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Astrophysical neutrino point sources as a probe of new physics

arXiv:2304.08533

in collaboration with Stefan Vogl

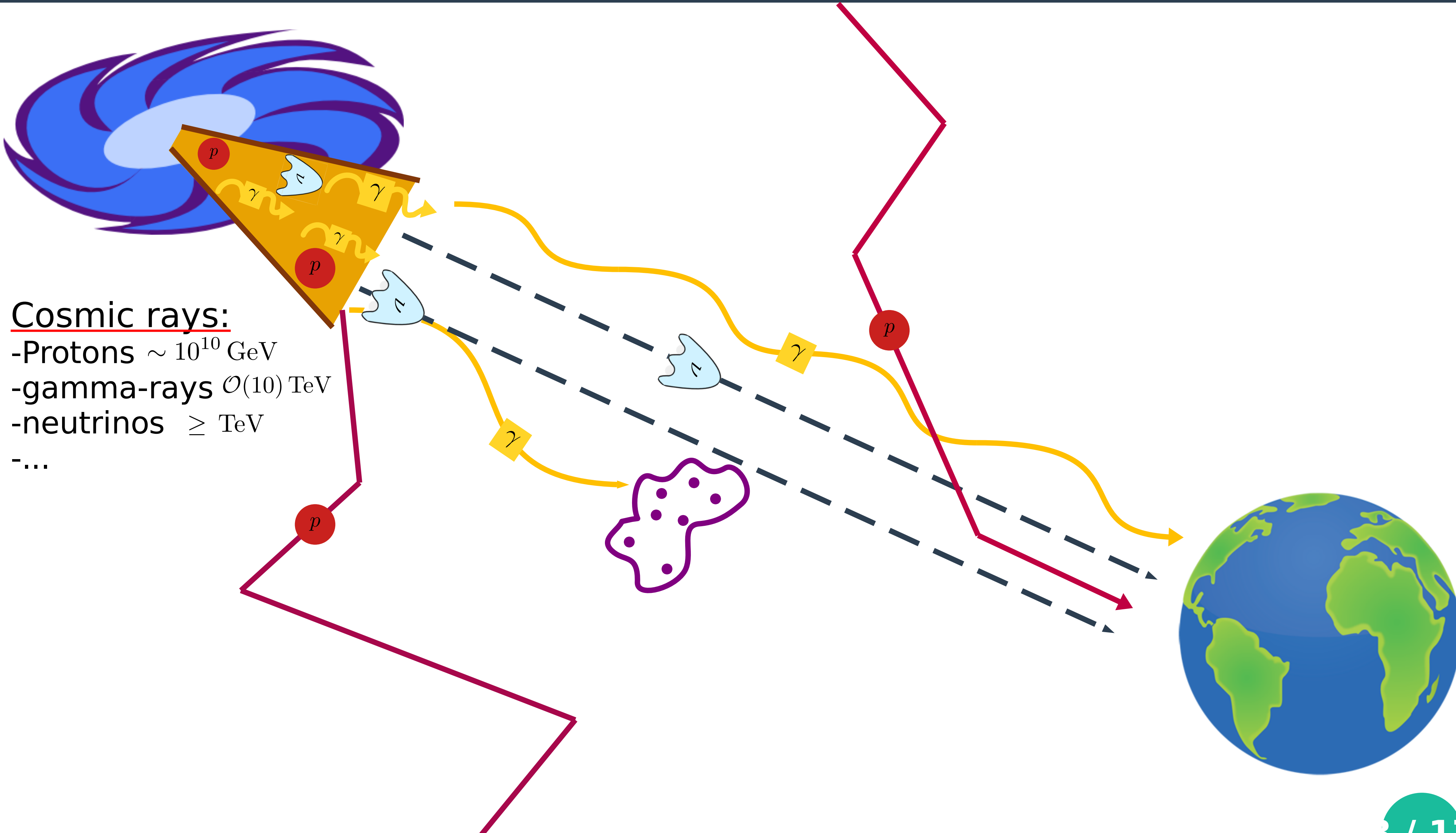
Christian Döring

Taup 2023 – Vienna 31.08.23

Brief Overview

- Cosmics Rays & Neutrinos
- Observations: TXS 0506+056 and NGC 1068
- Secret neutrino interaction and the cosmic neutrino background
- Mean free path and flux
  - Massfull case
  - Massless case
- Results
- Conclusion

Cosmic Rays and Neutrinos



Cosmic rays:

-Protons $\sim 10^{10}\,\mathrm{GeV}$

-gamma-rays $\mathcal{O}(10)\,\mathrm{TeV}$

-neutrinos $\geq \mathrm{TeV}$

-...

Galactic Neutrino Signals

Blazar TXS 0506+056

2018

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†

Multi-messenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams *†

Facts:
Distance: 1.2 Gpc
Flux: $\hat{\Phi}_0 = 1.2 \times 10^{-13} \frac{1}{\mathrm{TeV cm^2 s}}$
Spectral index: $\gamma = 2.0$
Energy: 40-4000 TeV

arXiv:1807.08794
arXiv:1807.08816

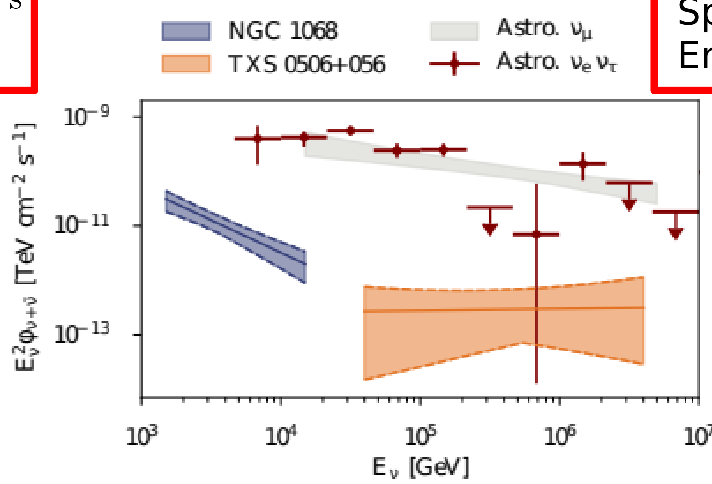
Active Galaxy NGC 1068

2022

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*

Facts:
Distance: 14.4 Mpc
Flux: $\hat{\Phi}_0 = 5 \times 10^{-11} \frac{1}{\mathrm{TeV cm^2 s}}$
Spectral index: $\gamma = 3.2$
Energy: 1.5-15 TeV

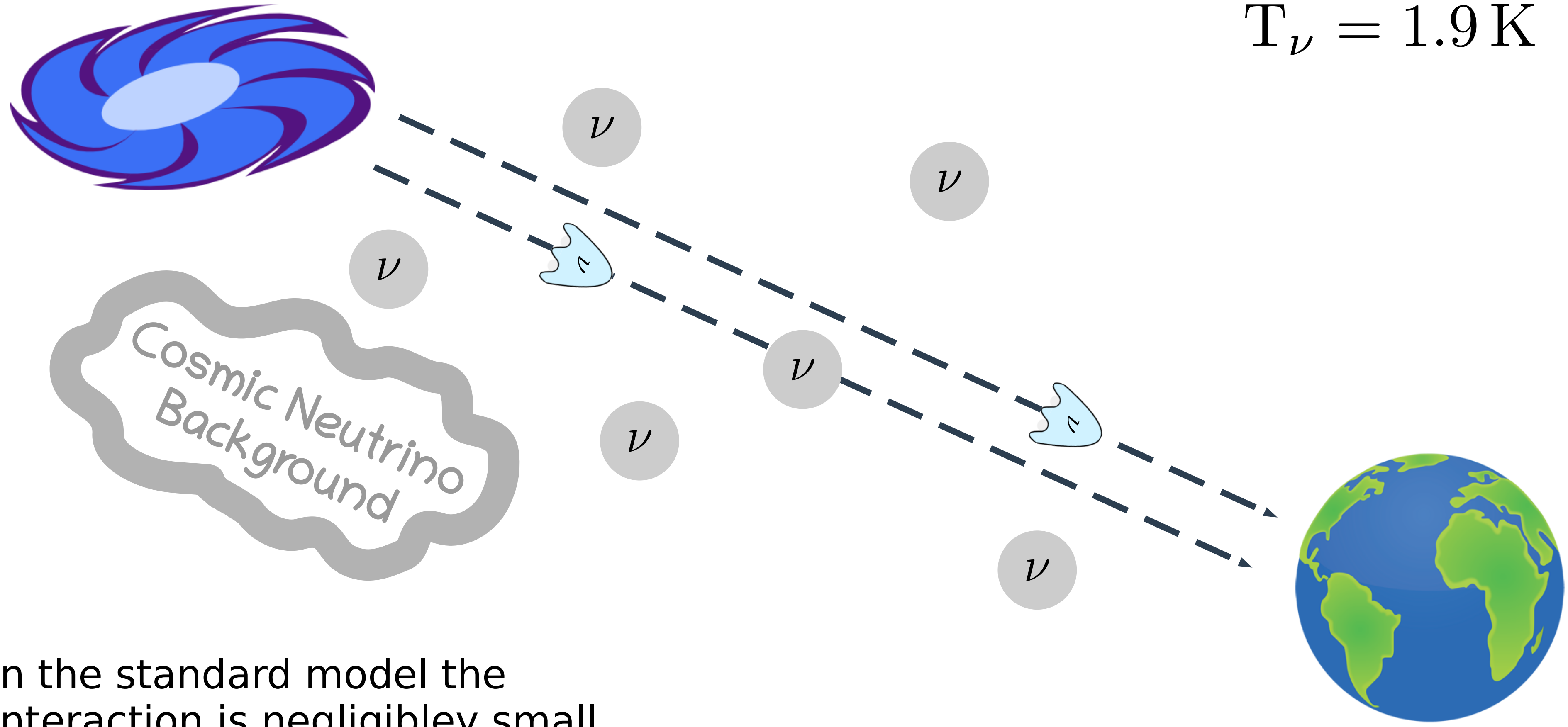


arXiv:2211.09972

Cosmic Neutrino Background

$$n_{tot} \approx 340\,\mathrm{cm}^{-3}$$

$$T_\nu = 1.9\,\mathrm{K}$$



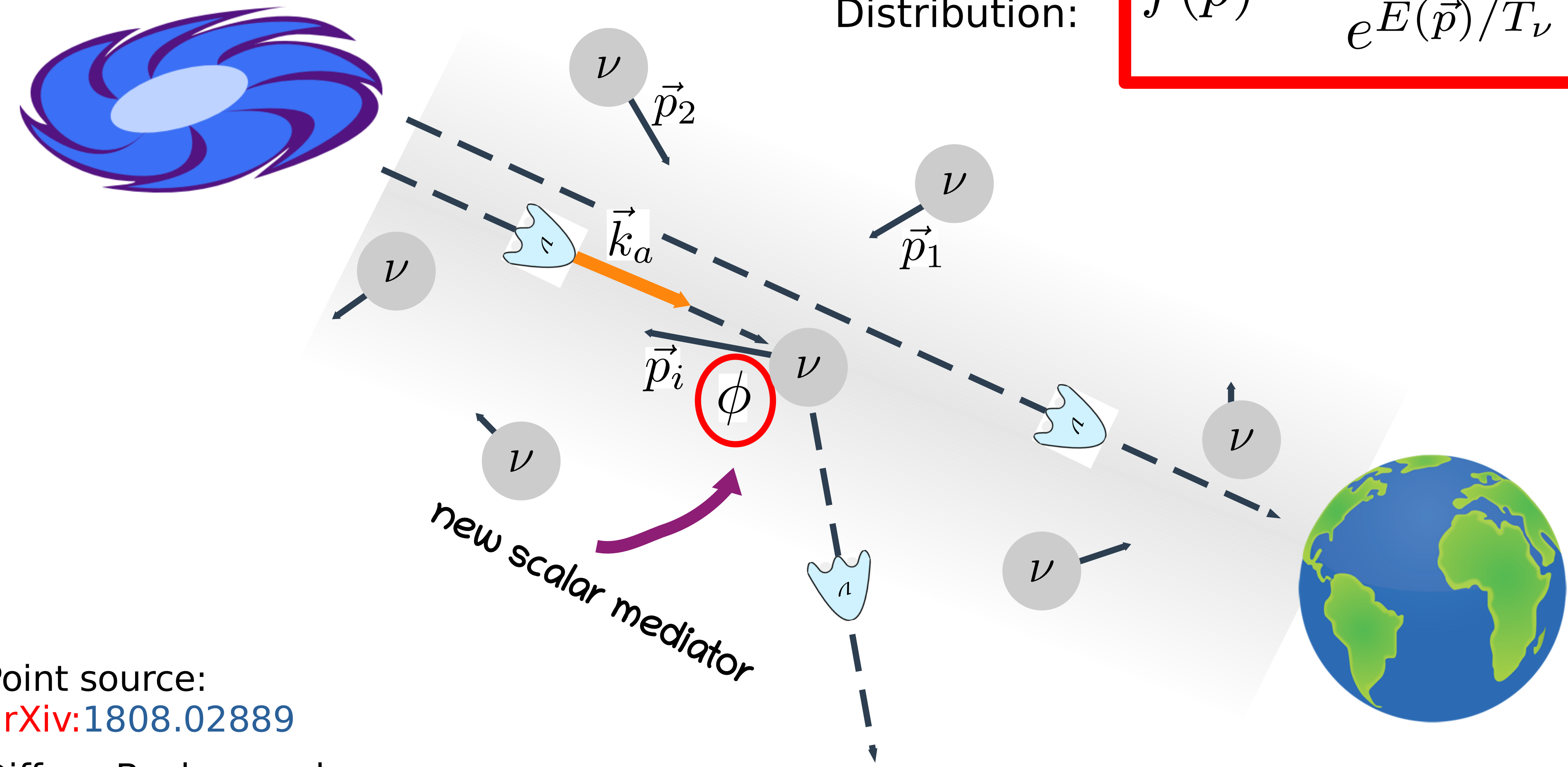
in the standard model the interaction is negligibley small but...

Cosmic Neutrino Background as a Milk Glass

… in physics beyond the SM interaction can be sizeable!

Momentum-Distribution:

$$\boxed{f(\vec{p}) = \frac{1}{e^{E(\vec{p})/T_\nu} + 1}}$$



Point source:
arXiv:1808.02889

Diffuse Background:
arXiv:2107.13568

Interaction Rate

Interaction rate

$$\Gamma_i(E_a) = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} f_i(\vec{p})\, v_{M\o l} \sigma(s(E_\mathrm{a}, \vec{p}))$$

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Energy of
astrophysical neutrino

Interaction Rate

momentum
distribution

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Energy of
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Møllervelocity

Interaction Rate

momentum distribution

cross section

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Energy of astrophysical neutrino

Møllervelocity

Interaction Rate

$$\mathcal{L}_{int} = \frac{1}{2}\sum_{i,j} y_{ij}\bar{\nu}_i\nu_j\phi$$

momentum
distribution

Interaction rate

cross section

$$\Gamma_i(E_a) = \int \frac{\mathrm{d}^3p}{(2\pi)^3} f_i(\vec{p})\, v_{M\o l}\, \sigma(s(E_\mathrm{a},\vec{p}))$$

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$\mathrm{m}_\nu \gg T_\nu$

Energy of
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Møllervelocity

$$\Gamma_i(E_\mathrm{a}) = \sigma(2E_\mathrm{a} m_i) n_i$$

Interaction Rate

momentum distribution

cross section

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We distinguish two cases:

Interaction Rate

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momentum distribution

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We distinguish two cases:

$\mathrm{m}(\nu_{\mathrm{light}})$

non-relativistic today
($\mathrm{m}_\nu \gg T_\nu$)

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momentum distribution

cross section

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Møllervelocity

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- non-relativistic today ($\mathrm{m}_\nu \gg T_\nu$)
- relativistic today (e.g. massless)

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Our Neutrino Sector (Assumptions):

-Flavor universal coupling
-Normal mass ordering
-Majorana fermion

We distinguish two cases:

$\mathrm{m}(\nu_\mathrm{light})$

- non-relativistic today ($\mathrm{m}_\nu \gg T_\nu$)
- relativistic today (e.g. massless)

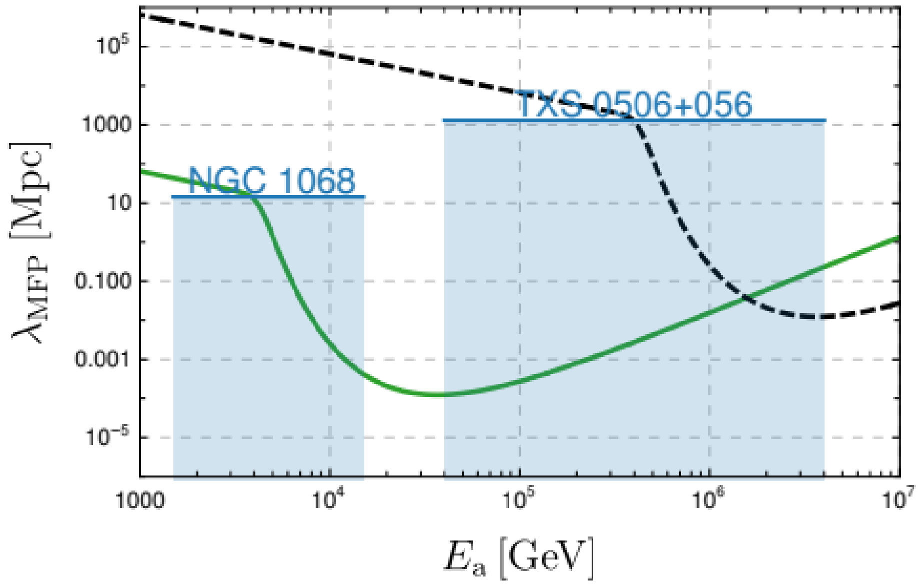
Mean Free Path

Mean free path: $\lambda_{\mathrm{MFP}} = 1/\sum_i \Gamma_i(E_{\mathrm{a}})$

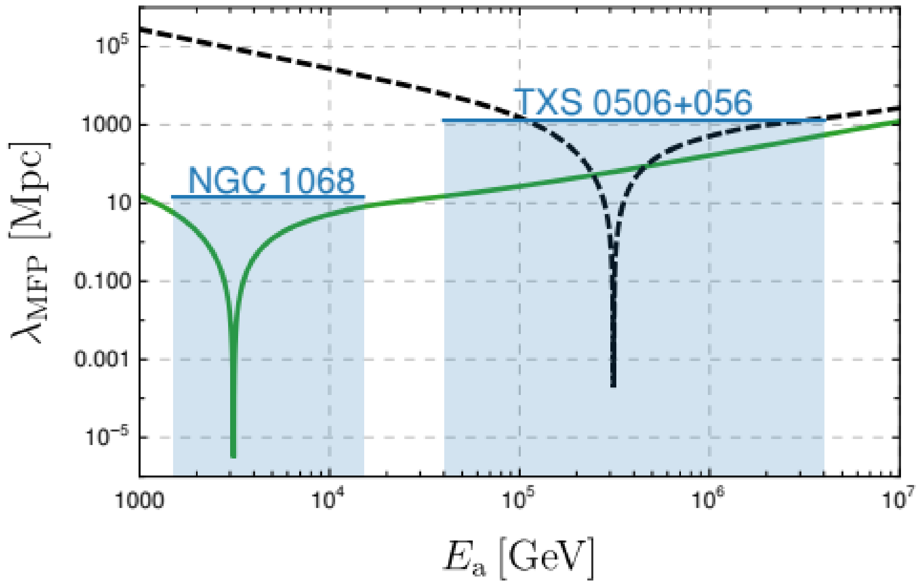
$\mathrm{y}{=}0.05$
$\mathrm{m}_\phi \in \{0.25, 2.5\}\,\mathrm{MeV}$

Easy example: single neutrino species

Relativistic today



Non-relativistic today $\mathrm{m}_i = 0.01\,\mathrm{eV}$



Flux

$$\Phi_0(E) = \hat{\Phi}_0 \cdot \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-\gamma} \cdot \mathrm{T}(E)$$

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Normalised flux

Flux

Spectral index

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Transmittance

$$\mathrm{T(E)}=\mathrm{e}^{-\frac{d}{\lambda_{\mathrm{MFP}}(E)}}$$

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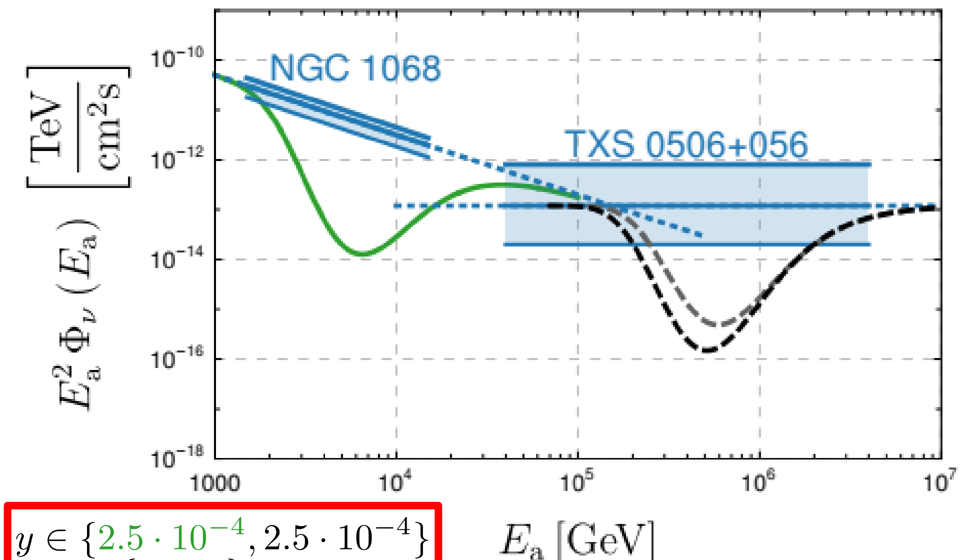

$y \in \{2.5 \cdot 10^{-4}, 2.5 \cdot 10^{-4}\}$
$m_\phi \in \{0.1, 1\}$ MeV

Flux

Spectral index

Transmittance

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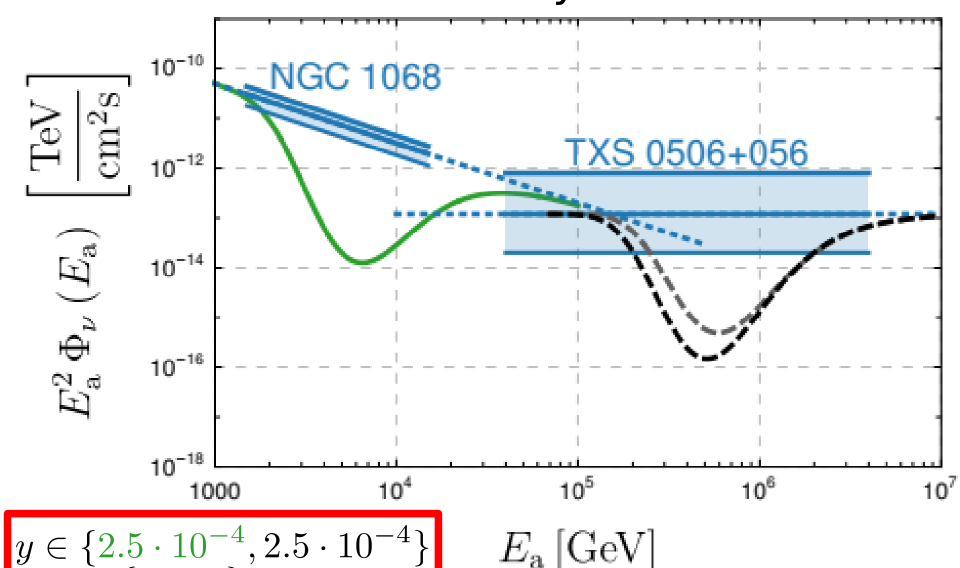

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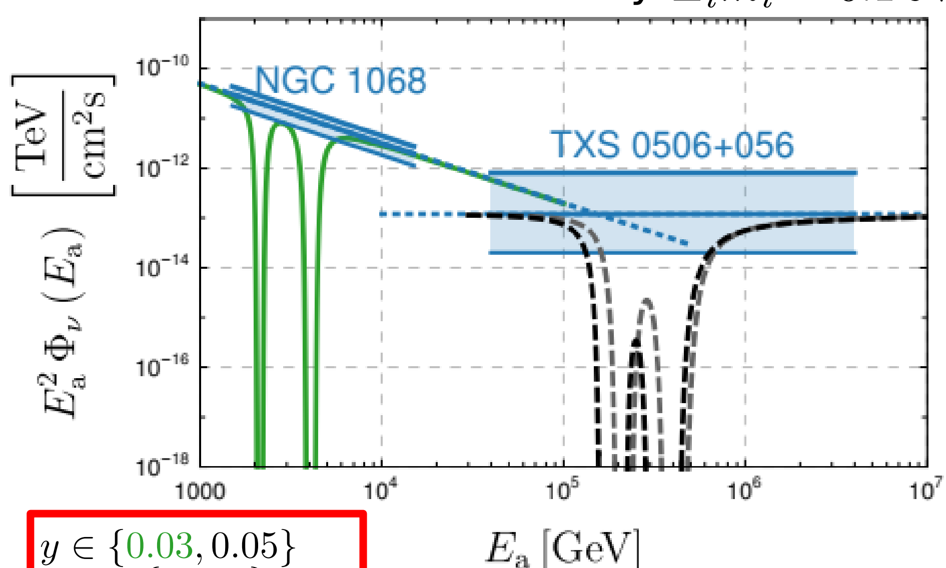
Non-relativistic today $\Sigma_i m_i = 0.1\,\mathrm{eV}$



$y \in \{0.03, 0.05\}$
$m_\phi \in \{0.5, 5\}\,\mathrm{MeV}$

Flux

Spectral index

Transmittance

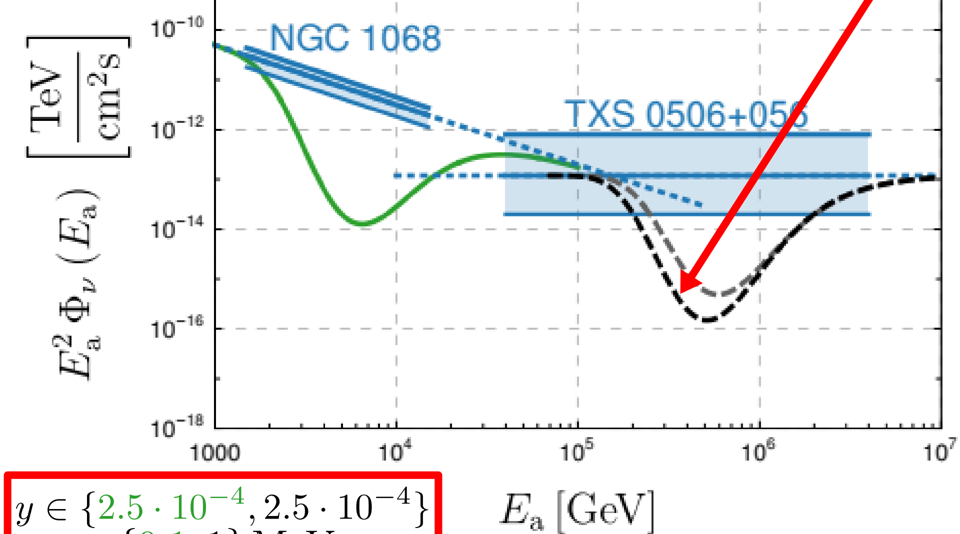
$$\mathrm{T(E)}{=}\mathrm{e}^{-\frac{d}{\lambda_{\mathrm{MFP}}(E)}}$$

$$\Phi_0(E) = \hat{\Phi}_0 \cdot \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-\gamma} \cdot \mathrm{T}(E)$$

Normalised flux

Redshift broadening

Relativistic today



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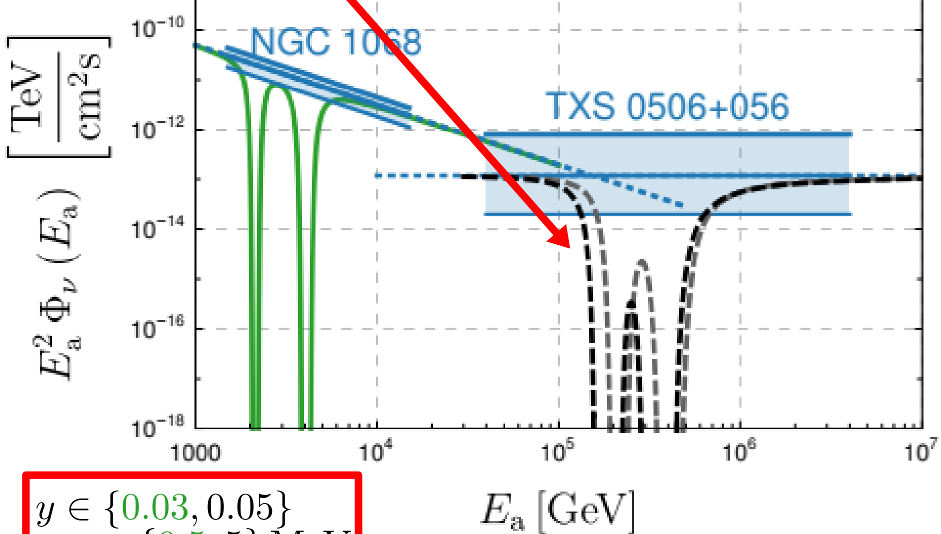

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Estimating the amount of absorbed neutrinos

Problem: We don‘t know the original amount of neutrinos emitted by the source...

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Estimate:

$$\frac{n}{n_0} = \frac{\int_{E_{\min}}^{E_{\max}} \mathrm{d}E \, A_{\mathrm{eff}}(E) \, \Phi(E)}{\int_{E_{\min}}^{E_{\max}} \mathrm{d}E \, A_{\mathrm{eff}}(E) \, \Phi_0(E)} \geq q$$

with absorption (milky)

measured number (transparent)

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Here: $\boxed{\mathrm{q}=0.5}$

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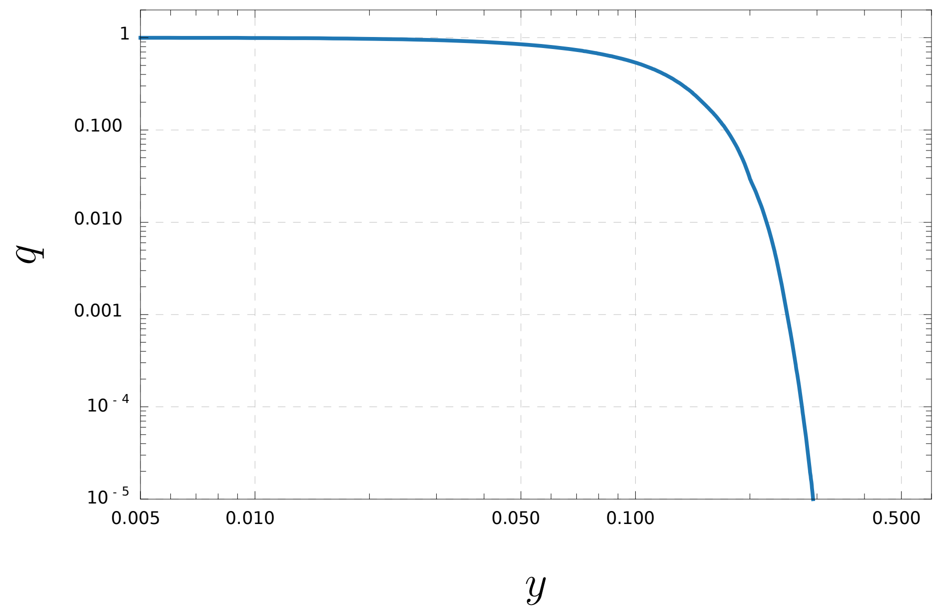

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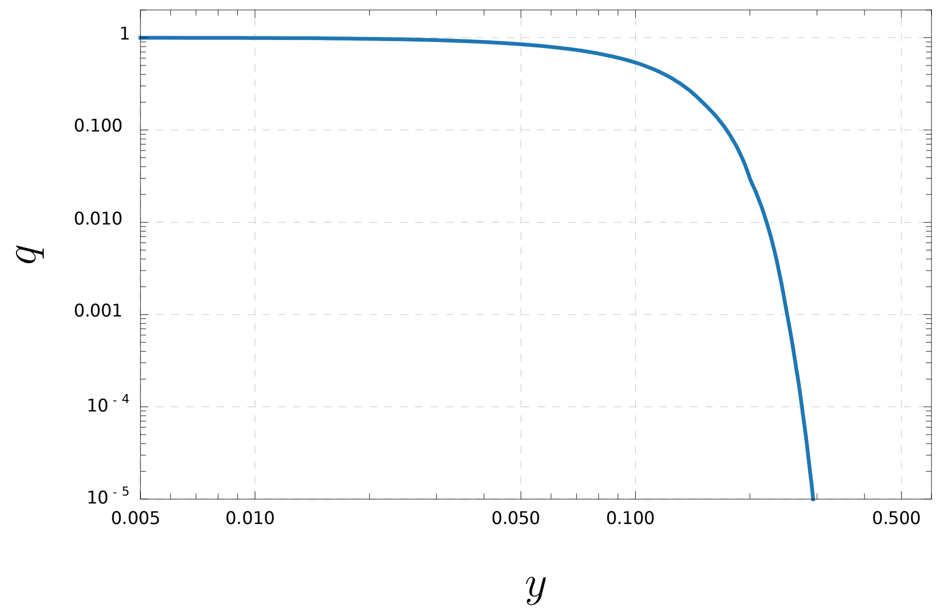
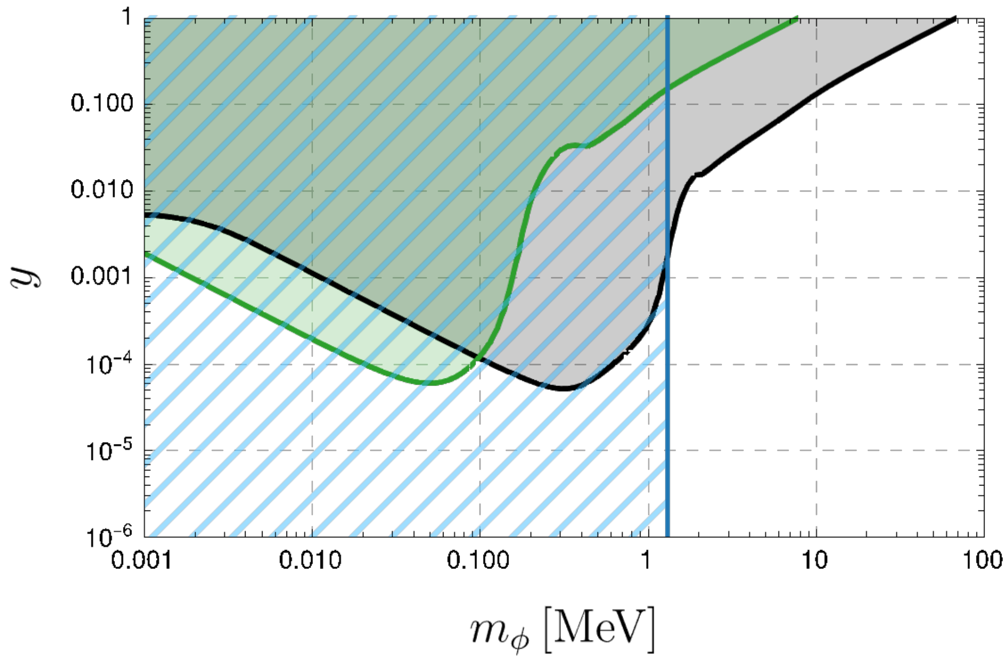


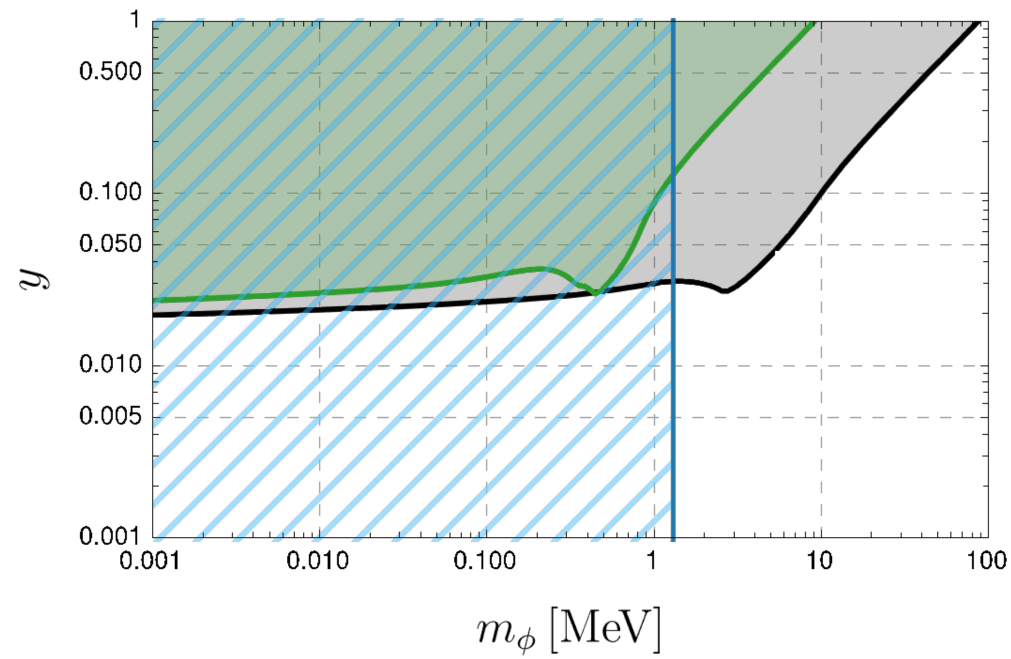
More dedicated analysis, see arXiv:2307.02361

Results

Relativistic today



Non-relativistic today



Conclusion

- Neutrinos from astrophysical point sources have been measured and are great messengers
- New physics (e.g. a scalar) can lead to interactions with the CNuB and thus turn the Universe opaque for them
- Using the two observed sources TXS 0506+056 and NGC 1068 we put new estimated constraints on light scalar masses and neutrino coupling
- Two cases: lightest neutrino relativistic vs non-relativistic today
- Only estimate: the original neutrino emission at the source is not known

THANK YOU !

BACKUP

Crosssection

Flavor universal neutrino scattering cross section

$$\sigma_{\nu\nu}(s) = \frac{y^4}{32\pi((m_\phi^2 - s)^2 + m_\phi^2\Gamma_\phi^2)s^2}\left(\frac{s(5m_\phi^6 - 9m_\phi^4 s + 6s^3)}{m_\phi^2 + s} + \frac{2(5m_\phi^8 - 9m_\phi^6 s + 4m_\phi^2 s^3)\log(\frac{m_\phi^2}{m_\phi^2+s})}{2m_\phi^2 + s}\right)$$

ϕ-pair production $\mathrm{E_{CM}} \geq m_\phi$

$$\sigma_{\phi\phi}(s) = \frac{y^4}{64\pi s^2}\left(\frac{s^2 - 4m_\phi^2 s + 6m_\phi^4}{s - 2m_\phi^2}\log\left[\left(\frac{(s(s-4m_\phi^2))^{1/2} + s - 2m_\phi^2}{(s(s-4m_\phi^2))^{1/2} - s + 2m_\phi^2}\right)^2\right] - 6(s(s-4m_\phi^2))^{1/2}\right)$$

See also arXiv:2107.13568

Massless Neutrino

Rate approximations in different limit cases:

Heavy mediator mass

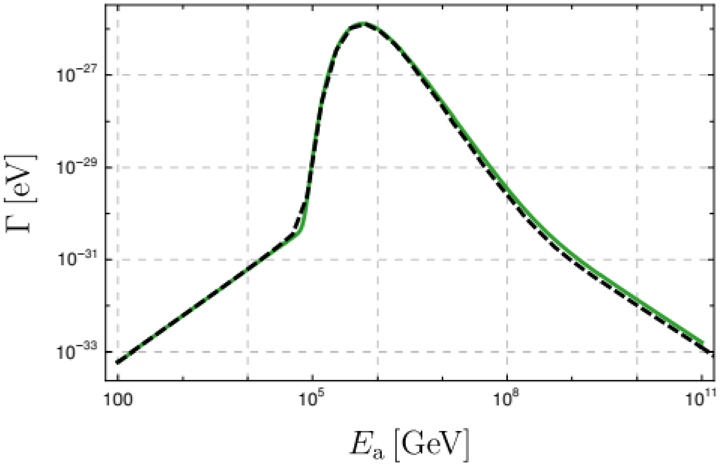
$$\Gamma_{\text{heavy}} \approx \frac{7\pi^3 y^4}{2592\,\zeta(3)} \frac{E_{\text{a}} T_\nu}{m_\phi^4} n_{\nu_1}$$

Small mediator mass

$$\Gamma_{\text{light}} \approx \frac{\pi y^4}{192\,\zeta(3)} \frac{1}{E_{\text{a}}\,T_\nu} n_{\nu_1}$$

Resonance

$$\Gamma_{\text{NWA}} \approx \frac{y^4}{384\zeta(3)} \frac{m_\phi^3}{E_\nu^2\,T_\nu^2\,\Gamma_\phi} \log[1 + e^{-\frac{m_\phi^2}{4E_\nu T_\nu}}] n_{\nu_1}$$



Redshift broadening

In expanding Universe: Flux evolves accoring to transport equation

$$\frac{\partial \Phi(t, E_\mathrm{a})}{\partial t} = \frac{\partial}{\partial E_\mathrm{a}}[H(t) E_\mathrm{a} \Phi(t, E_\mathrm{a})] - \Phi(t, E_\mathrm{a}) \Gamma(E_\mathrm{a}, t)$$

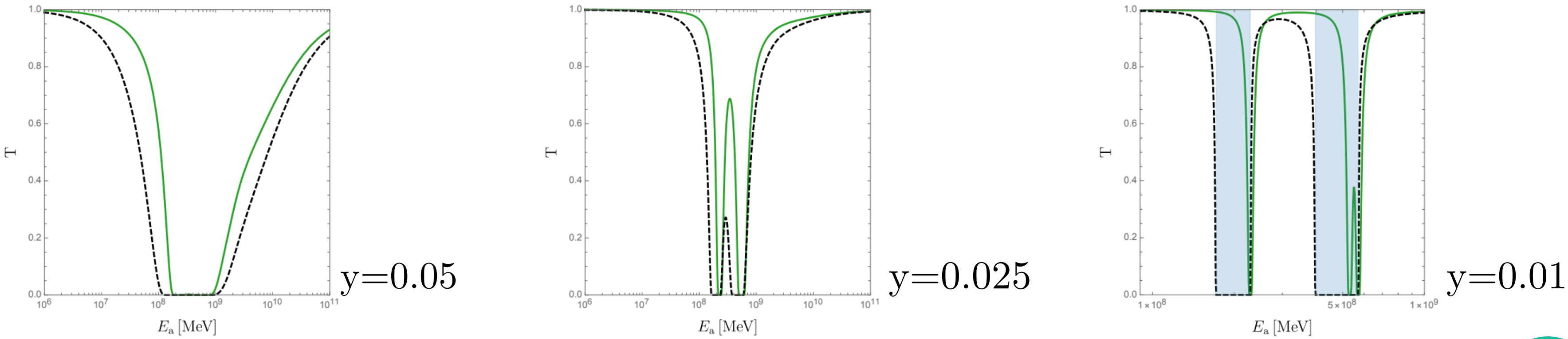
Which becomes $\frac{\partial Z(z, E_\mathrm{a})}{\partial z} = \frac{Z(z, E_\mathrm{a}) \Gamma(E_\mathrm{a}, z)}{H(z)(1+z)}$ with $Z(z, E_\mathrm{a}) := (1+z)\Phi(z, E_\mathrm{a}[1+z])$

The redshift dependent rate is:

$$\Gamma_i(E_\mathrm{a}, z) = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} (1+z)^3 f_i(\vec{p}(1+z))\, v_{M\o l} \sigma_{\nu\nu}(s(E_\mathrm{a}(1+z), \vec{p}(1+z)))$$

Transmittance:

$$T = \frac{Z(0, E_\nu)}{Z(z, E_\nu)} = \mathrm{Exp}\left[- \int_0^z \frac{1}{H(z')(1+z')} \Gamma(E_\nu, z')\, \mathrm{d}z' \right]$$



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