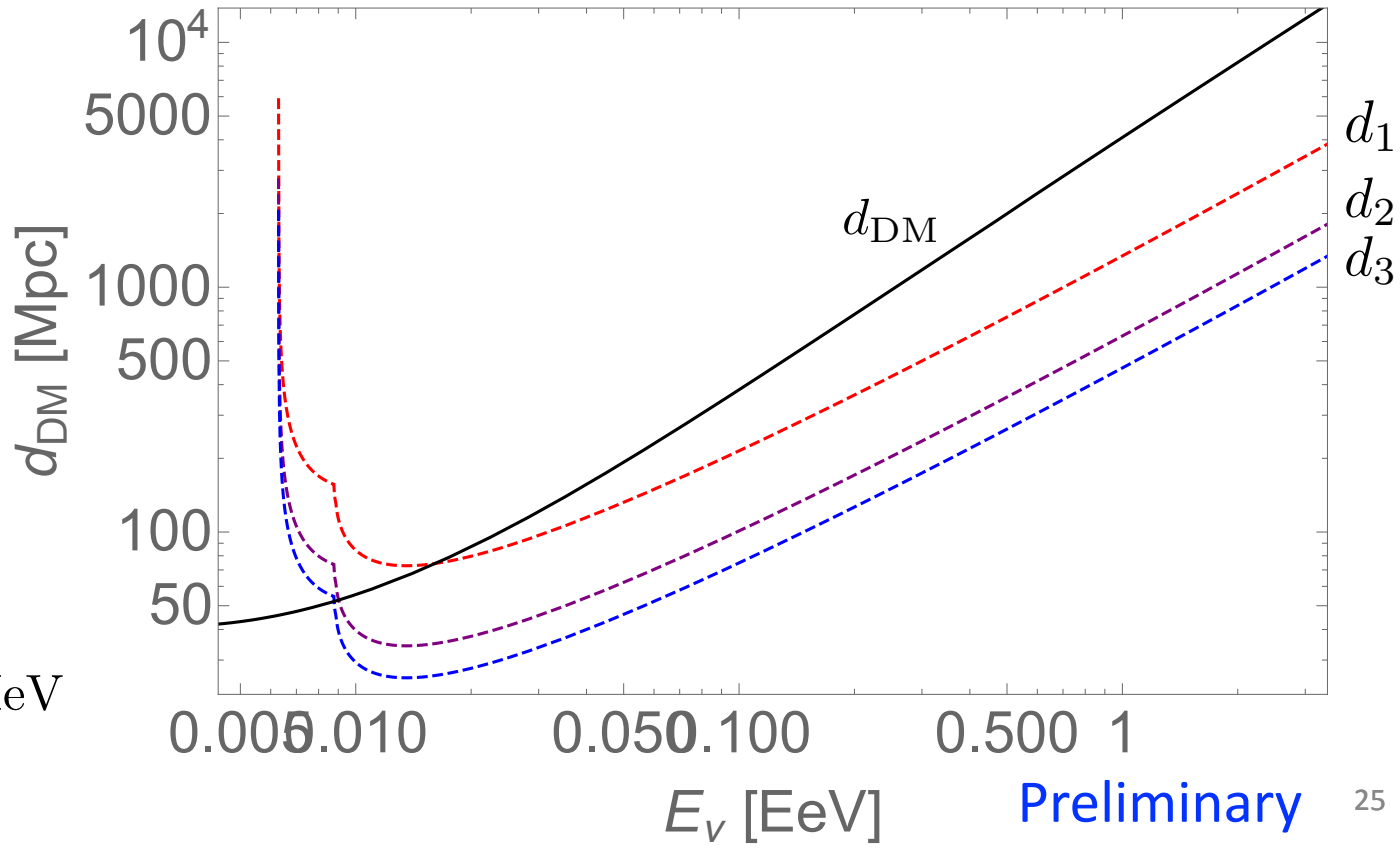
Energy loss rate

$$\Gamma_{\mathrm{DM},\alpha} \sim \frac{1}{3}\left(1+\log\left(\frac{E_{\mathrm{cm}}^2}{|M_\psi|^2}\right)\right)^{-1}\Gamma_\alpha.$$

Helicity suppression

$$d_{\mathrm{DM}} \equiv \frac{1}{\sum_\alpha \Gamma_{\mathrm{DM},\alpha}}.$$

$$d_\alpha(E,T) \equiv \frac{1}{\Gamma_\alpha(E,T)}.$$



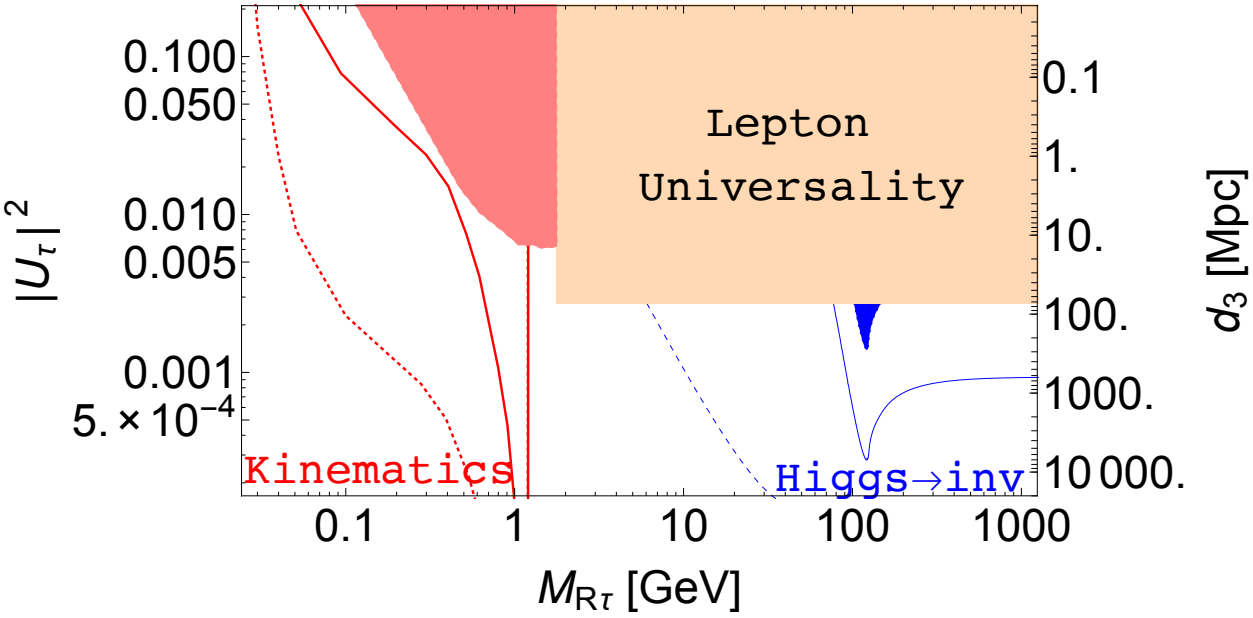
$M_\psi \simeq m_{\phi_\tau} = 15\,\mathrm{MeV}$

$g_{\mathrm{eff}} = 0.5$

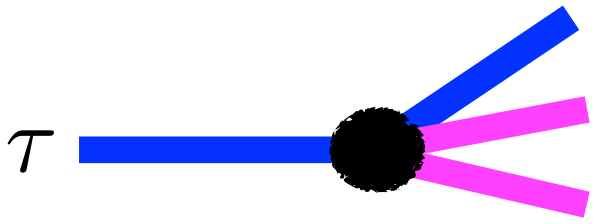
Preliminary

Lepton Universality

$$\tilde{y}_\tau = 4\pi$$



$G_F\sqrt{1-|U_\tau|^2}$

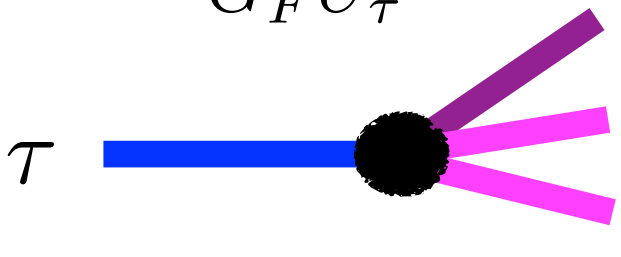


$\nu_1 \sim \nu_\tau$

$\bar{\nu}_e$

e

$G_F U_\tau$



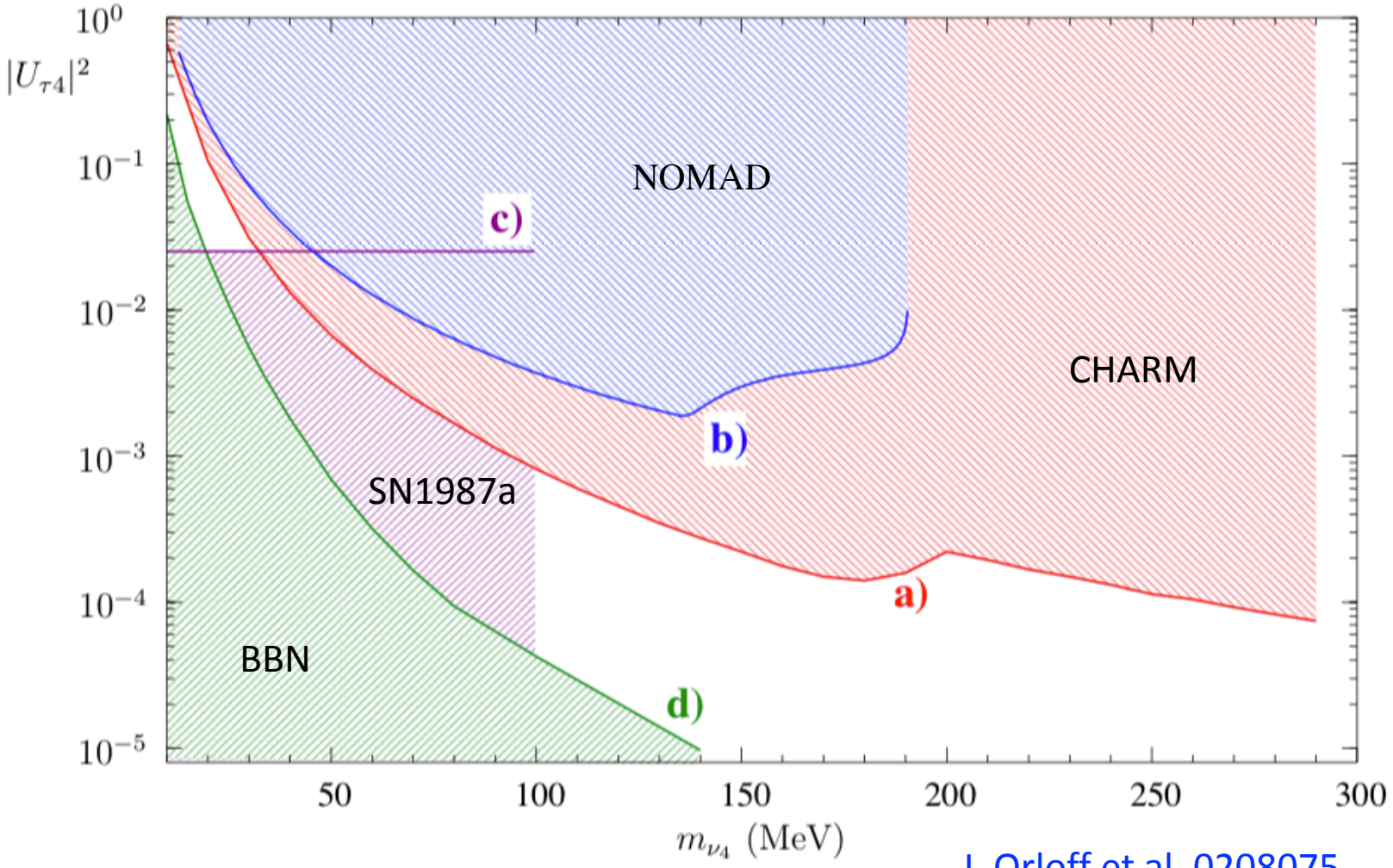
$\nu_2 \sim \nu_{R\tau}$

$\bar{\nu}_e$

e

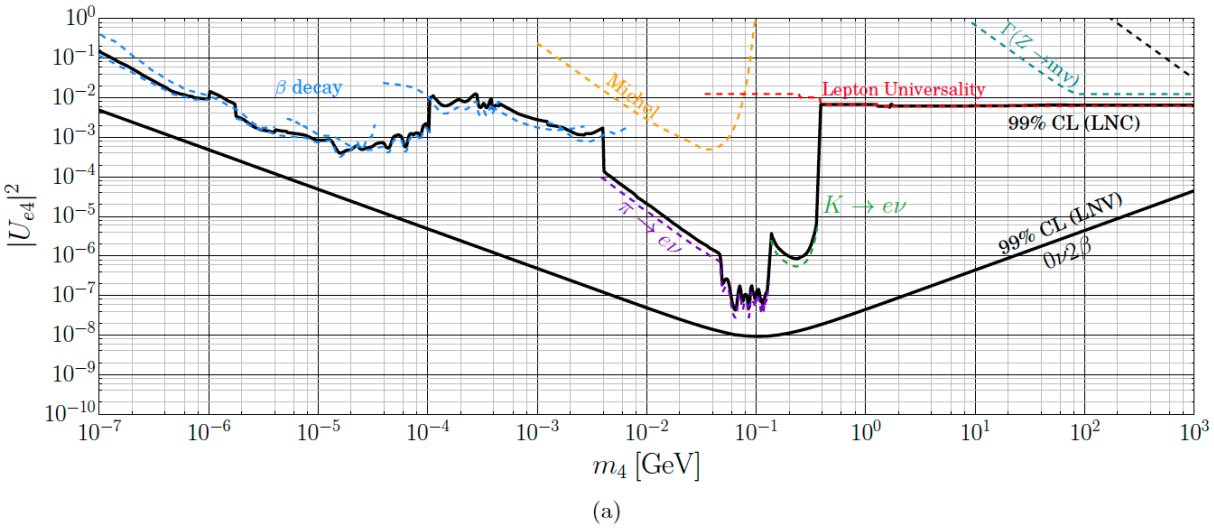
When $M_{R\tau} > m_\tau$, the latter is forbidden, lepton universality is violated due to the suppression to $\sqrt{1-|U_\tau|^2}$.

Constraints with $M_{R\tau} < m_{\phi_\tau} + M_\psi$

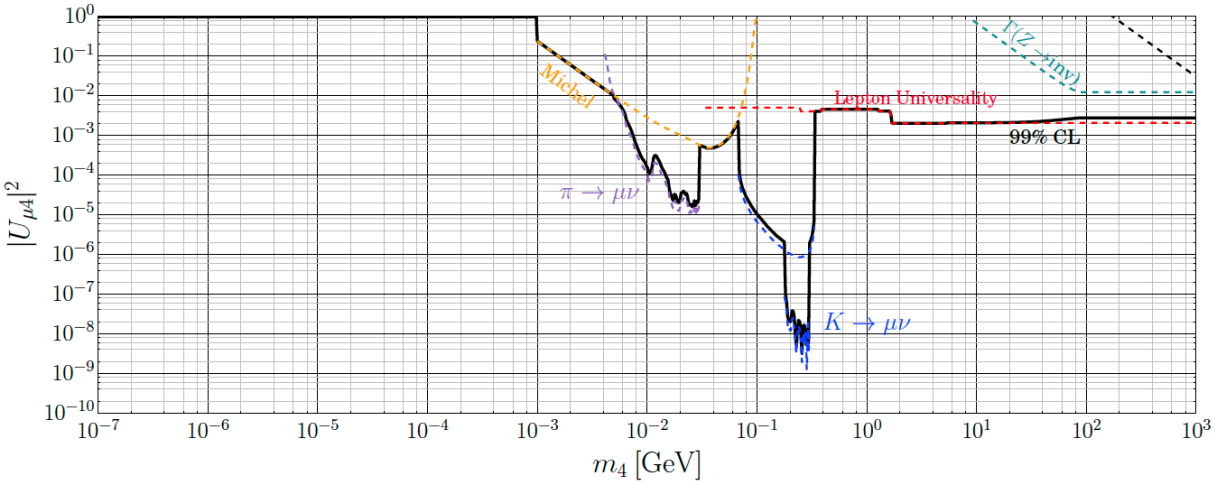


J. Orloff et al, 0208075

Constraints for e/mu-portal interaction



(a)



(b)

double beta decay constraint is not applied.

same prediction for Higgs invisible decay as the tau case.

Gouvea, Kobach, 1511.00683

Upward Air Showers in ANITA

TABLE I: *ANITA-I,-III anomalous upward air showers.*

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.[(1)]	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3°, 159.62 \pm 0.7°$	$-35.0 \pm 0.3°, 61.41 \pm 0.7°$
RA, Dec[(2)]	282.14064, +20.33043	50.78203, +38.65498
$E_{shower}^{(3)}$	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

[1] Latitude, Longitude of the estimated ground position of the event.
[2] Sky coordinates projected from event arrival angles at ANITA.
[3] For upward shower initiation at or near ice surface.

*Likely from tau leptons decay

However if is tau cosmogenic neutrino, the transmission probabilities, respectively, are,

$$4 \times 10^{-6} \qquad 7 \times 10^{-9}$$

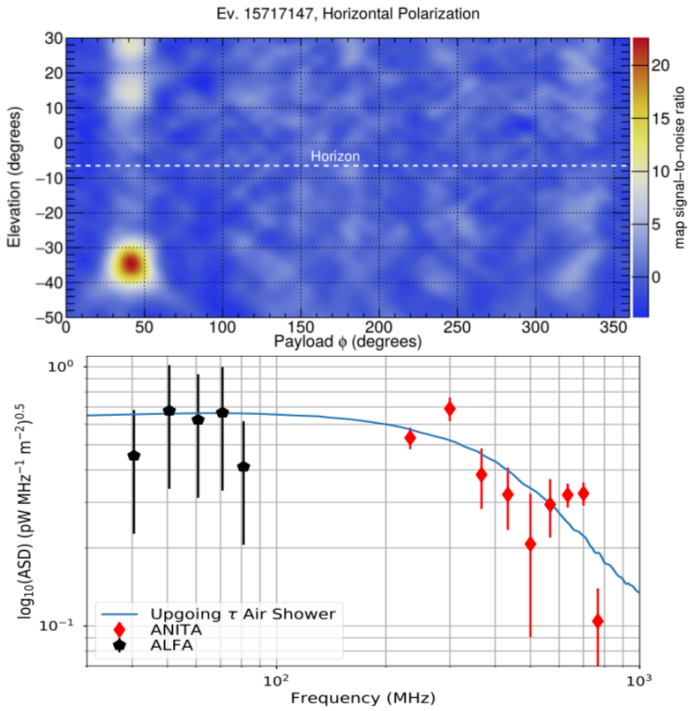
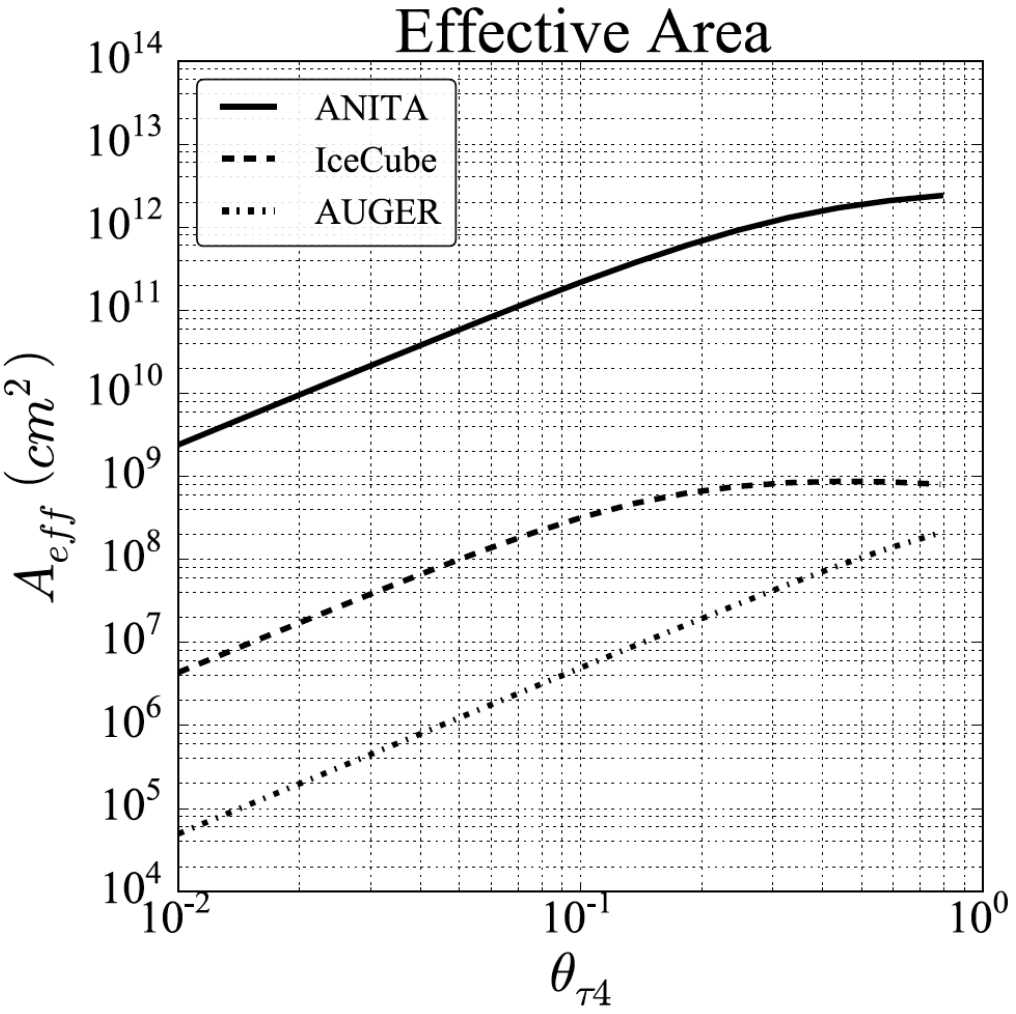


FIG. 4: *Top: Interferometric map of the arrival direction of the anomalous CR event 15717147. Bottom: ANITA combined amplitude spectral density (ASD) for the event, from 50-800 MHz, including data from the ANITA Low Frequency Antenna (ALFA). A simulated upward-propagating extensive air shower spectral-density curve is overlain.*

ANITA collaboration 1803.05088, 1603.05218

Right-handed neutrino scattering area



tau-portal interaction:

$$\phi_\tau + N \to \psi + \tau/\nu_\tau + N.$$

$$\sigma_{\phi_\tau N} \sim \frac{1}{16\pi^2} \left|\tilde{y} U_\tau\right|^2 \times \sigma_{\nu_\tau N}$$

Sterile neutrino for comparison:

$$\sigma_{\nu_R N} \sim \theta_{\tau 4}^2 \times \sigma_{\nu_\tau N}$$

Cherry et al, 1802.01611

FIG. 3: The total effective area for the production of upward directed cascades provided by the bulk of the Earth, assuming an initial neutrino energy of $E_i = 1\,\mathrm{EeV}$.