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Primordial High Energy Neutrinos

Theoretical & observational constraints and sharp spectral features

Nicolas Grimbaum Yamamoto

Arxiv:2506.xxxx in collaboration with T.Hambye and M. Hufnagel

Summary .

1 Motivations

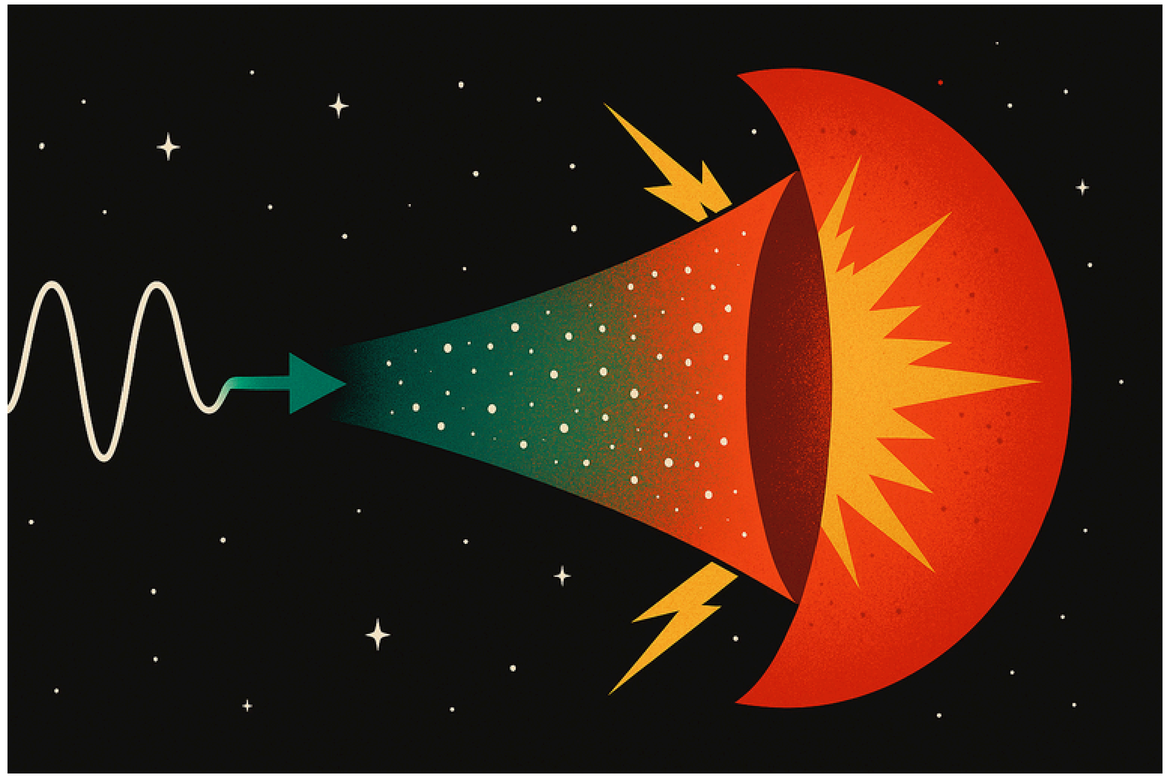
2 Sharp spectral features

3 Medium interactions

4 Constraints

Motivations.

Early universe SM probes:

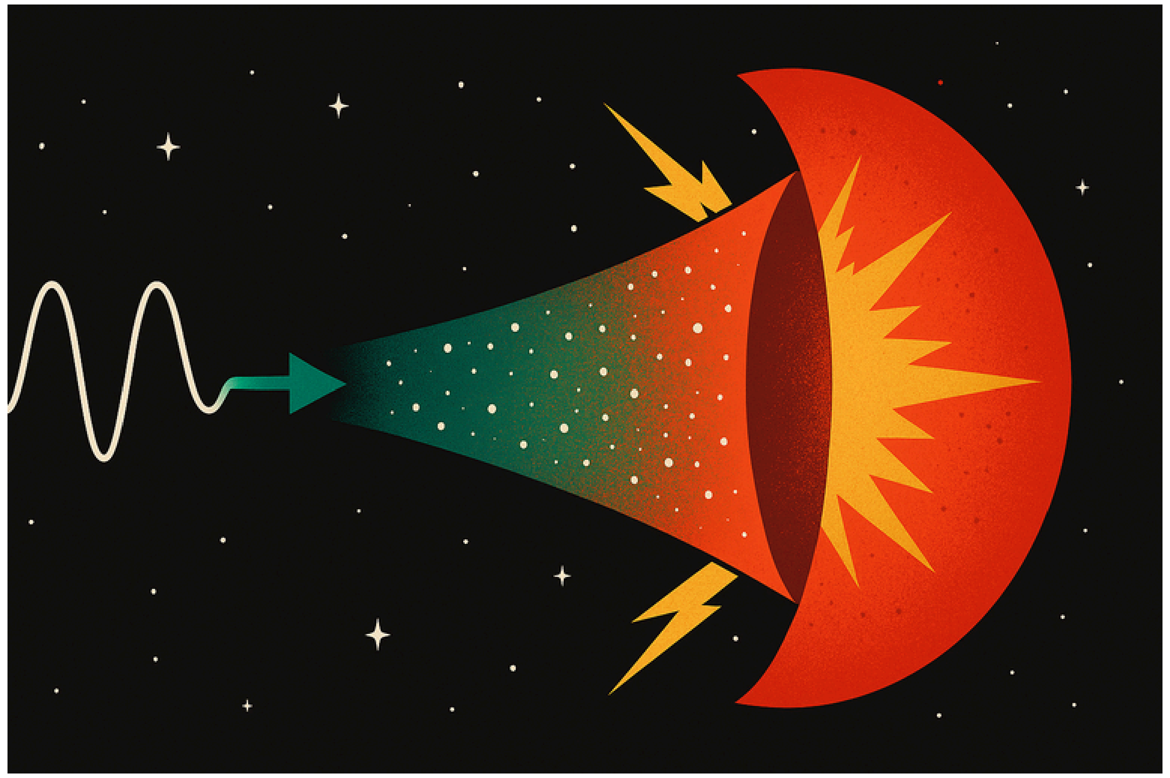


- CMB: z~1100, observed and well studied
- 21-cm: z~20, soon to be observed
- CνB: z~10^{10}, challenging detection prospects

→ **Primordial High Energy Neutrinos (PHENU) ?**

Nicolas Grimbaum Yamamoto
Planck - 2025

Motivations.

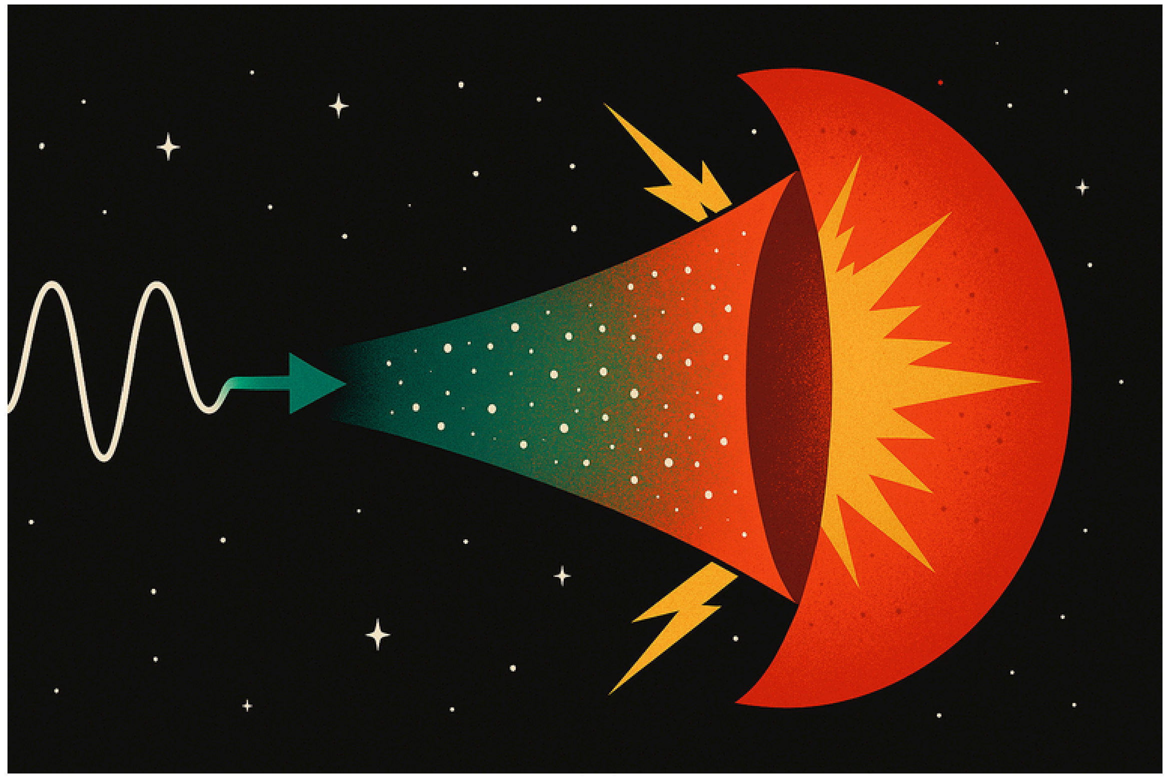


PHENUs:

- Simple BSM scenario
- Emitted anywhere after neutrino decoupling ($z \sim 10^{10}$)
- A sharp signal could remain unaffected and observable today

→ **Primordial High Energy Neutrinos (PHENU) !**

Motivations.

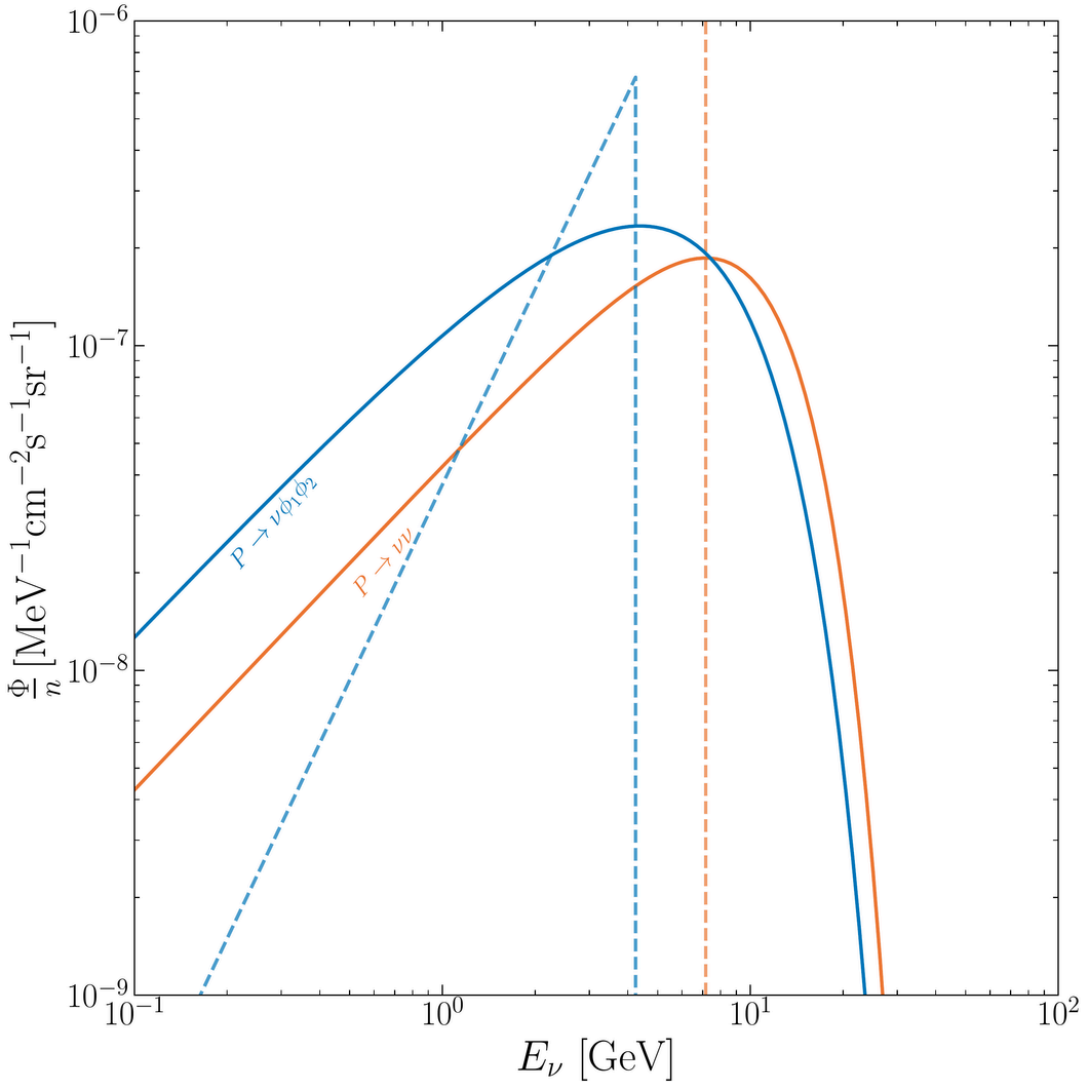


Few works on this topic:

- Frampton, Glashow, '80
- Gelmini, Gondolo, Sarkar '92
- Kanzaki, Kawasaki, Kohri, Moroi '07
- Ema, Jinno, Moroi '13, '14
- McKeen '18
- Jaeckel, Yin '20, '21
- ...

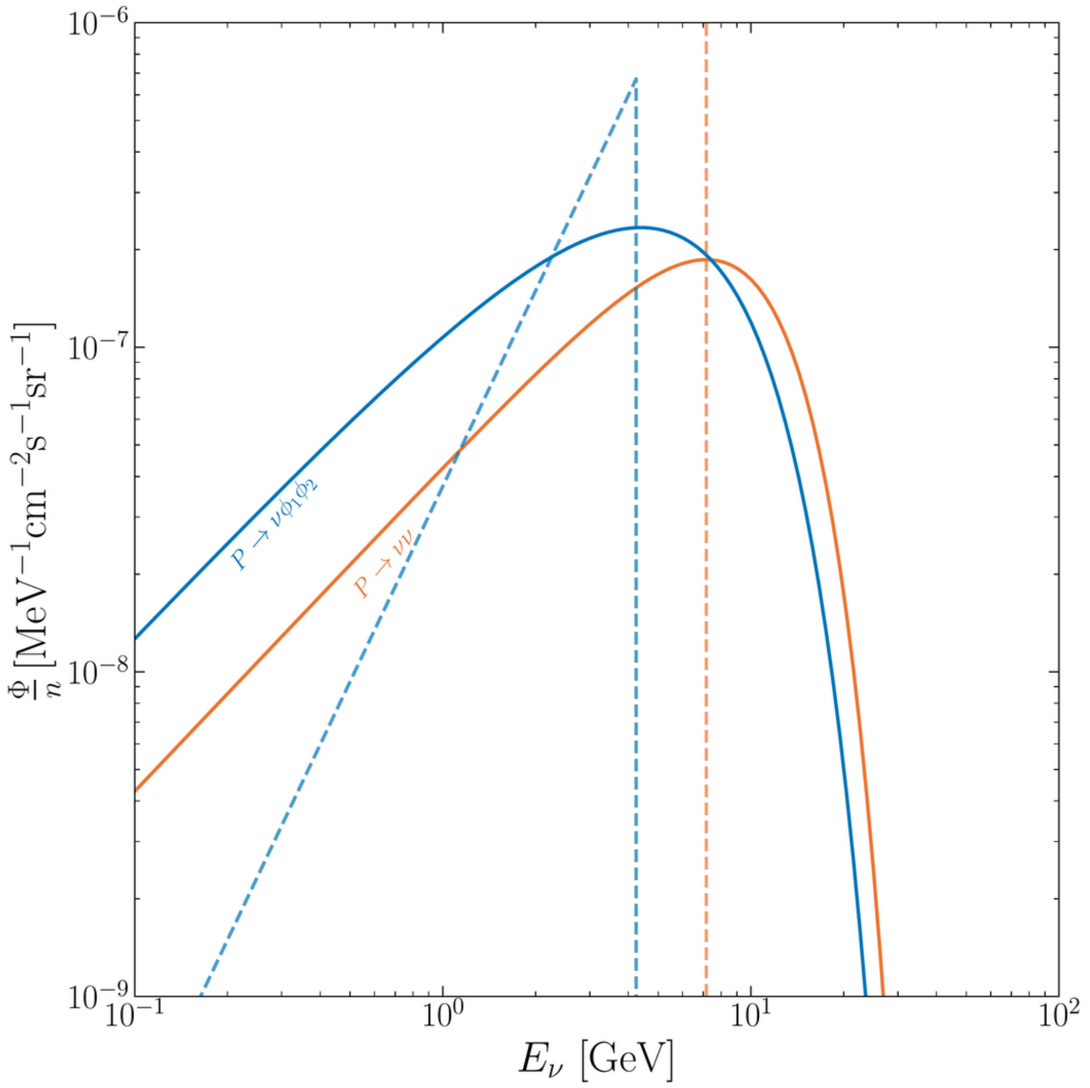
→ A general study is needed

Sharp Spectral Features.



$$\frac{d\phi_\nu}{dE_\nu} = \frac{n\Omega_P^0 \rho_{crit}^0}{4\pi m_P \tau_P} \int_0^\infty dz \frac{e^{-t(z)/\tau_P}}{H(z)} \left.\frac{dN}{dE}\right|_{E=E_\nu(1+z)}$$

Sharp Spectral Features.



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Number of
neutrinos
per decay

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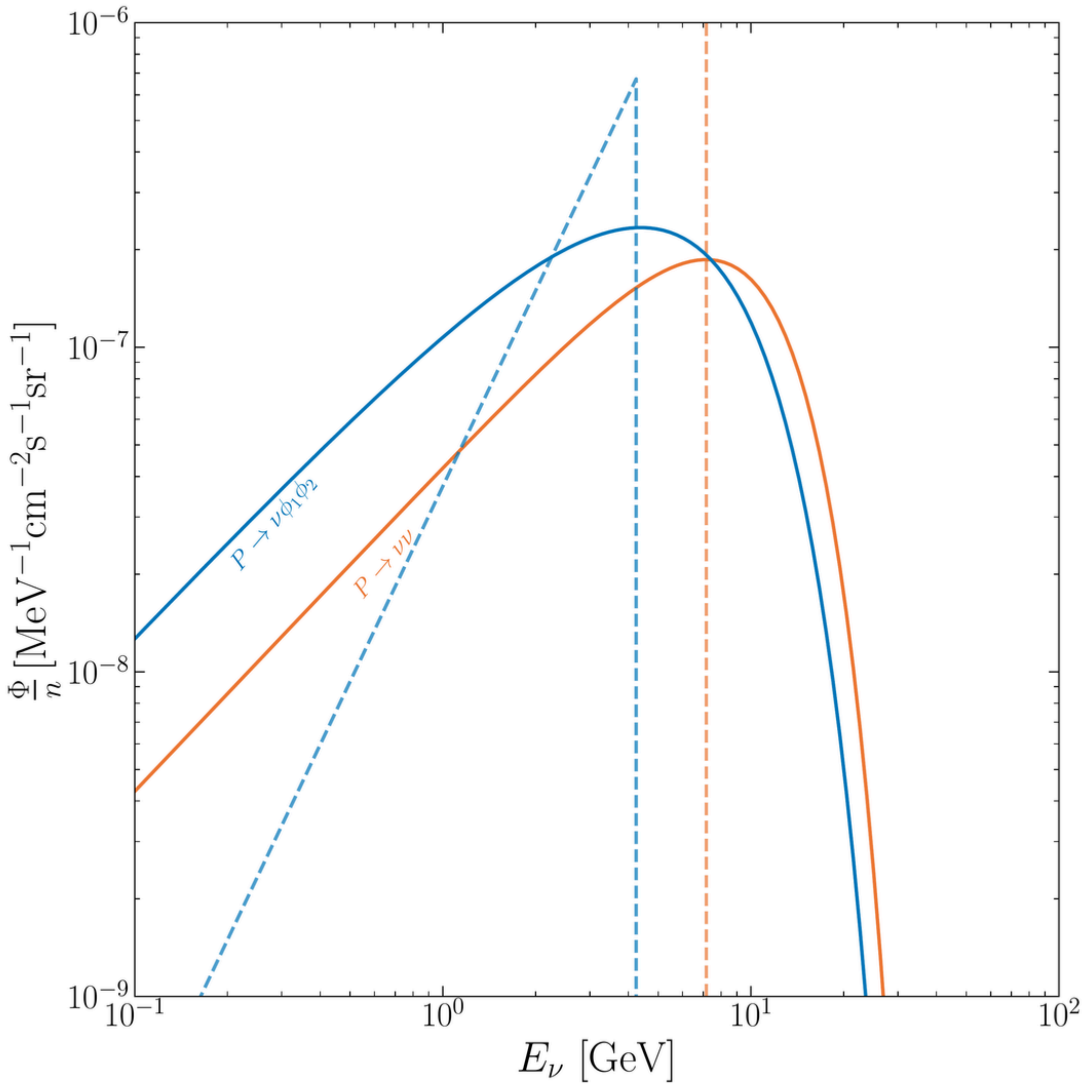
Sharp Spectral Features.



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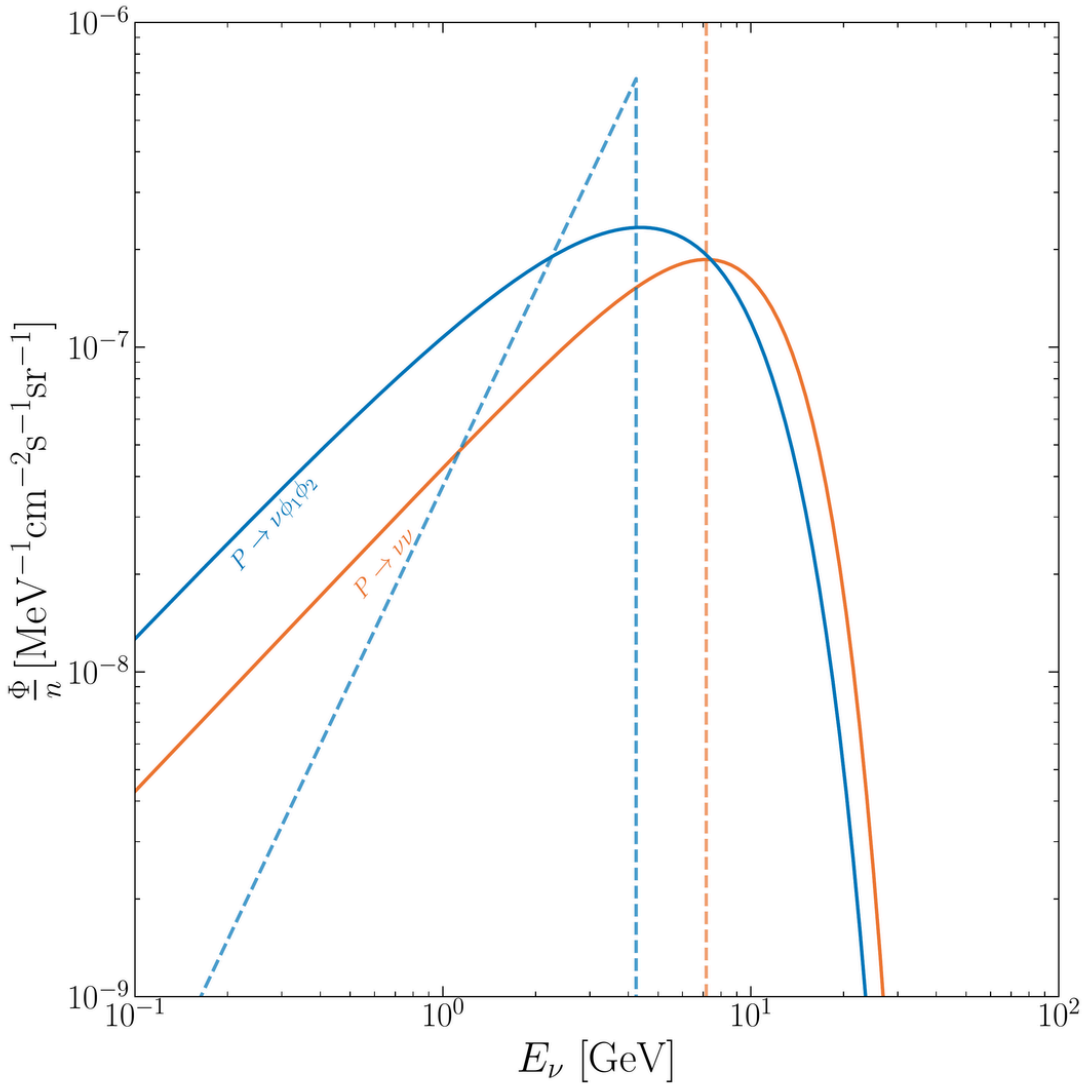
Number of neutrinos per decay

Isotropy

Sharp Spectral Features.



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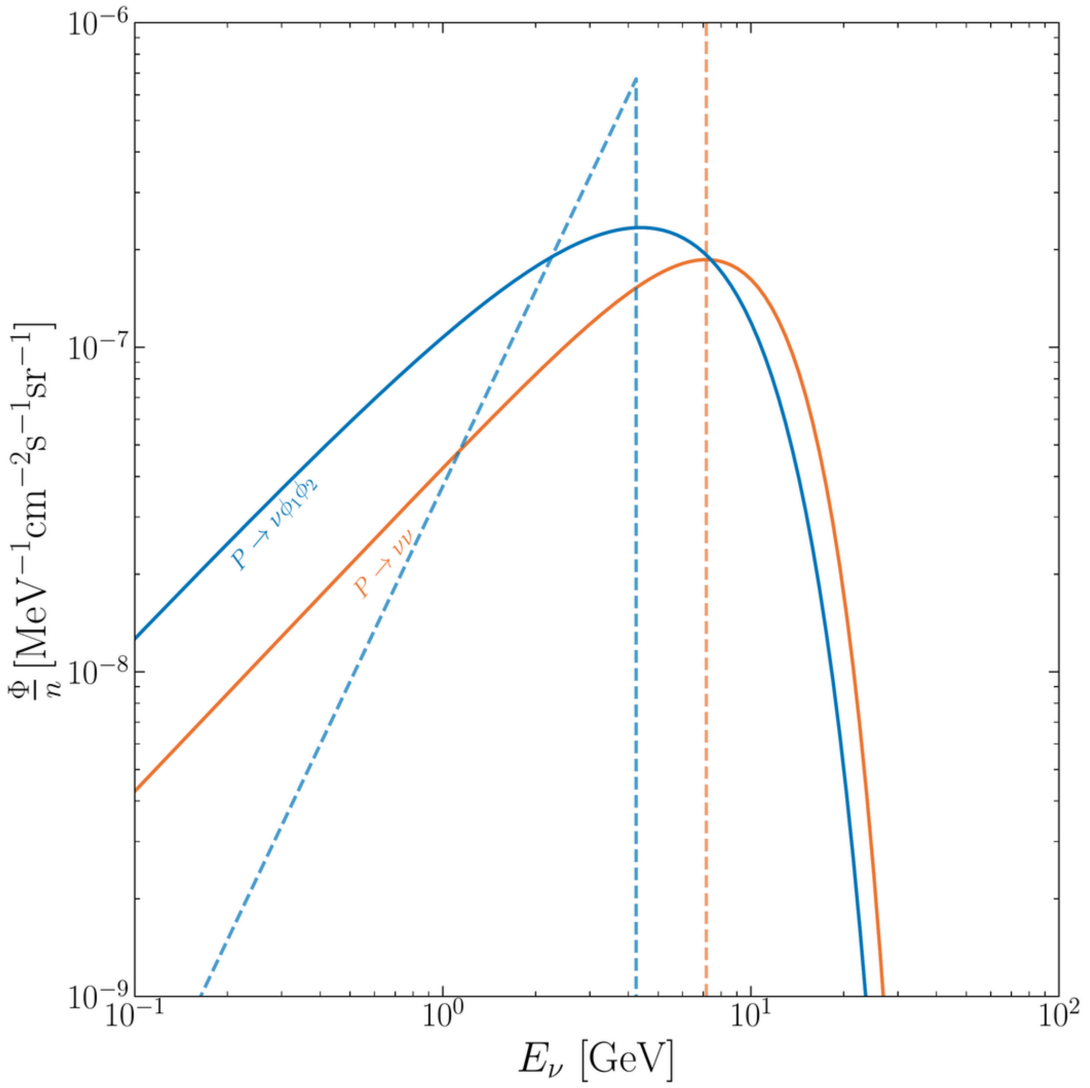
Number of neutrinos per decay

Isotropy

Decaying particle density

Sharp Spectral Features.



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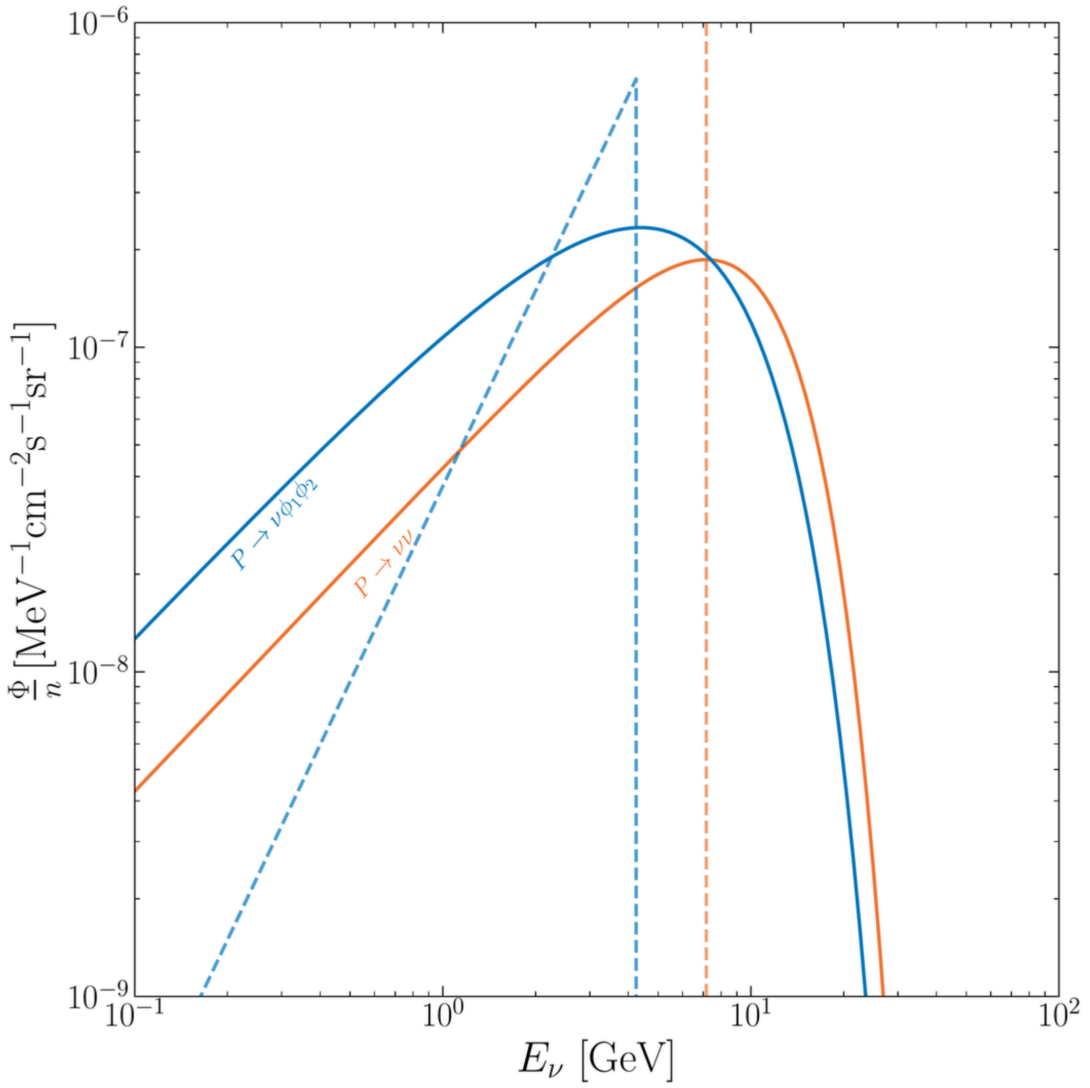
Number of neutrinos per decay

Isotropy

Decaying particle density

decay rate

Sharp Spectral Features.



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Number of neutrinos per decay

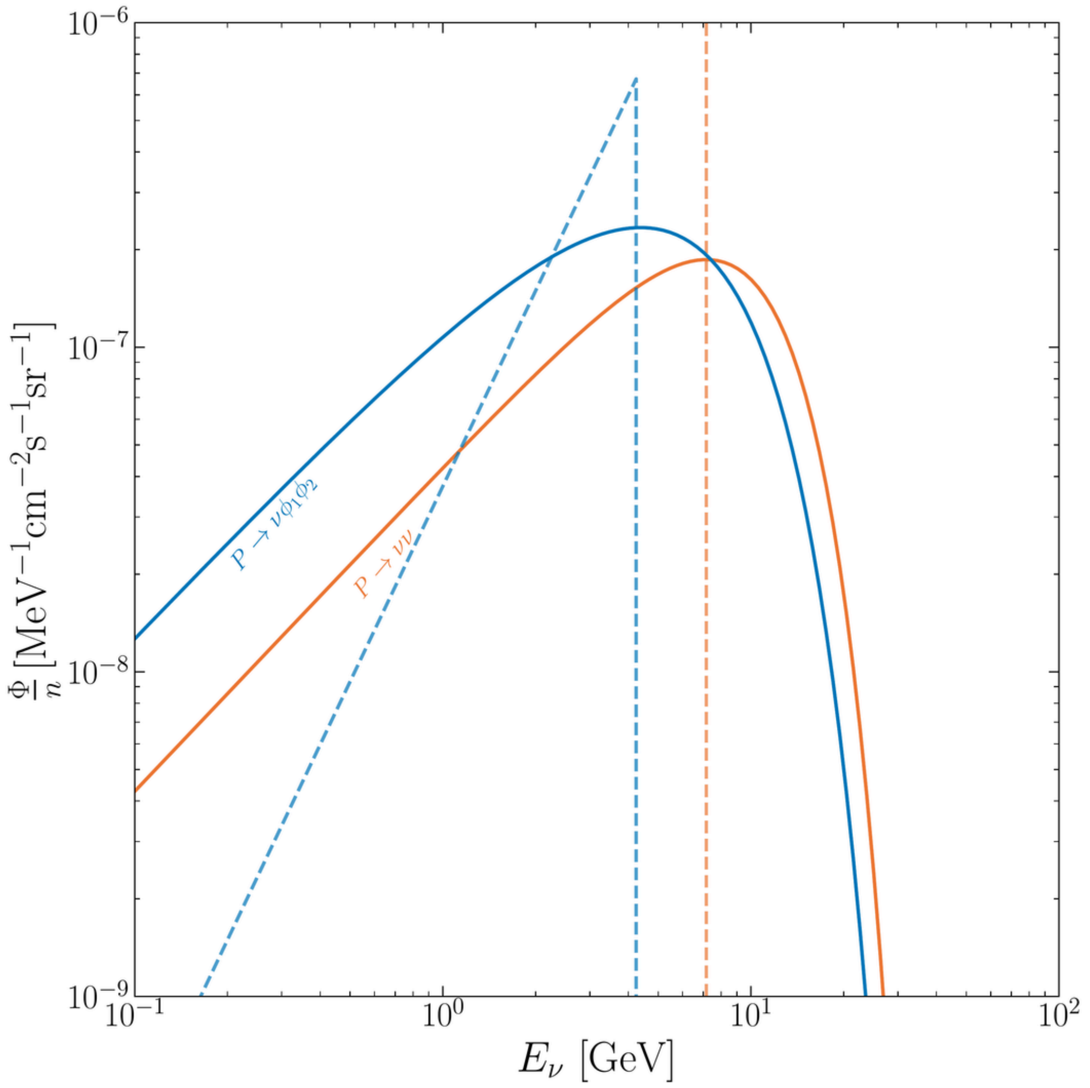
Isotropy

Decaying particle density

decay rate

Integration over the line of sight

Sharp Spectral Features.



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Number of neutrinos per decay

Isotropy

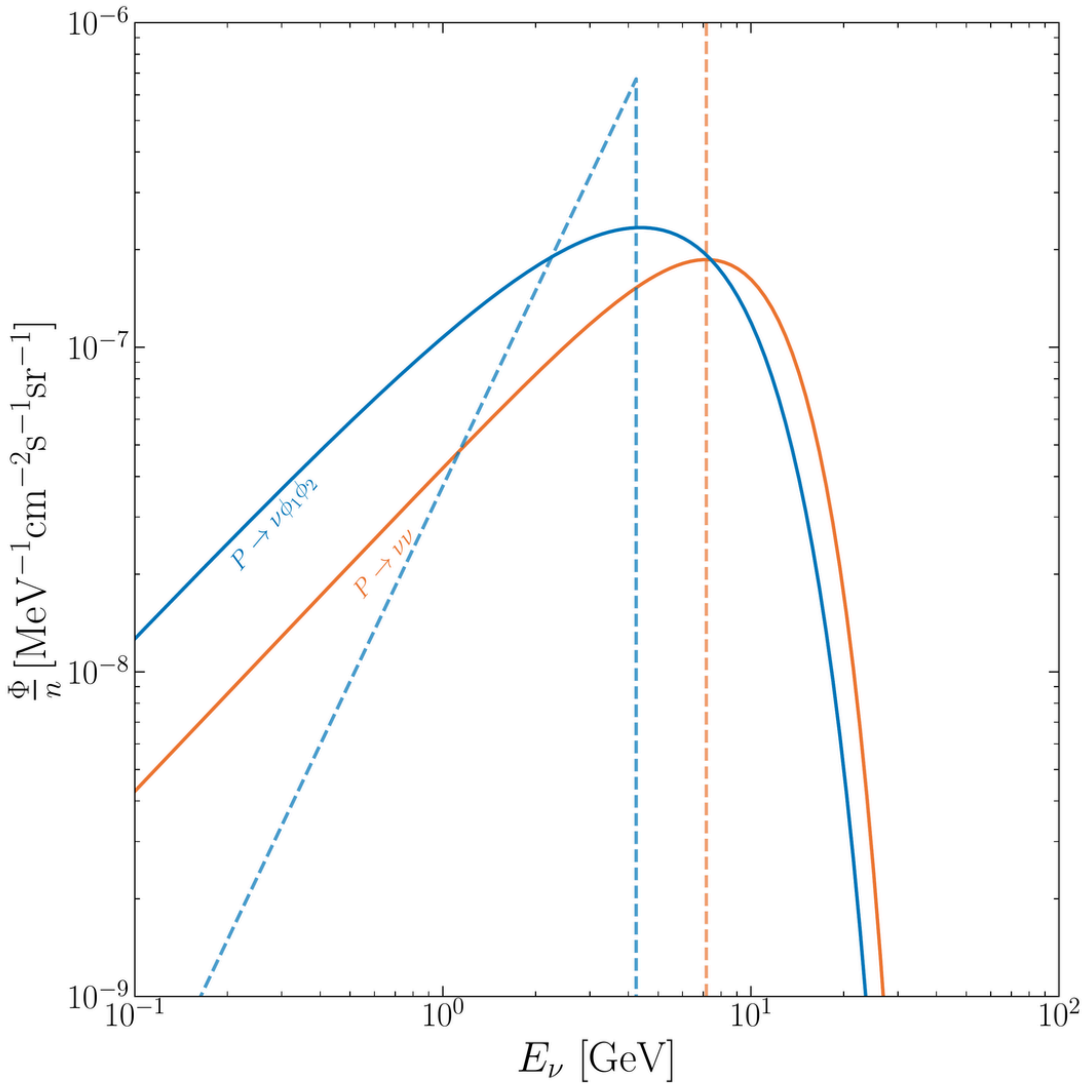
Decaying particle density

decay rate

Integration over the line of sight

Exponential decay

Sharp Spectral Features.



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Number of neutrinos per decay

Isotropy

Decaying particle density

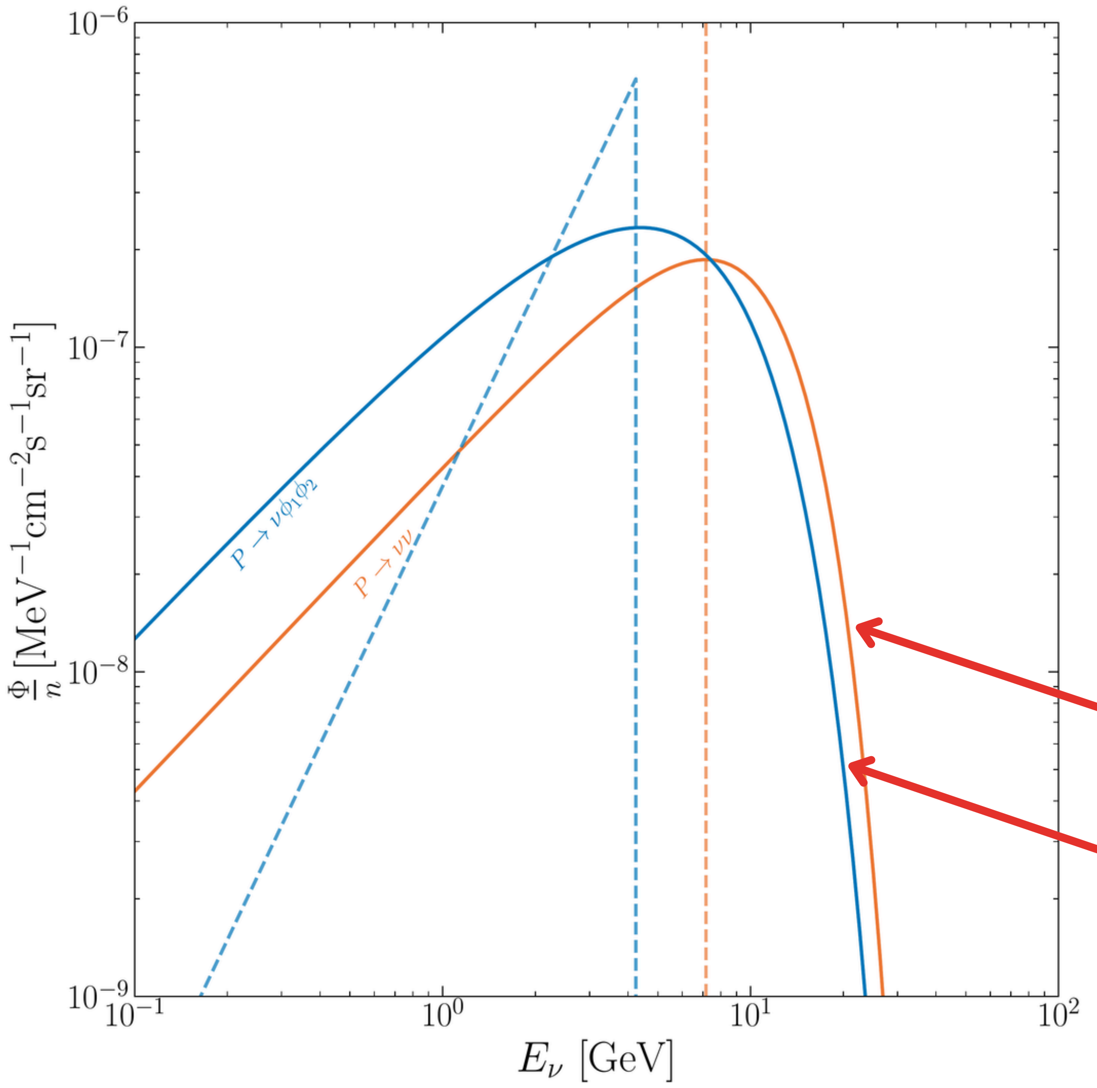
decay rate

Integration over the line of sight

Exponential decay

Spectrum at production

Sharp Spectral Features.



Gelmini, Gondolo, Sarkar 92'

2-body decay

3-body decay

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Number of neutrinos per decay

Isotropy

Decaying particle density

decay rate

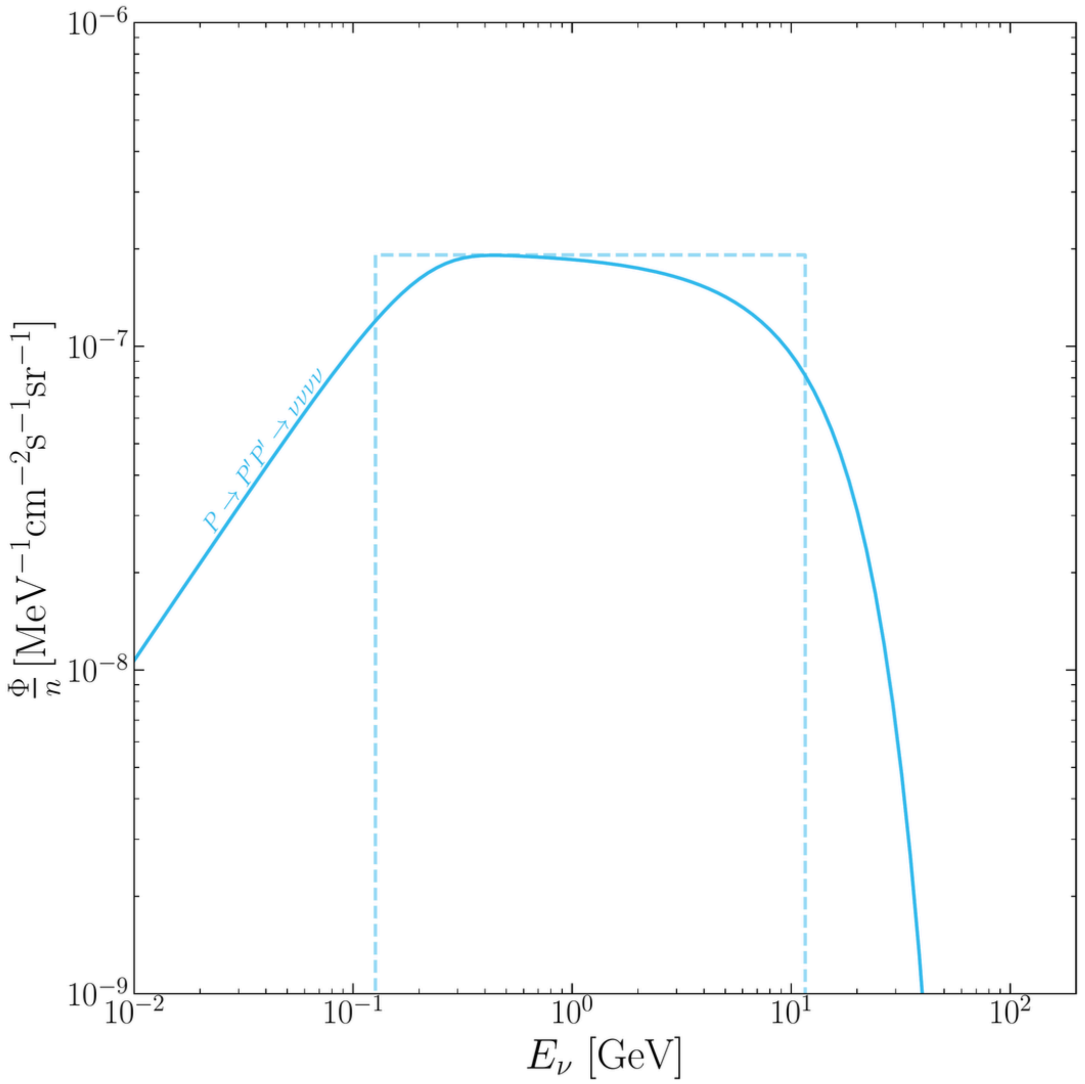
Integration over the line of sight

Exponential decay

Spectrum at production

Redshift broadening

Sharp Spectral Features.



Ibarra, Lopez Gehler, Pato, Miguel, 12'

$$\frac{d\phi_\nu}{dE_\nu} = \frac{n\Omega_P^0\rho_{crit}^0}{4\pi m_P \tau_P}\int_0^\infty dz \frac{e^{-t(z)/\tau_P}}{H(z)} \frac{dN}{dE}\bigg|_{E=E_\nu(1+z)}$$

Number of neutrinos per decay

Isotropy

Decaying particle density

decay rate

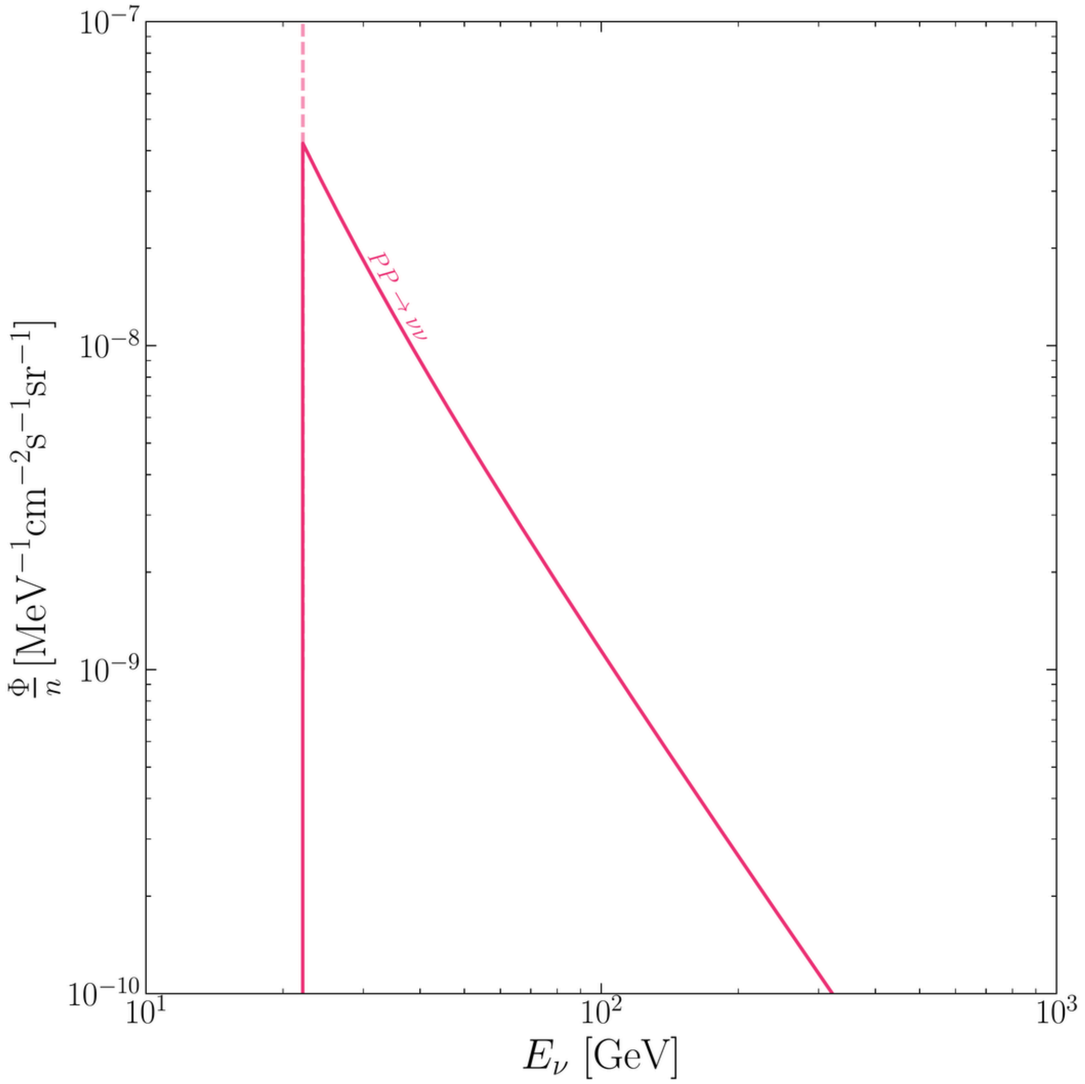
Integration over the line of sight

Exponential decay

Spectrum at production

Box shaped spectrum $P \to P'P' \to \nu\nu\nu\nu$

Sharp Spectral Features.



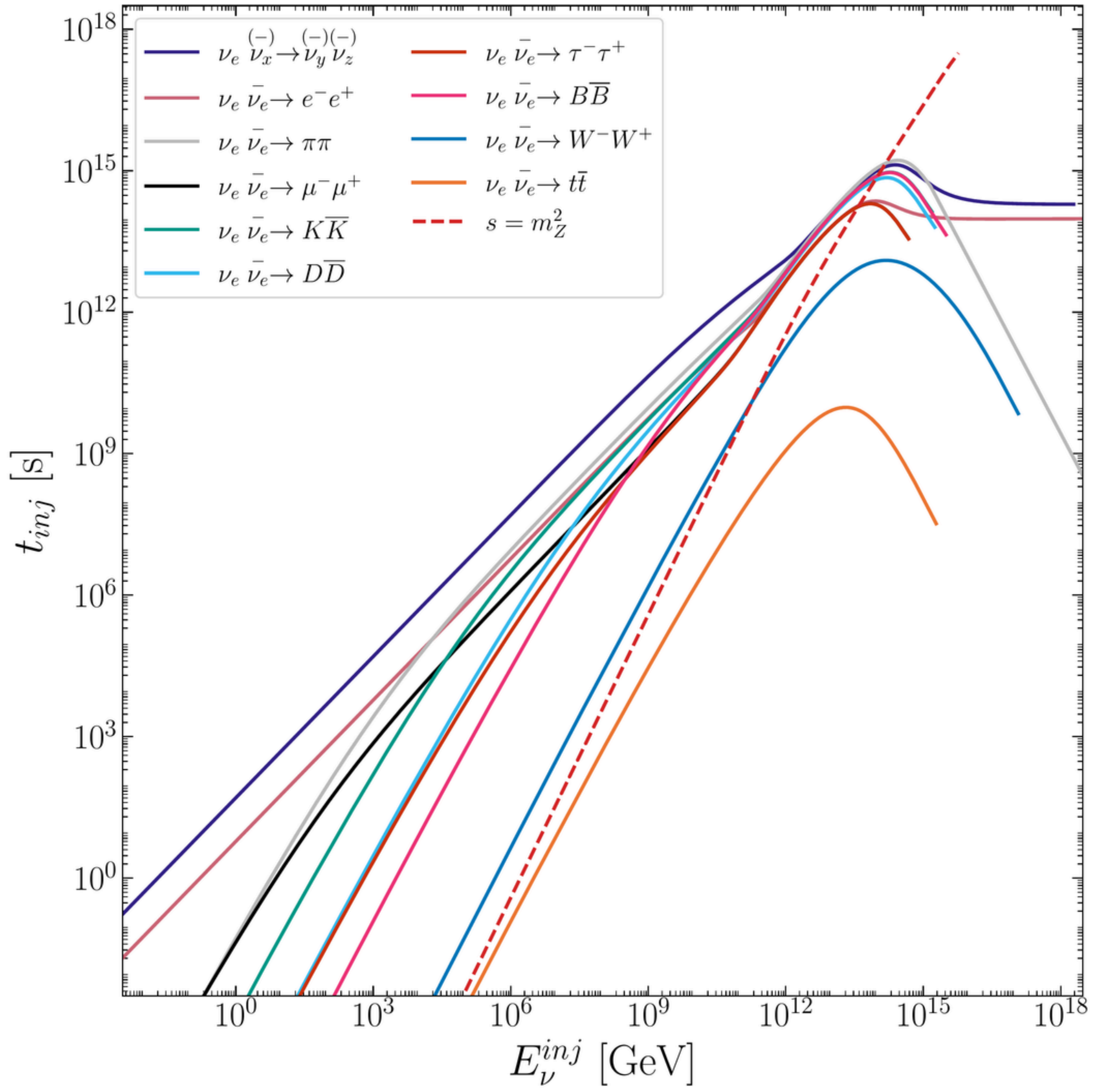
Out of equilibrium annihilation

New type of spectral feature

From, e.g., an asymmetric population of P oscilatting into anti-P after a phase transition

Medium interactions.

$$S_\nu(z_e, E_0) = \int_0^{z_e} \frac{dz}{(1+z)H(z)} \langle \sigma v \rangle n_{\nu_{BG}}$$



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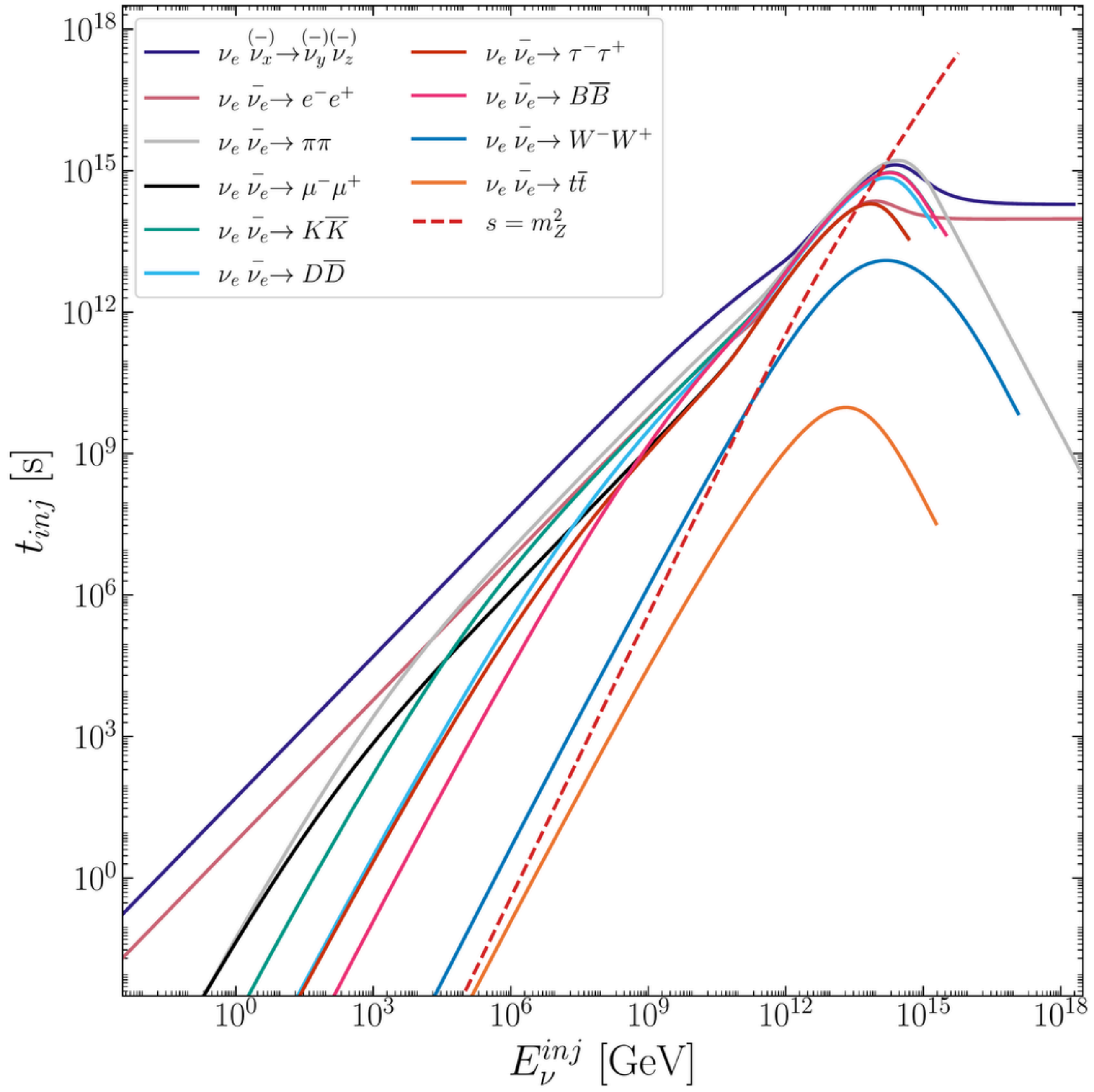
Average number of scattering



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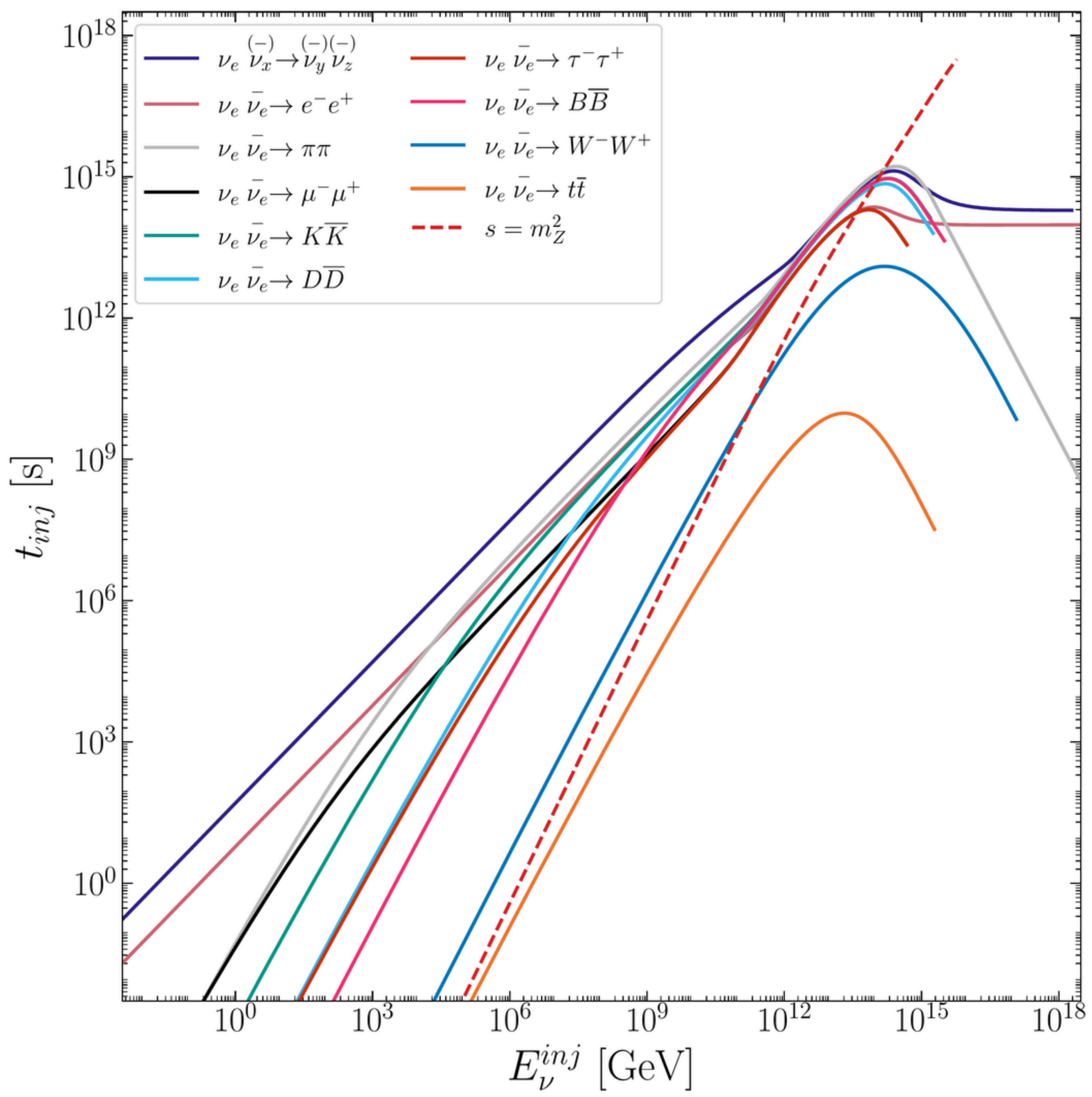

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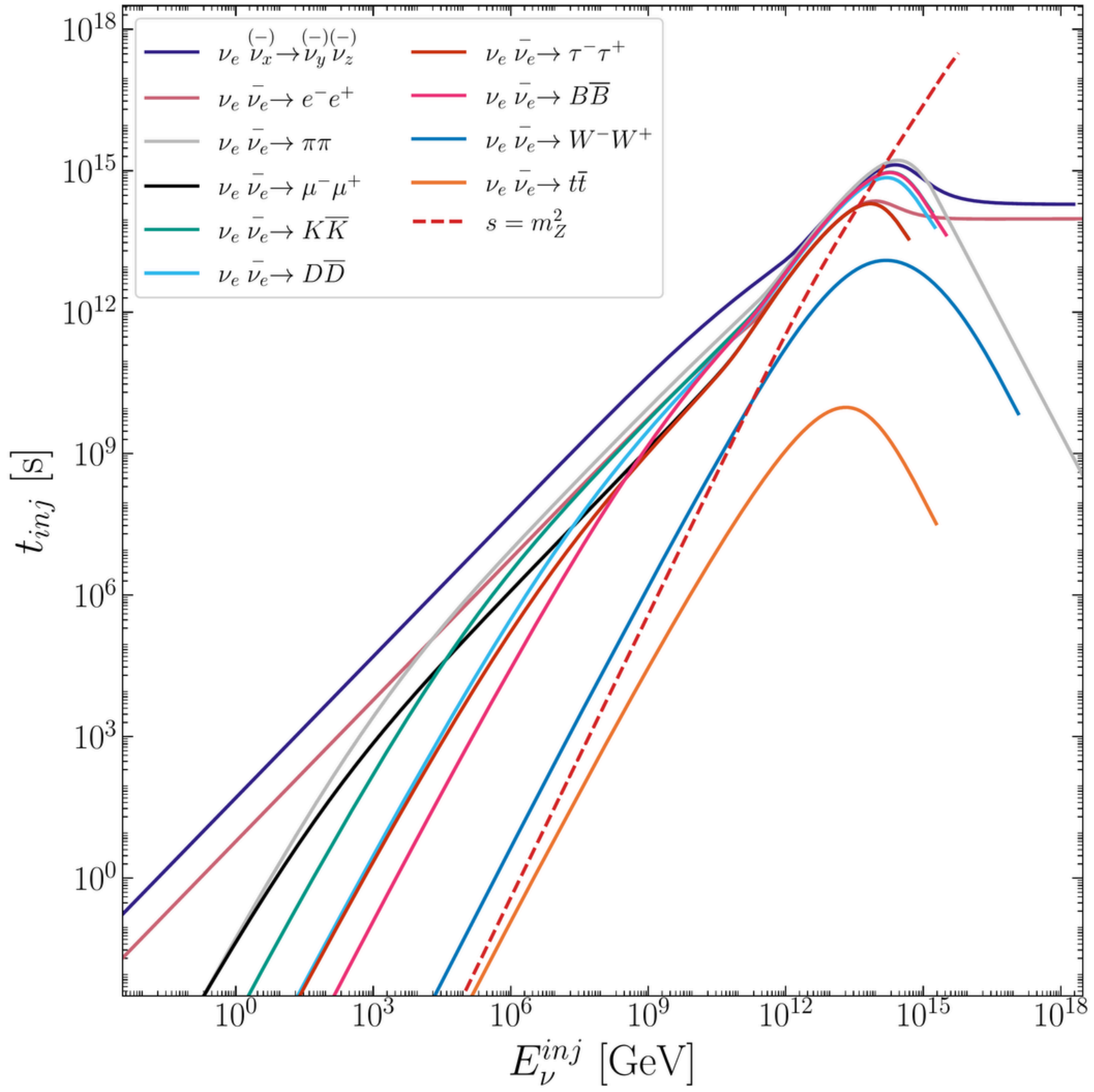
Average number of scattering

Integration over the line of sight

cross section averaged over target distribution function



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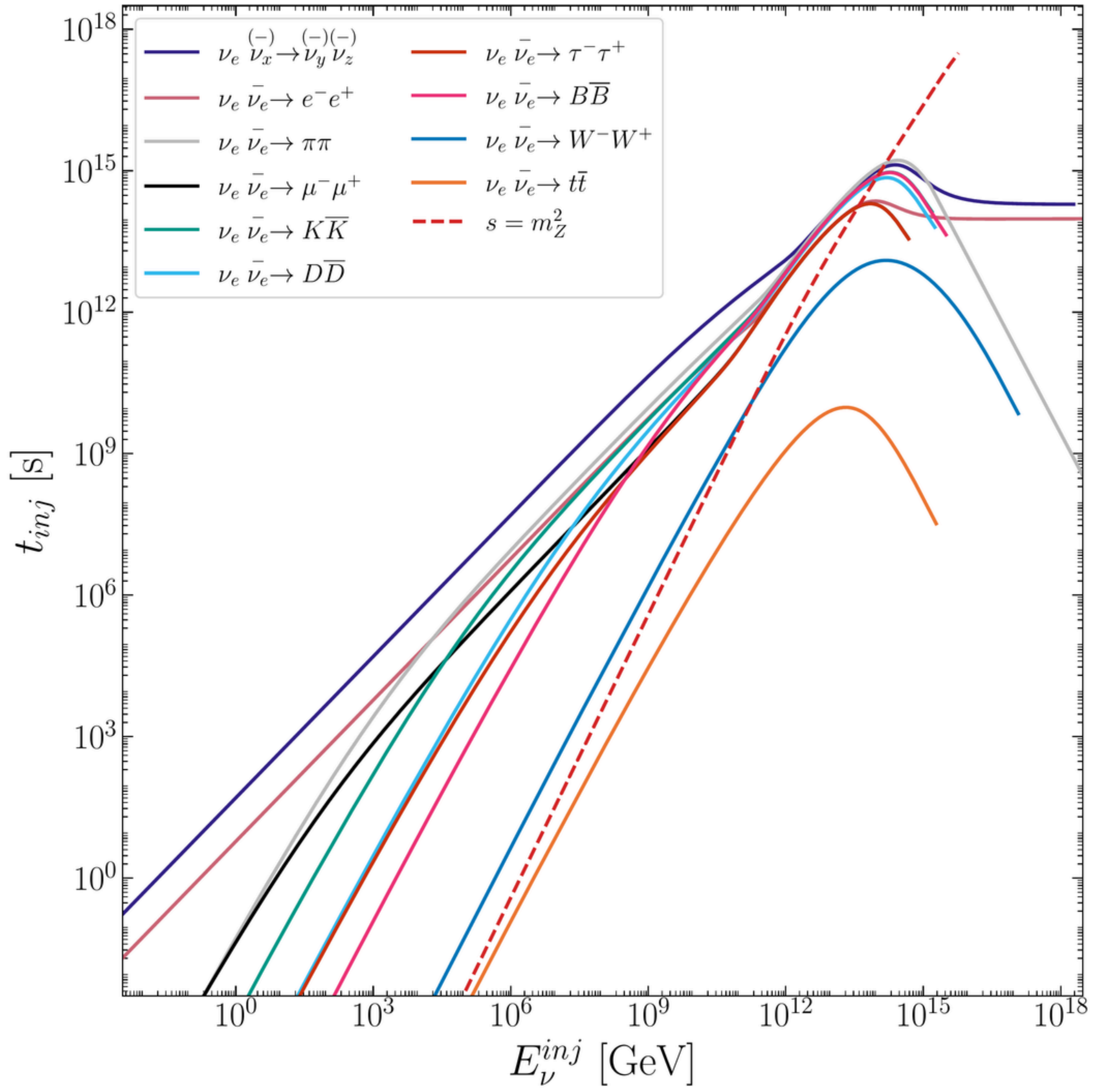
Average number of scattering

Integration over the line of sight

cross section averaged over target distribution function

target neutrino number density



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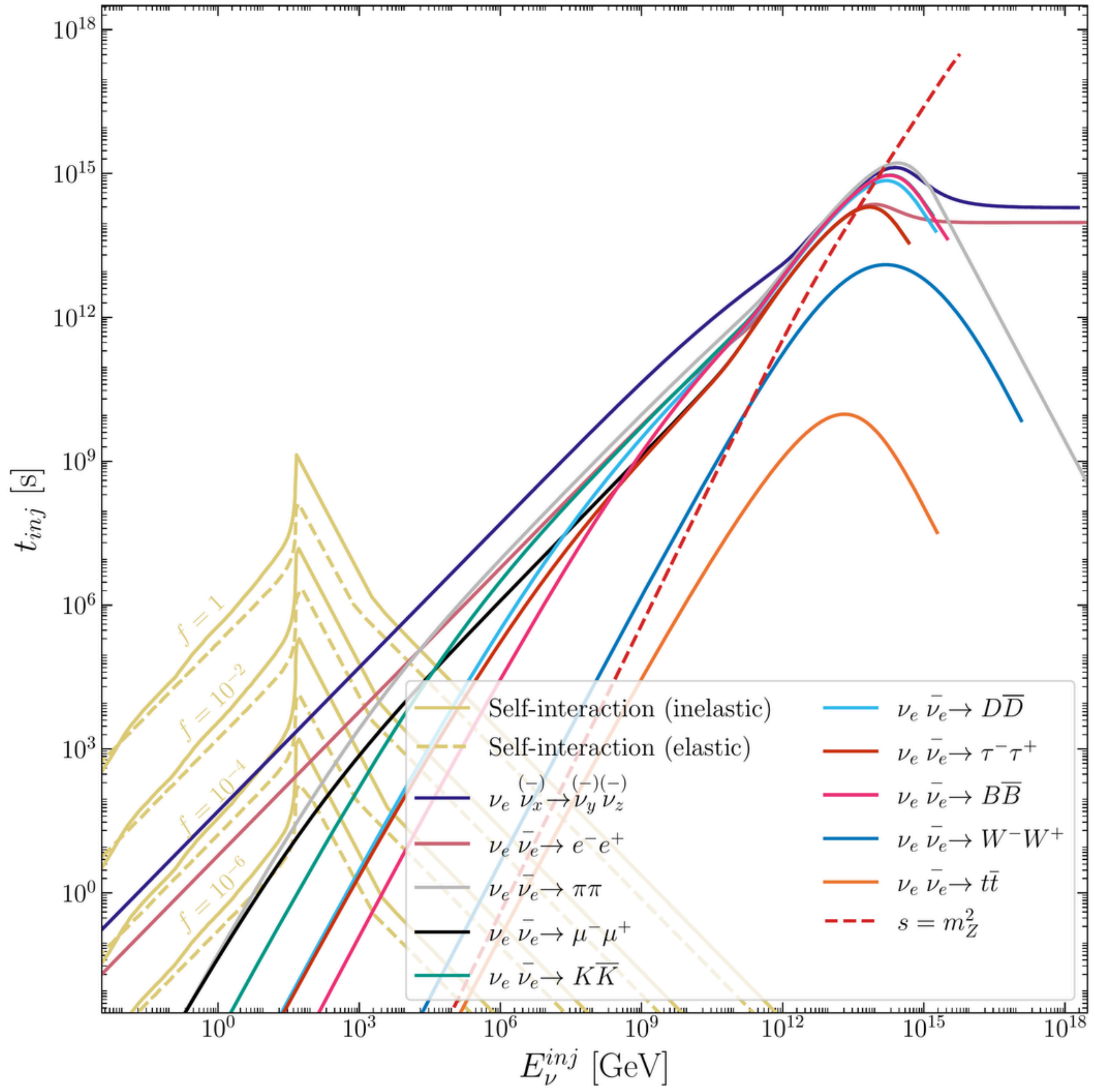


$$f = \frac{\Omega_P^0}{\Omega_{DM}^0}$$

Medium interactions.

$$S_\nu(z_e, E_0) = \int_0^{z_e} \frac{dz}{(1+z)H(z)} \langle \sigma v \rangle n_{\nu_{BG}}$$

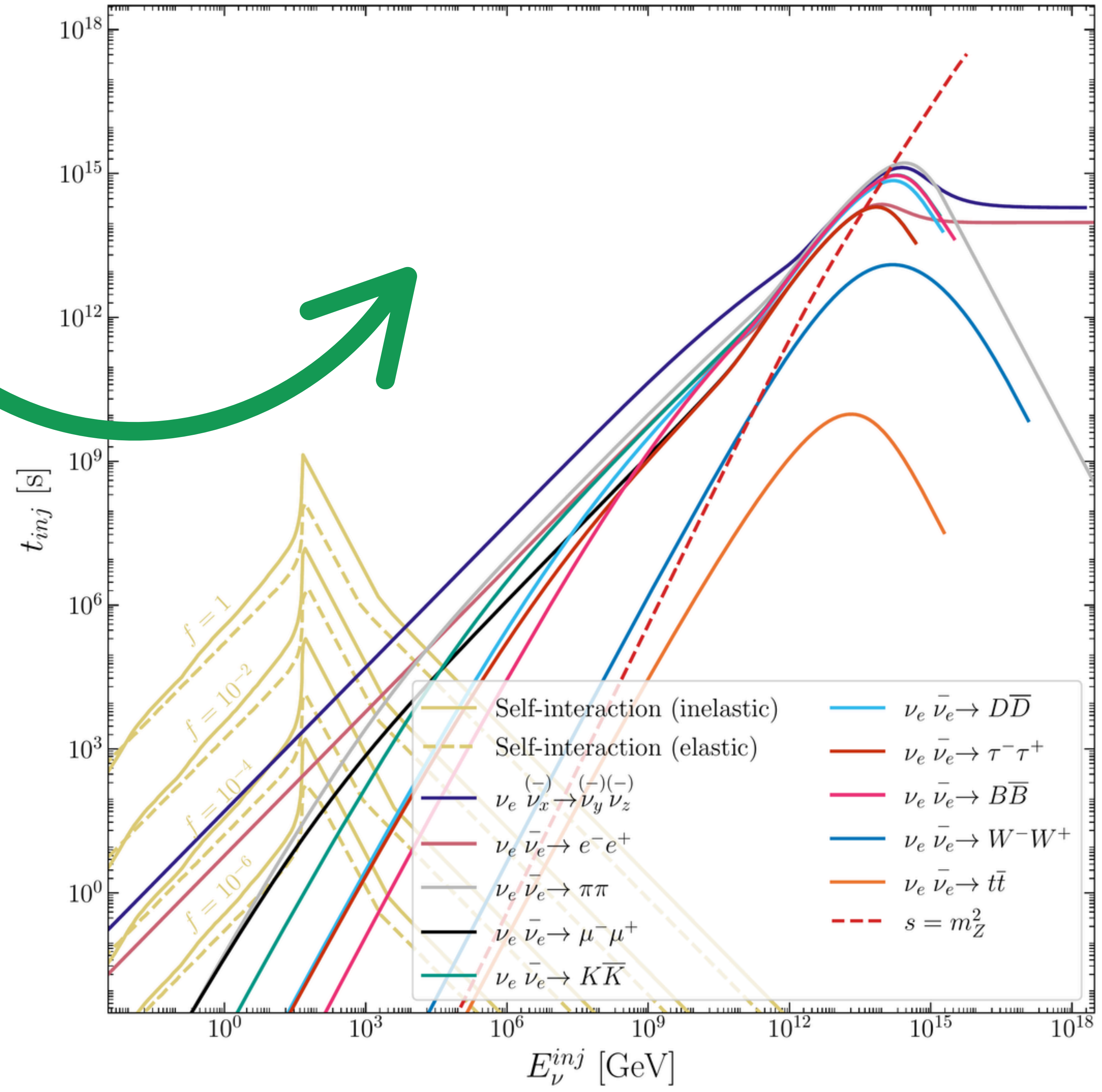
Average number of scattering

Integration over the line of sight

Thermally averaged cross section

Background neutrino number density

Sharp spectral features mostly unaffected

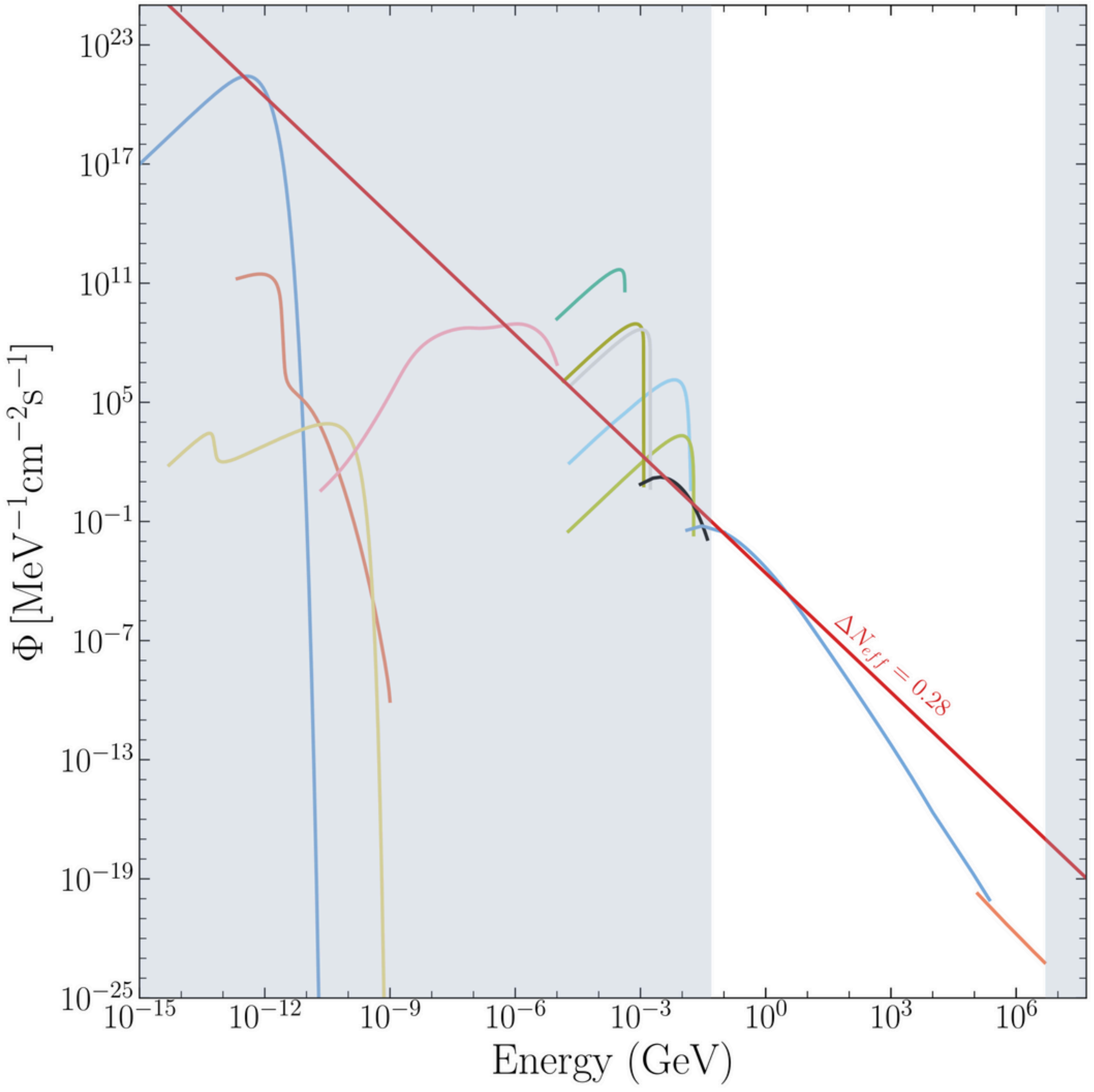


$$E_\nu^{inj} = E_\nu^0 (1+z)$$

$$t_{inj} = t(z)$$

$$f = \frac{\Omega_P^0}{\Omega_{DM}^0}$$

Constraints.

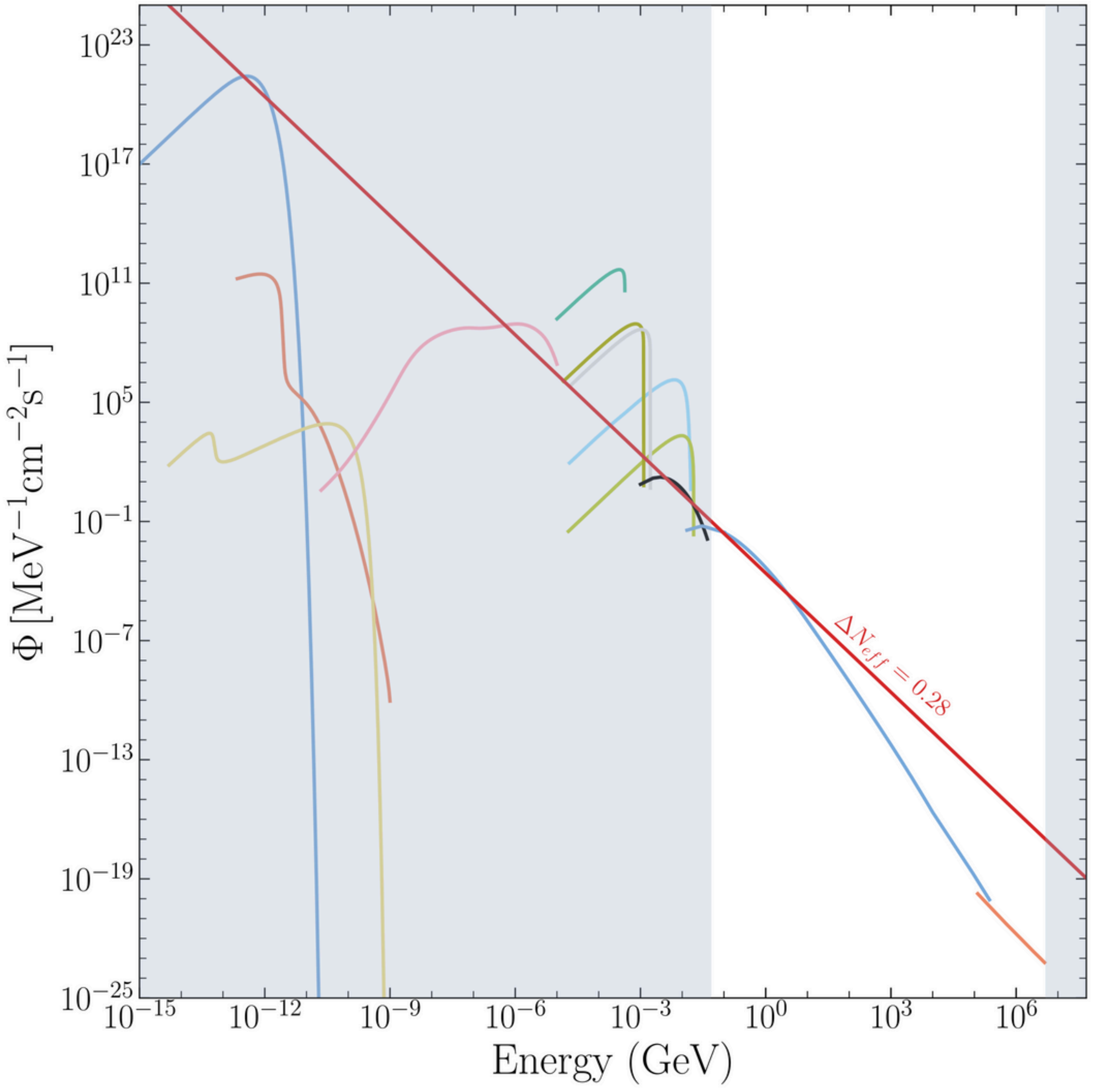


Vitagliano, Tamborra, Raffelt 19'

Observational:

- Atmospheric flux (SuperKamiokande, Icecube) > 50 MeV
- Astrophysical flux (Icecube) < 5 PeV

Constraints.



Vitagliano, Tamborra, Raffelt 19'

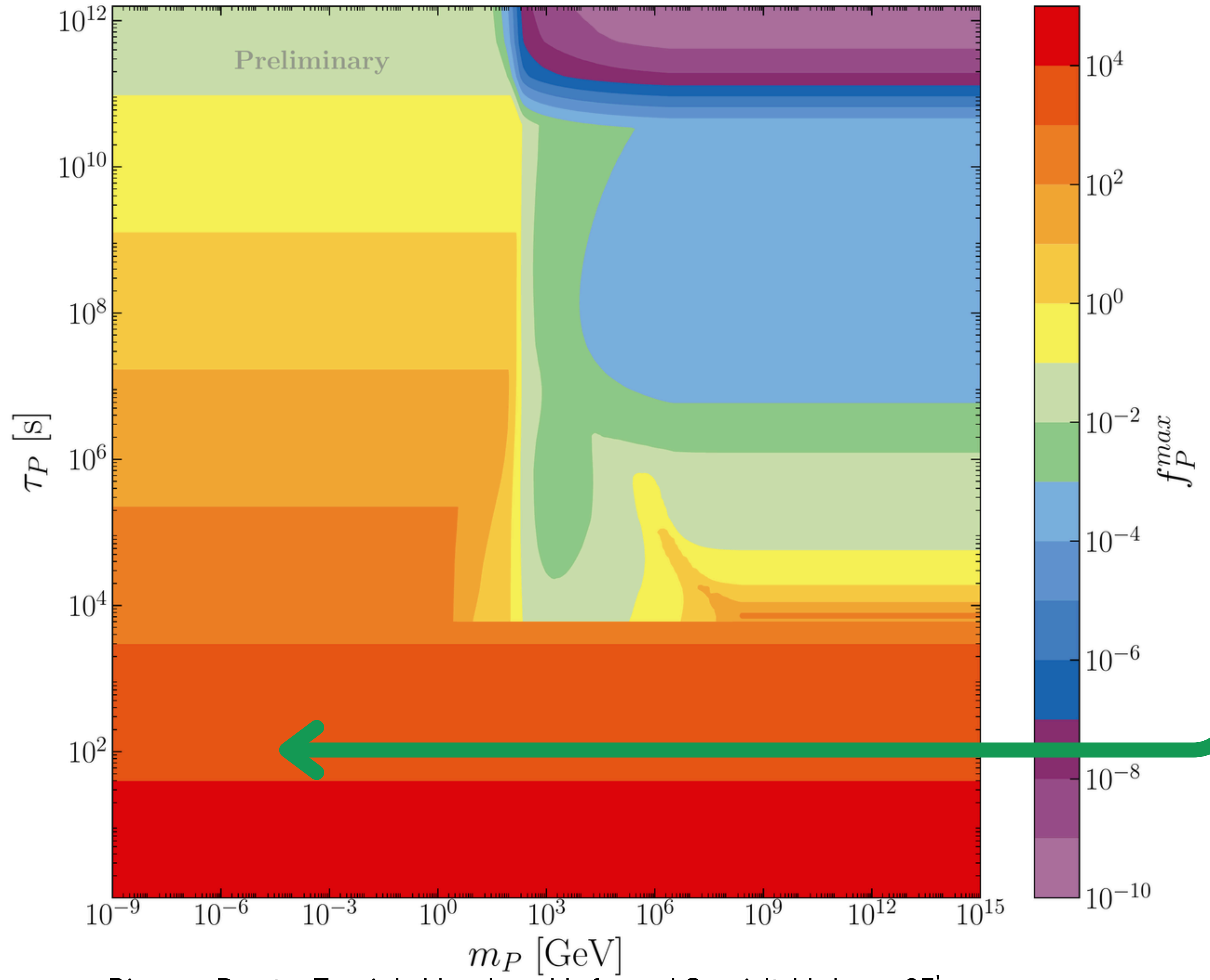
Observational:

- Atmospheric flux (SuperKamiokande, Icecube) > 50 MeV
- Astrophysical flux (Icecube) < 5 PeV

PHENU flux must be at most of the value of the observed flux

→ Upper bound on f

Constraints.

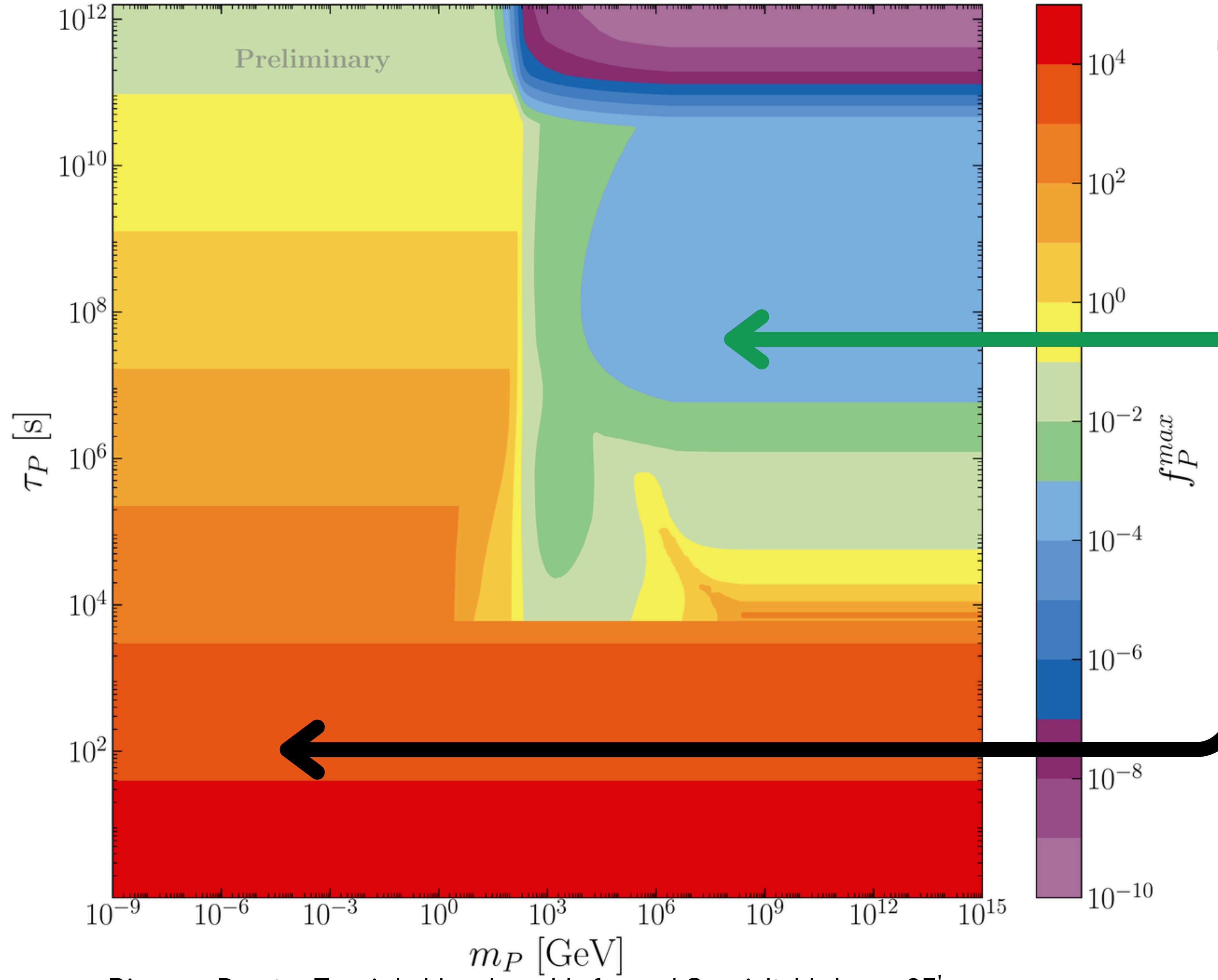


Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'
Hambye, Hufnagel, Lucca, 21'
Acharya, Khatri, 19'

Theoretical:

N_{eff} bound on additional neutrino energy density

Constraints.



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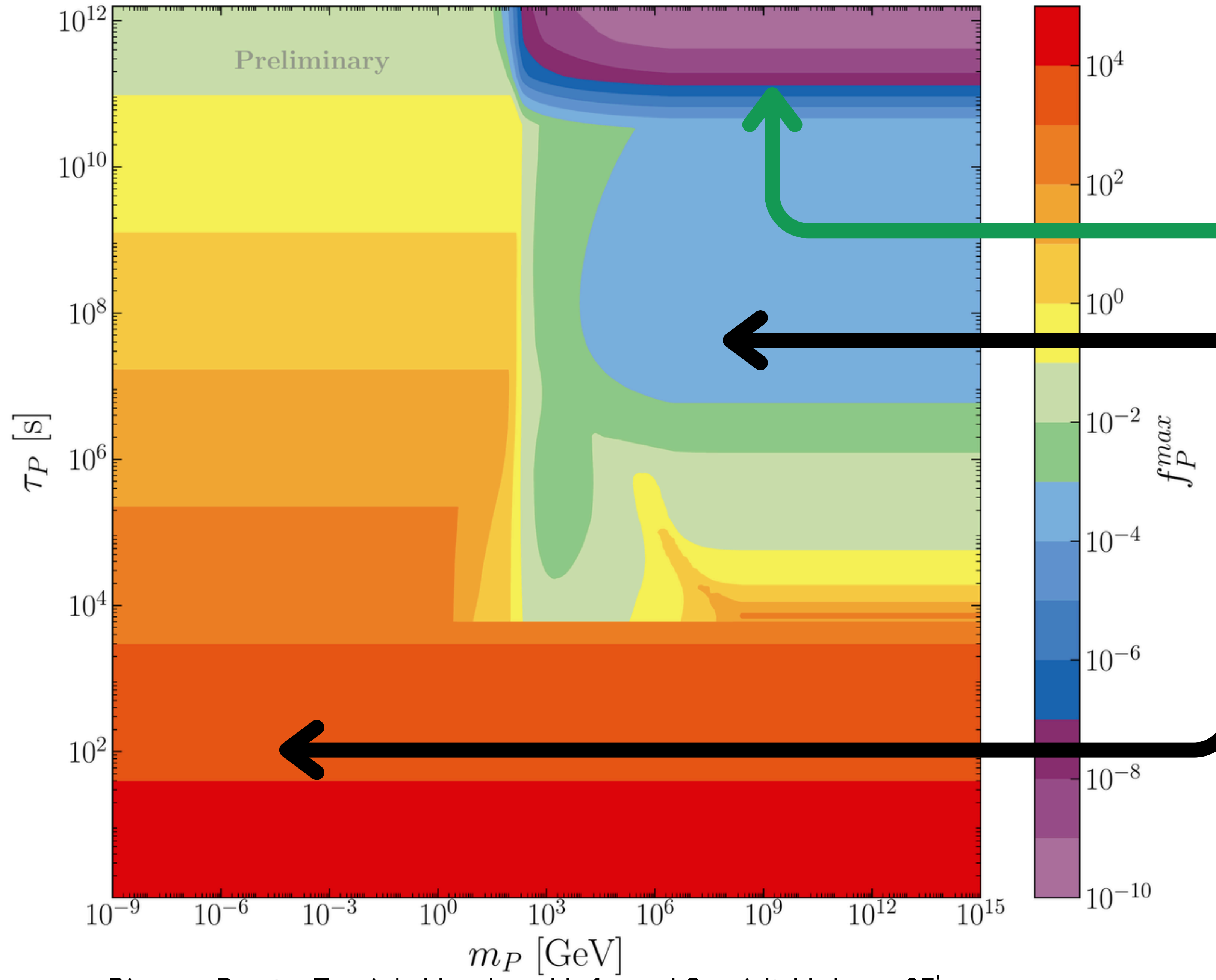
Theoretical:

BBN bound from photo and hadro disintegration of light elements (see Sara Bianco's talk tomorrow)

N_{eff} bound on additional neutrino energy density

Constraints.



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Theoretical:

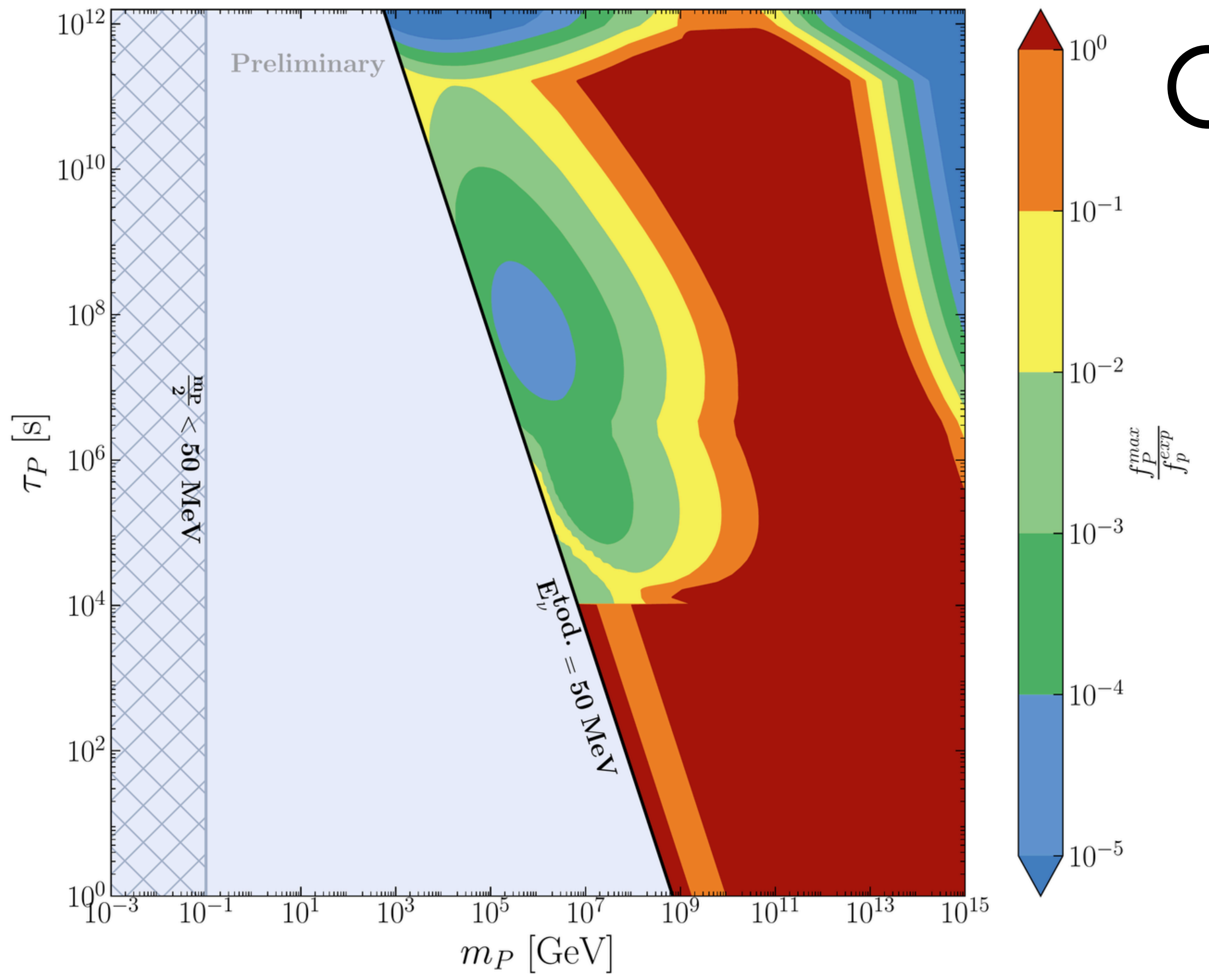
CMB anisotropies bound

BBN bound from photo and hadro disintegration of light elements (see Sara Bianco's talk tomorrow)

N_{eff} bound on additional neutrino energy density

Competing bounds with observations

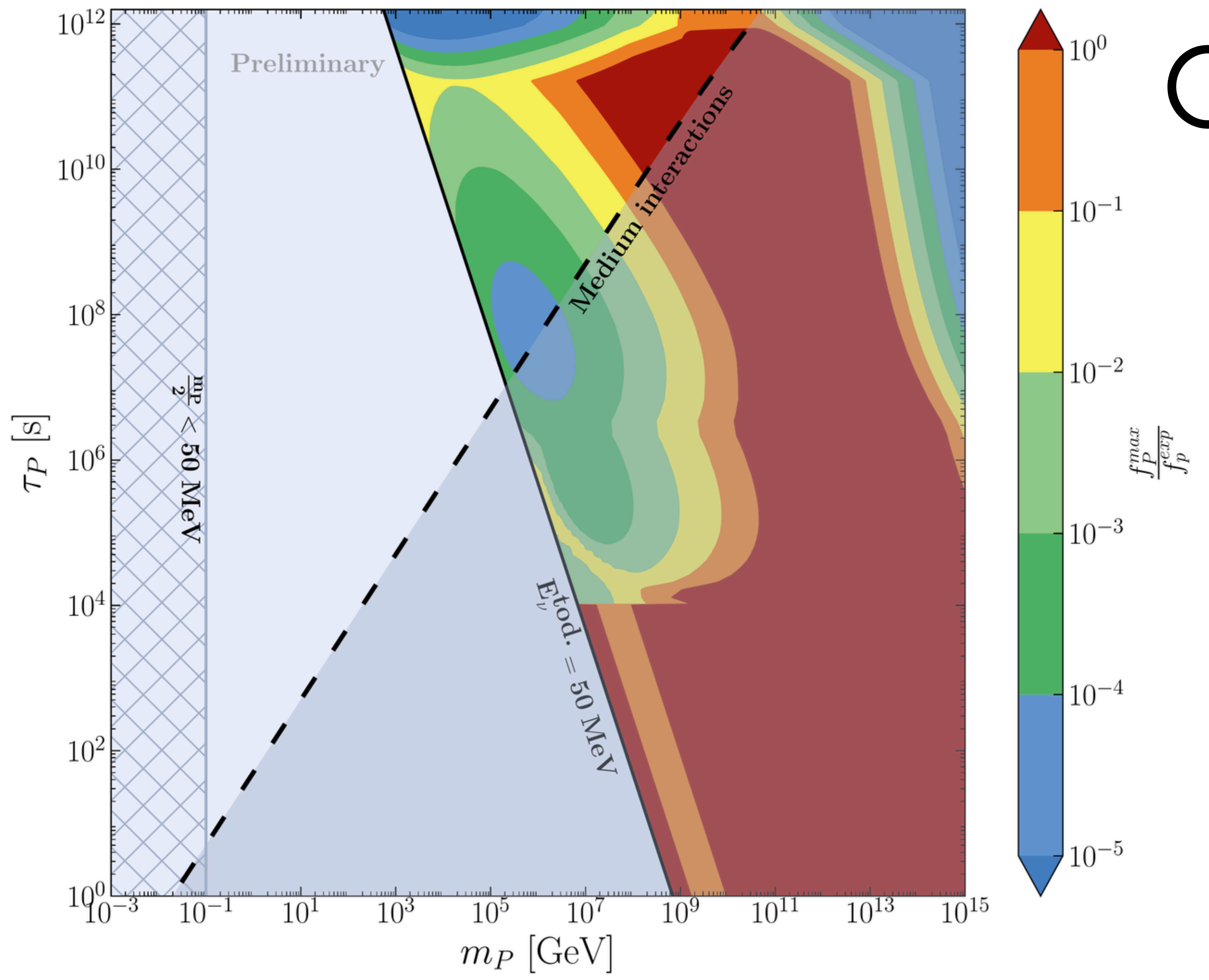
Constraints.



Combination: $\frac{f^{th.}}{f^{obs.}}$

- Ratio > 1: Unconstrained by theoretical bounds
- Ratio > 10^{-2}: Potentially observable today
- Ratio < 10^{-2}: Signal too weak to be observed
- Ratio < 10^{-5}: Hopeless

Constraints.



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$$10 \text{ TeV} \lesssim m_P \lesssim 10^{11} \text{ GeV} \qquad 10^{-8} \lesssim f_P \lesssim 10^{-2}$$

$$10^9 \text{ s} \lesssim \tau_P \lesssim 10^{12.5} \text{ s}$$

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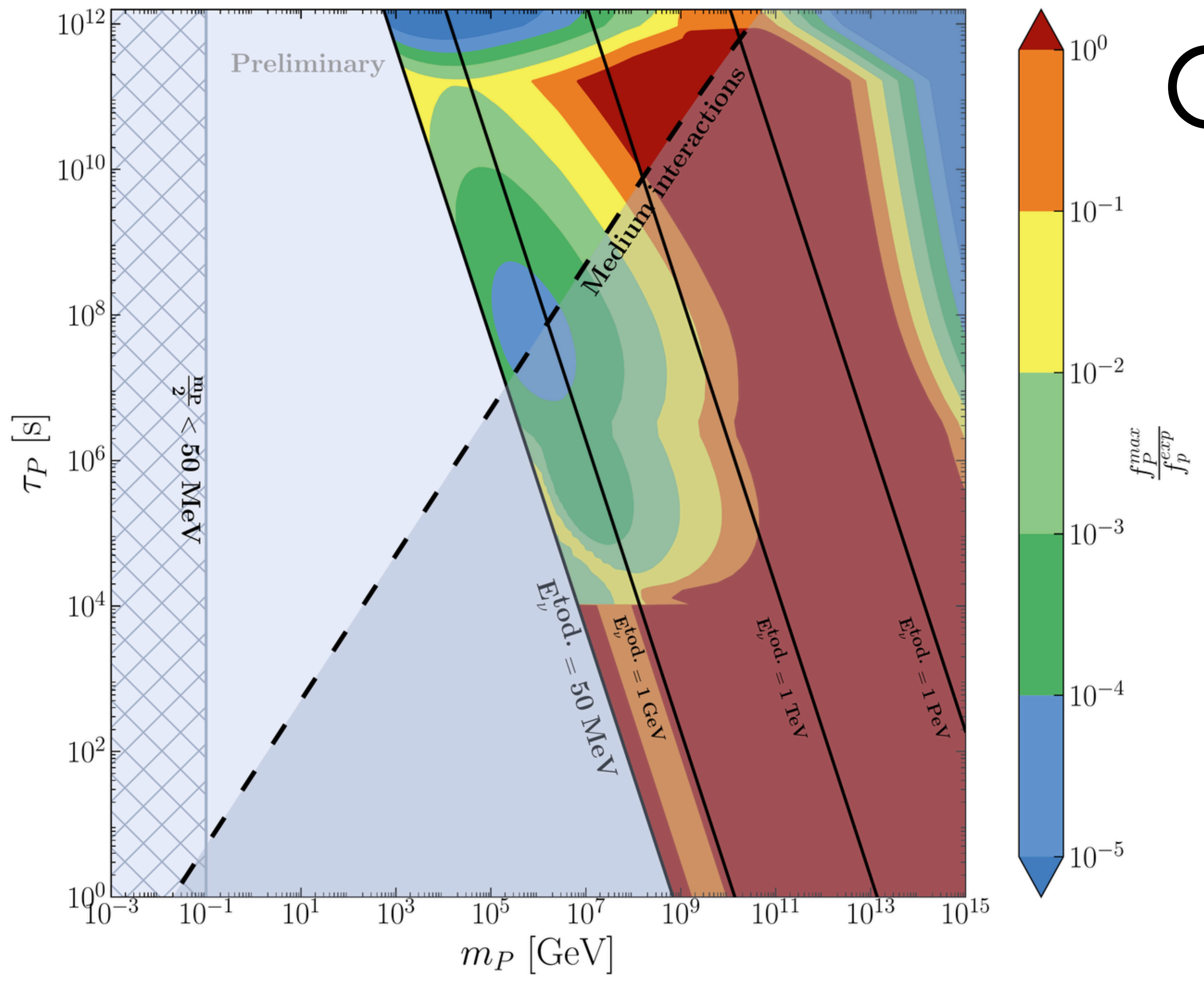

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$$10^9 \text{ s} \lesssim \tau_P \lesssim 10^{12.5} \text{ s}$$
$$10^{-8} \lesssim f_P \lesssim 10^{-2}$$

Potentially observable over the whole energy range of observatories

Conclusions:

- PHENUs could be produced in the early universe with sharp spectral features
- Scattering on the background or with other PHENUs is negligible
- Region of lifetime, mass and abundance of the relic for which sharp spectral features are observable

Further work:

- Distortion of the spectrum
- ...

Thank you for your attention

Backup slides

Decay Spectra.

$$\frac{d\phi_\nu}{dE_\nu} = \frac{2\,\Omega_P^0\,\rho_{crit}^0}{m_P H \tau_P E_\nu} e^{-t/\tau_P}\,\Theta\left(\frac{m_P}{2} - E_\nu\right)$$

$$\frac{d\phi_\nu}{dE_\nu} = \frac{6\Omega_P^0\rho_{crit}^0}{\pi m_P^4 \tau_P E_\nu} \int_{E_\nu}^{\frac{m_P}{2}} dx x^2 \frac{e^{-t(E_\nu/x)/\tau_P}}{H(E_\nu/x)}$$

$$\frac{d\phi_\nu}{dE_\nu} = \frac{4\Omega_0^P\,\rho_{crit}^0}{\pi m_P^2 \tau_P E_\nu \sqrt{1-(1-\Delta)^2}} \int_{\max(E_\nu, E_-)}^{E_+} dx \frac{e^{-t(E_\nu/x)/\tau_P}}{H(E_\nu/x)}$$

$$\Delta = 1 - \frac{2m_{P'}}{m_P} \qquad E^{\pm} = \frac{m_P}{4}(1 \pm \sqrt{1-(1-\Delta)^2})$$

2-body decay $\frac{dN}{dE} = \delta(E - m_P/2)$

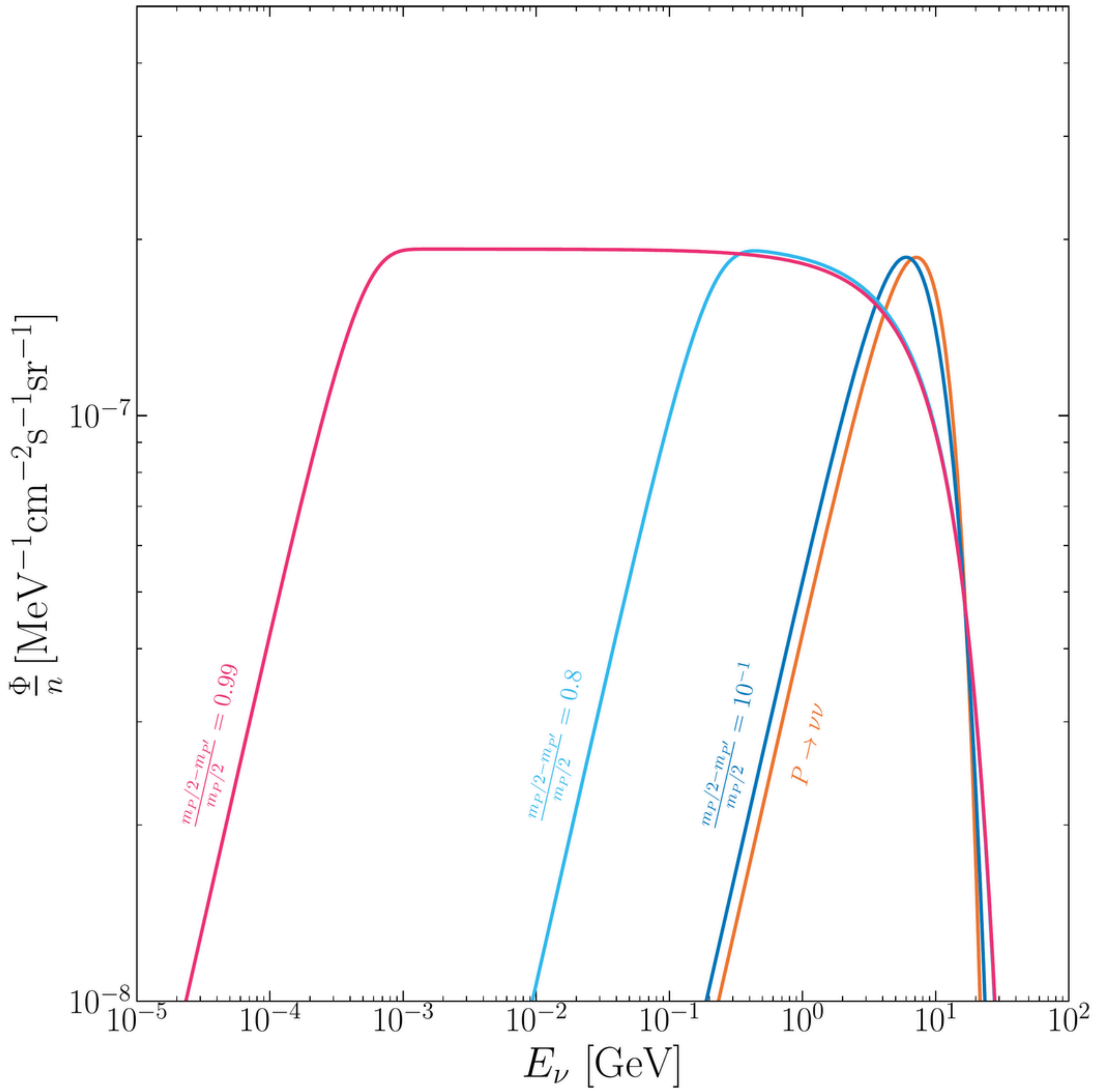
3-body decay $\frac{dN}{dE} = \Theta(m_P/2 - E) \cdot 24\frac{E^2}{m_P^3}$

Box shaped $\frac{dN}{dE} = \frac{8}{m_P\sqrt{1-\frac{4m_{P'}^2}{m_P^2}}}\Theta(E - E_-)\Theta(E_+ - E)$

Decay Spectra.

Δ controls the width of the box.

In the limit where Δ = 0 we recover the 2-body decay spectrum



Annihilation.

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Delta n_\nu}{8\pi} \frac{(\Omega_P^0 \rho_{crit}^0)^2 m_P \langle\sigma v\rangle}{E_\nu^4 H} \frac{1}{(1 - \frac{\langle\sigma v\rangle s}{H}\left(1 - \frac{E_\nu(1+z_*)}{m_P}\right)\frac{n}{s}|_{t_*})^2}$$

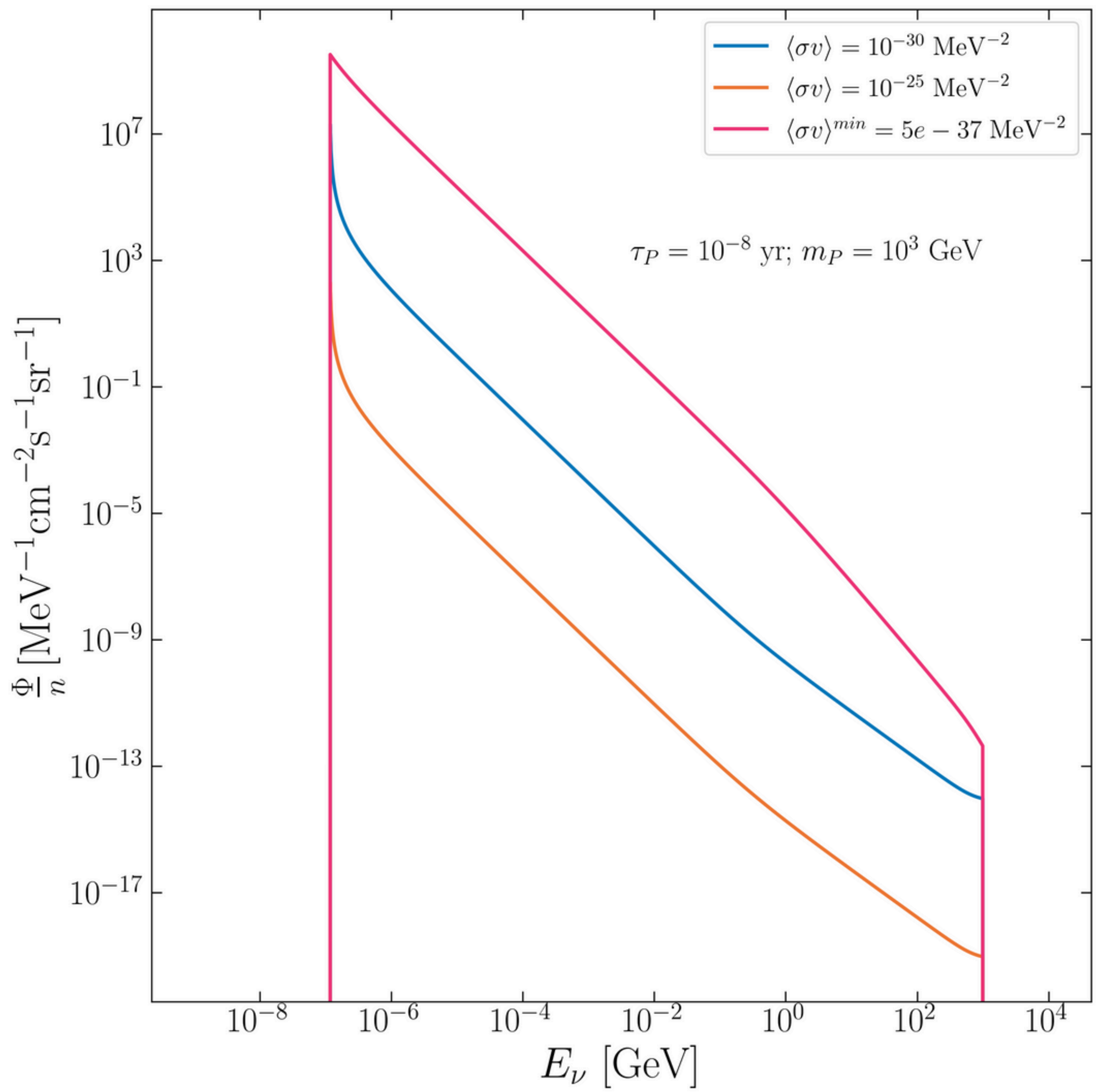
$$\langle\sigma v\rangle n_P^{eq} < H(t^{inj}) \longrightarrow \langle\sigma v\rangle < \left(\frac{2\pi}{m_P T^{inj}}\right)^{3/2} \frac{e^{m_P/T^{inj}}}{2g_i t^{inj}}$$

Not too constraining for large mass as it is satisfied as longas T_{inj} is sufficiently lower than m_P

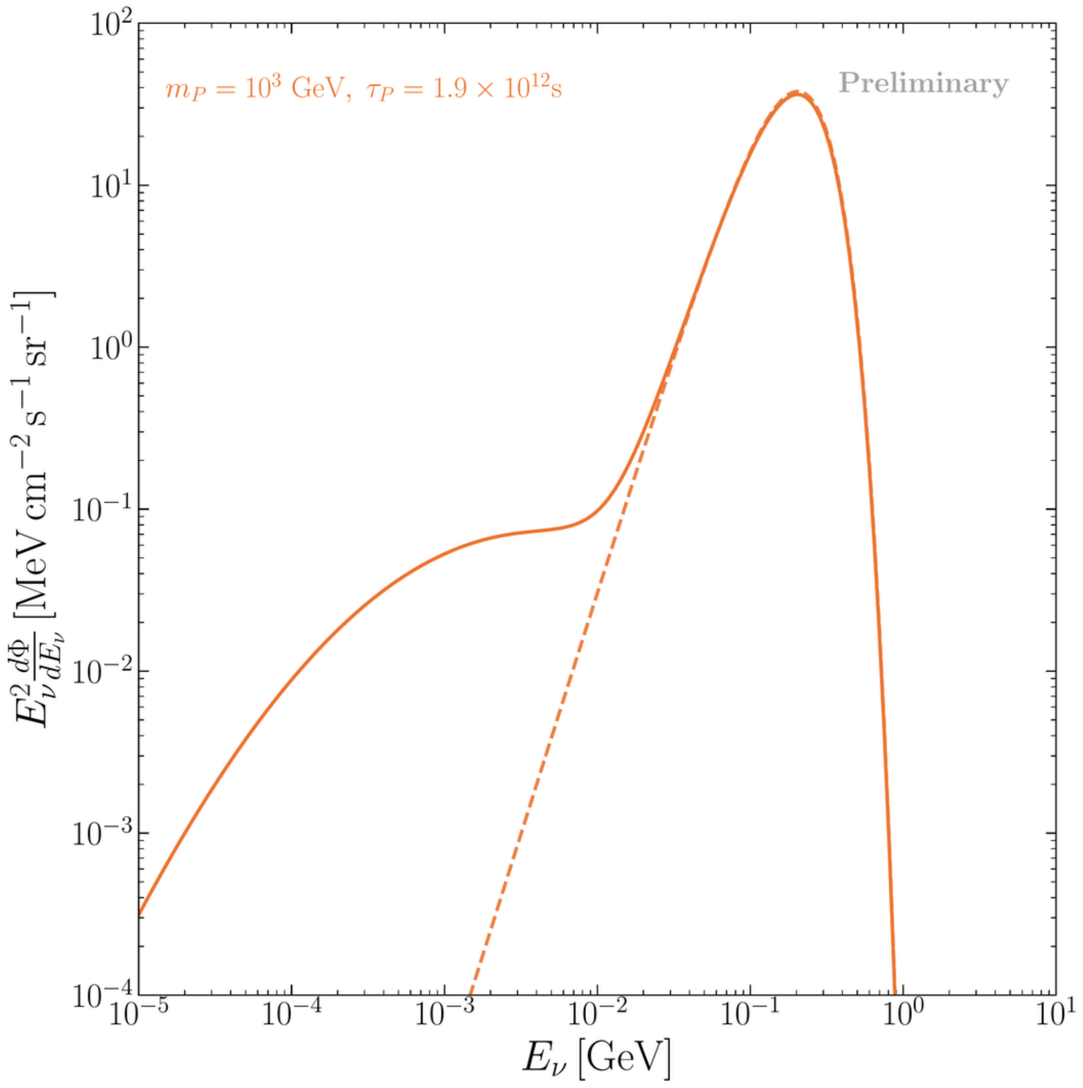
$$\langle\sigma v\rangle n_P^{inj} > H(t^{inj}) \longrightarrow \langle\sigma v\rangle > \frac{m_P}{2\Omega_P^0 \rho_{crit}^0}\sqrt{\frac{t^{inj}}{t_r^3}}$$

Annihilation.

$$\langle \sigma v \rangle > \frac{m_P}{2\Omega_P^0 \rho_{crit}^0} \sqrt{\frac{t^{inj}}{t_r^3}}$$



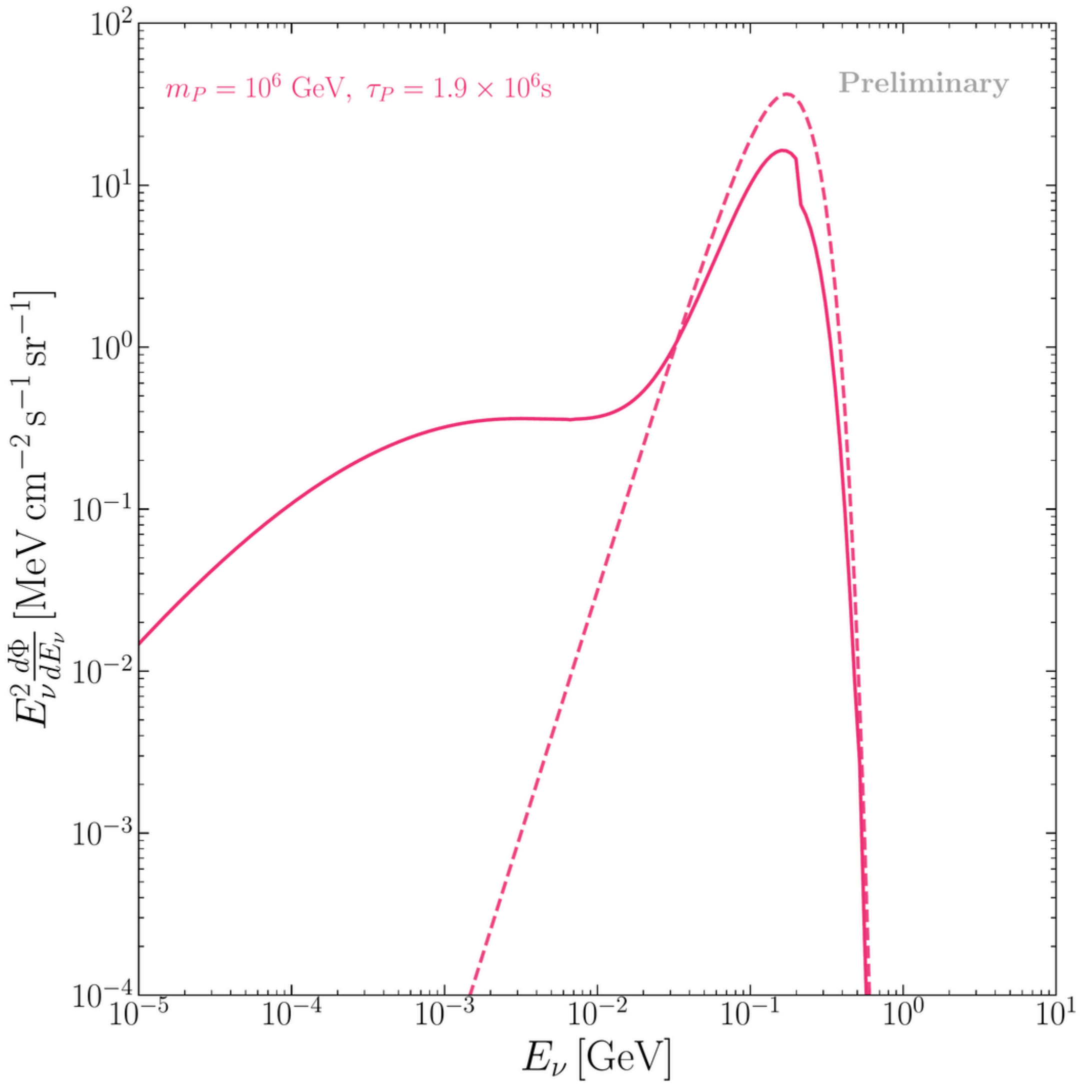
Sharp Spectral Features.



Final state radiation broadening

- If $E_\nu > M_{Z/W}$, gauge bosons can be radiated and generate a shower
- Production of (many) secondary neutrinos of lower energies
- Energy dependent process

Sharp Spectral Features.



Final state radiation broadening

- If $E_\nu > M_{Z/W}$, gauge bosons can be radiated and generate a shower
- Production of (many) secondary neutrinos of lower energies
- Energy dependent process

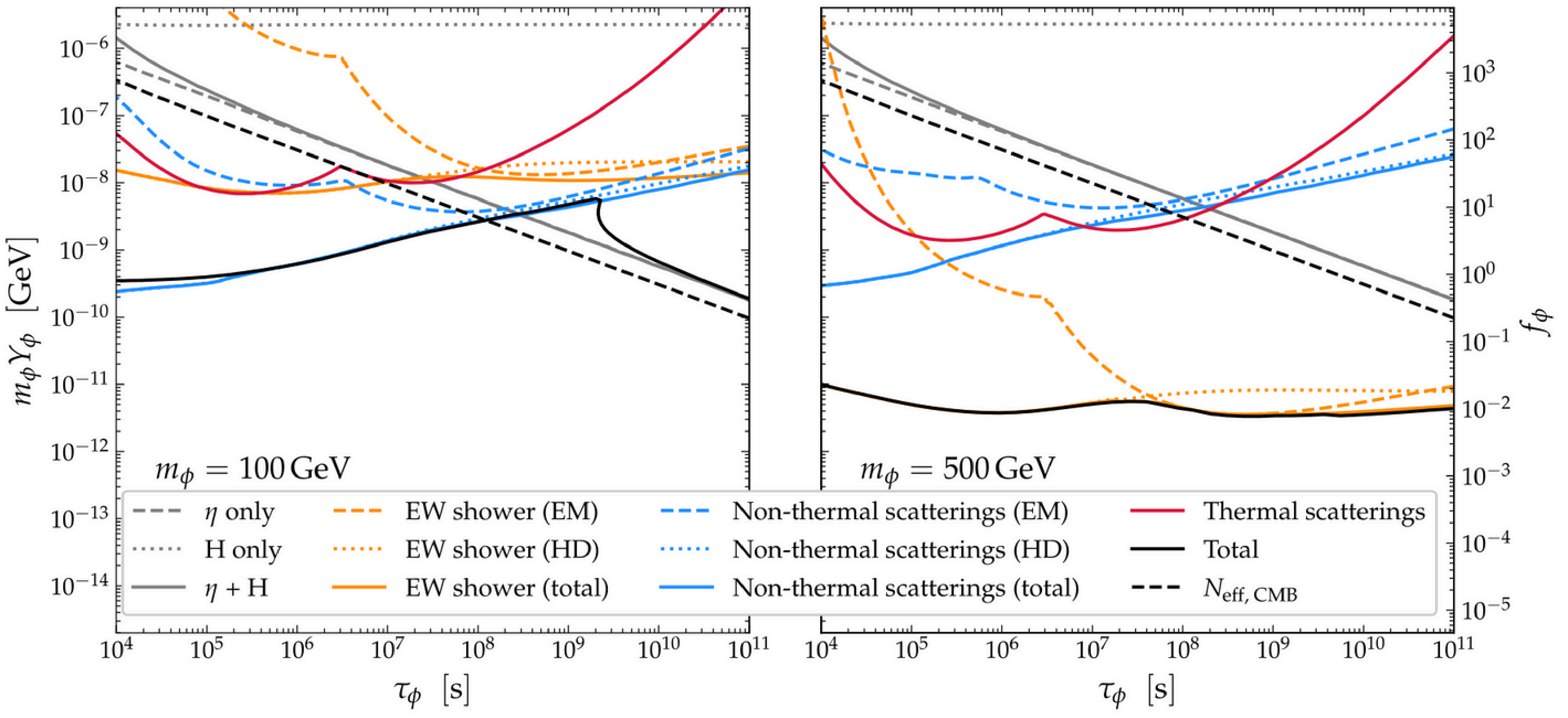
Sharp feature mostly unaffected

Self-scattering.

$$S_\nu(z, E_\nu^0) = \int_0^z \frac{dz'}{(1+z')H(z')}\Gamma(E_\nu^0(1+z'), z')$$

$$\langle\Gamma(E_0, z)\rangle = \frac{\Omega_P^0 \rho_{crit}^0 (1+z)^3}{4E_0^2(1+z)^2 m_P \tau_P} \int_0^{2E_0(1+z)m_P} ds\sigma(s)s \int_{\frac{s}{4E_0(1+z)}}^{m_P/2} \frac{dE}{E^3} \frac{e^{-t(a_E)/\tau_P}}{H(a_E)}$$

BBN constraints.



Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'

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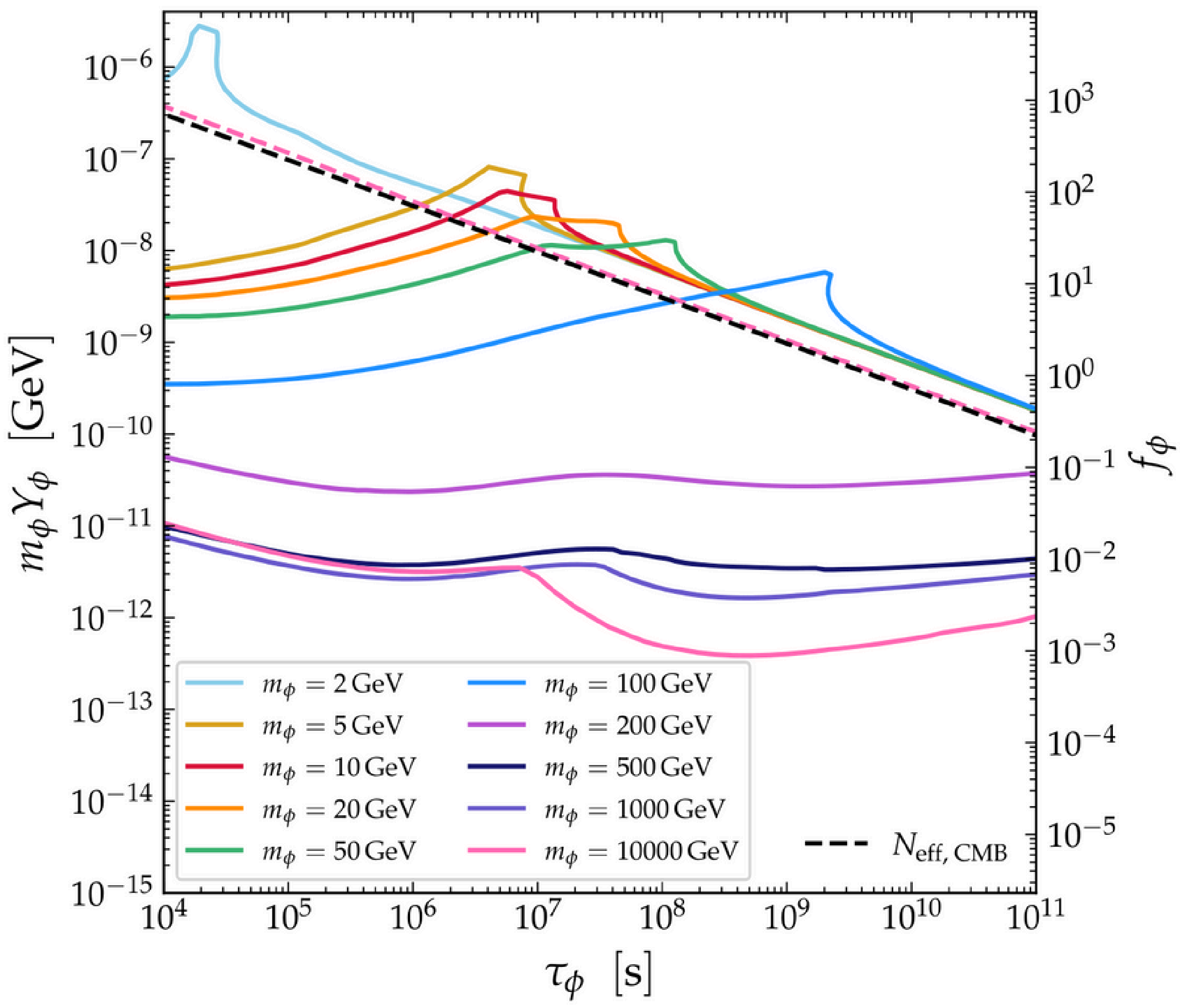
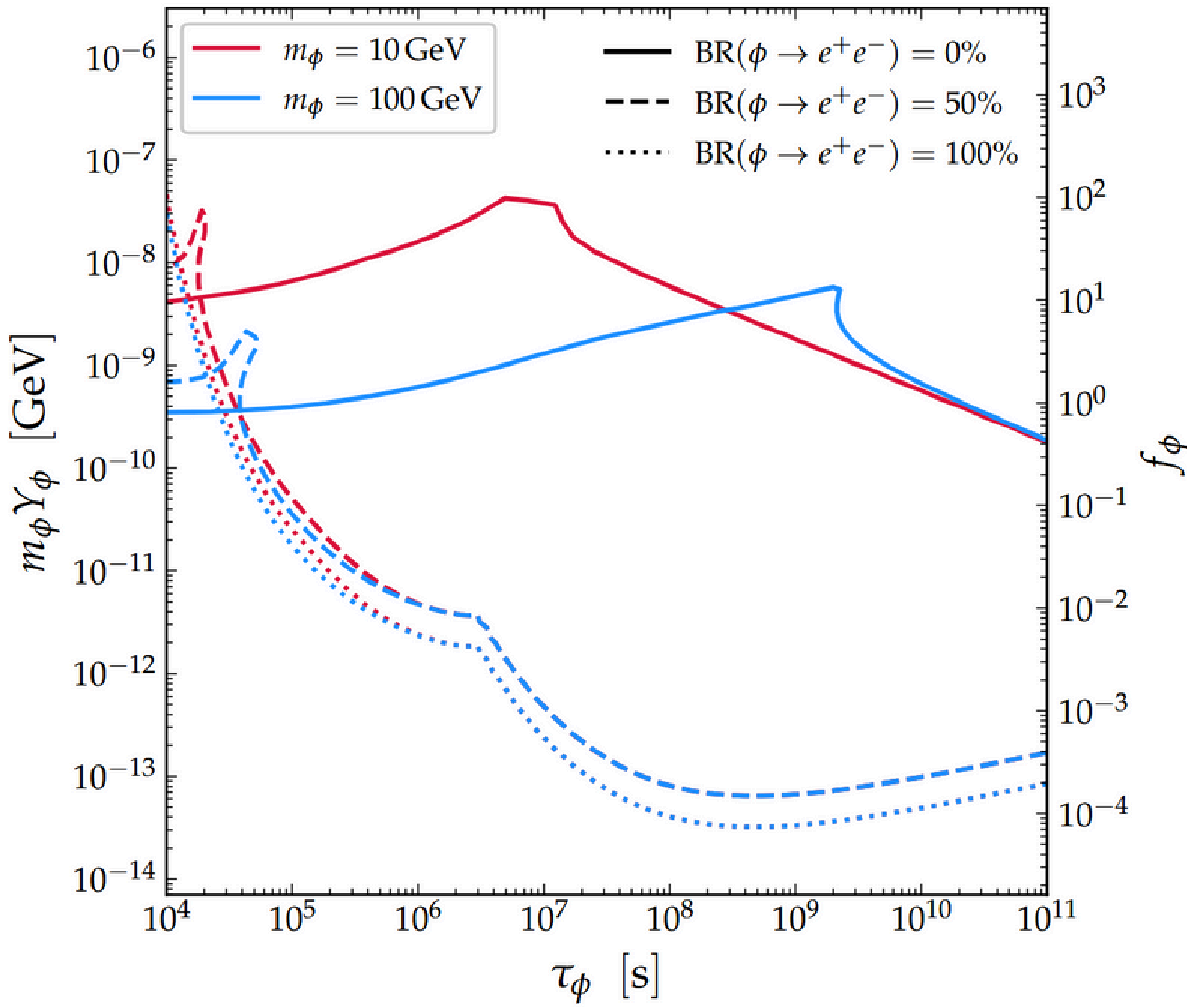
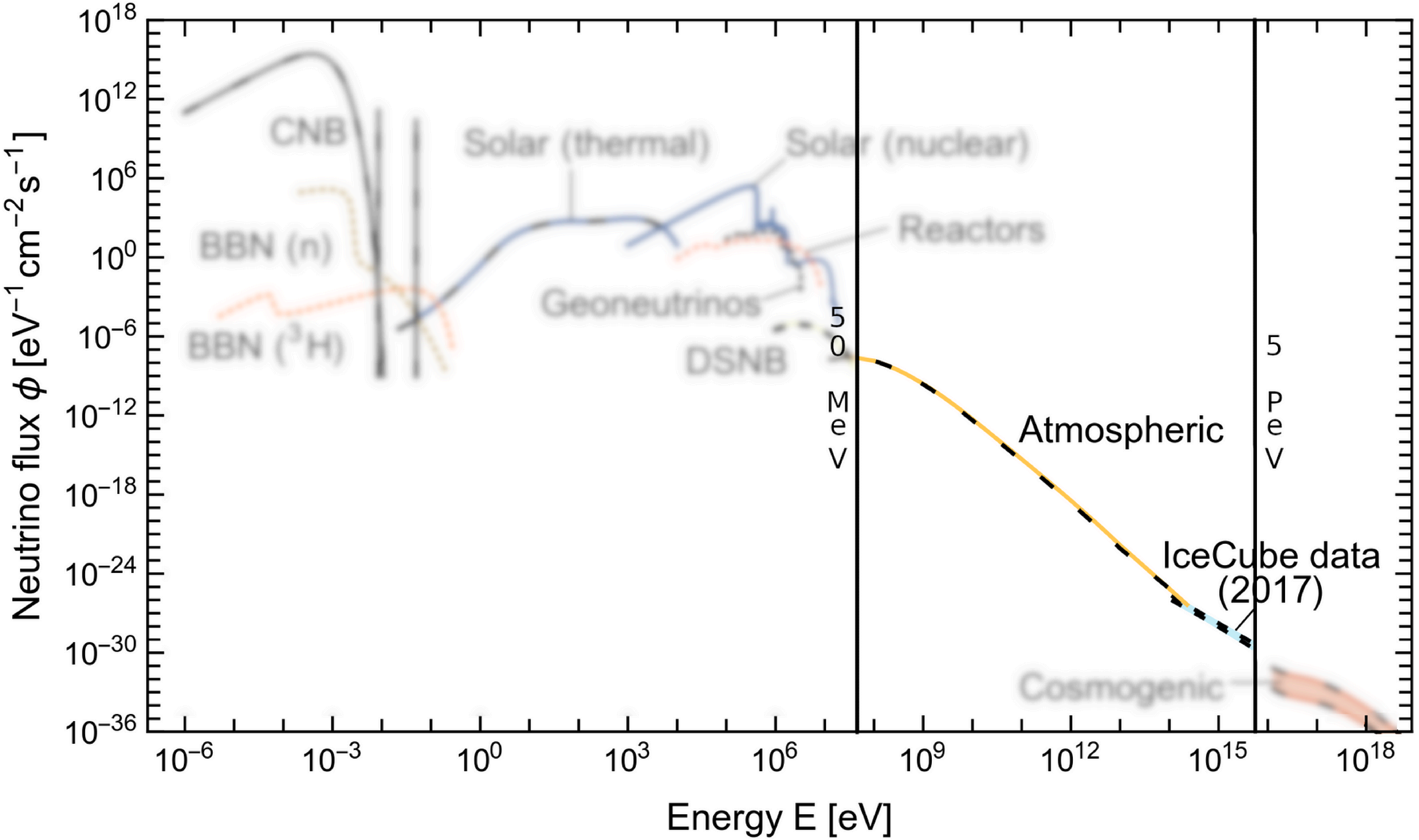


Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'

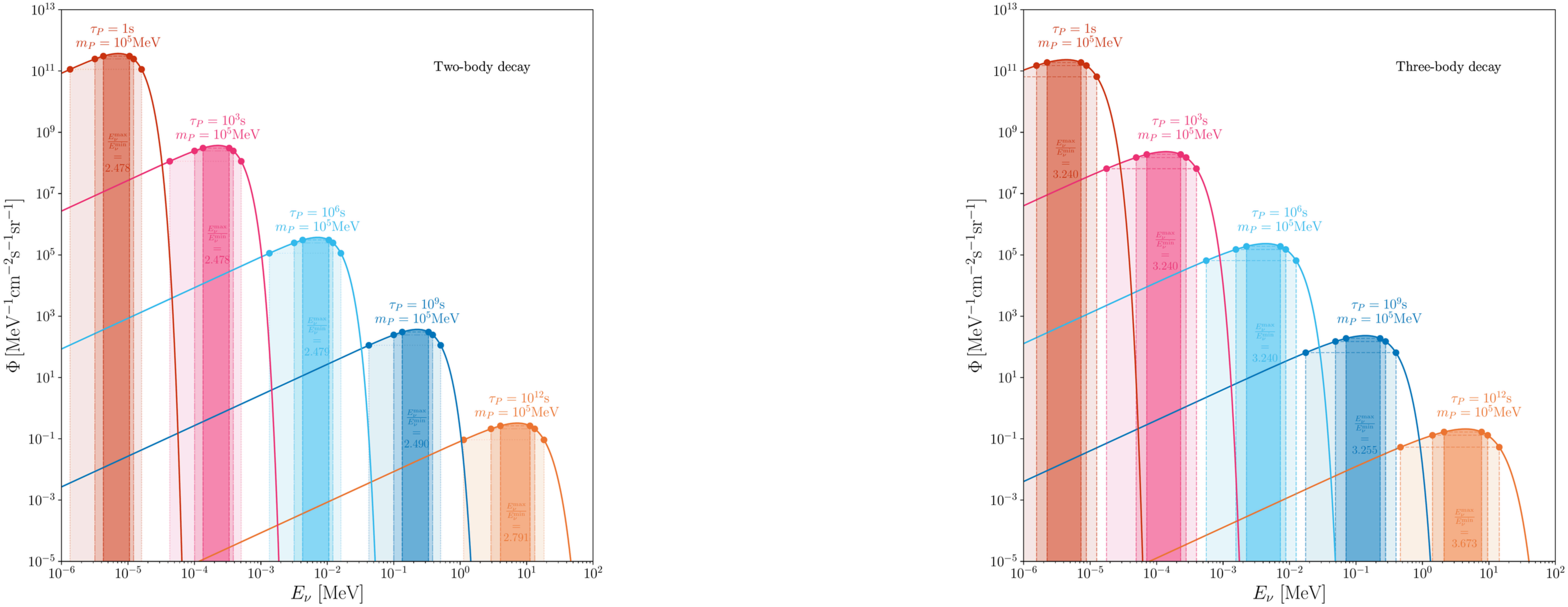
BBN constraints.



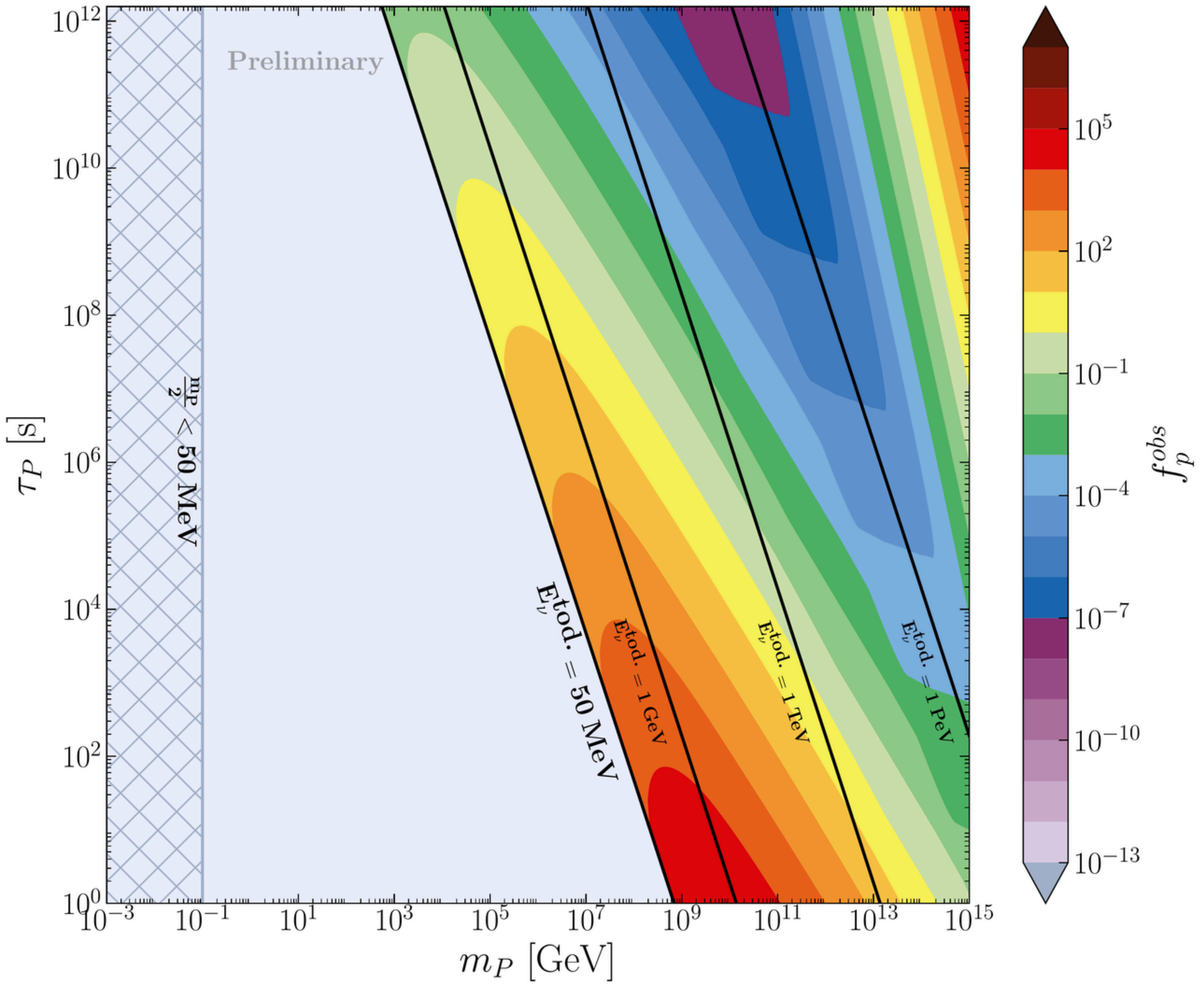
Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'



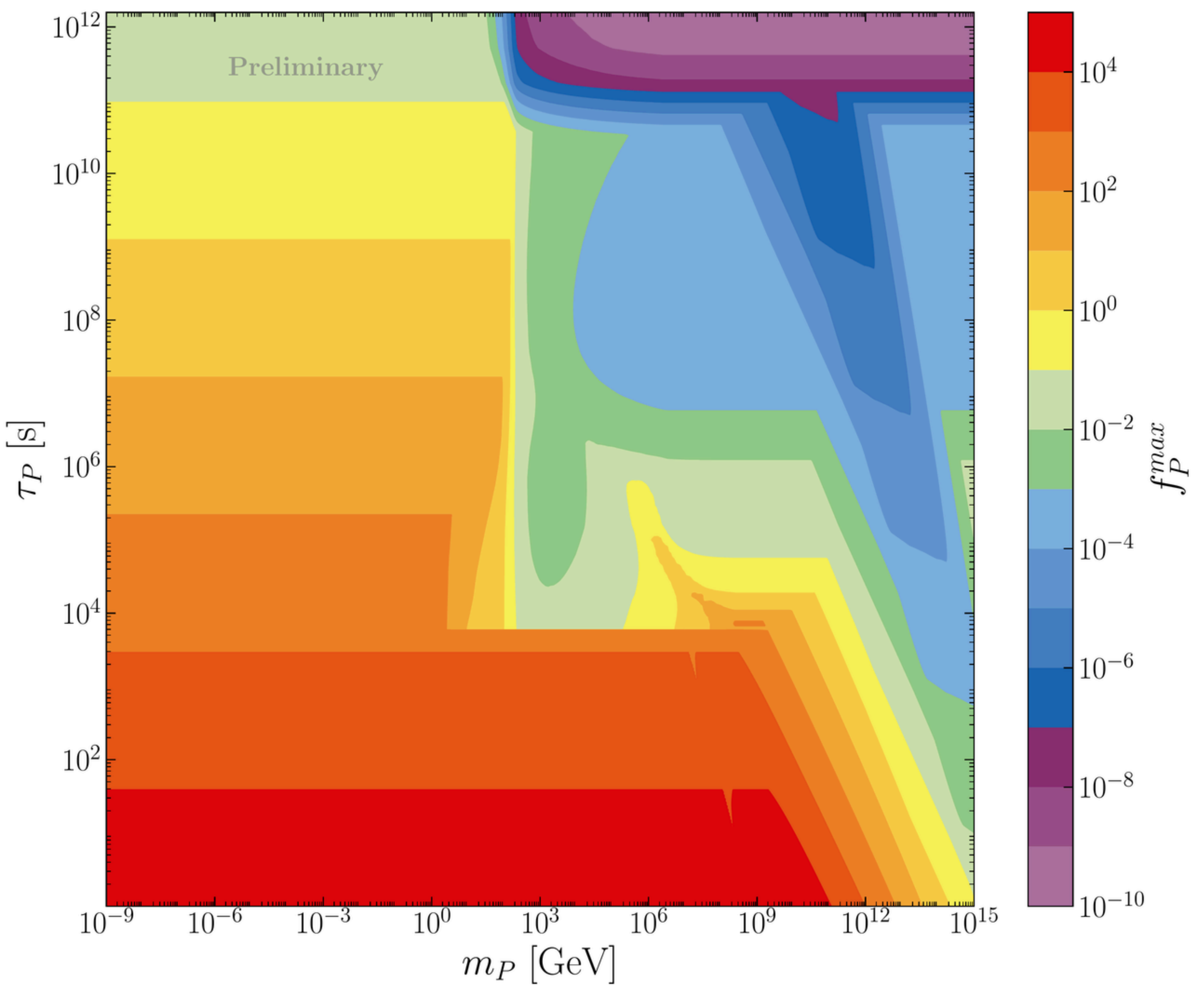
Vitagliano, Tamborra, Raffelt '19



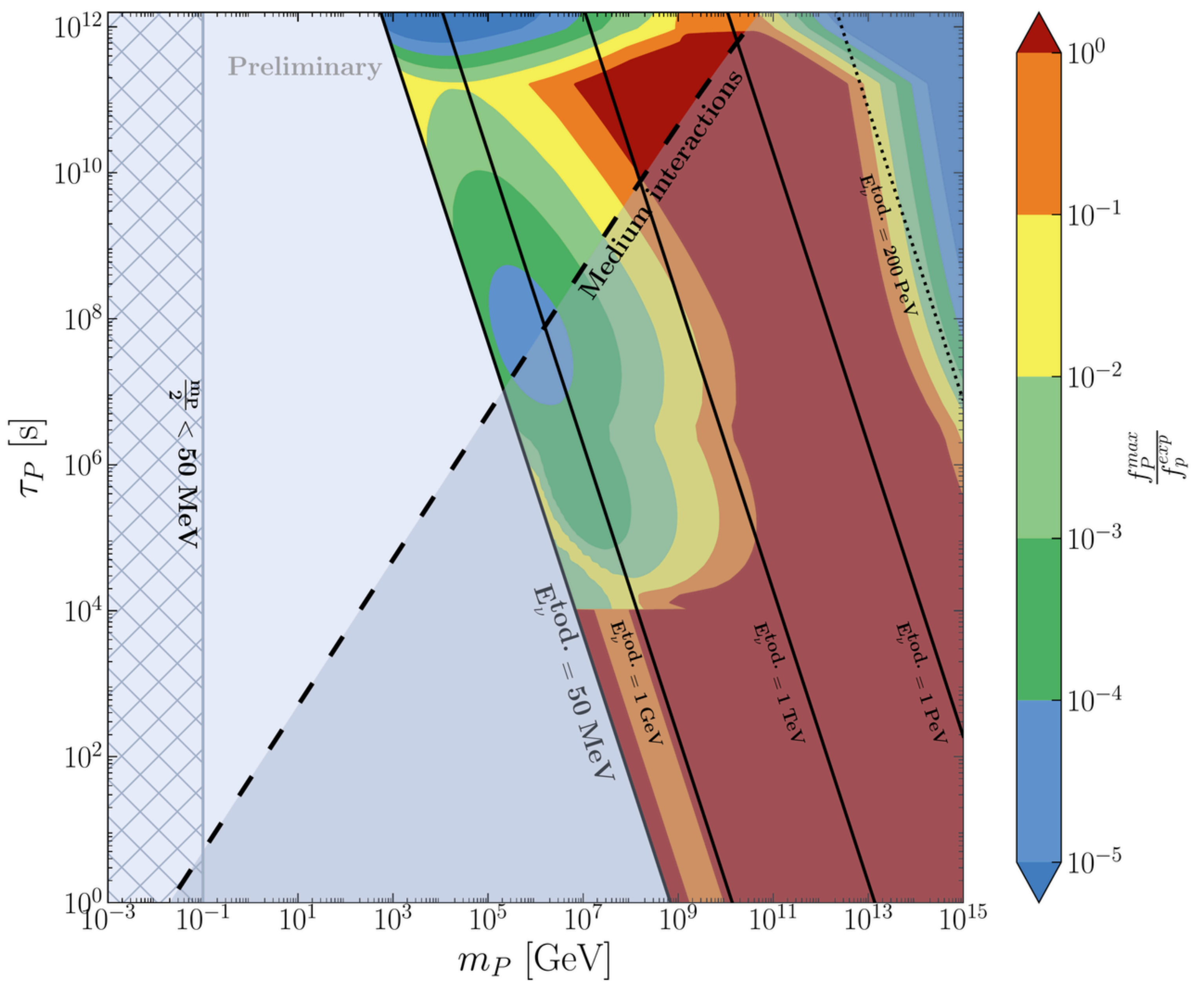
Two-body decay
Three-body decay
$\tau_P = 1$s
$m_P = 10^5$MeV
$\tau_P = 10^3$s
$m_P = 10^5$MeV
$\tau_P = 10^6$s
$m_P = 10^5$MeV
$\tau_P = 10^9$s
$m_P = 10^5$MeV
$\tau_P = 10^{12}$s
$m_P = 10^5$MeV
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.478$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.478$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.479$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.490$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.791$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 3.240$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 3.240$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 3.240$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 3.255$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 3.673$
$\Phi\ [\mathrm{MeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$
E_ν [MeV]



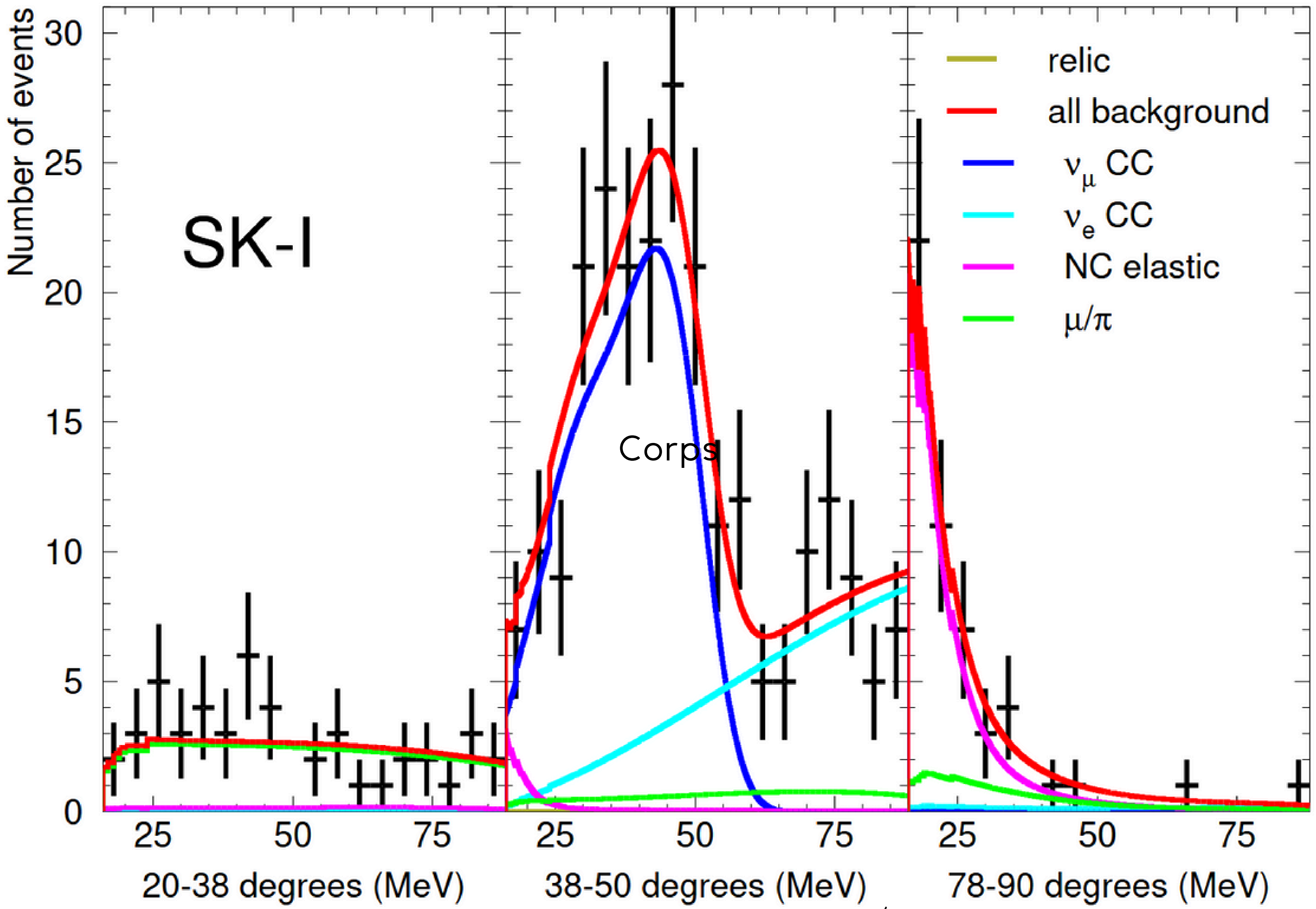
Preliminary
$\frac{m_P}{2} < 50$ MeV
$E_\nu$tod. = 50 MeV
$E_\nu$tod. = 1 GeV
$E_\nu$tod. = 1 TeV
$E_\nu$tod. = 1 PeV
τ_P [s]
m_P [GeV]
f_p^{obs}



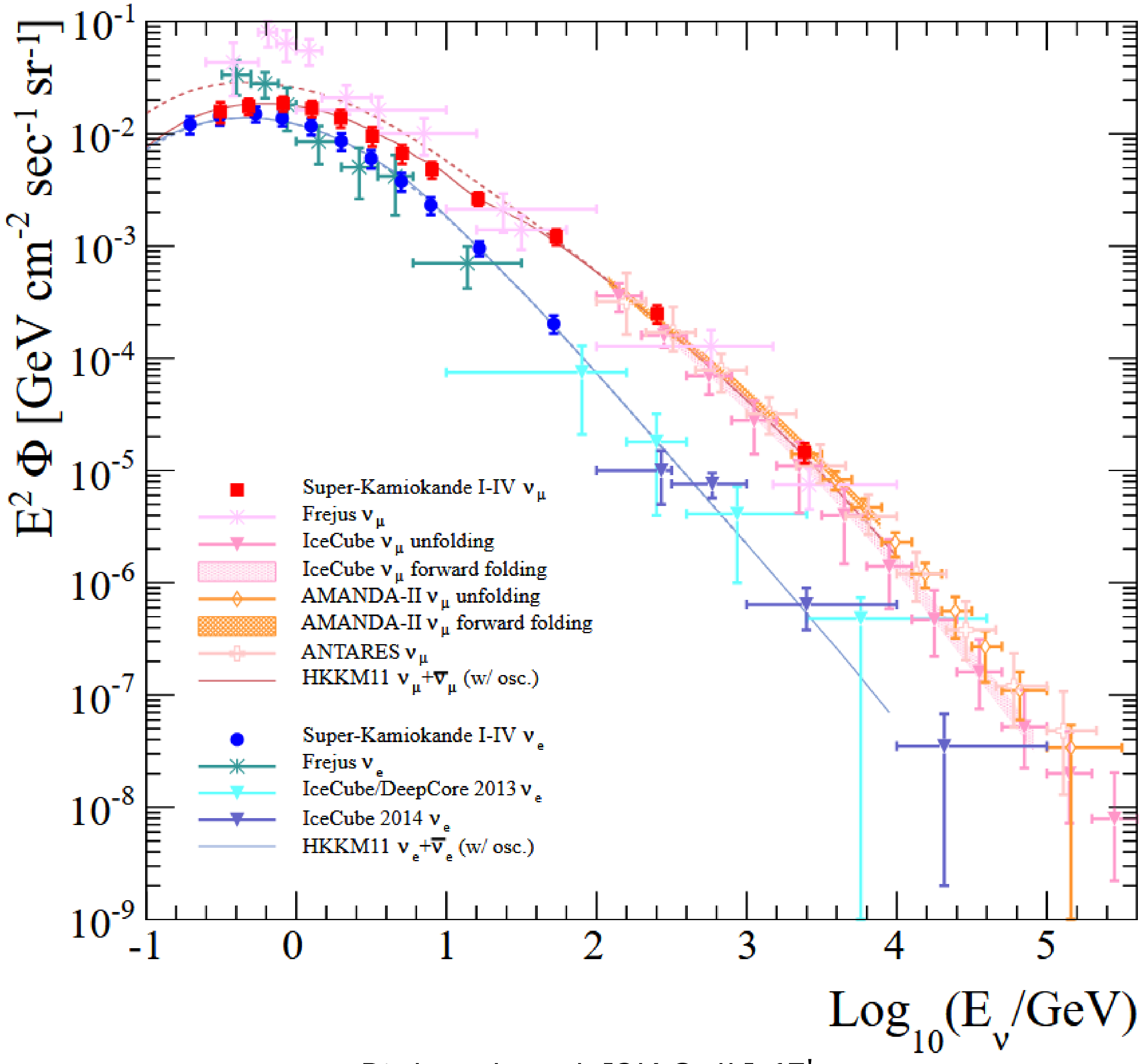
Preliminary
τ_P [s]
m_P [GeV]
f_P^{max}



Preliminary
$\frac{m_P}{2} < 50$ MeV
Medium interactions
$E_\nu$tod. = 50 MeV
$E_\nu$tod. = 1 GeV
$E_\nu$tod. = 1 TeV
$E_\nu$tod. = 1 PeV
$E_\nu$tod. = 200 PeV
τ_P [s]
m_P [GeV]
$\frac{f_P^{max}}{f_p^{exp}}$



K. Bays et al. [SK coll.], '12



Richard et al. [SK Coll.] 15'