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Primordial High Energy Neutrinos

Theoretical & observational constraints and sharp spectral features

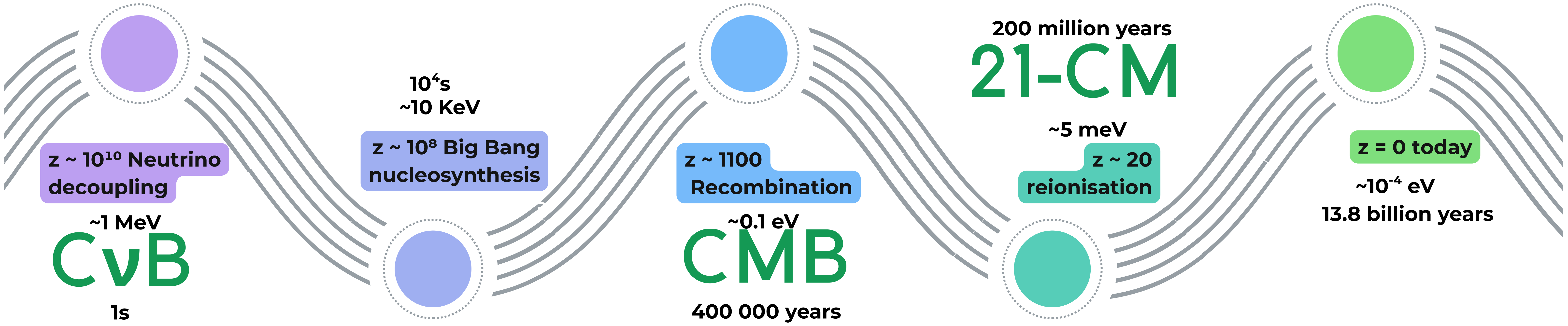
Nicolas Grimbaum Yamamoto
arXiv:2507.02063 in collaboration with T.Hambye

Nicolas Grimbaum Yamamoto
LPTHE

Summary .

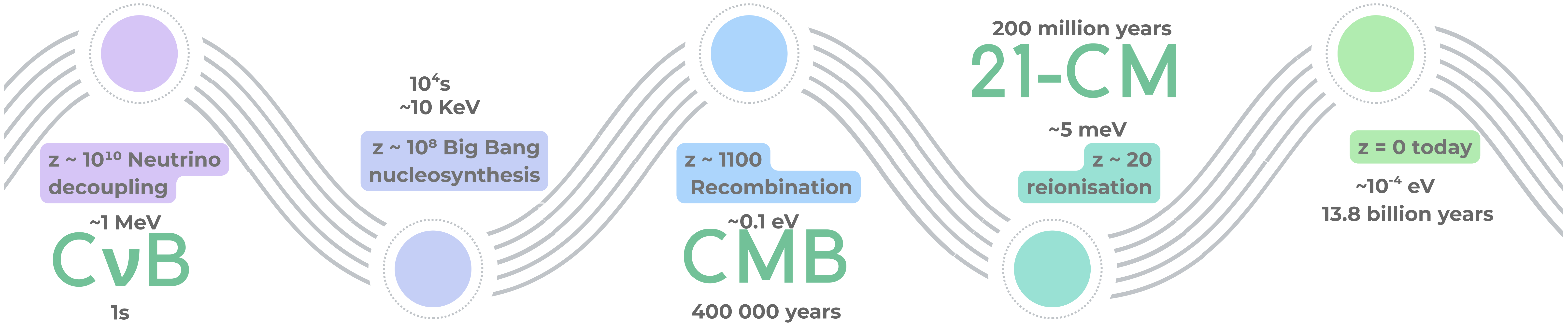
1. Motivations
2. Sharp spectral features
3. Medium interactions
4. Constraints

Motivations.



→ Primordial High Energy Neutrinos (PHENUs)

Motivations.



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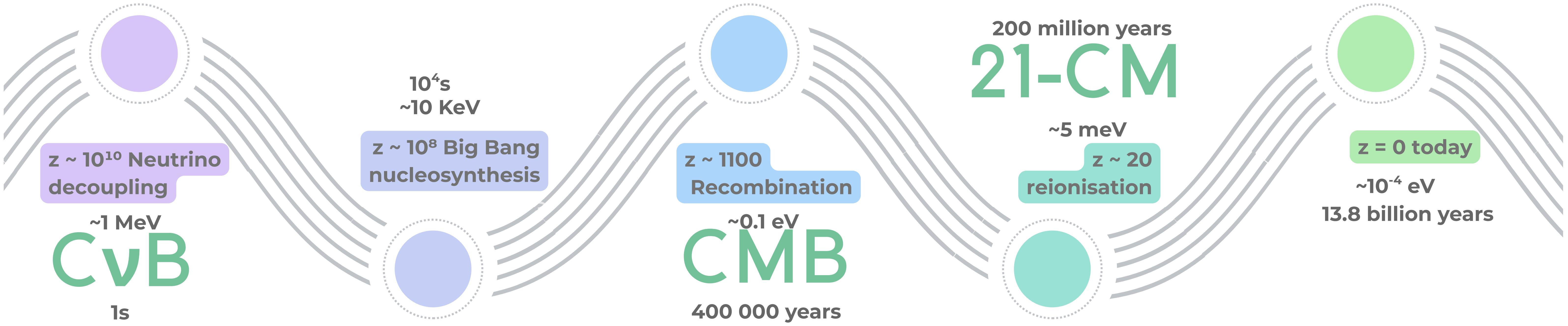

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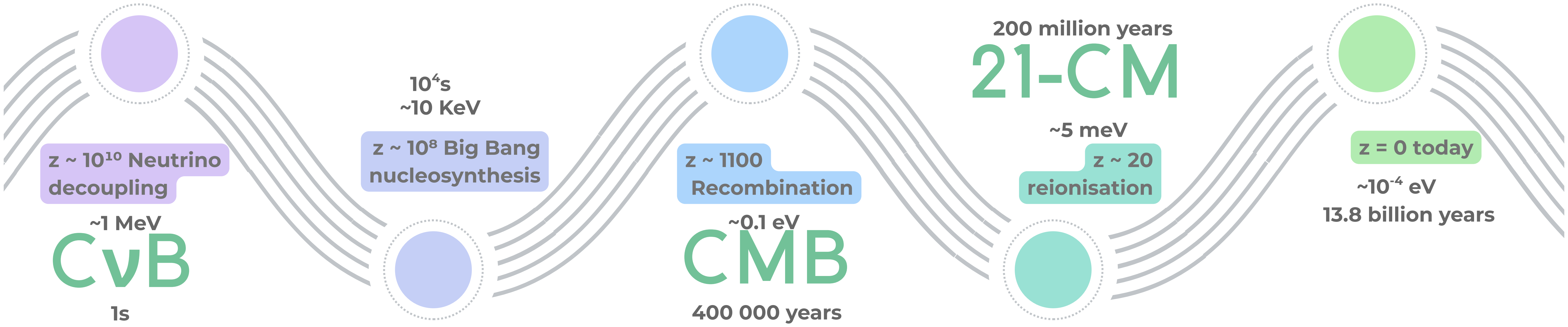
Motivations.



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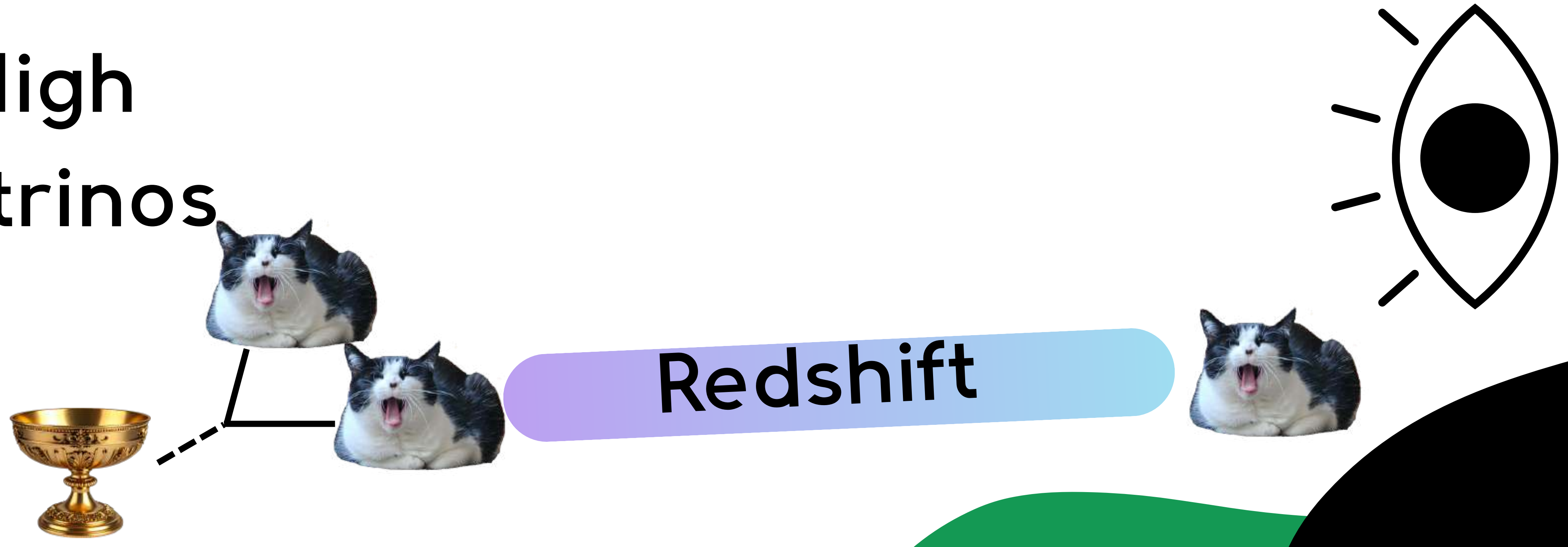

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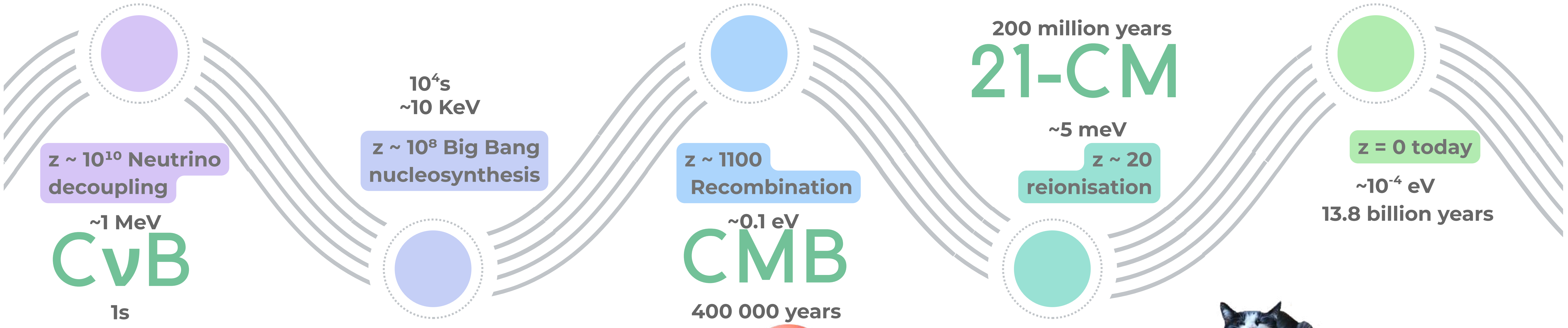

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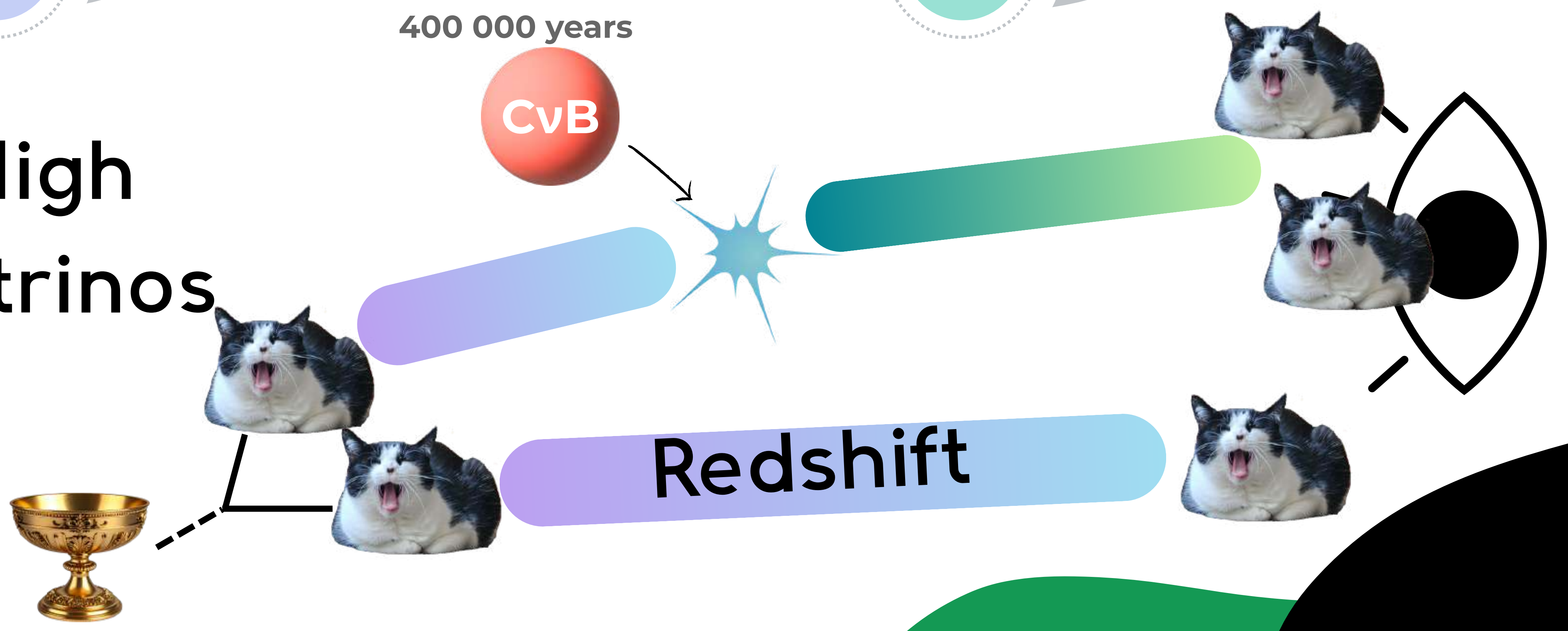

Motivations.

Few works on this topic:

- Frampton, Glashow, '80
- Gelmini, Gondolo, Sarkar '92
- Kanzaki, Kawasaki, Kohri, Moroi '07
- Ema, Jinno, Moroi '13, '14
- McKeen '18
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UNSTABLE HEAVY PARTICLES*

P. H. Frampton and S. L. Glashow

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Harvard University
Cambridge, MA 02138

ABSTRACT

It is pointed out that for very massive particles in our universe there exist stringent bounds on their possible properties. New experiments which will search primarily for proton decay can usefully extend the domain of these bounds.

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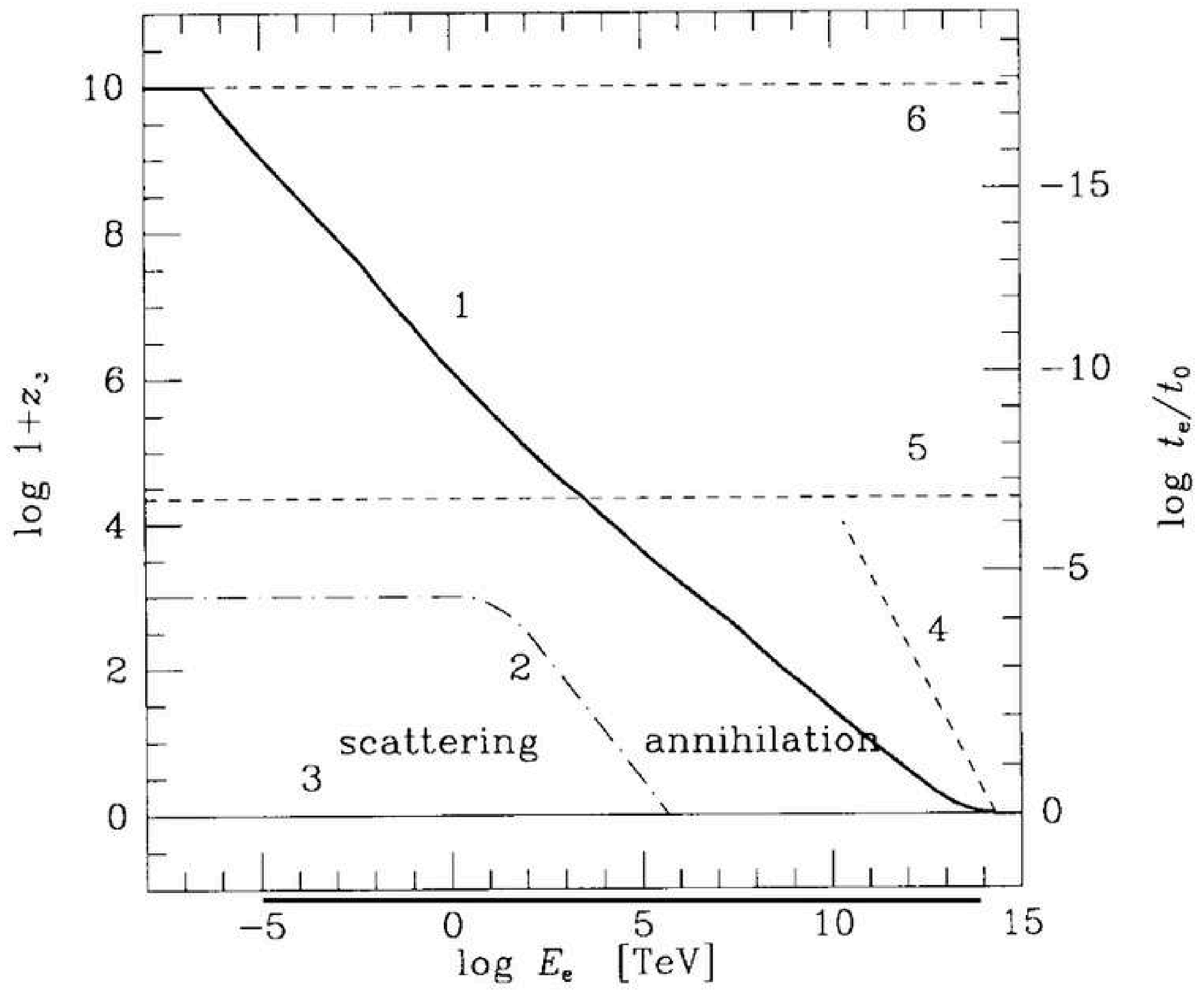

Fig. 1. The absorption redshift z_a (line 1) for cosmic neutrinos as a function of the neutrino energy at emission E_e taking $\Omega_0 h^2 = 1$. The other lines indicate: (2) the boundary between the two regions where absorption due to annihilation and scattering dominate; (3) the present epoch; (4) the Z-boson pole; (5) the epoch of matter-radiation equality; (6) the epoch of light–neutrino decoupling.

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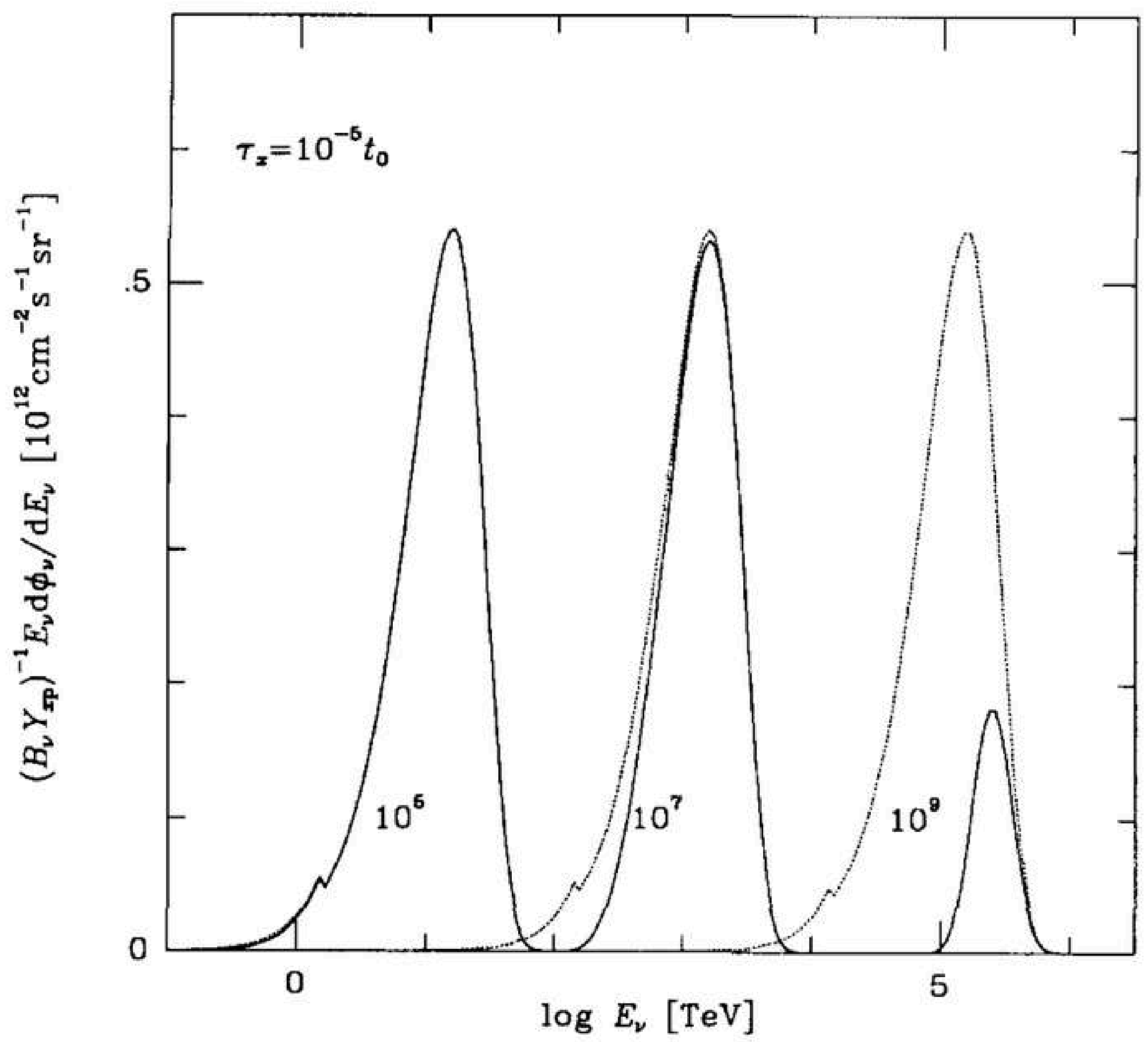

Fig. 2. The present energy spectrum of decay generated neutrinos for $\tau_x = 10^{-5}t_0$ and $3E_e = 10^5$ TeV 10^7 TeV and 10^9 TeV. The full lines show the effect of cosmological neutrino absorption.

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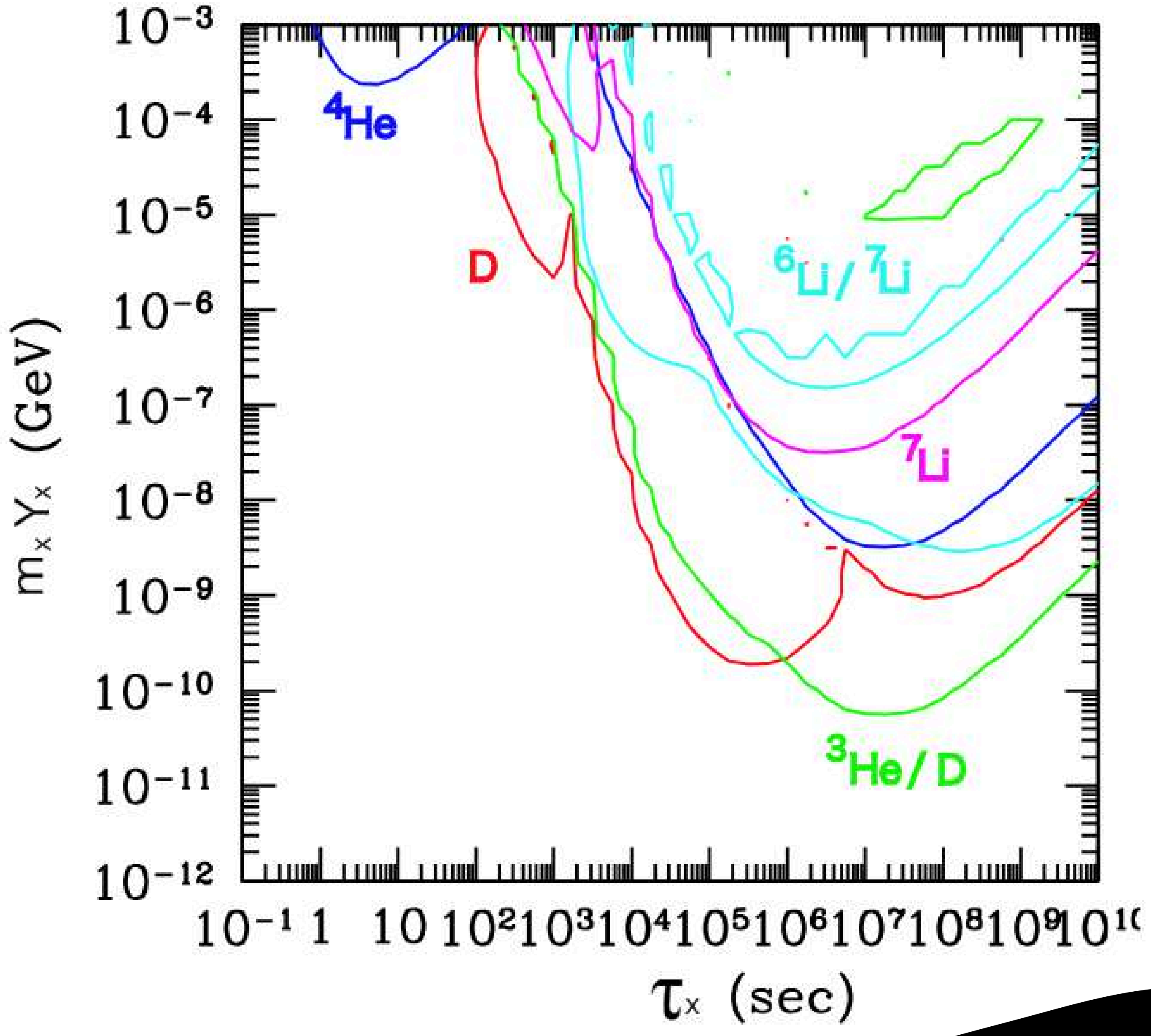

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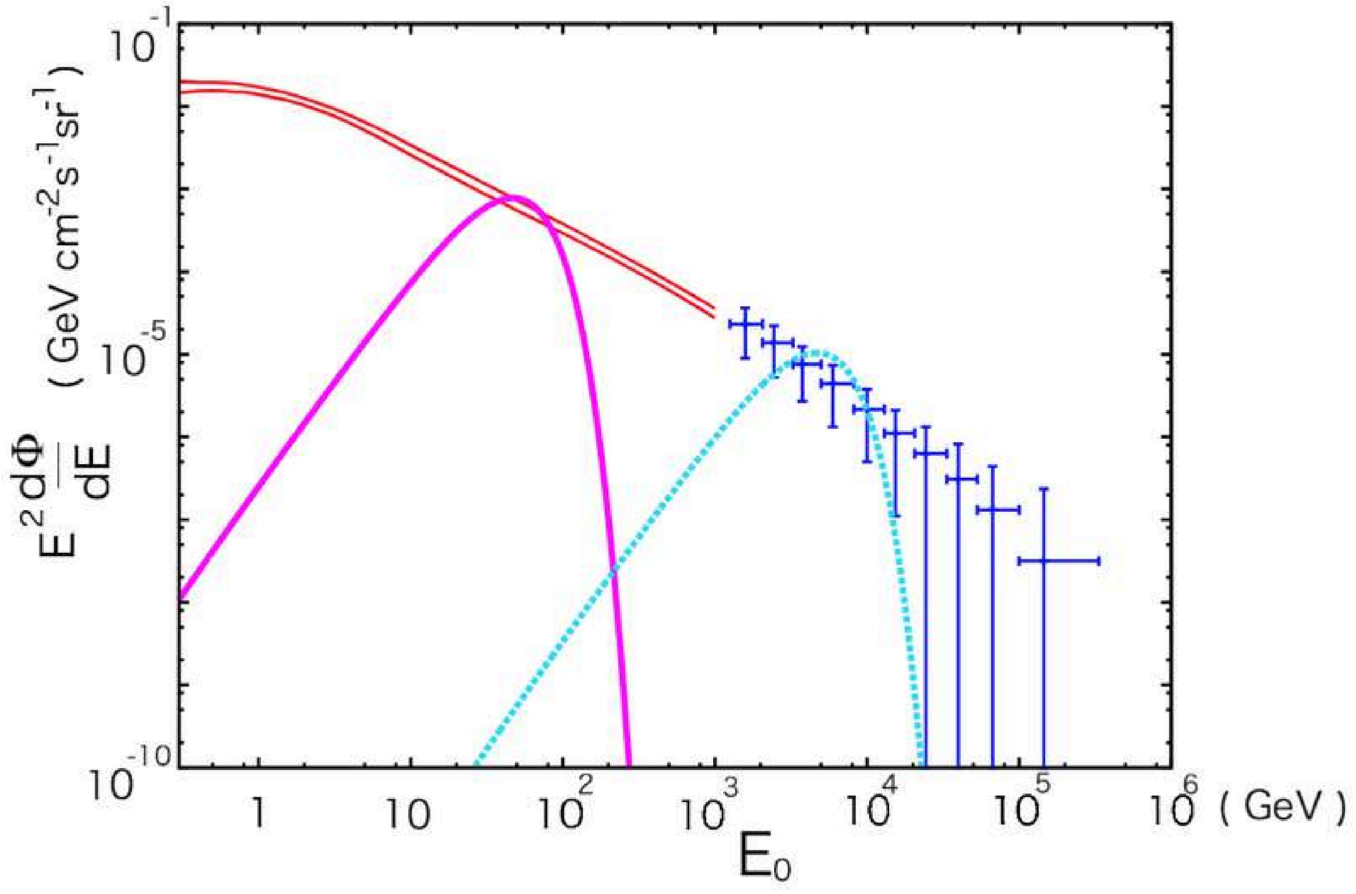

Figure 16. Atmospheric neutrino flux. Thin solid lines represent 1σ range of the atmospheric neutrino fluxes [42]. The point data are from AMANDA. Thick solid and dotted lines represent diffuse neutrino signal with $m_X = 10^3$GeV and $Y_X = 2.53\times10^{-17}$ (thick solid line) and 10^5GeV and $Y_X = 3.37 \times 10^{-21}$(thick dotted line). The lifetime is $\tau_X = 10^{16}$sec.

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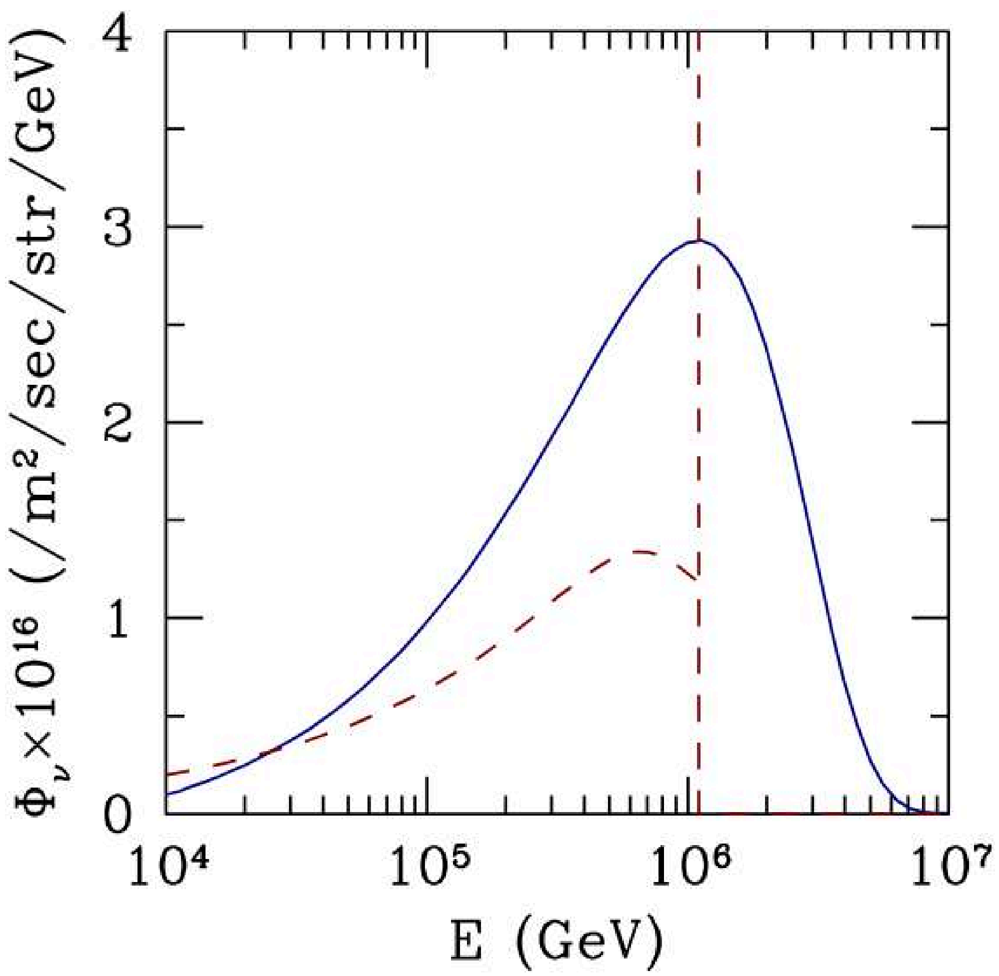

Figure 3: The total present cosmic-ray neutrino flux from the long-lived particle X, normalized by $10^{-16}\ \mathrm{m}^{-2}\mathrm{sec}^{-1}\mathrm{str}^{-1}\mathrm{GeV}^{-1}$. Here, we take $(\tau_X, \bar{E}_\nu, Y_X) = (5.2\times10^{14}\ \mathrm{sec}, 2.2\times10^{2}\ \mathrm{PeV}, 1.2\times10^{-26})$ (blue-solid, corresponding to $1 + z_* = 100$), and $(10^{29}\ \mathrm{sec}, 1.1\ \mathrm{PeV}, 4.0\times10^{-16})$ (red-dashed). The vertical line at $E = 1.1$ PeV is the contribution from the Galaxy.

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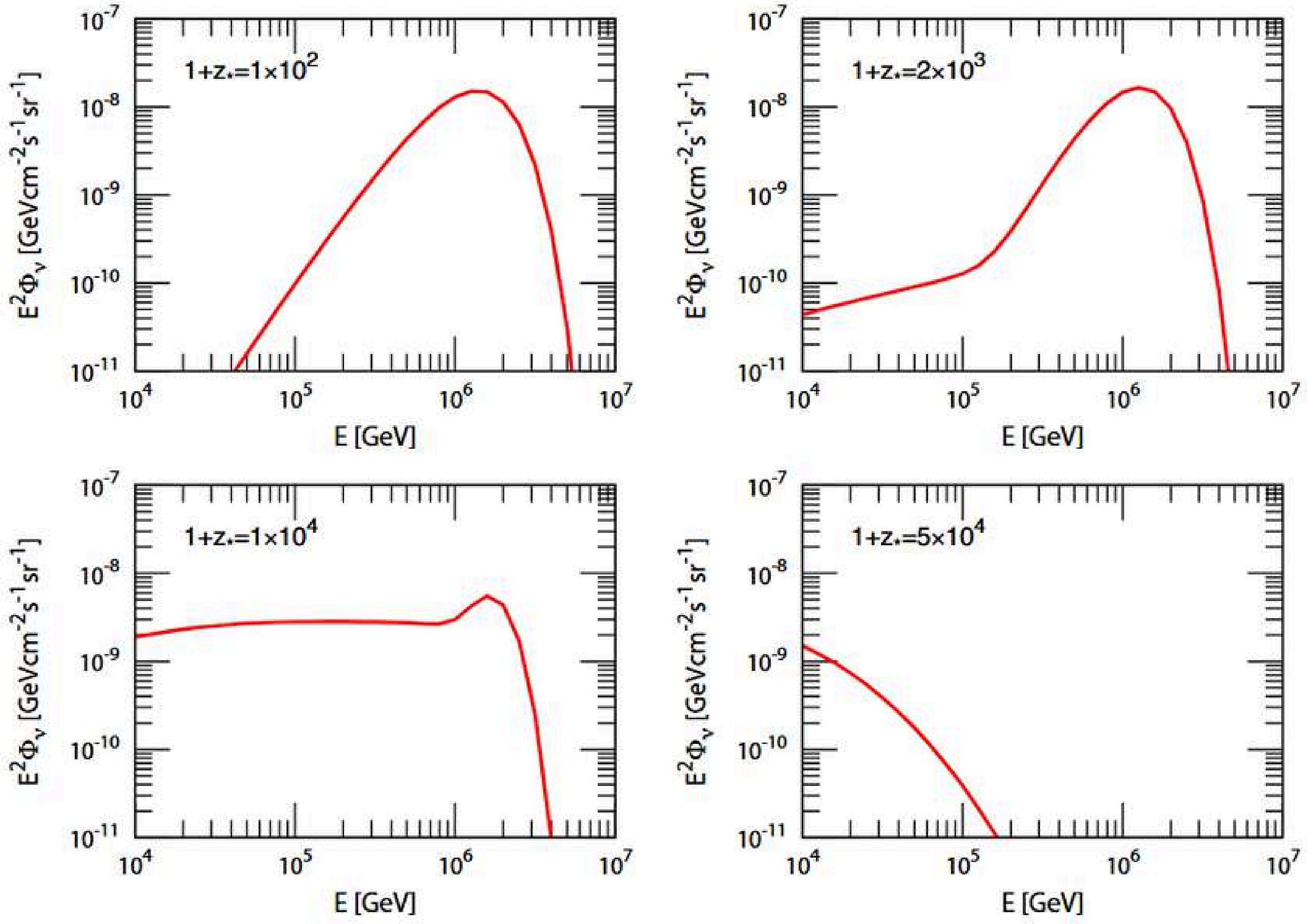

Figure 2: The present per-flavor neutrino fluxes for some different input parameters. Top left: $(\bar{E}_\nu, 1+z_*, Y_X) = (10^8\ \mathrm{GeV}, 10^2, 10^{-26})$. Top right: $(\bar{E}_\nu, 1+z_*, Y_X) = (2\times10^9\ \mathrm{GeV}, 2\times10^3, 10^{-26})$. Bottom left: $(\bar{E}_\nu, 1+z_*, Y_X) = (10^{10}\ \mathrm{GeV}, 10^4, 10^{-26})$. Bottom right: $(\bar{E}_\nu, 1+z_*, Y_X) = (5\times10^{10}\ \mathrm{GeV}, 5\times10^4, 10^{-26})$.

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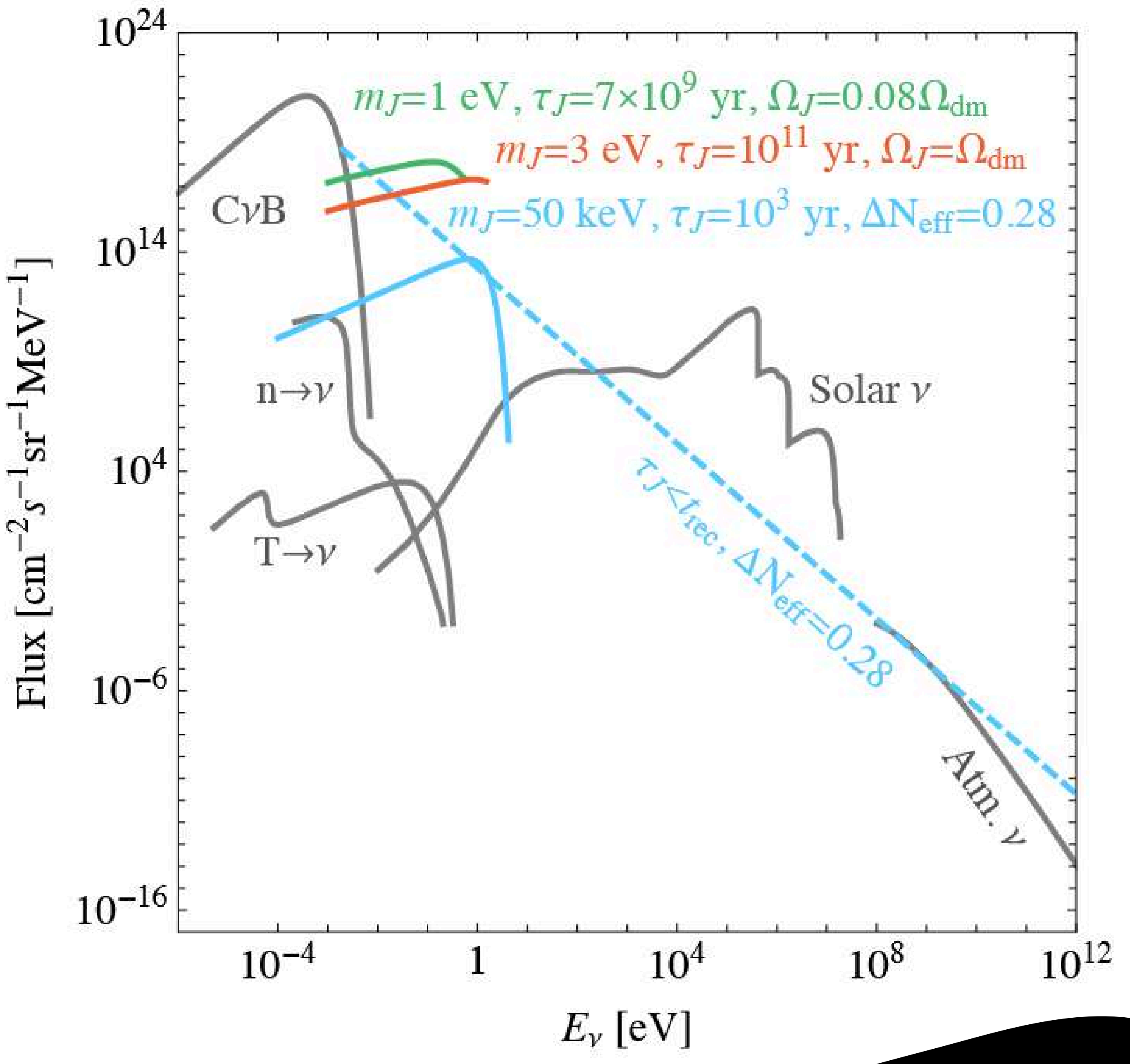

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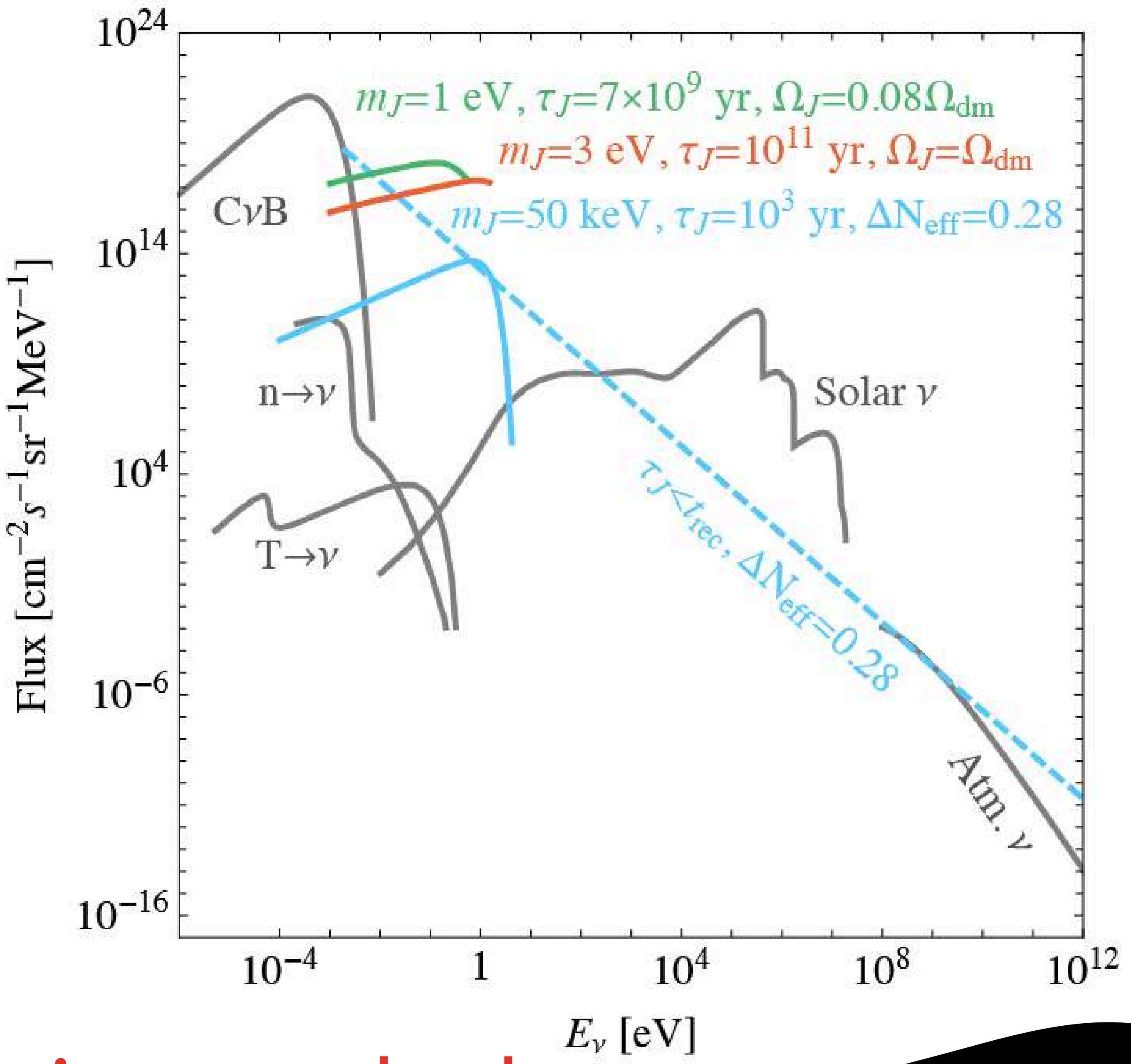
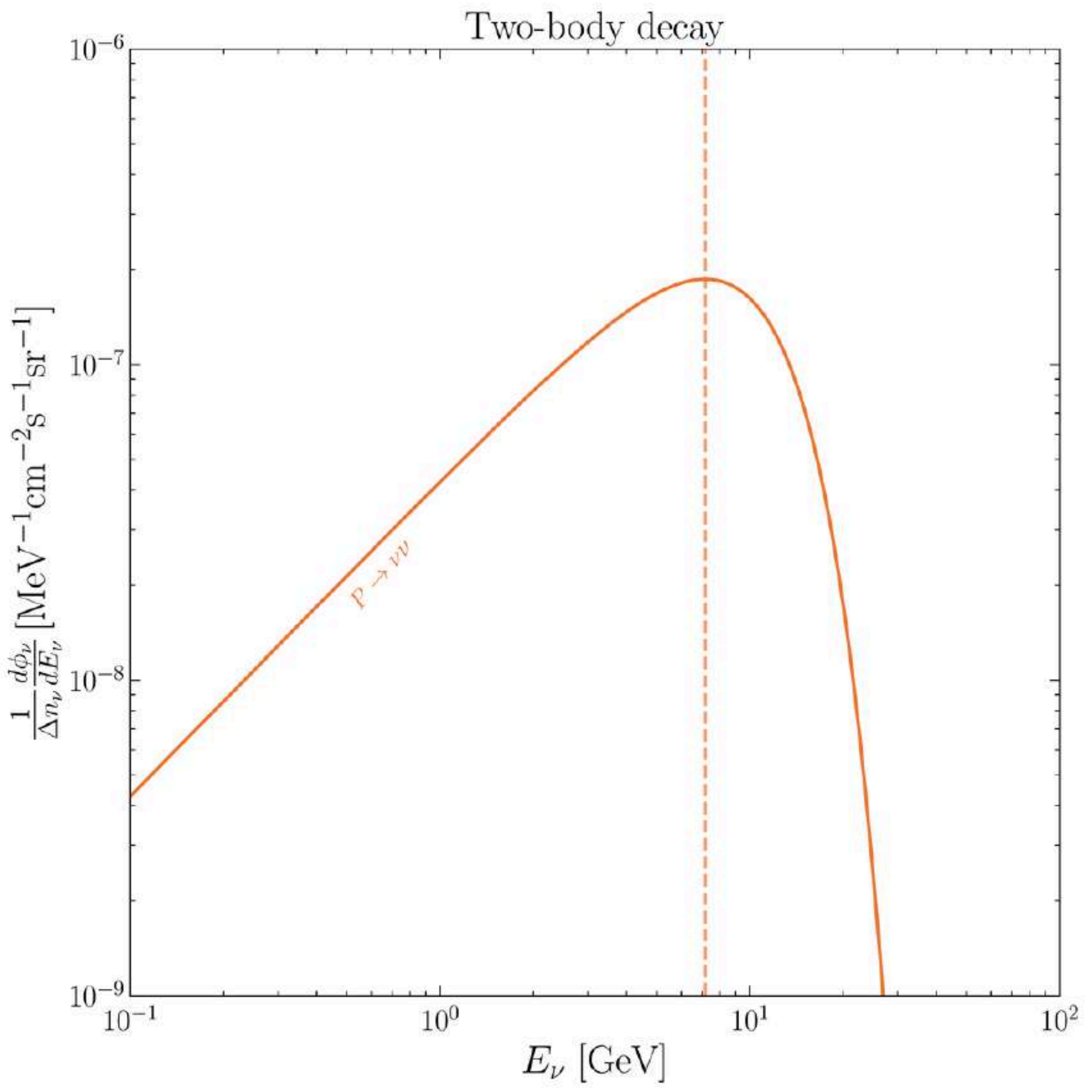


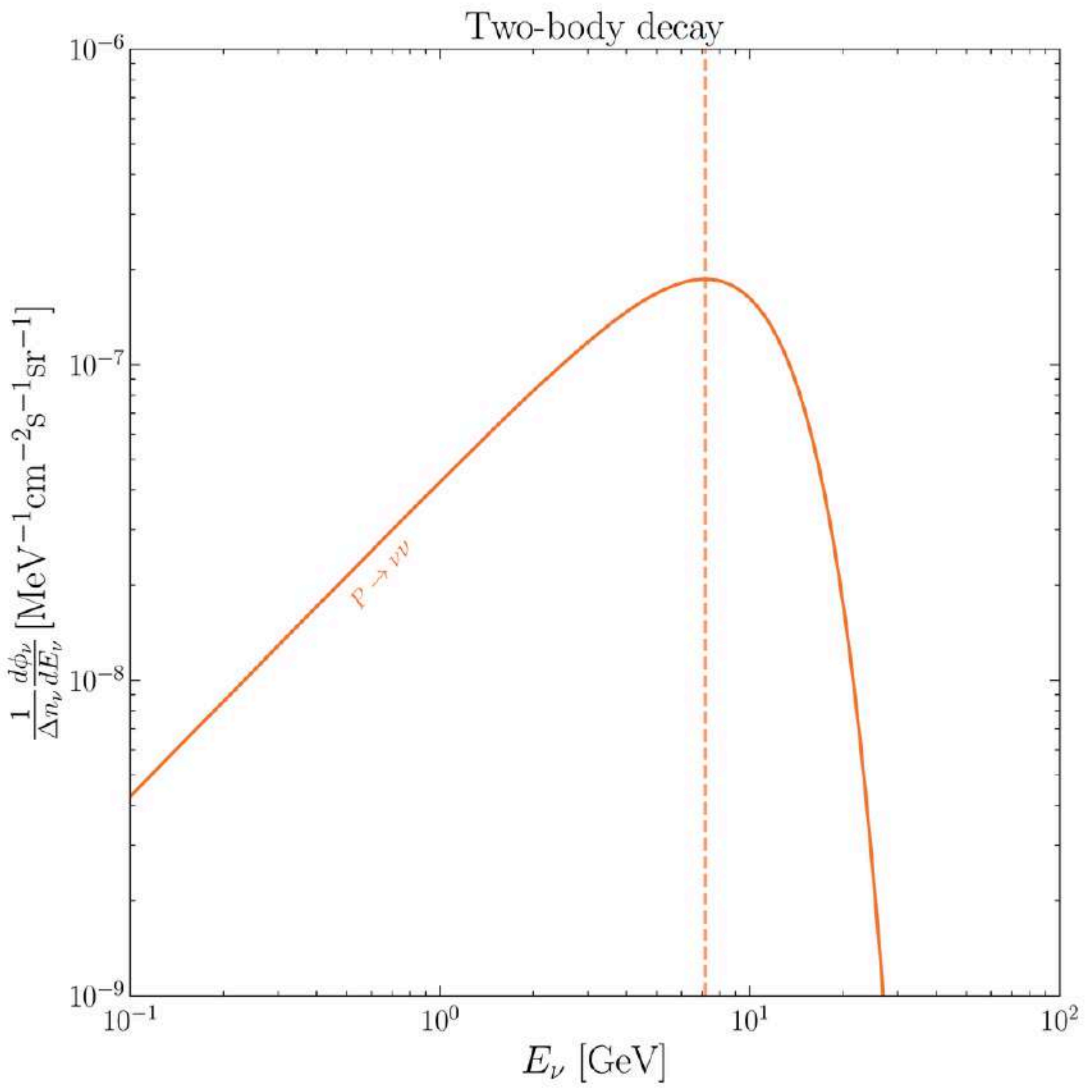
→ A general study is needed

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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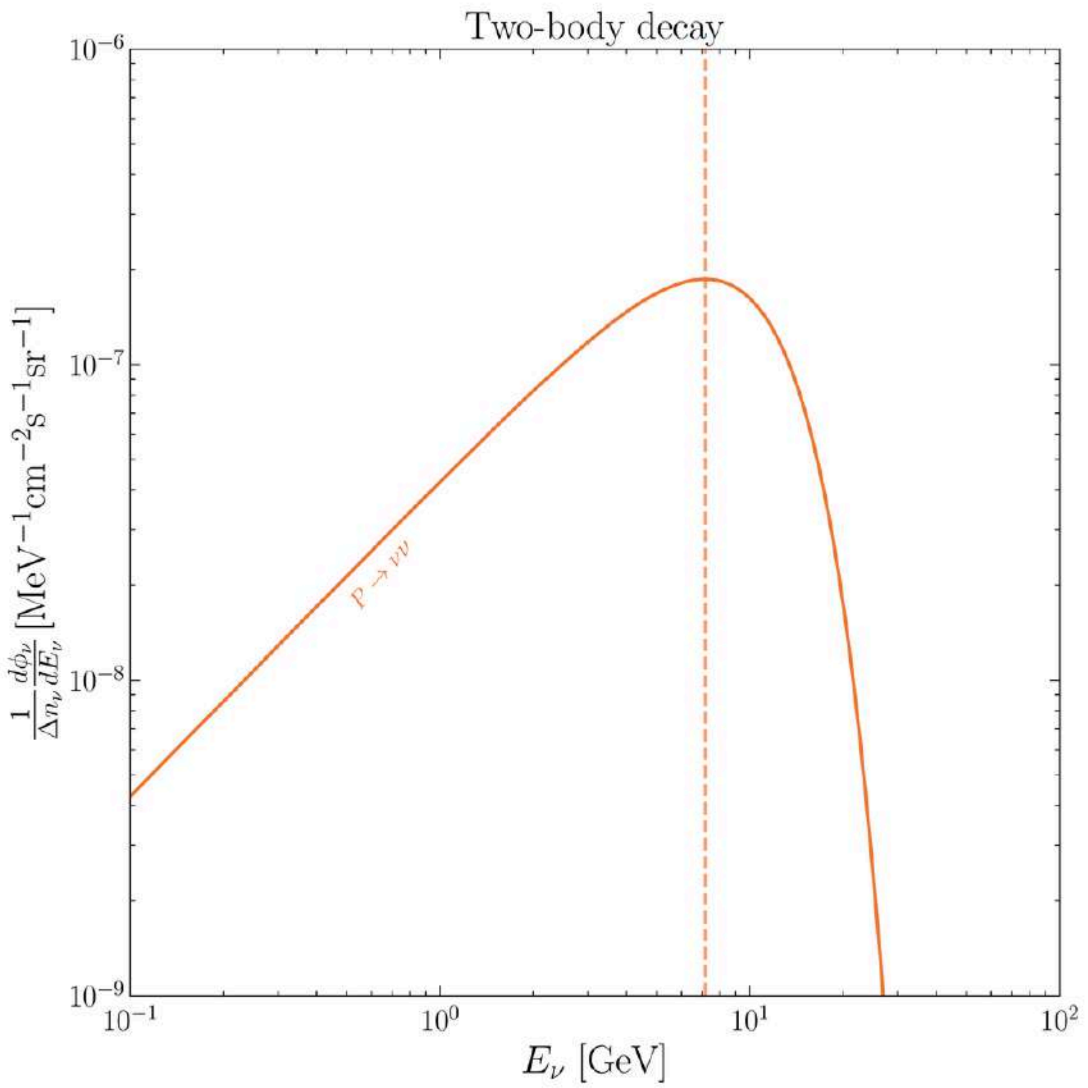
Number of neutrinos per decay

Sharp Spectral Features.



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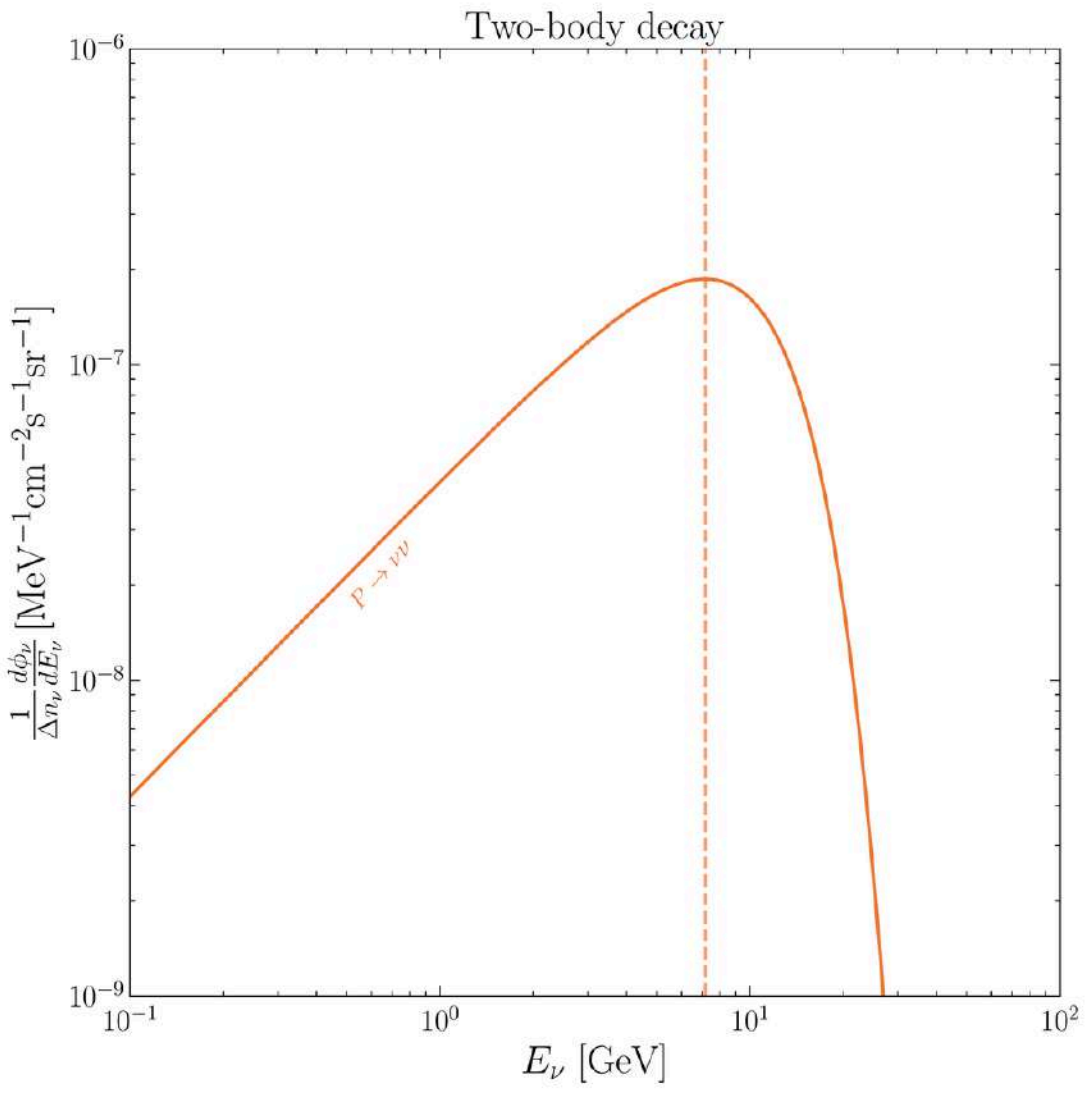
Number of neutrinos per decay

Isotropy

Sharp Spectral Features.



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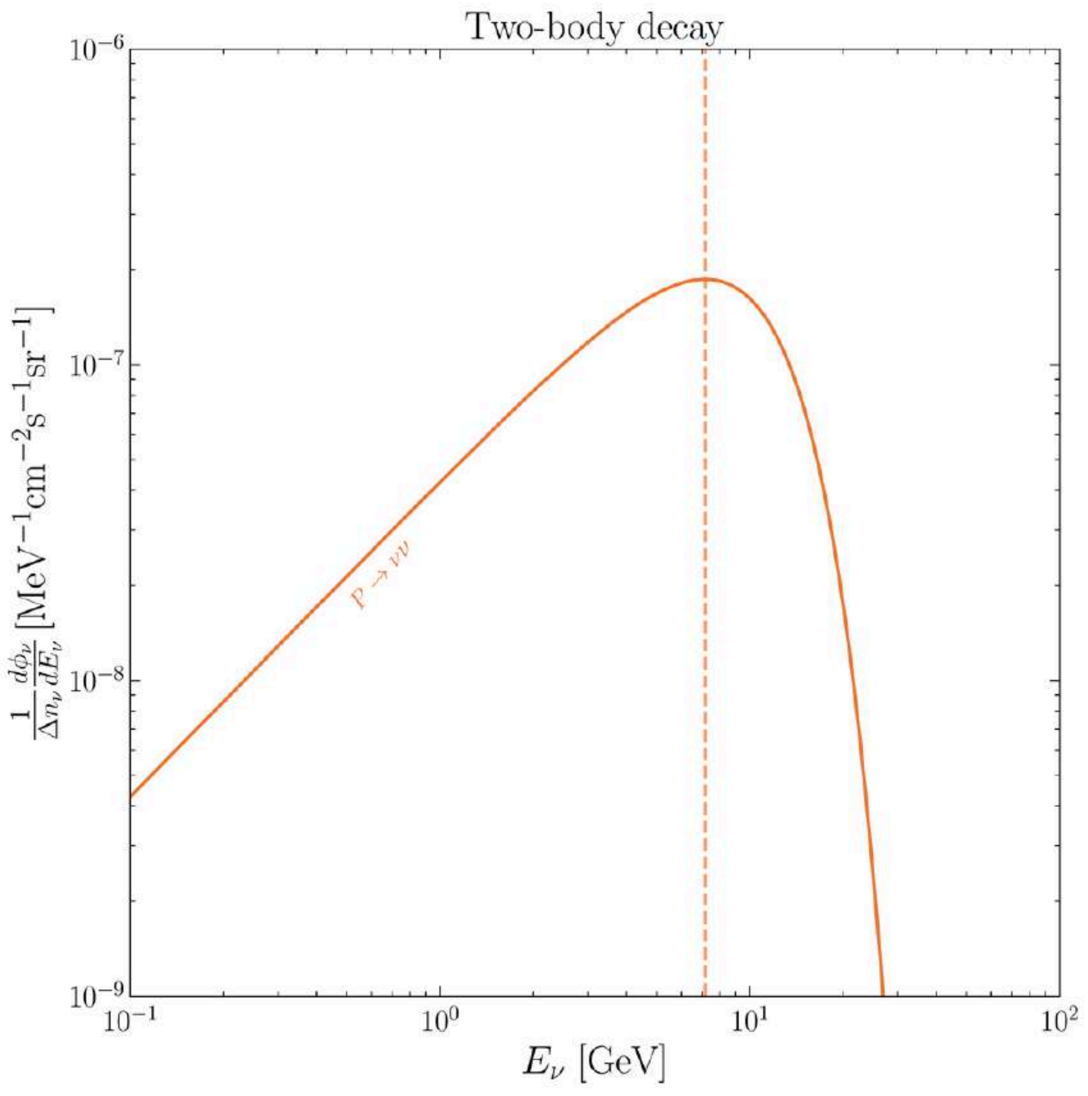
Number of neutrinos per decay

Isotropy

Decaying particle density

Sharp Spectral Features.



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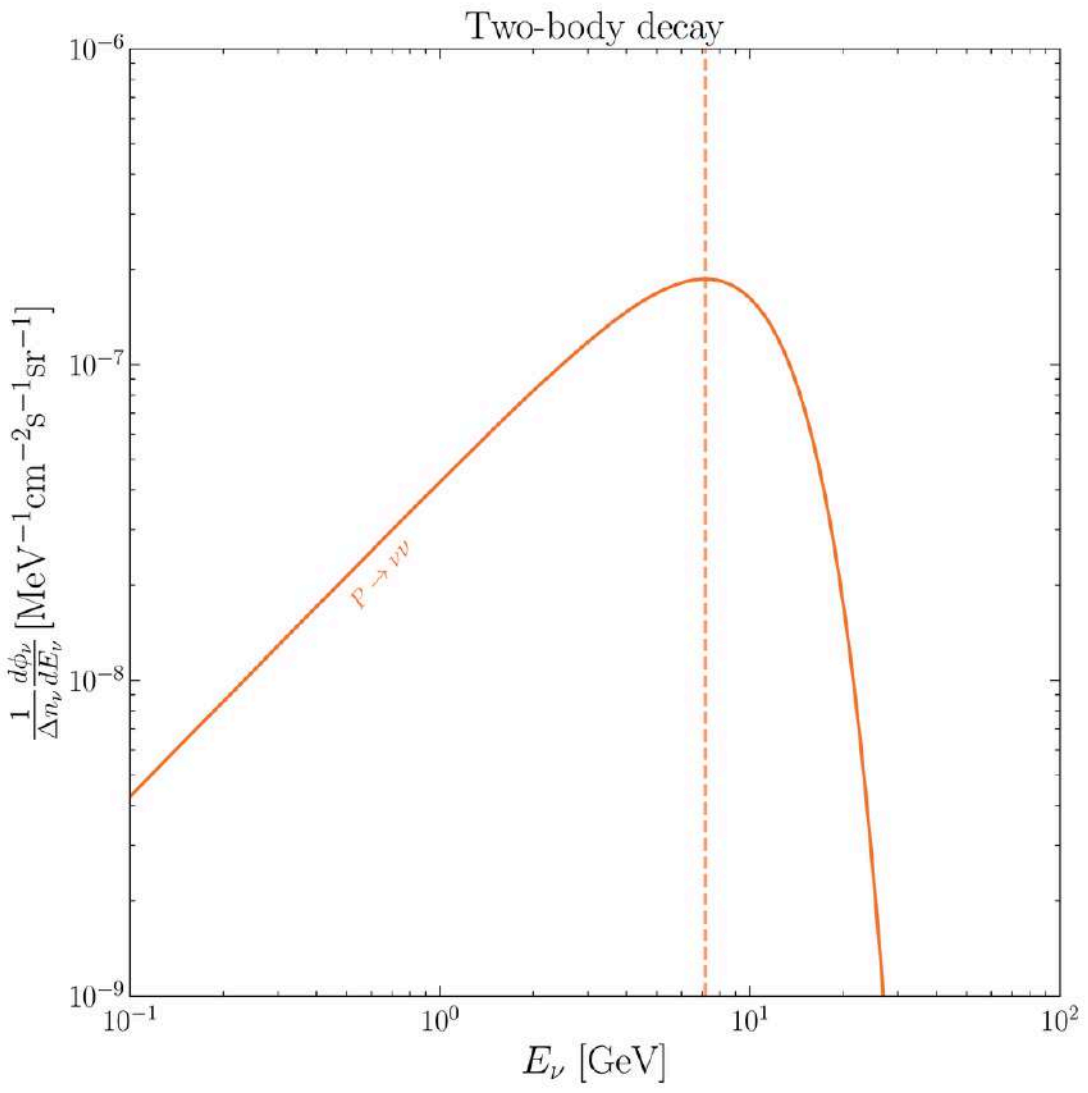
Number of neutrinos per decay

Isotropy

Decaying particle density

decay rate

Sharp Spectral Features.



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Number of neutrinos per decay

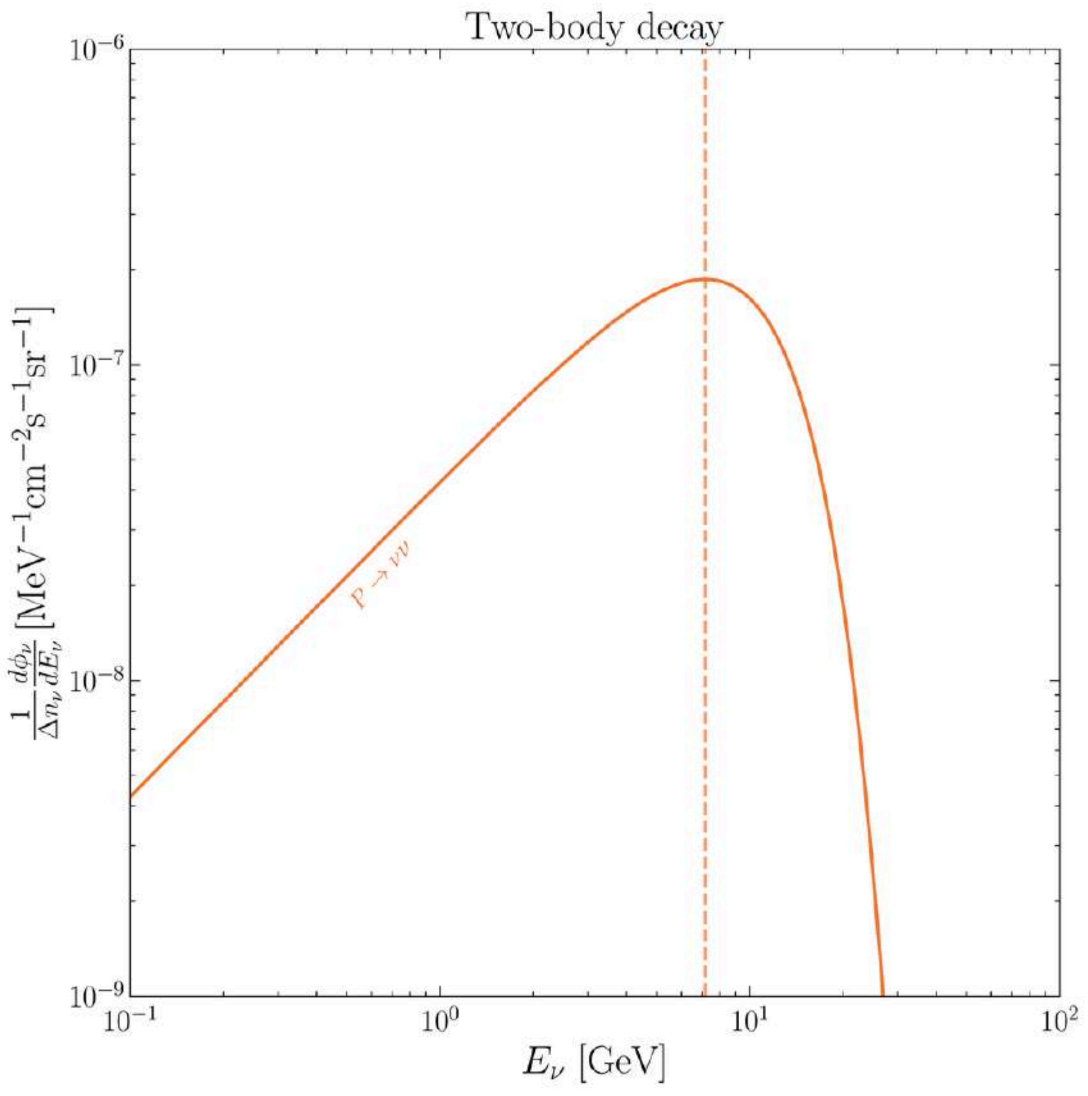
Isotropy

Decaying particle density

decay rate

Integration over the line of sight

Sharp Spectral Features.



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Number of neutrinos per decay

Isotropy

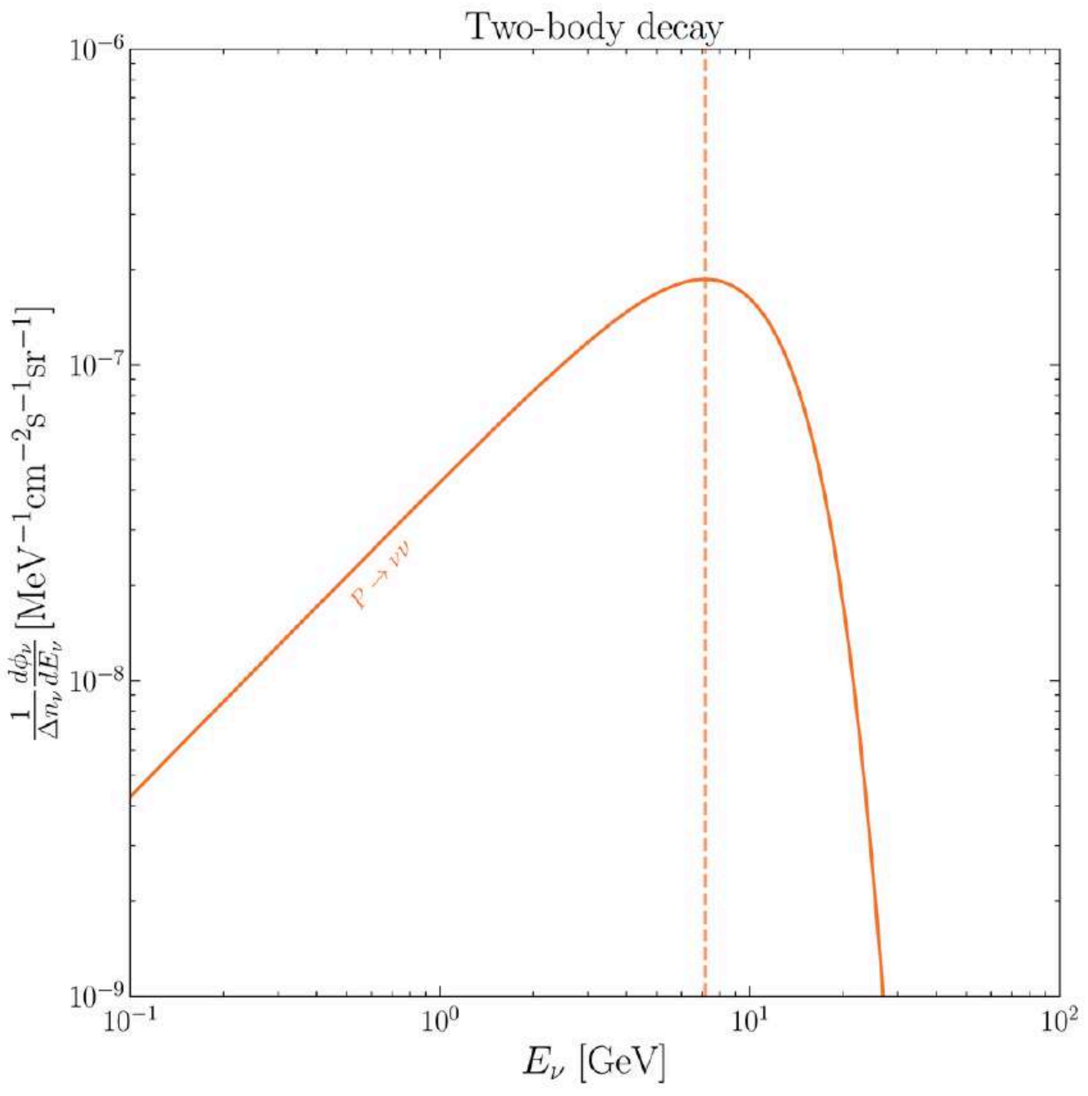
Decaying particle density

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

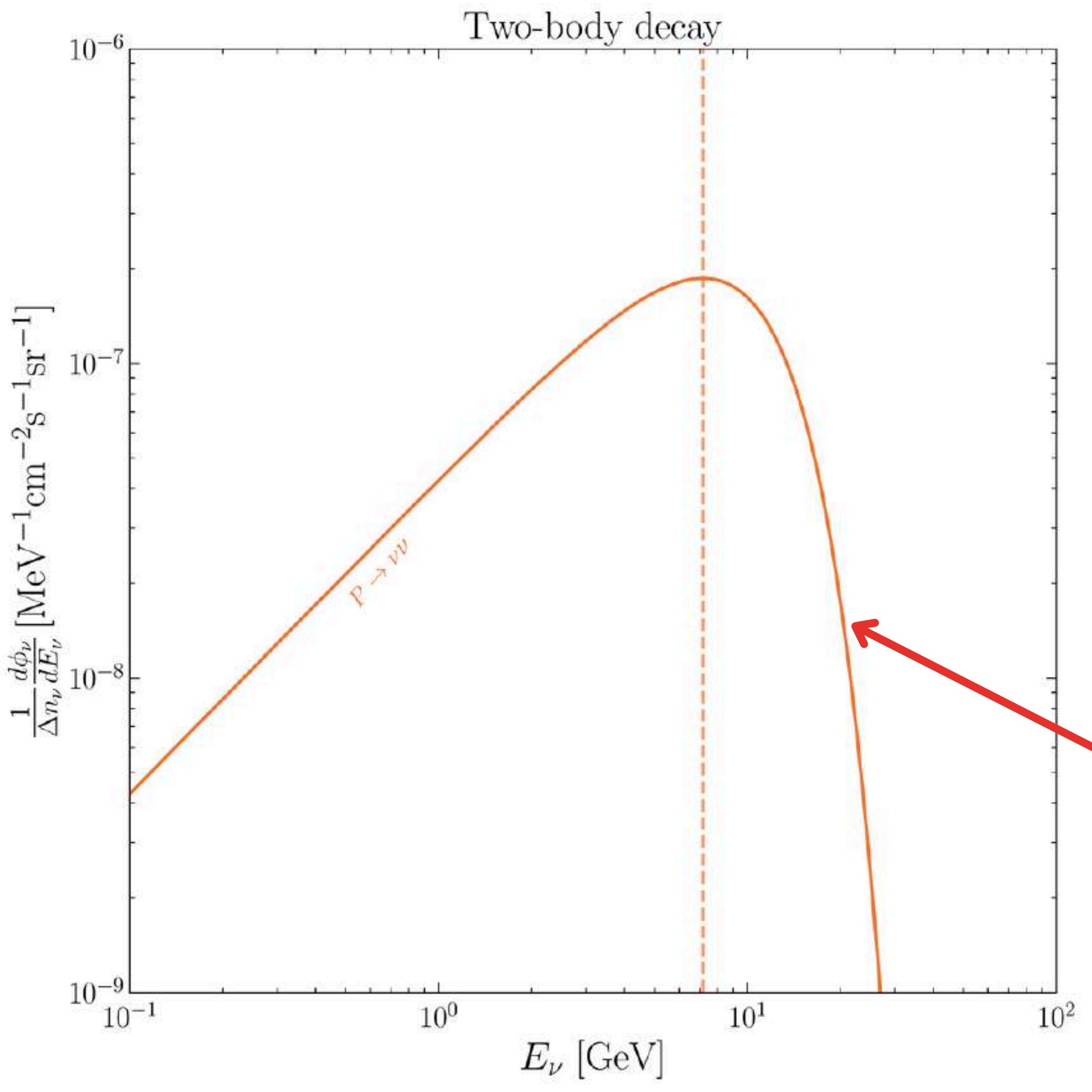
decay rate

Integration over the line of sight

Exponential decay

Spectrum at production

Sharp Spectral Features.



Gelmini, Gondolo, Sarkar 92'

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Number of neutrinos per decay

Isotropy

Decaying particle density

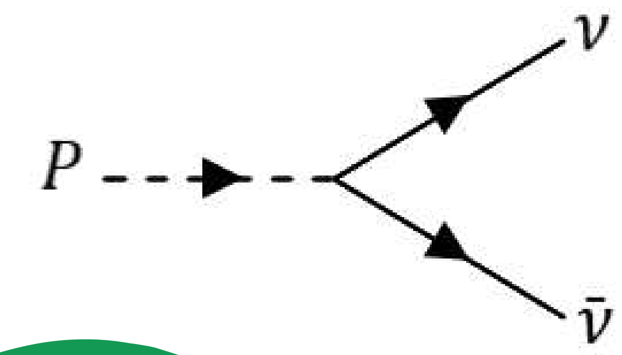
decay rate

Integration over the line of sight

Exponential decay

Spectrum at production

2-body decay $P \to \nu\bar{\nu}$



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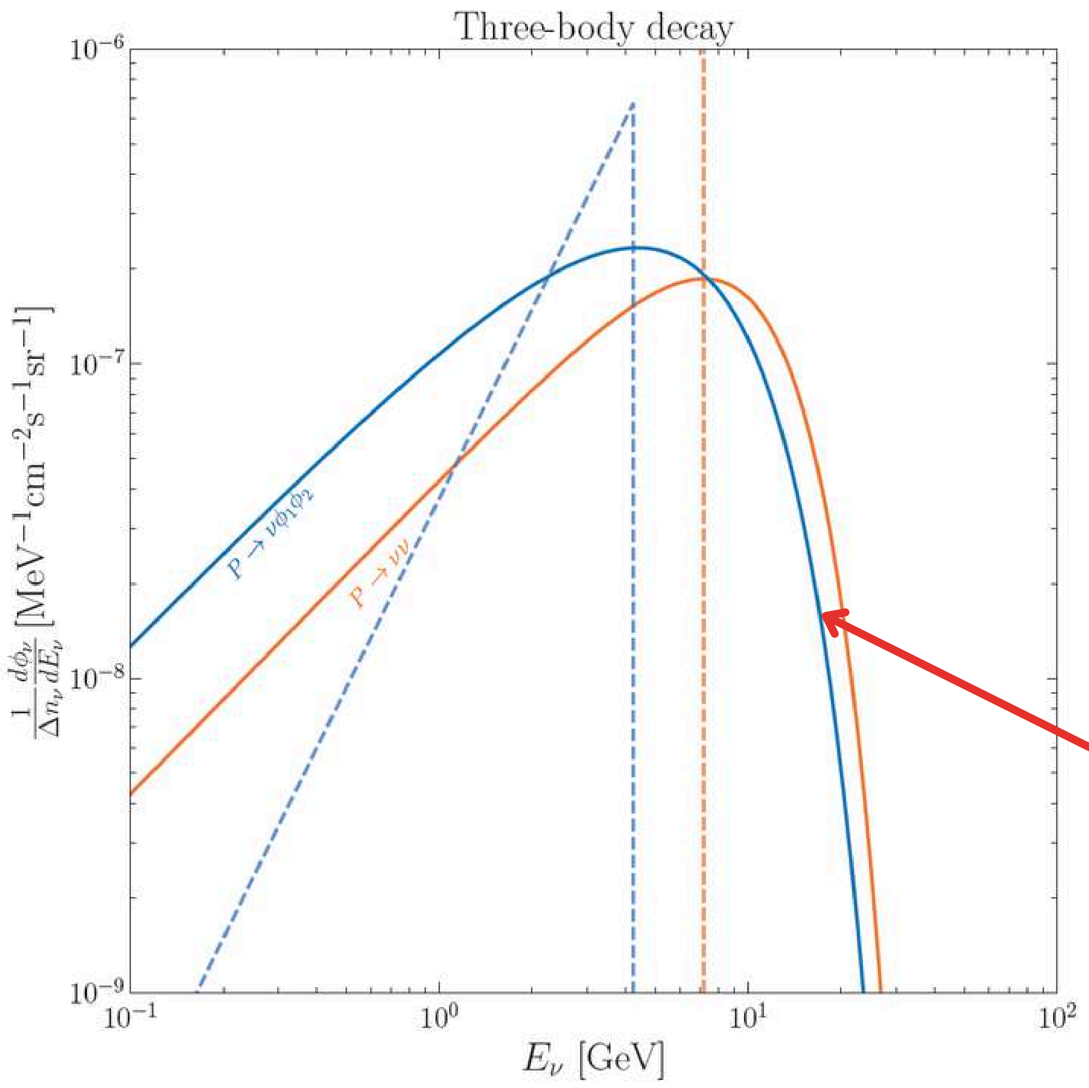

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Number of neutrinos per decay

Isotropy

Decaying particle density

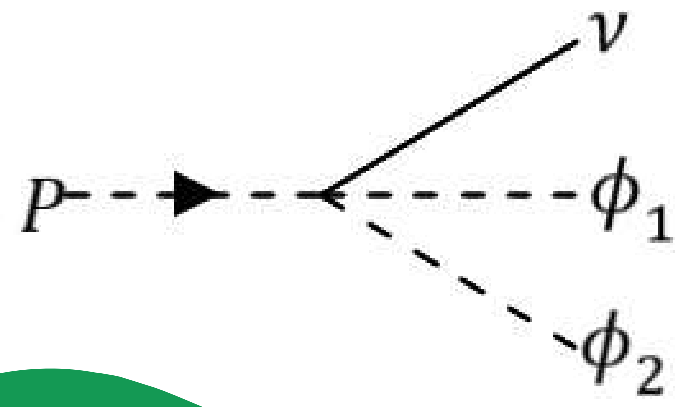
decay rate

Integration over the line of sight

Exponential decay

Spectrum at production

3-body decay $P \to \nu\phi_1\phi_2$



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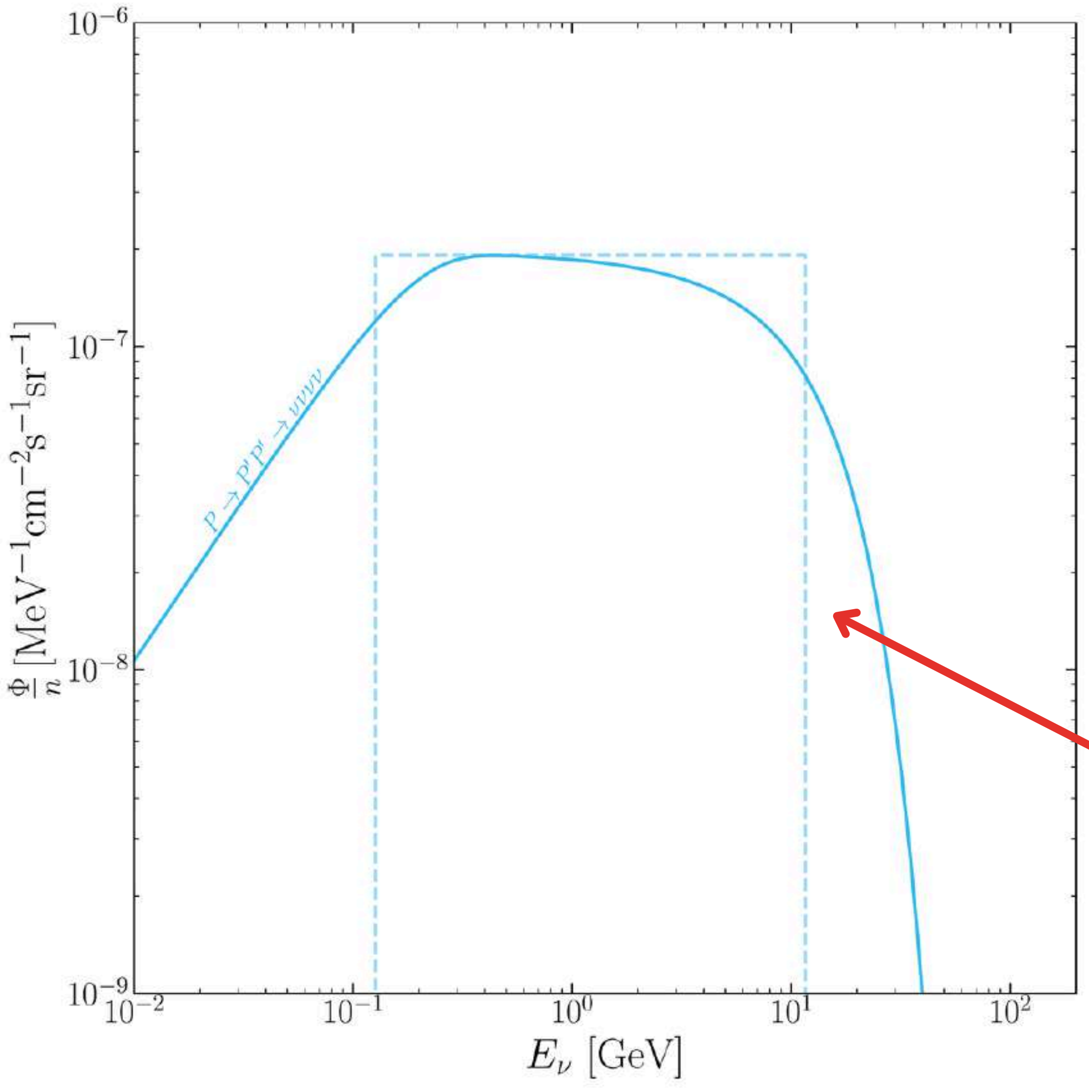

Ibarra, Lopez Gehler, Pato, Miguel, 12'

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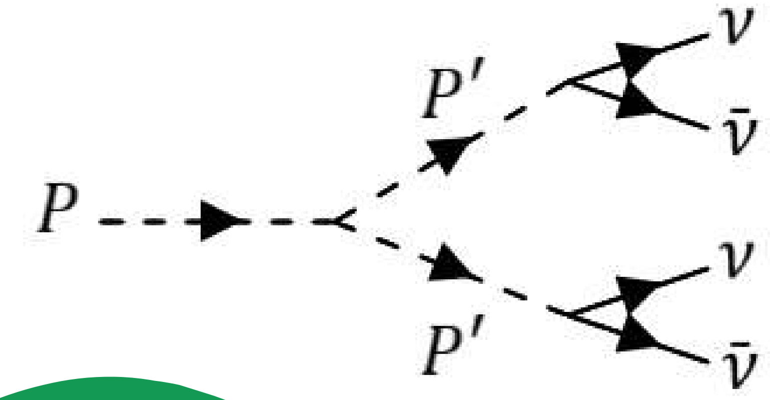
- Number of neutrinos per decay
- Isotropy
- Decaying particle density
- decay rate
- Integration over the line of sight
- Exponential decay
- Spectrum at production

Box shaped spectrum $P \to P'P' \to \nu\bar{\nu}\nu\bar{\nu}$



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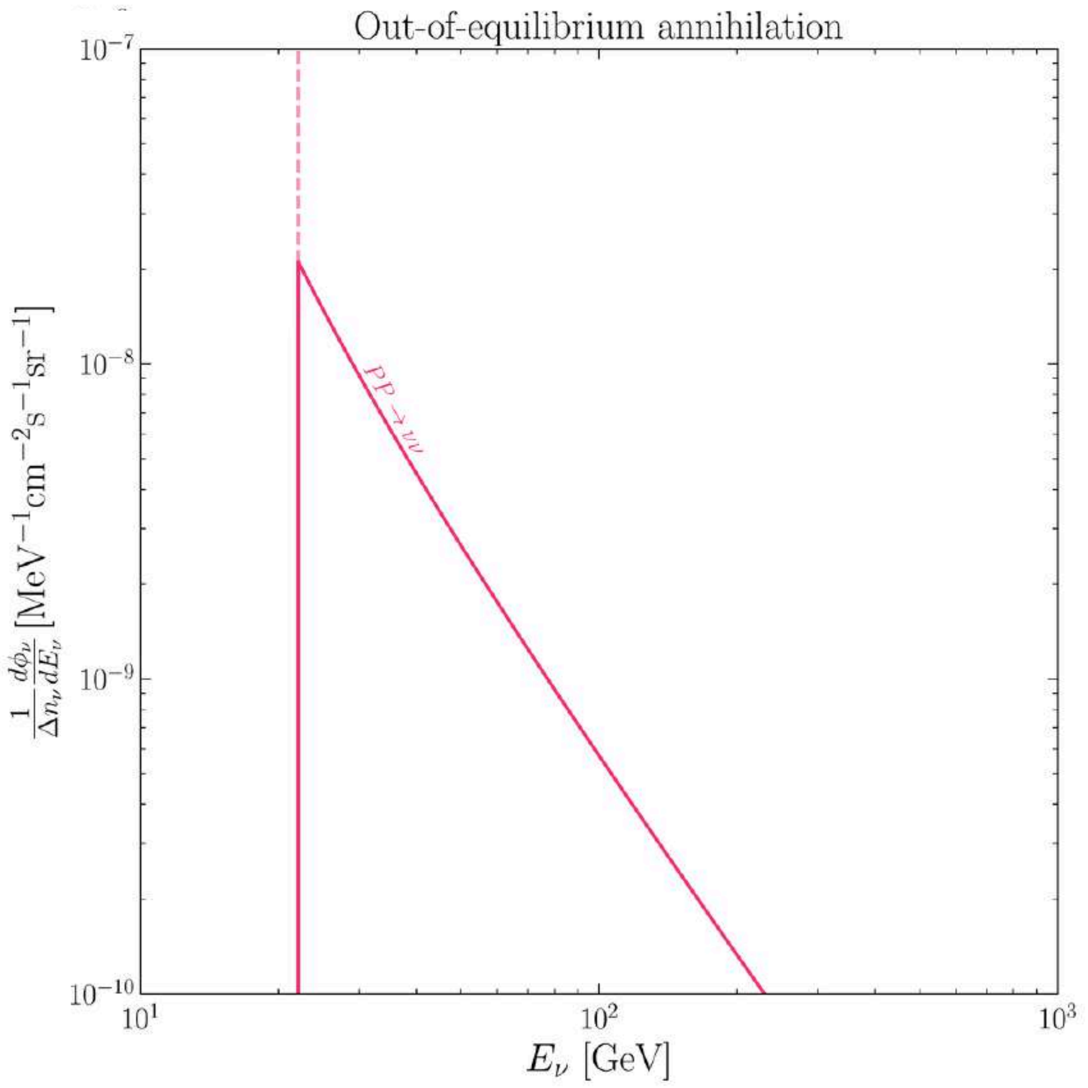
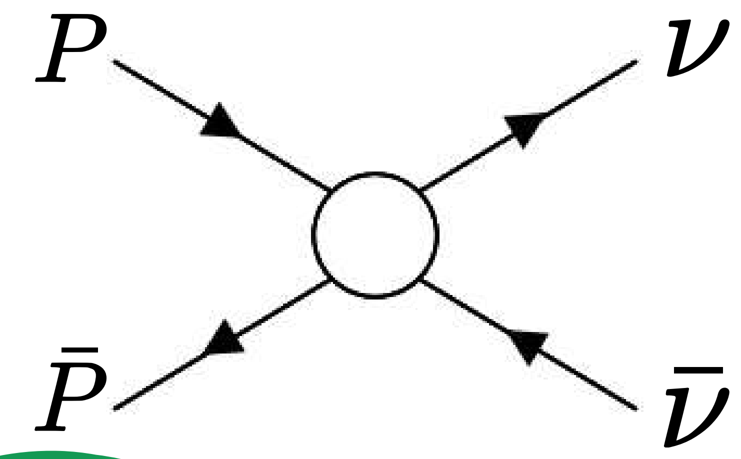


Out of equilibrium annihilation

$$P\bar{P} \to \nu\bar{\nu}$$

New type of spectral feature

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



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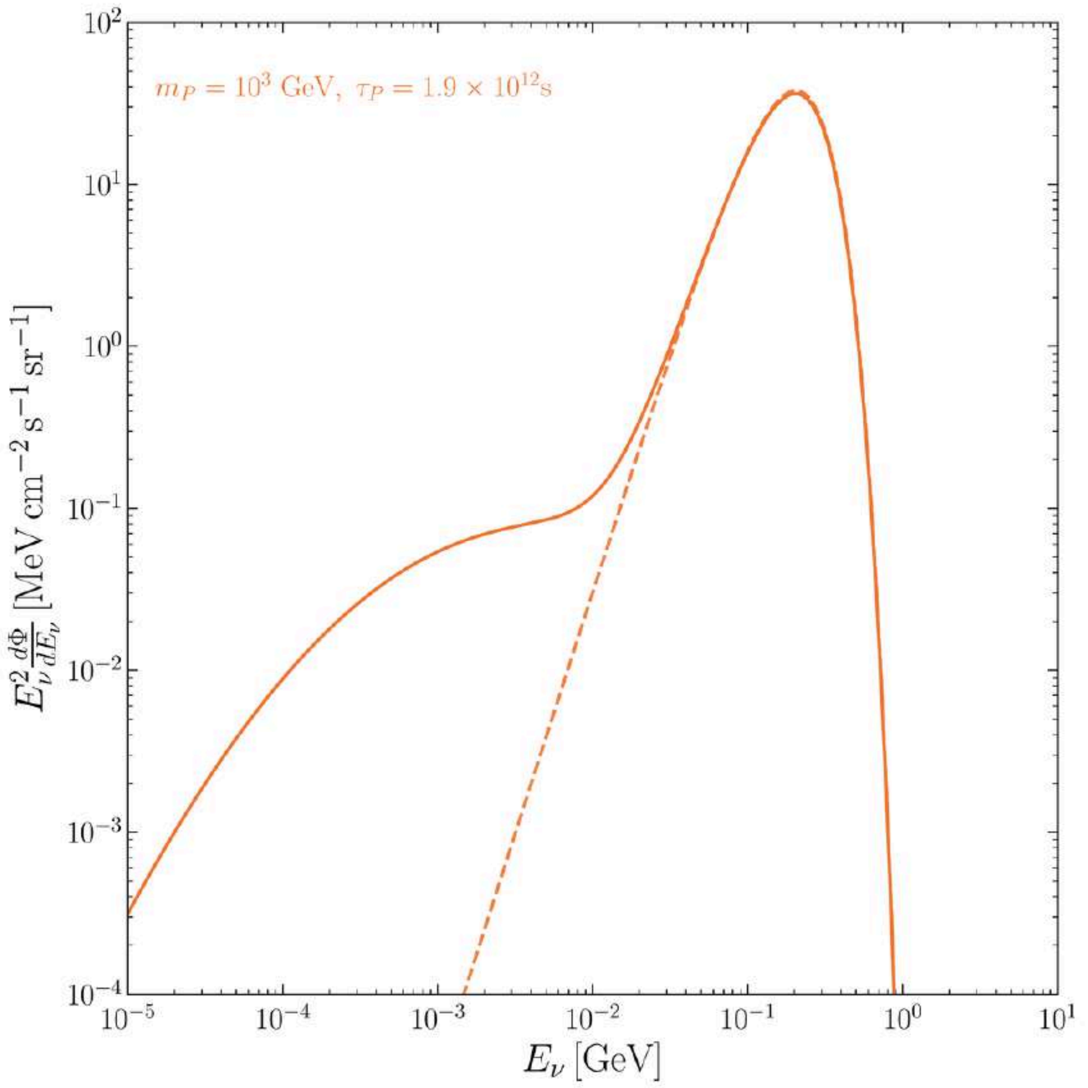
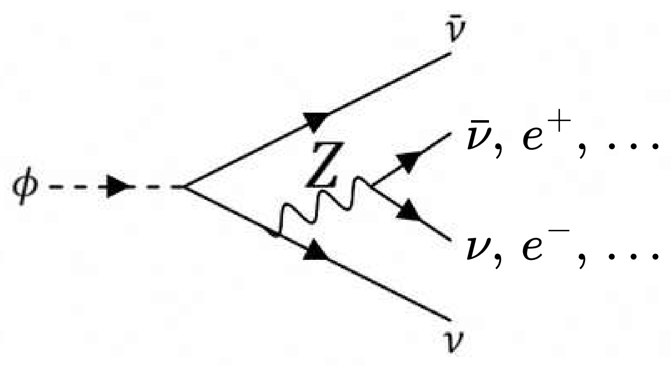


Final state radiation broadening

- 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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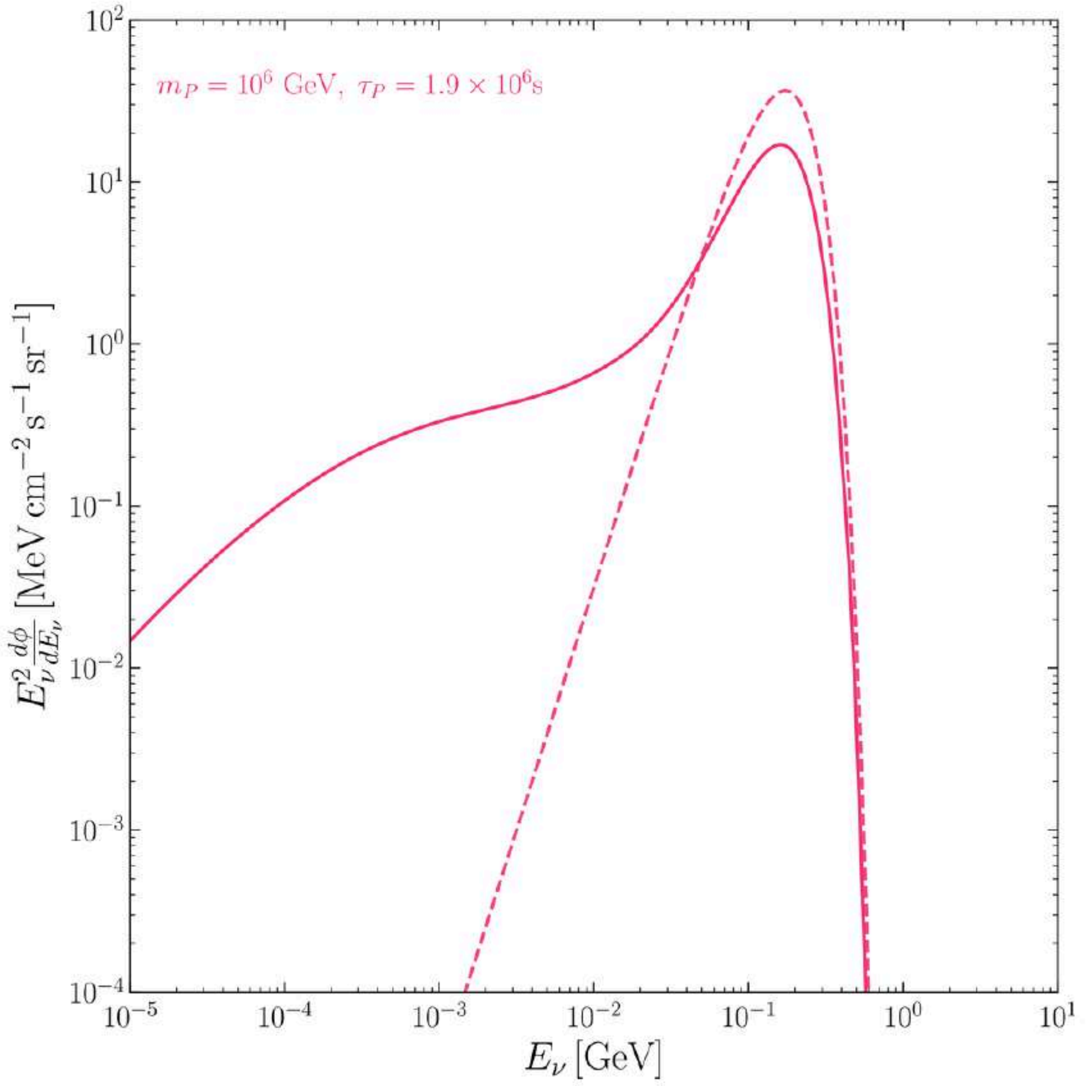

Final state radiation broadening

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→ **Broadening of the peak mostly due to redshift effect**

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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Average number of scattering

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

Medium interactions.

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target neutrino number density

Medium interactions.

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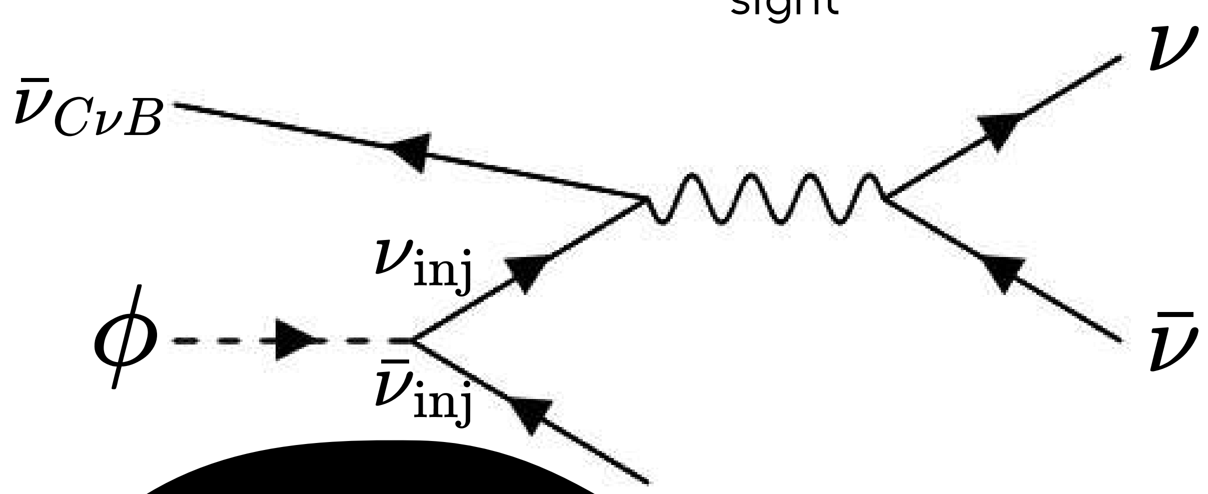
Average number of scattering

Integration over the line of sight

target neutrino number density



elastic

CνB:

- Decoupled at T~1 MeV from the thermal bath
- Has a present density of 336 cm^{-3}
- Non-relativistic today

$$T^0_{C\nu B} = \left(\frac{4}{11}\right)^{1/3} T^0_{\rm CMB} \simeq 1.95 \rm K$$

Medium interactions.

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Average number of scattering

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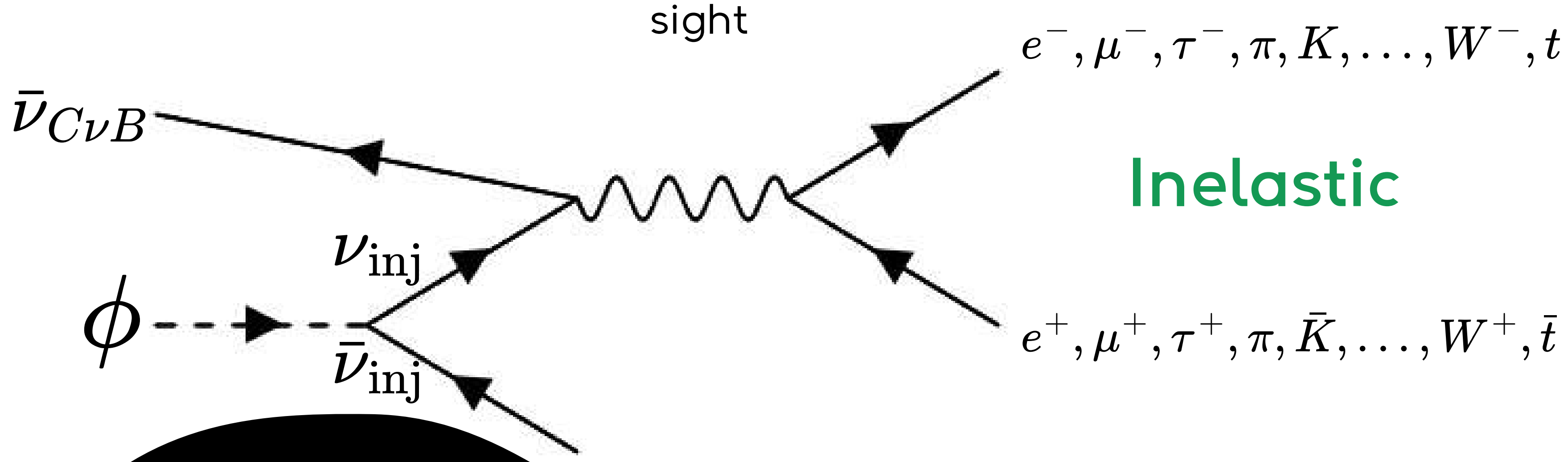

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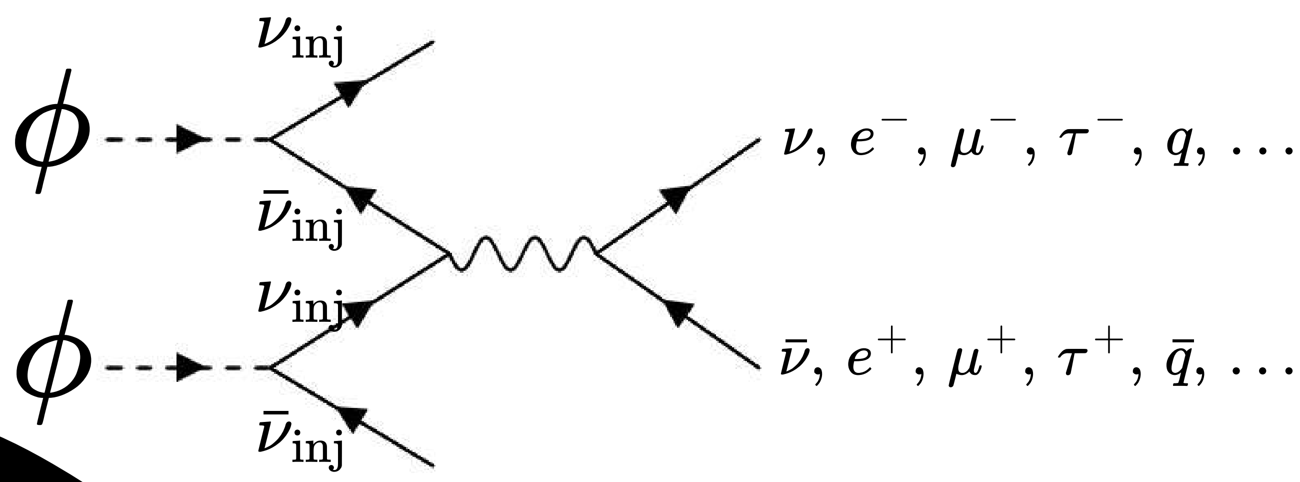
Average number of scattering

Integration over the line of sight

target neutrino number density



Self-scattering:

- Very low density, but high energies
- Numerically hard (triple integral)

→ Assume instantaneous decay, i.e. all neutrinos produced at the same redshift with energy m/2

Medium interactions.

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

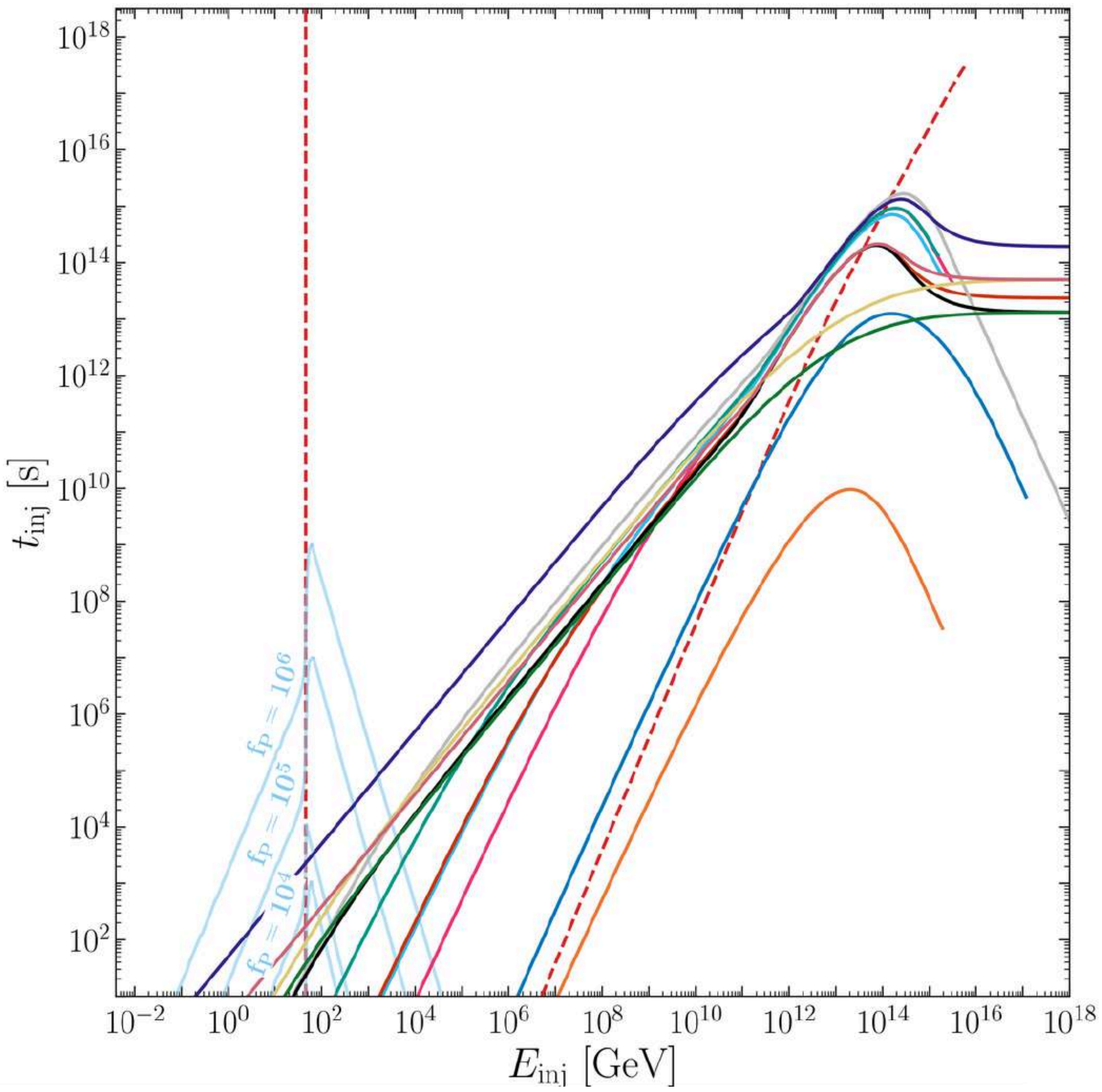
Average number of scattering

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.

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

Average number of scattering

Integration over the line of sight

cross section averaged over target distribution function

target neutrino number density

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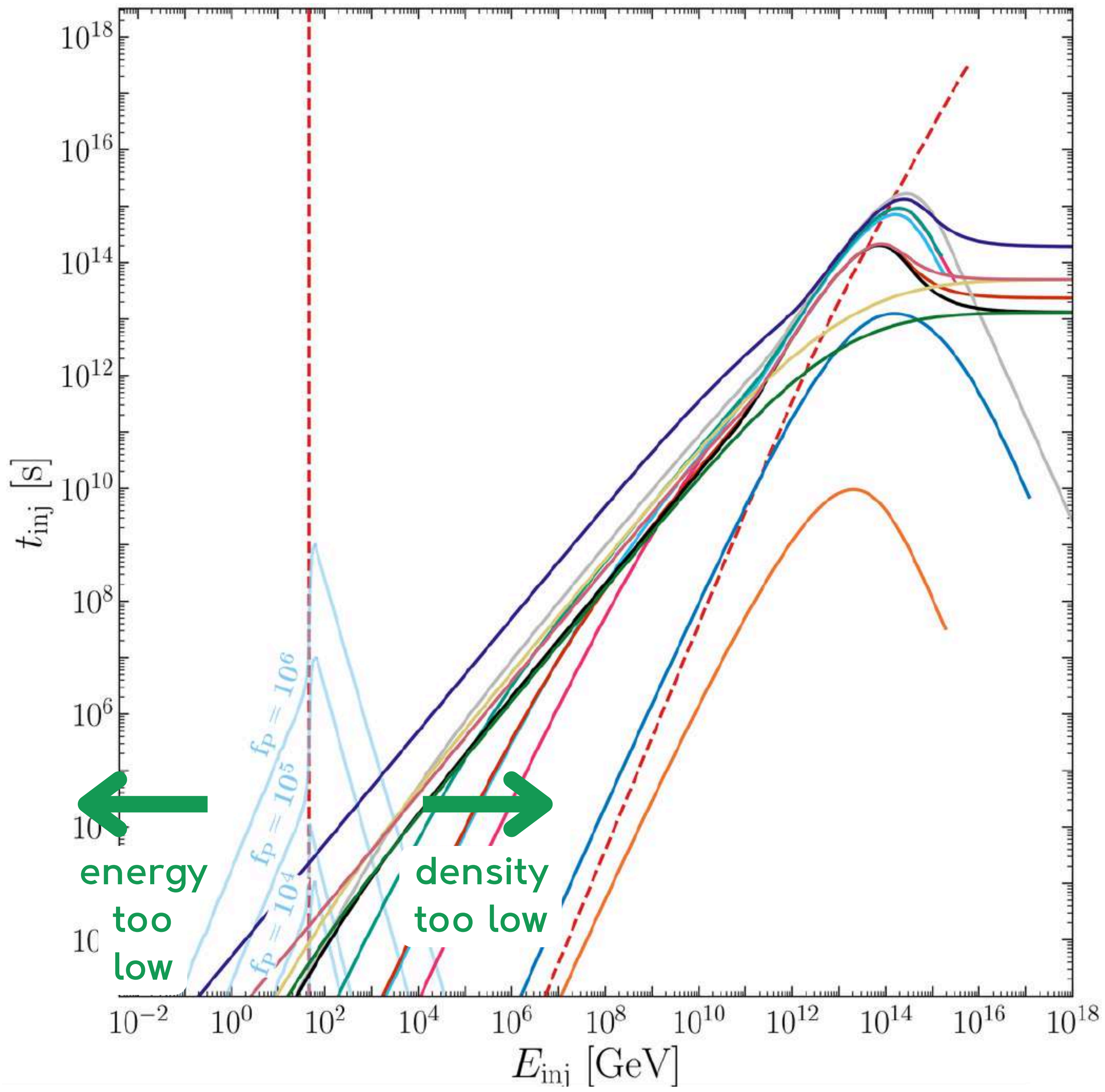

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$$S_\nu(z_e, E_0) = \int_0^{z_e} \frac{dz}{(1+z)H(z)} \langle \sigma v \rangle n_{\nu_{BG}}$$

Average number of scattering

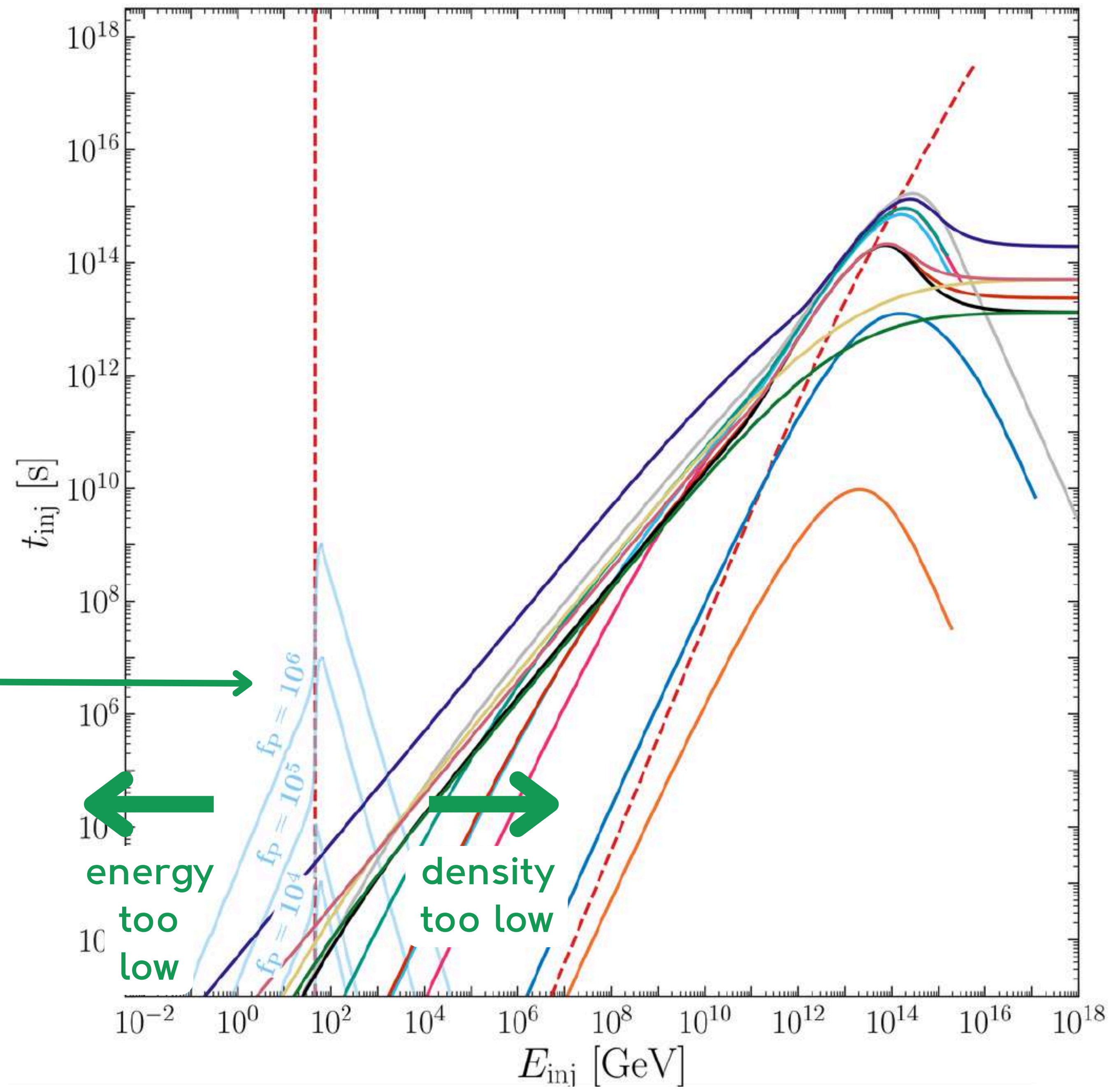
Integration over the line of sight

cross section averaged over target distribution function

target neutrino number density

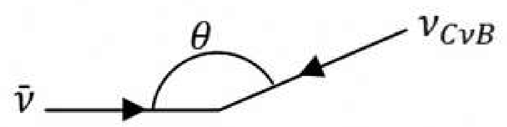
Self-scatterings are negligible except around the Z resonance

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

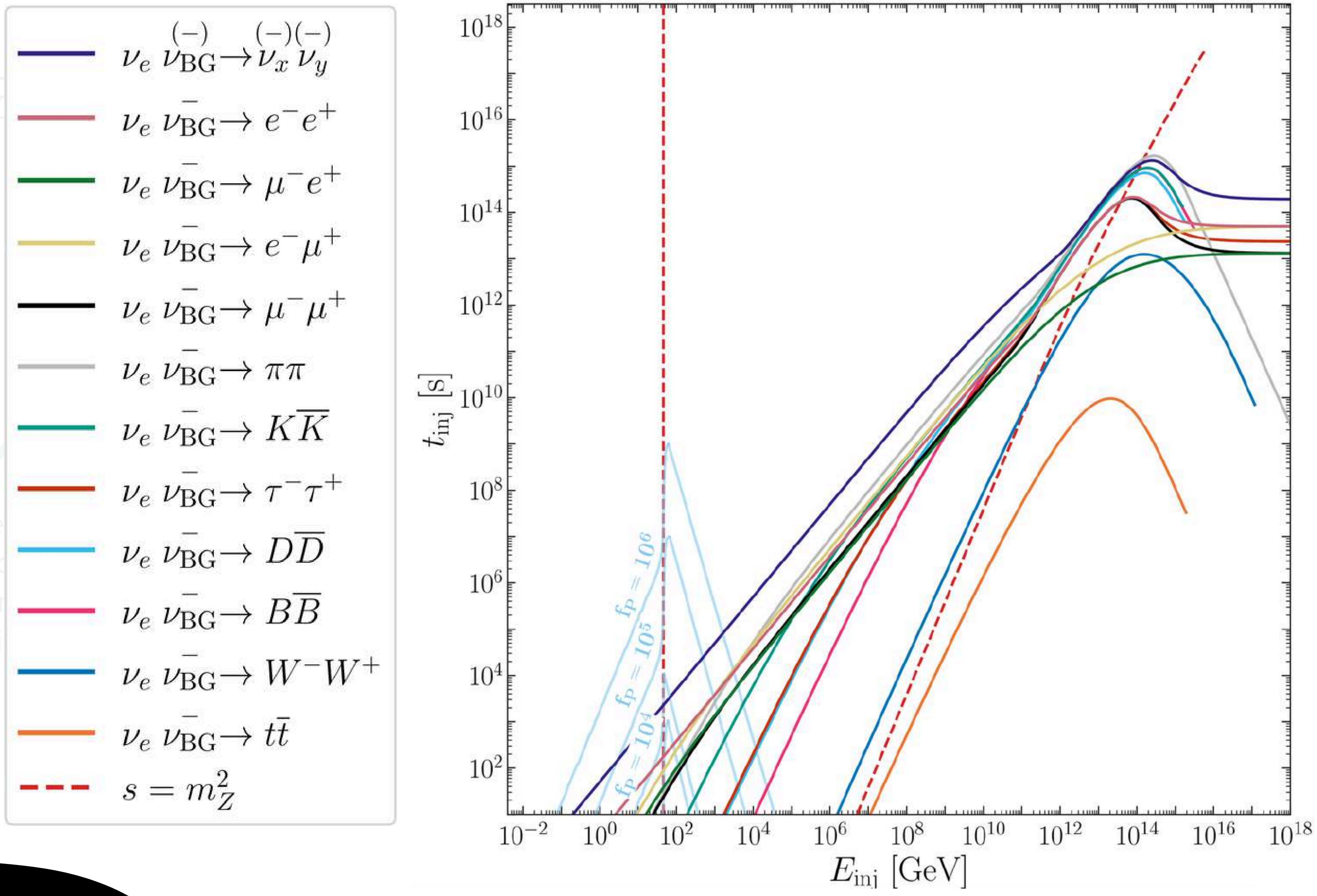


Medium interactions.

$$s = 2E_\nu E_{C\nu B}(1 - \cos(\theta))$$



$$E_\nu^{\mathrm{res}} = \frac{m_Z^2}{4 \cdot 3.15 T_{\nu_{\mathrm{BG}}}}$$



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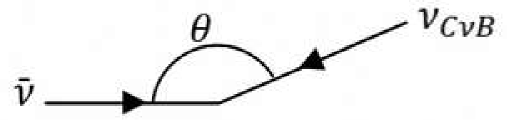
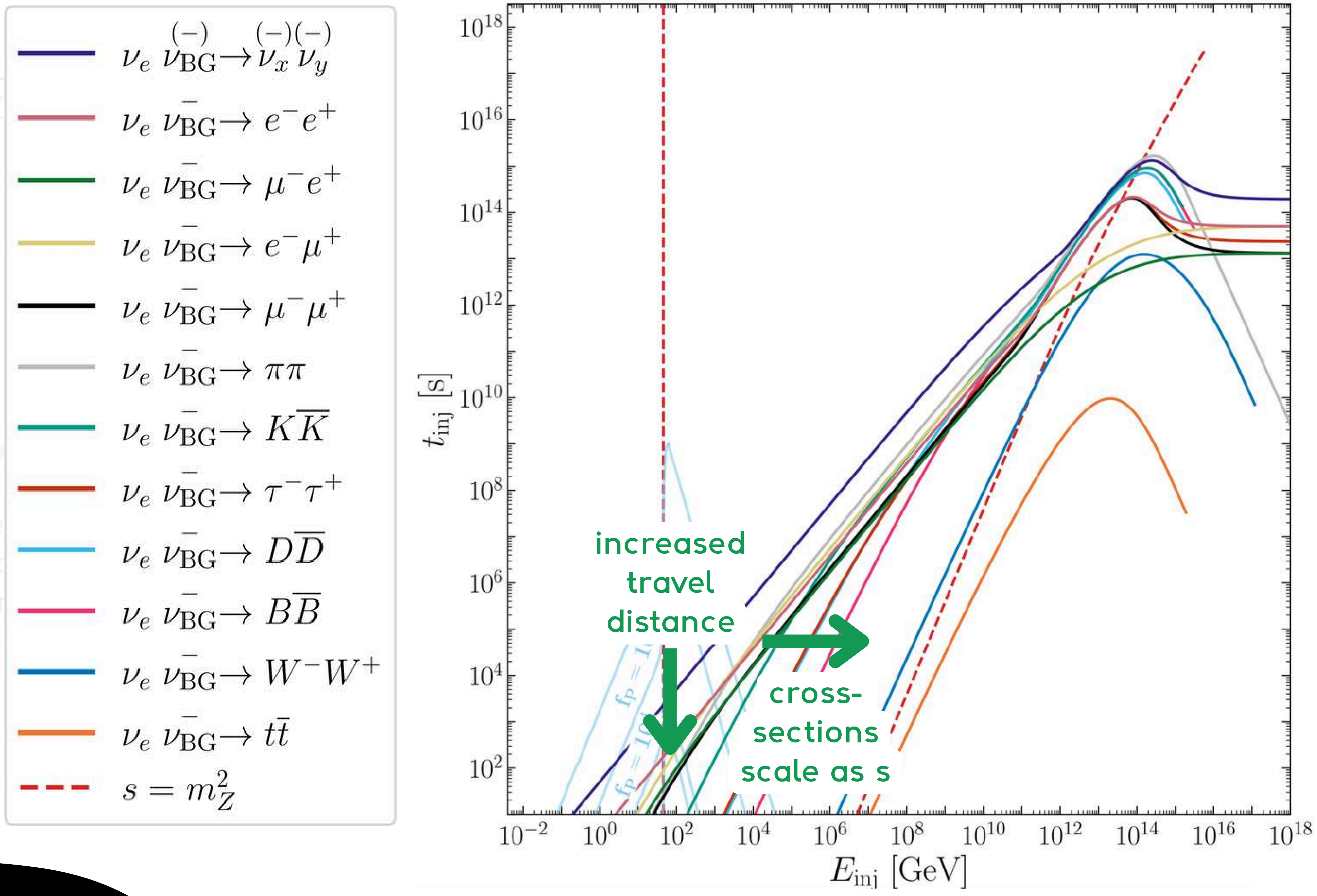
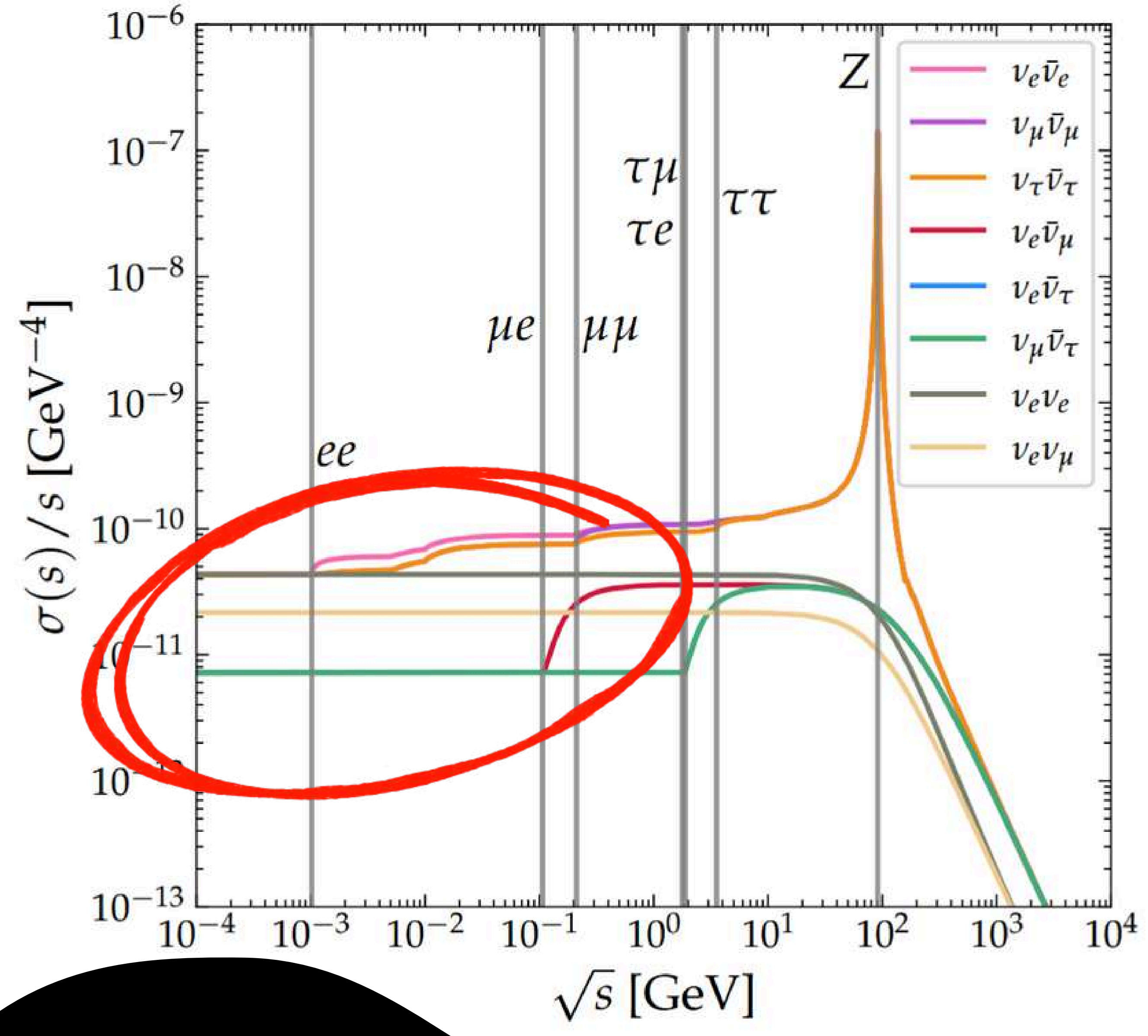


$$E_{\text{inj}} << E_\nu^{\text{res}}$$

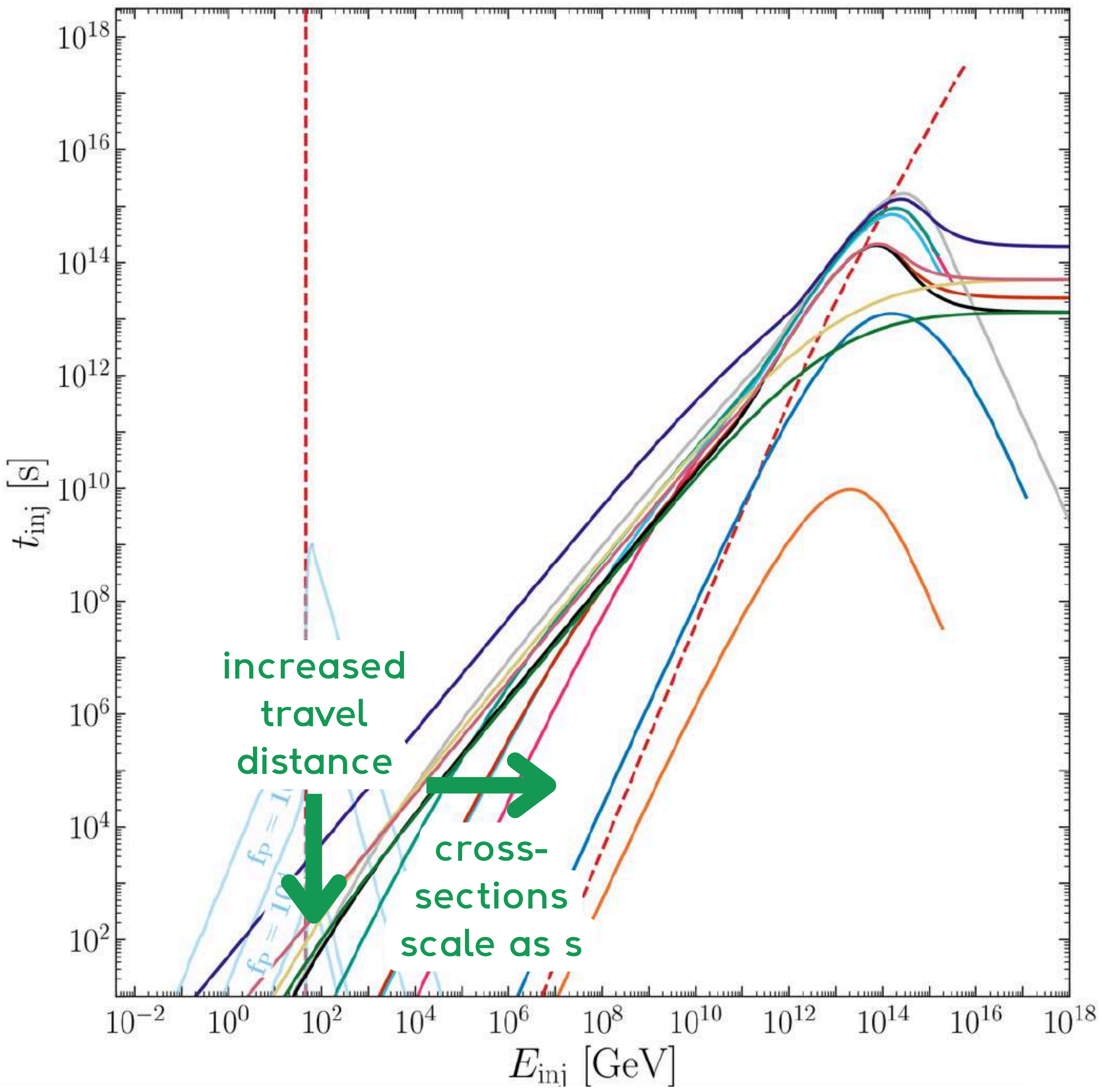
$$E_\nu^{\text{res}} = \frac{m_Z^2}{4 \cdot 3.15 T_{\nu_{\text{BG}}}}$$



Medium interactions.



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



Medium interactions.

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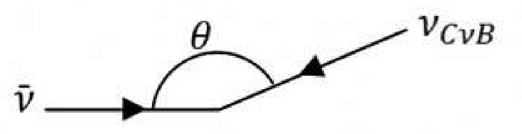
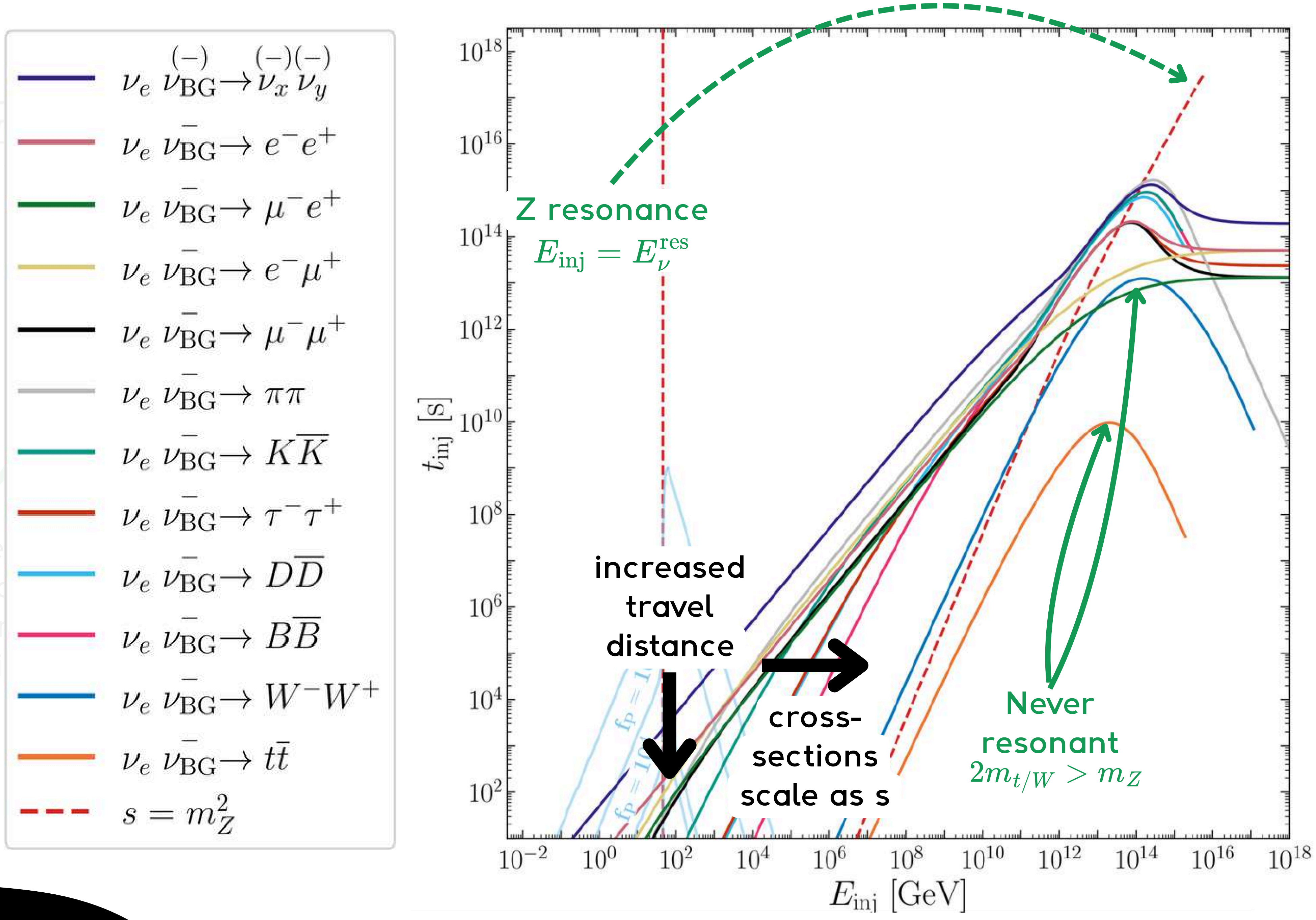


$$E_{\rm inj} \sim E_\nu^{\rm res}$$

$$E_\nu^{\rm res} = \frac{m_Z^2}{4 \cdot 3.15 T_{\nu_{\rm BG}}}$$



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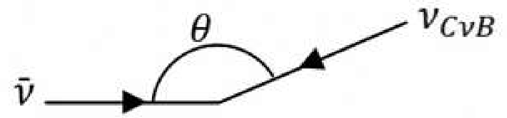
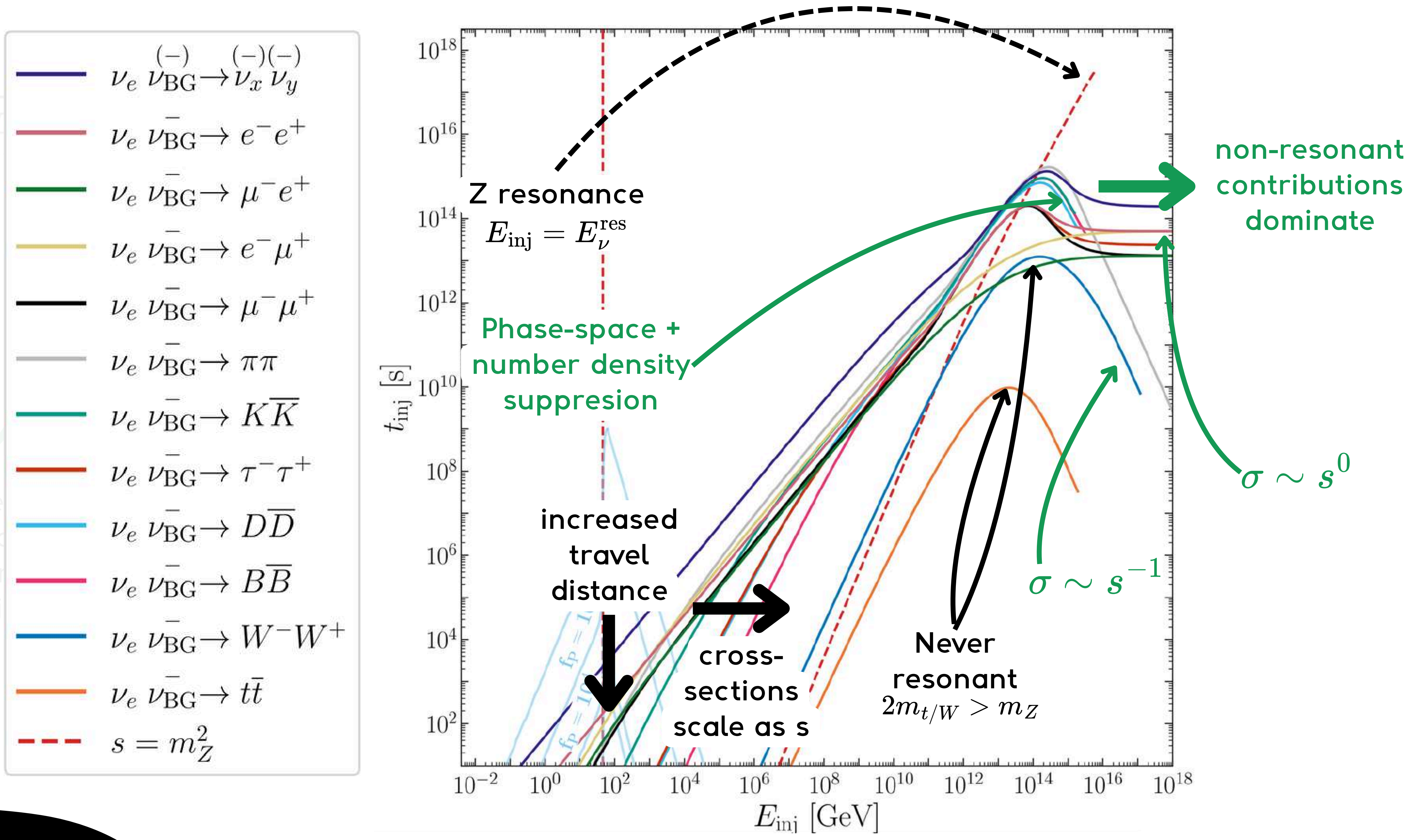
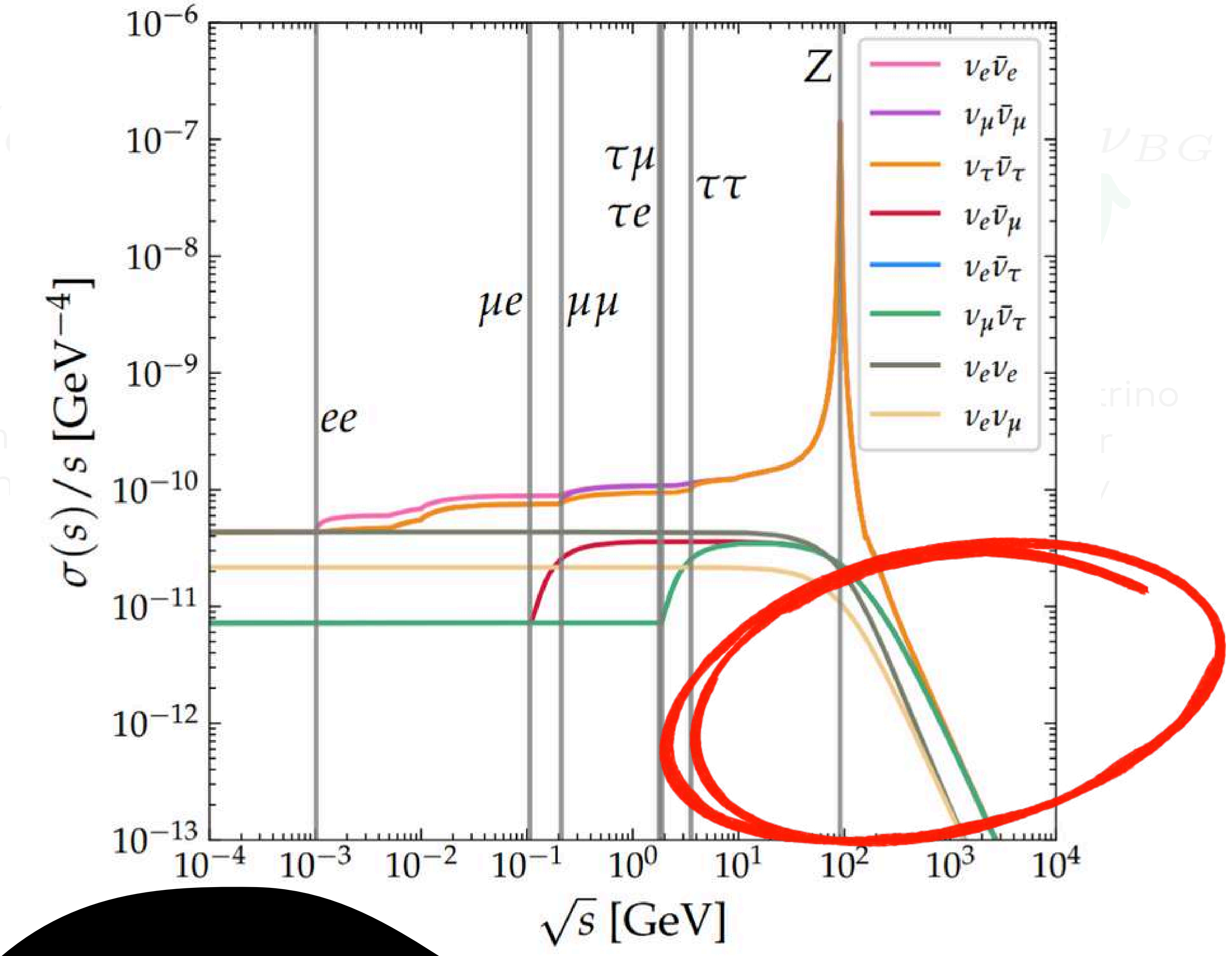


$$E_{\text{inj}} >> E_\nu^{\text{res}}$$

$$E_\nu^{\text{res}} = \frac{m_Z^2}{4\cdot 3.15 T_{\nu_{\text{BG}}}}$$



Medium interactions.



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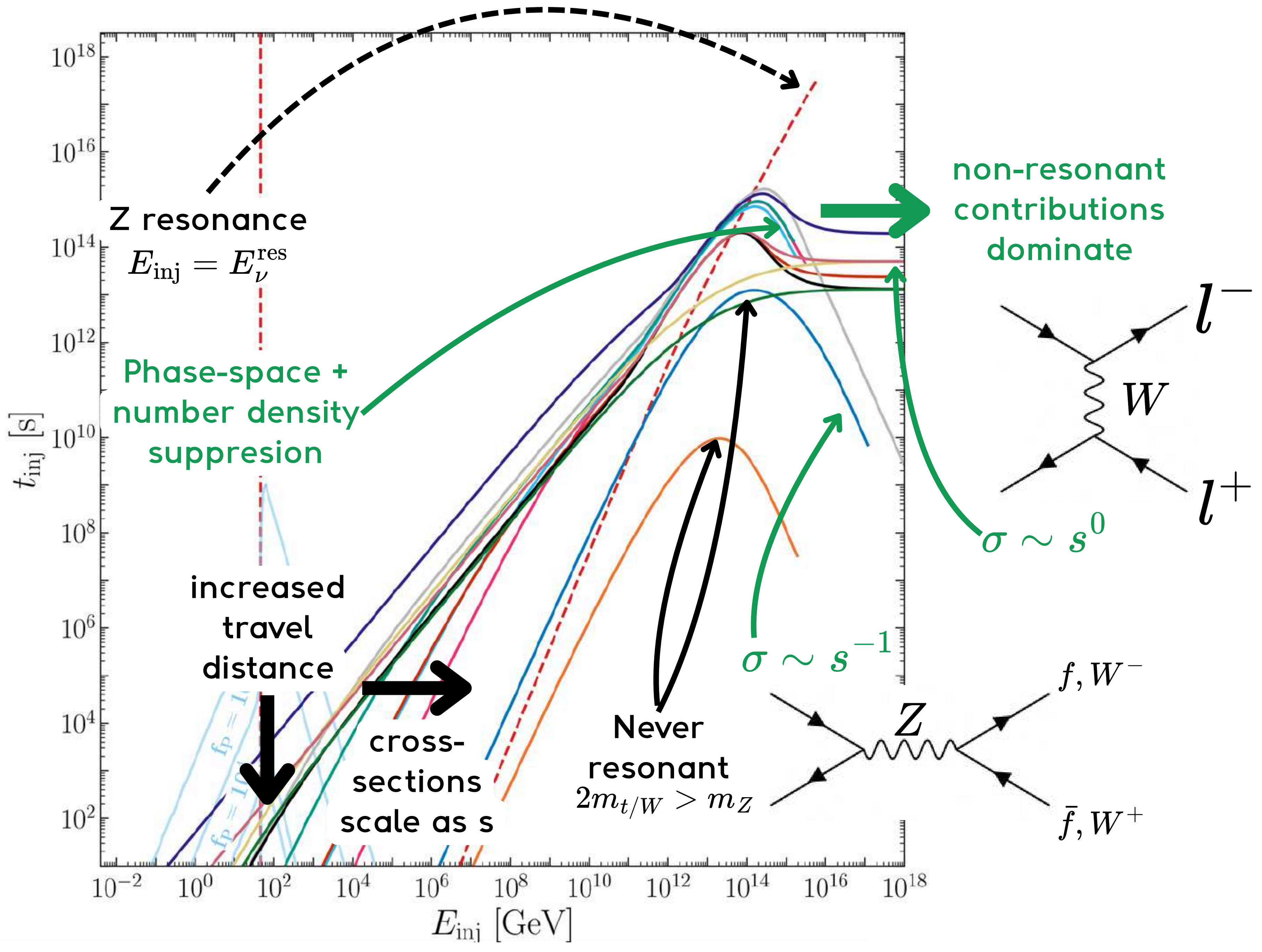
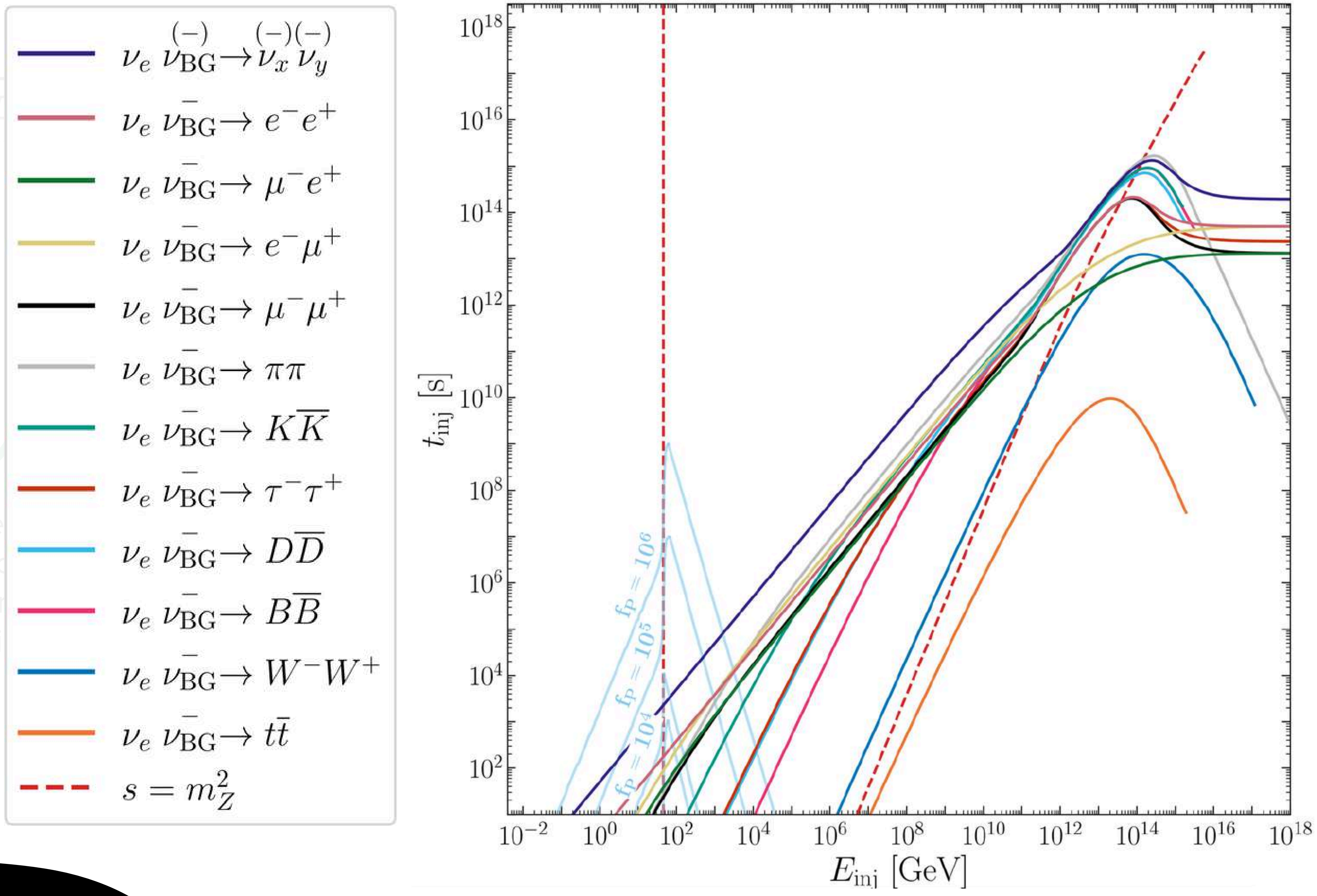


Medium interactions.



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

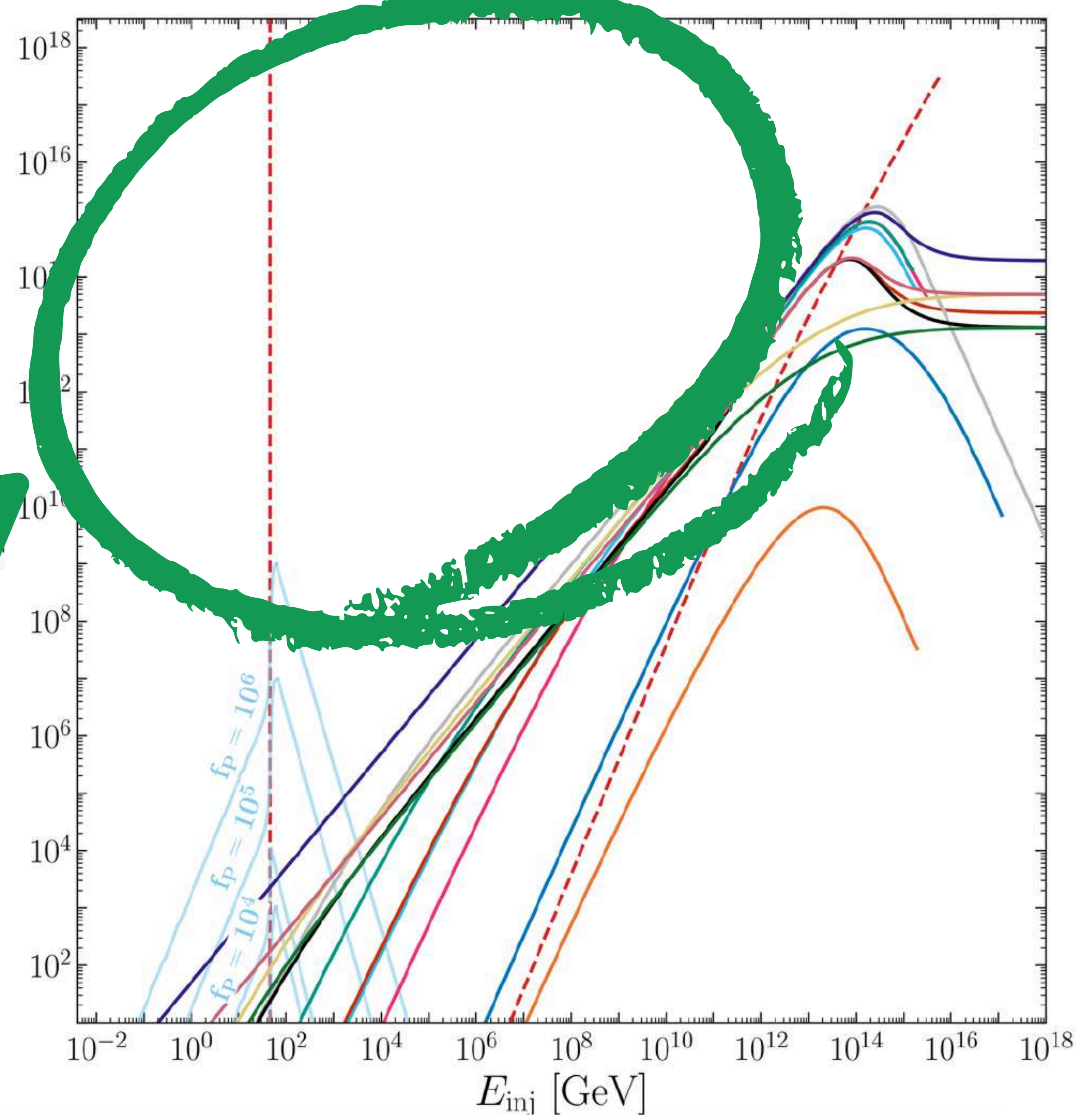
Average number of scattering

Integration over the line of sight

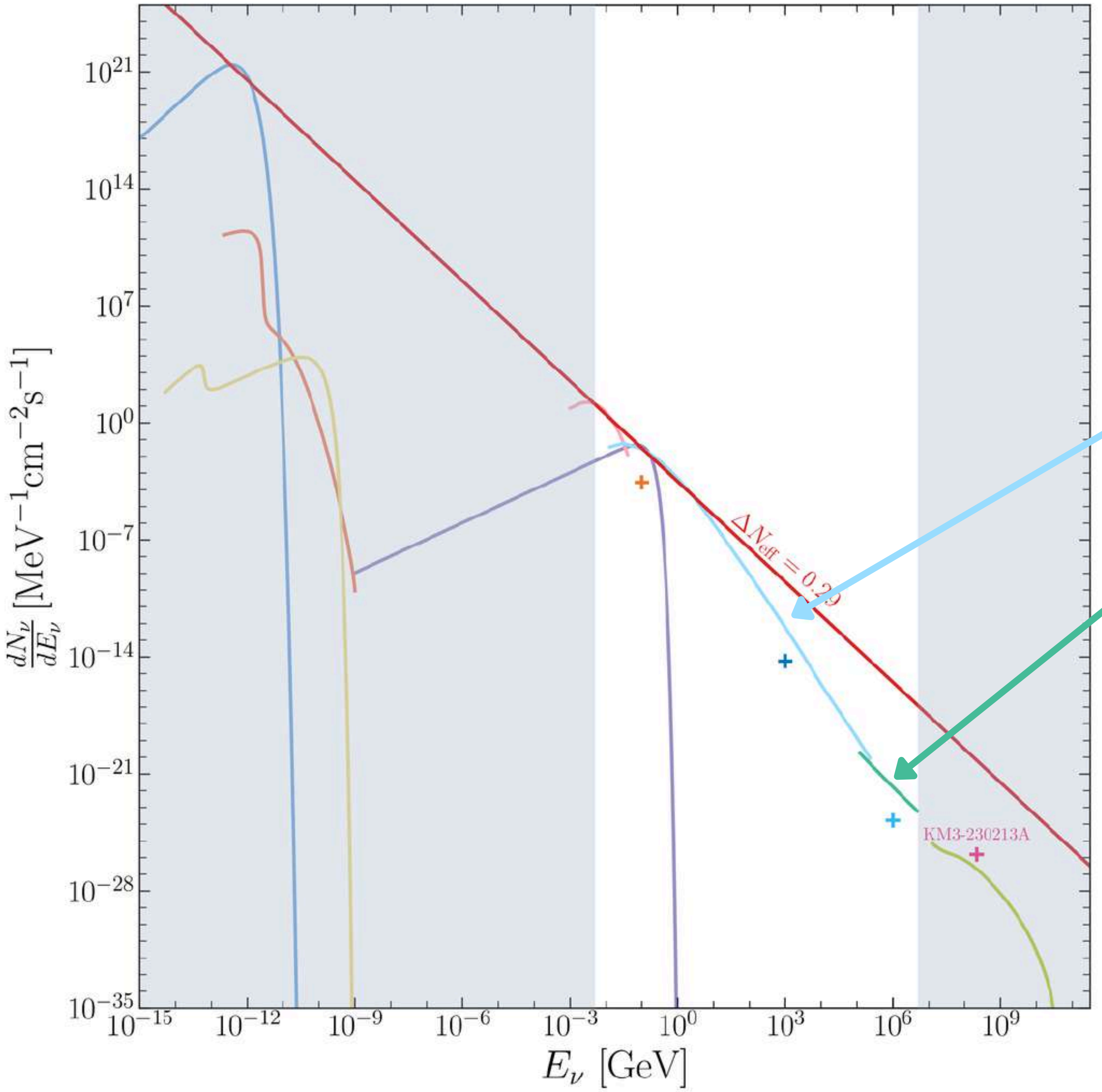
cross section averaged over target distribution function

target neutrino number density

Sharp spectral features mostly unaffected



Constraints.

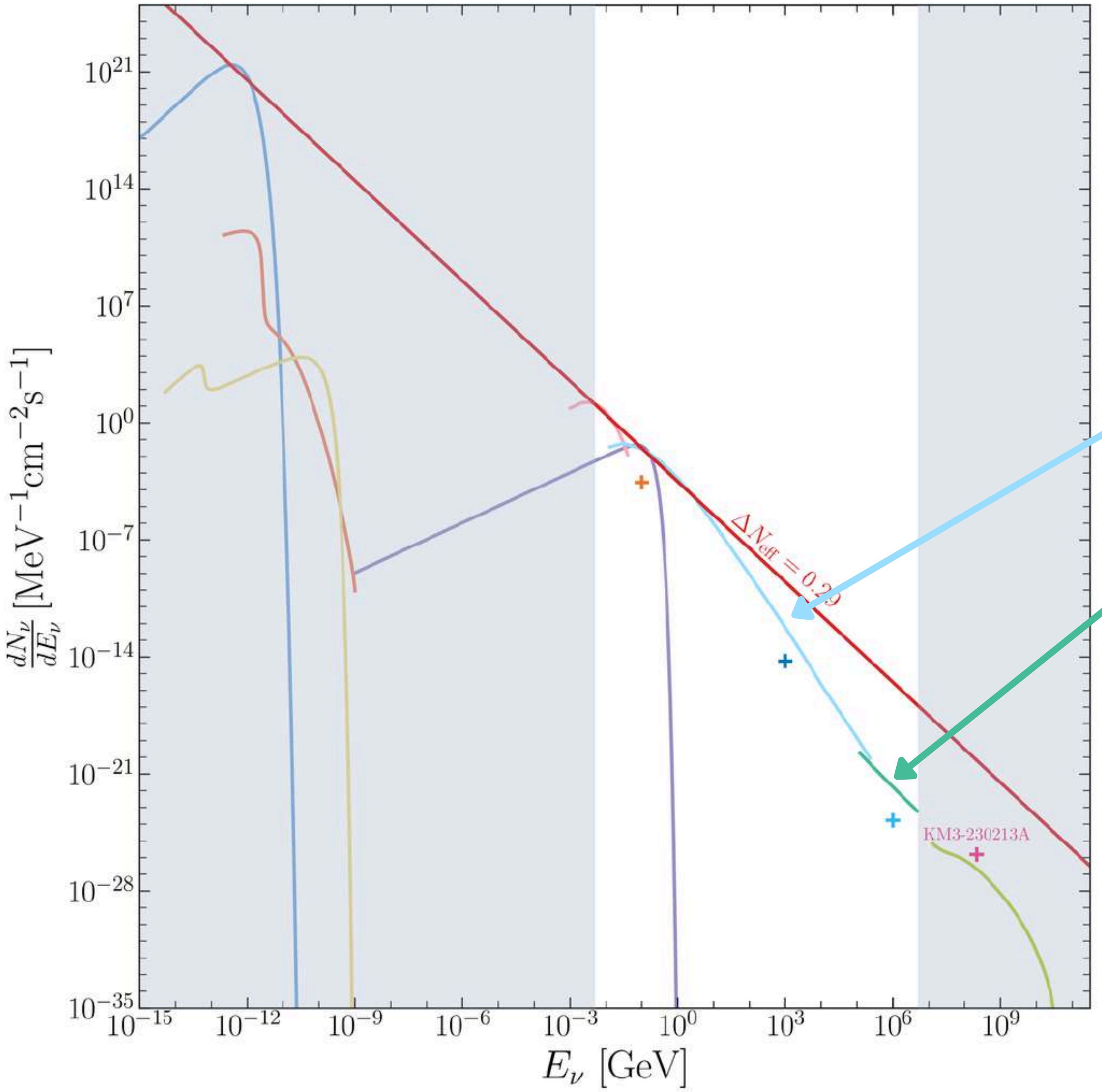


Vitagliano, Tamborra, Raffelt 19'

Observational:

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

Constraints.



Vitagliano, Tamborra, Raffelt 19'

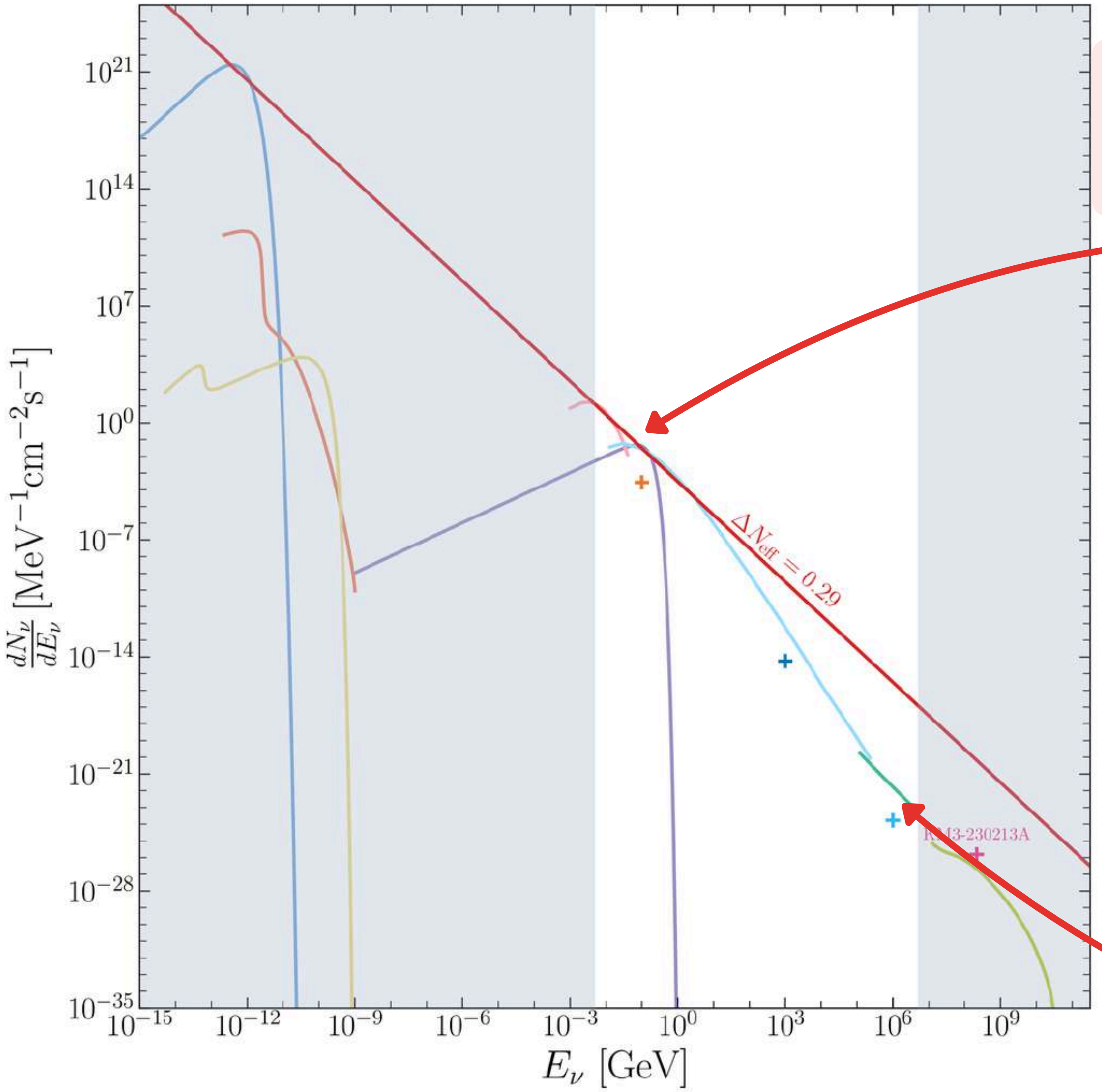
Observational:

- 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

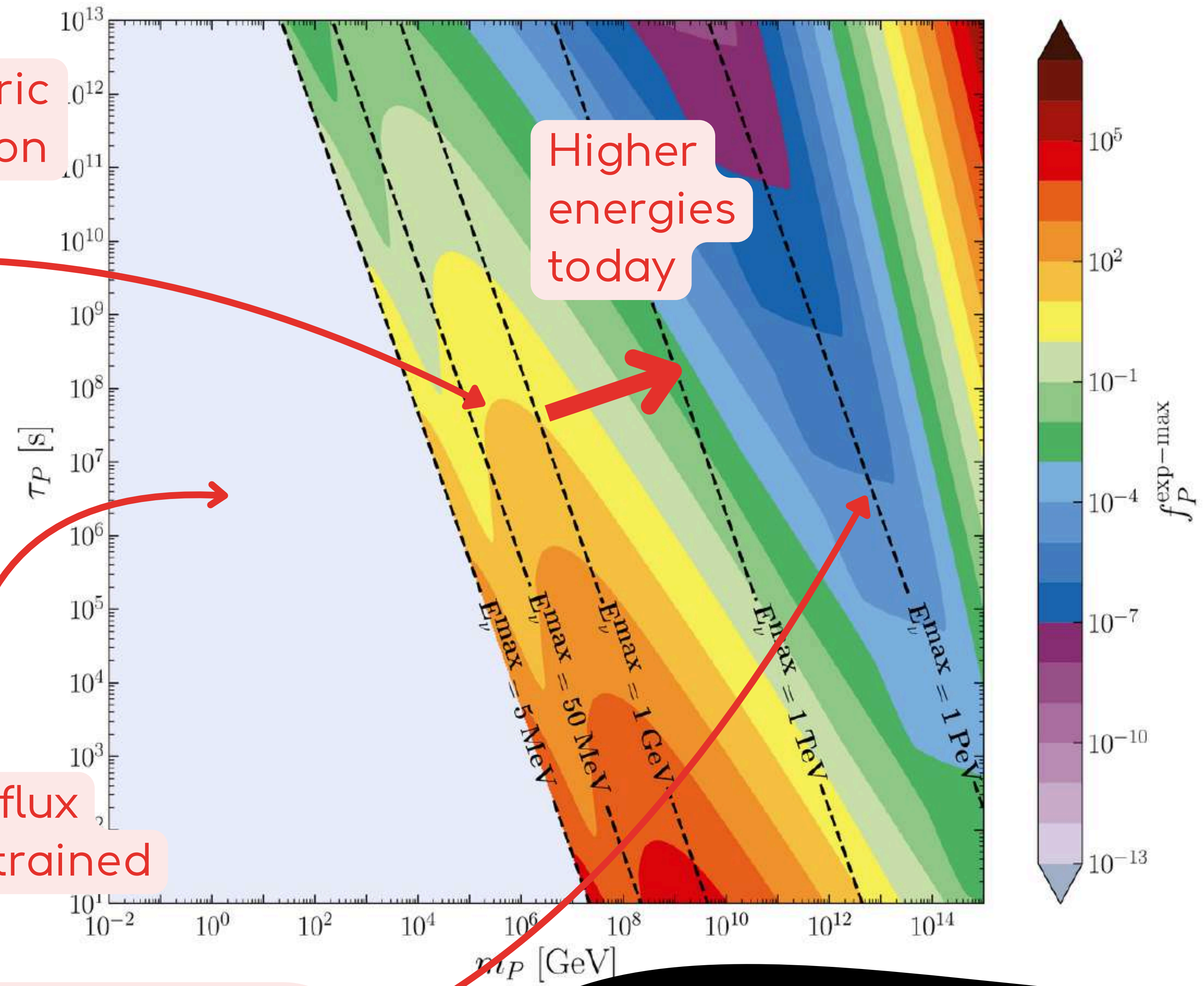
→ Upper bound on f

Constraints.



Vitagliano, Tamborra, Raffelt 19'

Atmospheric flux inflexion point



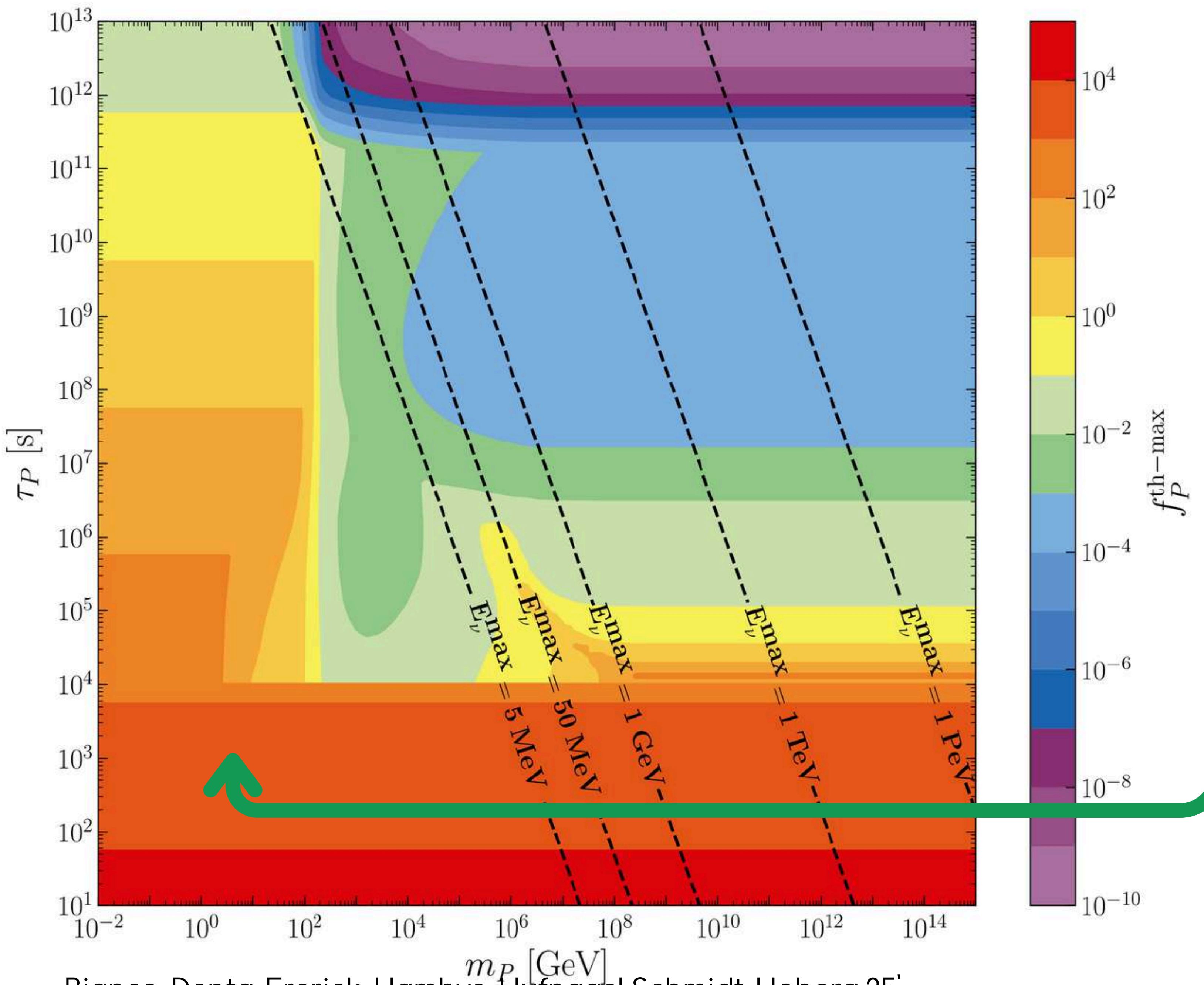
Higher energies today

PHENU flux unconstrained

$$\frac{dN^{\rm PHENU}}{dE} \propto E^{-2}$$

$$\frac{dN^{\rm Astro}}{dE} \underset{\sim}{\propto} E^{-2}$$

Constraints.



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

Cosmological:

Pl18[TT,TE,EE+lowE]	ΛCDM+N_{eff}	$2.92^{+0.36}_{-0.37}$

Planck '18

N_{eff} bound on additional neutrino energy density

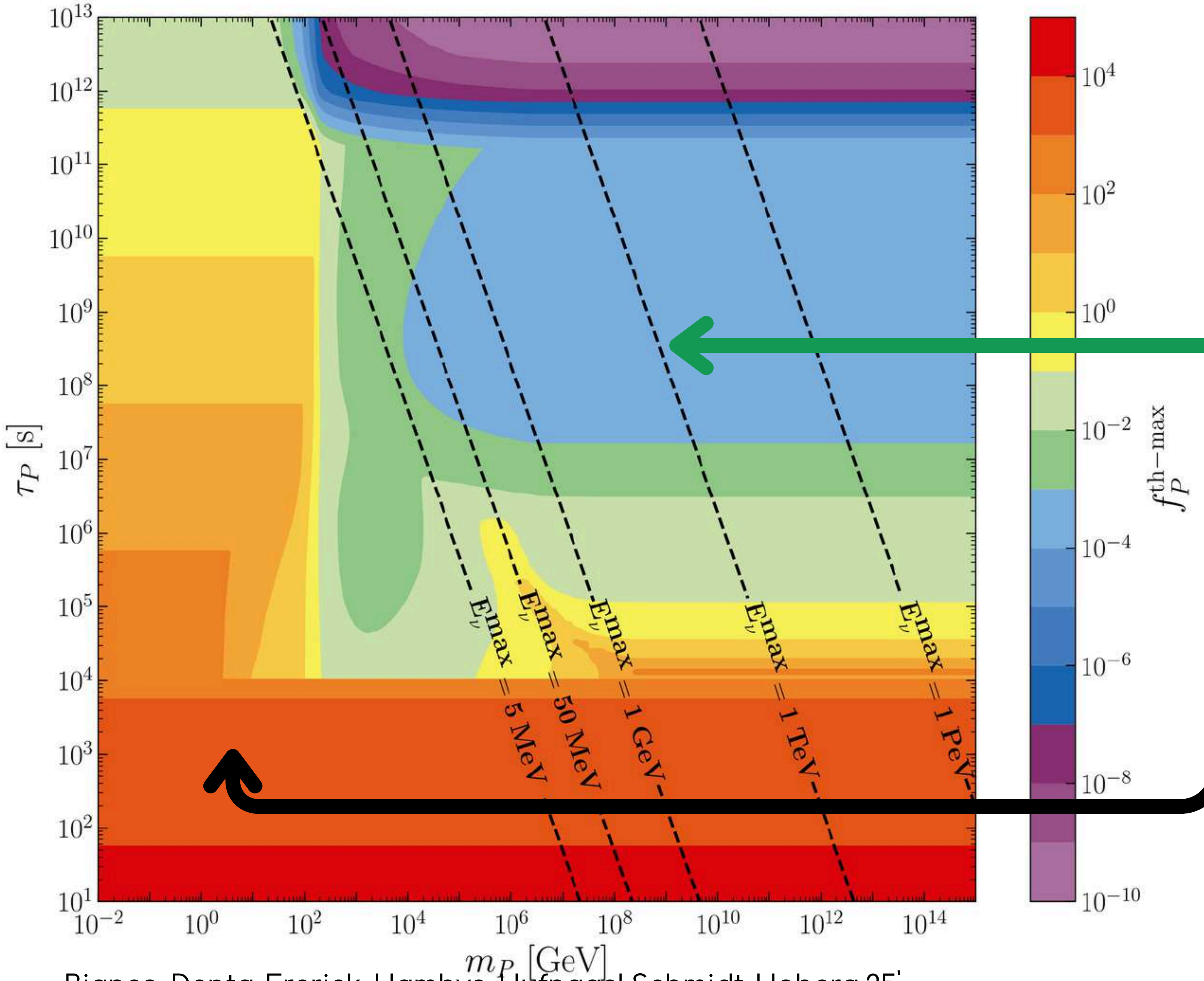
$$N_{\mathrm{eff}}^{\mathrm{SM}} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_\nu}{\rho_\gamma}\right)$$

$$= 3.0432(2) \simeq 3.043$$

Cielo, Escudero, Mangano, Pisanti '23

Constraints.

Cosmological:



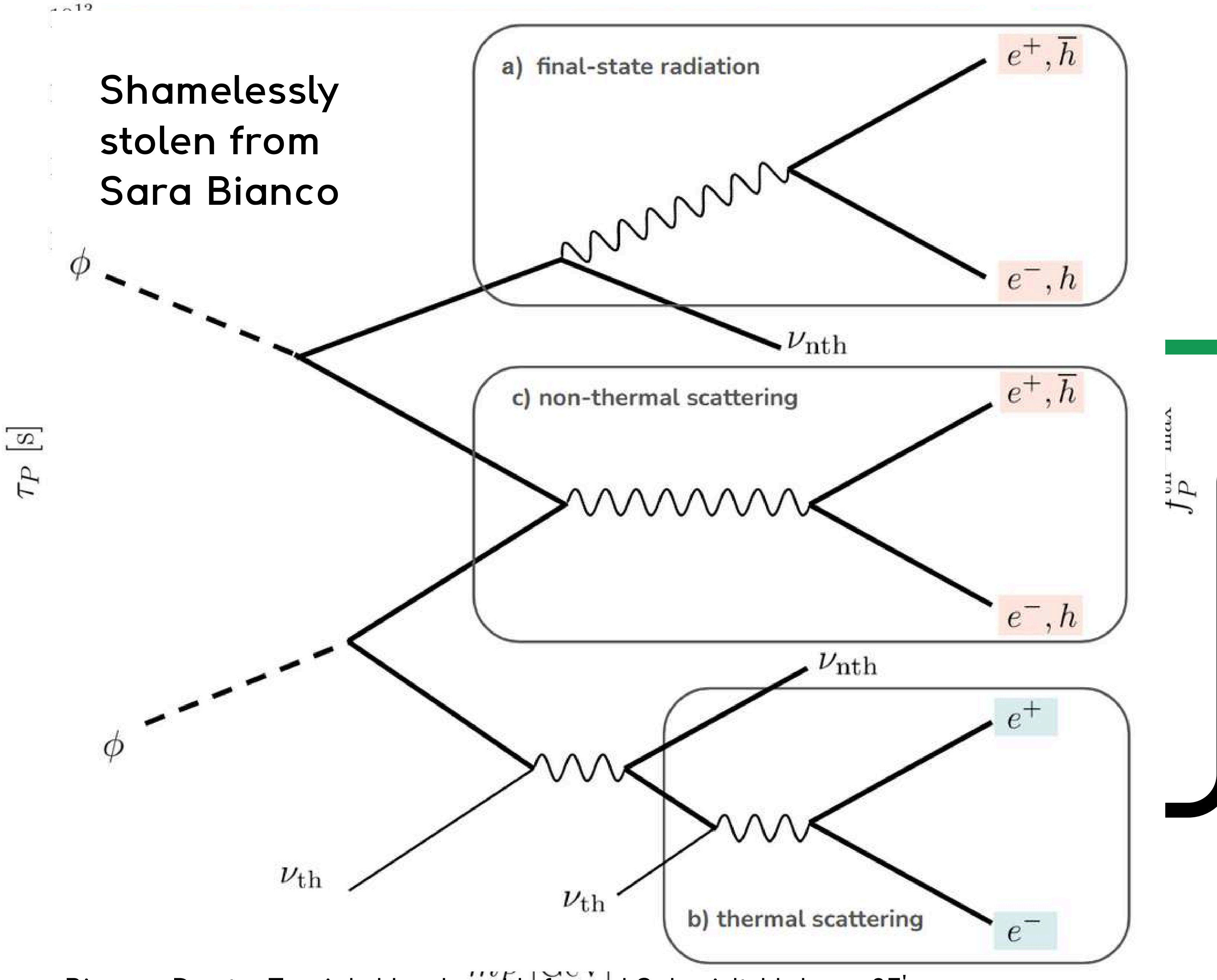
BBN bound from photo and hadro disintegration of light elements

N_{eff} bound on additional neutrino energy density

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

Constraints.

Shamelessly stolen from Sara Bianco



Bianco, Depta, Frerick, Hambye, Hufnagel, Schmidt-Hoberg 25'
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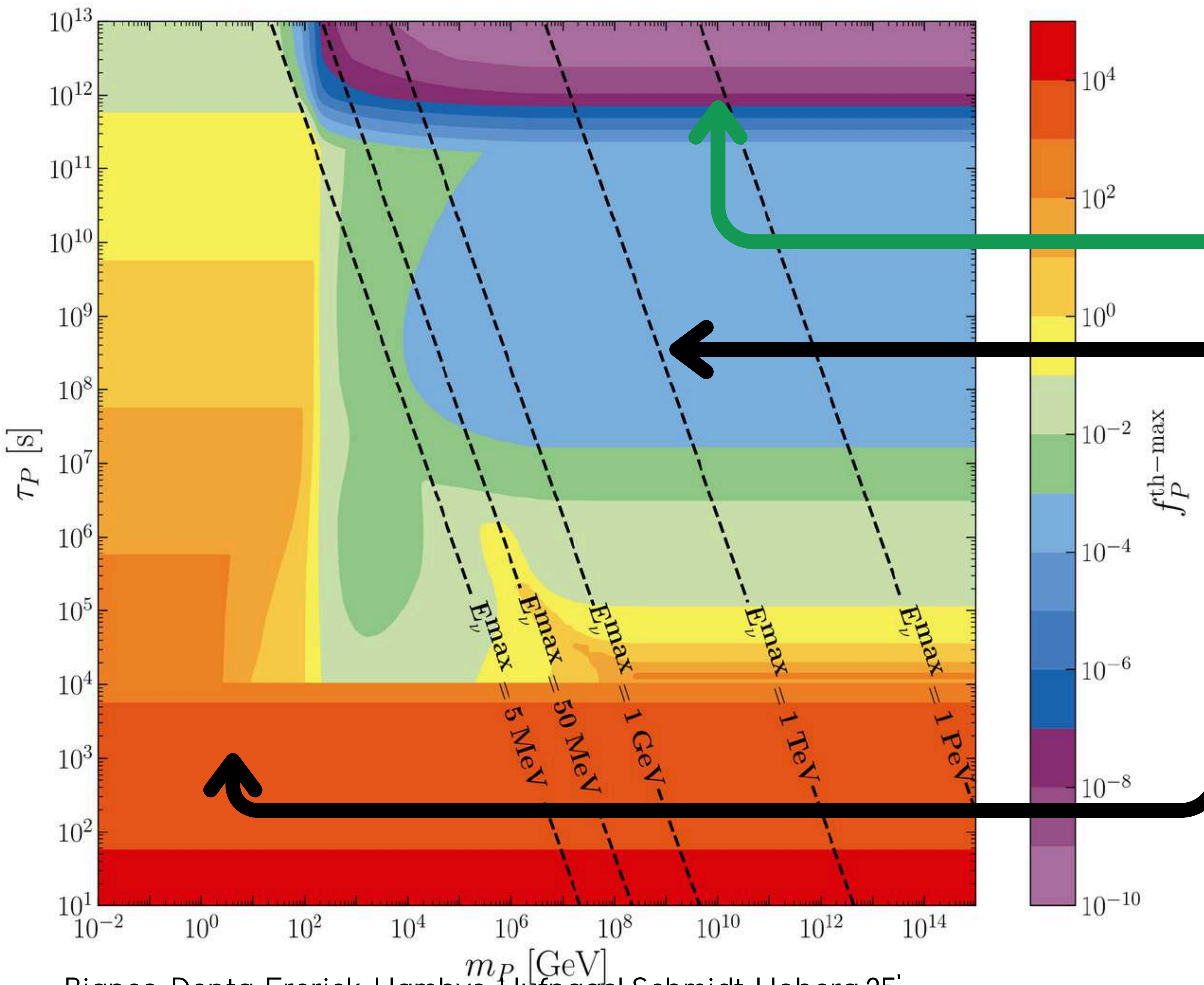
Cosmological:

BBN bound from photo and hadro disintegration of light elements

N_{eff} bound on additional neutrino energy density

Constraints.



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

Cosmological:

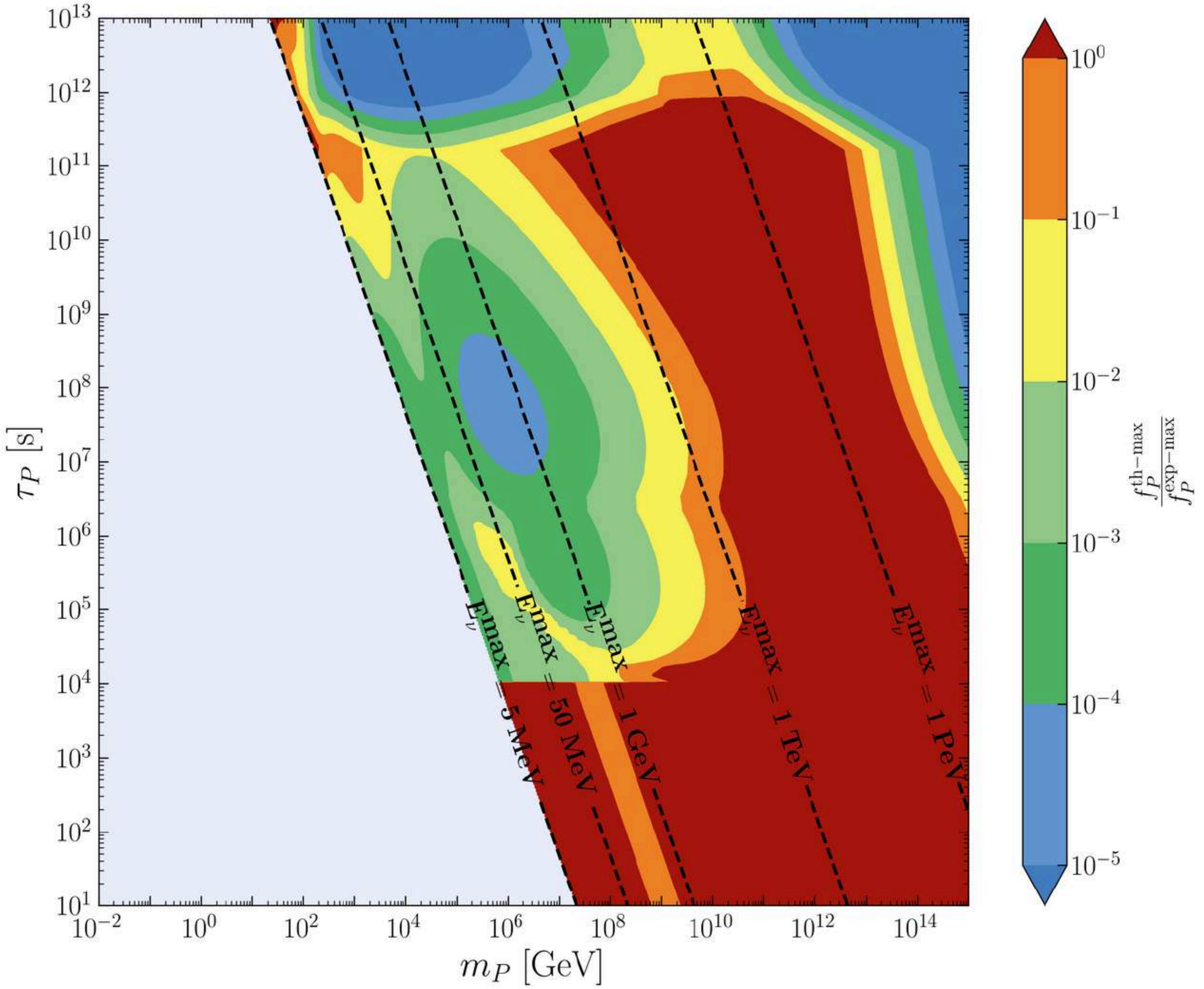
CMB anisotropies bound

BBN bound from photo and hadro disintegration of light elements

N_{eff} bound on additional neutrino energy density

Competing bounds with observations

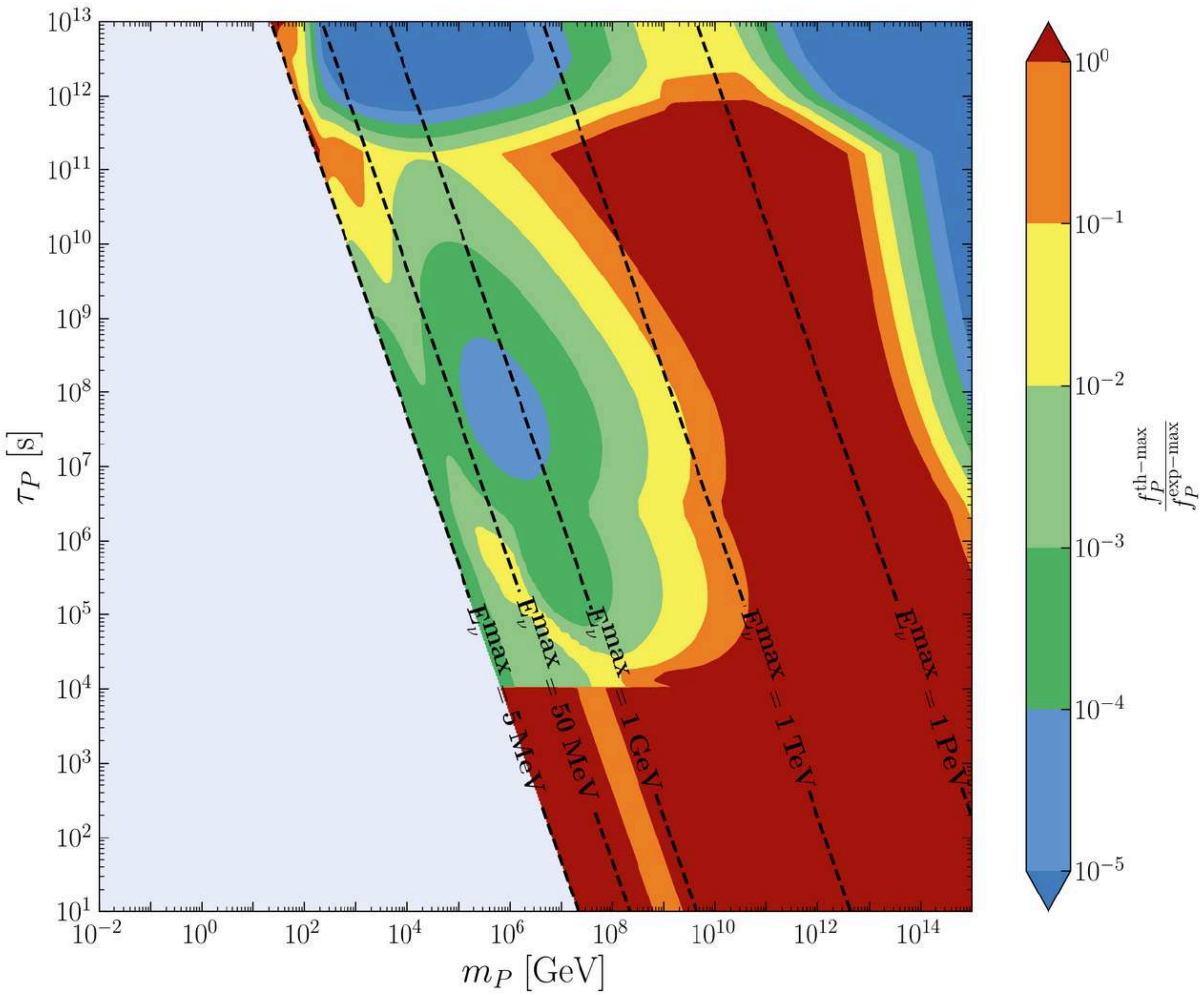
Constraints.



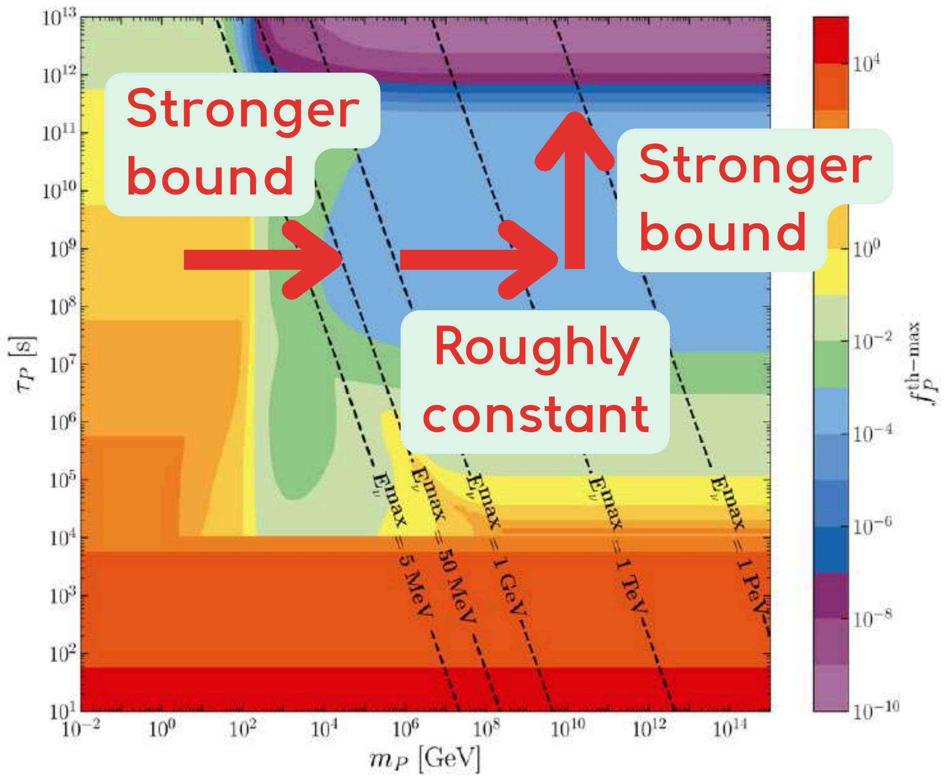
Combination: $\frac{f^{cosmo}}{f^{obs}}$

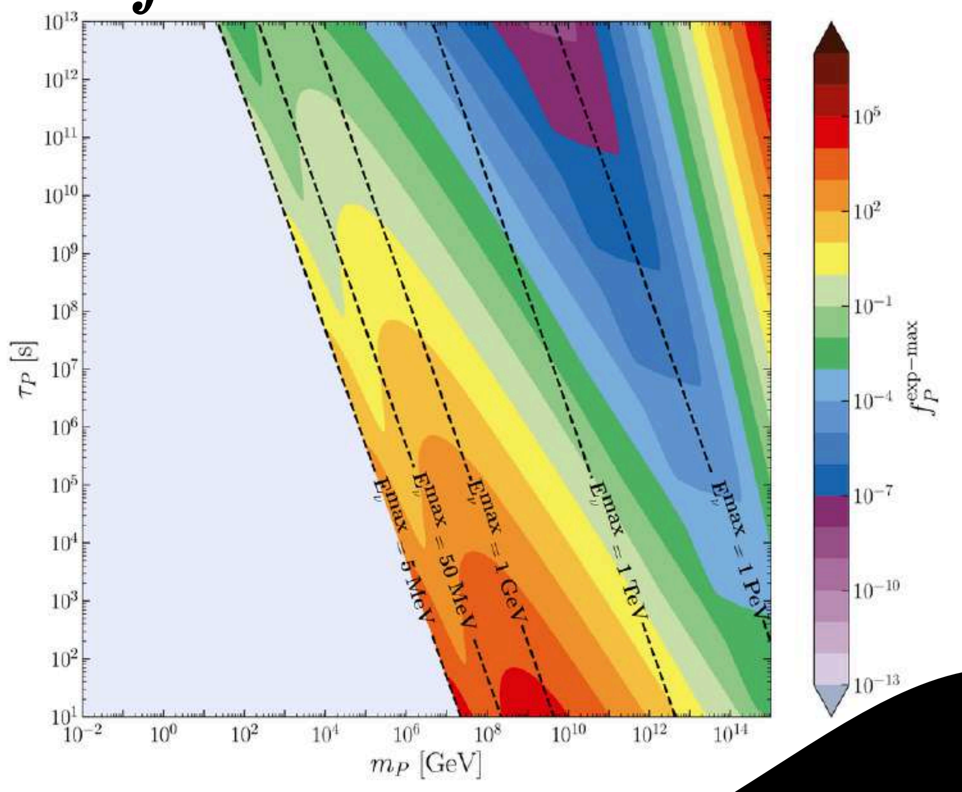
- Ratio > 1: Unconstrained by theoretical bounds
- Ratio > 10^{-2}: Potentially observable today
- Ratio < 10^{-2}: Signal too weak to be observed
- Ratio < 10^{-5}: Hopeless

Constraints.



Combination: $\frac{f^{cosmo}}{f^{obs}}$





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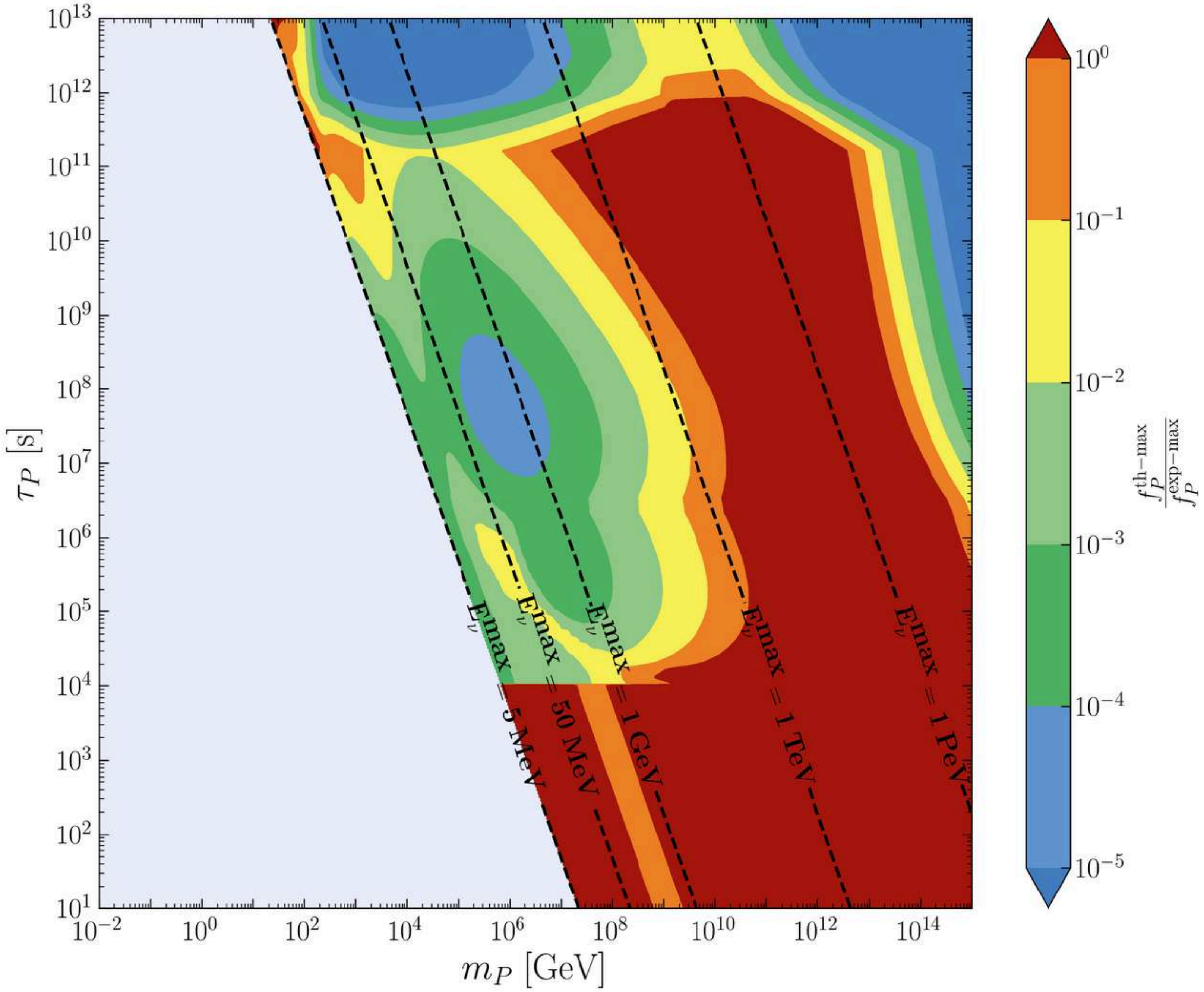
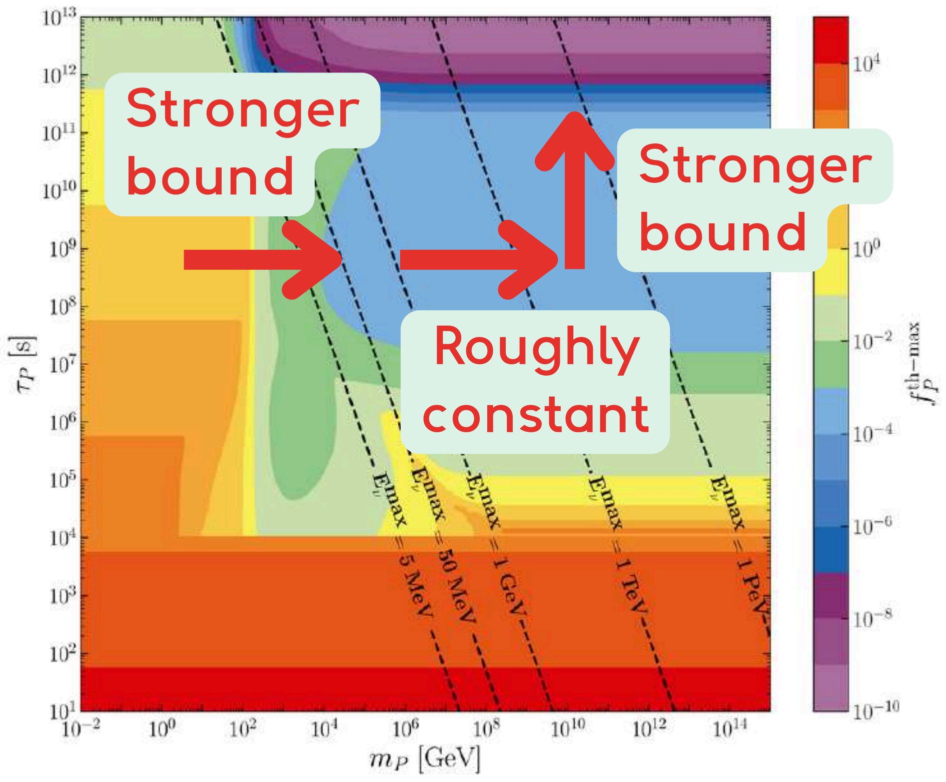
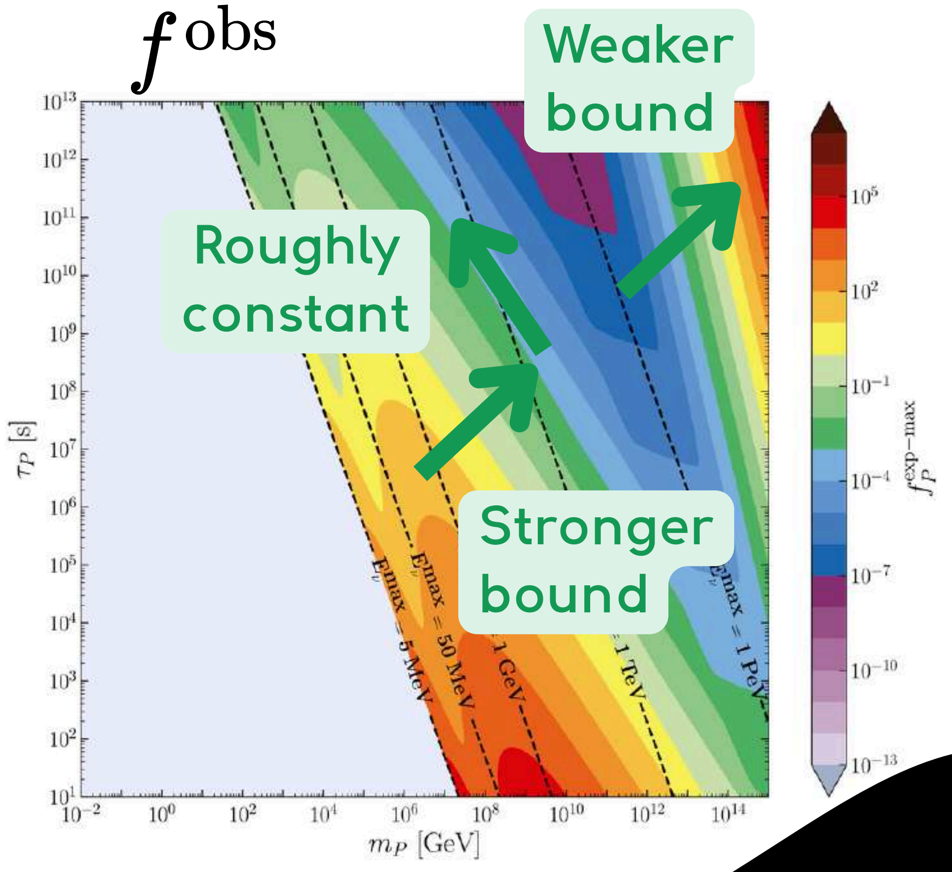


Combination: $\frac{f^{\text{cosmo}}}{f^{\text{obs}}}$





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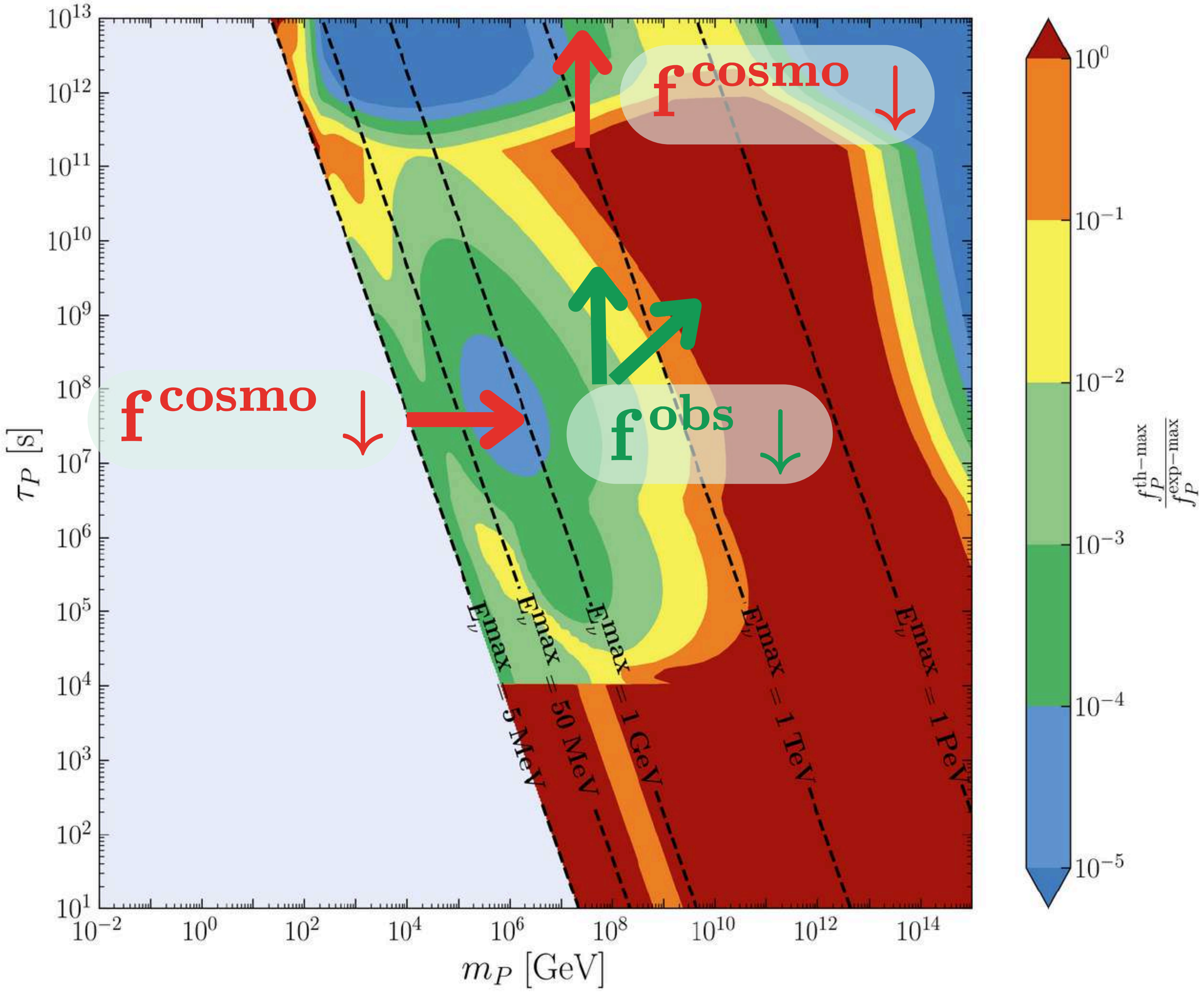

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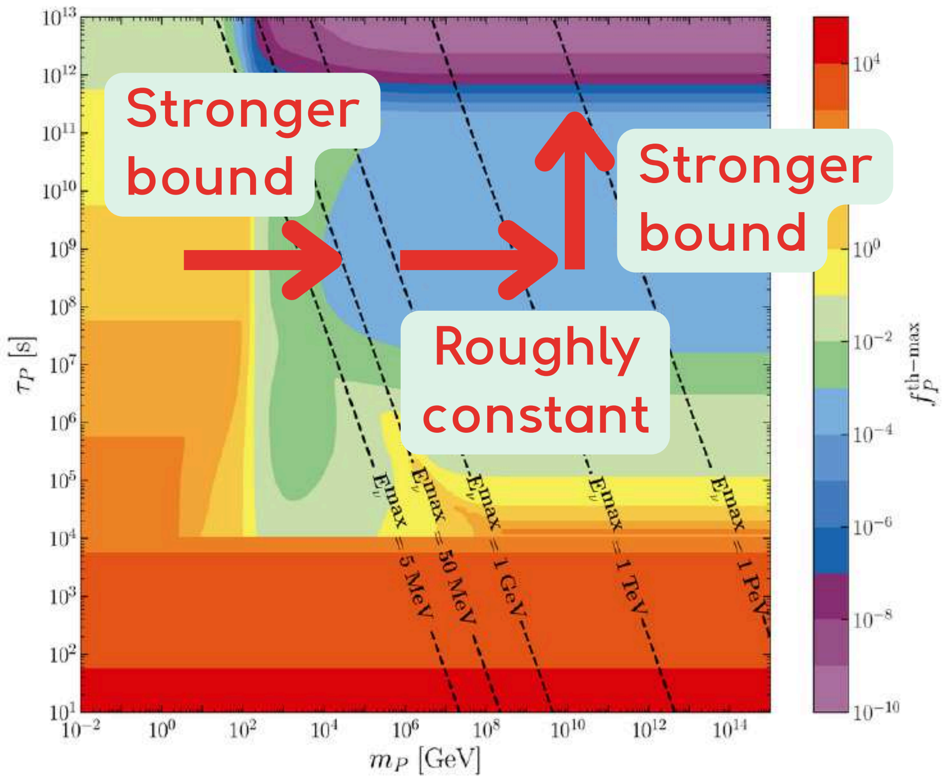

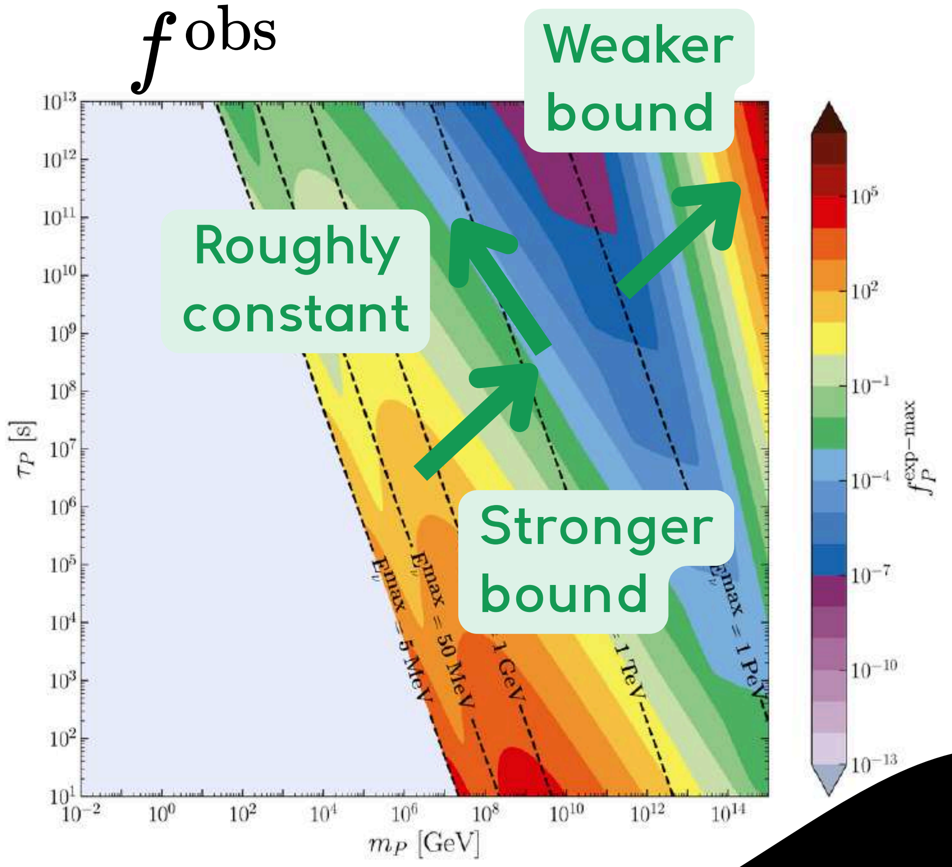

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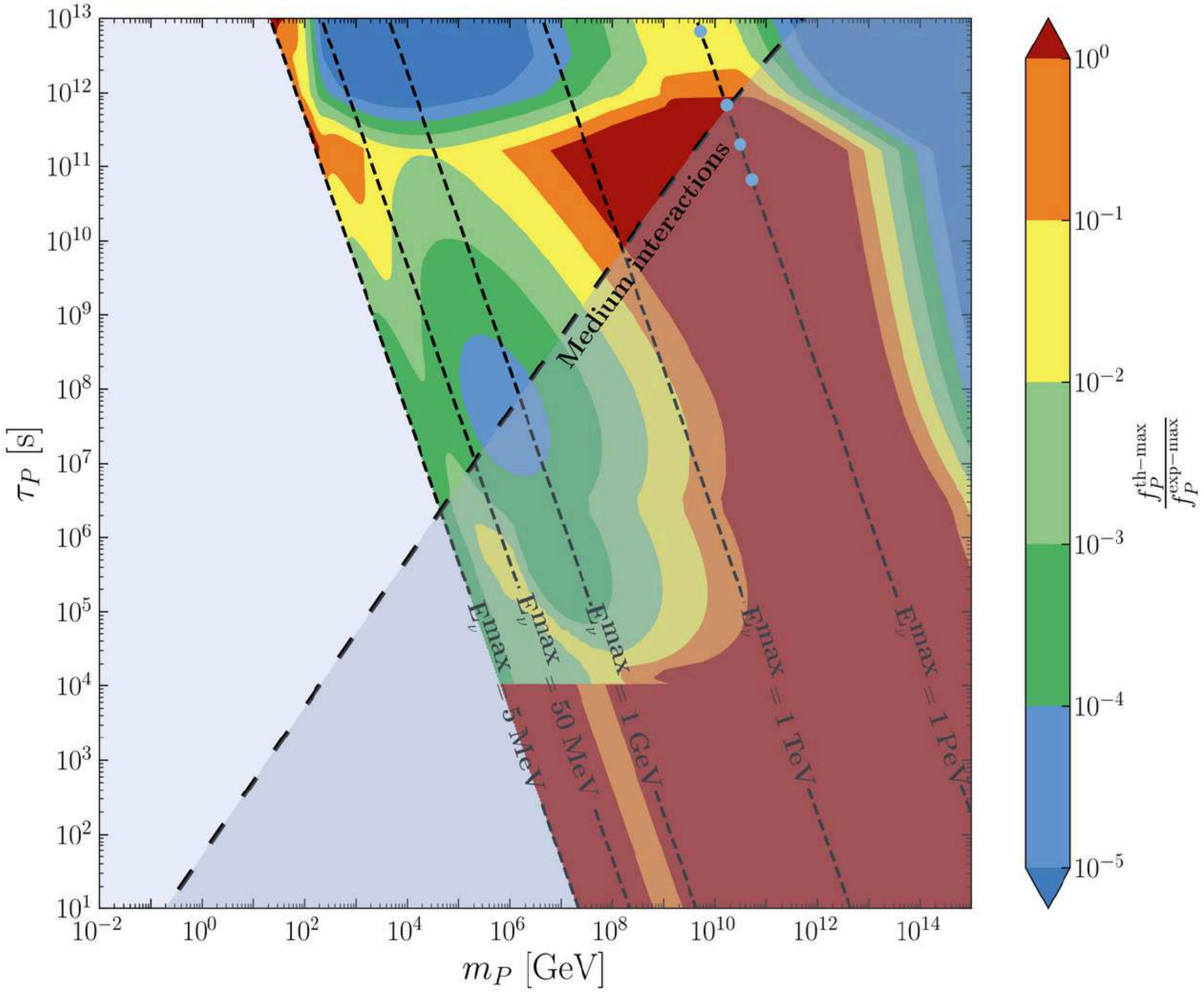

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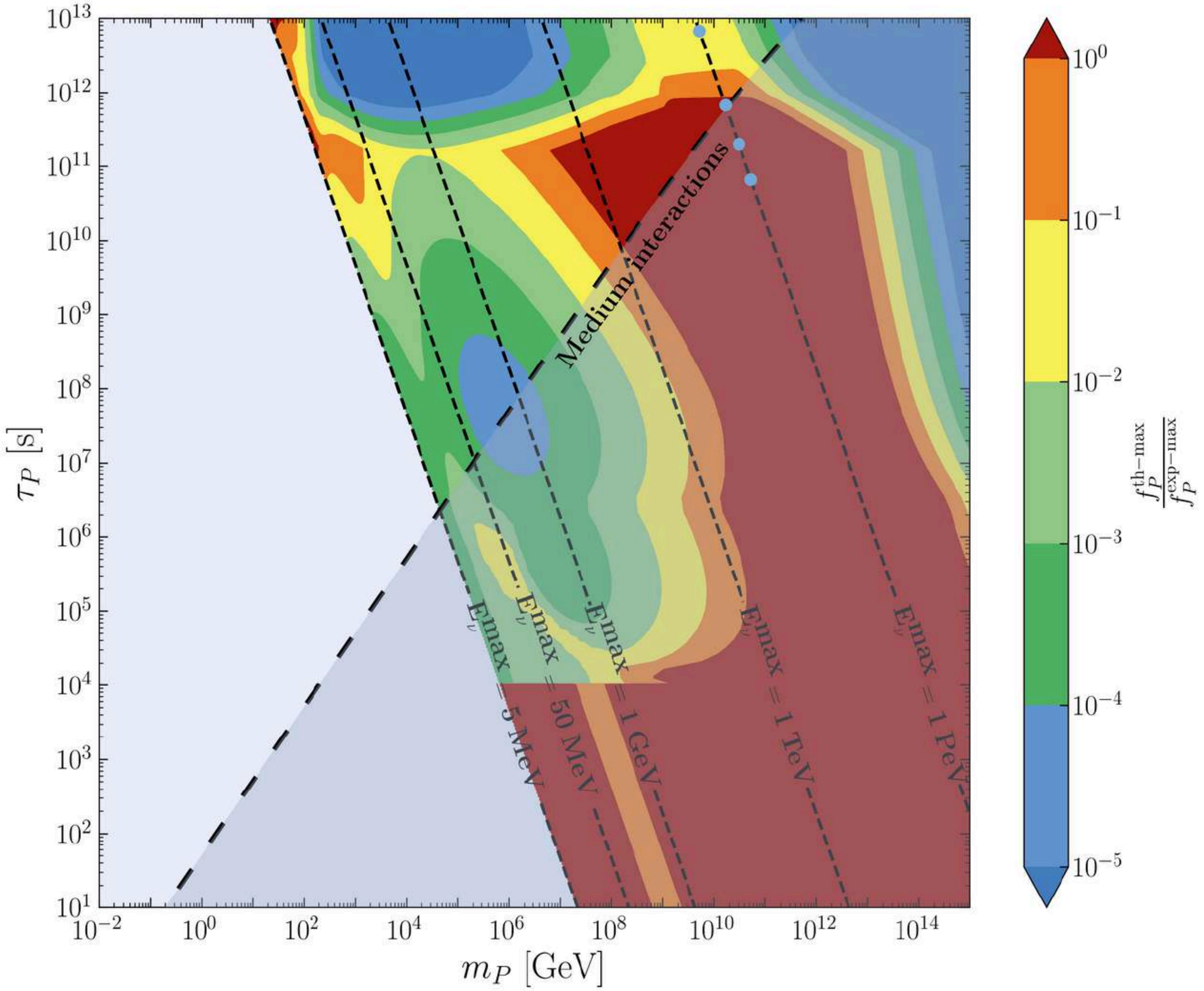
$$10 \text{ TeV} \lesssim m_P \lesssim 10^{11} \text{ GeV} \qquad 10^{-8} \lesssim f_P \lesssim 10^{-2}$$

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

Constraints.



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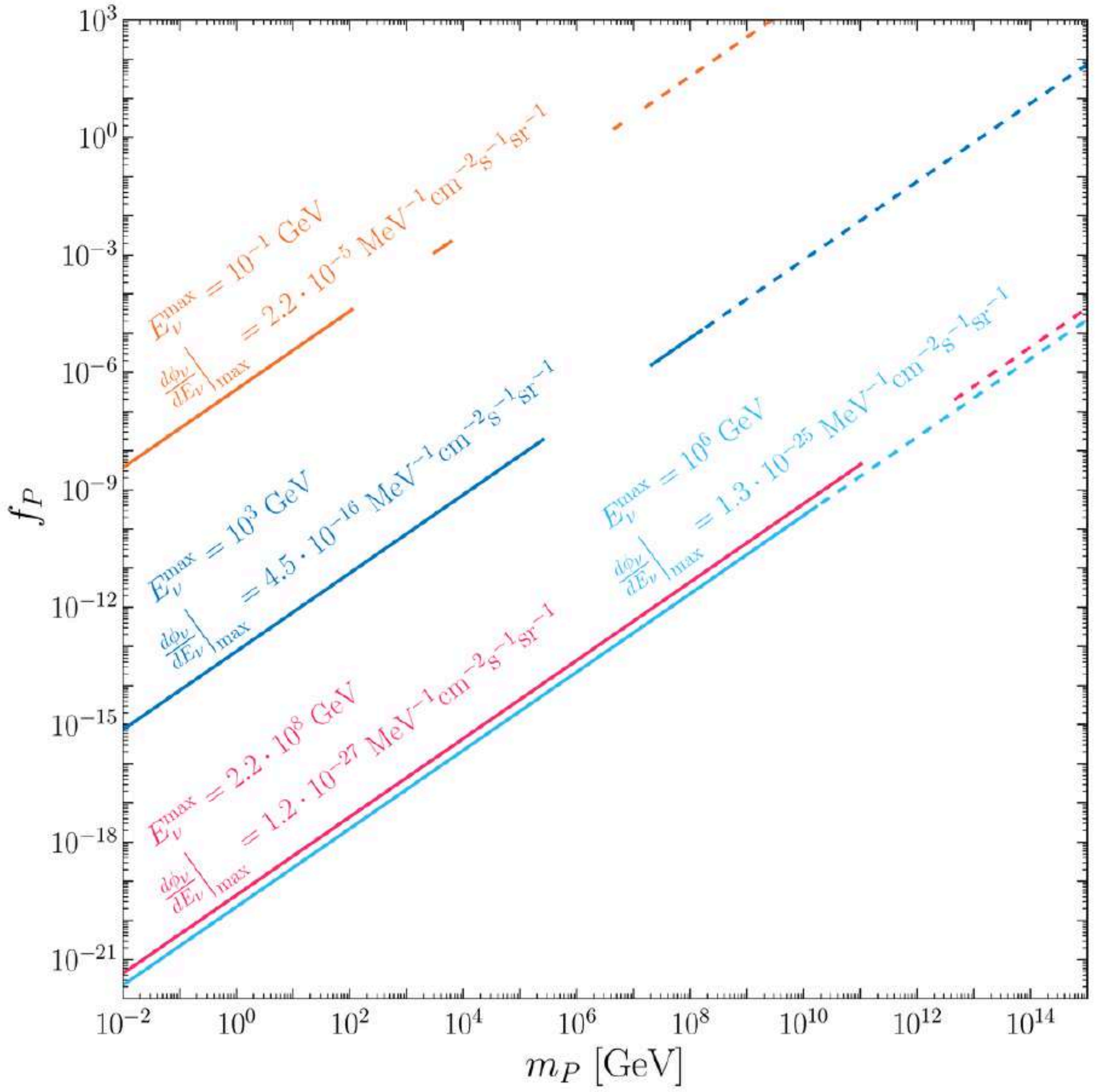
$$10^{9} \text{ s} \lesssim \tau_P \lesssim 10^{12.5} \text{ s}$$
$$10^{-8} \lesssim f_P \lesssim 10^{-2}$$

Potentially observable in IceCube, HyperK, KM3NeT

Constraints.

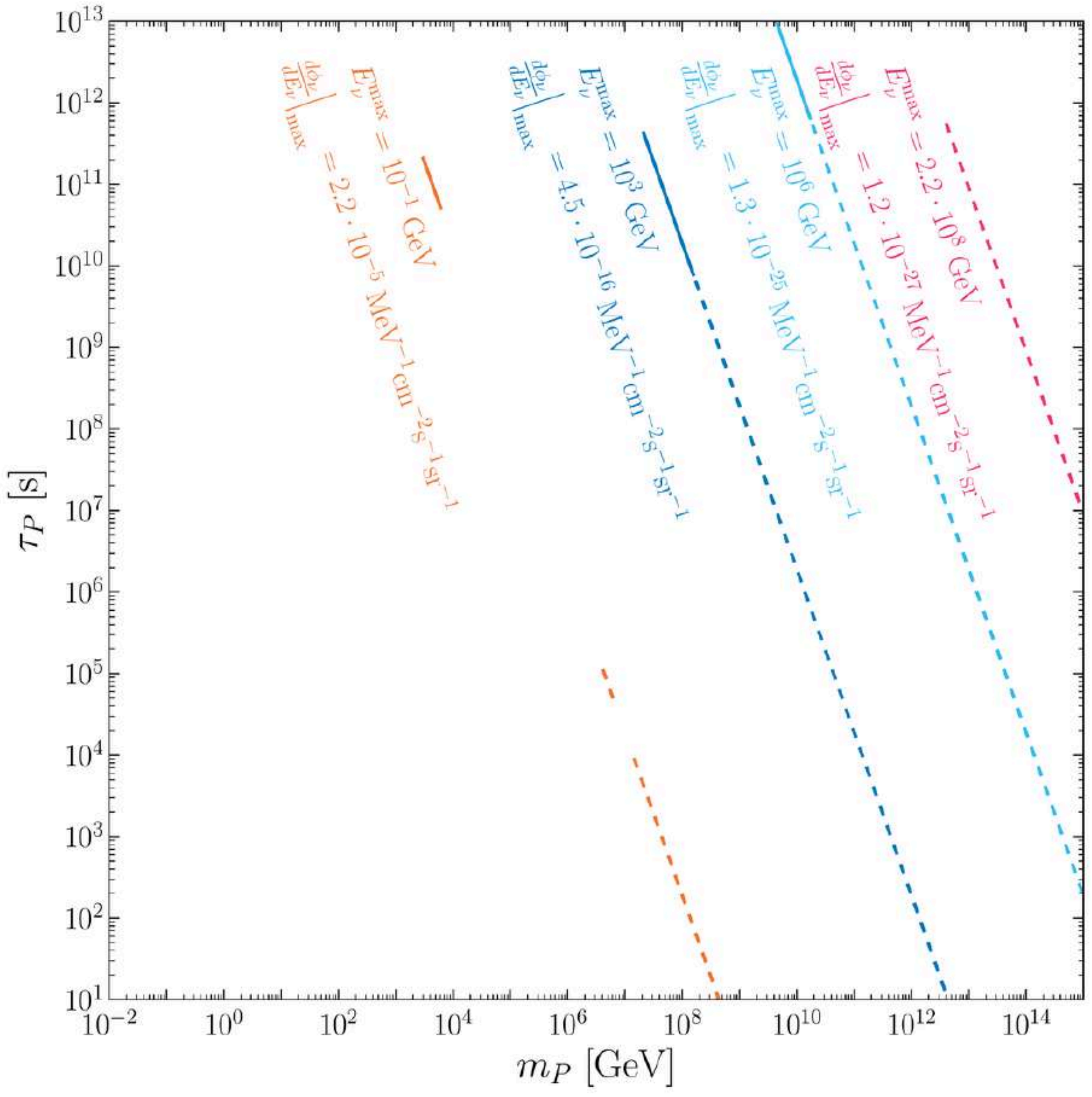


Reconstruction of the heavy relic parameters:

Given the energy at the peak and the amplitude of a spectrum, 2 parameters can be reconstructed:

- Abundance and mass

Constraints.



Reconstruction of the heavy relic parameters:

Given the energy at the peak and the amplitude of a spectrum, 2 parameters can be reconstructed:

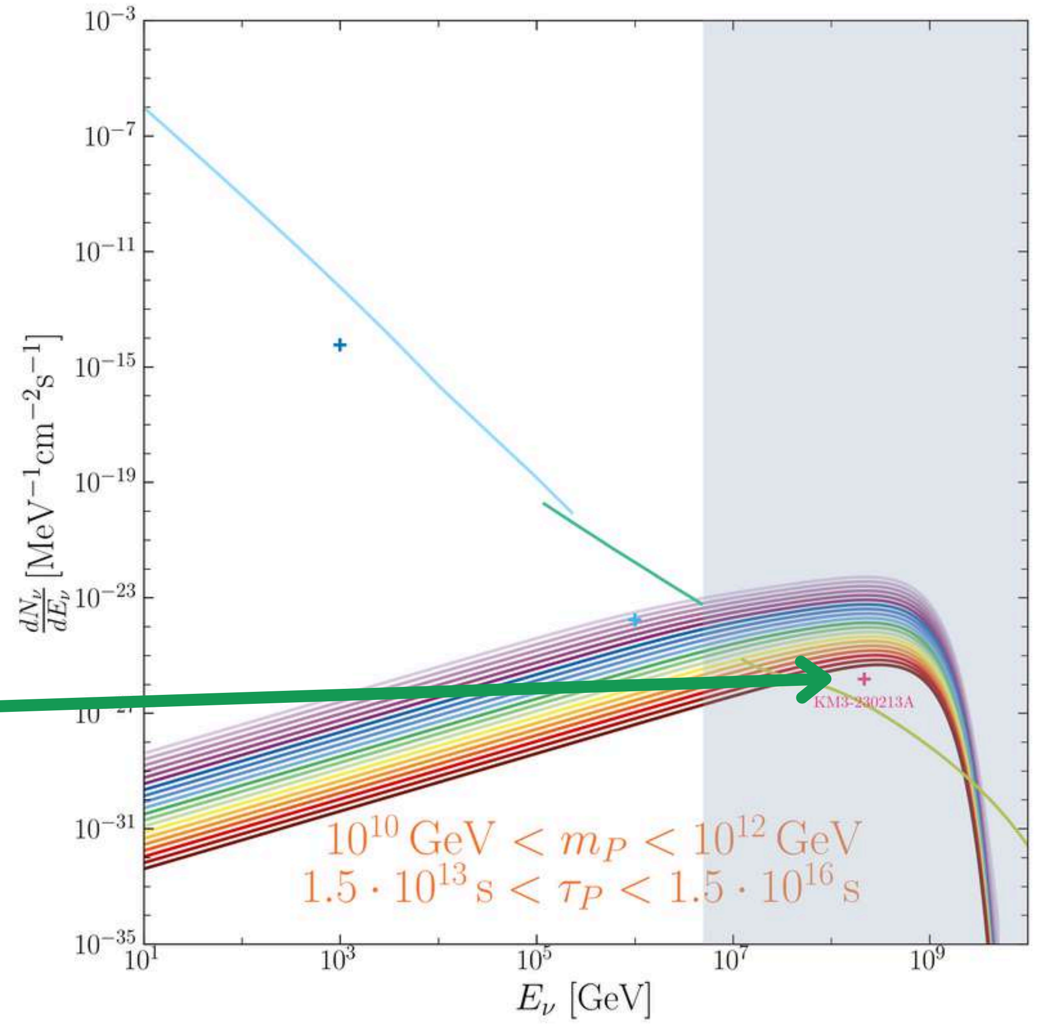
- Abundance and mass
- Lifetime and mass

Take home message:

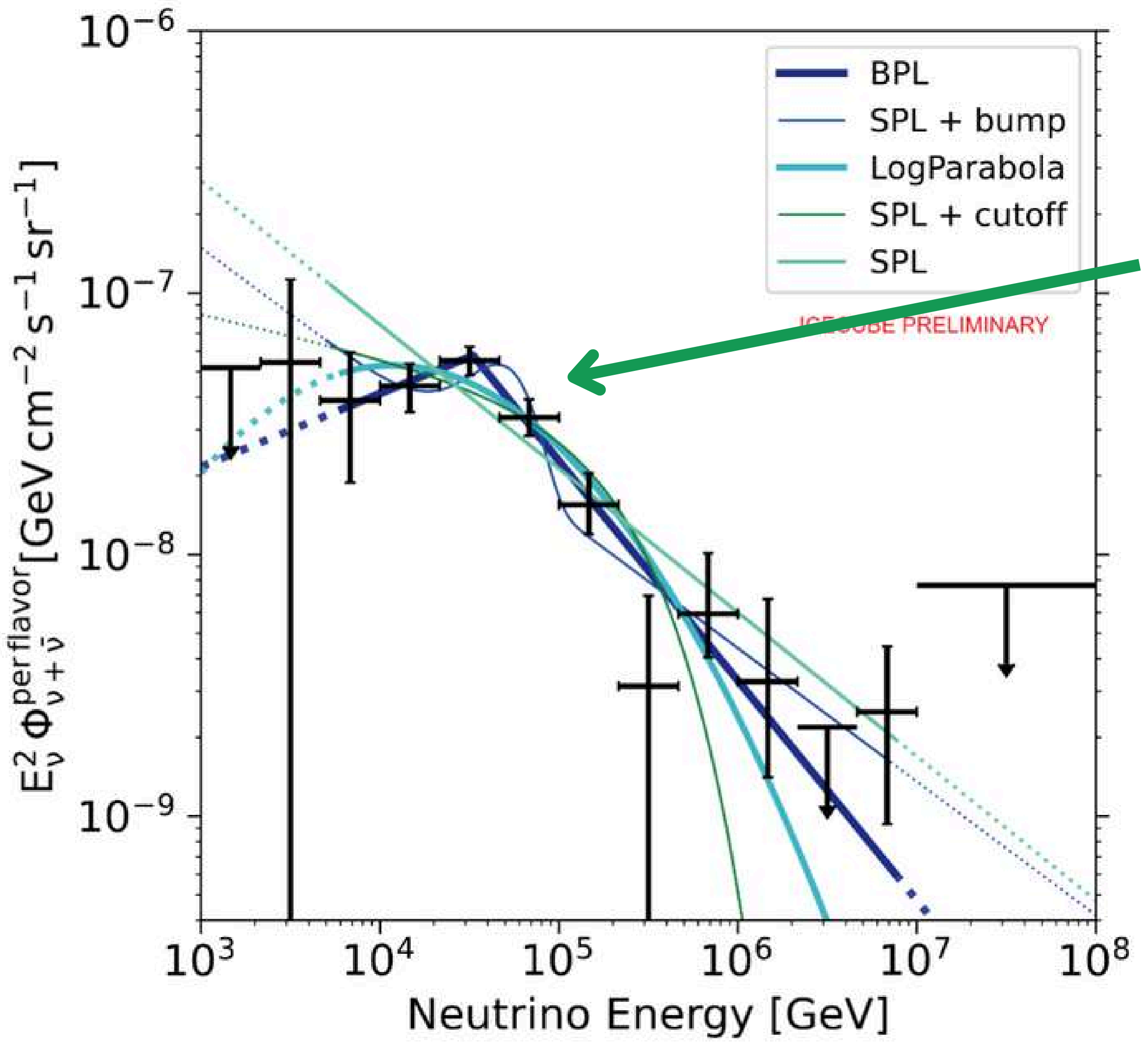
- PHENUs could be produced in the early universe with sharp spectral features
- Scattering on the background or with other PHENUs is negligible
- Sharp spectral features are observable for a range of lifetime, mass and abundance

Bumps ?

PHENUs could potentially explain the KM3NeT event



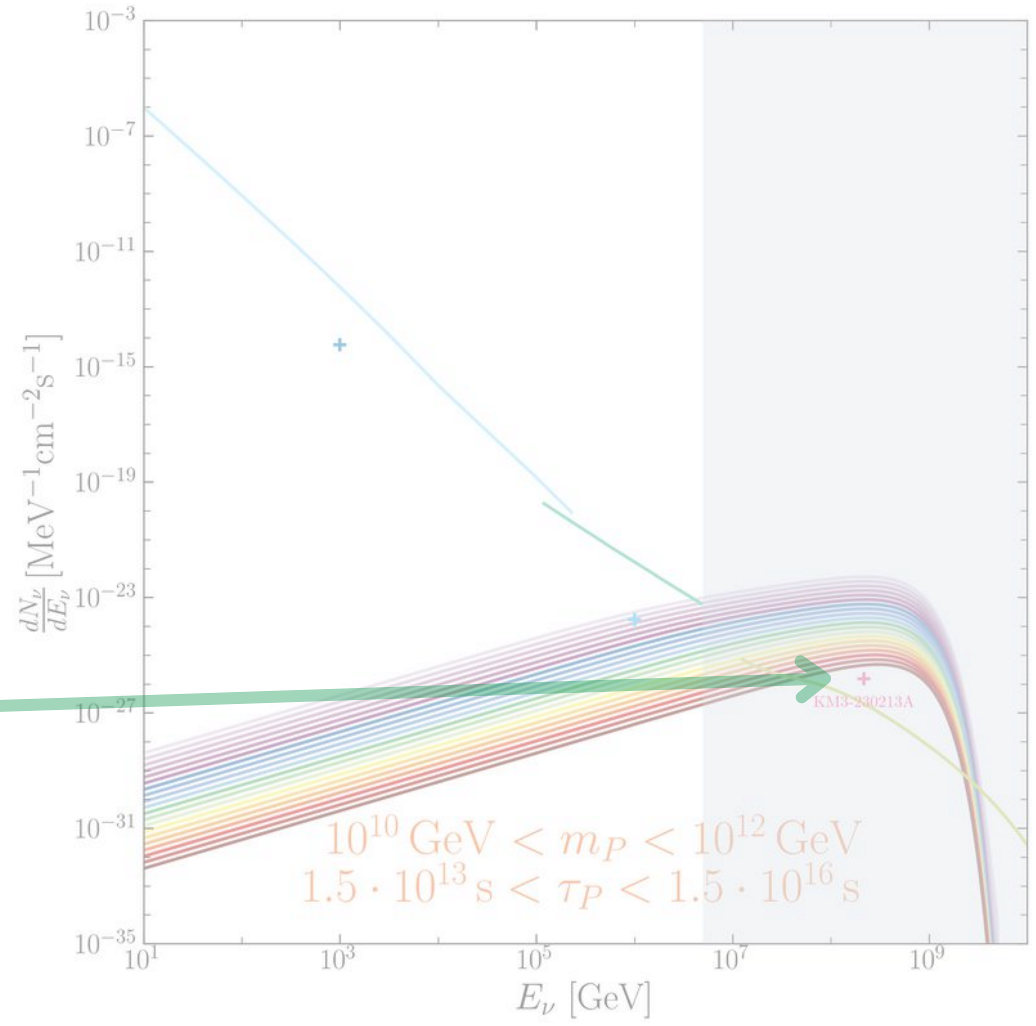
Bumps ?



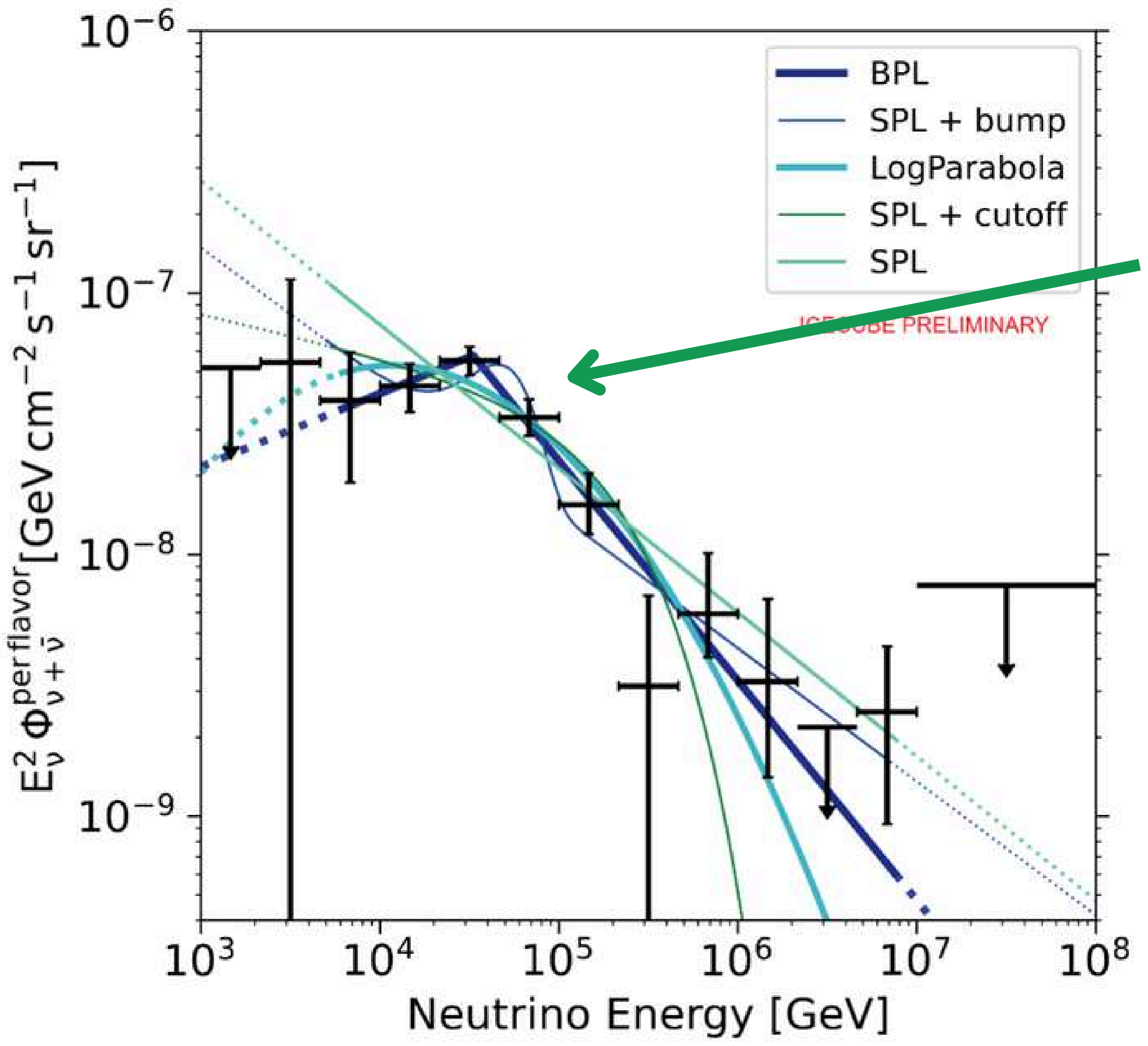
arXiv:2507.06002v1

Substructure emerging in the diffuse astrophysical flux ~30 TeV and ~100 TeV

PHENUs could potentially explain the KM3NeT event



Bumps ?



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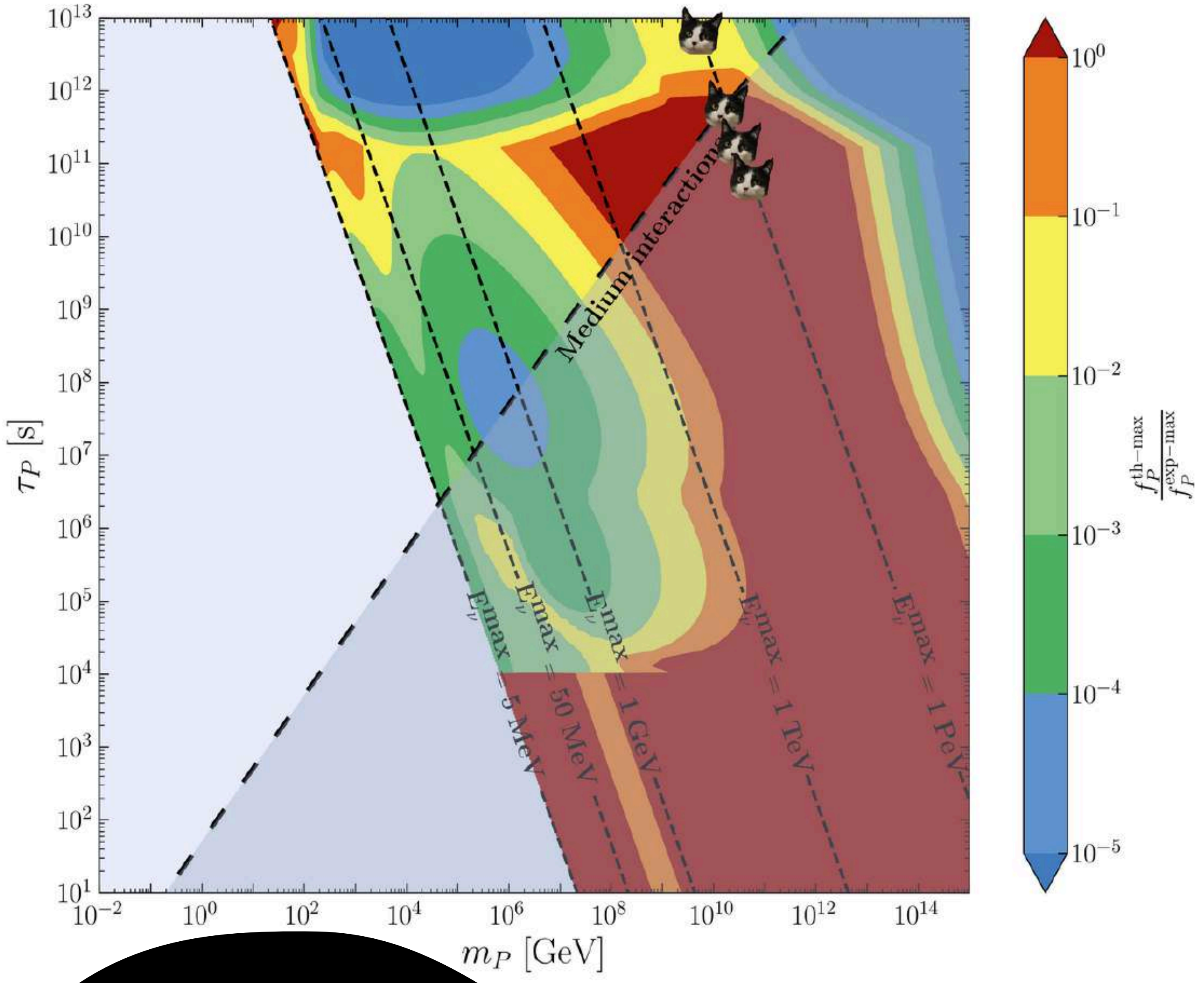
PHENUs could potentially explain the KM3NeT event

Medium interactions II.



Medium interactions II.

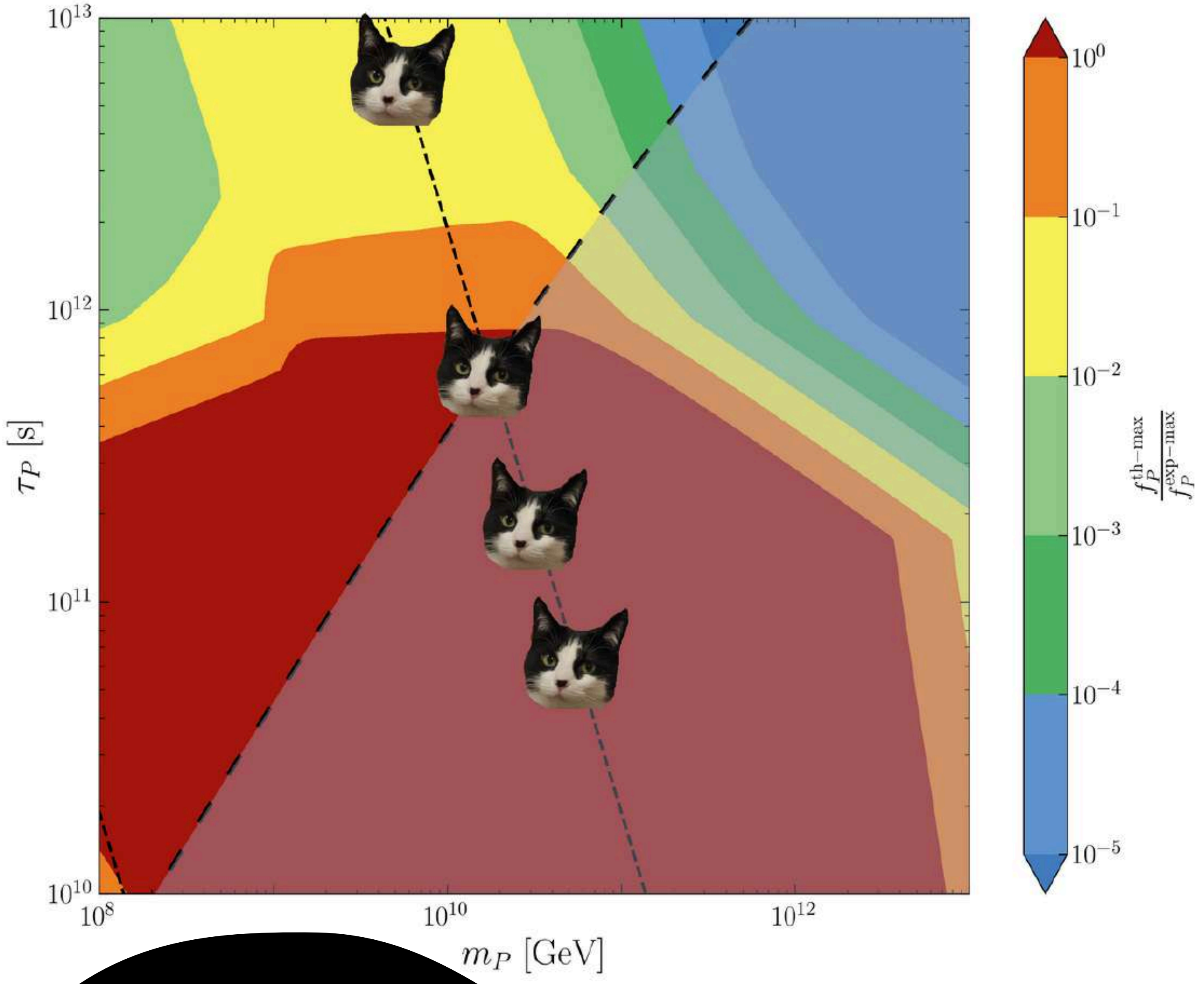
Elastic interactions

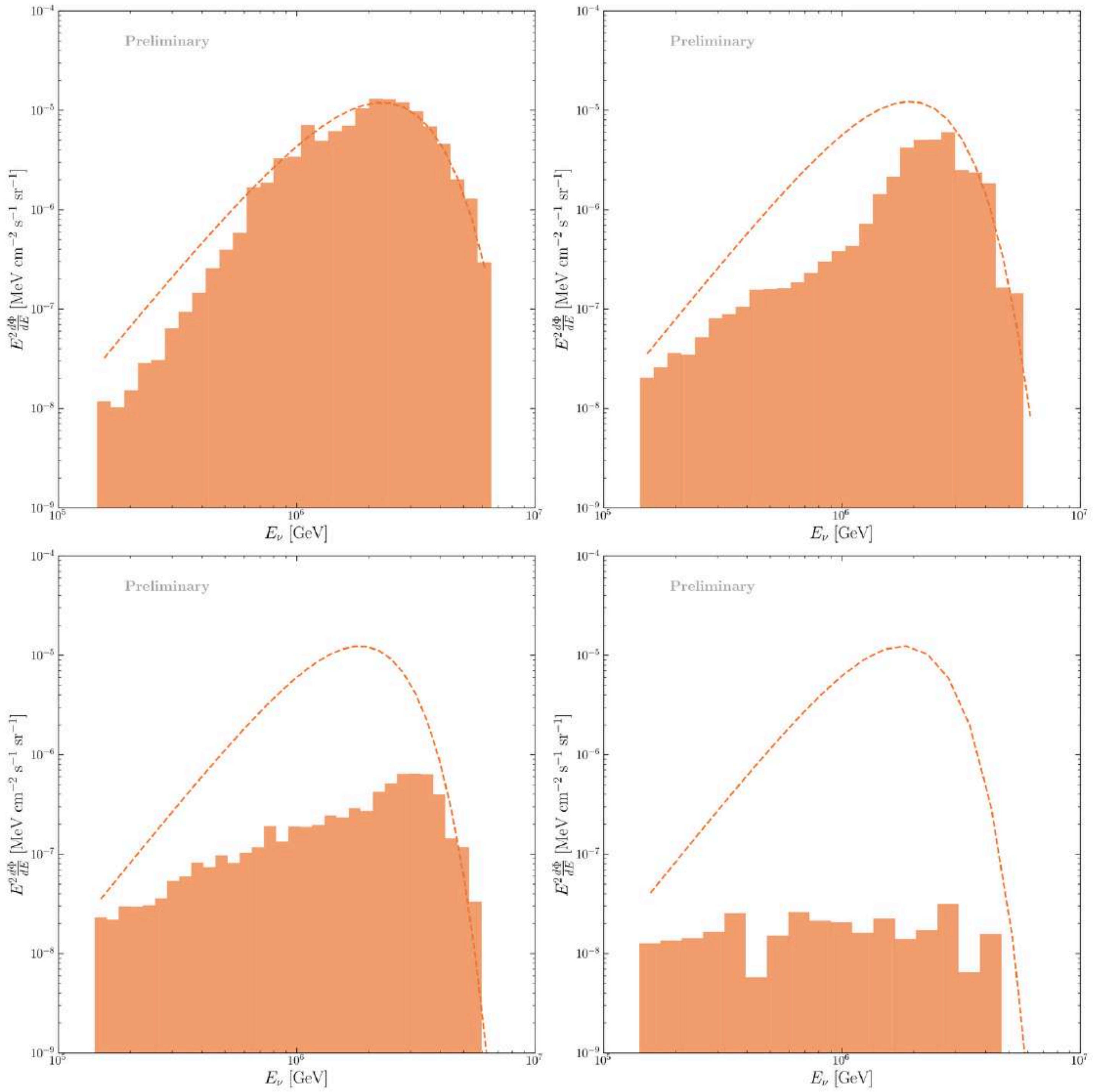
- Replace one PHENU by two high-energy neutrinos of smaller energies (upscatter CNB)
- Easy to implement
- More neutrinos to track → computationally expensive

Inelastic interactions

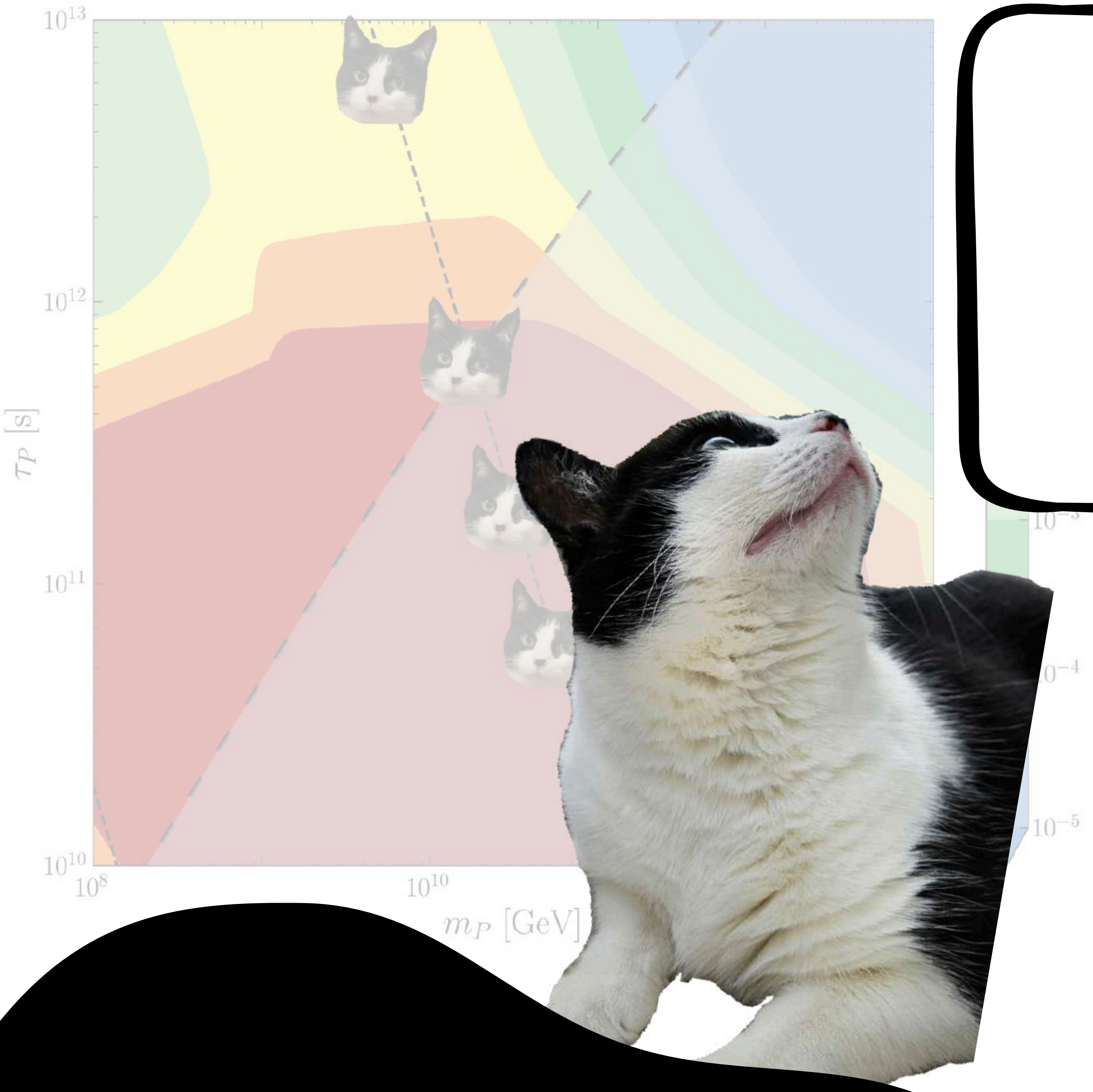
- For a proper treatment, need to implement EM and hadronic cascades → Hard to implement
- Most secondary neutrinos at lower energy → can be neglected
- → PHENU disappears into other SM particles
- Less neutrinos to track → simplifies computation

Medium interactions II.





Medium interactions II.



Stay tuned!

Thank you for your attention

arXiv:2507.02063

2512.XX???

Backup slides

Nicolas Grimbaum Yamamoto
LPTHE

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

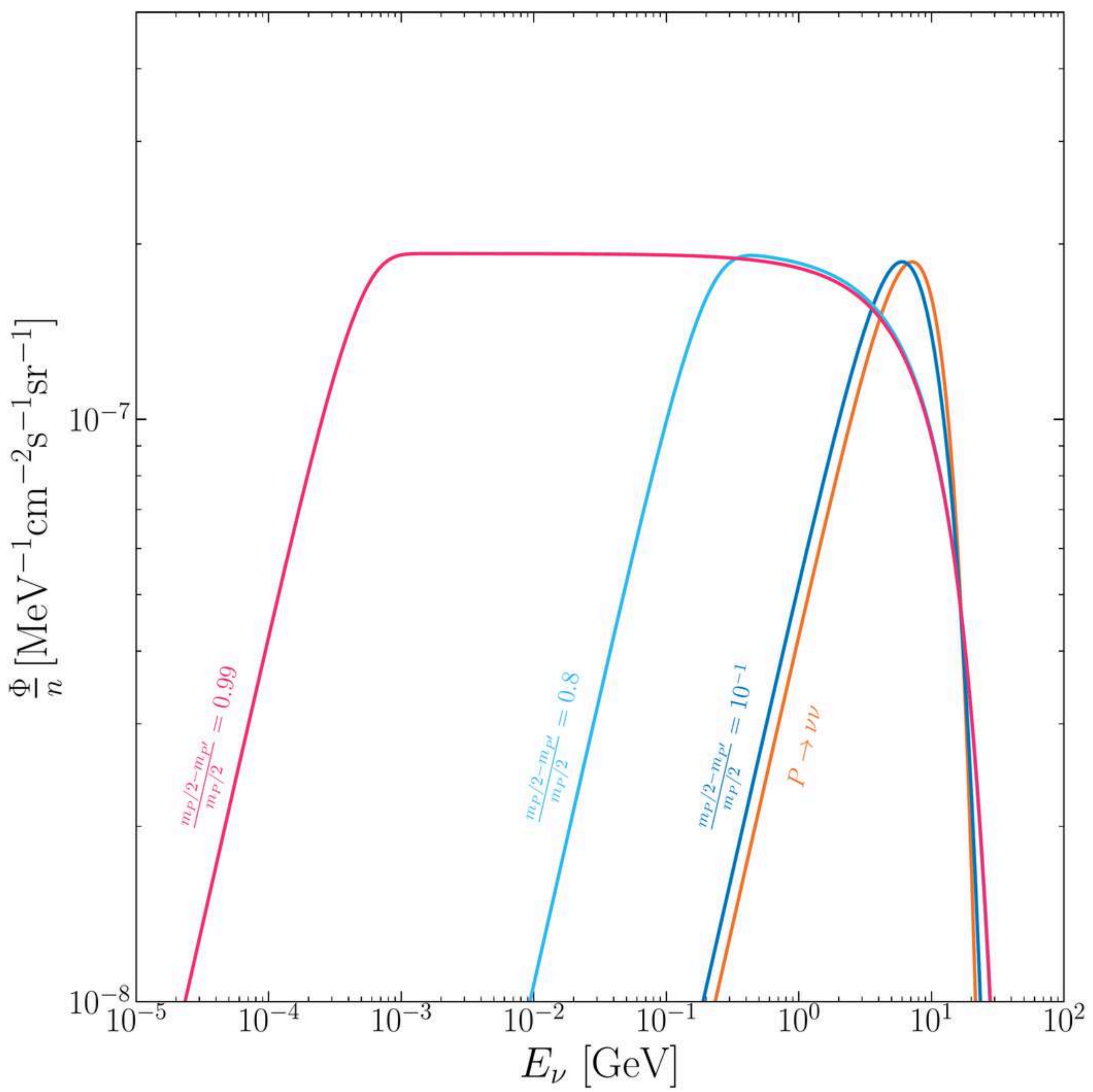
Box shaped $\frac{dN}{dE} = \frac{8}{m_P\sqrt{1-\frac{4m_{P'}^2}{m_P^2}}}\Theta(E - E_-)\Theta(E_+ - E)$

Nicolas Grimbaum Yamamoto
LPTHE

Decay Spectra.

Δ controls the width of the box.

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



Annihilation.

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

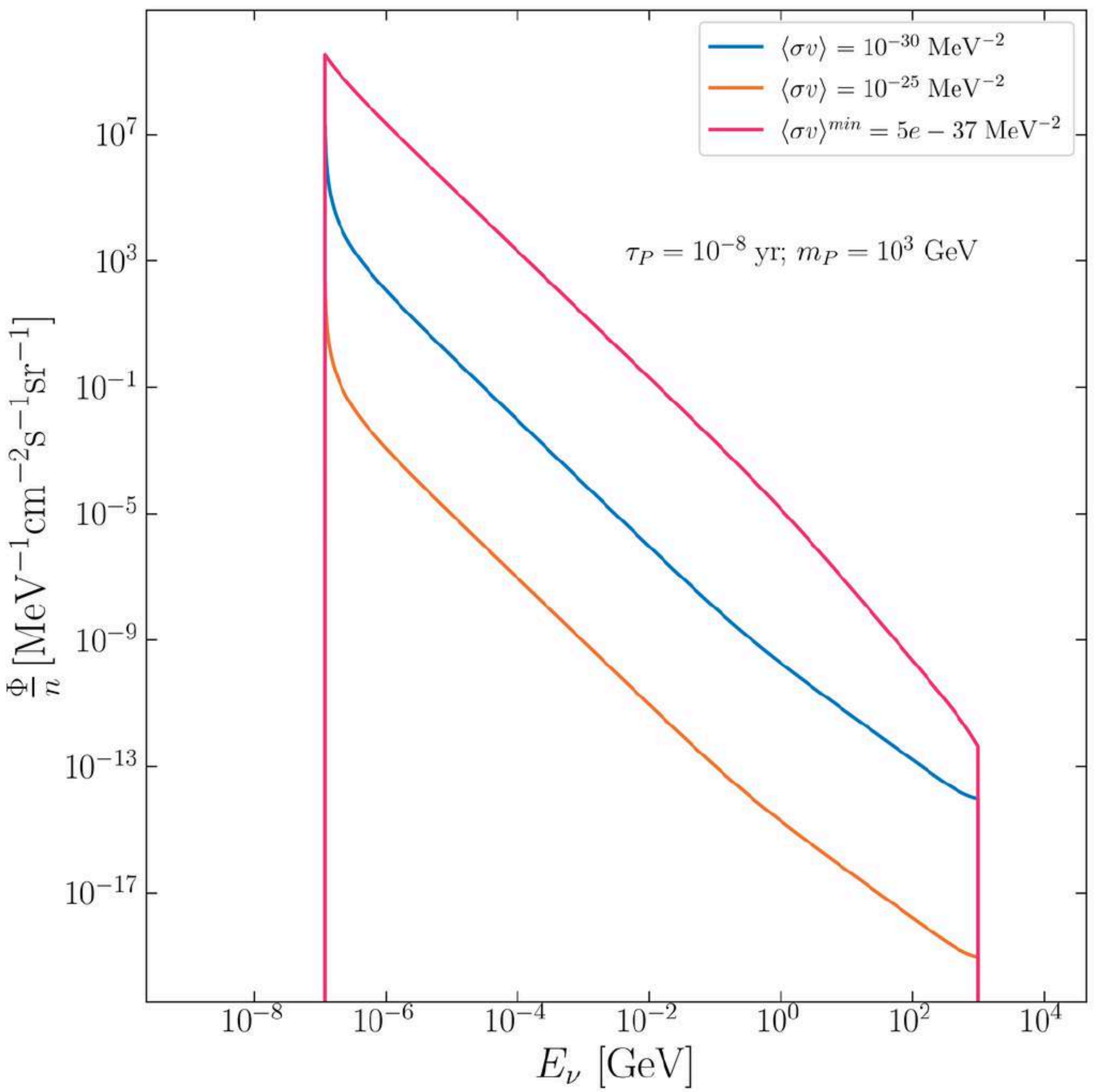
$$\langle\sigma v\rangle n_P^{eq} < H(t^{inj}) \rightarrow \langle\sigma v\rangle < \left(\frac{2\pi}{m_P T^{inj}}\right)^{3/2} \frac{e^{m_P/T^{inj}}}{2 g_i t^{inj}}$$

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

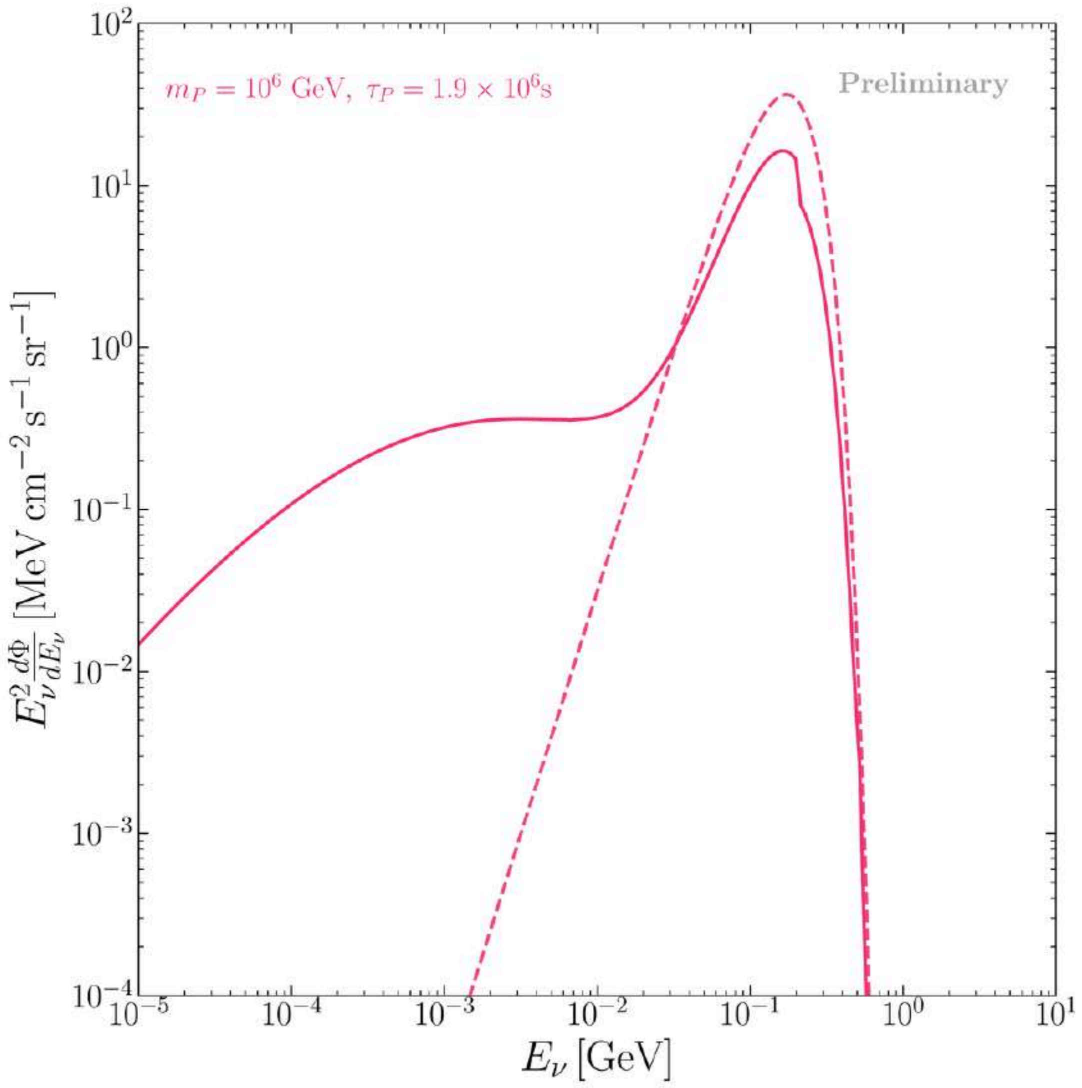
$$\langle\sigma v\rangle n_P^{inj} > H(t^{inj}) \rightarrow \langle\sigma v\rangle > \frac{m_P}{2\Omega_P^0 \rho_{crit}^0} \sqrt{\frac{t^{inj}}{t_r^3}}$$

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.

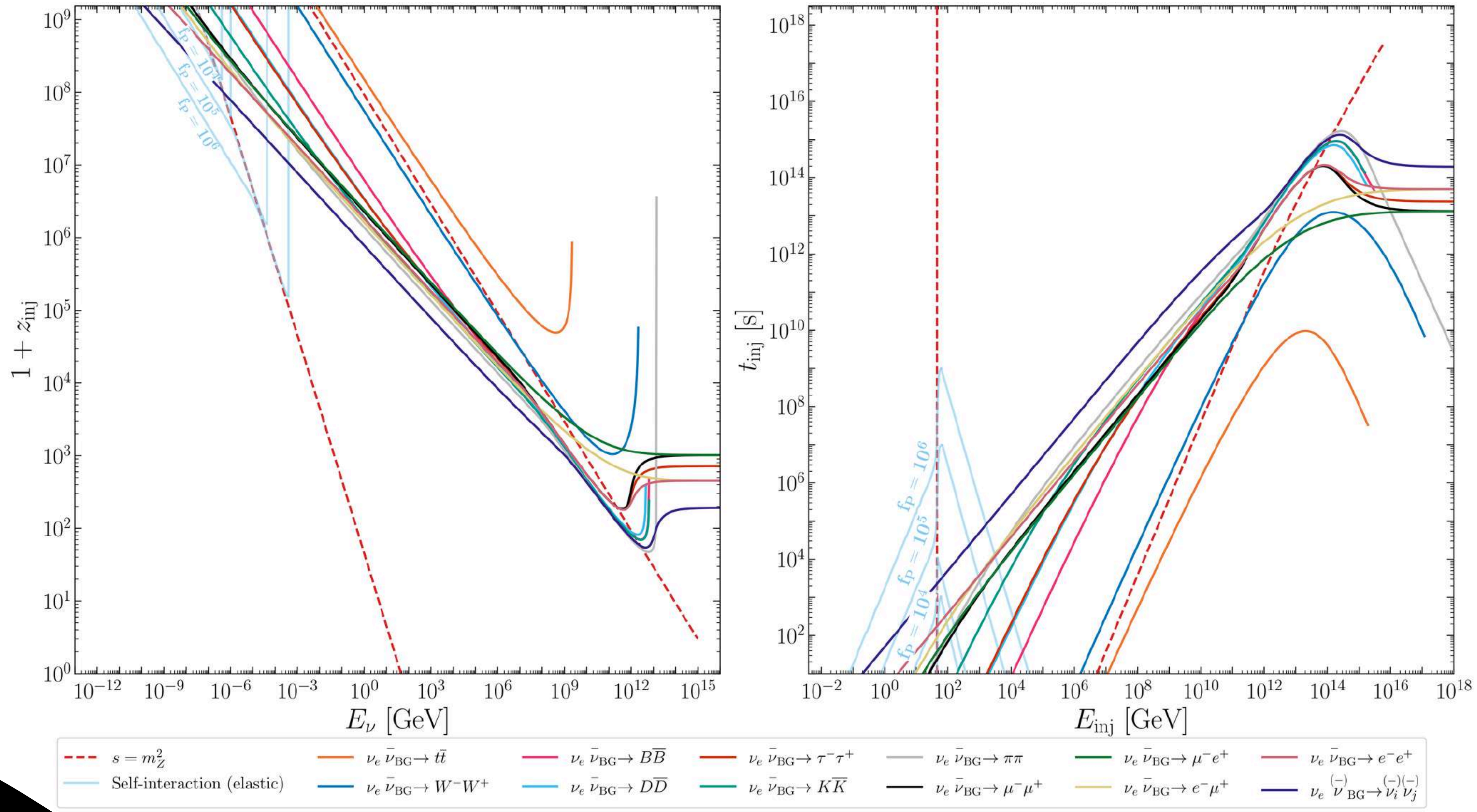


Final state radiation broadening

- 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 feature mostly unaffected

Medium interactions.



Cross-sections.

Elastic

$$\frac{d\sigma}{dt} = \frac{g^4}{64\pi \cos(\theta_W)^4} \frac{C(s,t,m_Z)}{(t-m_Z^2)^2}$$

Process	$C(s,t,m_Z)$
$\nu_l\bar{\nu}_l \to \nu_l\bar{\nu}_l$	$\frac{(s+t)^2(s+t-2m_Z^2)^2}{s^2(s-m_Z^2)^2}$
$\nu_l\bar{\nu}_l \to \nu_{l'}\bar{\nu}_{l'}$	$\frac{(s+t)^2(t-m_Z^2)^2}{s^2(s-m_Z^2)^2}$
$\nu_l\nu_l \to \nu_l\nu_l$	$\frac{(s+2m_Z^2)^2}{(s+t+m_Z^2)^2}$
$\nu_l\bar{\nu}_{l'} \to \nu_l\bar{\nu}_{l'}$	$\frac{(s+t)^2}{s^2}$
$\nu_l\nu_{l'} \to \nu_l\nu_{l'}$	1

Cross-sections.

Inelastic $\nu_l \bar{\nu}_l \to l^- l^+$

$$\frac{d\sigma}{dt} = \frac{g^4}{64\pi s^2 (s - m_Z^2)(t - m_W^2)} \left\{ K_1 + \frac{s - m_Z^2}{t - m_W^2} K_2 + \frac{(t - m_W^2)\tan(\theta_W)^4}{s - m_Z^2} K_3 \right\}$$

$$K_1 = (2\sin(\theta_W)^2 - 1)\left(s\frac{m_l^4}{2m_W^2} + (s + t - m_l^2)^2 \right) + 2\sin(\theta_W)^2 m_l^2 \left(s + \frac{(m_l^2 - t)^2}{2m_W^2} \right)$$

$$K_2 = (s + t)(s + t + 2m_l^2) + m_l^4 \left(1 + \frac{s}{m_W^2} + \frac{(m_l^2 - t)^2}{4m_W^4} \right) ,$$

$$K_3 = s^2 + 2(m_l^4 - 2m_l^2 t + t(s + t)) - \frac{m_l^2 s + (s + t - m_l^2)^2}{\sin(\theta_W)^2} + \left(\frac{s + t - m_l^2}{2\sin(\theta_W)^2} \right)^2 .$$

Cross-sections.

Inelastic $\nu_l \bar{\nu}_l \to l'^+ l'^-$

$$\frac{d\sigma}{dt} = \frac{g^4 \tan(\theta_W)^4}{64\pi s^2 (s - m_Z^2)^2} K_3$$

$$K_1 = (2\sin(\theta_W)^2 - 1)\left(s\frac{m_l^4}{2m_W^2} + (s + t - m_l^2)^2\right) + 2\sin(\theta_W)^2 m_l^2 \left(s + \frac{(m_l^2 - t)^2}{2m_W^2}\right)$$

$$K_2 = (s+t)(s+t+2m_l^2) + m_l^4\left(1 + \frac{s}{m_W^2} + \frac{(m_l^2 - t)^2}{4m_W^4}\right),$$

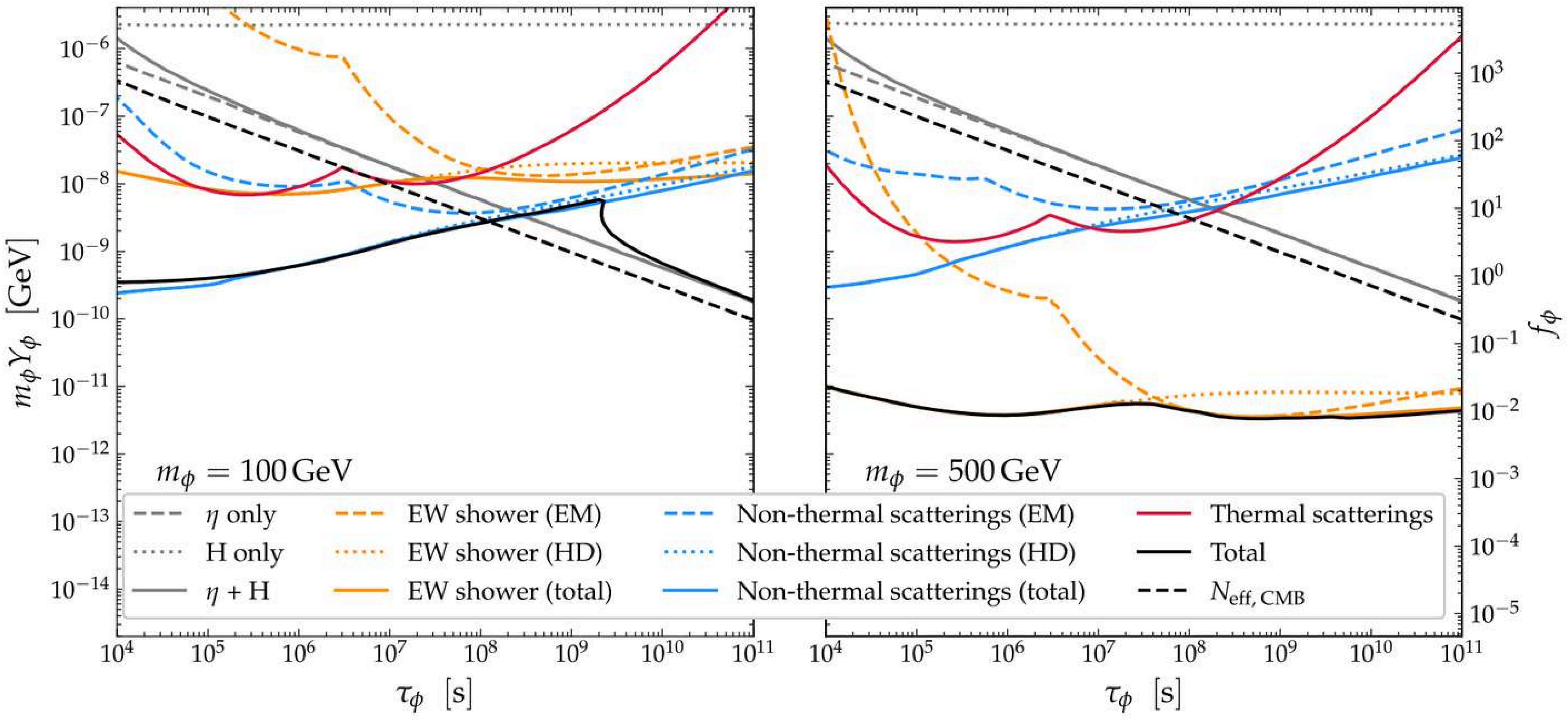
$$K_3 = s^2 + 2(m_l^4 - 2m_l^2 t + t(s+t)) - \frac{m_l^2 s + (s + t - m_l^2)^2}{\sin(\theta_W)^2} + \left(\frac{s + t - m_l^2}{2\sin(\theta_W)^2}\right)^2.$$

Self-scattering.

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

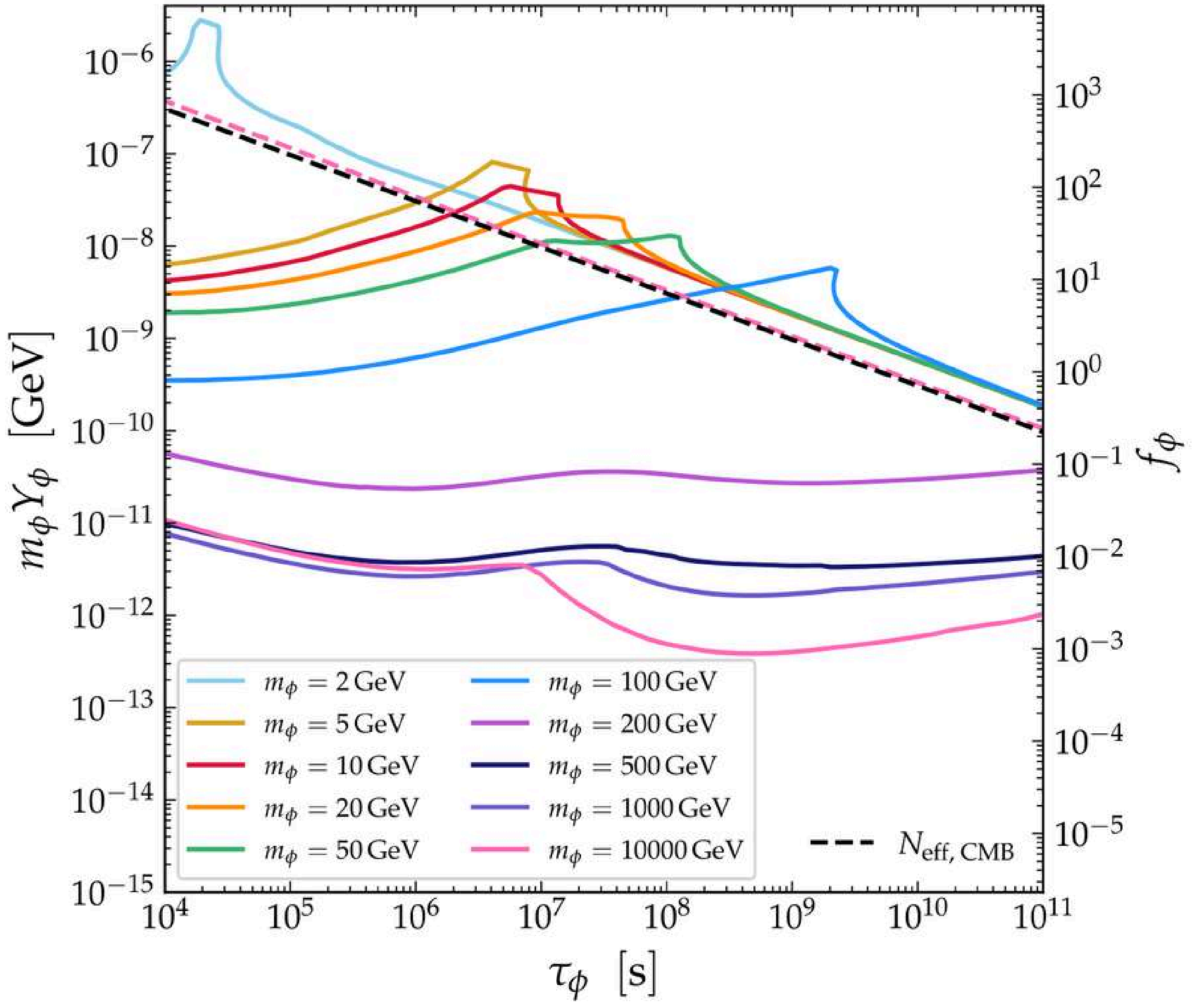
$$\langle\Gamma(E_0, z)\rangle = \frac{\Omega_P^0 \rho_{crit}^0 (1+z)^3}{4E_0^2(1+z)^2 m_P \tau_P} \int_0^{2E_0(1+z)m_P} ds\sigma(s)s \int_{\frac{s}{4E_0(1+z)}}^{m_P/2} \frac{dE}{E^3} \frac{e^{-t(a_E)/\tau_P}}{H(a_E)}$$

BBN constraints.



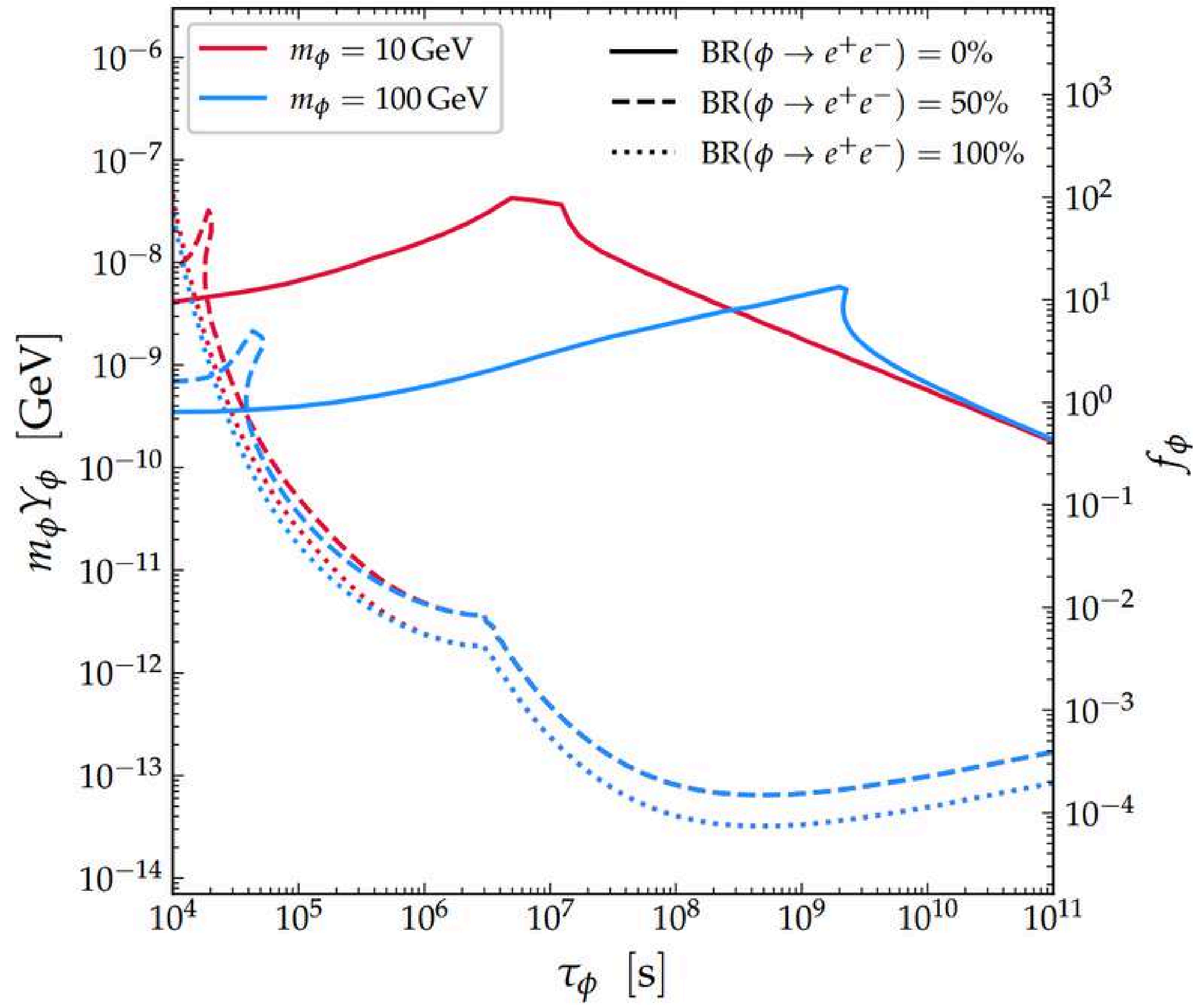
Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'

BBN constraints.

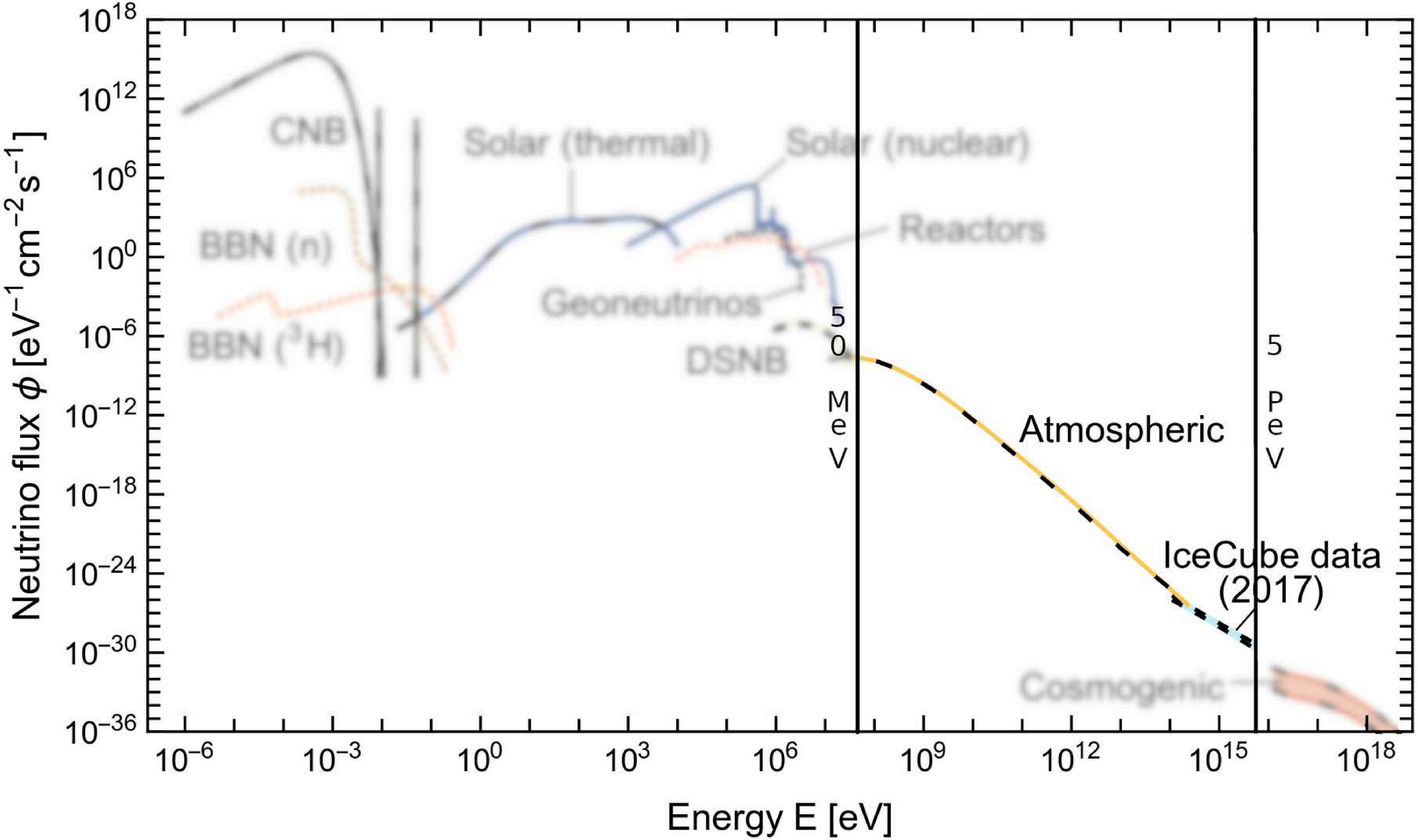


Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'

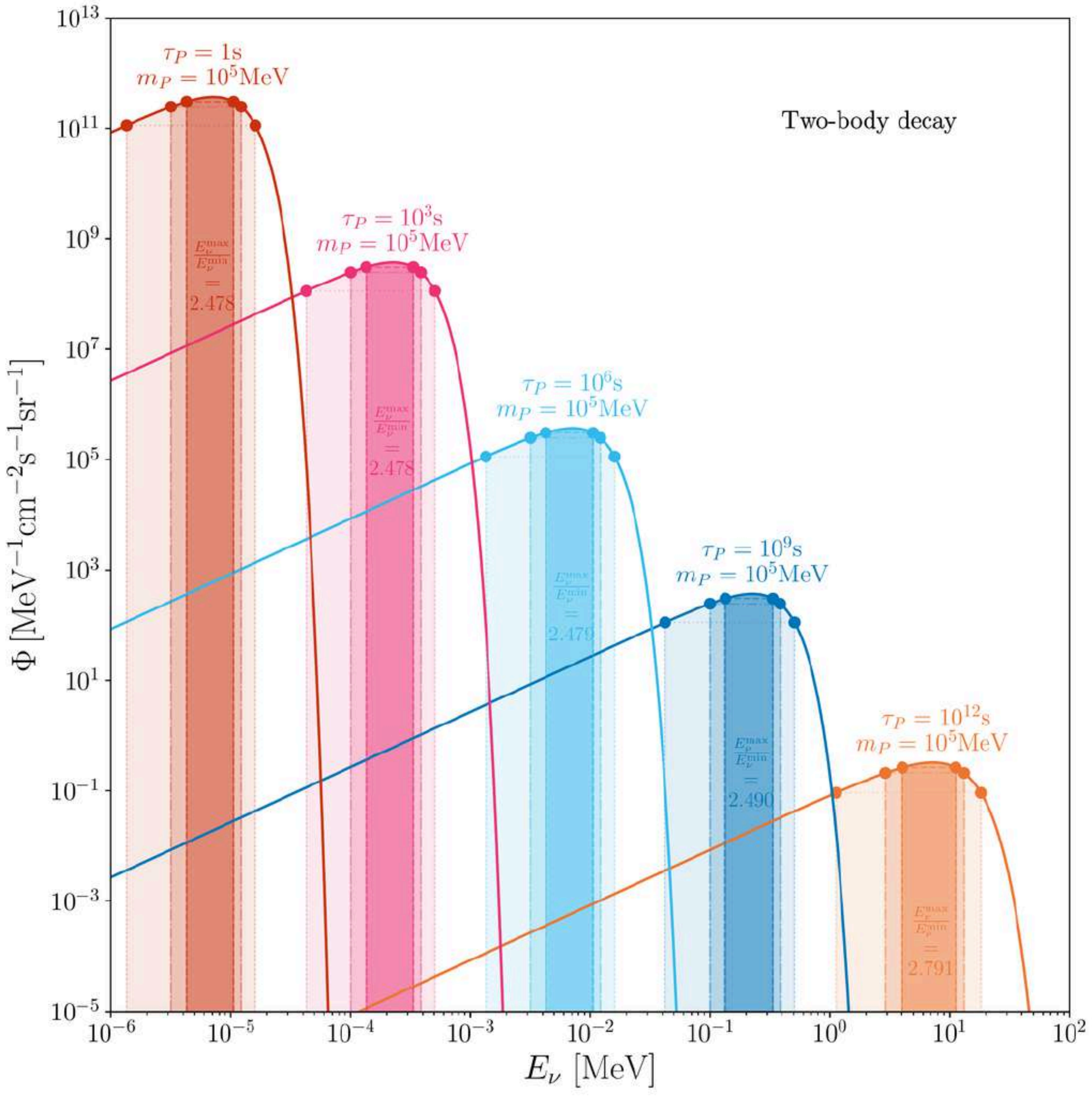
BBN constraints.



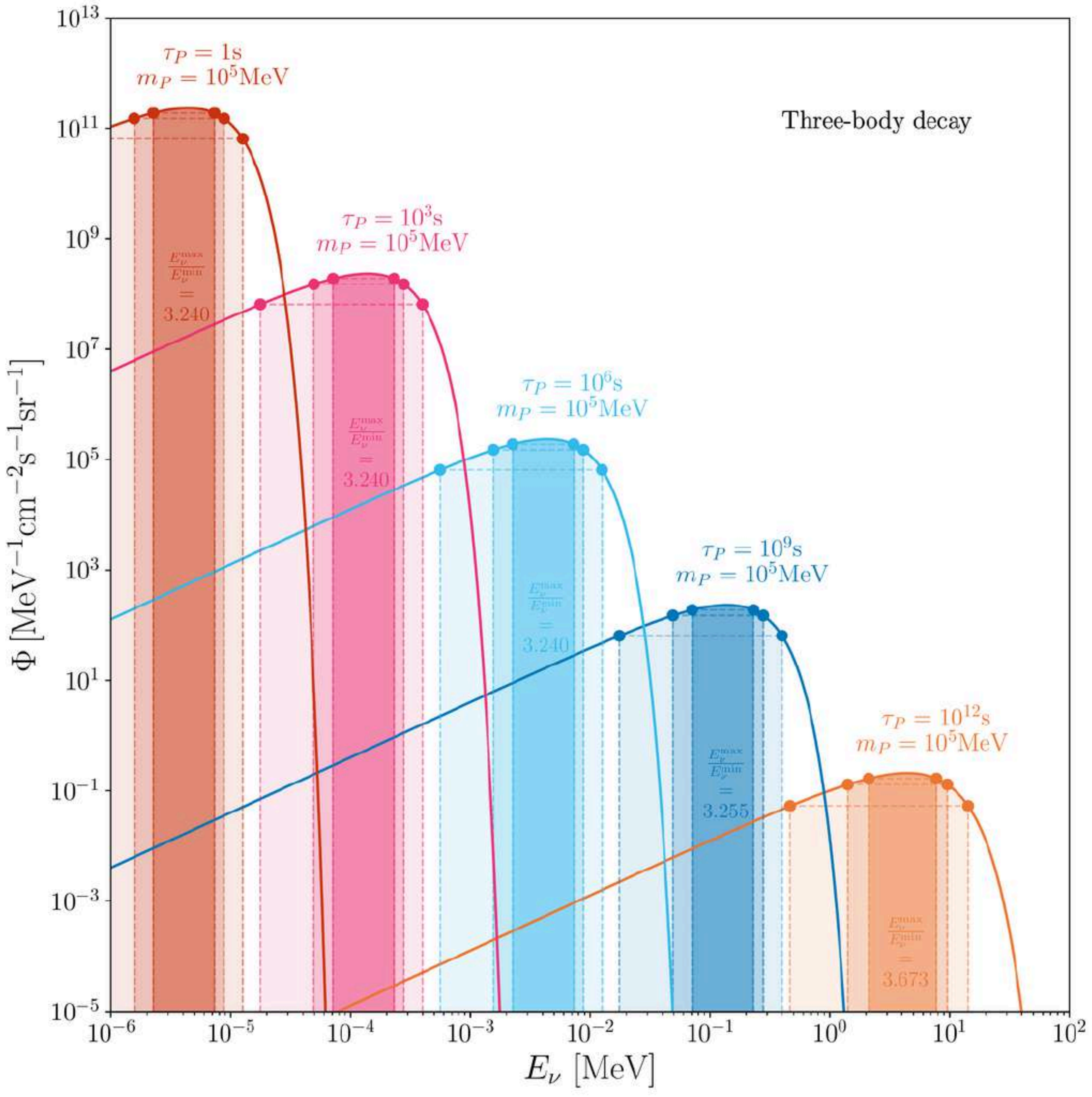
Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'



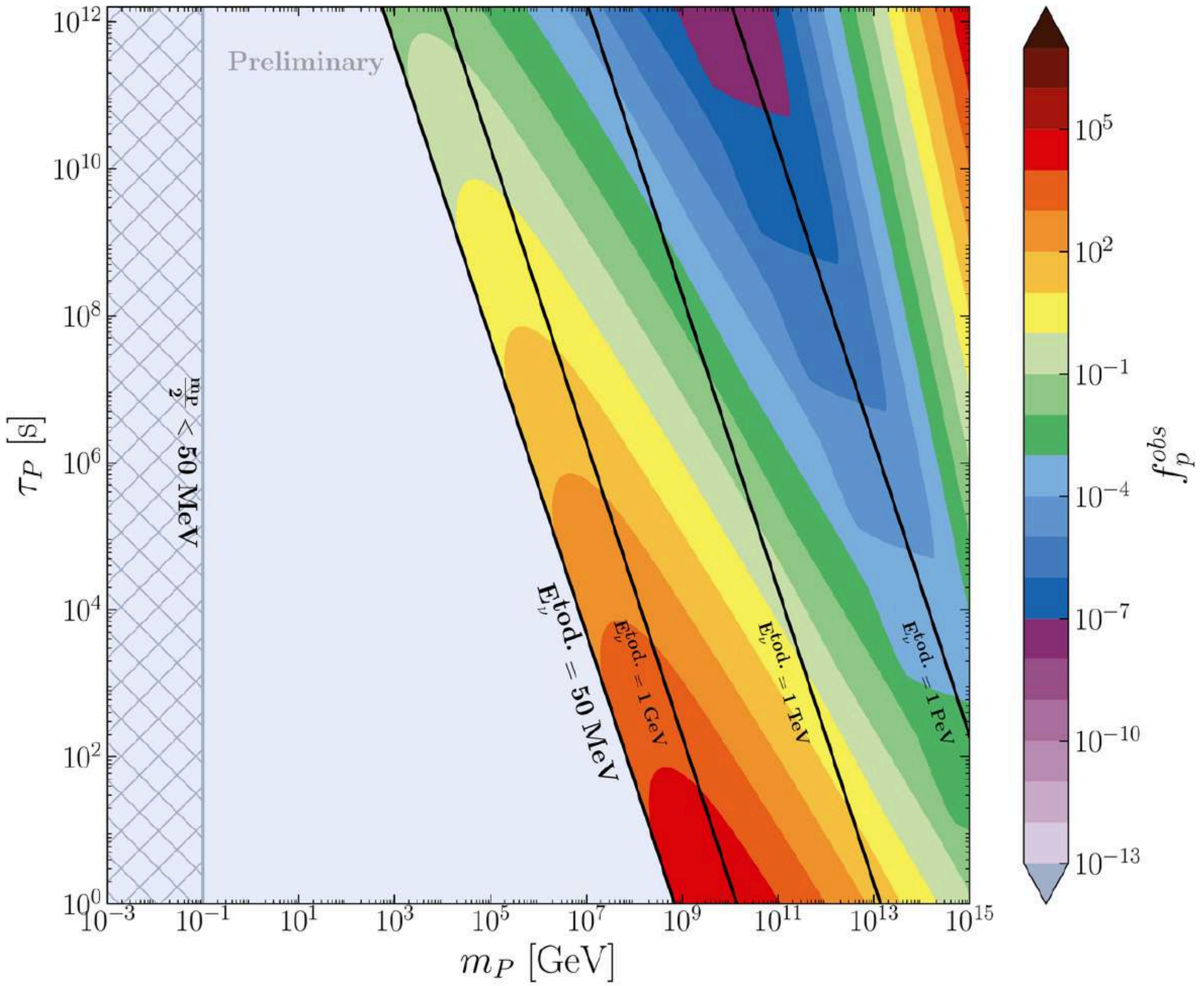
Vitagliano, Tamborra, Raffelt '19

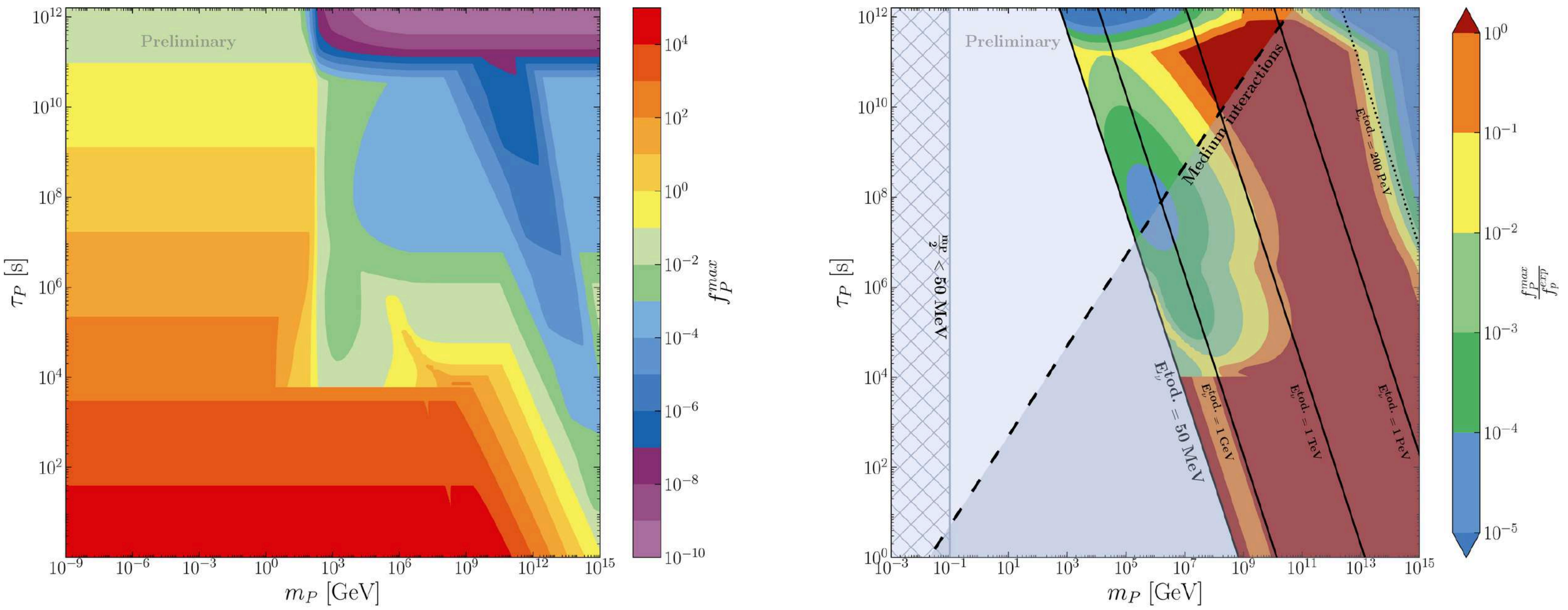


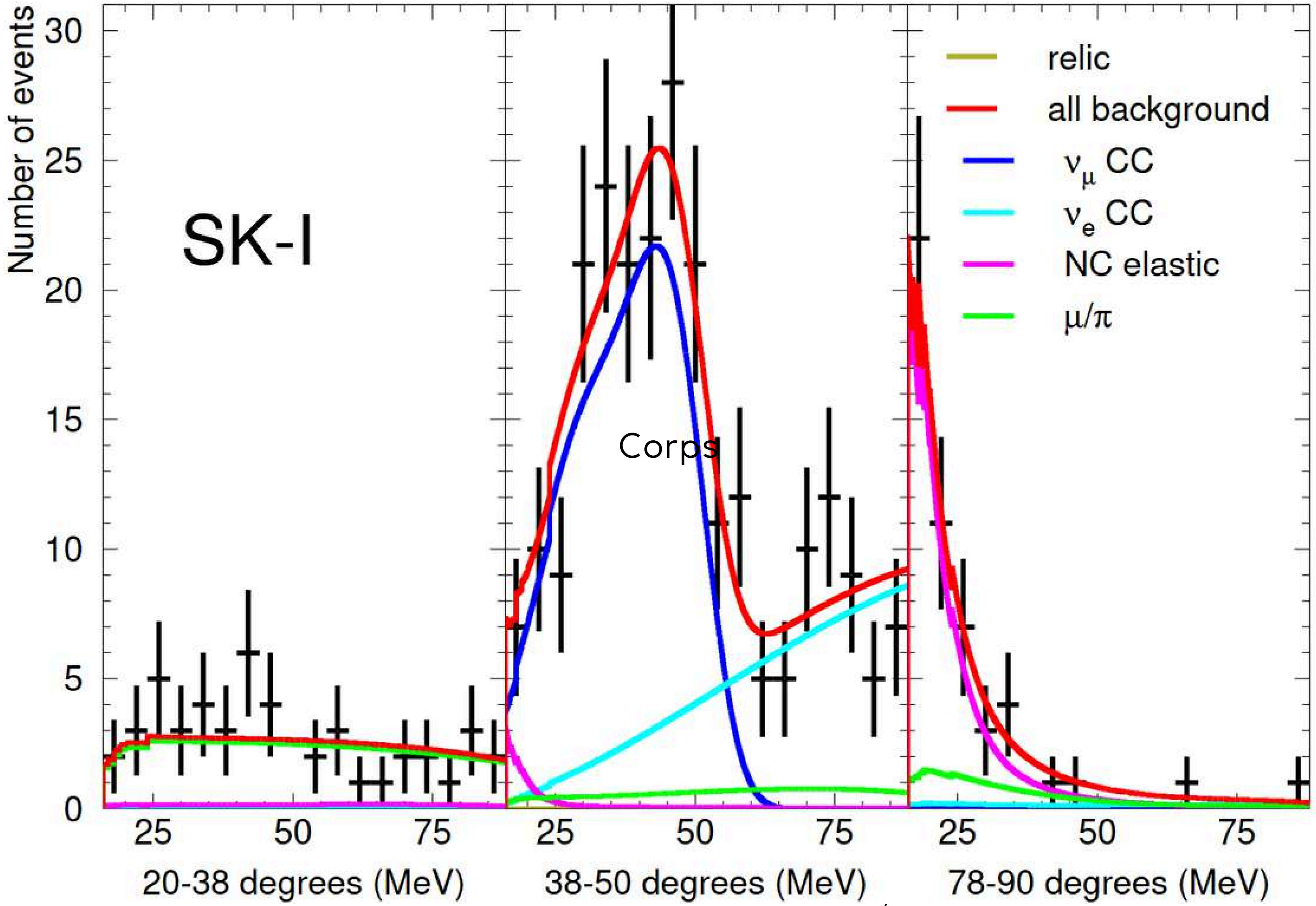
Two-body decay
$\tau_P = 1$s
$m_P = 10^5$MeV
$\tau_P = 10^3$s
$m_P = 10^5$MeV
$\tau_P = 10^6$s
$m_P = 10^5$MeV
$\tau_P = 10^9$s
$m_P = 10^5$MeV
$\tau_P = 10^{12}$s
$m_P = 10^5$MeV
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.478$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.478$
$\frac{E_\nu^{\max}}{E_\nu^{\min}}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



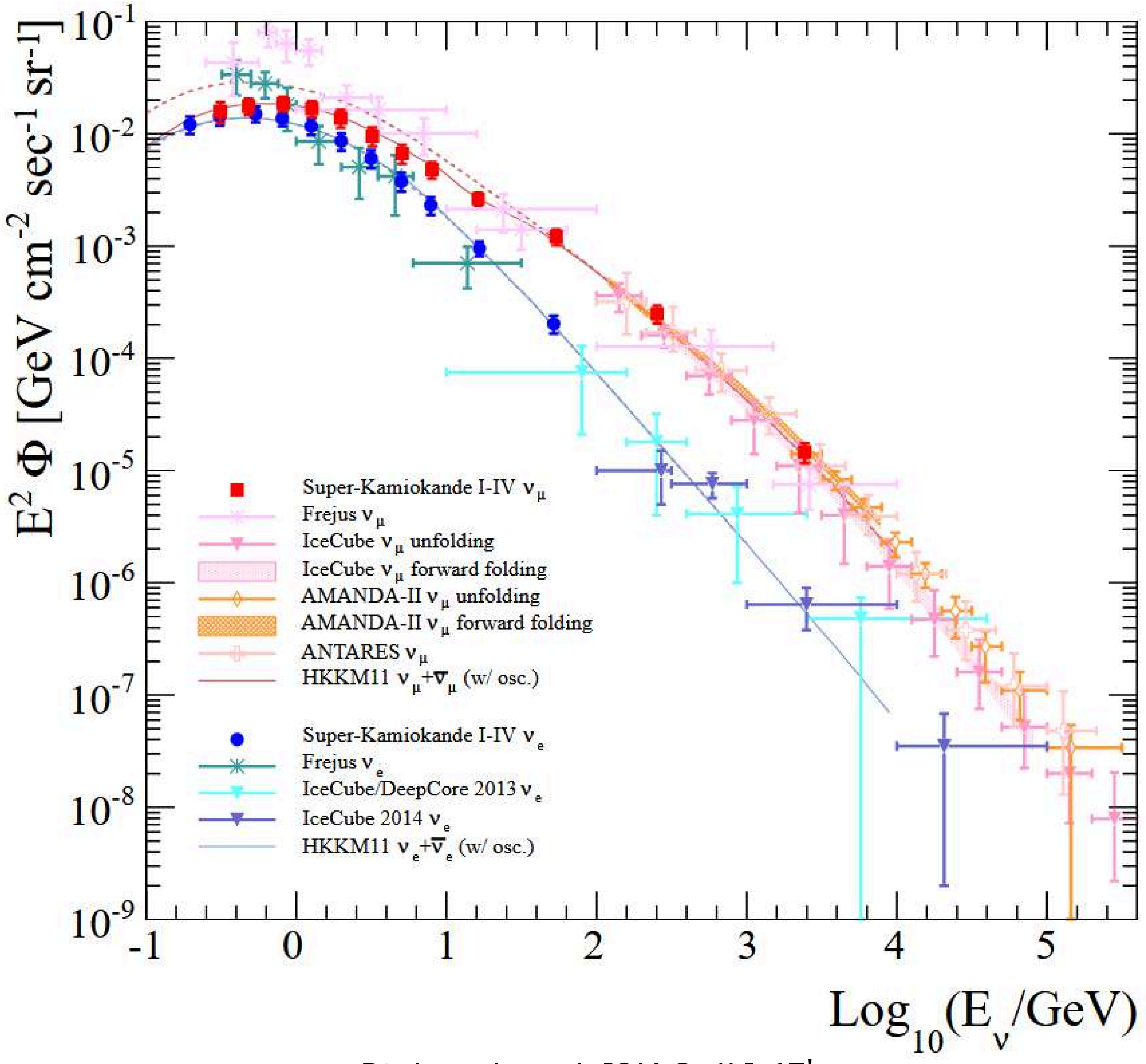
Three-body decay
$\tau_P = 1$s
$m_P = 10^5$MeV
$\tau_P = 10^3$s
$m_P = 10^5$MeV
$\tau_P = 10^6$s
$m_P = 10^5$MeV
$\tau_P = 10^9$s
$m_P = 10^5$MeV
$\tau_P = 10^{12}$s
$m_P = 10^5$MeV
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 3.240$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 3.240$
$\frac{E_\nu^{\max}}{E_\nu^{\min}}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



K. Bays et al. [SK coll.], ‘12



Richard et al. [SK Coll.] 15'

Models

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