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TeV Particle Astrophysics TeVPA Valencia 2025

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# Primordial High Energy Neutrinos

## Theoretical & observational constraints and sharp spectral features

Nicolas Grimbaum Yamamoto

arXiv:2507.02063 in collaboration with T.Hambye

# Summary .

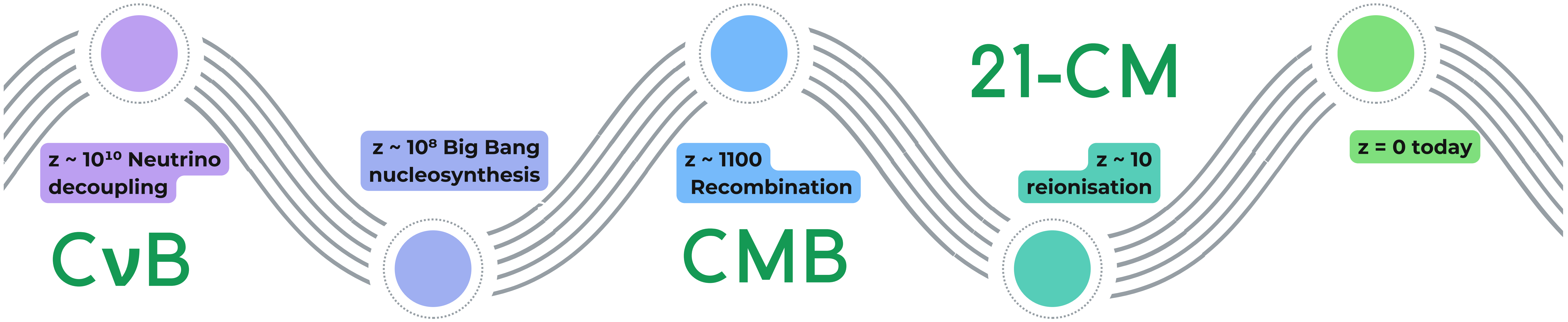
1 Motivations

2 Sharp spectral features

3 Medium interactions

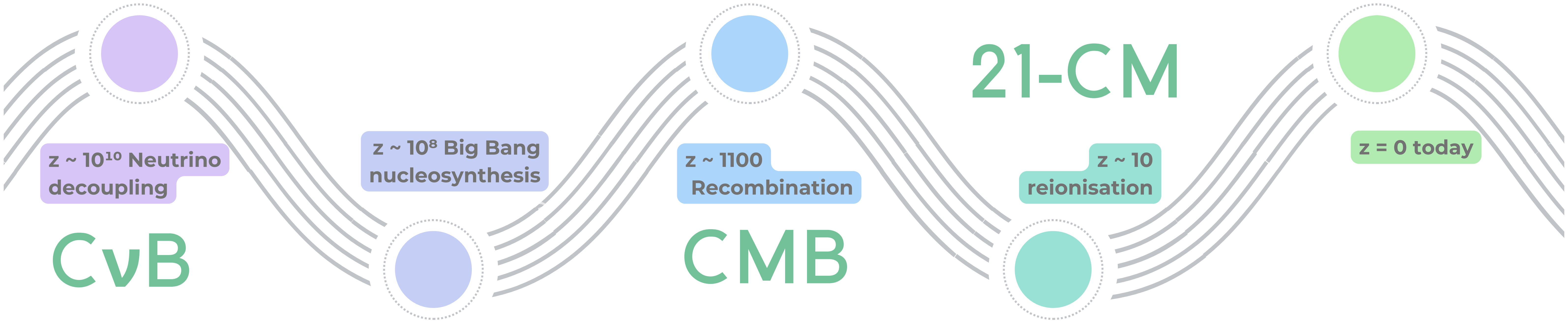
4 Constraints

# Motivations.




→ Primordial High Energy Neutrinos (PHENUs)

# Motivations.

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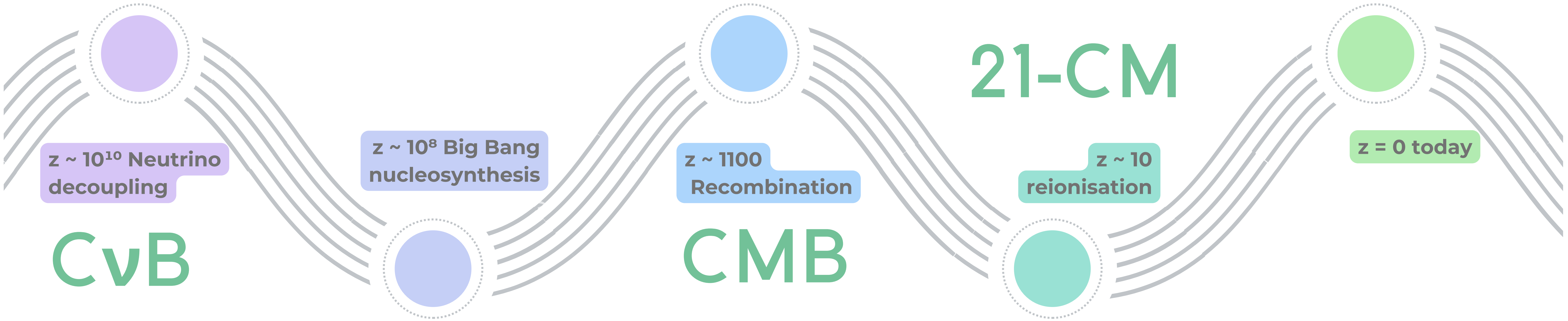
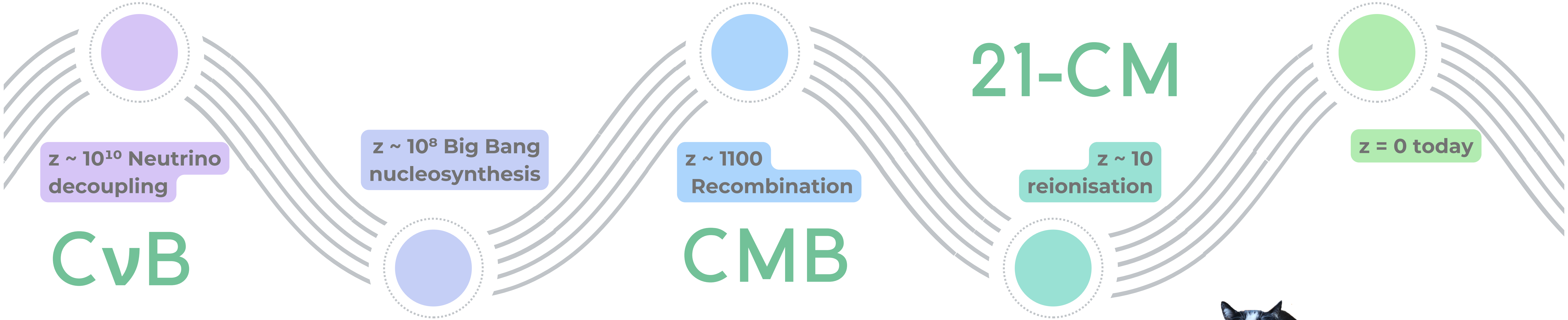
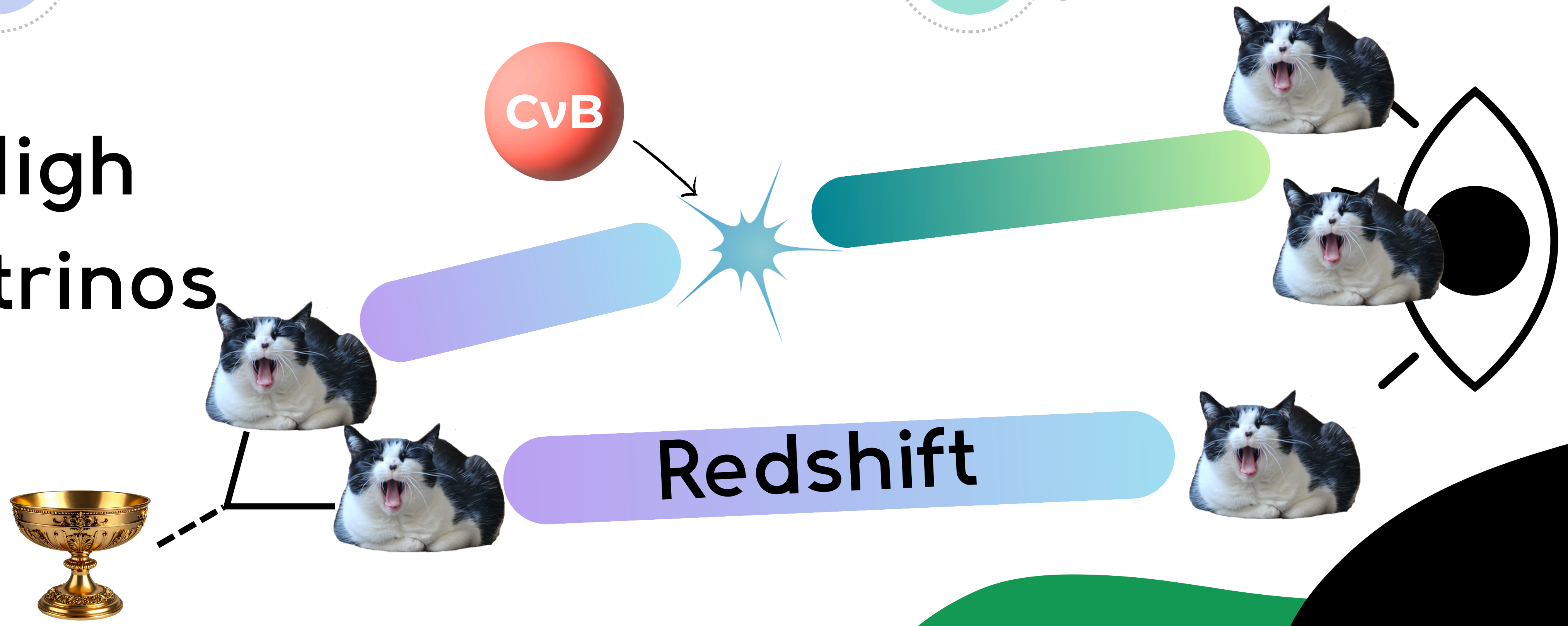



→ Primordial High Energy Mewtrinos **(PHEMEW) !**

# Motivations.

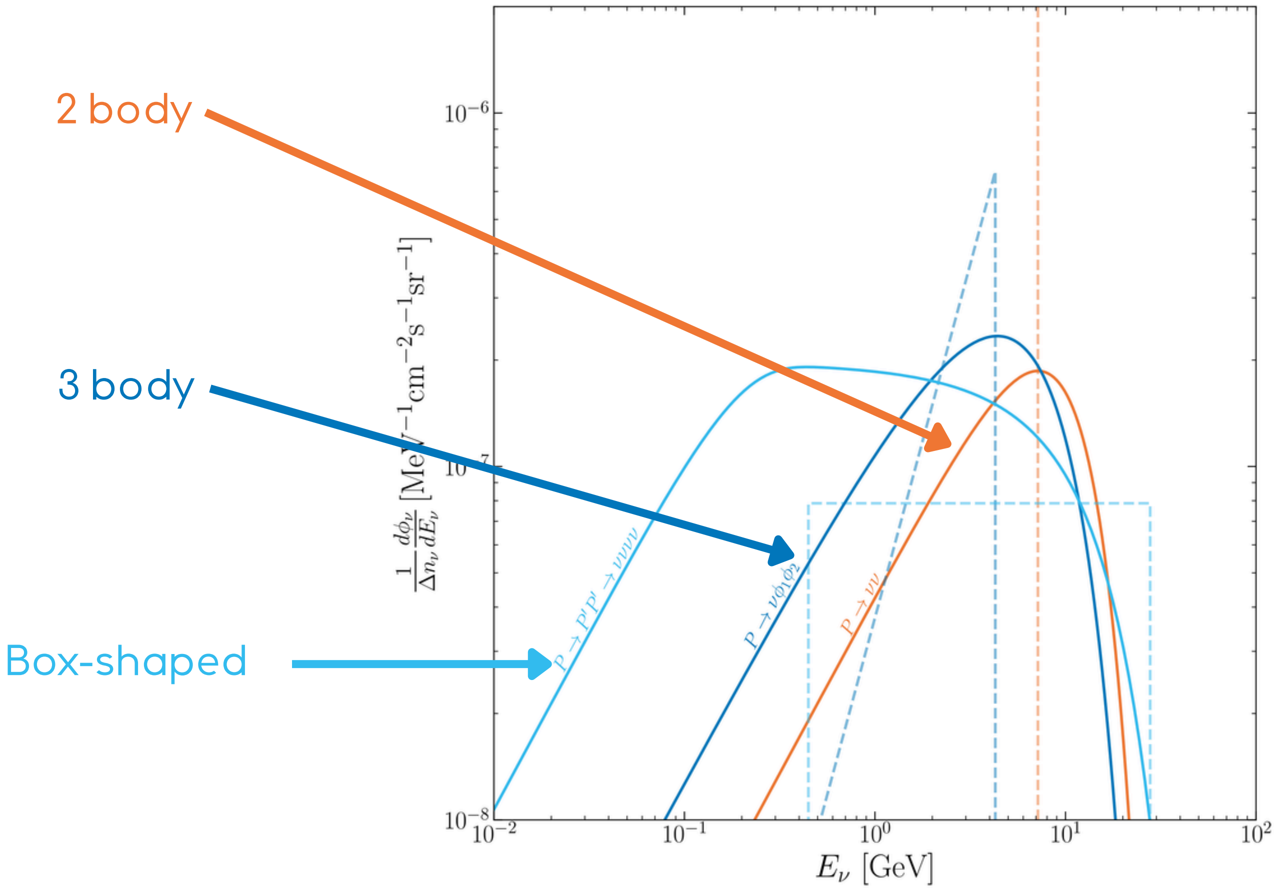



→ Primordial High Energy Mewtrinos (PHEMEW) !



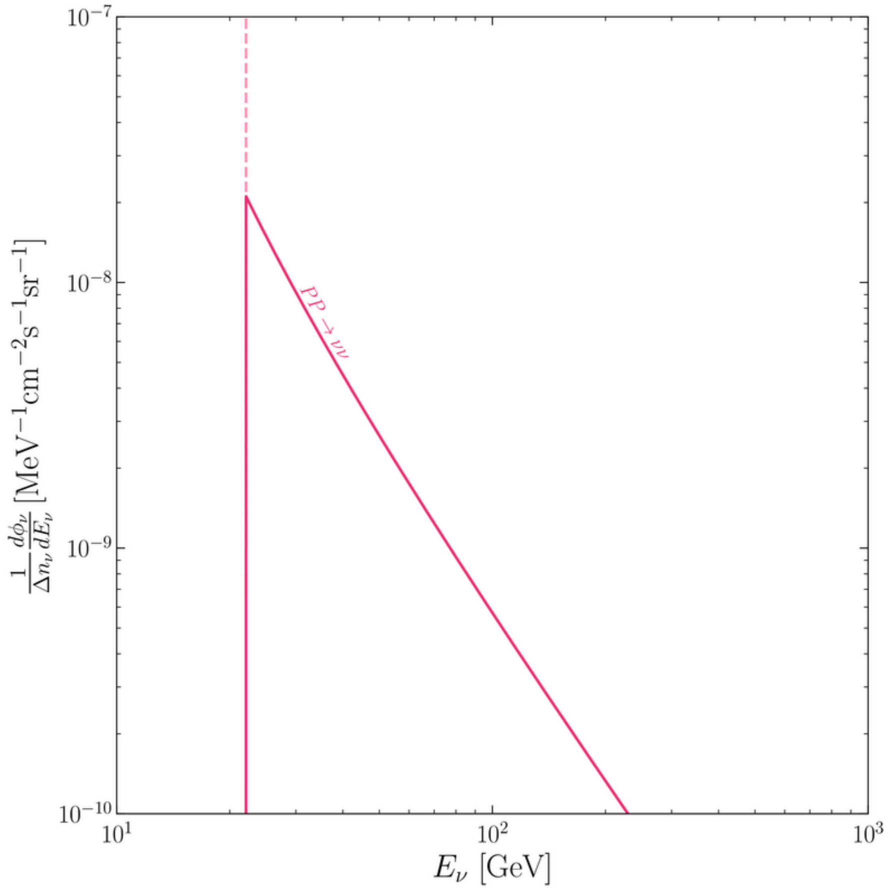
# Sharp Spectral Features.

## Decays




$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Delta n_\nu \Omega_P^0 \rho_{crit}^0}{4\pi m_P \tau_P}\int_0^\infty dz_{\rm inj}\, \frac{e^{-t_{\rm inj}/\tau_P}}{H_{\rm inj}} \frac{df_\nu}{dE_{\rm inj}}\Big|_{E_{\rm inj}=E_\nu(1+z_{\rm inj})}$$

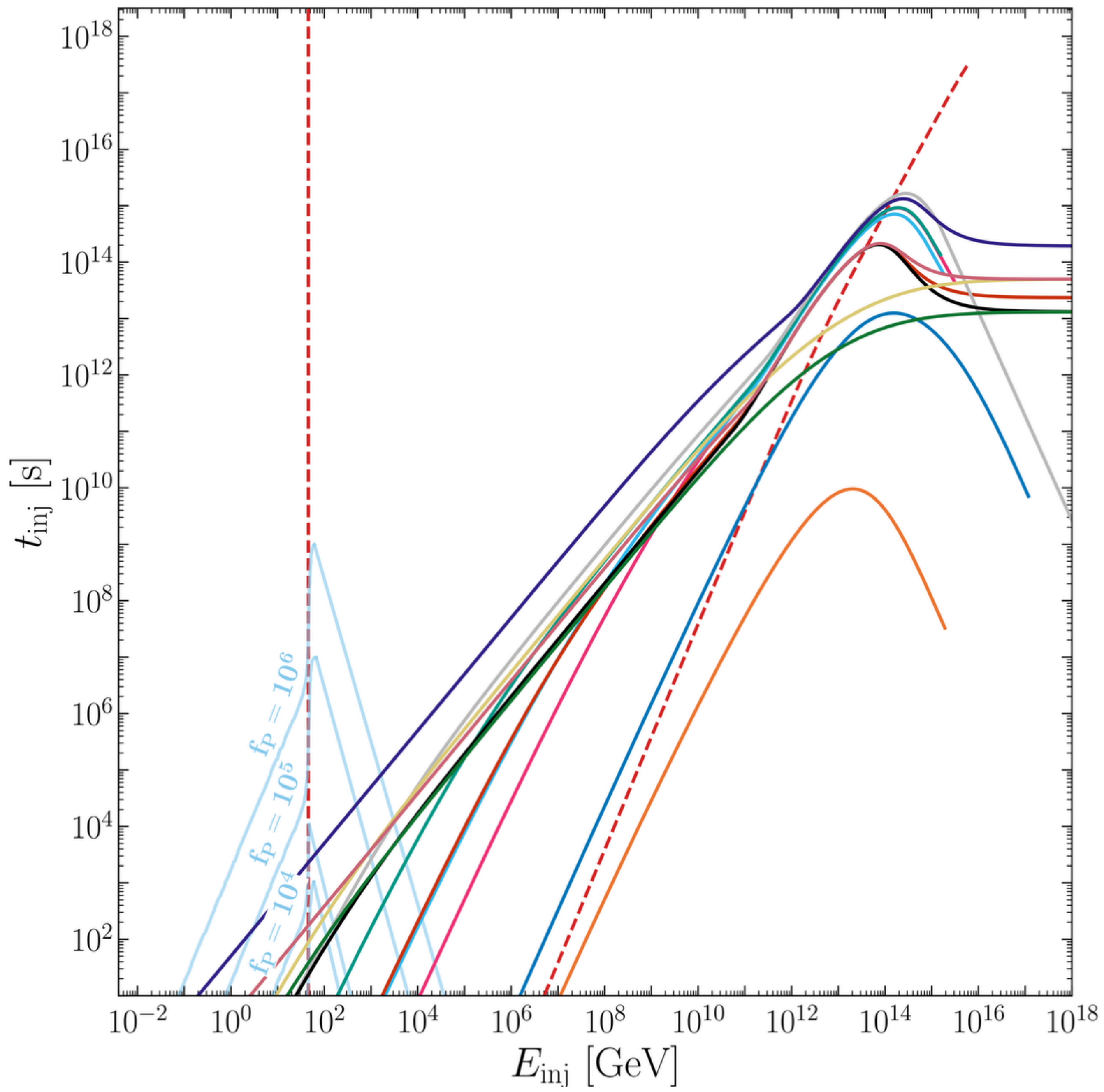
## Out of equilibrium annihilation




$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Delta n_\nu}{16\pi}\frac{(\Omega_P^0\rho_{\rm crit}^0)^2 m_P\langle\sigma v\rangle}{E_\nu^4 H_{\rm inj}}\frac{1}{\left(1+\Omega_P^0\rho_{\rm crit}^0\frac{\langle\sigma v\rangle}{2H_{\rm inj}}\frac{m_P^2}{E_\nu^3}\left(\frac{E_\nu}{m_P a_\star}-1\right)\right)^2}$$

# 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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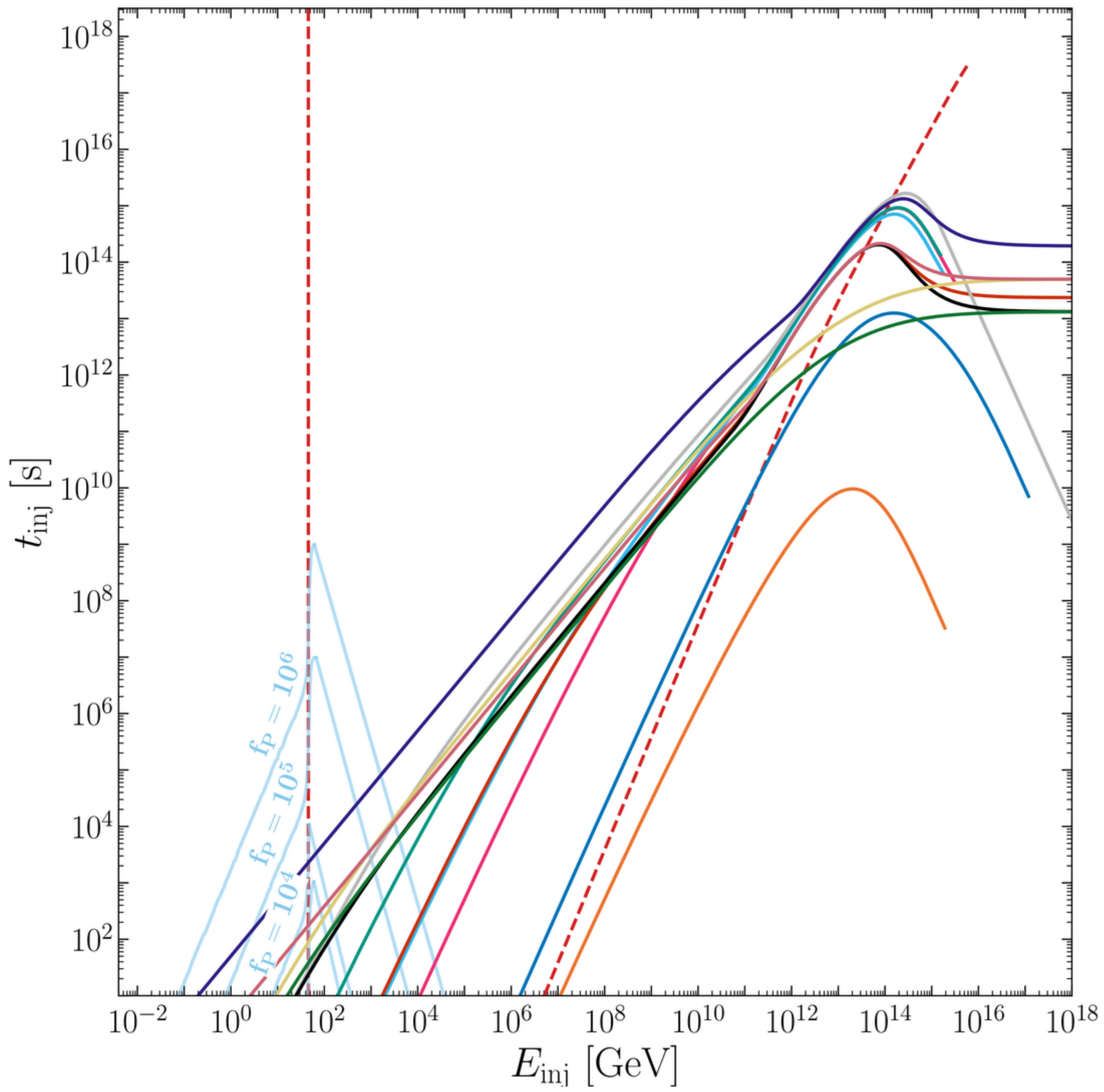
Average number
of scattering



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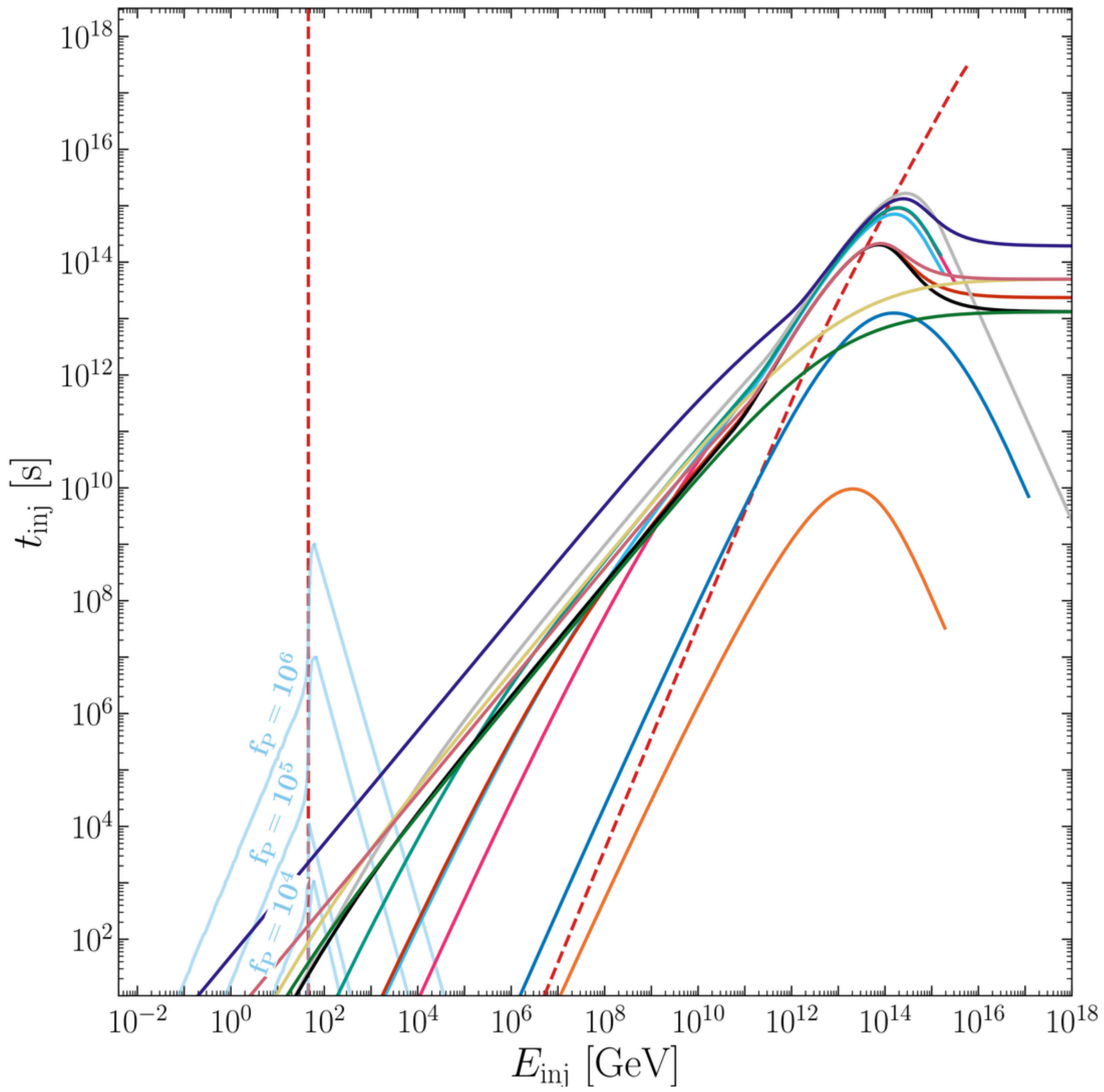
Integration over the line of sight



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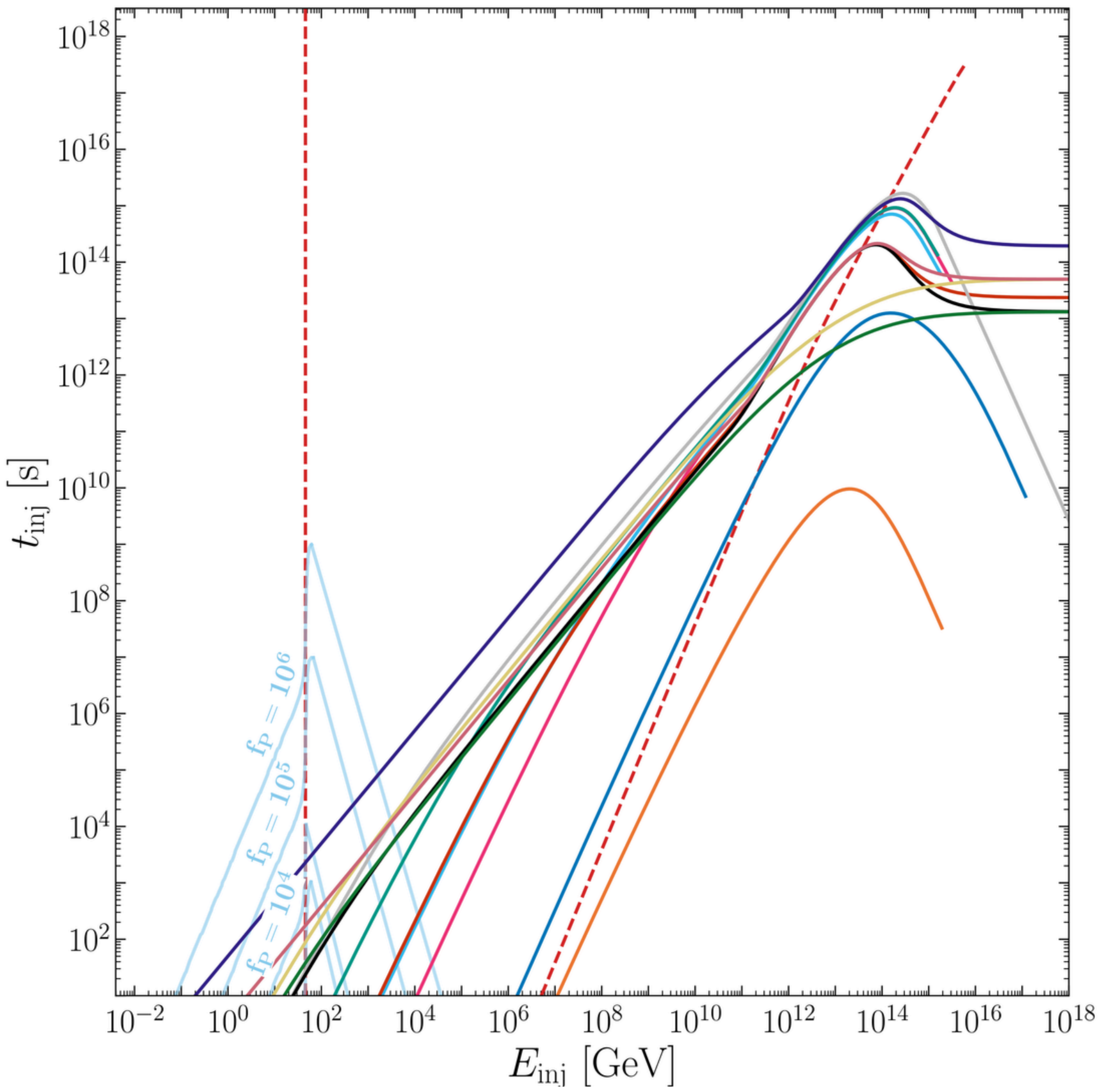
Average number of scattering

Integration over the line of sight

cross section averaged over target distribution function



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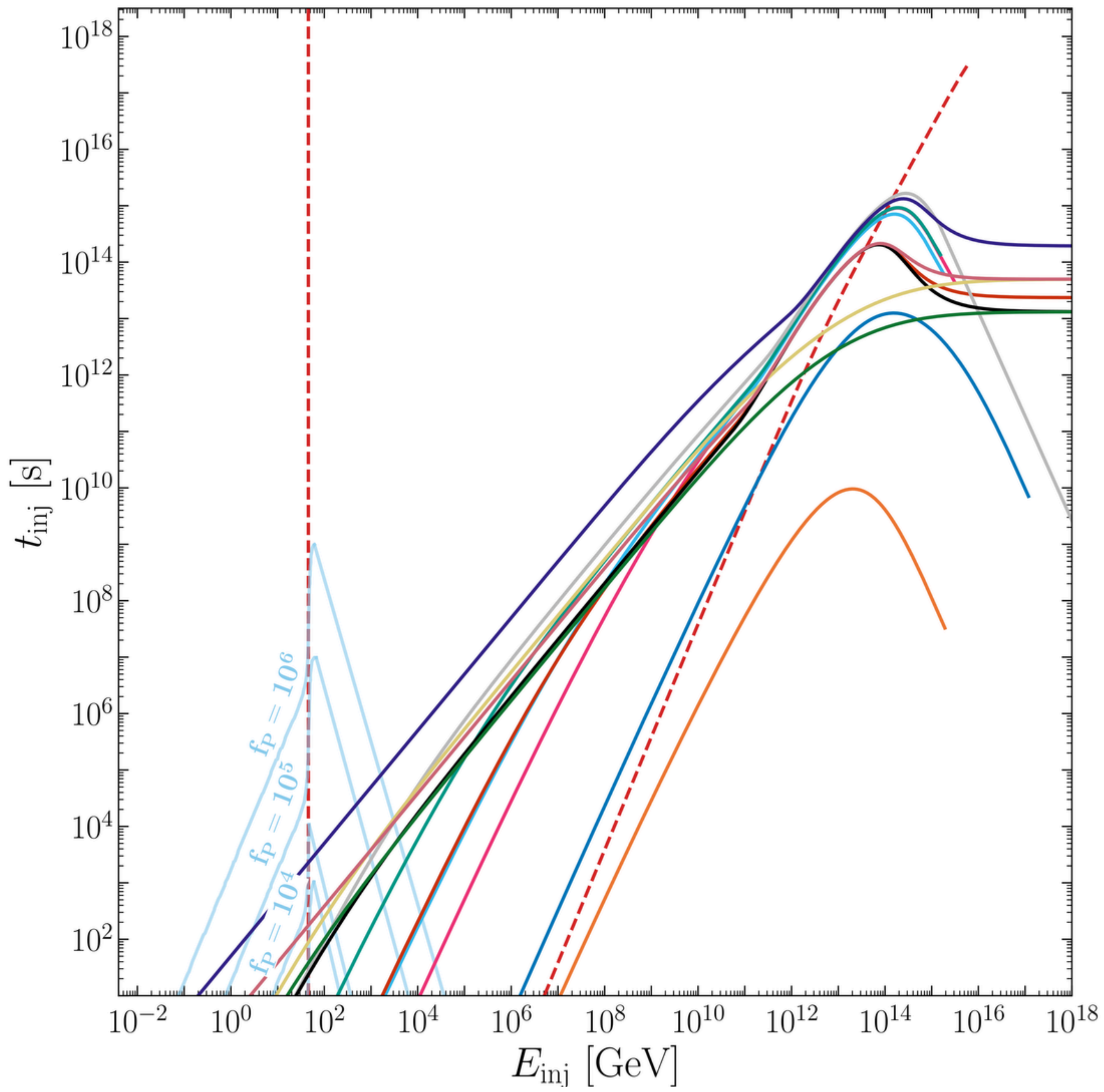
Average number of scattering

Integration over the line of sight

cross section averaged over target distribution function

target neutrino number density




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

# Medium interactions.

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

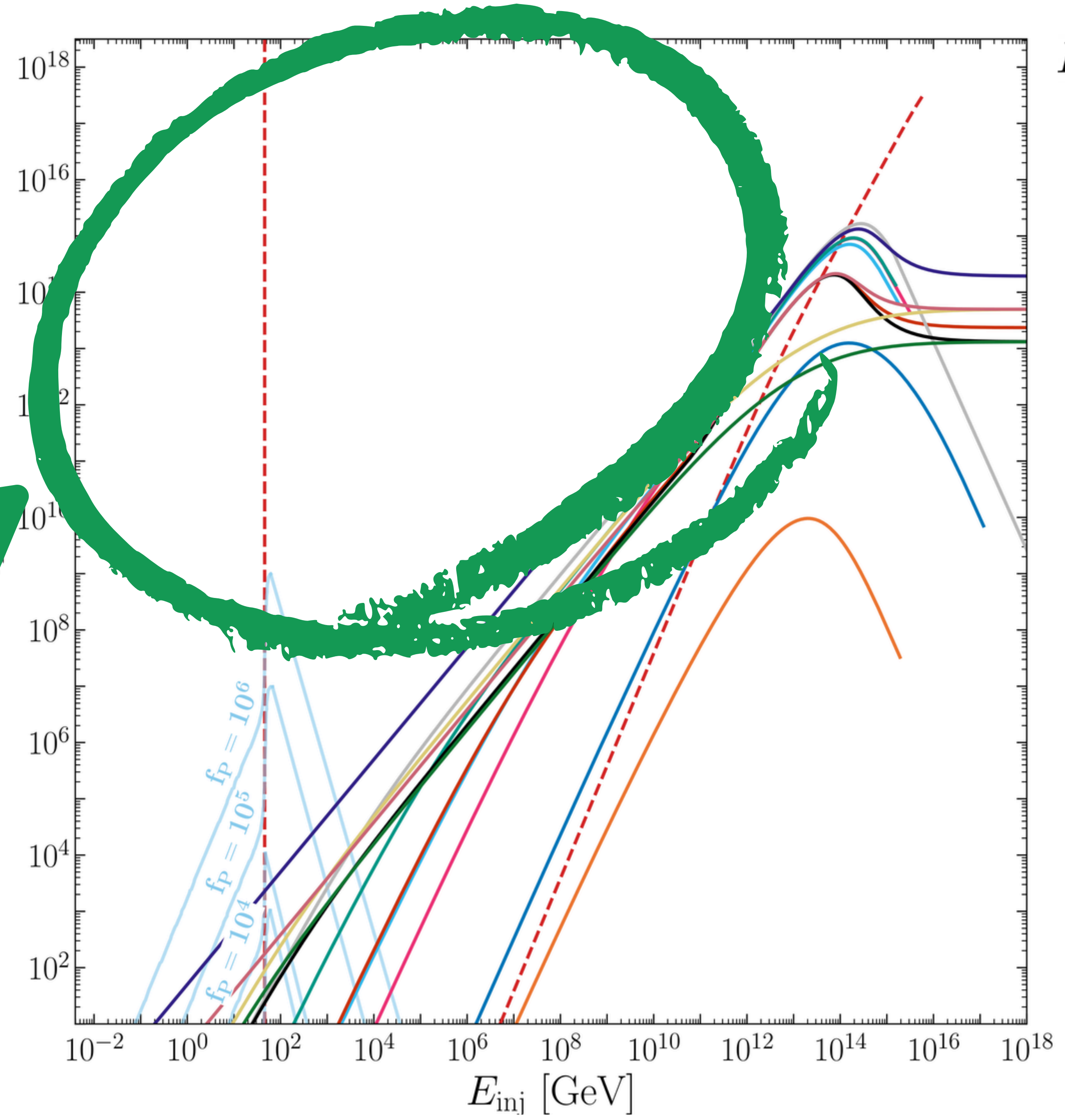
Average number of scattering

Integration over the line of sight

Thermally averaged cross section

Background neutrino number density

Sharp spectral features mostly unaffected

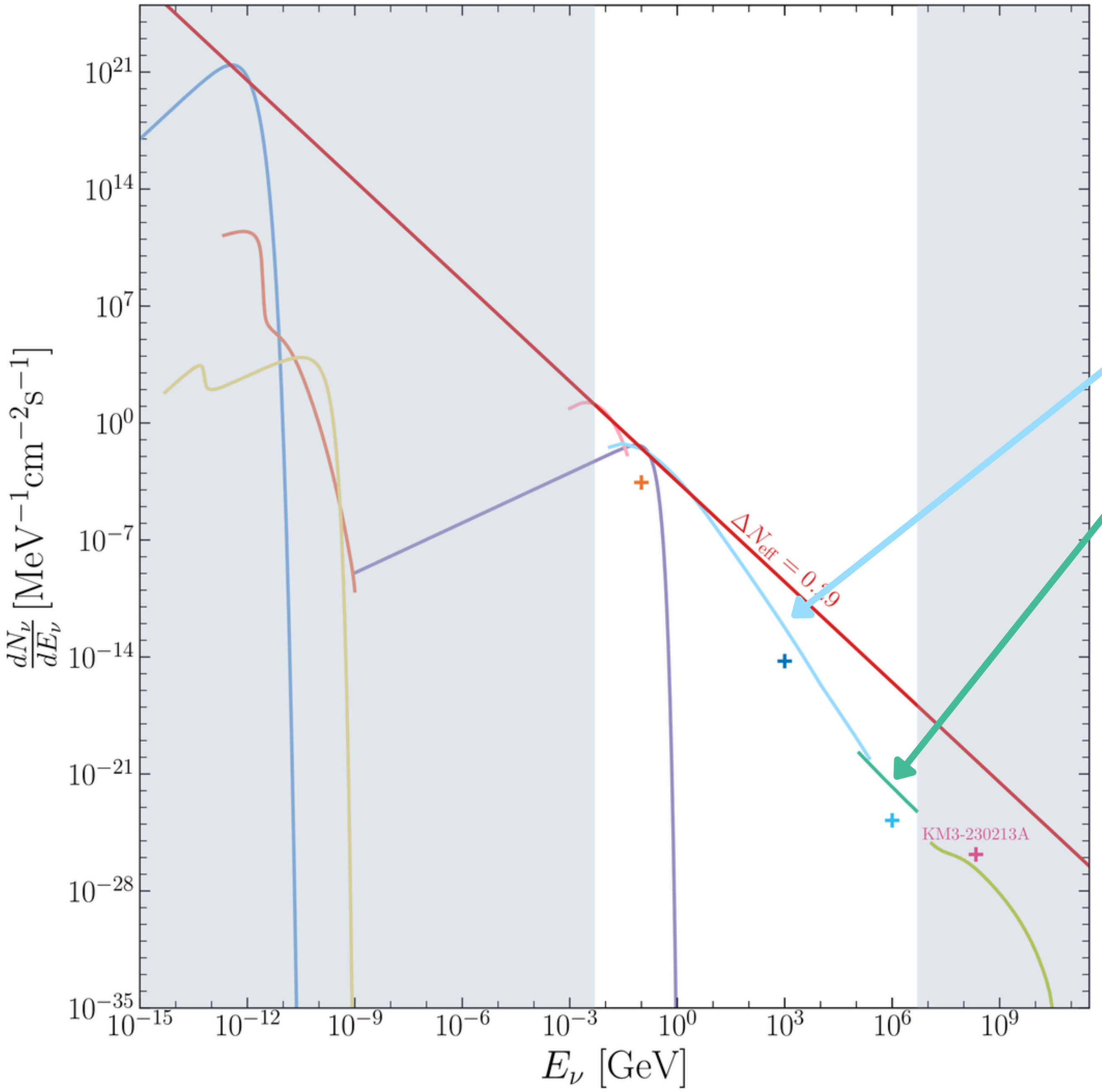



$$E_\nu^{inj} = E_\nu^0(1+z)$$

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

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

# Constraints.

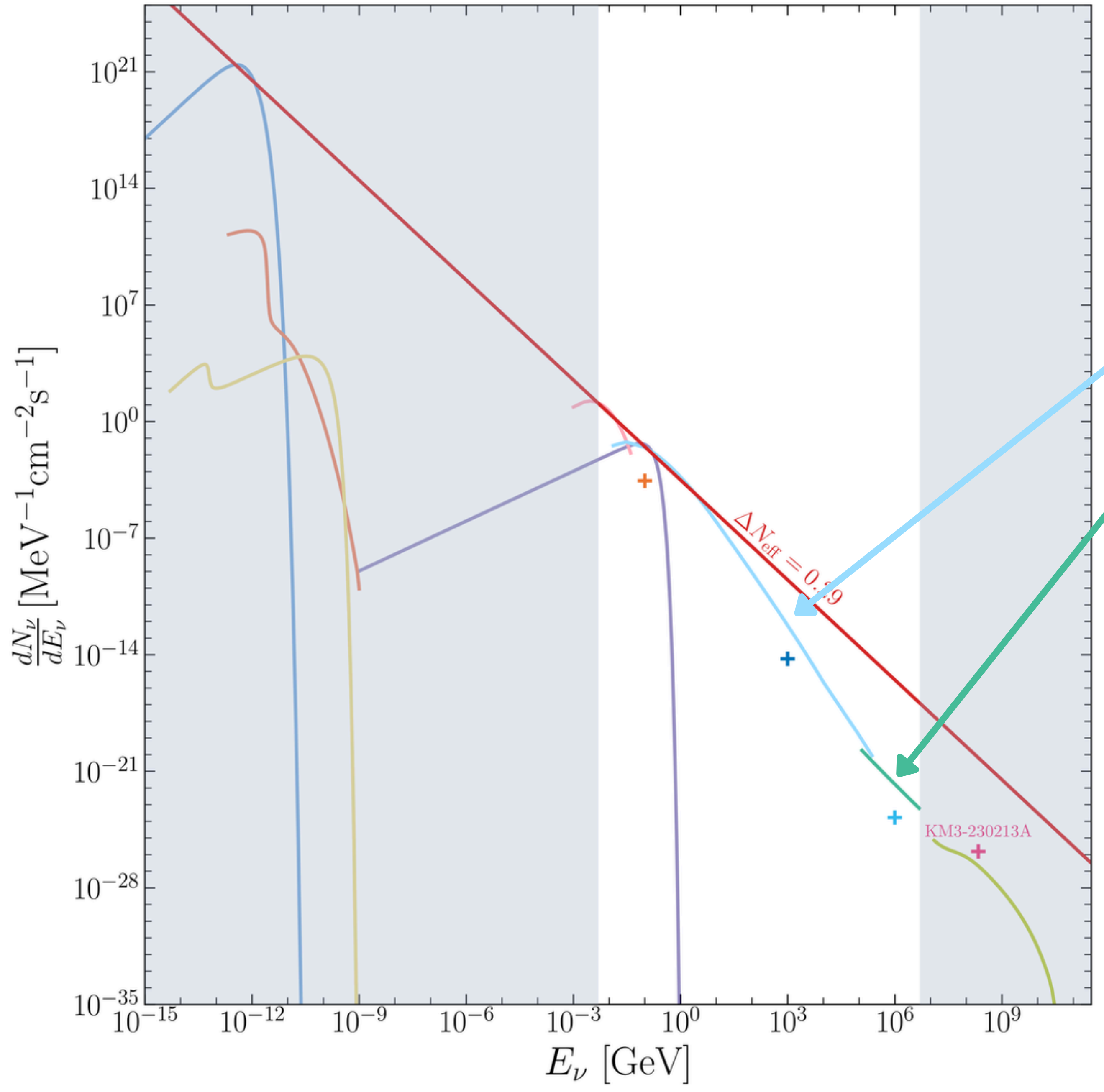



Vitagliano, Tamborra, Raffelt 19'

## Observational:

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

# Constraints.

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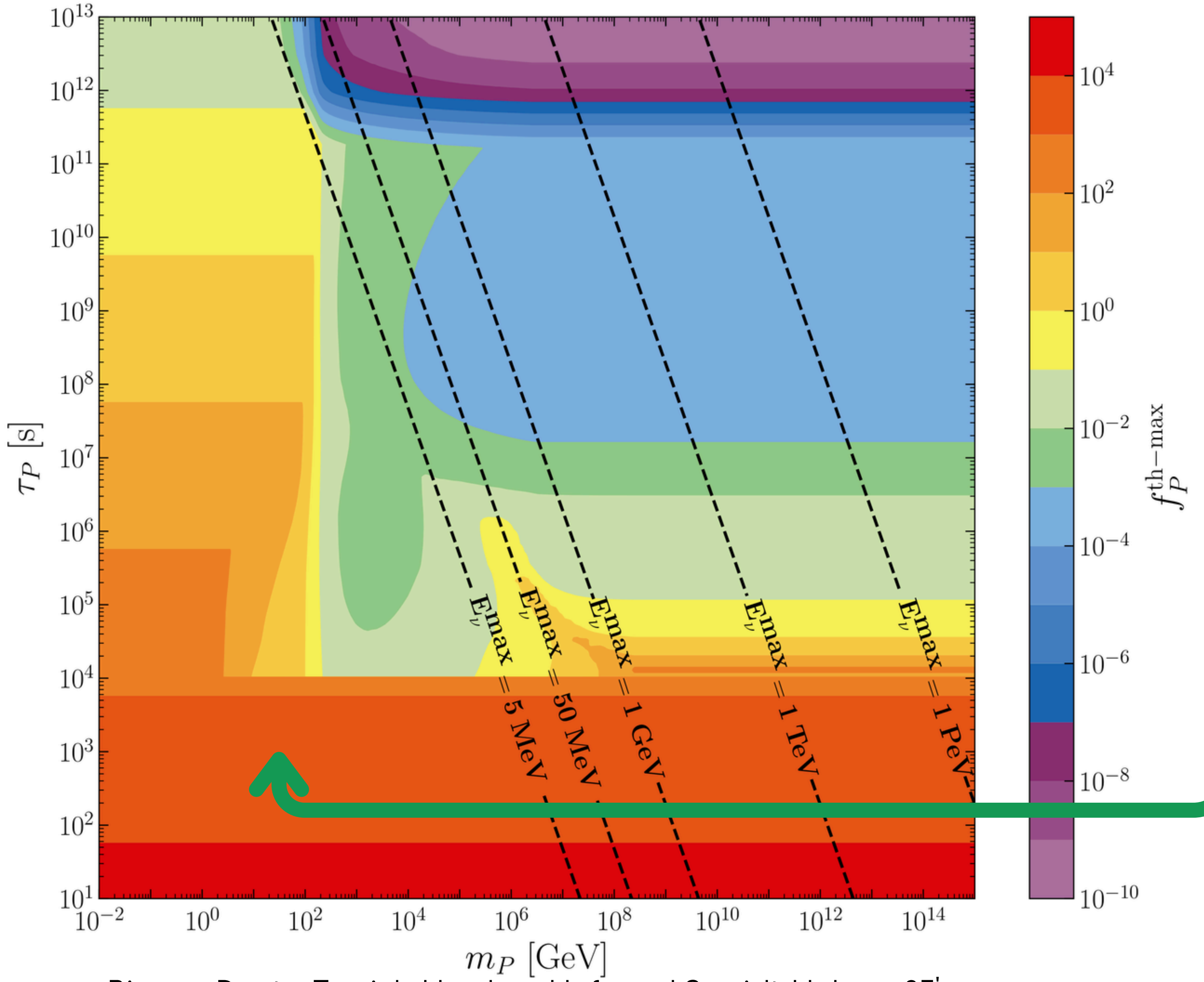
## Observational:

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

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

→ Upper bound on f

# Constraints.

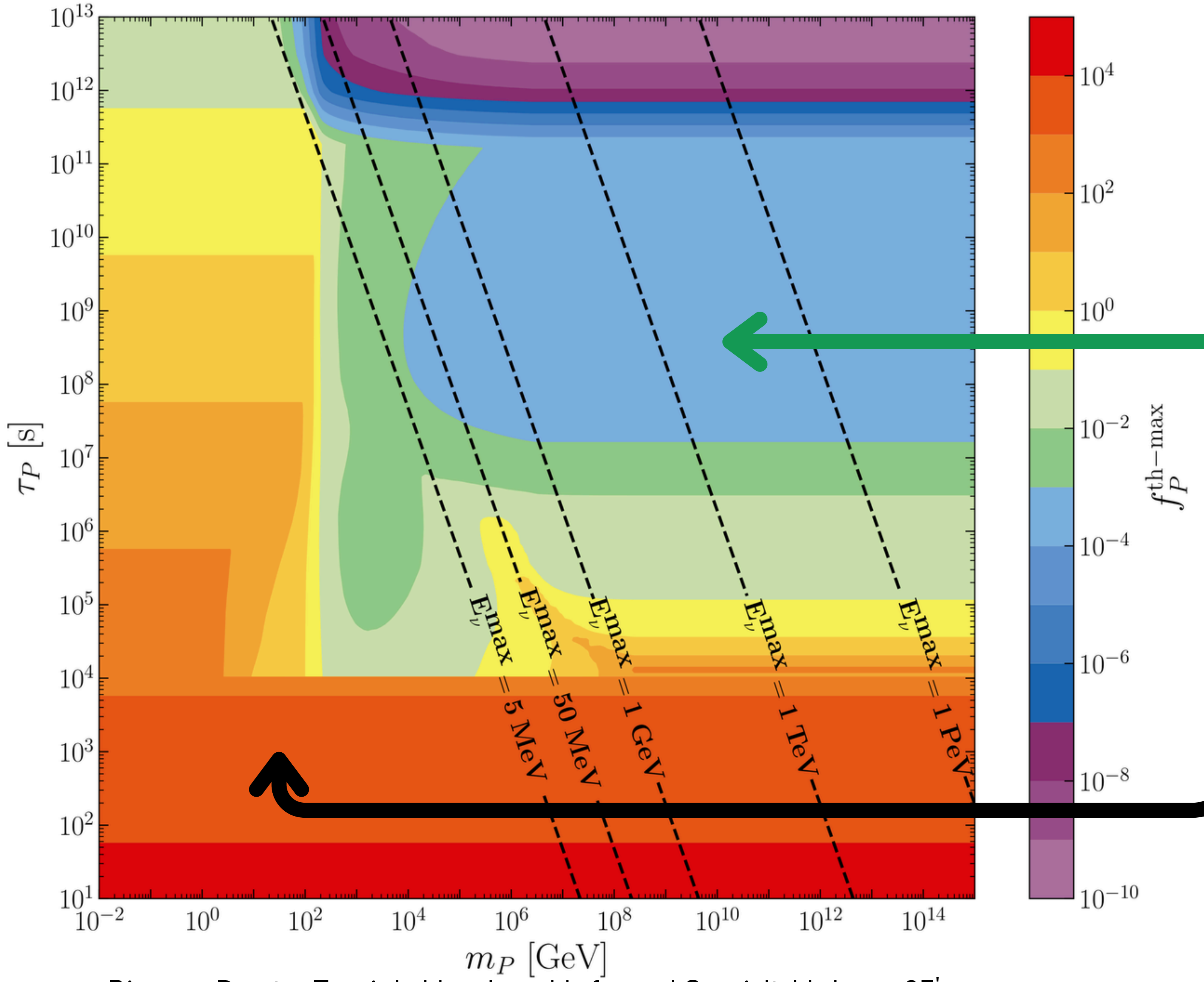



Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'
Hambye, Hufnagel, Lucca, 21'
Acharya, Khatri, 19'

## Theoretical:

$N_{eff}$ bound on additional neutrino energy density

# Constraints.

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BBN bound from photo and hadro disintegration of light elements

$N_{\mathrm{eff}}$ bound on additional neutrino energy density

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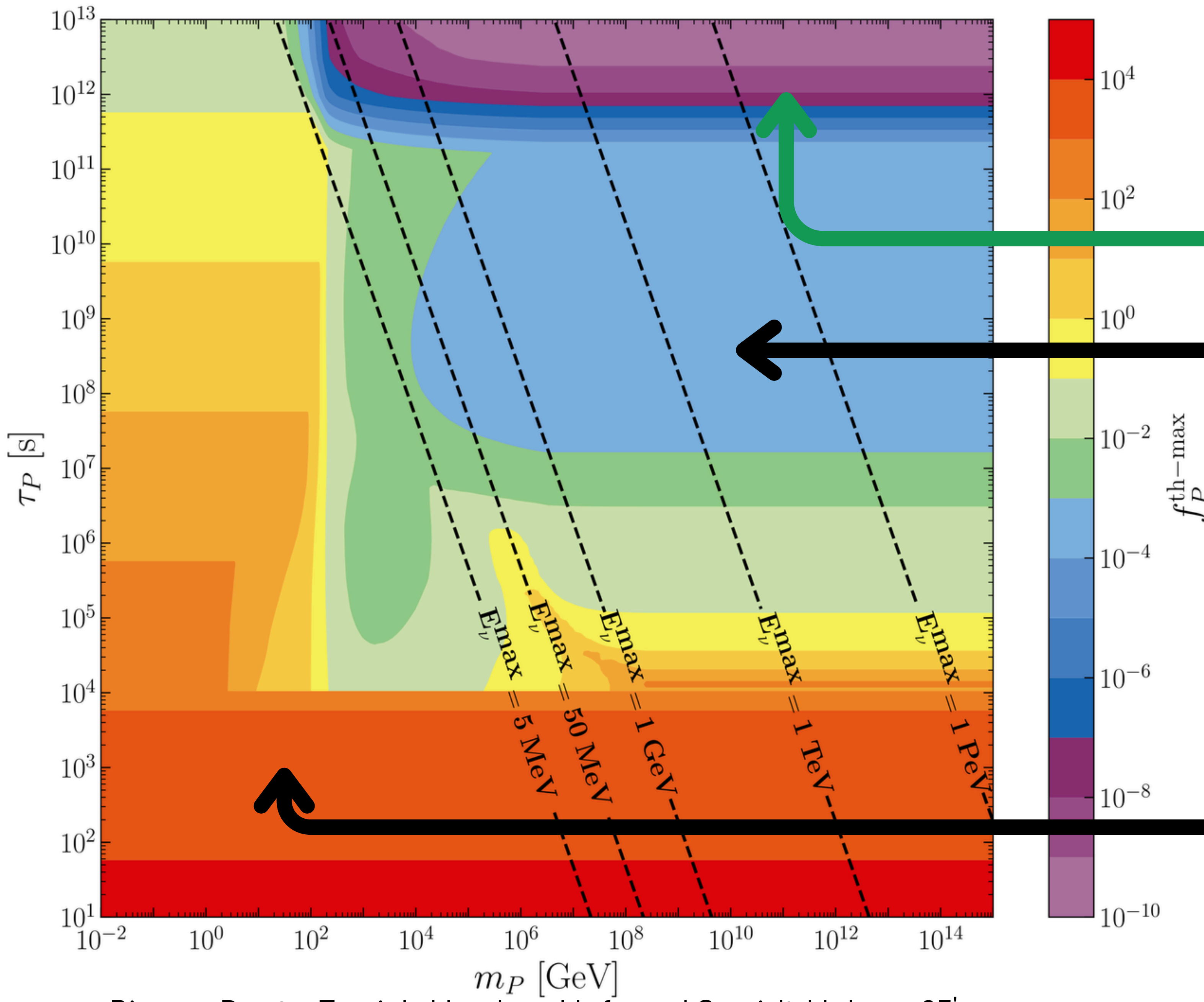


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## Theoretical:

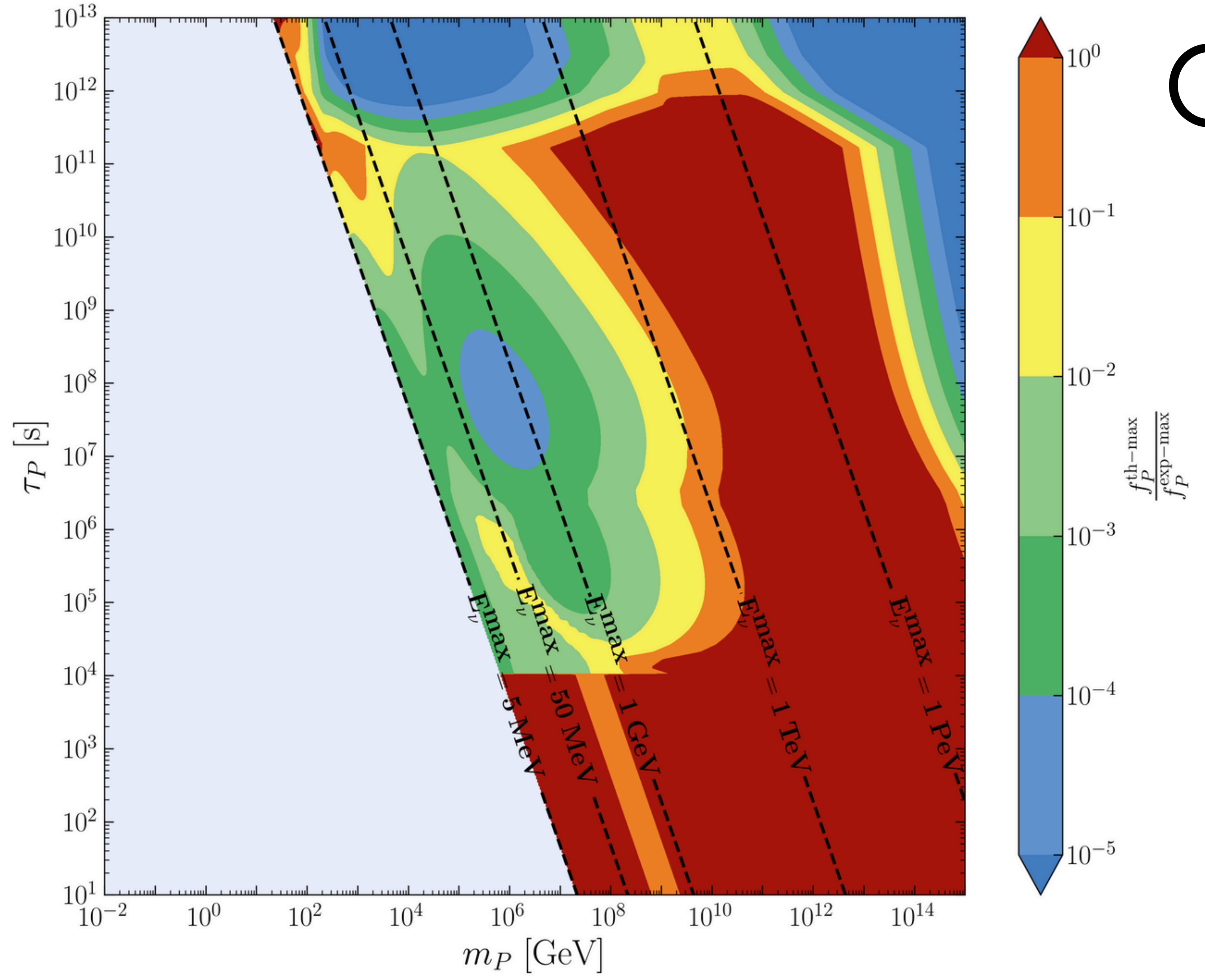
CMB anisotropies bound

BBN bound from photo and hadro disintegration of light elements

$N_{\mathrm{eff}}$ bound on additional neutrino energy density

**Competing bounds with observations**

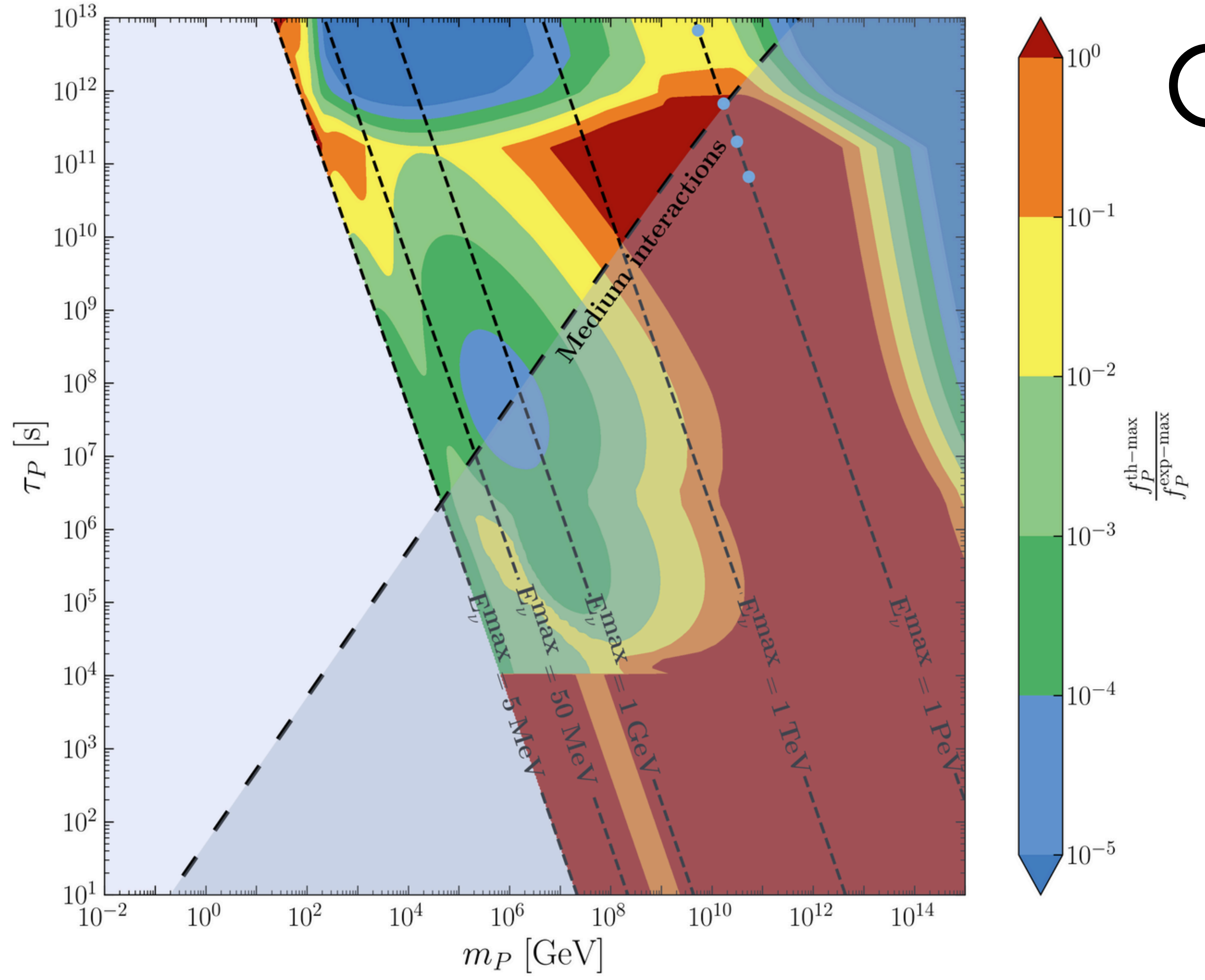
# Constraints.




## 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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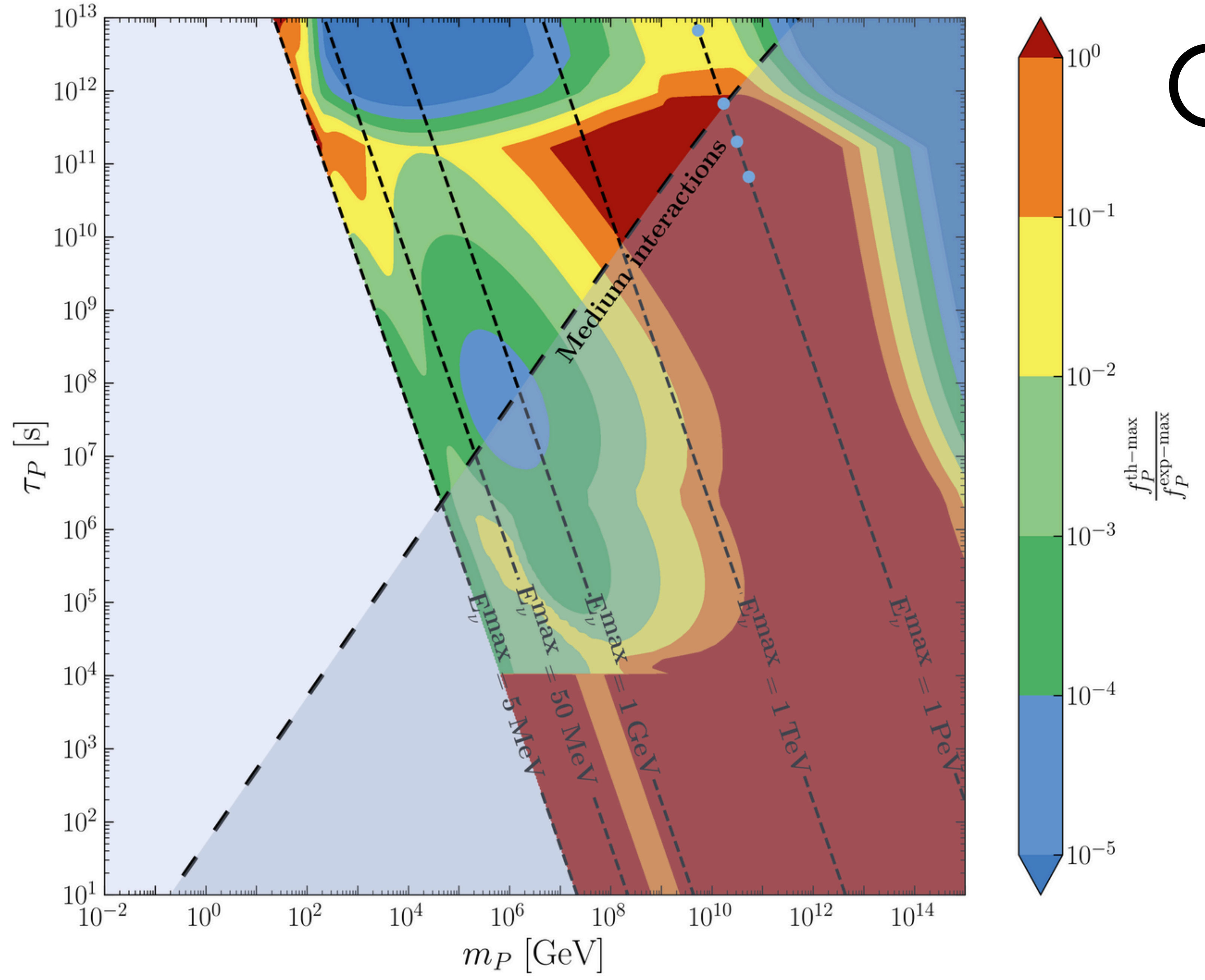


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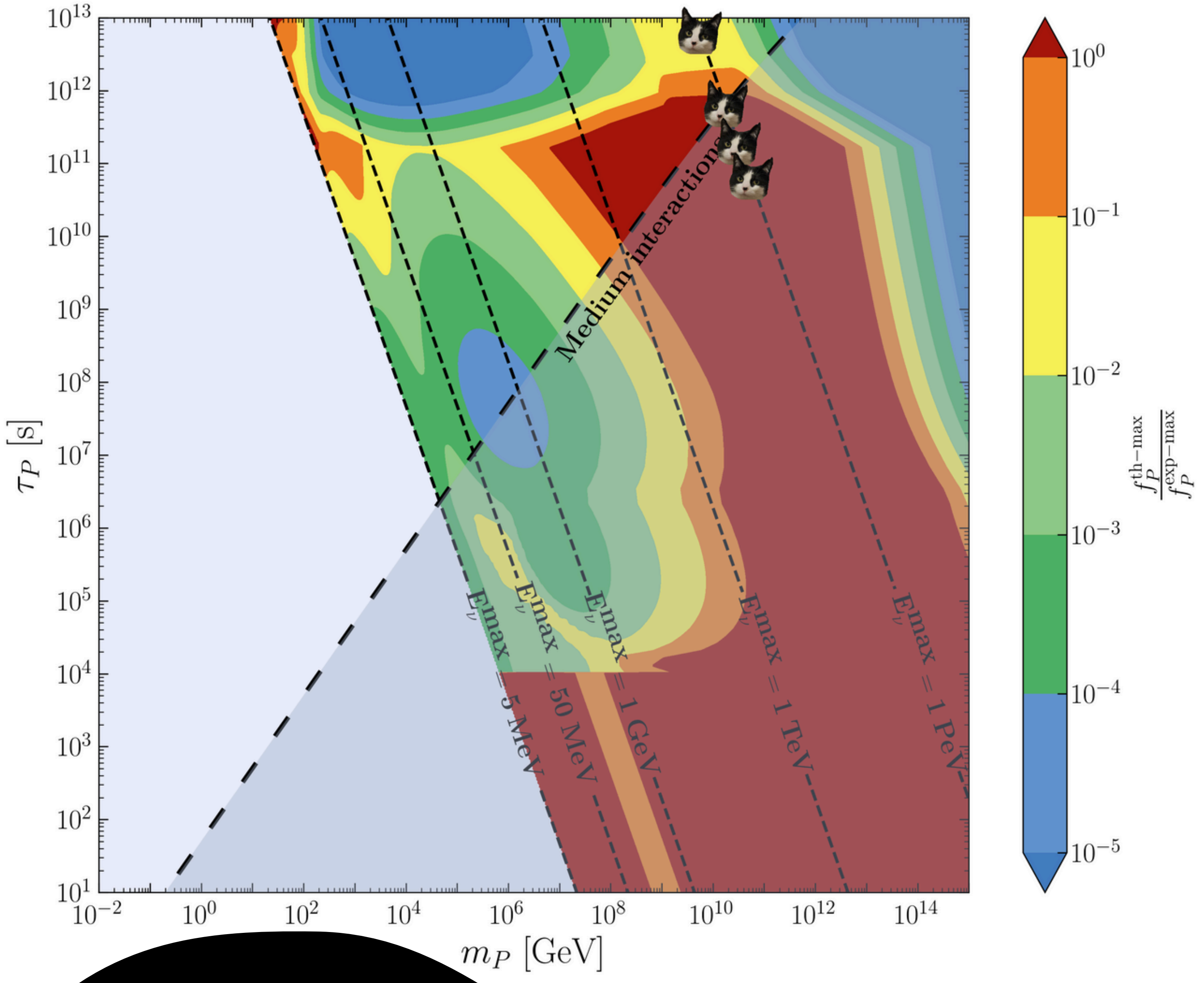
$$10^9 \text{ s} \lesssim \tau_P \lesssim 10^{12.5} \text{ s}$$
$$10^{-8} \lesssim f_P \lesssim 10^{-2}$$

Potentially observable in IceCube, HyperK, KM3NeT

# Take home message:

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

# Medium interactions II.



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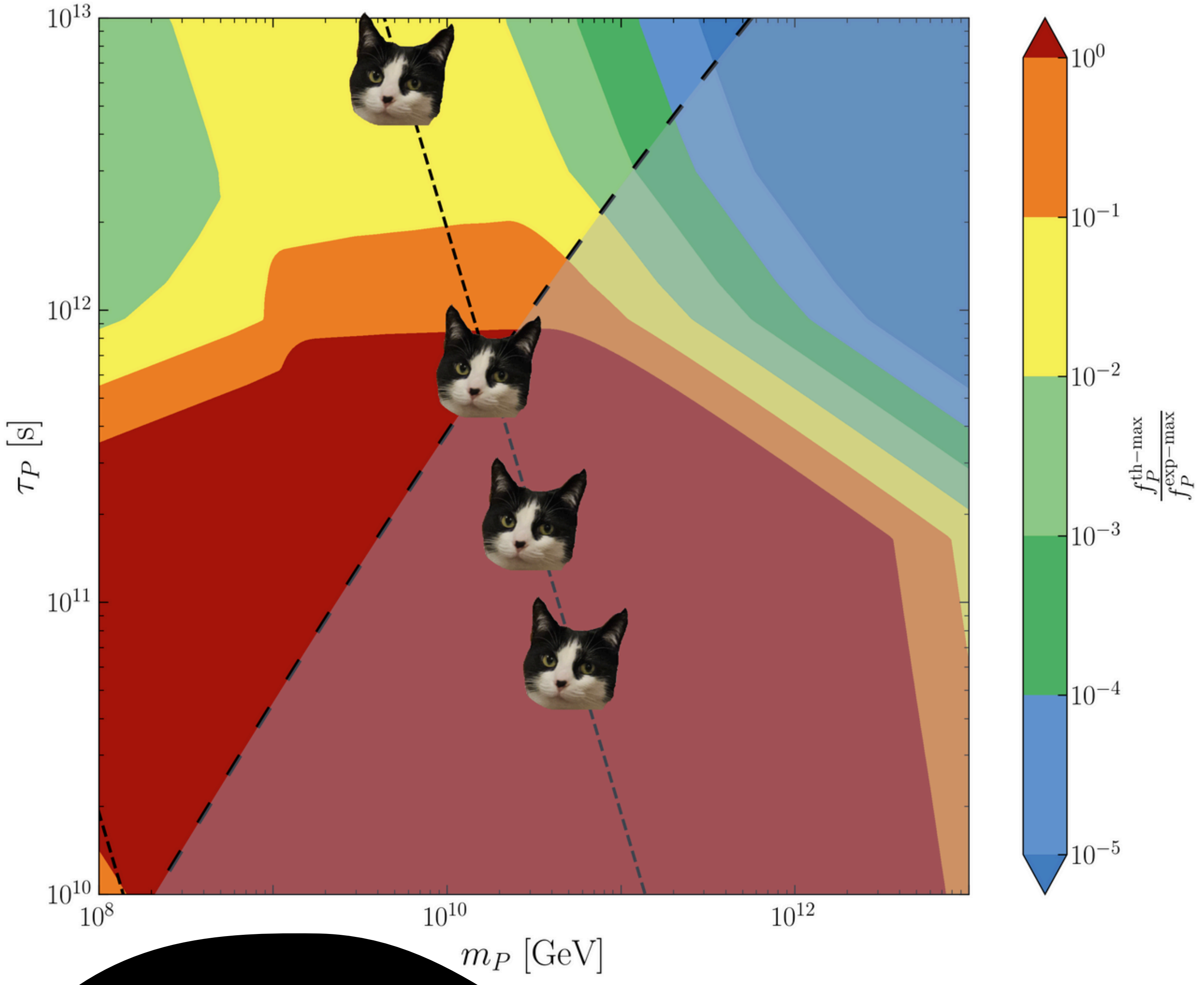
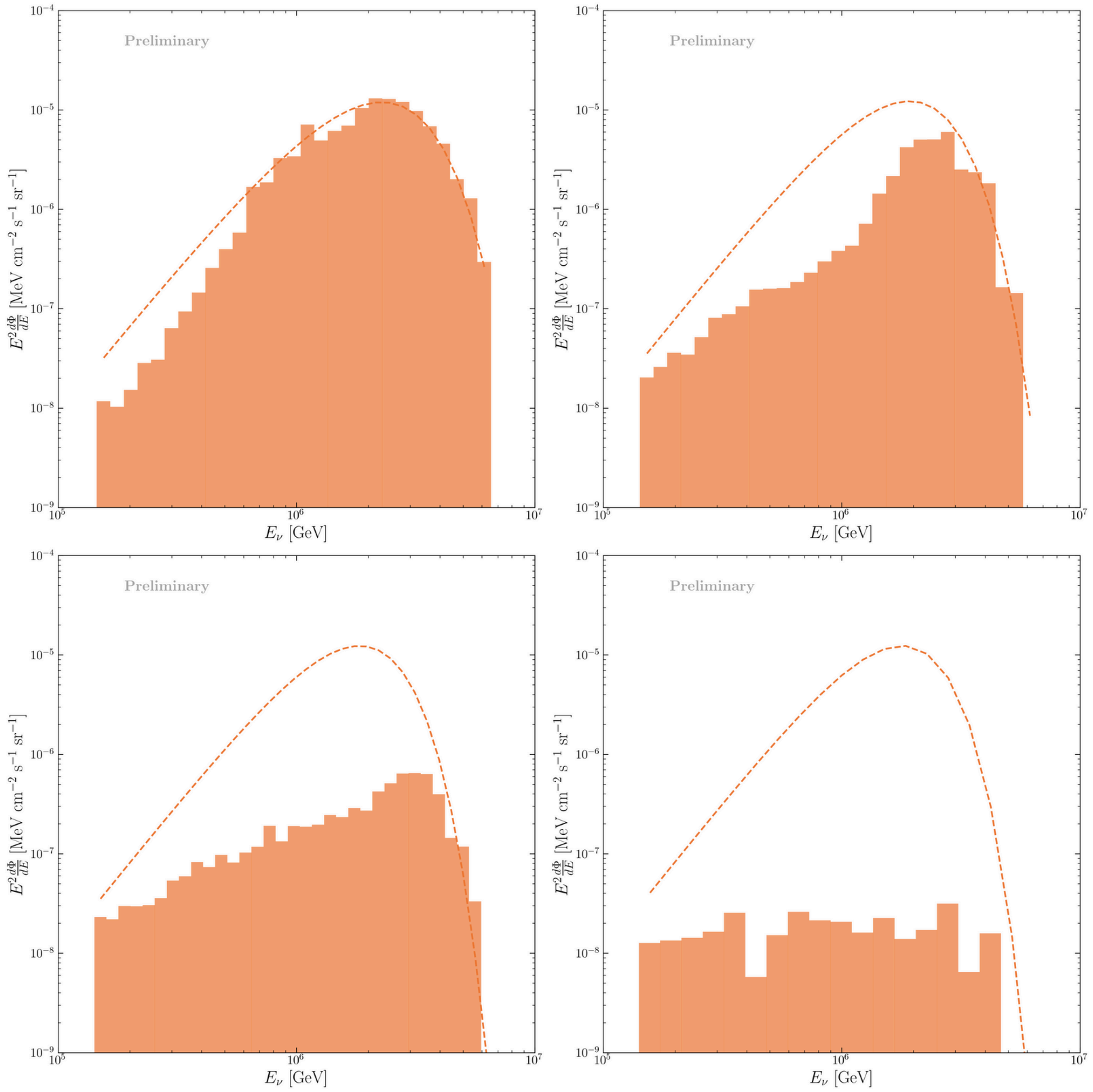


# Medium interactions II.

# Thank you for your attention

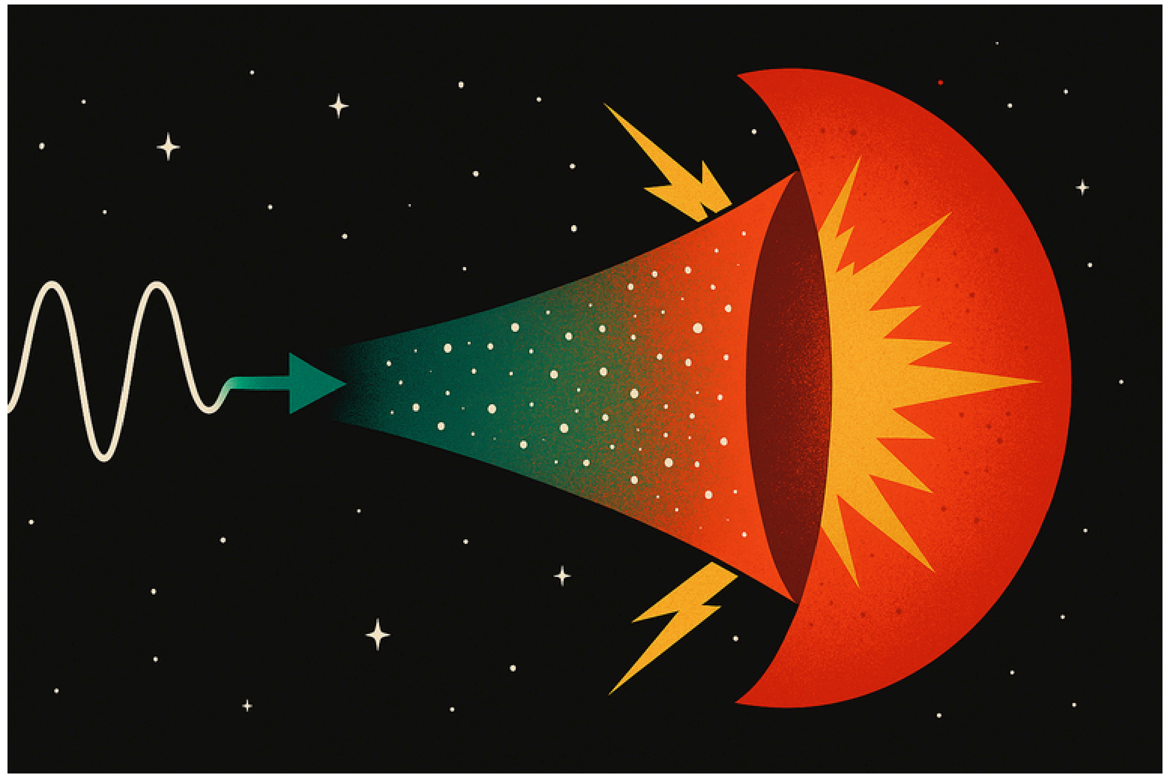

arXiv:2507.02063
2512.XX???

# Backup slides

# 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

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

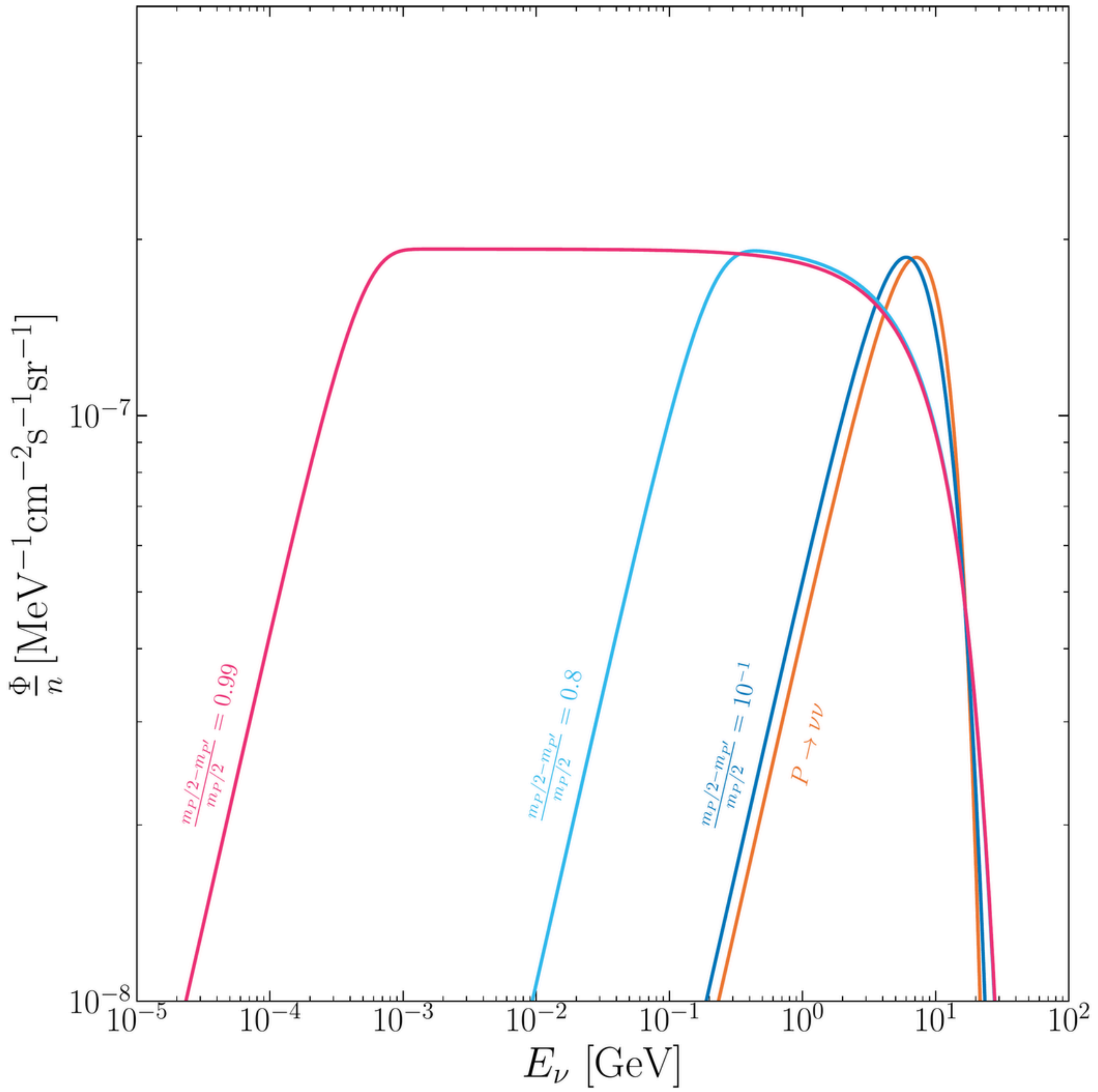
3-body decay $\frac{dN}{dE} = \Theta(m_P/2 - E)\cdot 24\frac{E^2}{m_P^3}$

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.

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

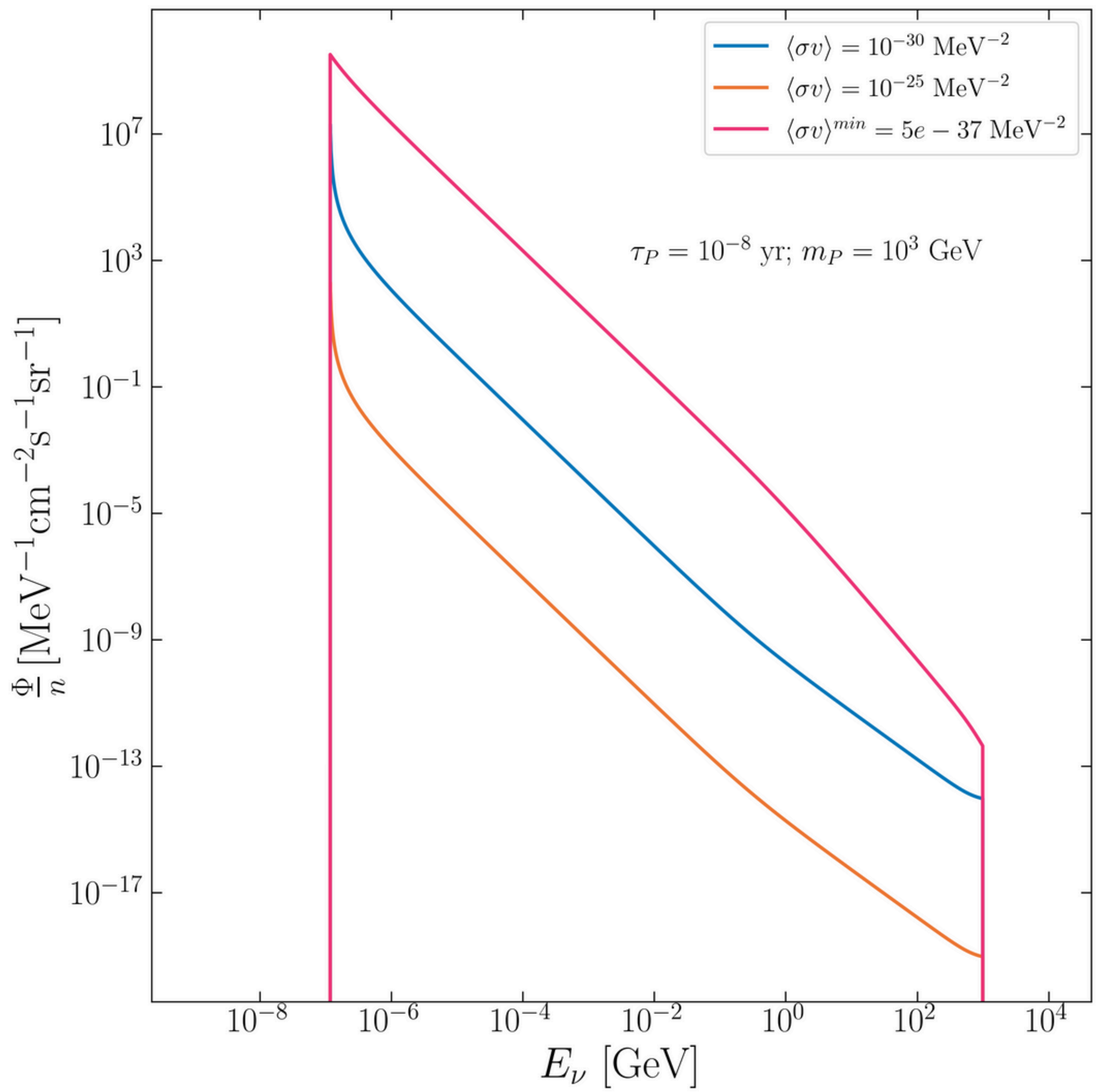
$$\langle\sigma v\rangle n_P^{eq} < H(t^{inj}) \longrightarrow \langle\sigma v\rangle < \left(\frac{2\pi}{m_P T^{inj}}\right)^{3/2}\frac{e^{m_P/T^{inj}}}{2g_i t^{inj}}$$

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

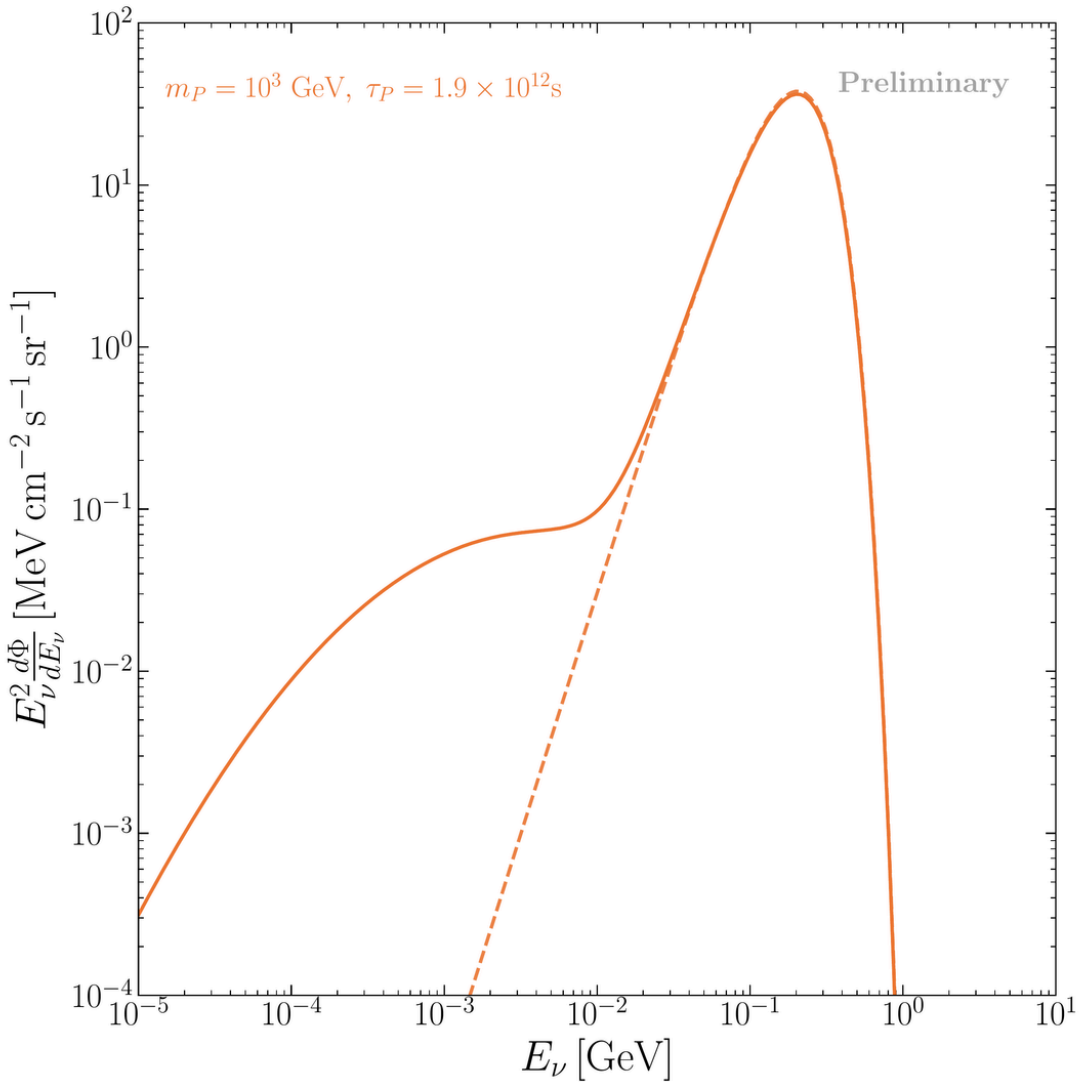
$$\langle\sigma v\rangle n_P^{inj} > H(t^{inj}) \longrightarrow \langle\sigma v\rangle > \frac{m_P}{2\Omega_P^0\rho_{crit}^0}\sqrt{\frac{t^{inj}}{t_r^3}}$$

# 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

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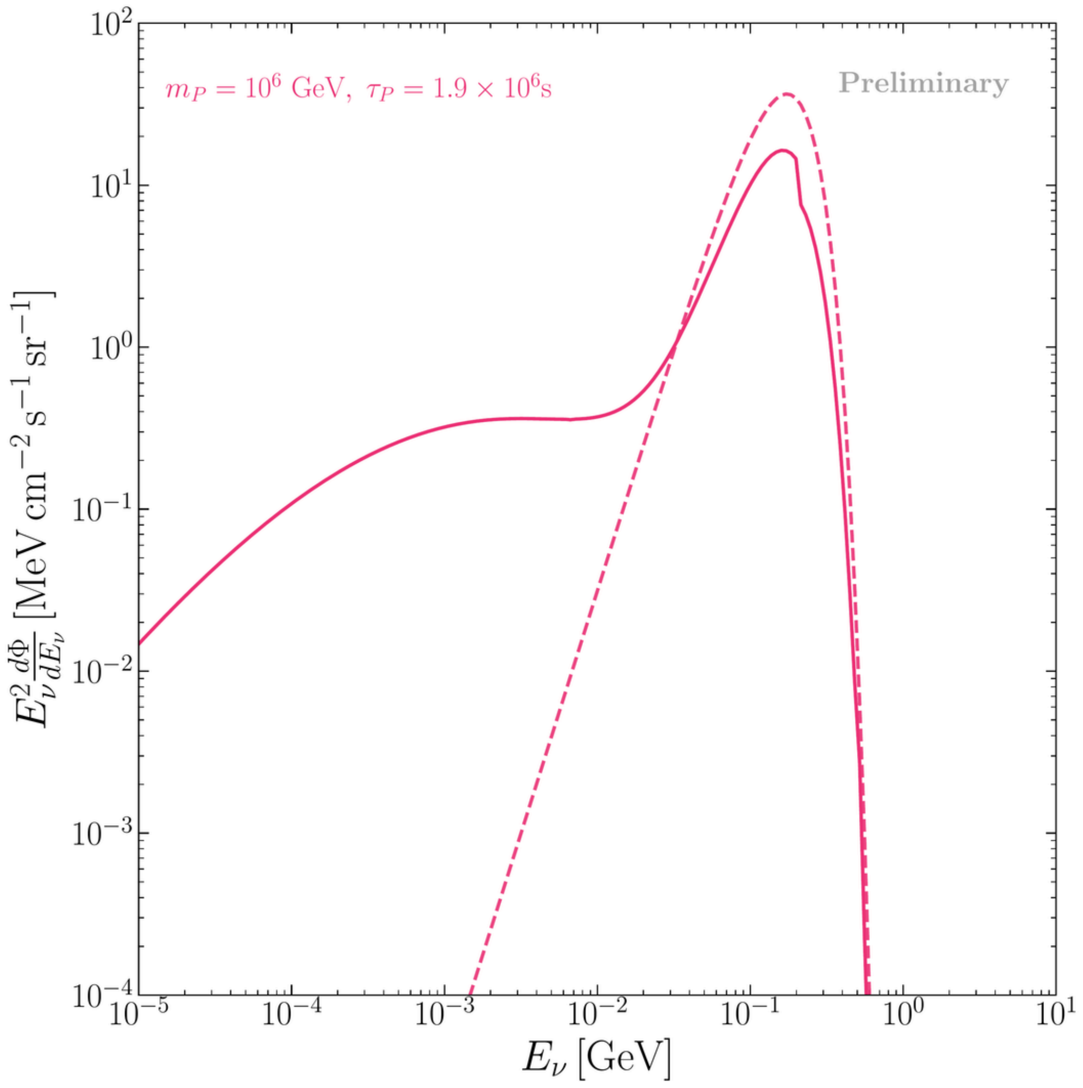


## Final state radiation broadening

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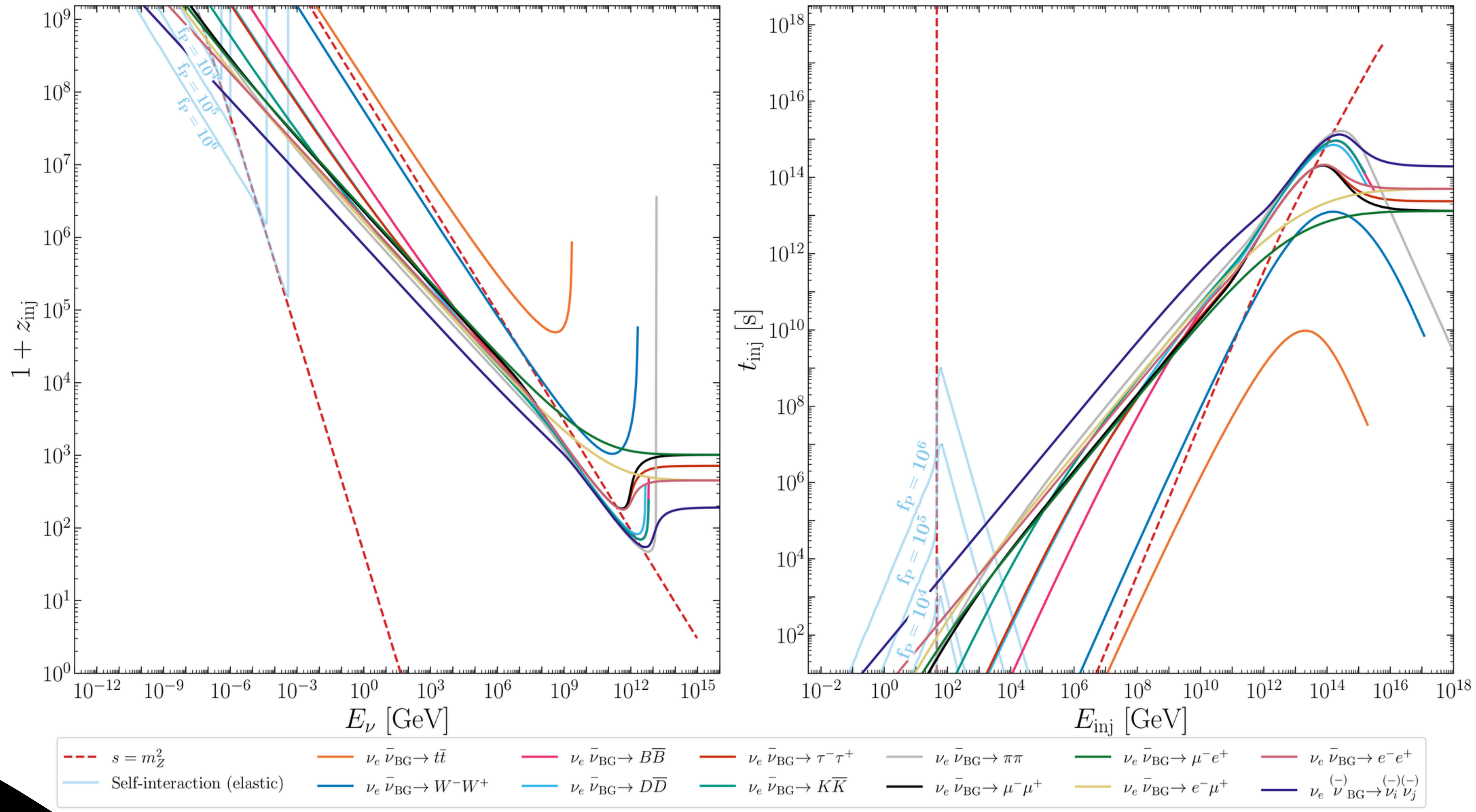
**Sharp feature mostly unaffected**

# Medium interactions.

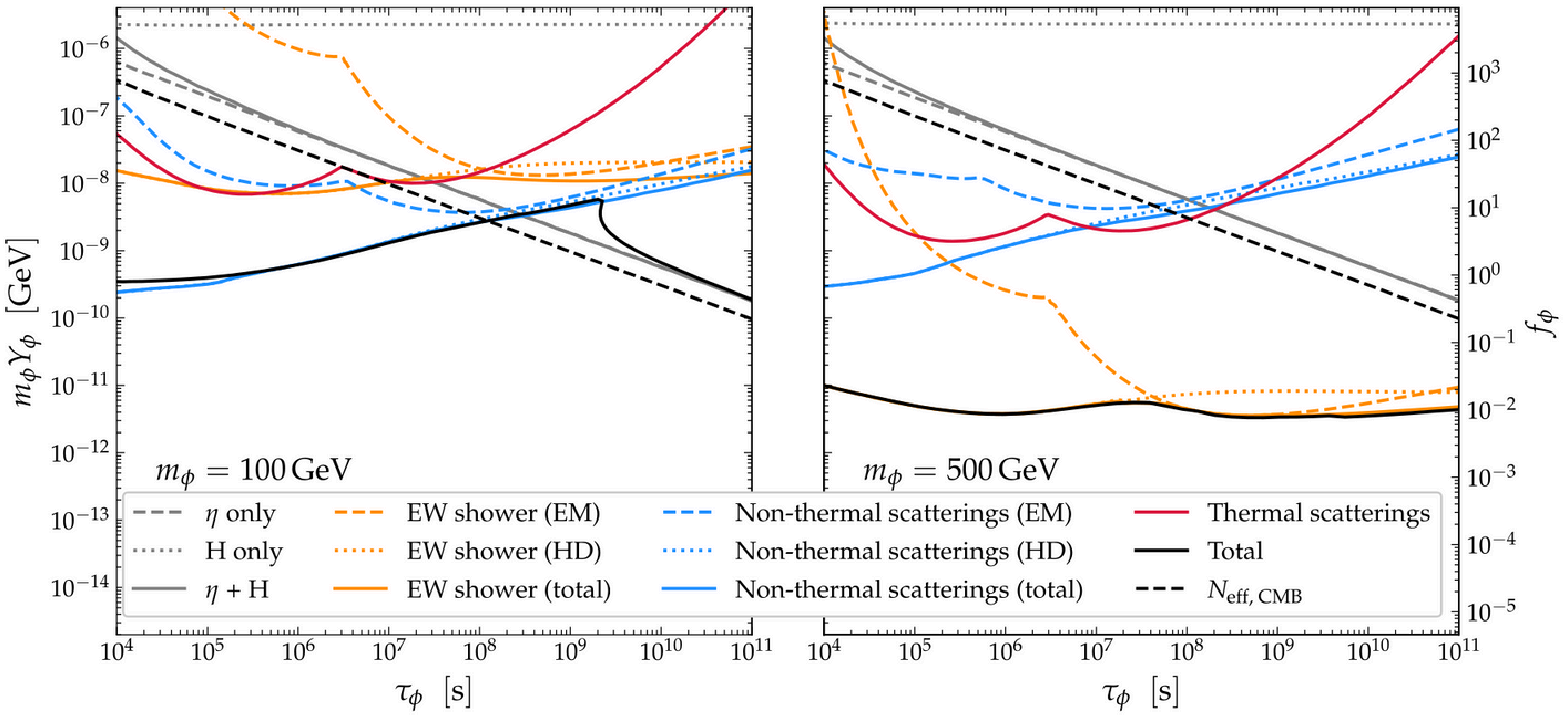


# Self-scattering.

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

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

# BBN constraints.




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

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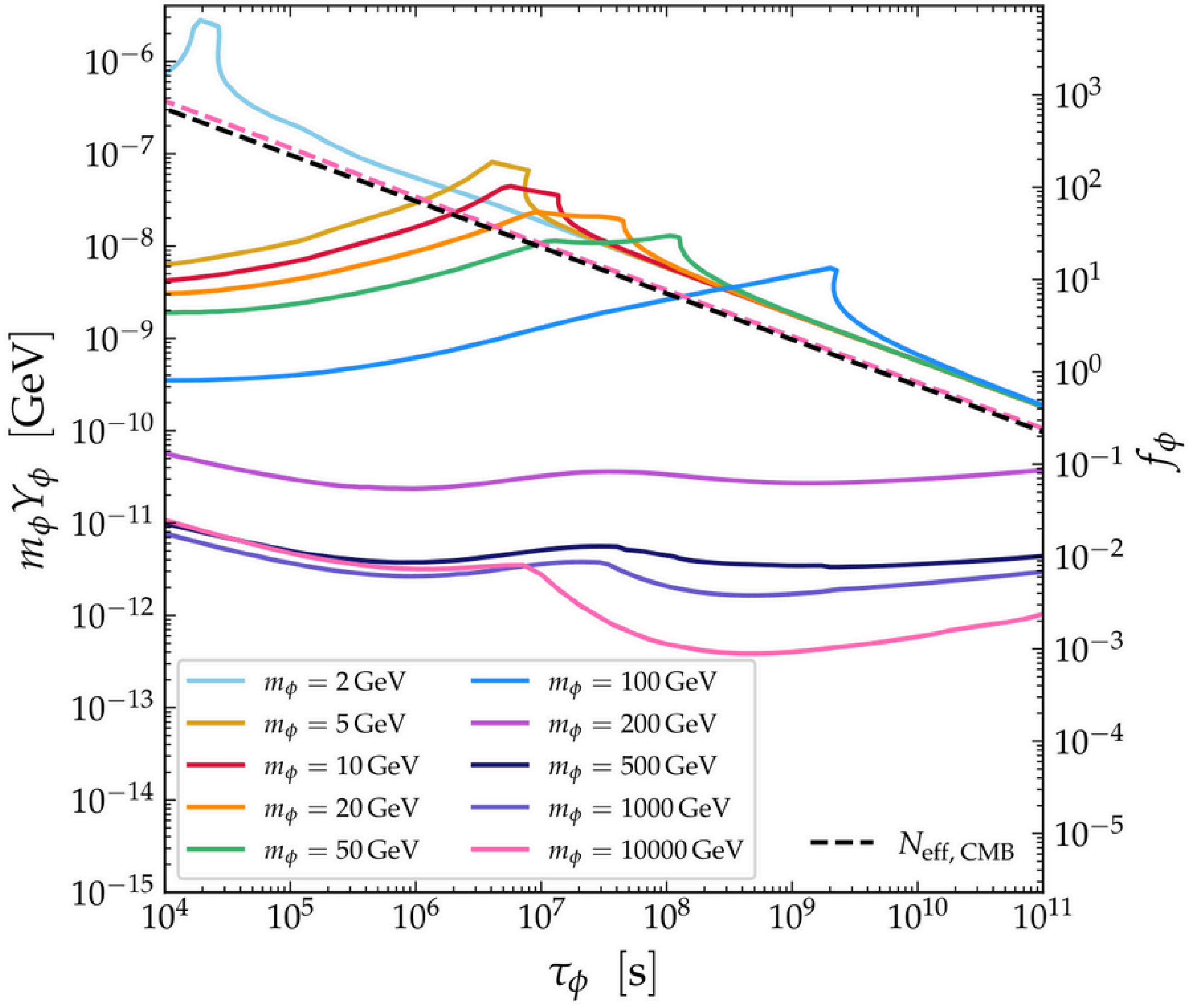


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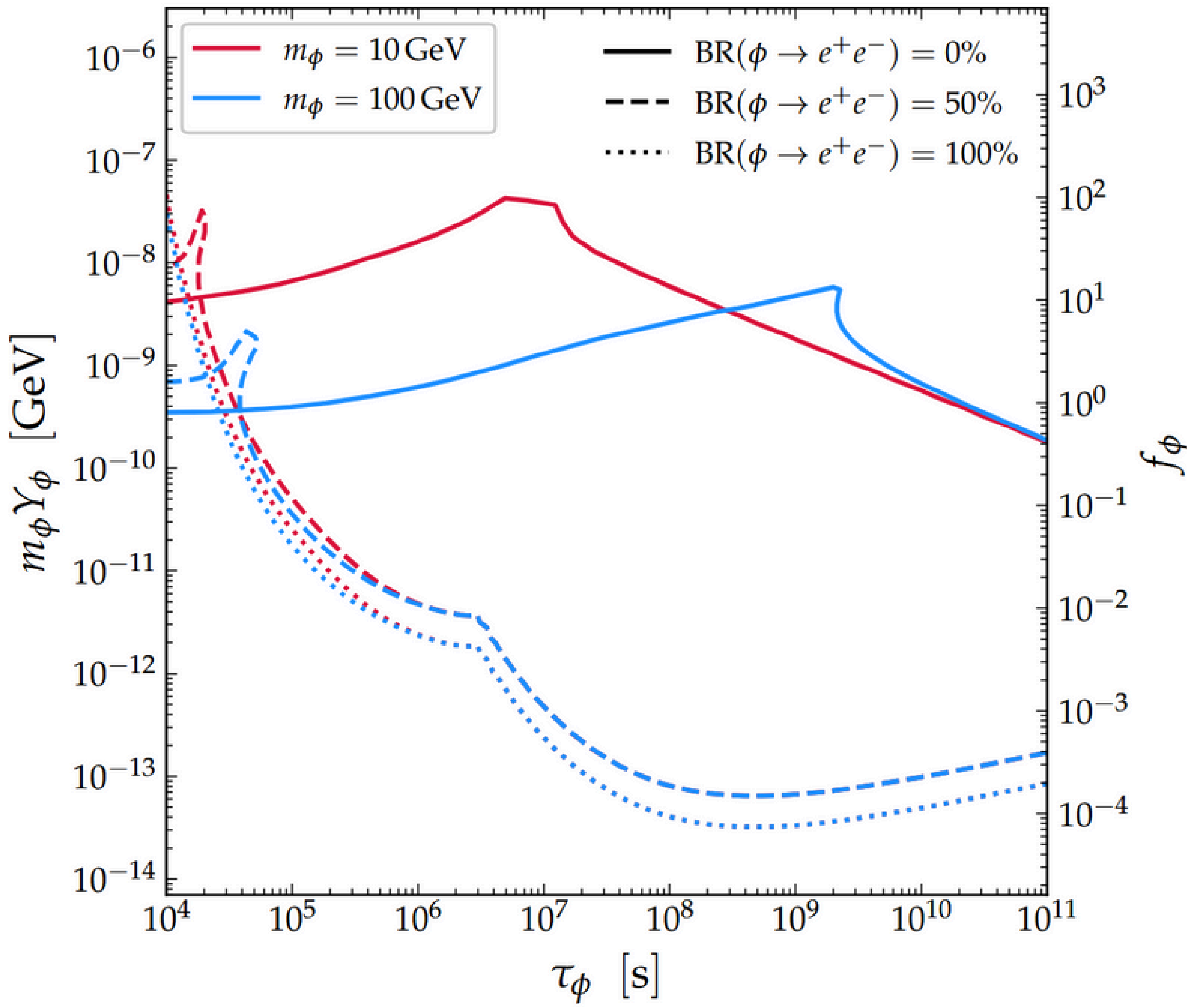
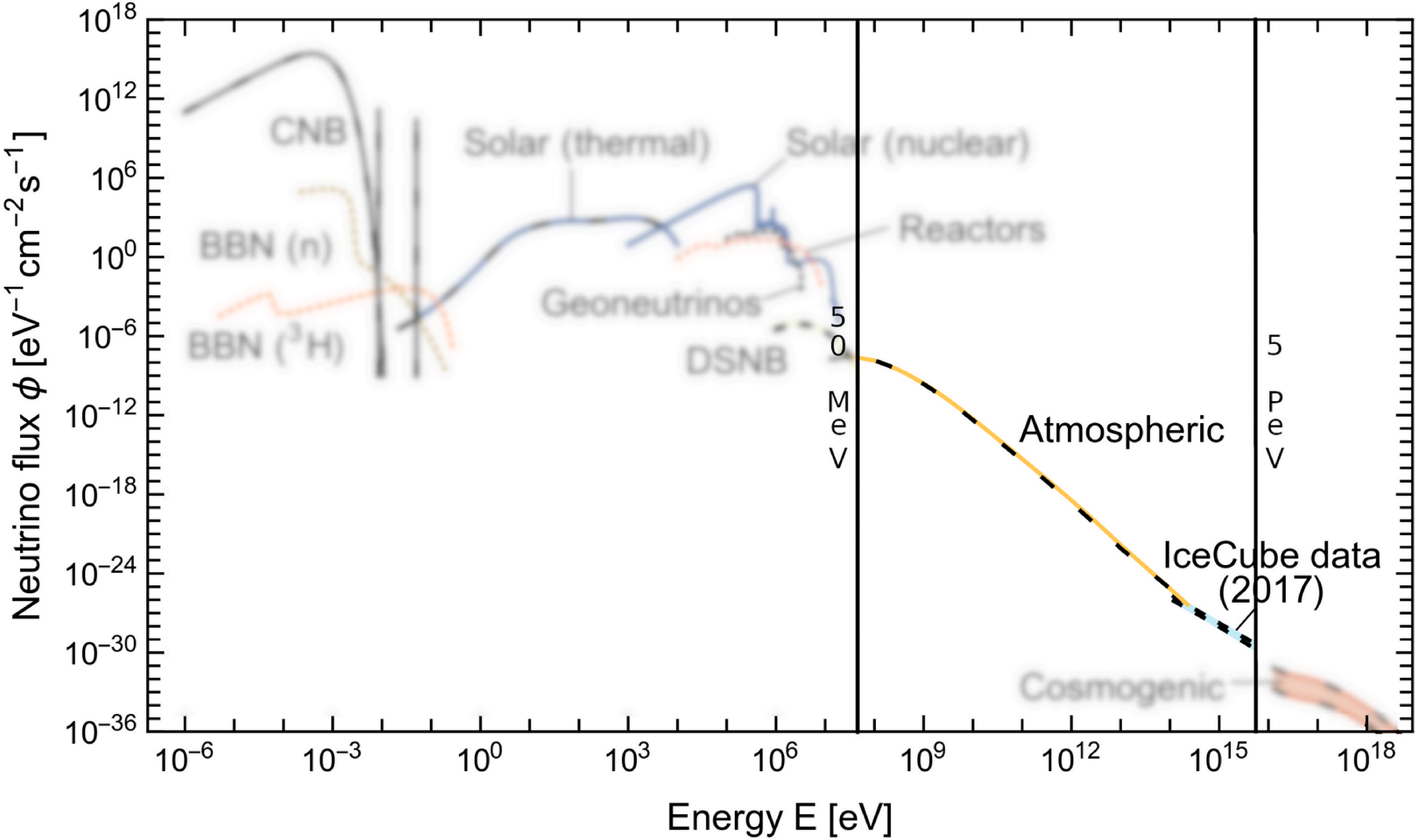
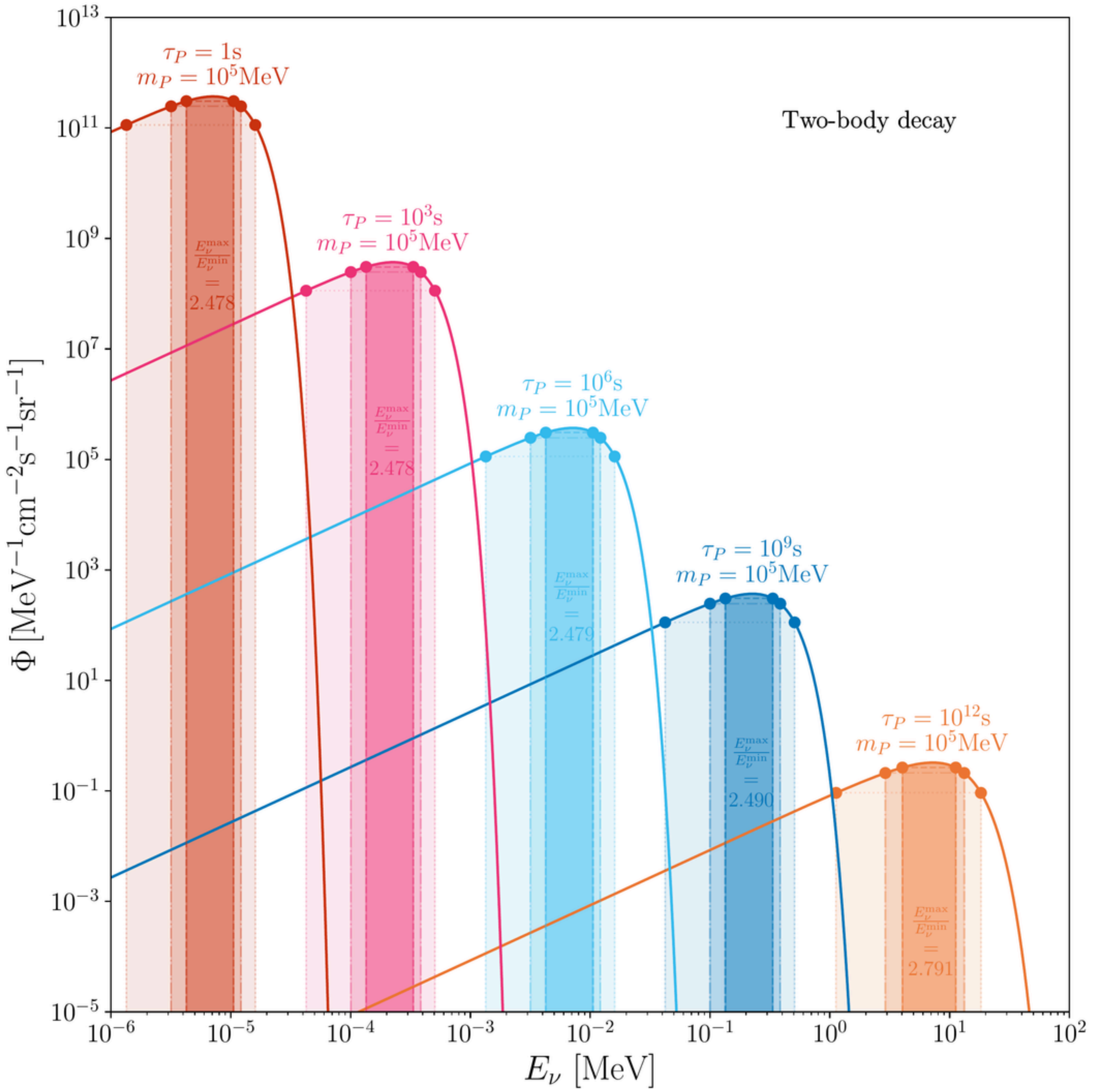


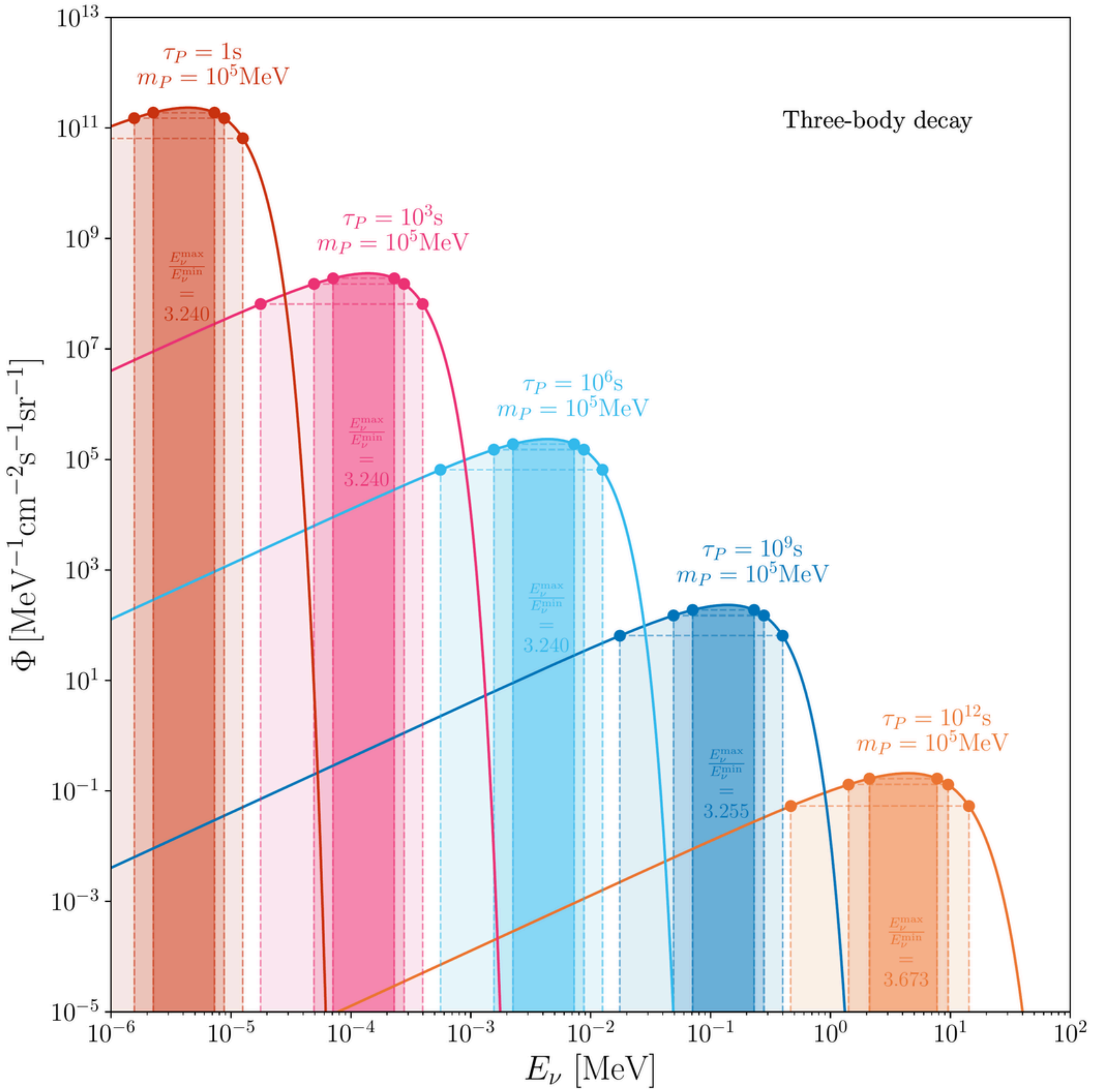

Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'




Vitagliano, Tamborra, Raffelt '19



Two-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
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.478$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.478$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.479$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.490$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.791$
$\Phi$ [MeV$^{-1}$cm$^{-2}$s$^{-1}$sr$^{-1}$]
$E_\nu$ [MeV]

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
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 3.240$
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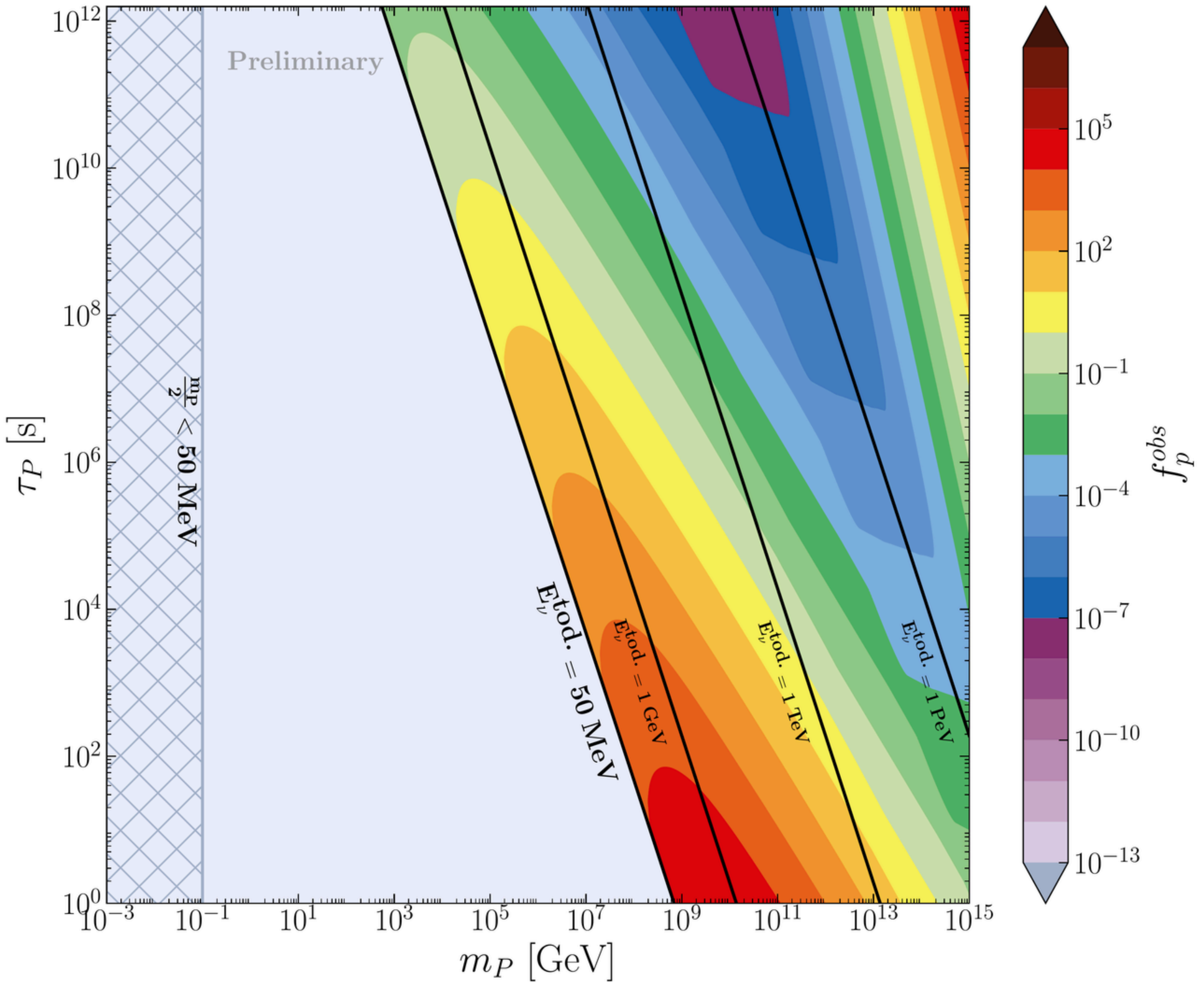
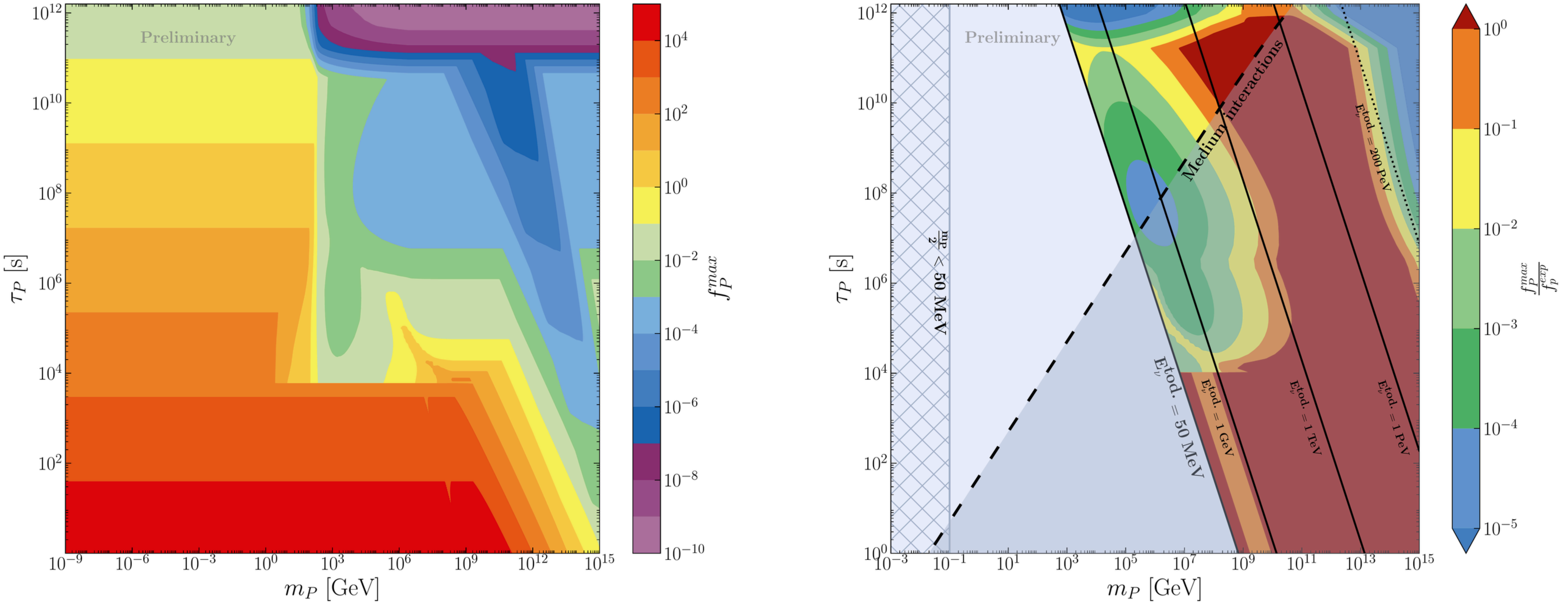
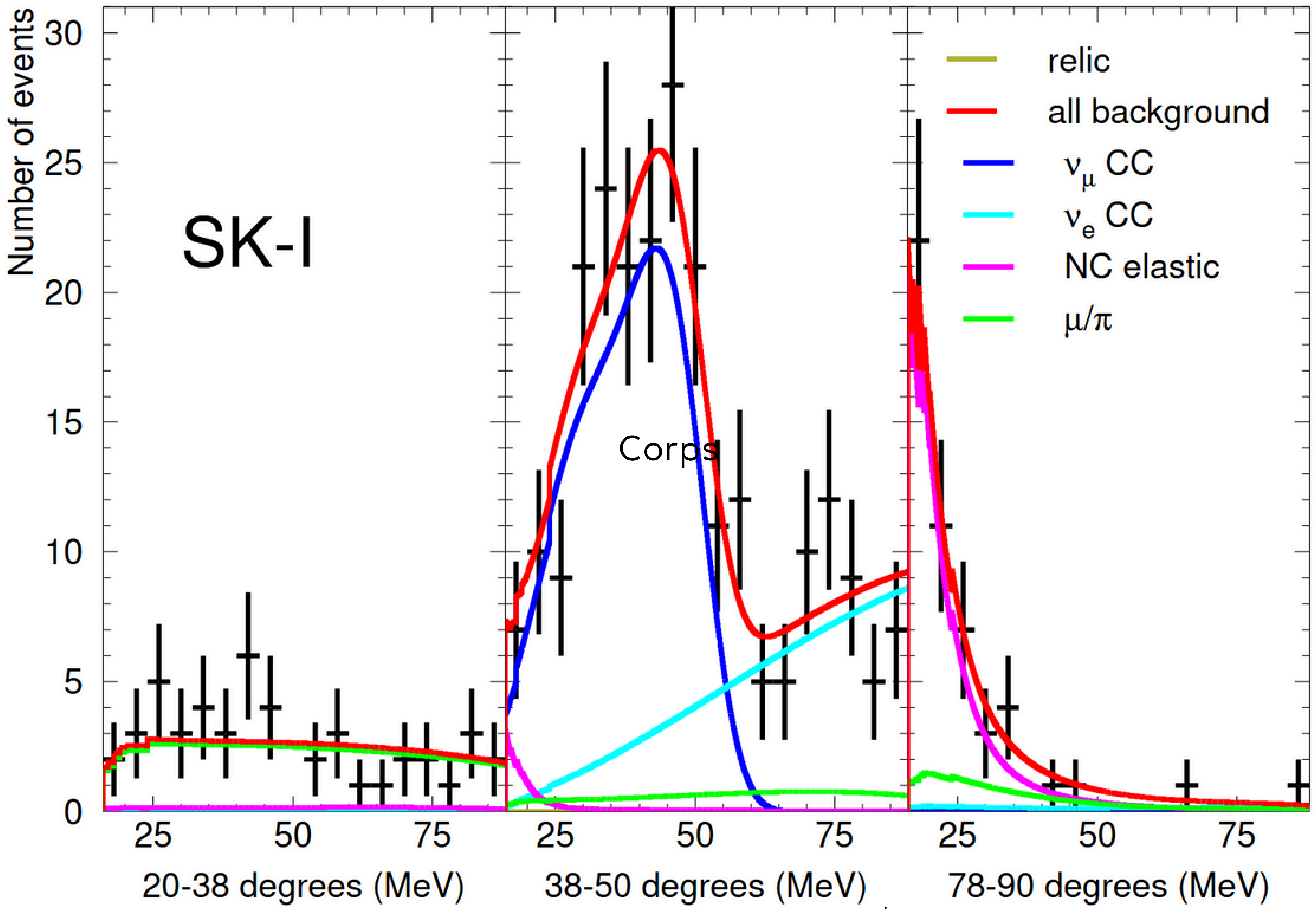
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 3.255$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 3.673$
$\Phi$ [MeV$^{-1}$cm$^{-2}$s$^{-1}$sr$^{-1}$]
$E_\nu$ [MeV]



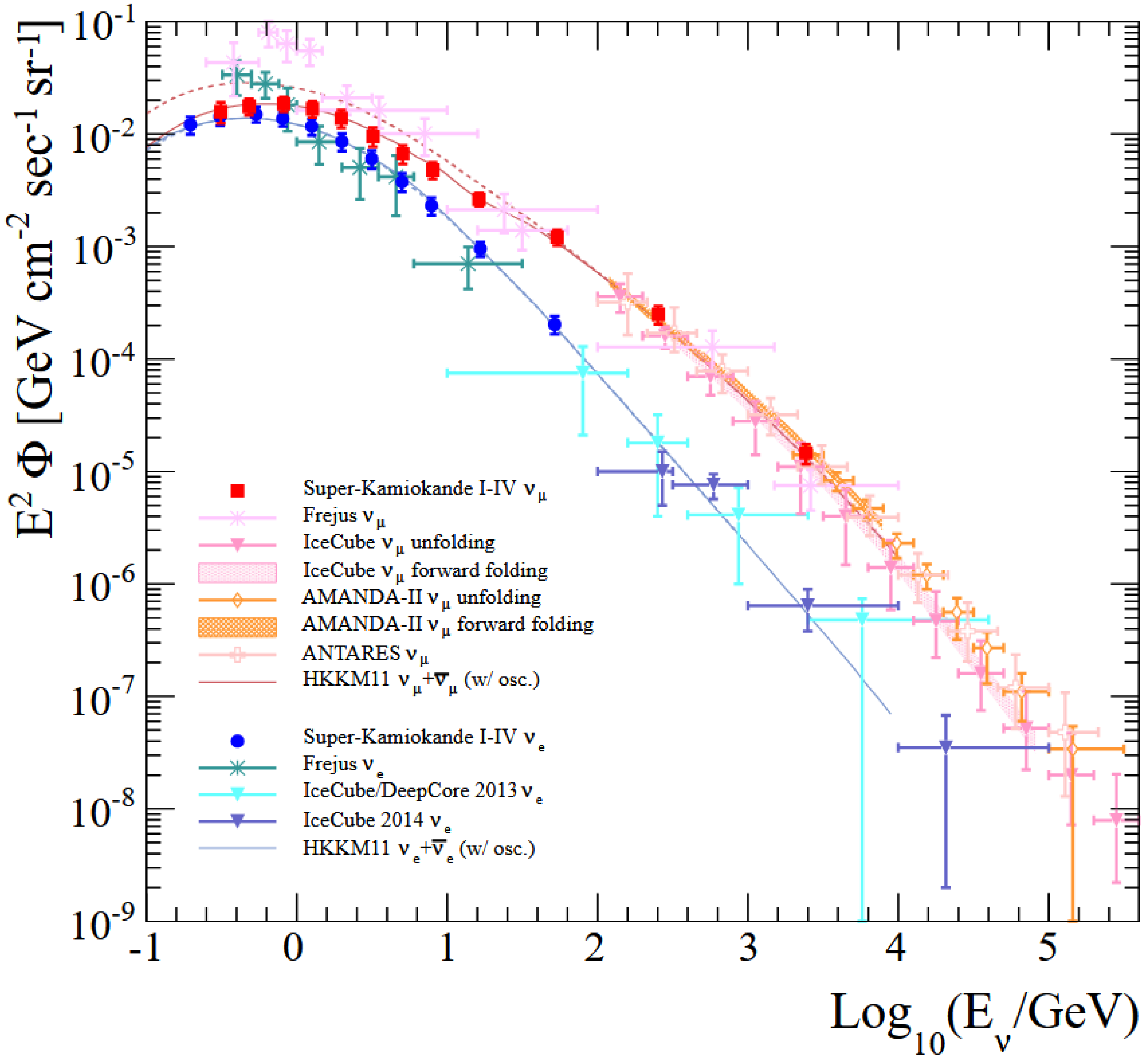
Preliminary
$\frac{m_P}{2} < 50$ MeV
$E_\nu^{\rm tod.} = 50$ MeV
$E_\nu^{\rm tod.} = 1$ GeV
$E_\nu^{\rm tod.} = 1$ TeV
$E_\nu^{\rm tod.} = 1$ PeV
$\tau_P$ [s]
$m_P$ [GeV]
$f_p^{obs}$



Preliminary
$\tau_P$ [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
$\tau_P$ [s]
$m_P$ [GeV]
$\frac{f_P^{max}}{f_p^{exp}}$



K. Bays et al. [SK coll.], ‘12




Richard et al. [SK Coll.] 15'

# Models

- Scalar triplet
- Majoron
- Vector decay (Coy, Hambye '20)