17/03/2026

UNIVERSITÉ LIBRE DE BRUXELLES

Primordial High Energy Neutrinos

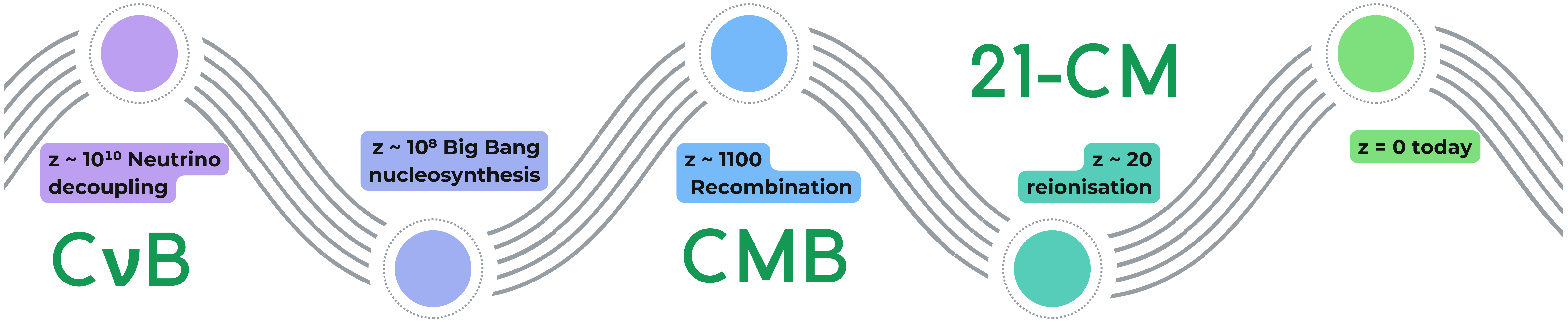
Theoretical & observational constraints and sharp spectral features

Nicolas Grimbaum Yamamoto

arXiv:2507.02063 in collaboration with T.Hambye

LA LIBERTÉ DE CHERCHER

Motivations.



→ Primordial High Energy Neutrinos (PHENUs)

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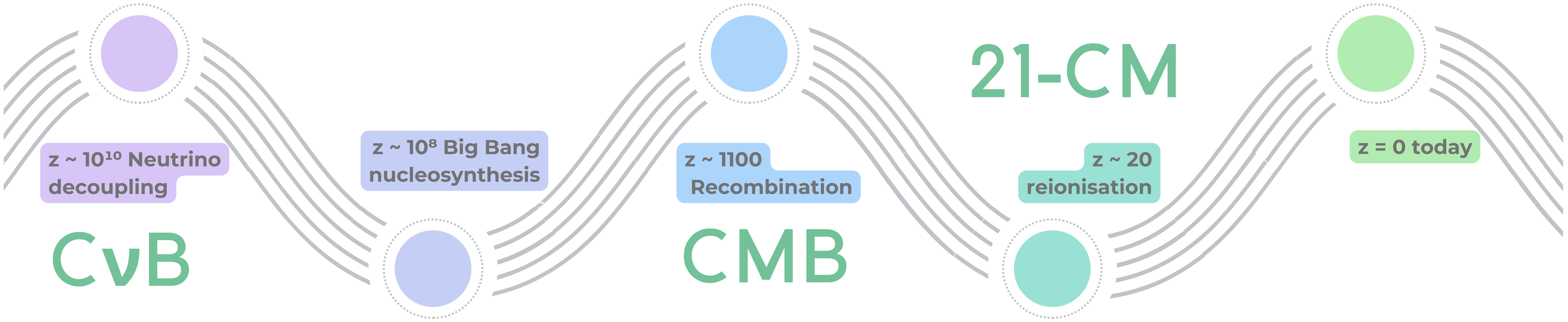

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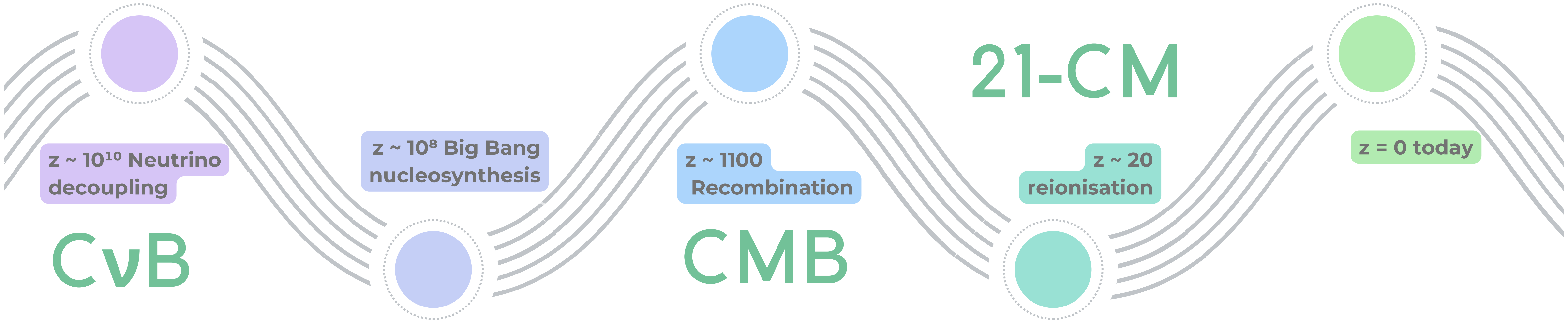

→ Primordial High Energy Mewtrinos (PHEMEW) !

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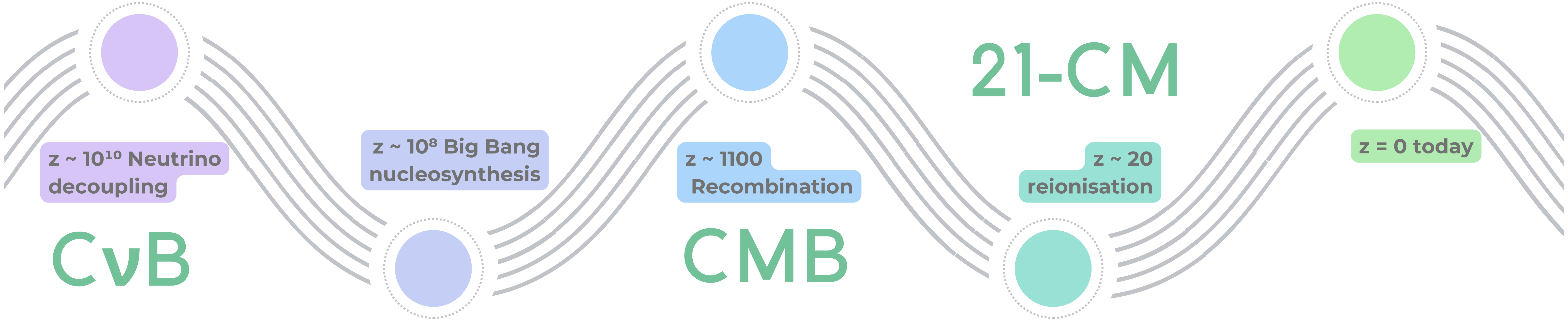
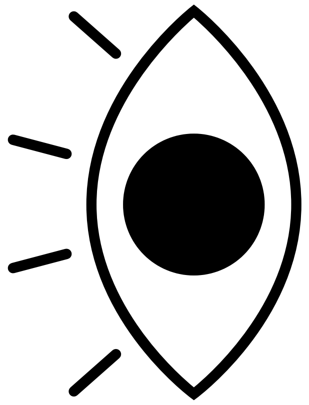


→ Primordial High Energy Mewtrinos (PHEMEW) !



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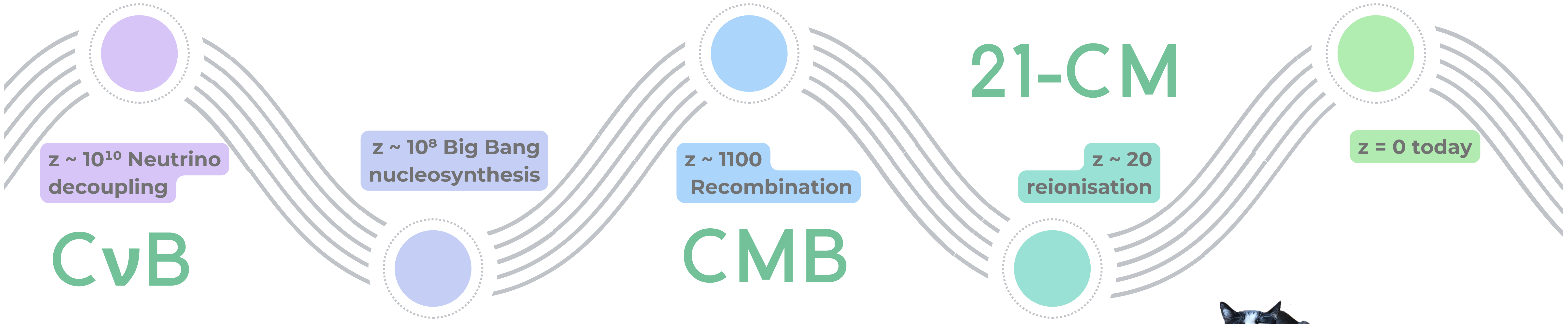
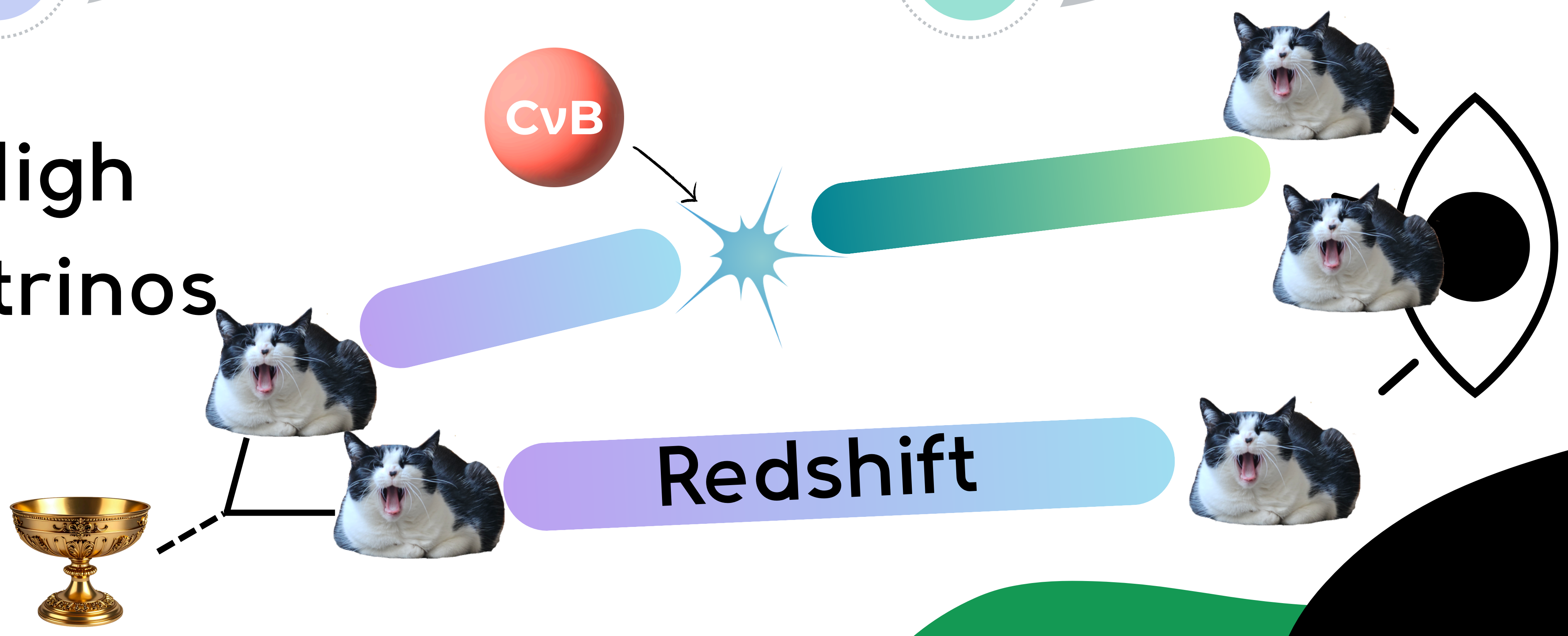
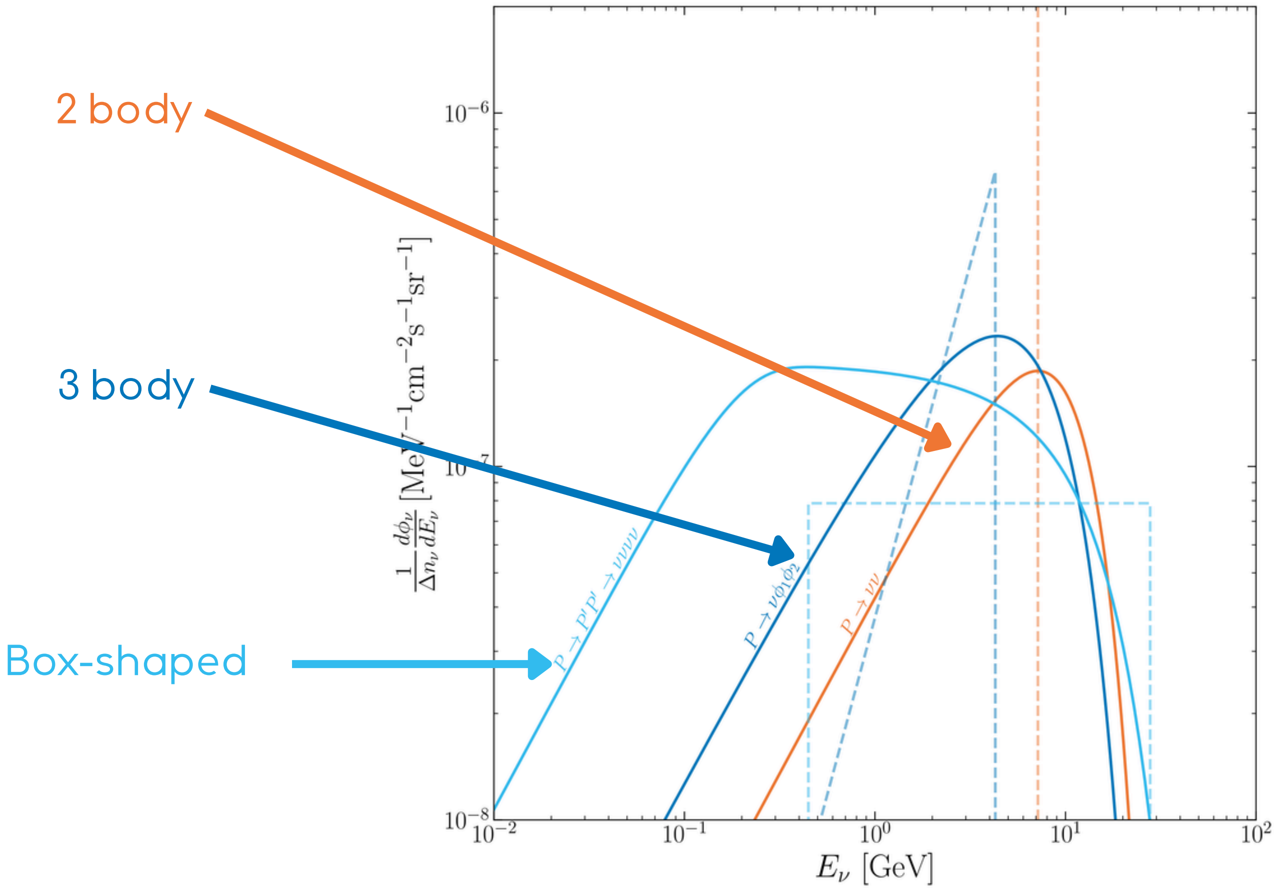


→ Primordial High Energy Mewtrinos **(PHEMEW) !**



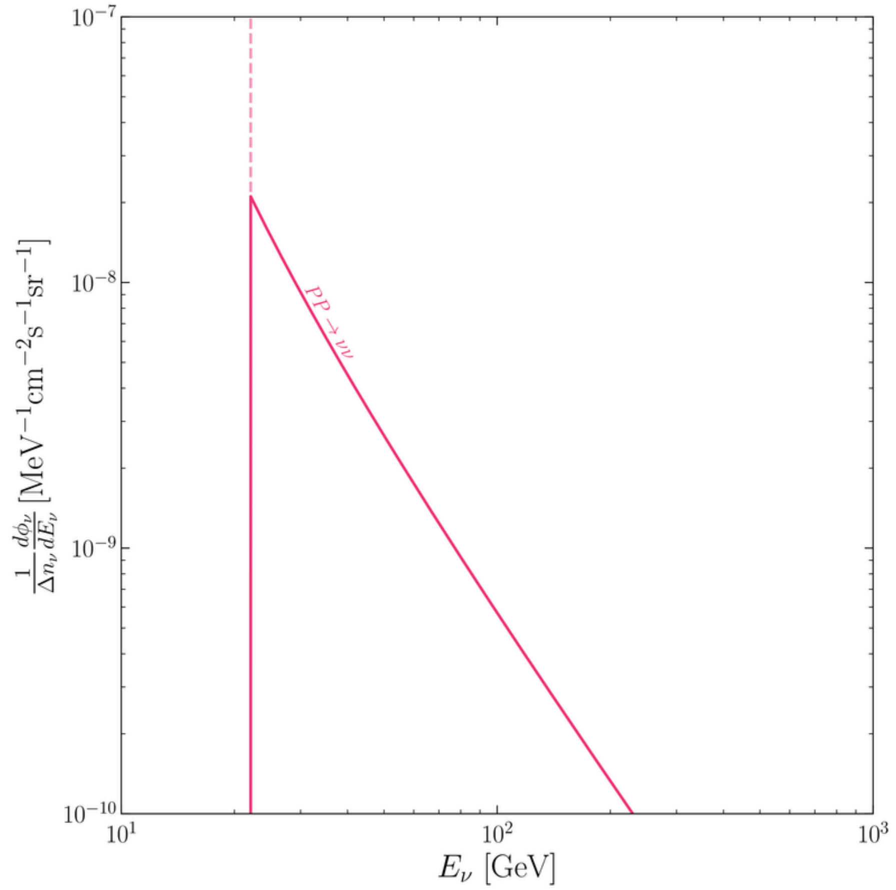
Sharp Spectral Features.

Decays



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

Out of equilibrium annihilation

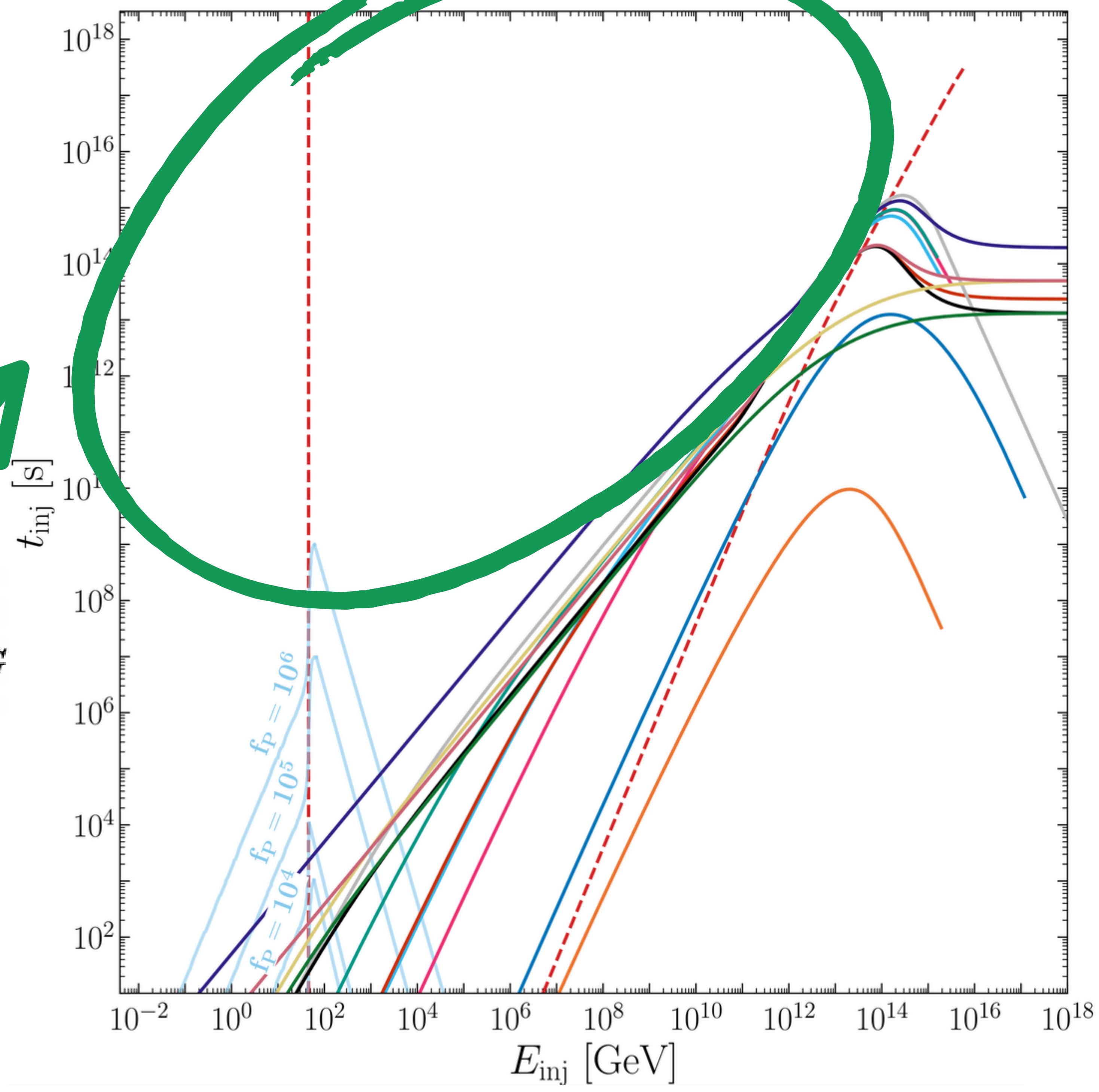


$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Delta n_\nu}{16\pi} \frac{(\Omega_P^0 \rho_{\rm crit}^0)^2 m_P \langle \sigma v \rangle}{E_\nu^4 H_{\rm inj}} \frac{1}{\left(1 + \Omega_P^0 \rho_{\rm crit}^0 \frac{\langle \sigma v \rangle}{2H_{\rm inj}} \frac{m_P^2}{E_\nu^3}\left(\frac{E_\nu}{m_P a_\star} - 1\right)\right)^2}$$

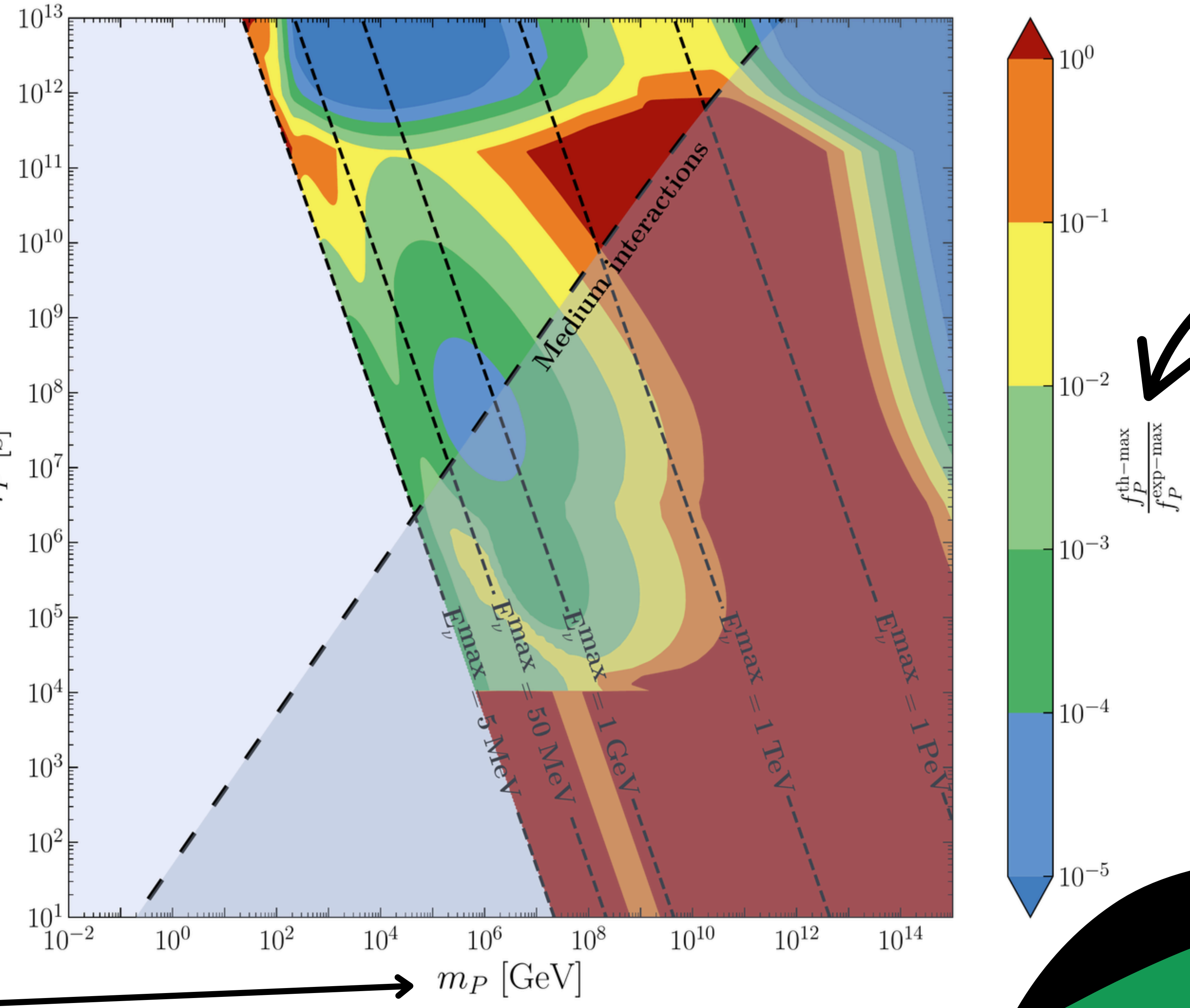
Medium interactions.

Sharp spectral features mostly unaffected

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



Results.



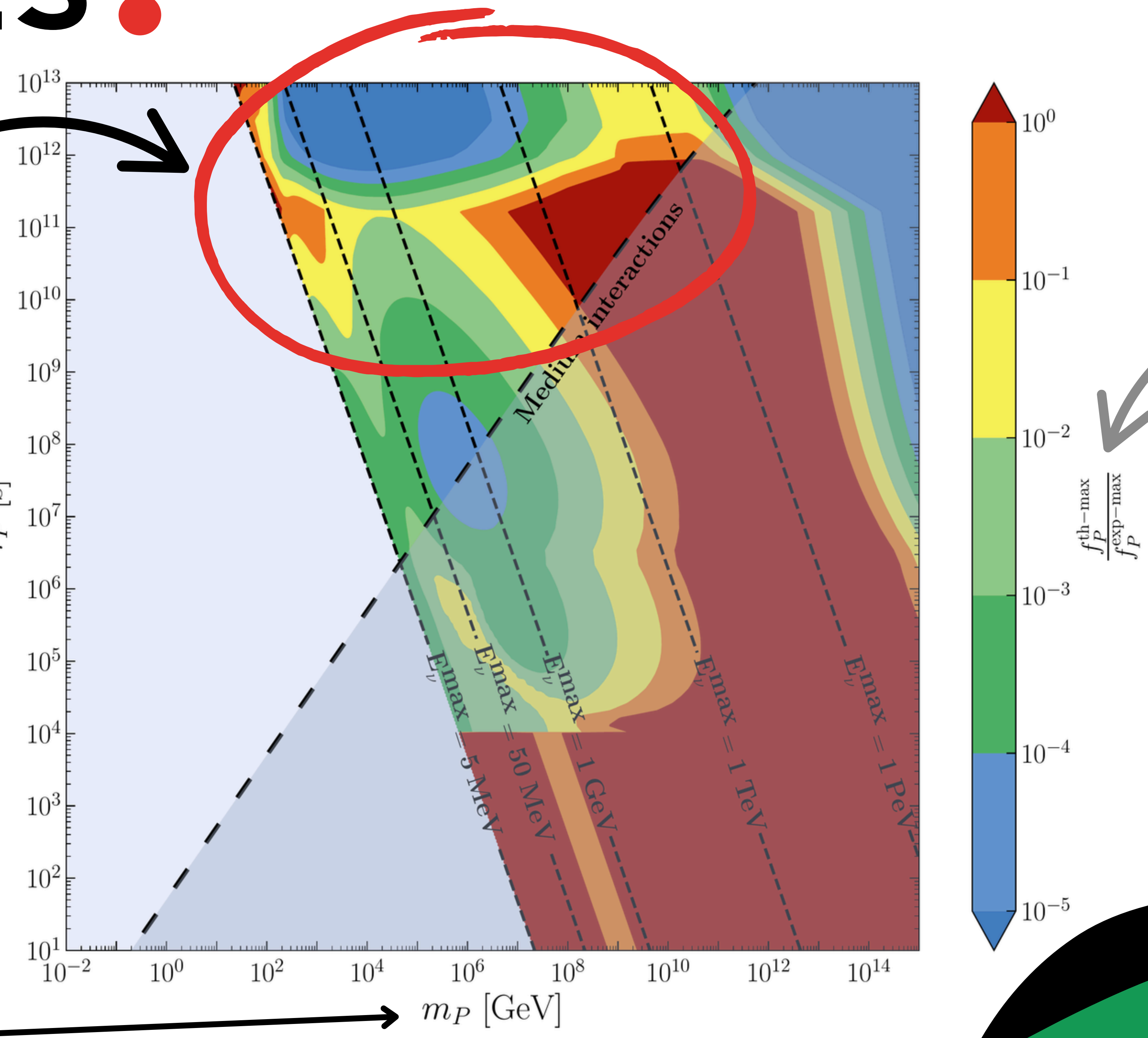
Ratio of theoretical (CMB, BBN, N_{eff}) to observational (IceCube, SuperK) constraints

Heavy relic lifetime

Heavy relic mass

Results.

Potentially observable in existing and future neutrino telescopes



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Heavy relic lifetime

$$10^9\,\mathrm{s} \lesssim \tau_P \lesssim 10^{12.5}\,\mathrm{s}$$

Heavy relic abundance

$$10^{-8} \lesssim f_P \lesssim 10^{-2}$$

Heavy relic mass

$$10\,\mathrm{TeV} \lesssim m_P \lesssim 10^{11}\,\mathrm{GeV}$$

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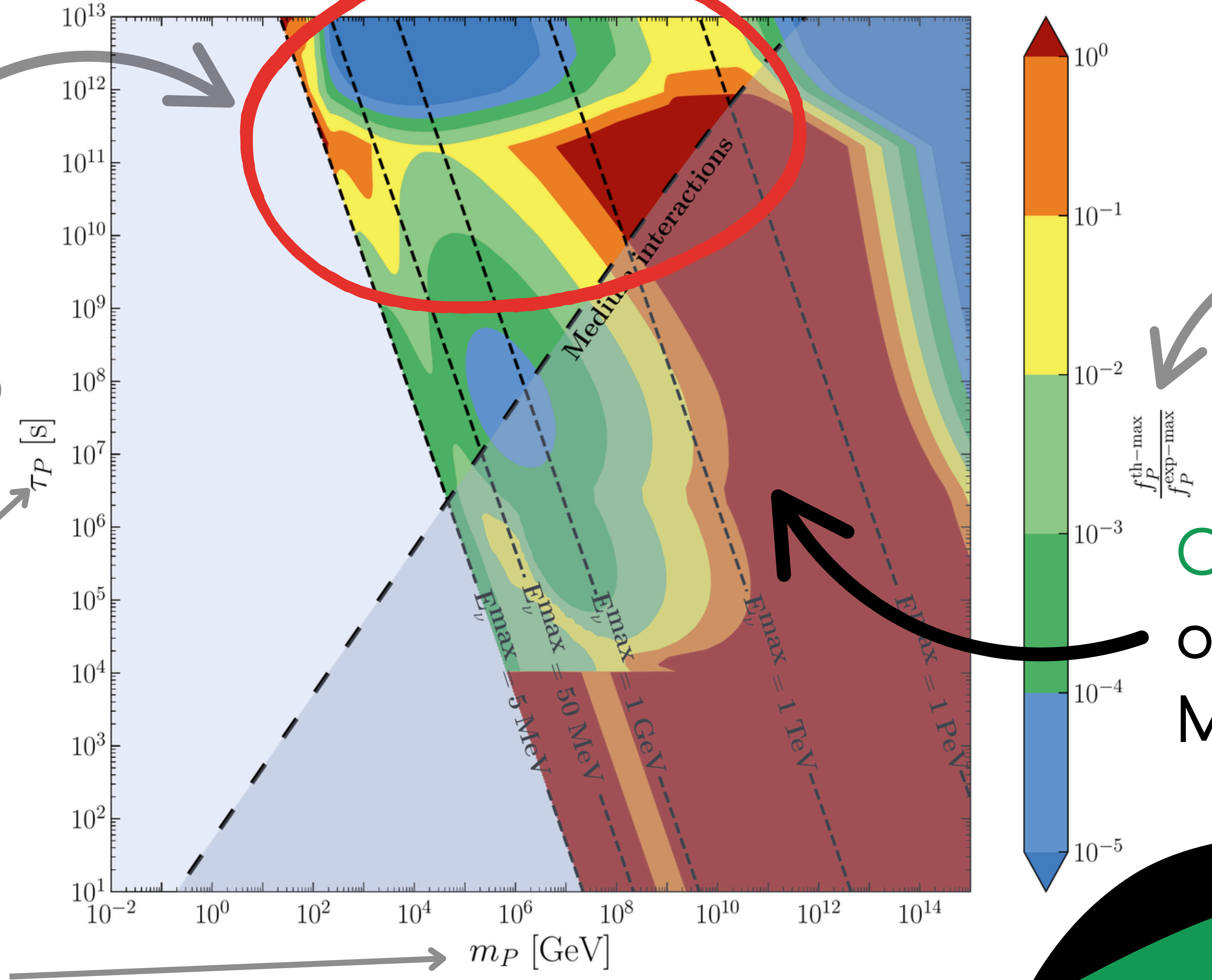

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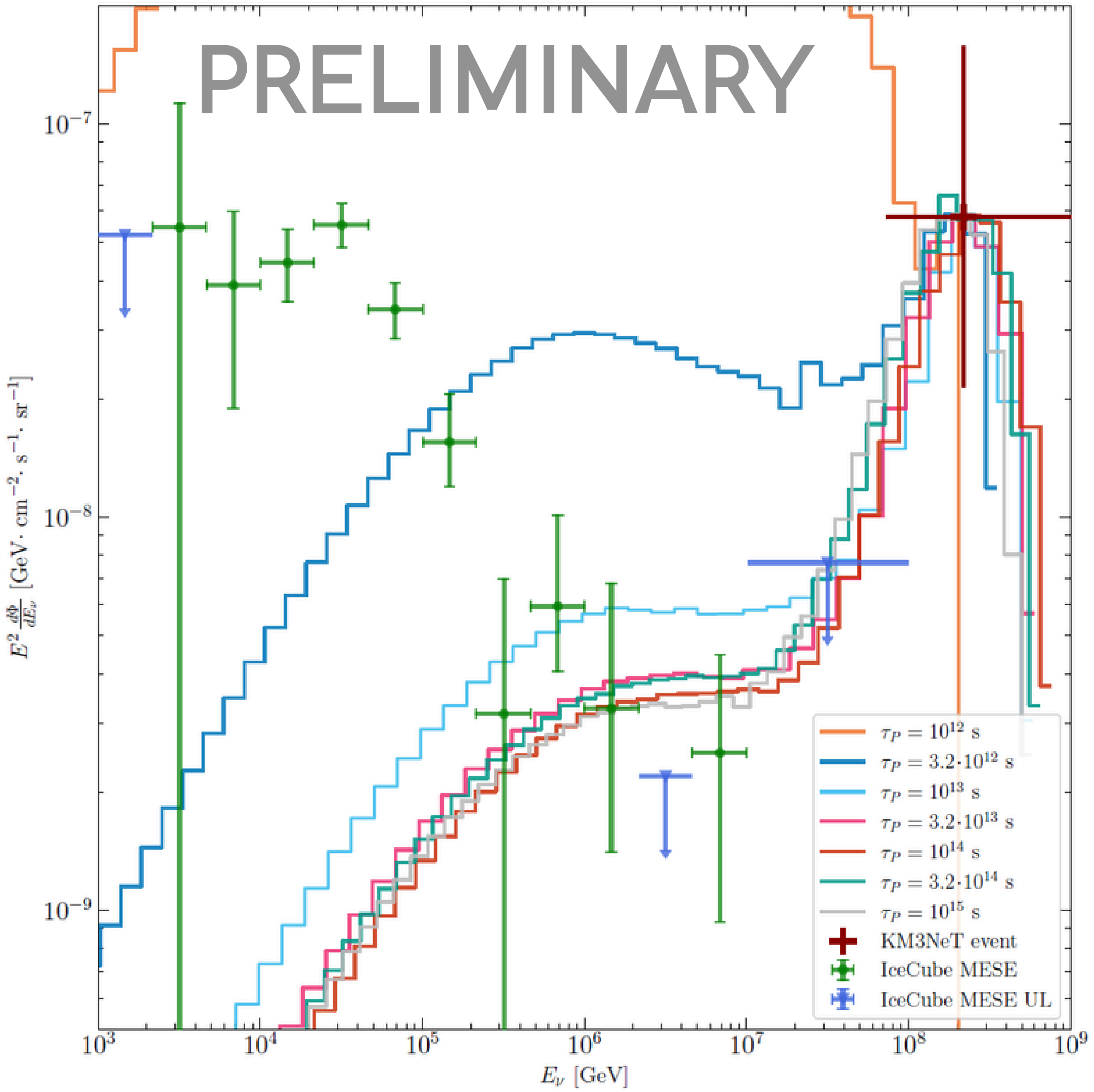
Ongoing work: distortion of the spectrum using Monte Carlo techniques

Results.



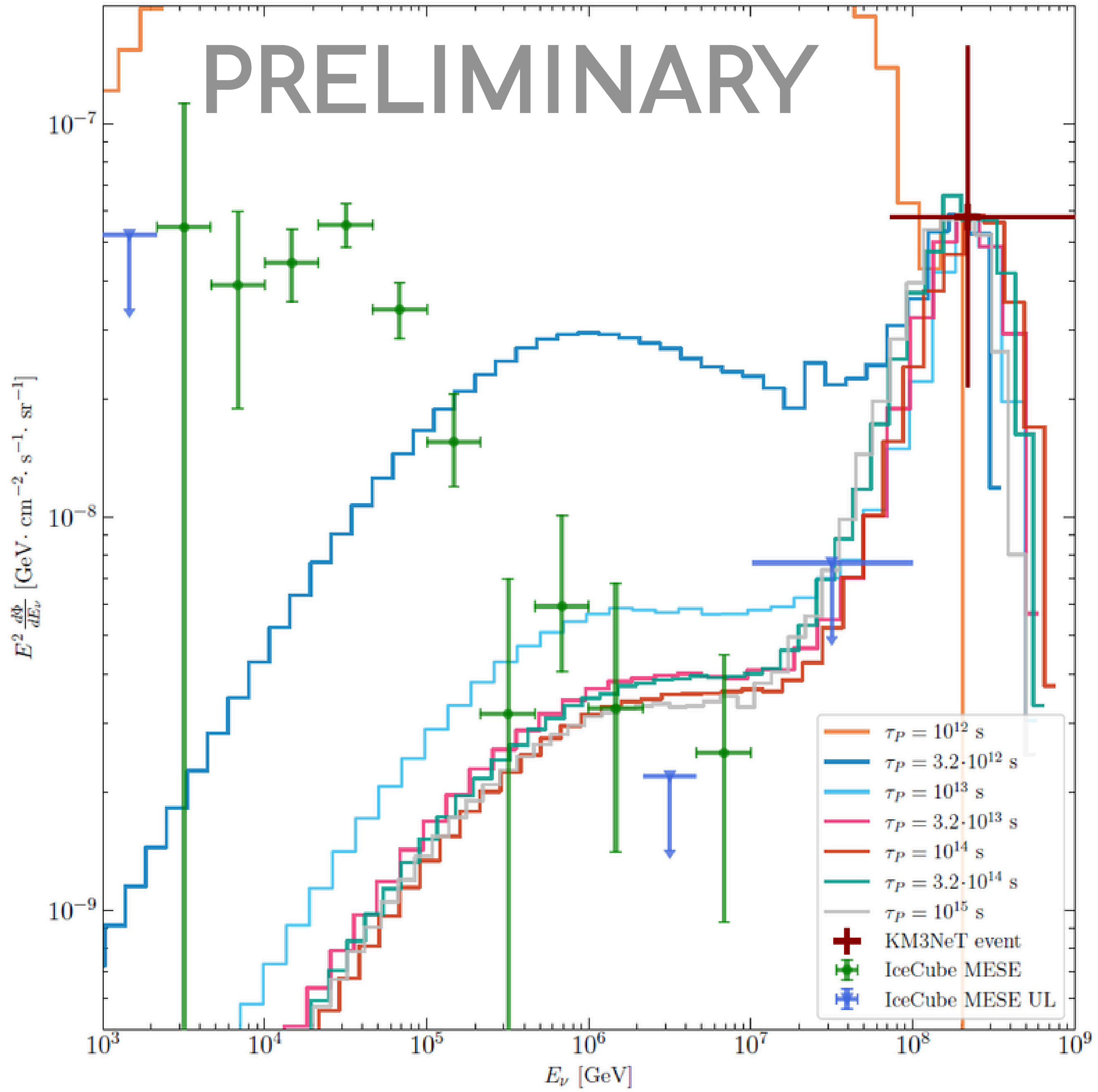
Monte carlo integration over adaptative redshift steps:

- Fully probabilistic approach
- Scatterings over CNB
- Final state radiation

Next step: joint likelihood analysis of IceCube 7.5 years HESE sample and the 2023 KM3Net event

τ_P [s]	m_P [GeV]	f_P
1.0×10^{12}	8.0×10^{11}	2.7×10^{-4}
3.2×10^{12}	5.3×10^{11}	2.0×10^{-6}
1.0×10^{13}	4.0×10^{11}	1.2×10^{-7}
3.2×10^{13}	2.3×10^{11}	3.9×10^{-8}
1.0×10^{14}	1.3×10^{11}	1.6×10^{-8}
3.2×10^{14}	5.0×10^{10}	8.4×10^{-9}
1.0×10^{15}	2.0×10^{10}	3.6×10^{-9}

Results.



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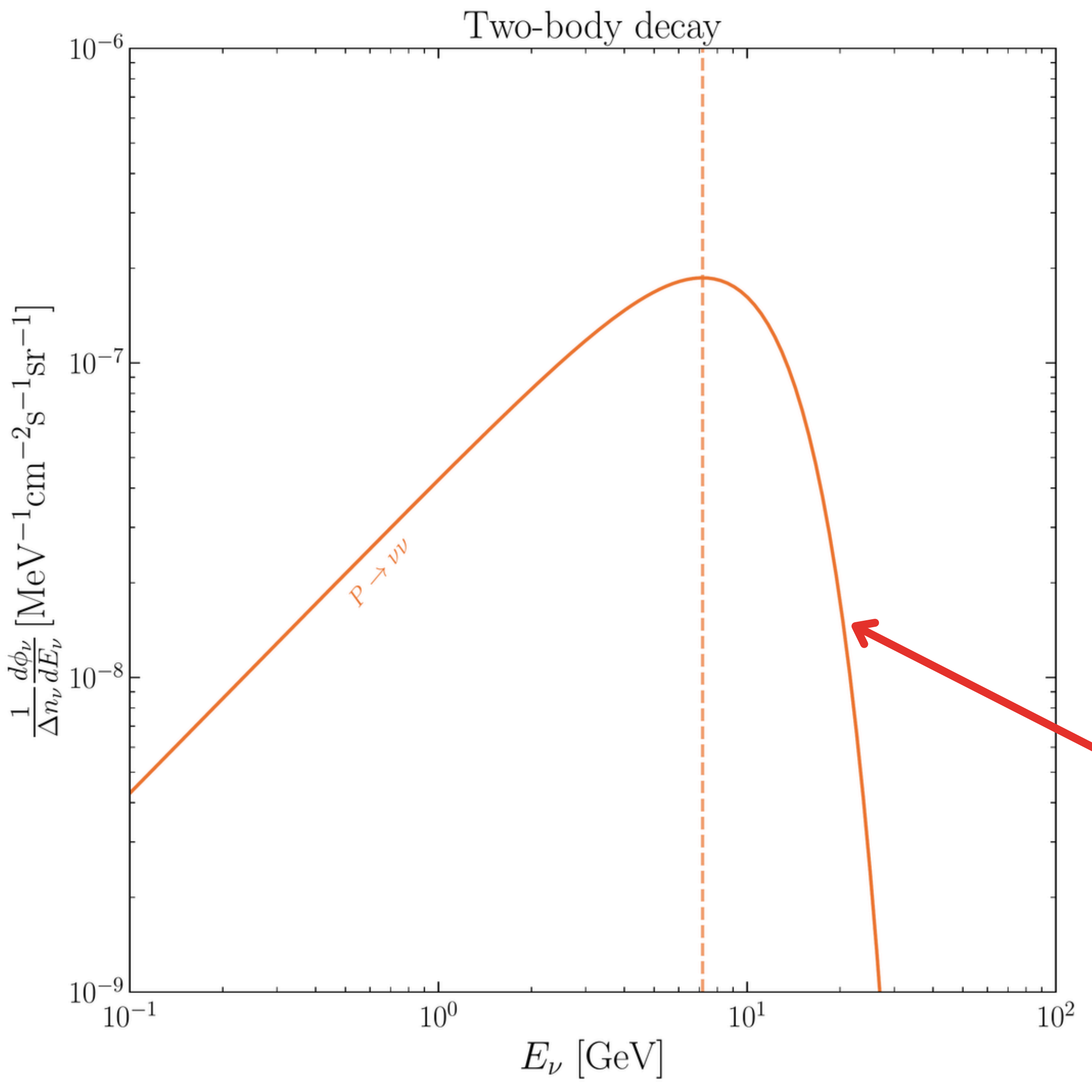
Stay tuned!

Thank you for your attention

arXiv:2507.02063
2604.xxxxx

Sharp Spectral Features.



Gelmini, Gondolo, Sarkar 92'

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Number of neutrinos per decay

Isotropy

Decaying particle density

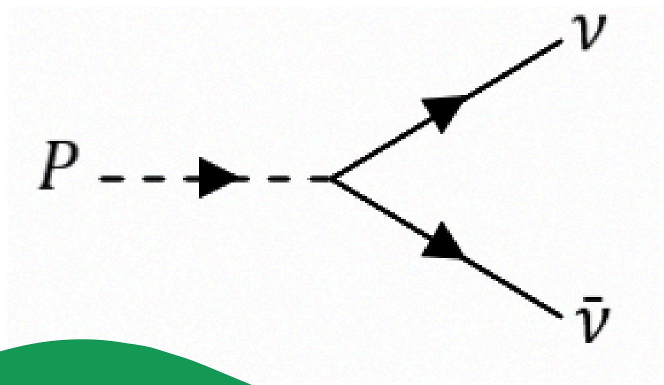
decay rate

Integration over the line of sight

Exponential decay

Spectrum at production

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



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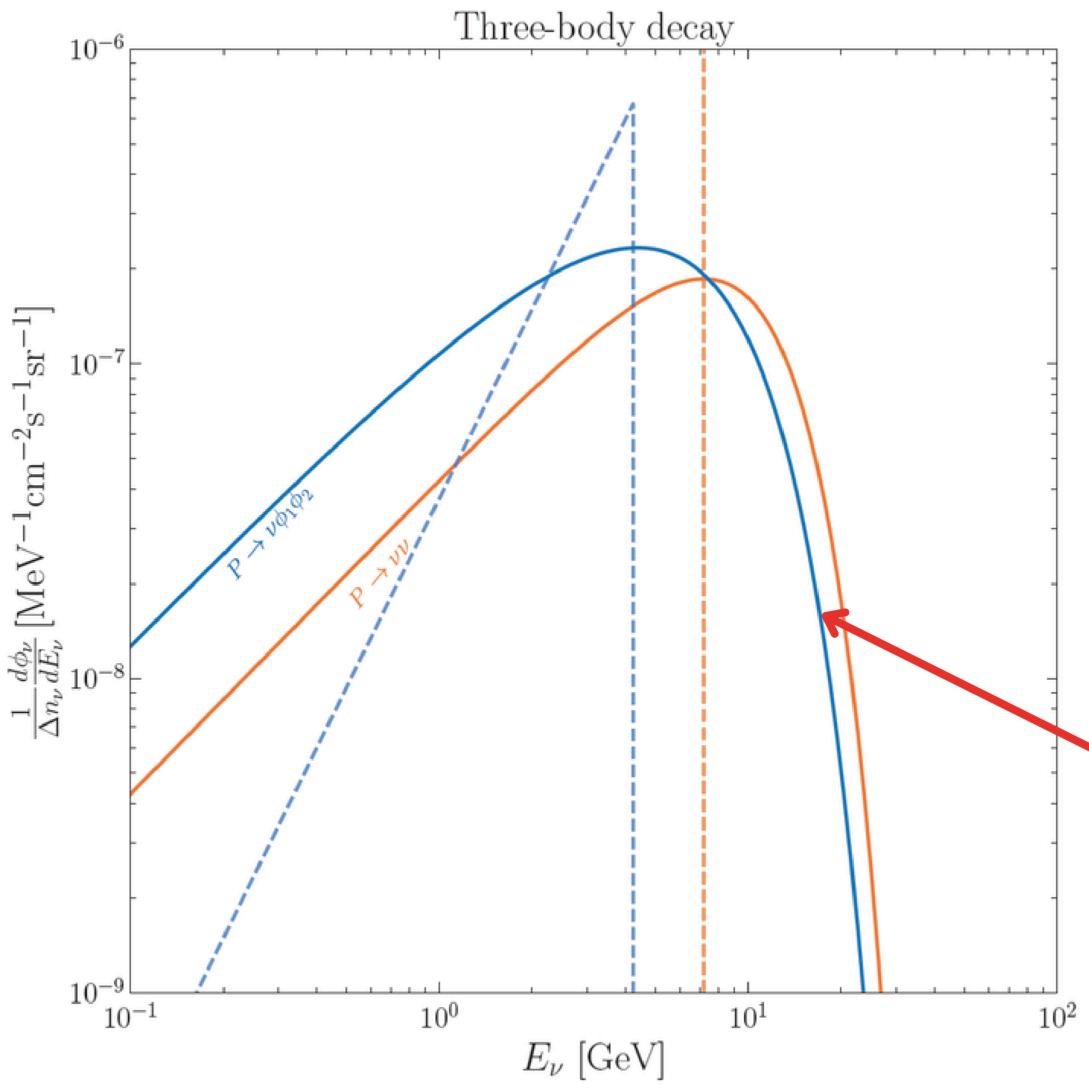

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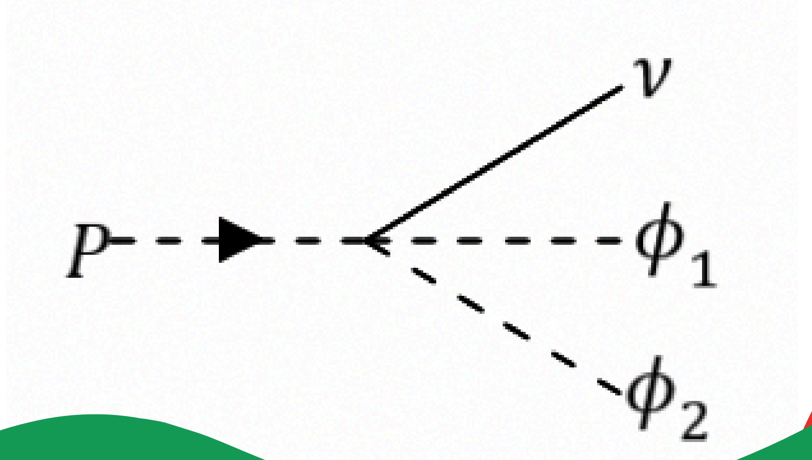

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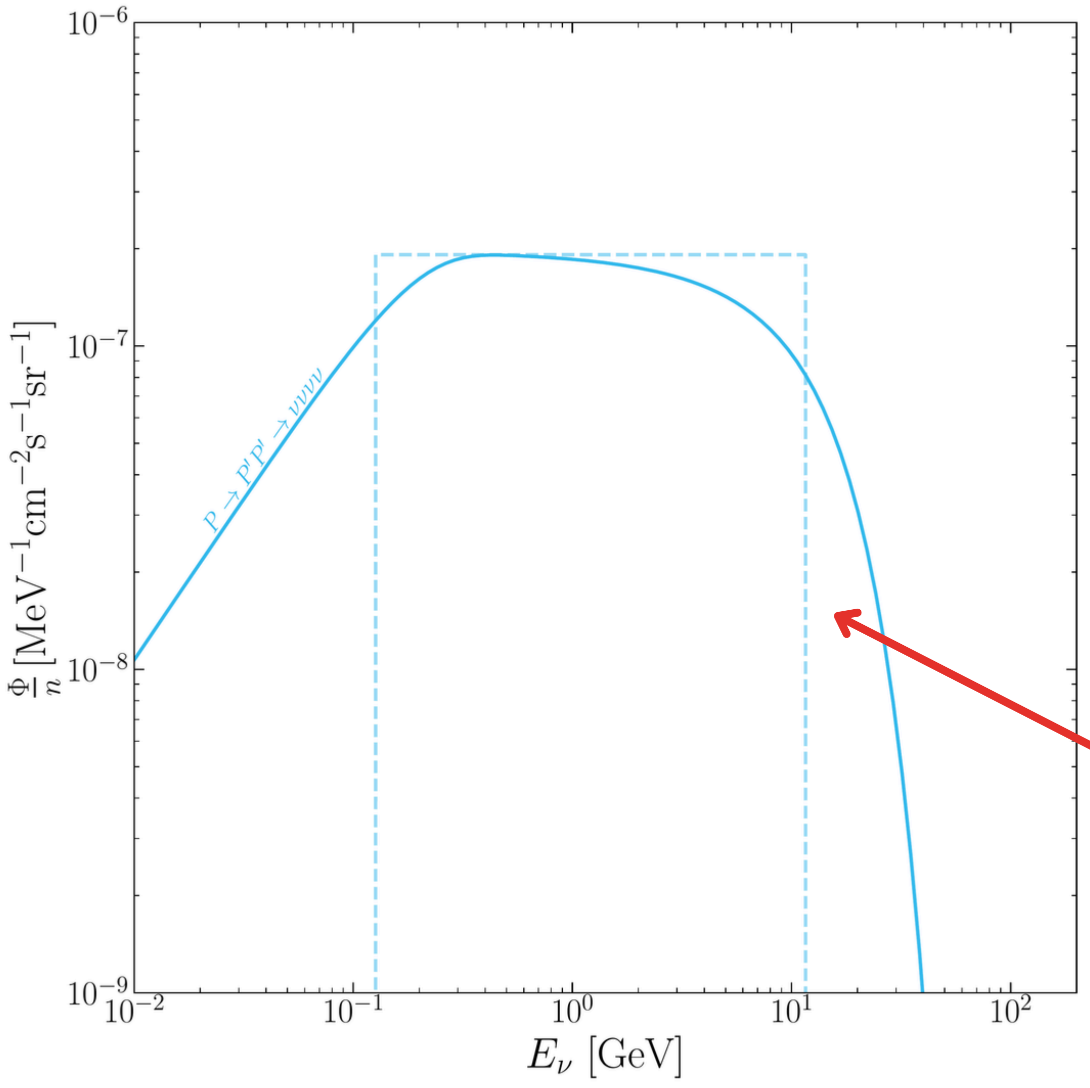

Ibarra, Lopez Gehler, Pato, Miguel, 12'

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

Number of neutrinos per decay

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Decaying particle density

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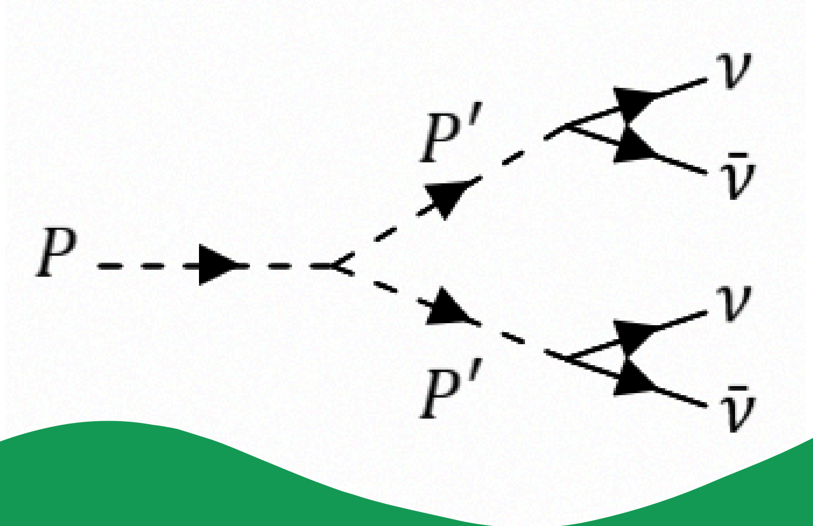
Integration over the line of sight

Exponential decay

Spectrum at production

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



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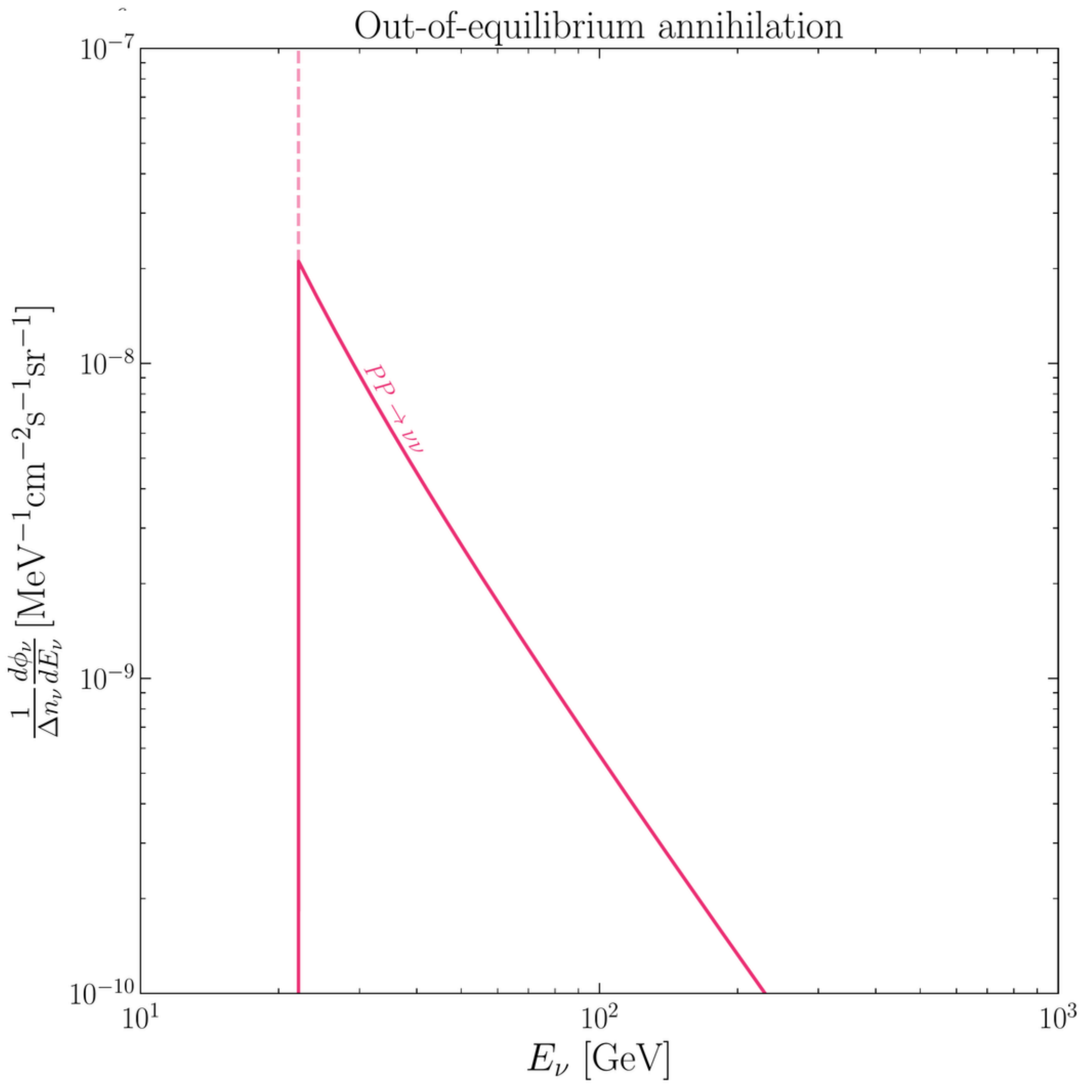
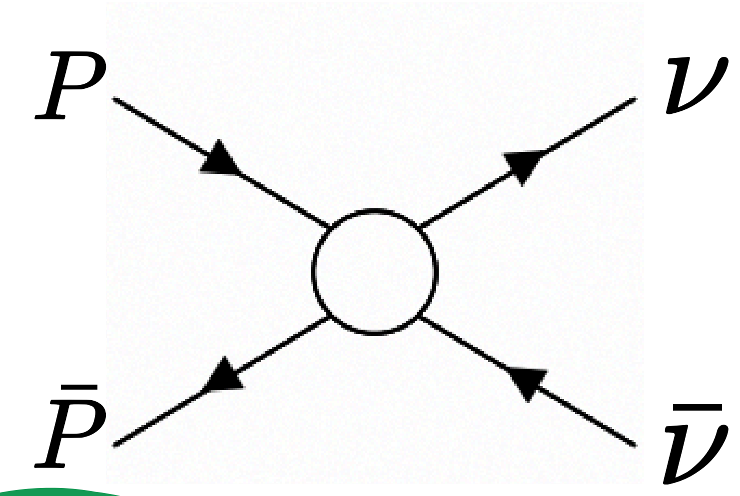


Out of equilibrium annihilation

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

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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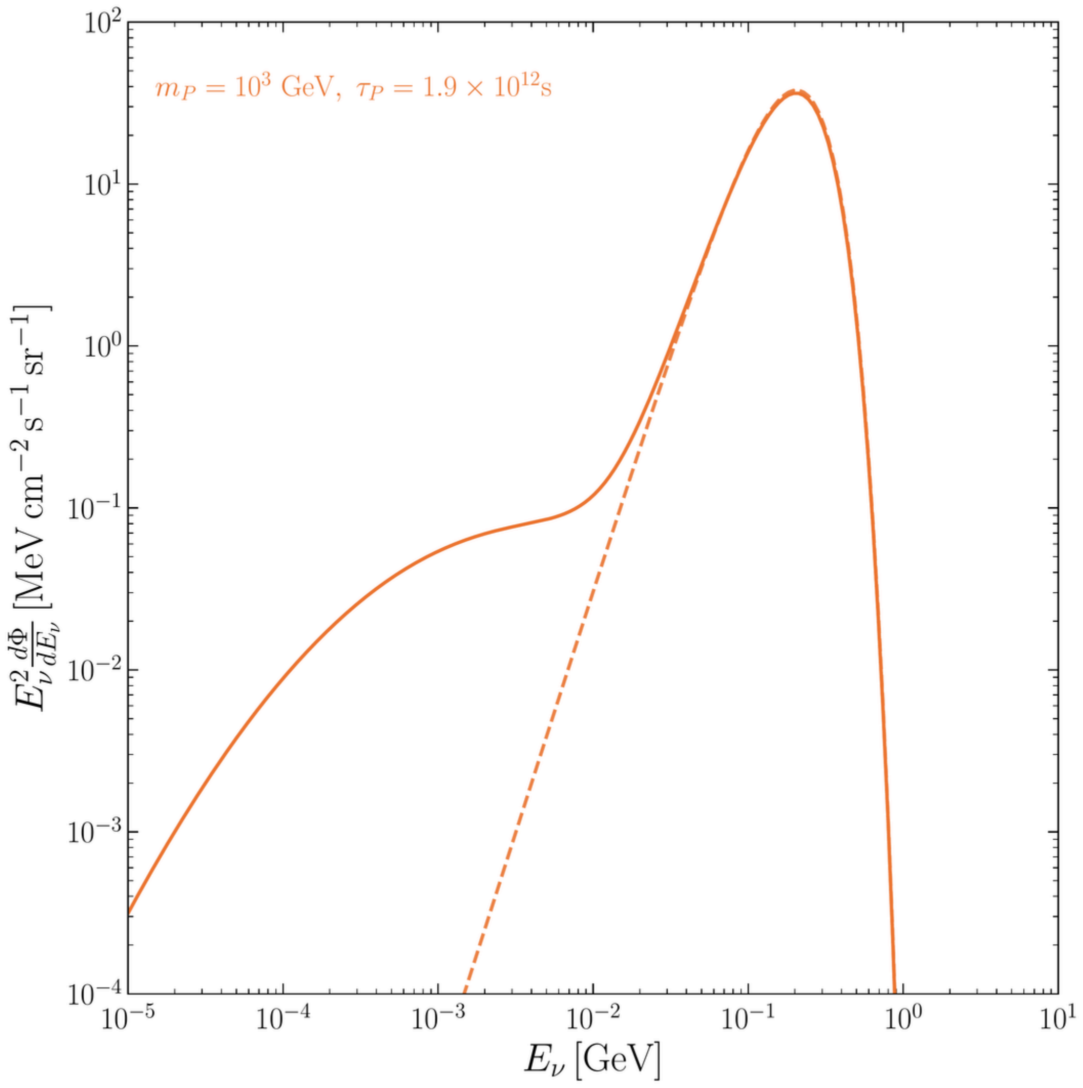
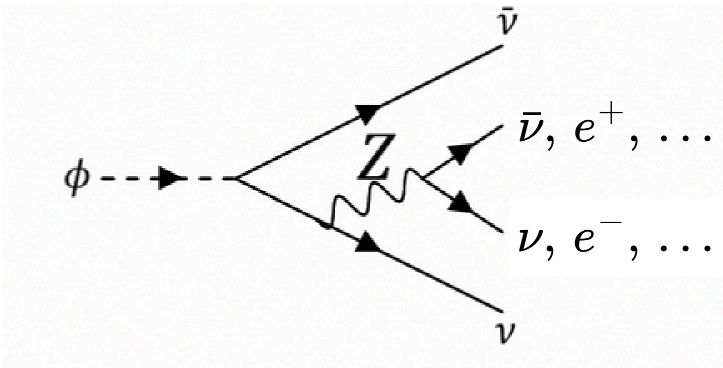


Final state radiation broadening

- 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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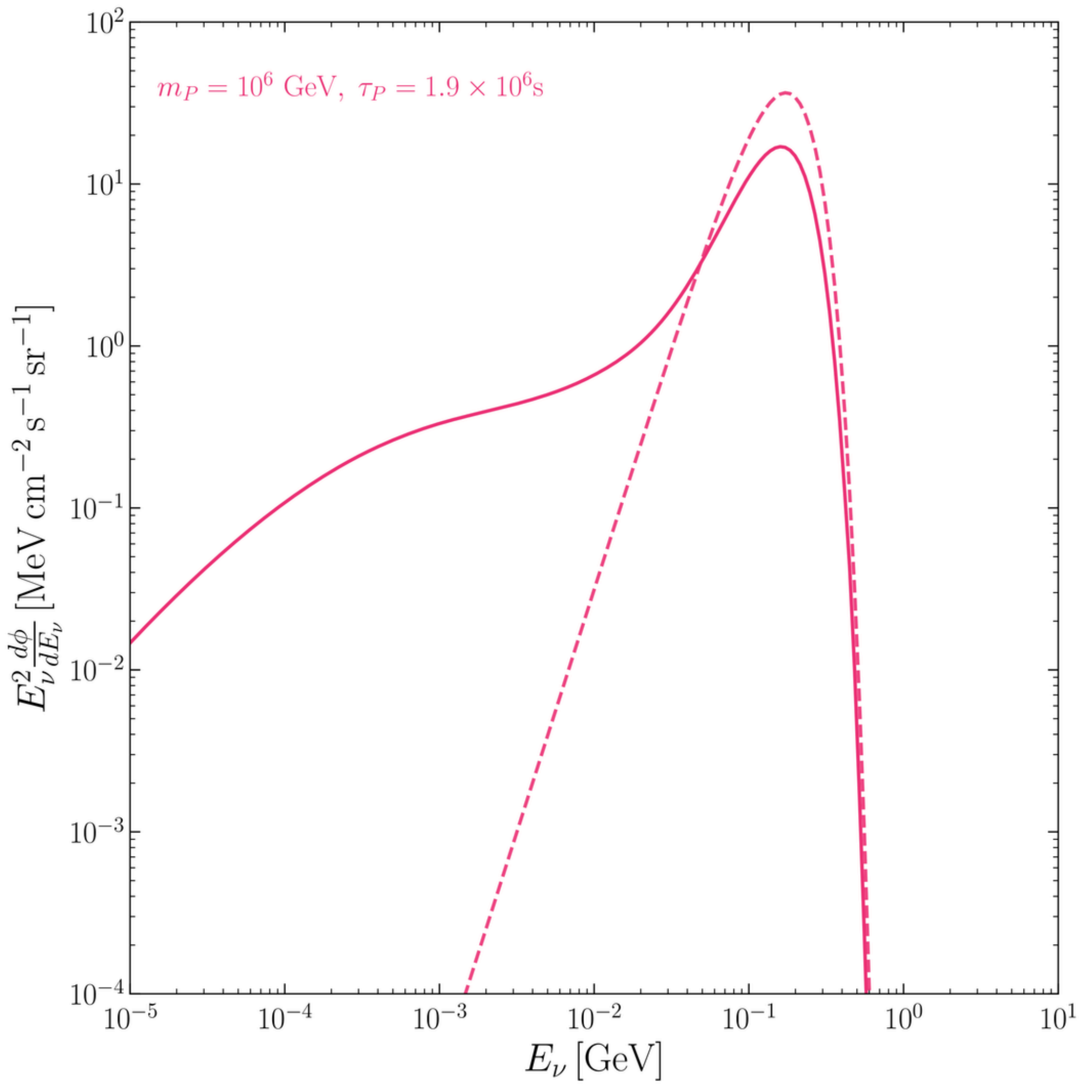

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→ **Broadening of the peak mostly due to redshift effect**

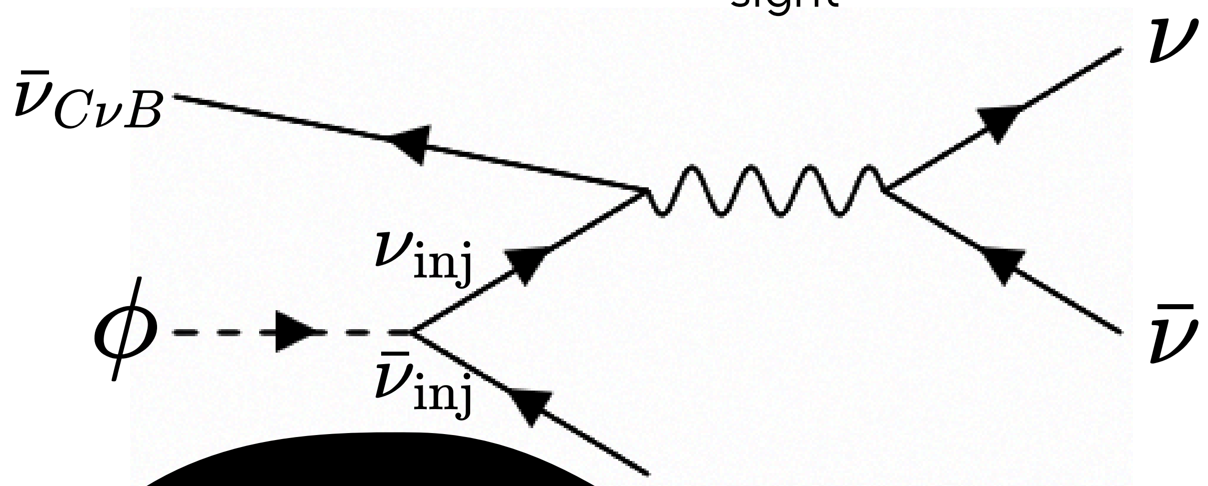
Medium interactions.

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

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

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

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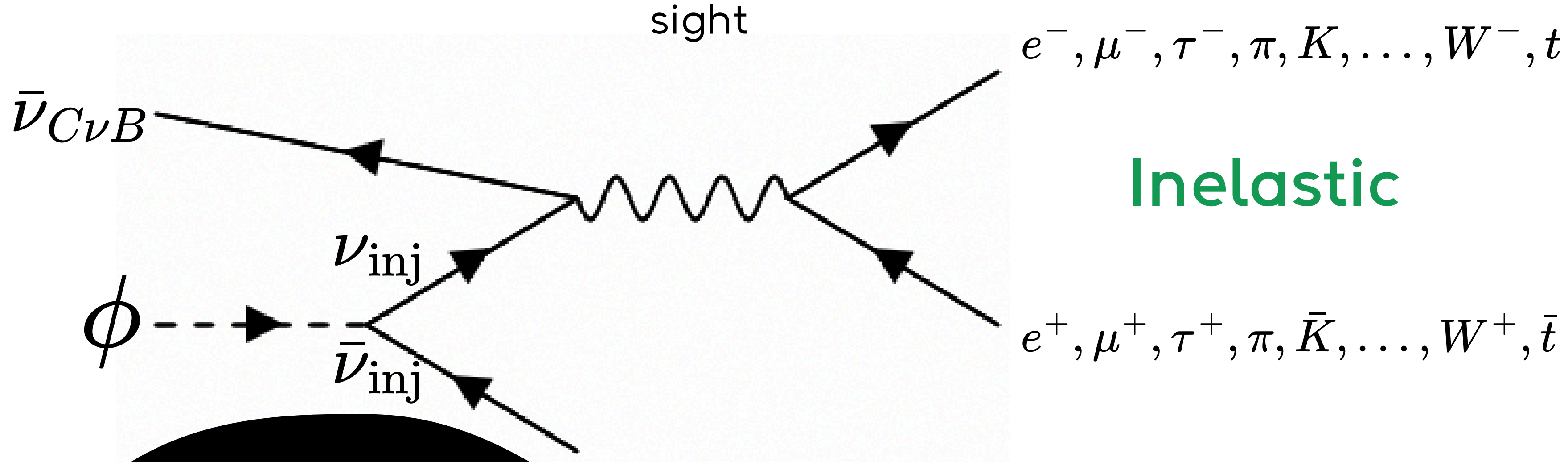

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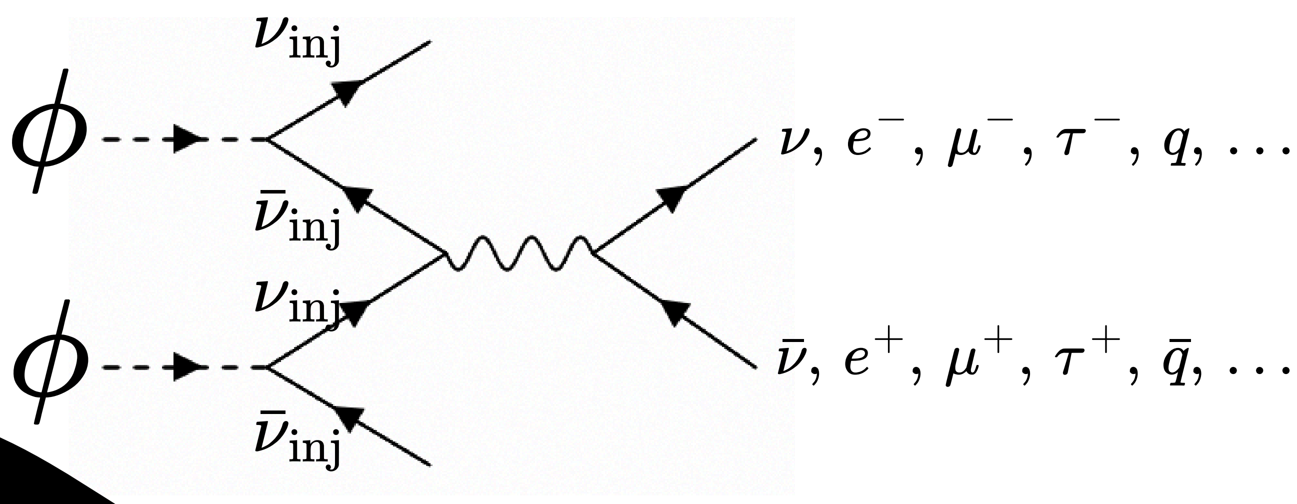

Self-scattering:

- 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.

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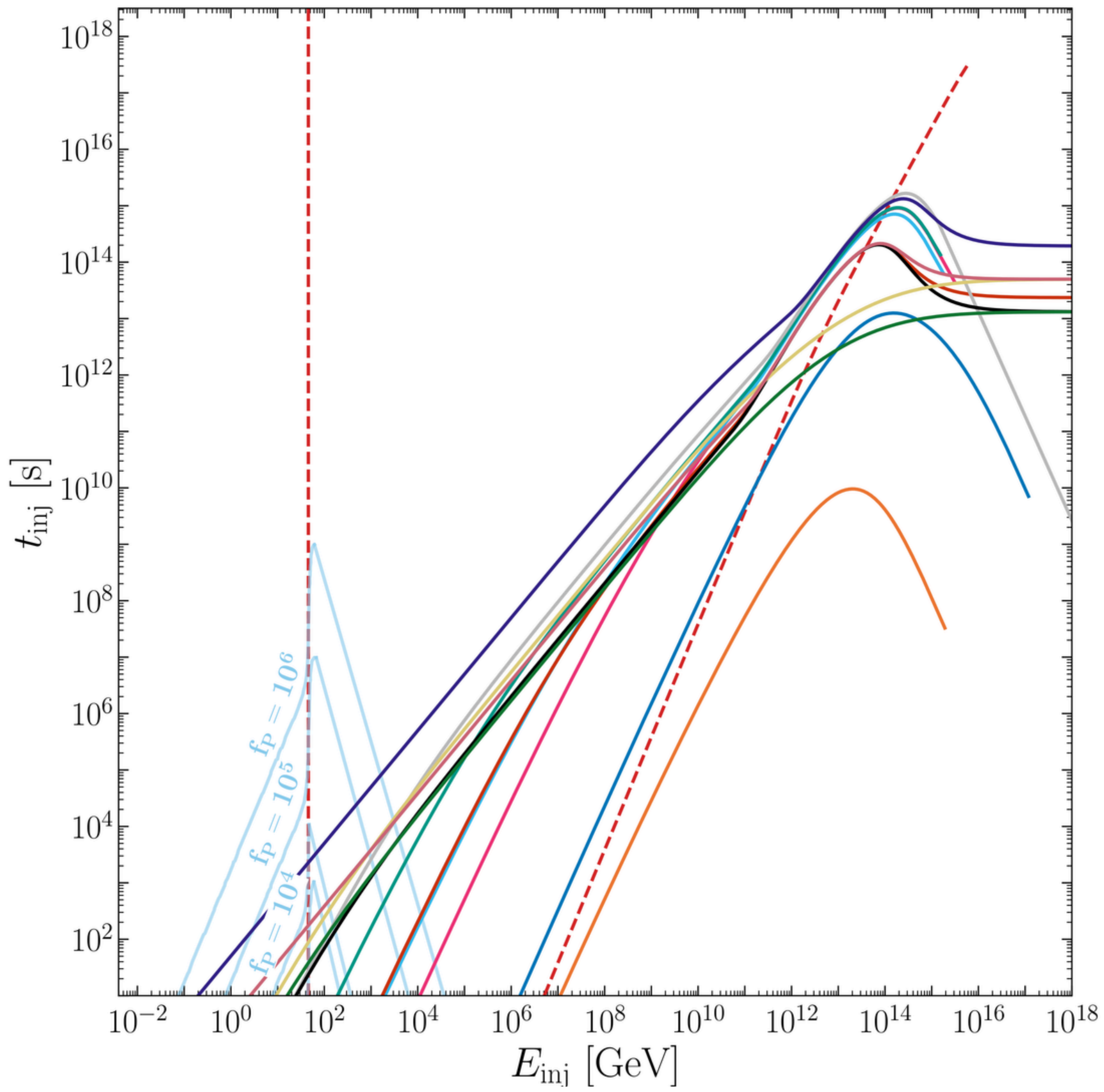
Average number of scattering

Integration over the line of sight

cross section averaged over target distribution function

target neutrino number density

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



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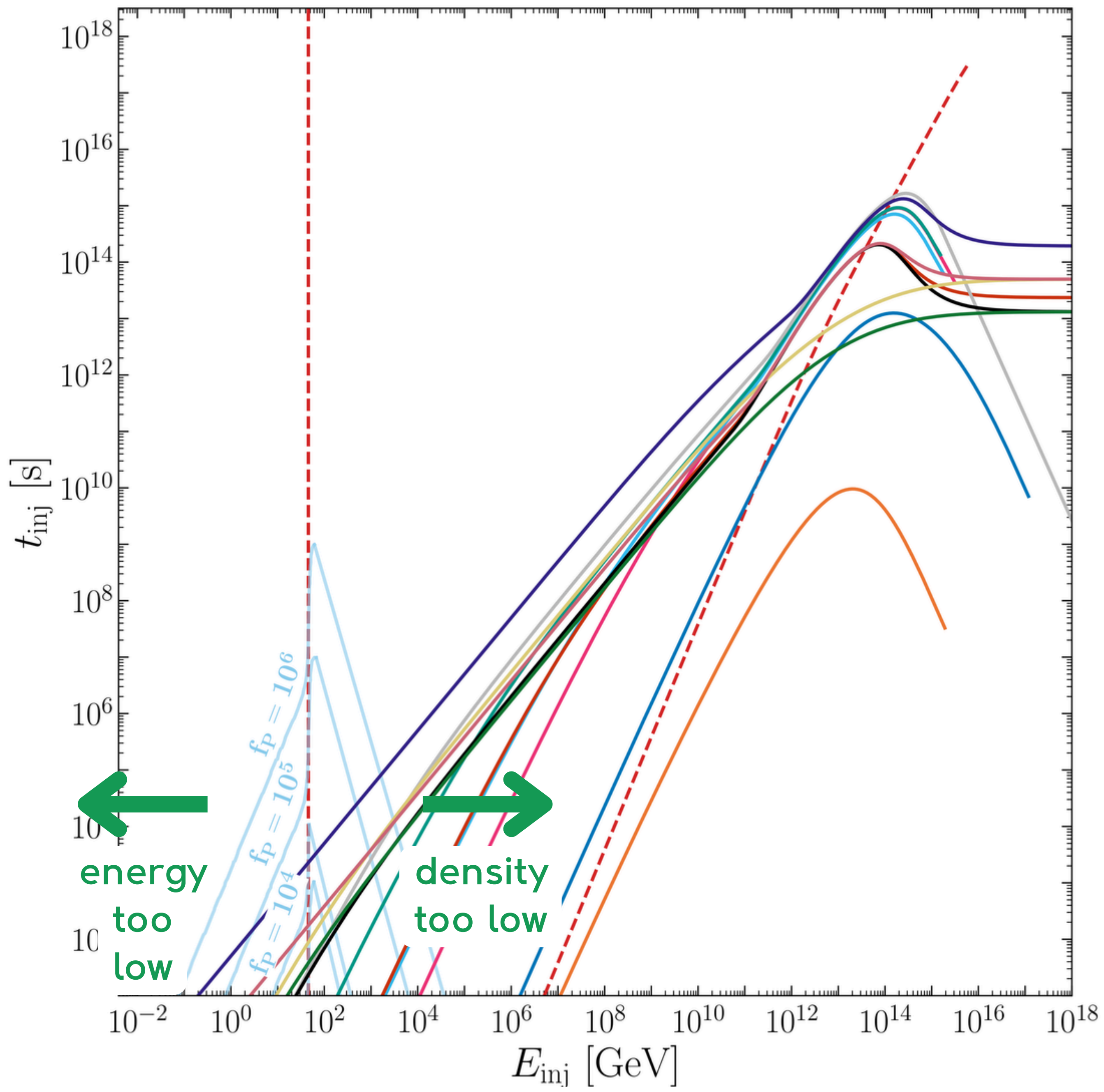

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Self-scatterings are negligible except around the Z resonance

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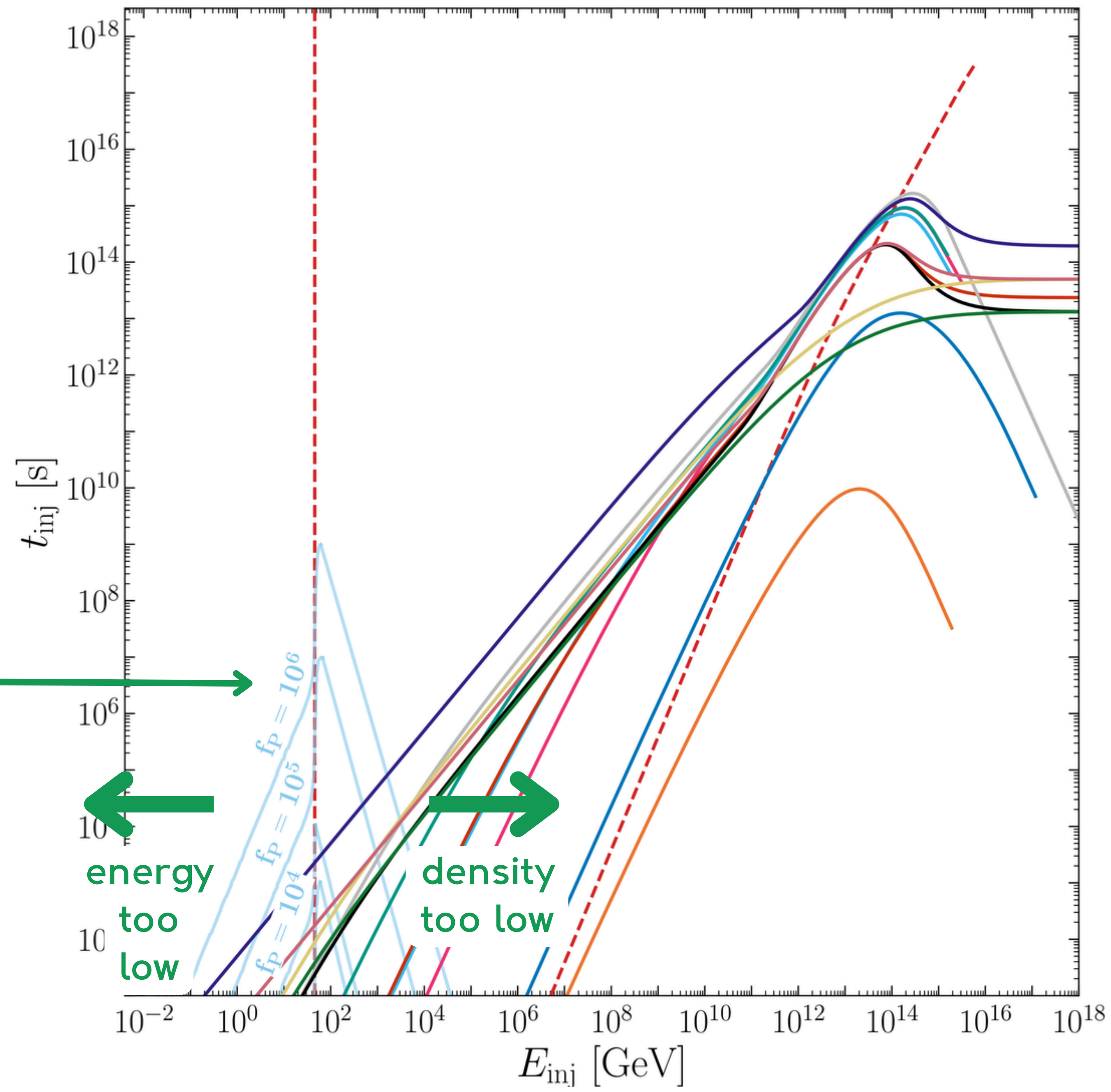
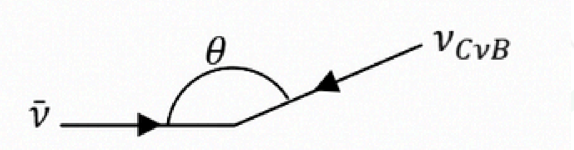


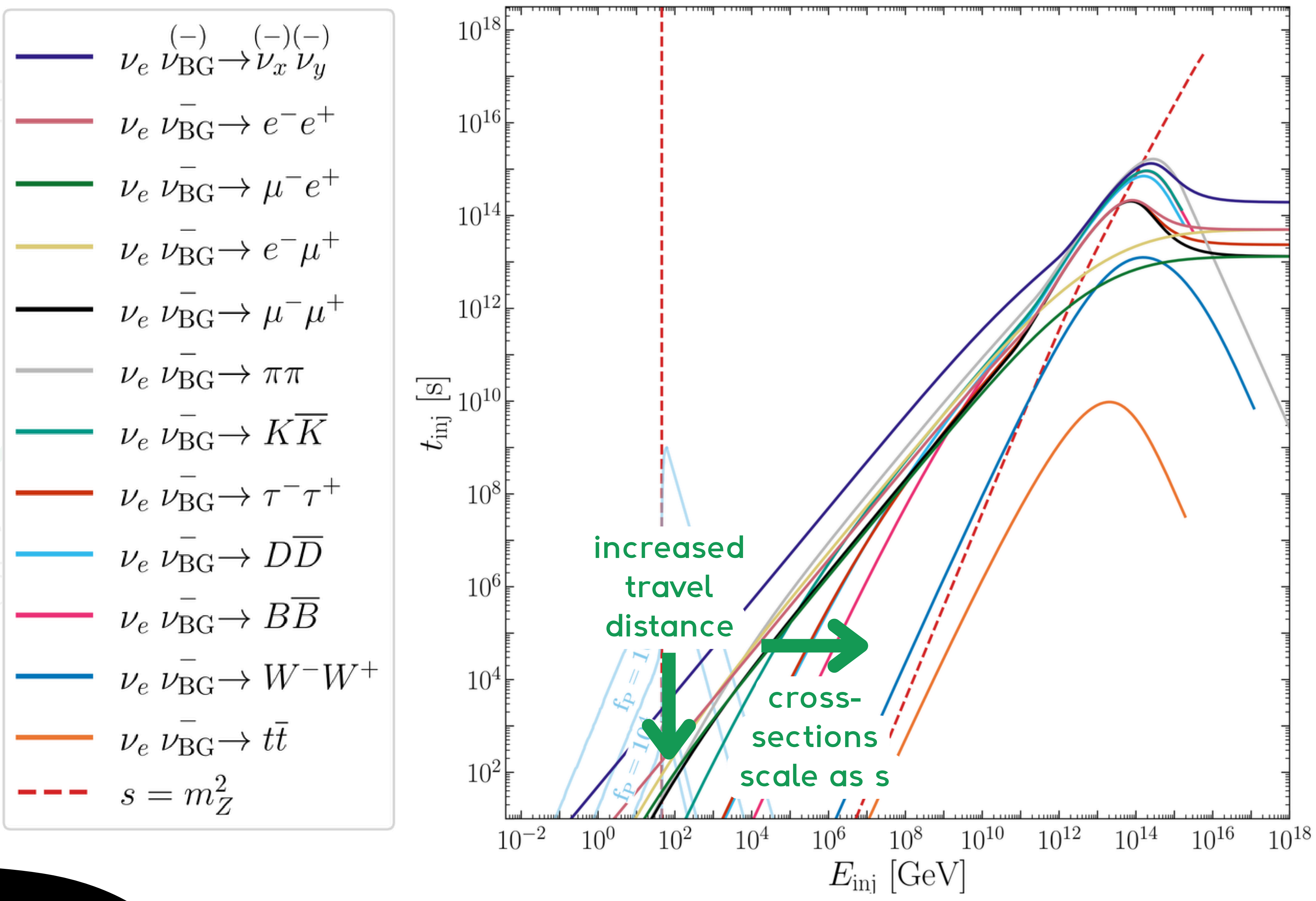
Medium interactions.

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



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

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



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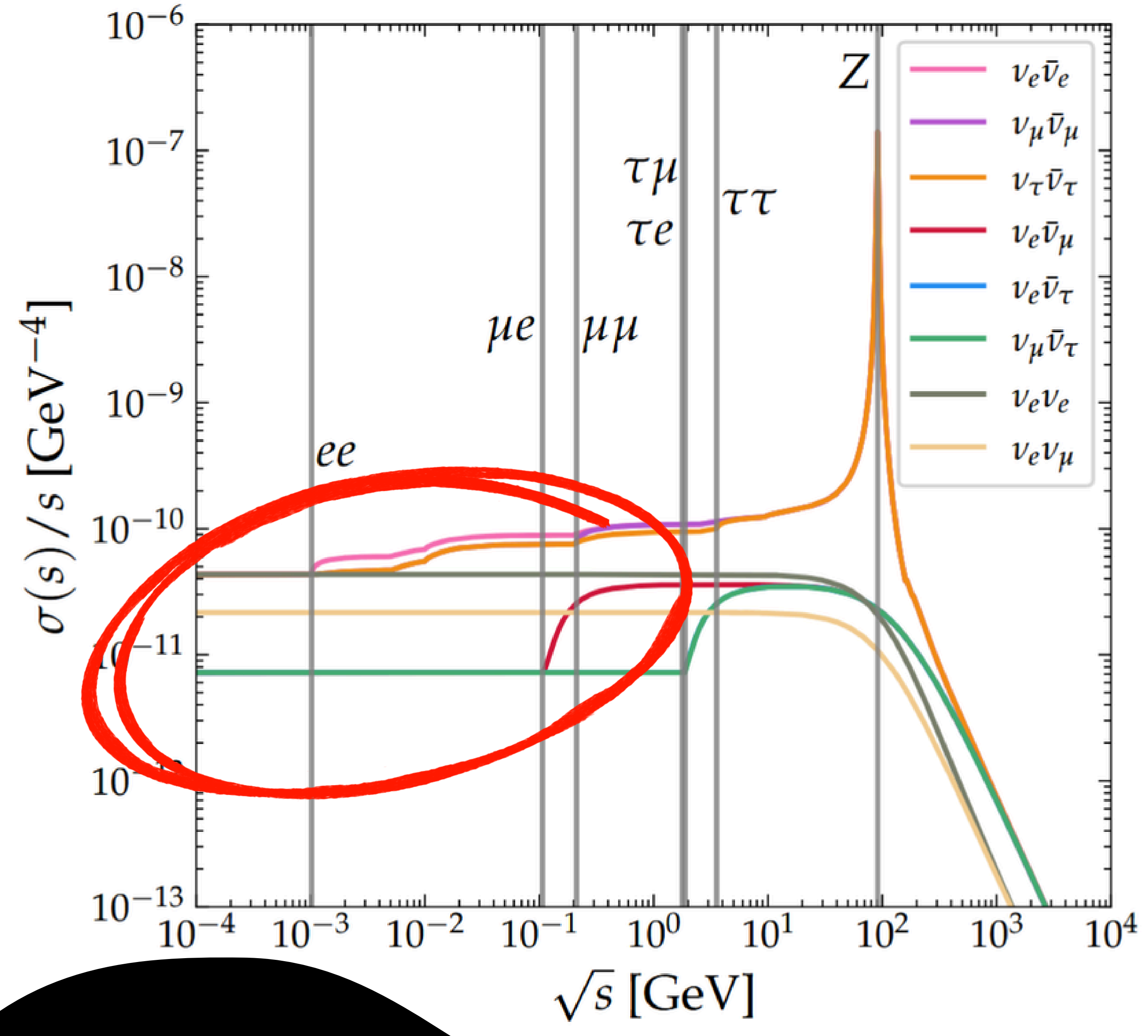
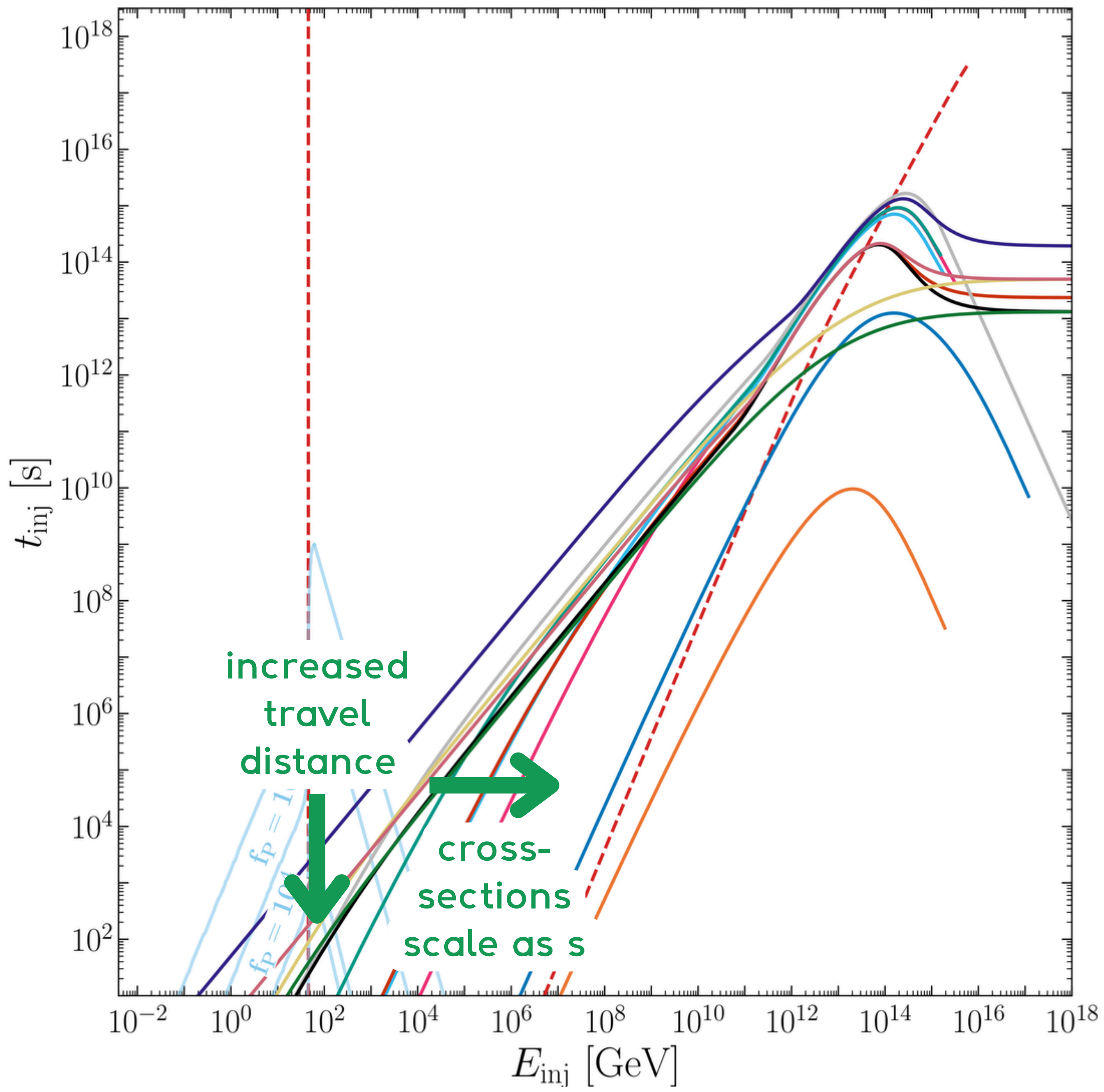


Bianco, Depta, Frerick, Hambye, Hufnagel,Schmidt-Hoberg 25'



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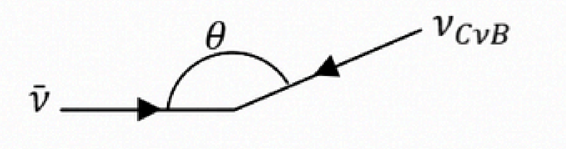
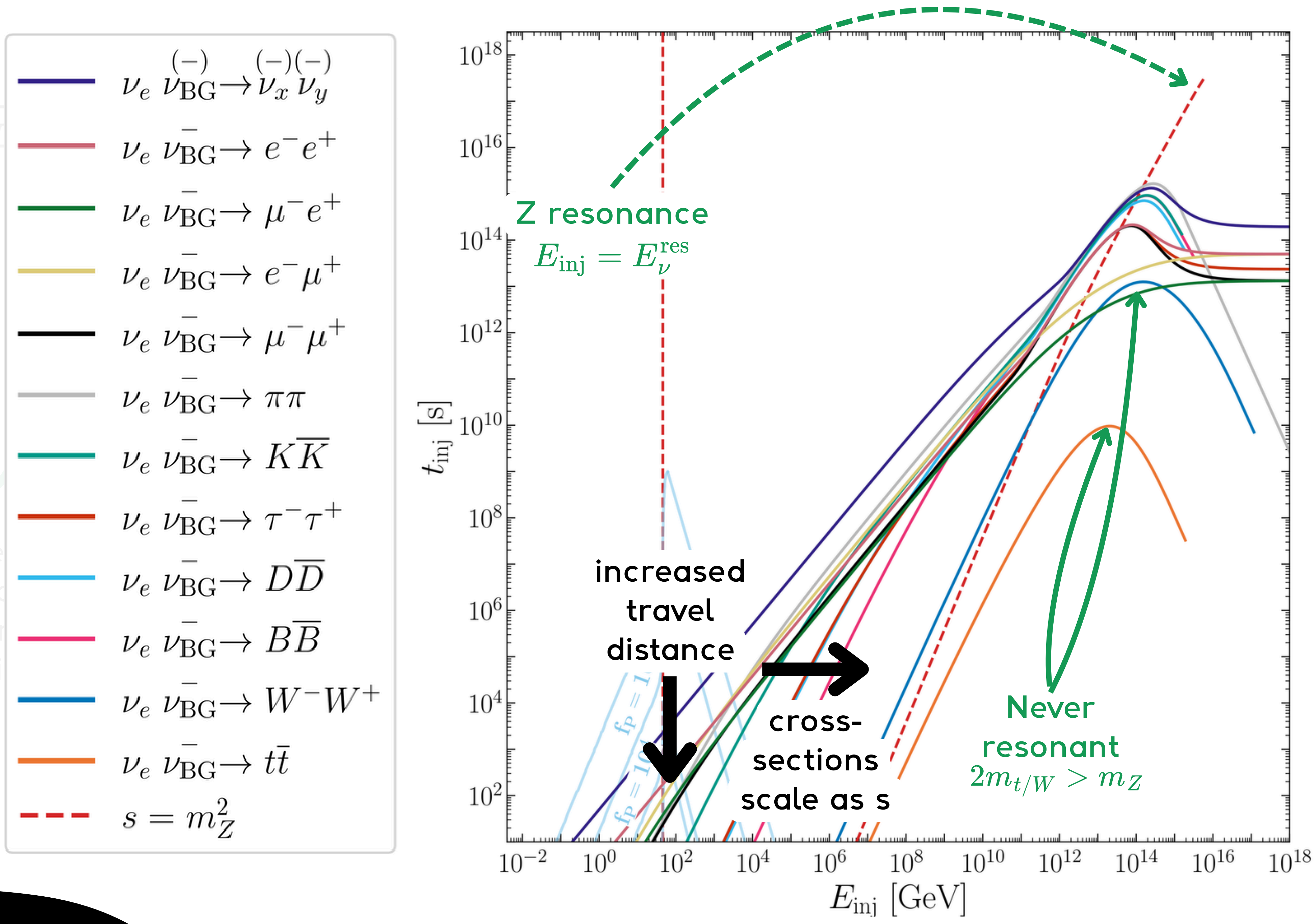


$$E_{\rm inj} \sim E_\nu^{\rm res}$$

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



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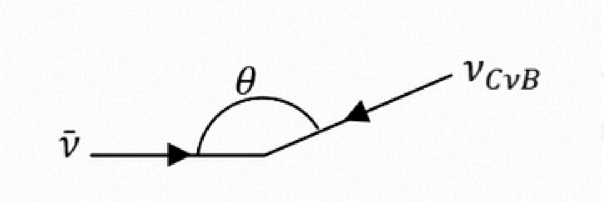
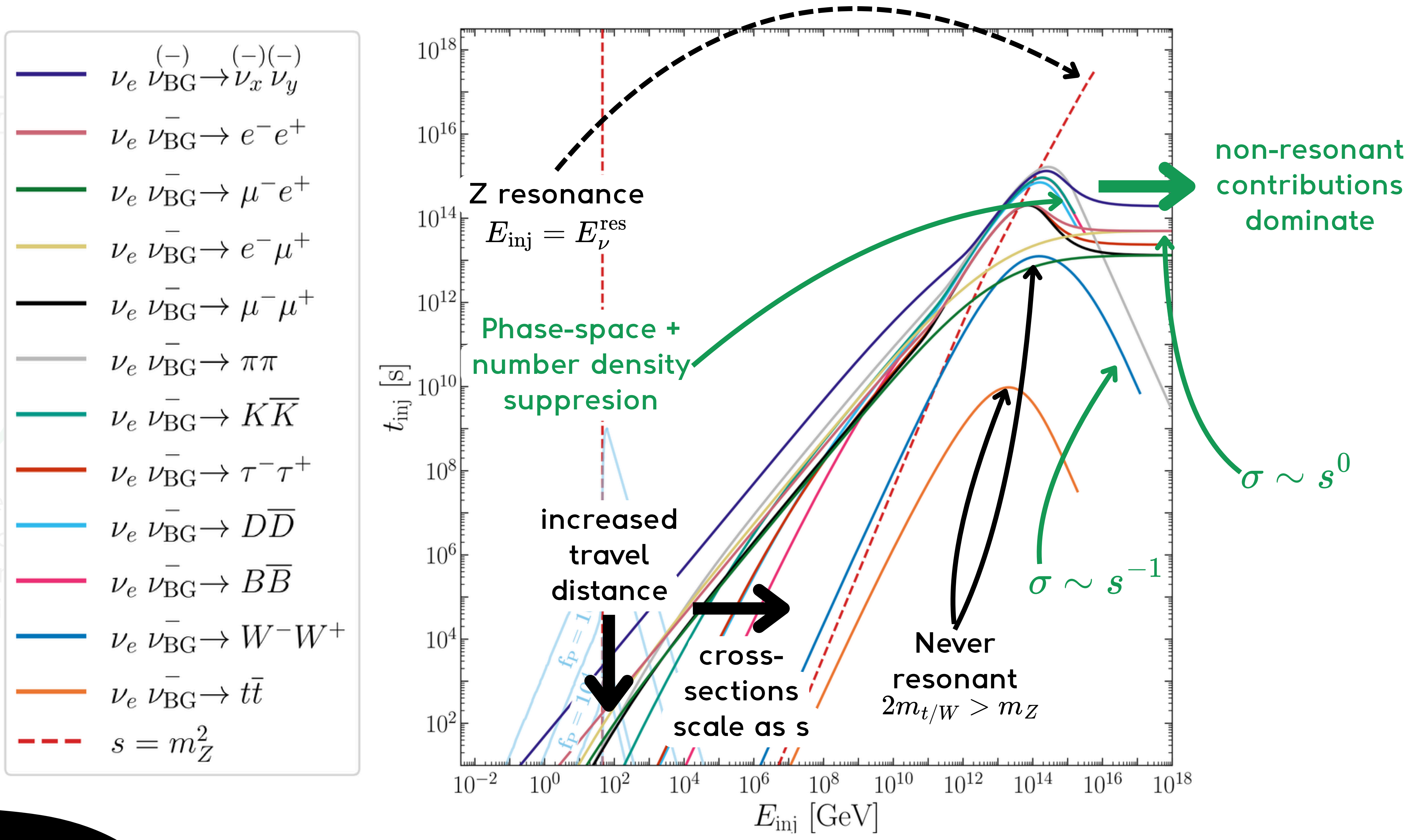


$$E_{\rm inj} >> E_\nu^{\rm res}$$

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



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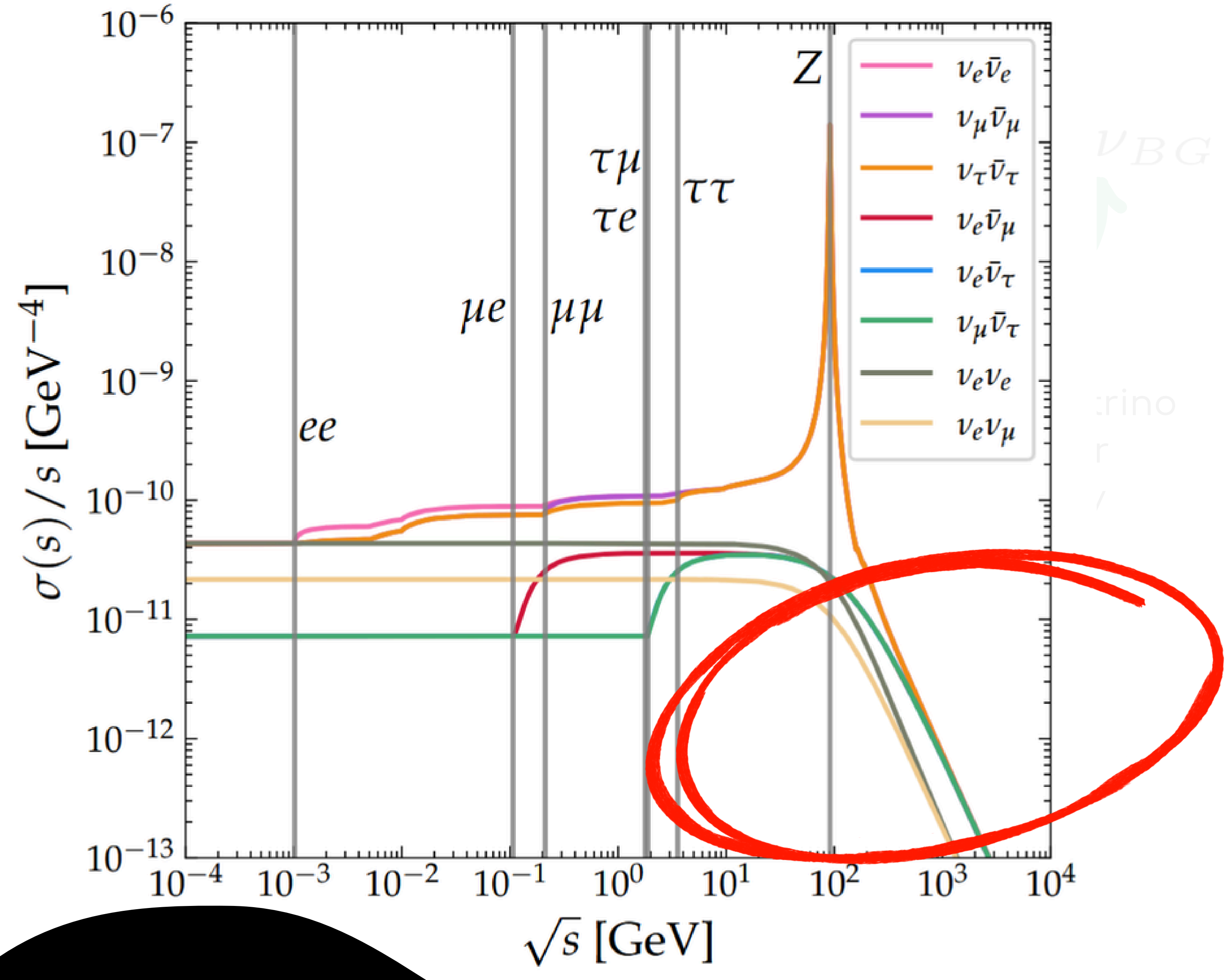

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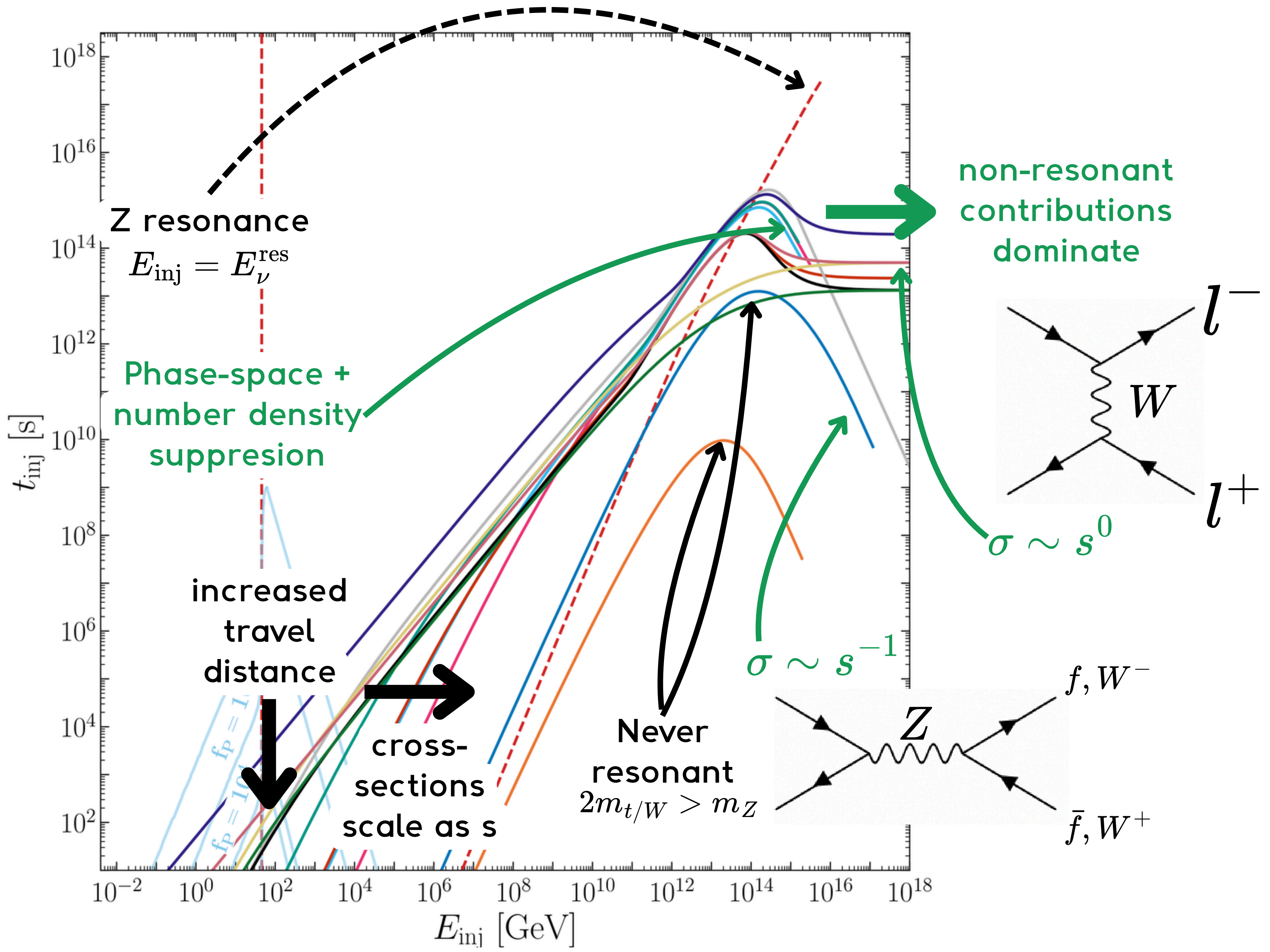
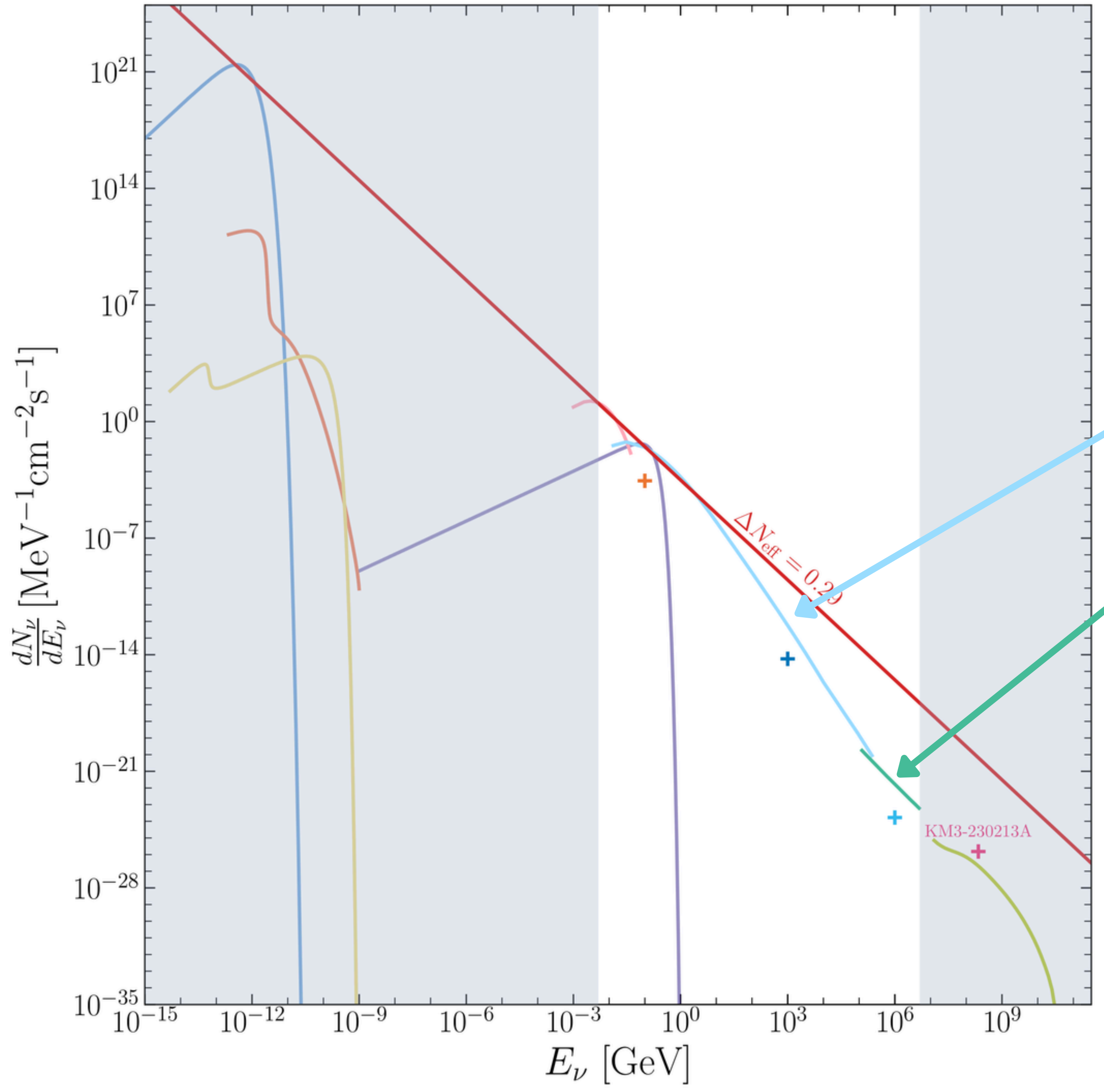


Constraints.



Vitagliano, Tamborra, Raffelt 19'

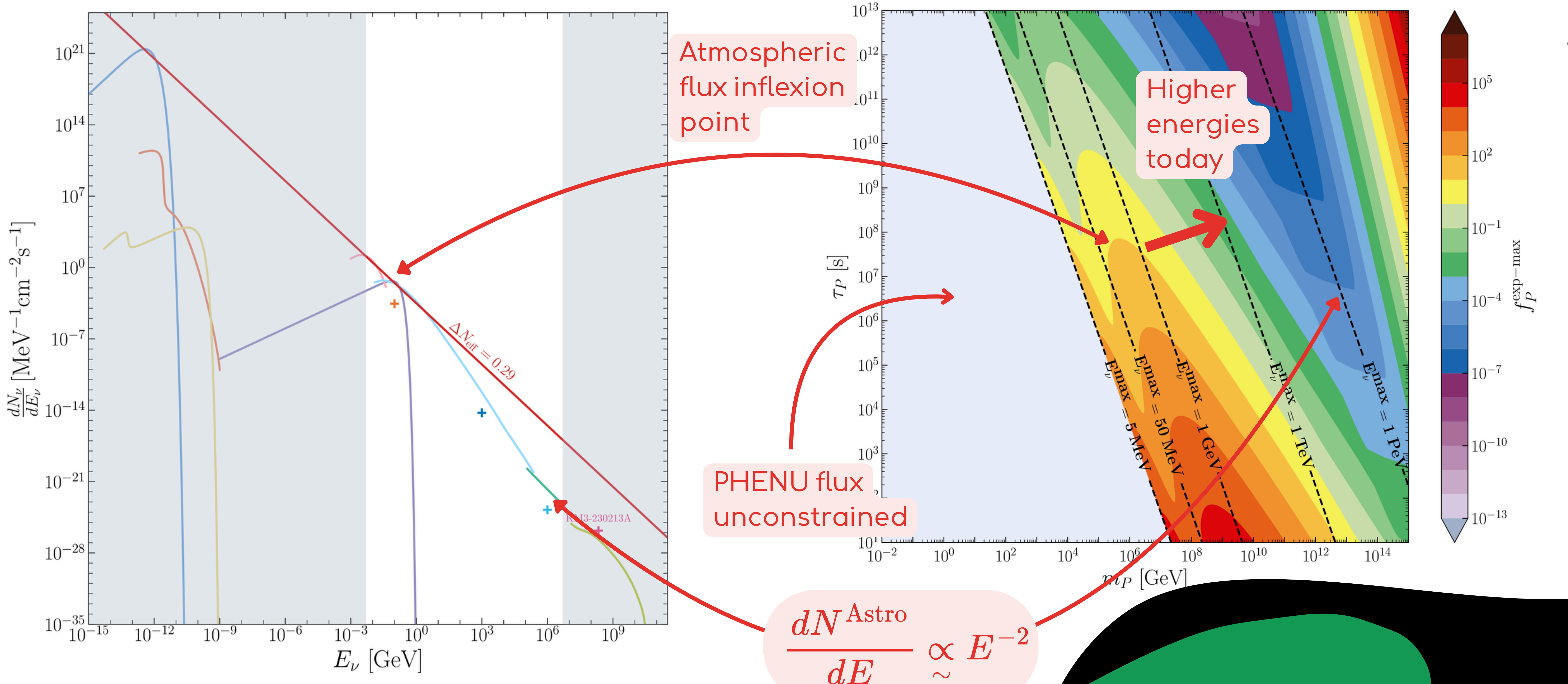
Observational:

- 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

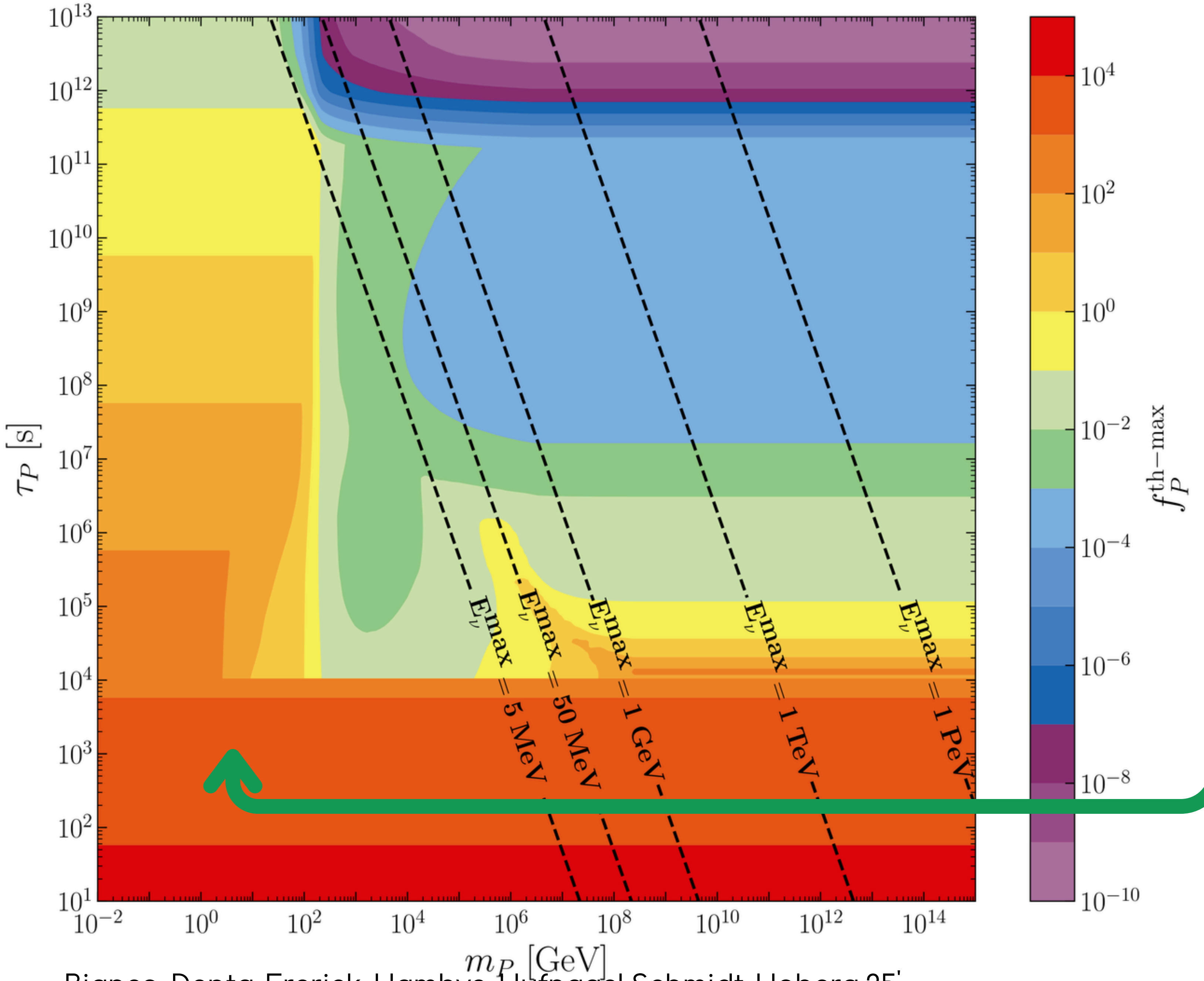
Constraints.



Vitagliano, Tamborra, Raffelt 19'

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

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

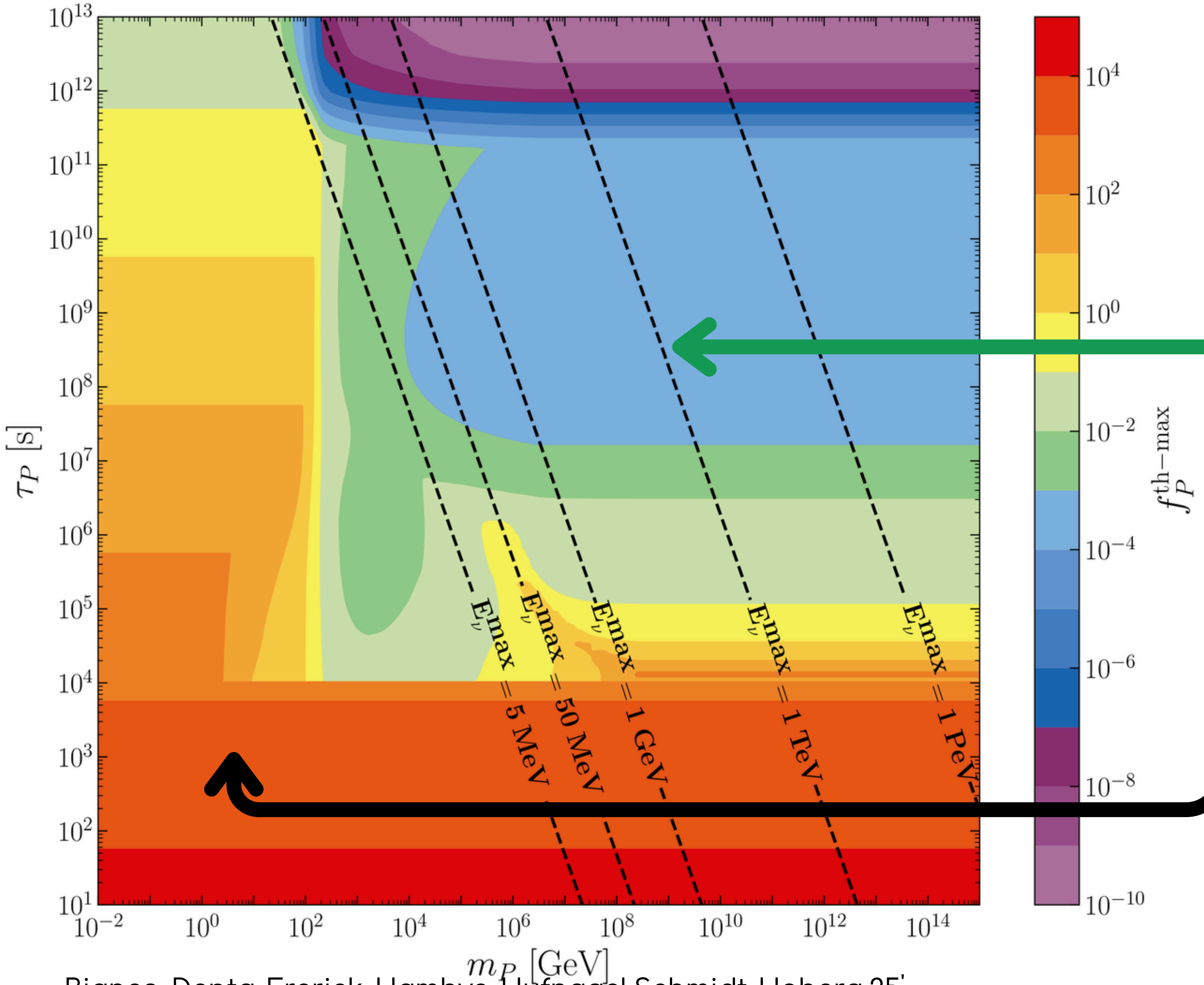
N_{eff} bound on additional neutrino energy density

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

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

Cielo, Escudero, Mangano, Pisanti '23

Constraints.



Cosmological:

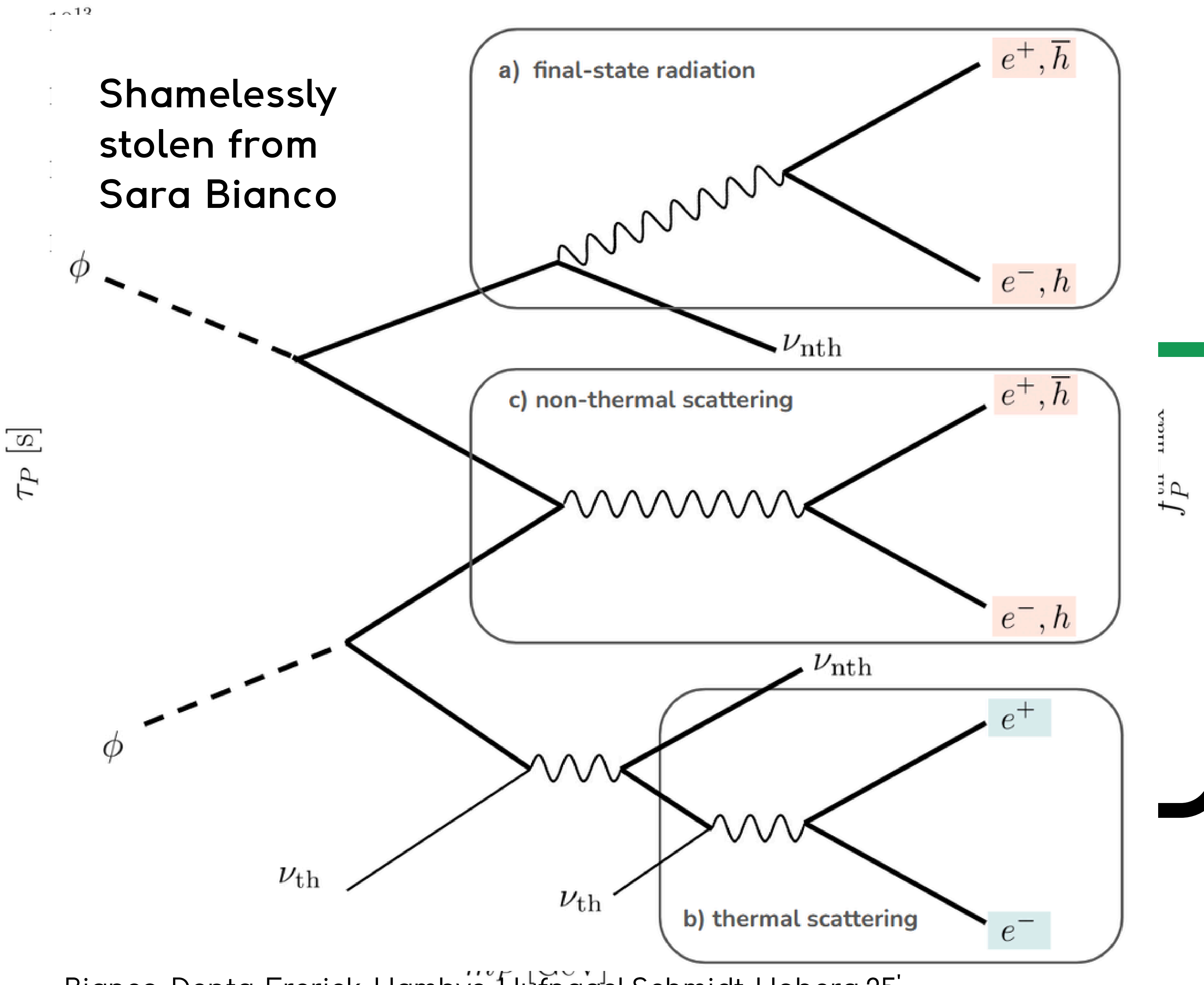
BBN bound from photo and hadro disintegration of light elements

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



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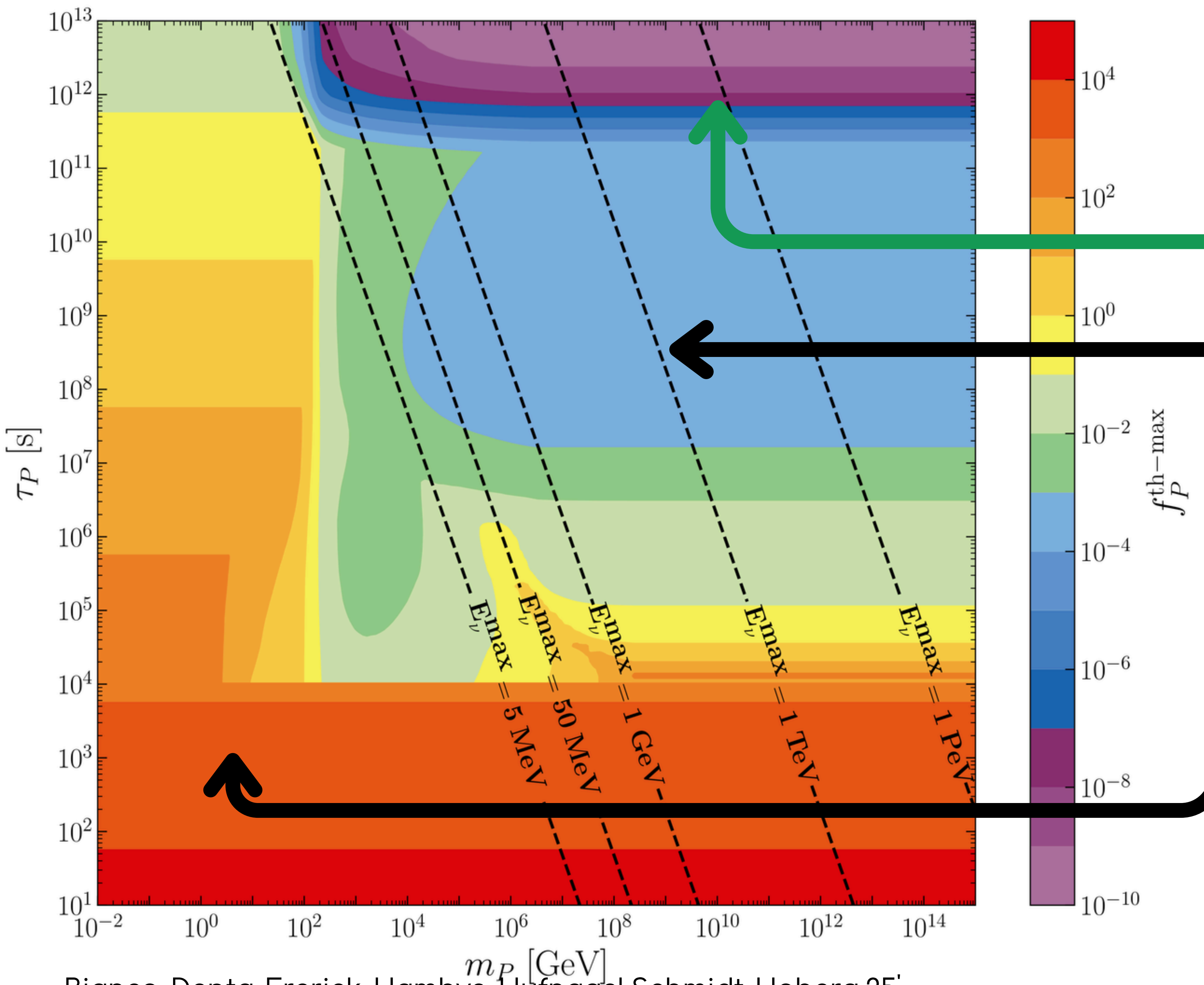
Constraints.



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

Cosmological:

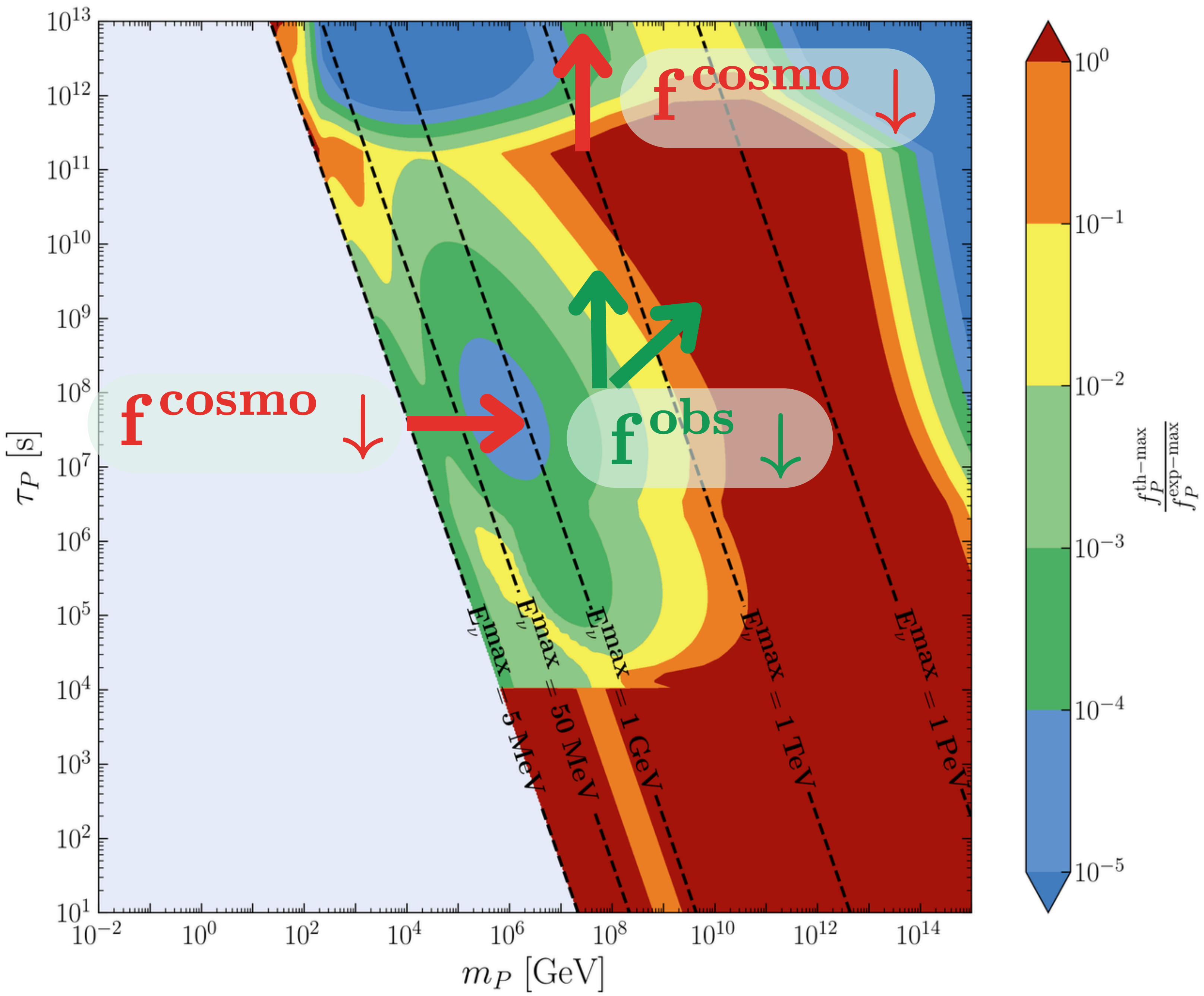
CMB anisotropies bound

BBN bound from photo and hadro disintegration of light elements

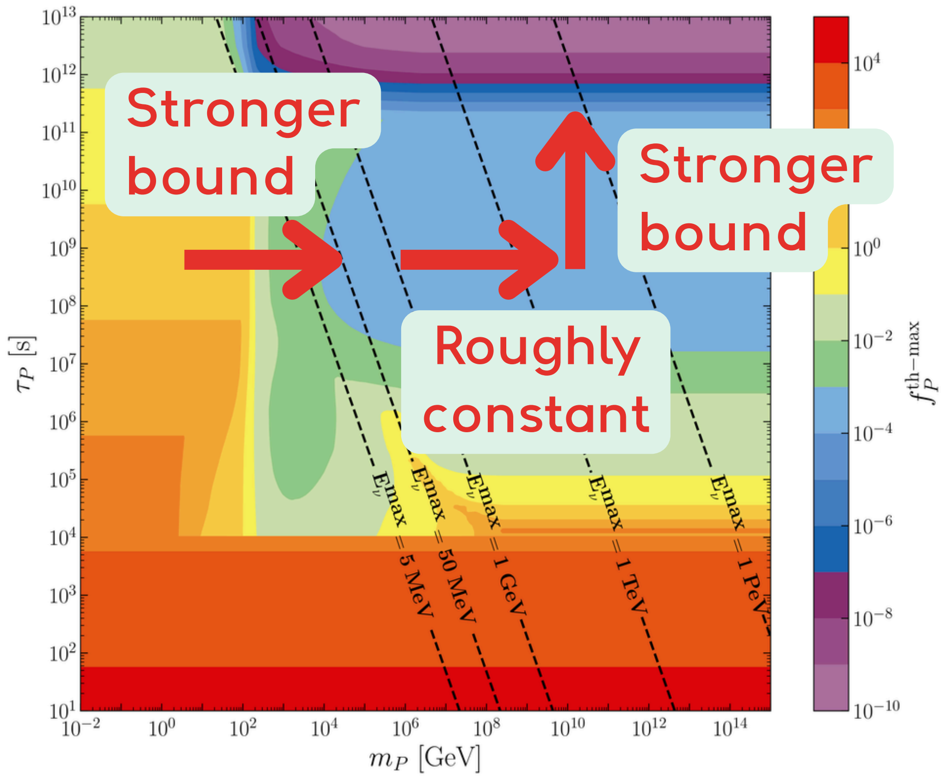
N_{eff} bound on additional neutrino energy density

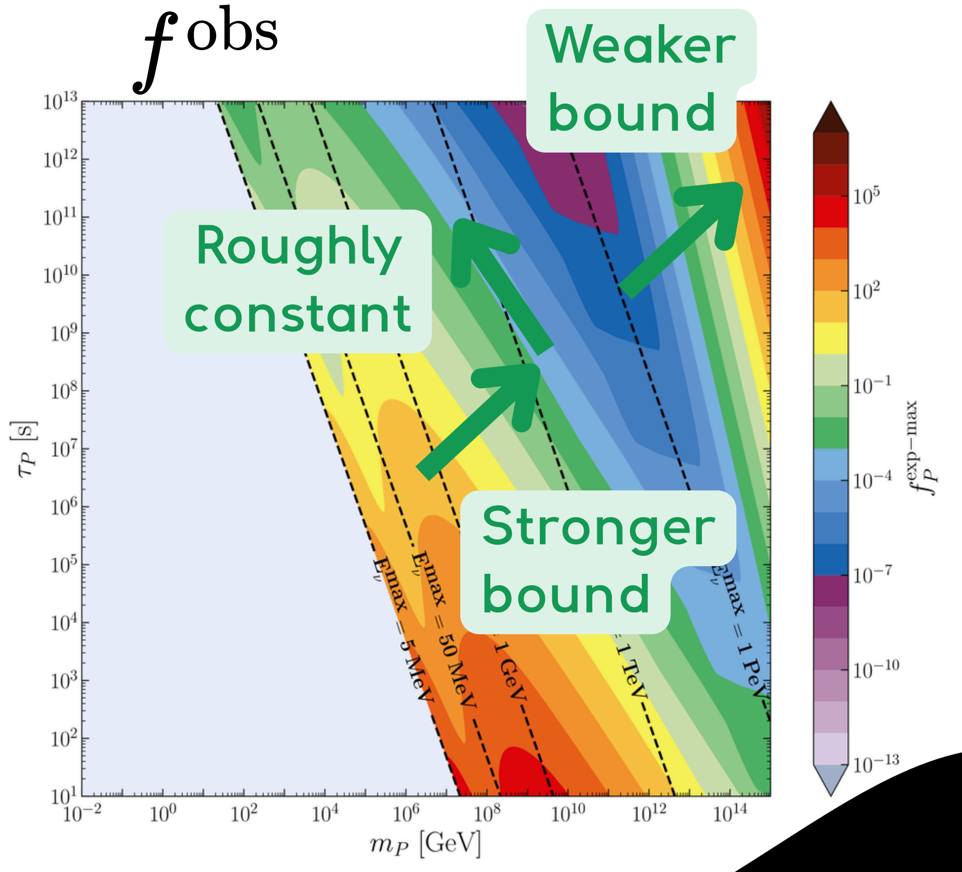
Competing bounds with observations

Constraints.

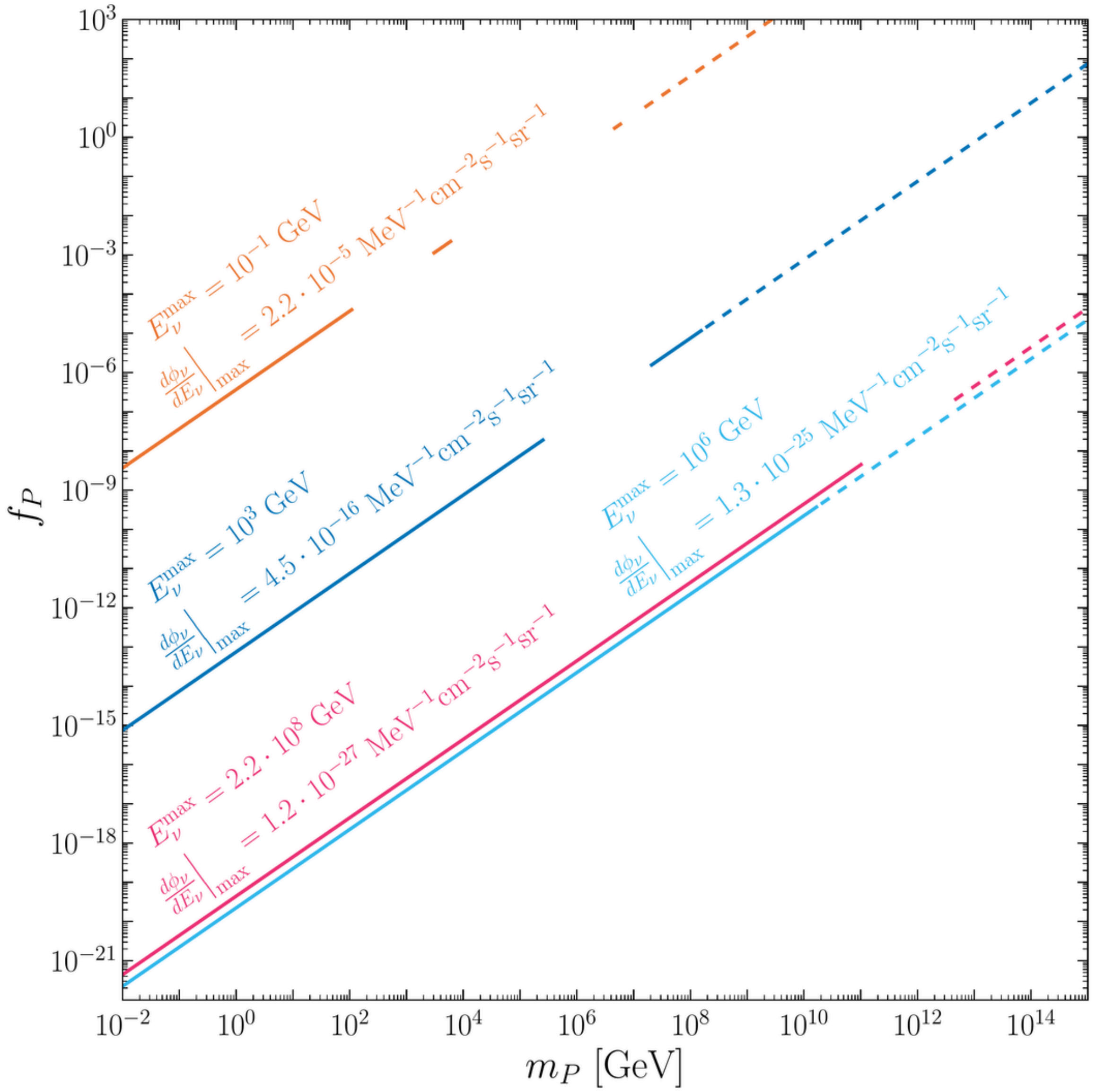


Combination: $\frac{f^{cosmo}}{f^{obs}}$





Constraints.

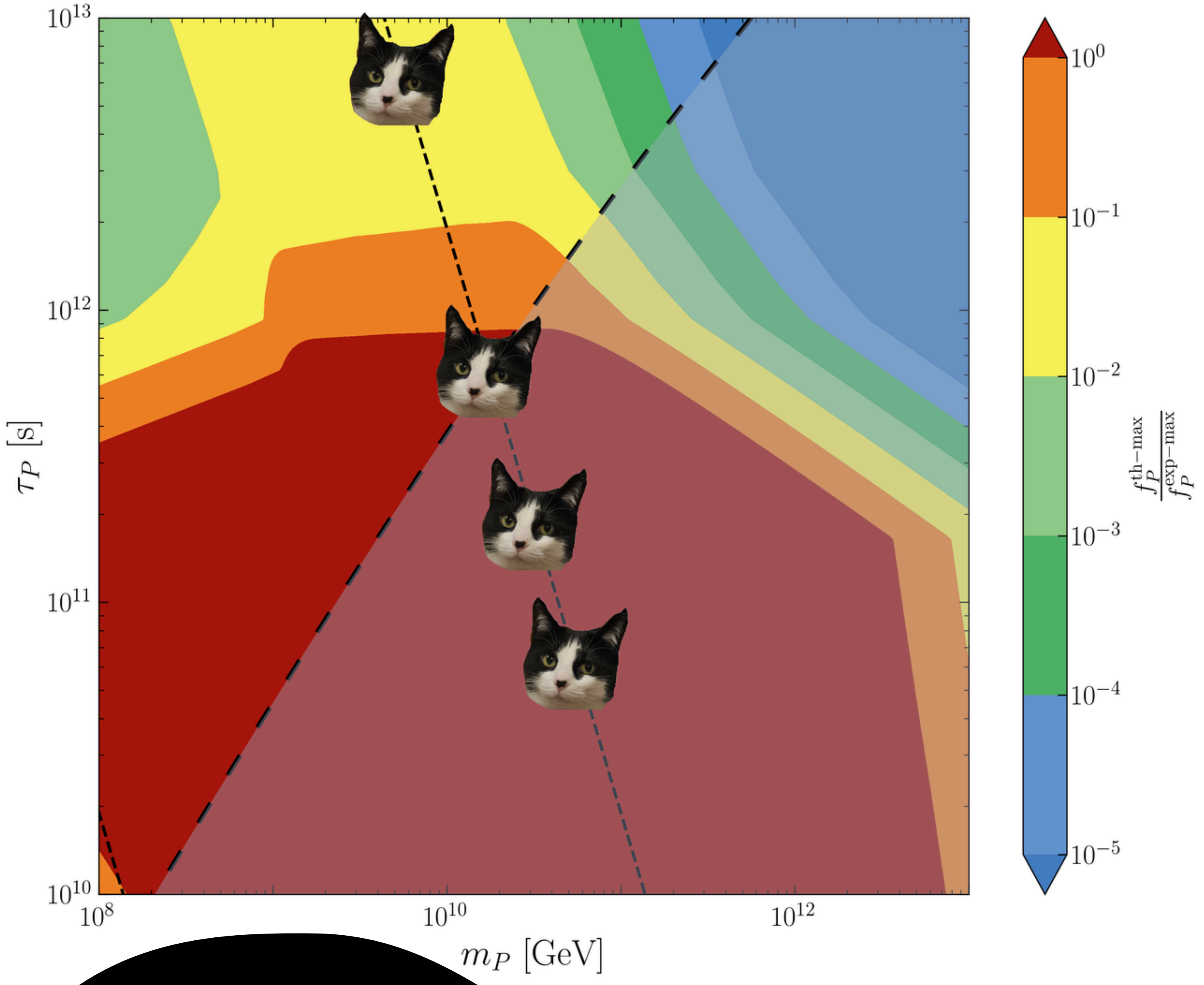


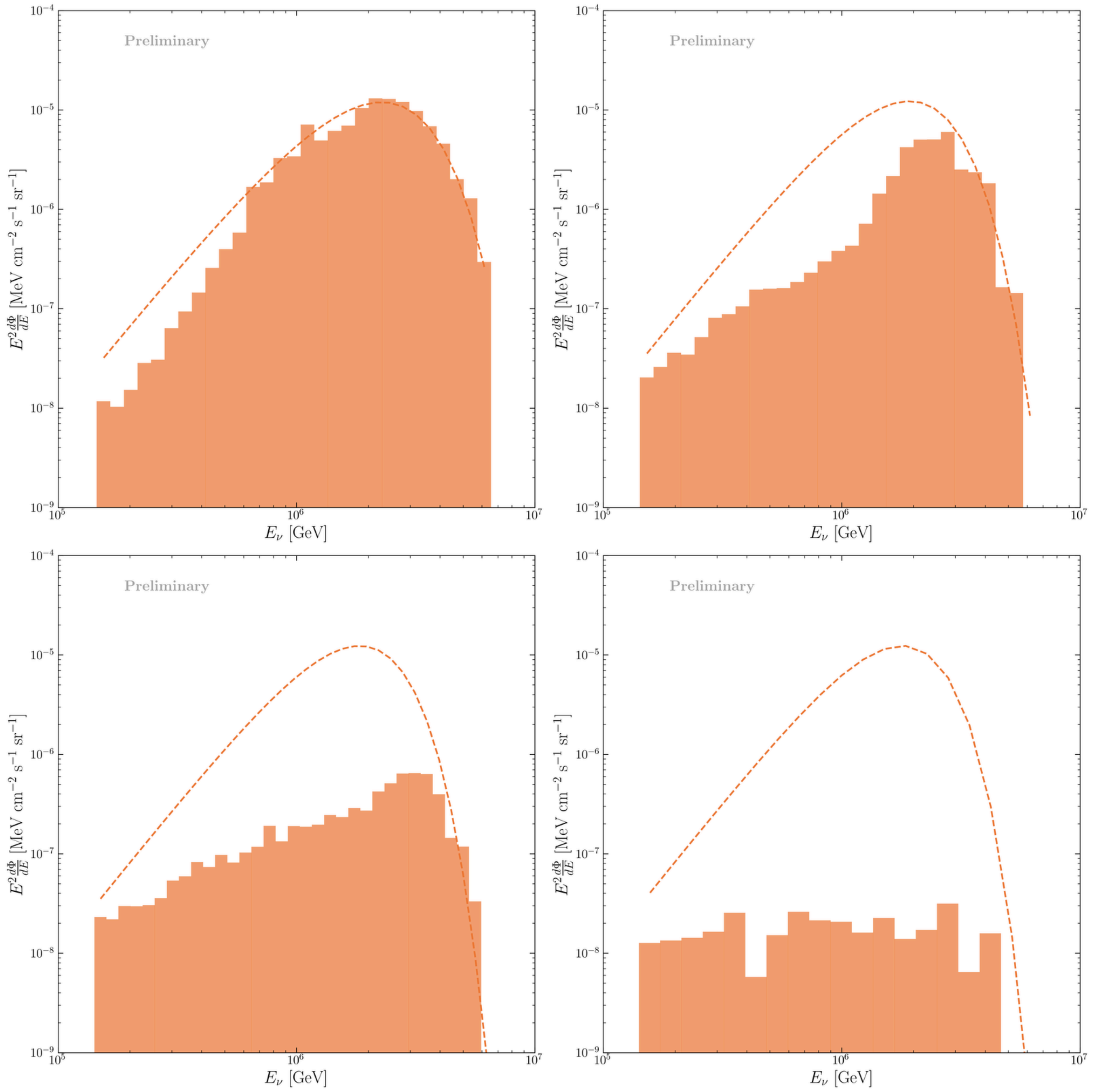
Reconstruction of the heavy relic parameters:

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

- Abundance and mass

Medium interactions II.





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

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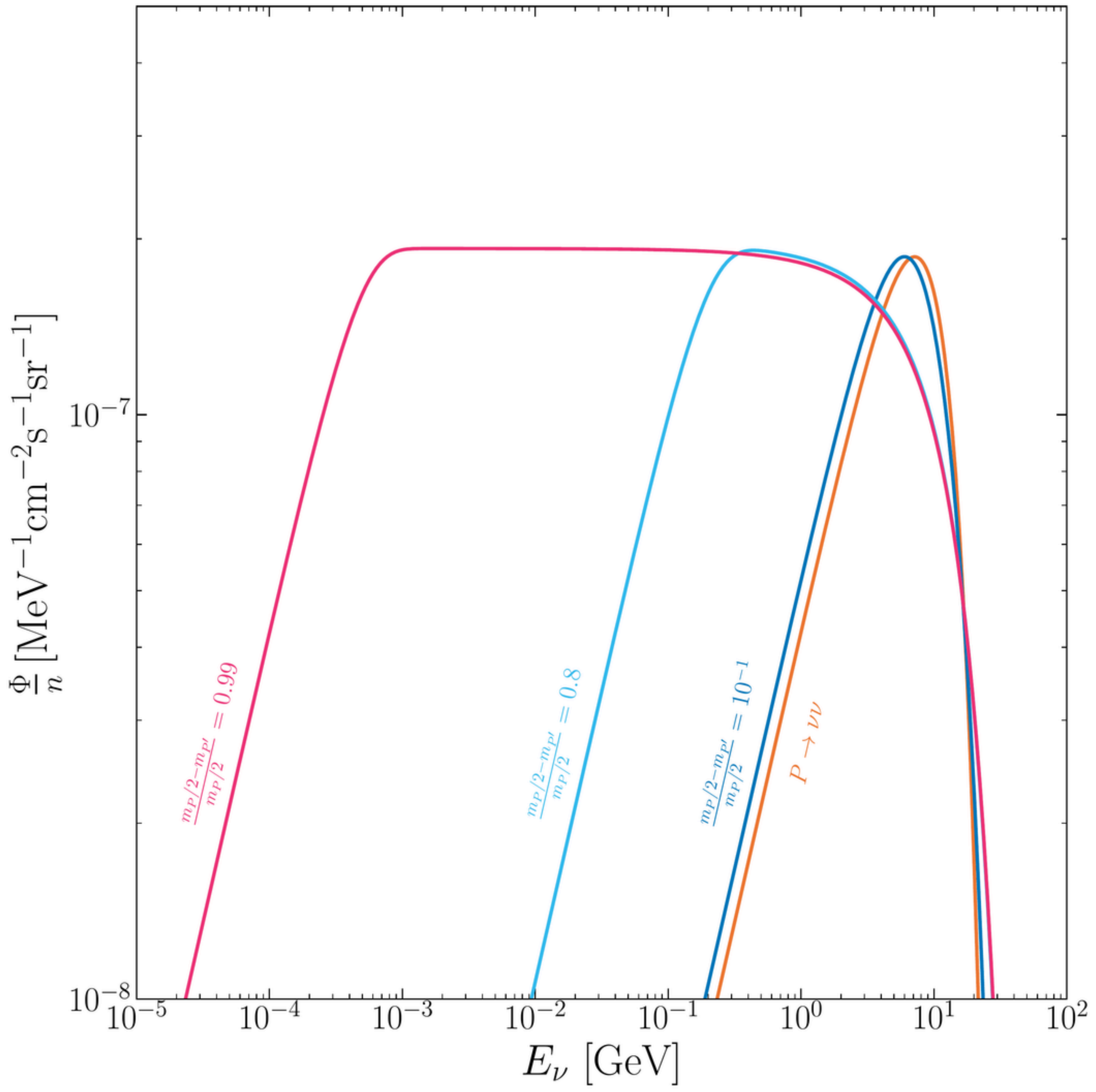
Decay Spectra.

Δ controls the width of the box.

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



Annihilation.

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

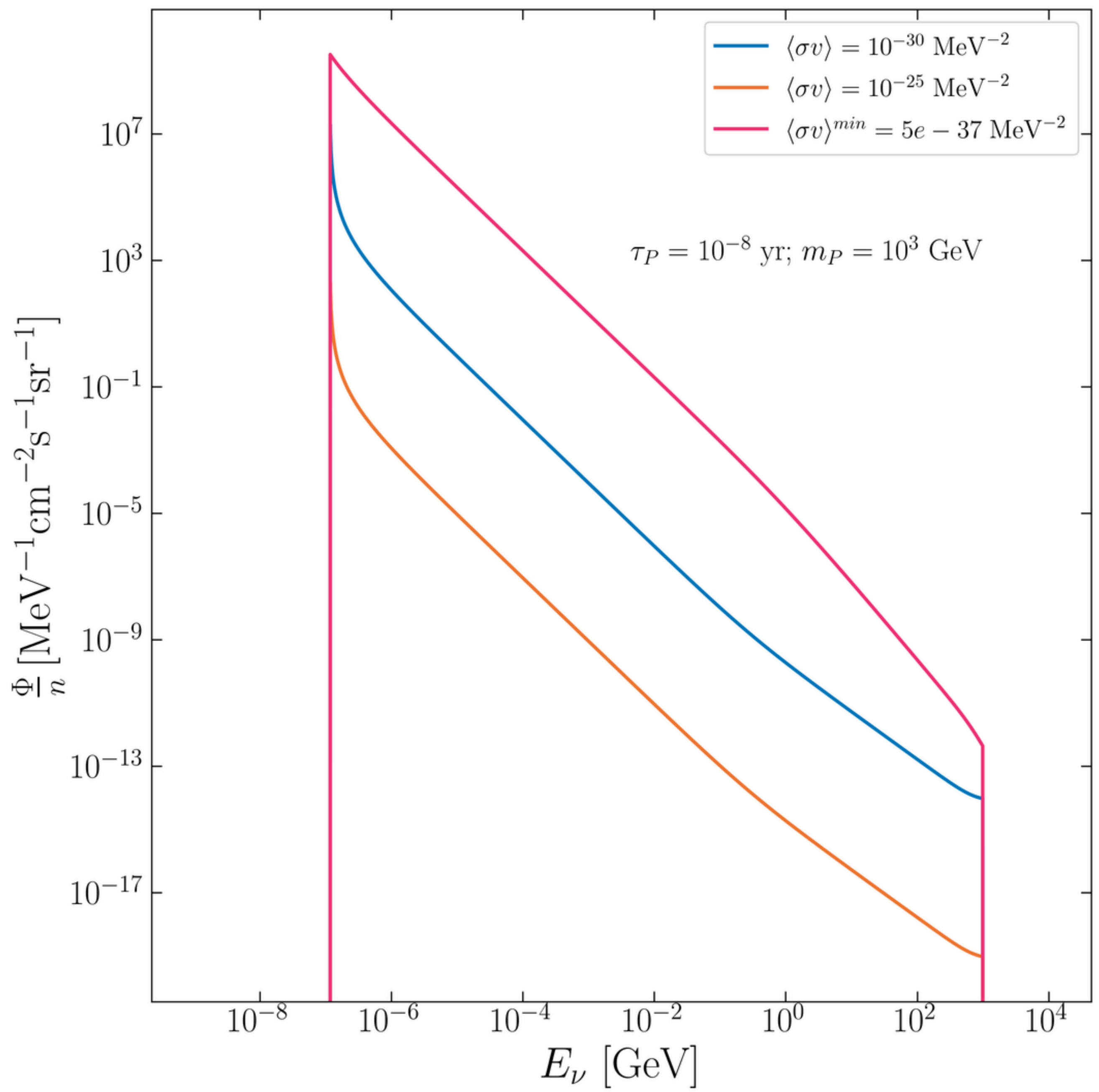
$$\langle \sigma v \rangle n_P^{eq} < H(t^{inj}) \rightarrow \langle \sigma v \rangle < \left(\frac{2\pi}{m_P T^{inj}}\right)^{3/2} \frac{e^{m_P/T^{inj}}}{2 g_i t^{inj}}$$

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.

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



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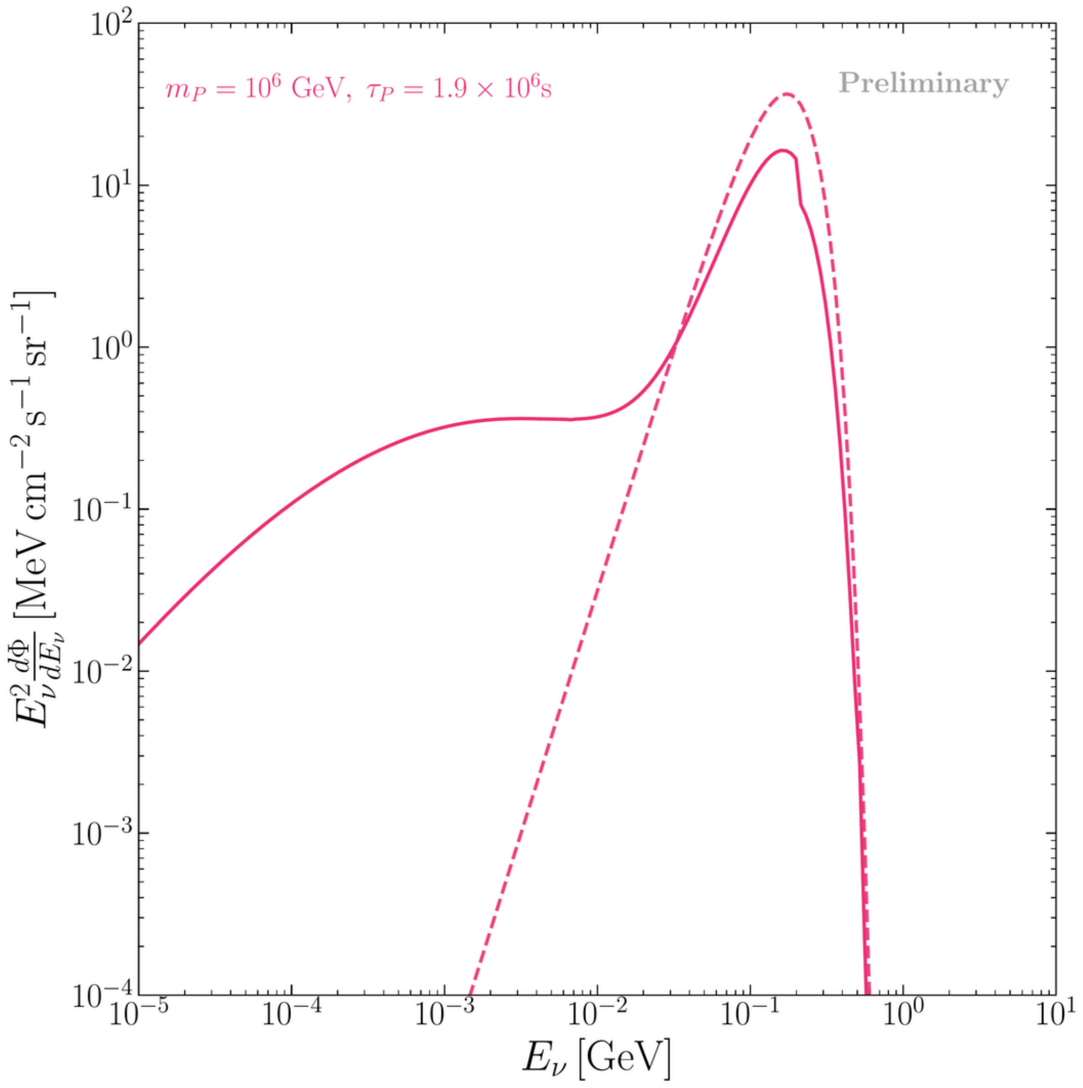
Sharp Spectral Features.

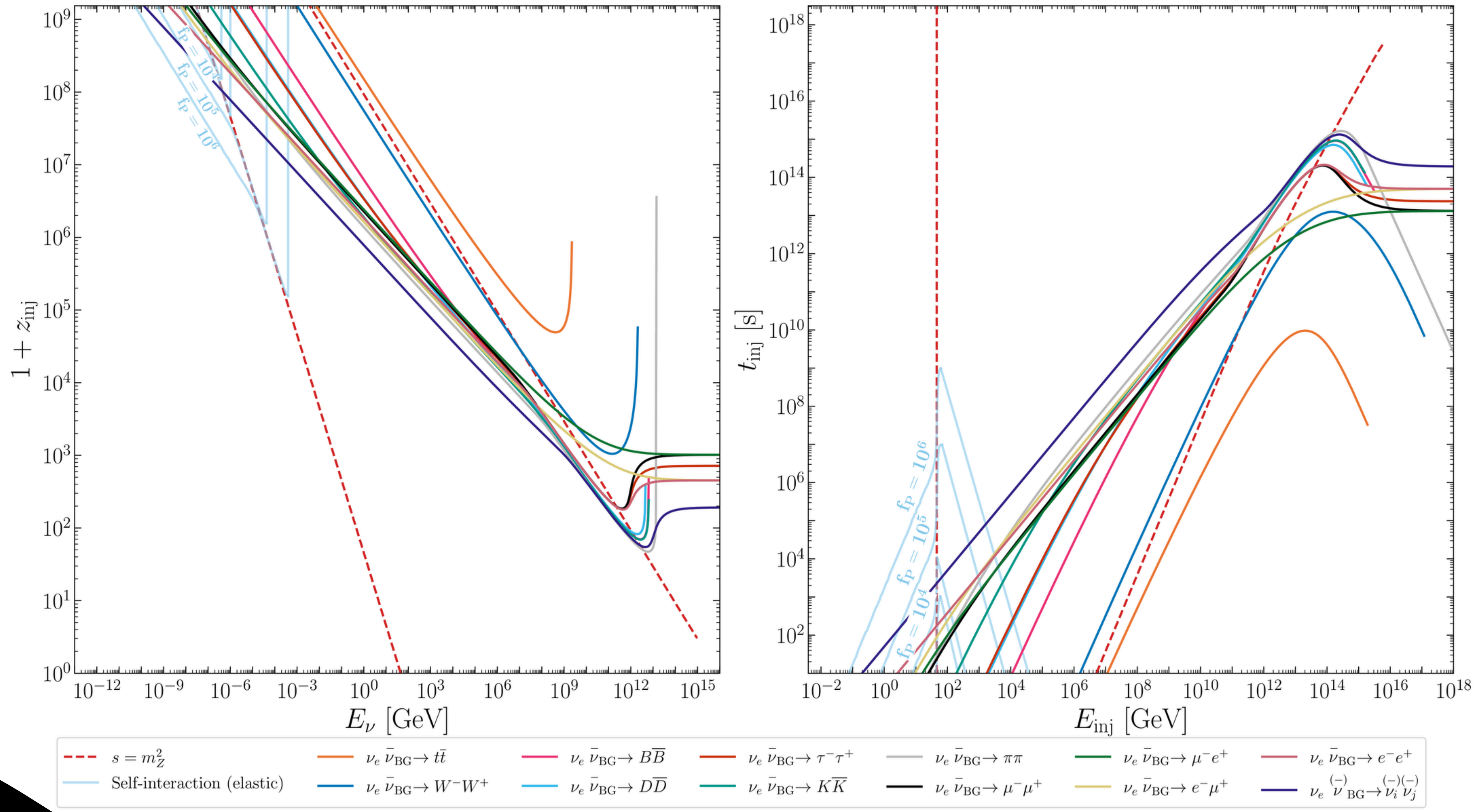


Final state radiation broadening

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

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

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

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

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

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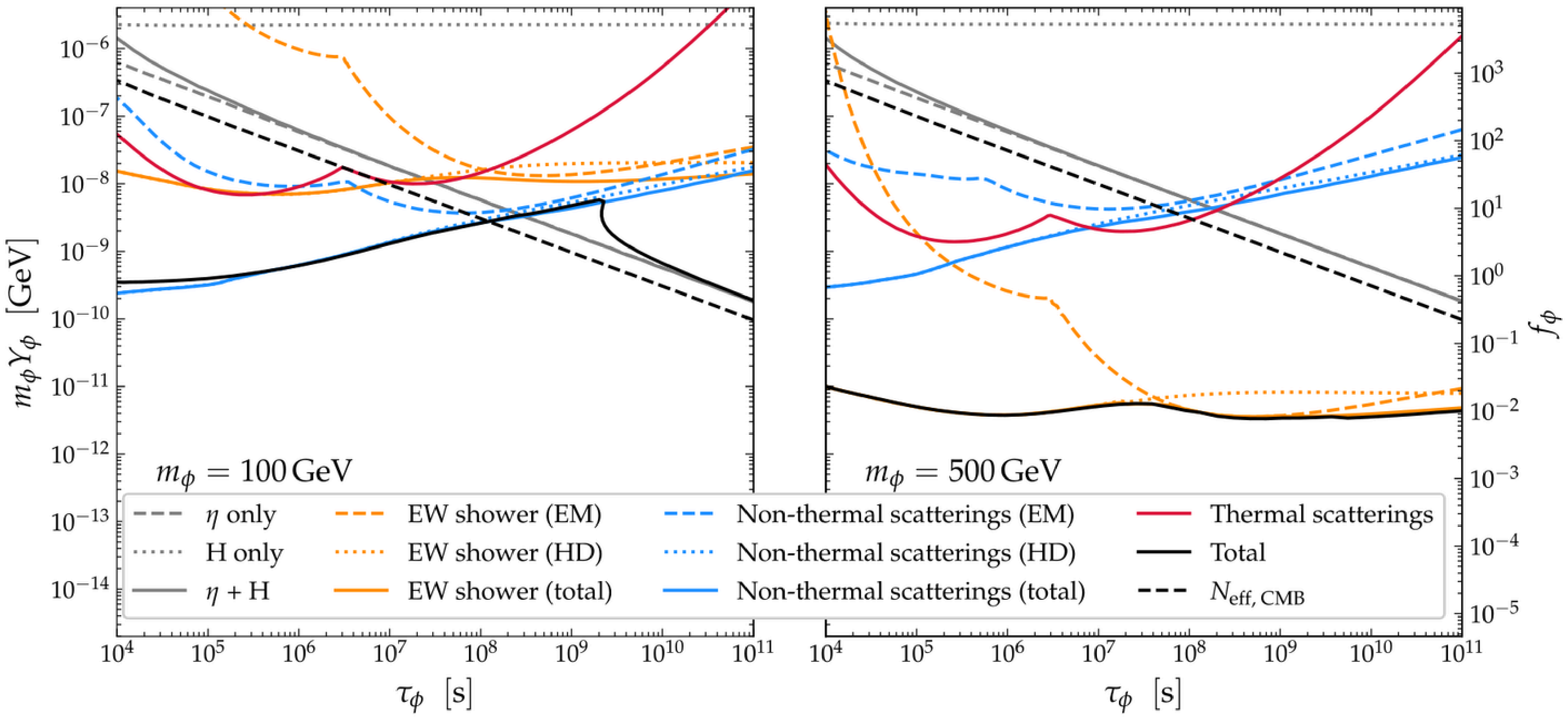
Self-scattering.

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

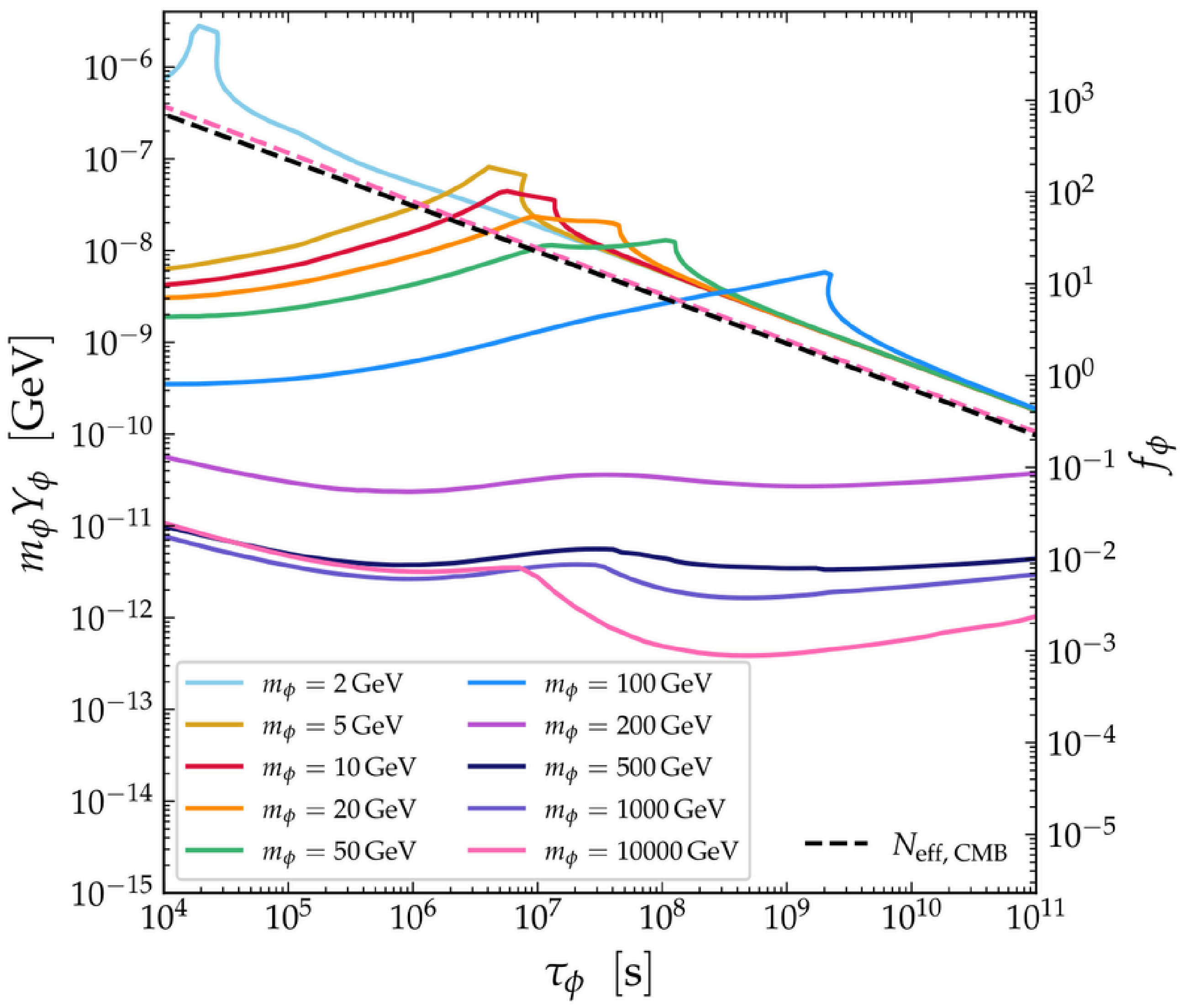
$$\langle\Gamma(E_0, z)\rangle = \frac{\Omega_P^0 \rho_{crit}^0 (1+z)^3}{4E_0^2(1+z)^2 m_P \tau_P} \int_0^{2E_0(1+z)m_P} ds\sigma(s)s \int_{\frac{s}{4E_0(1+z)}}^{m_P/2} \frac{dE}{E^3}\frac{e^{-t(a_E)/\tau_P}}{H(a_E)}$$

BBN constraints.



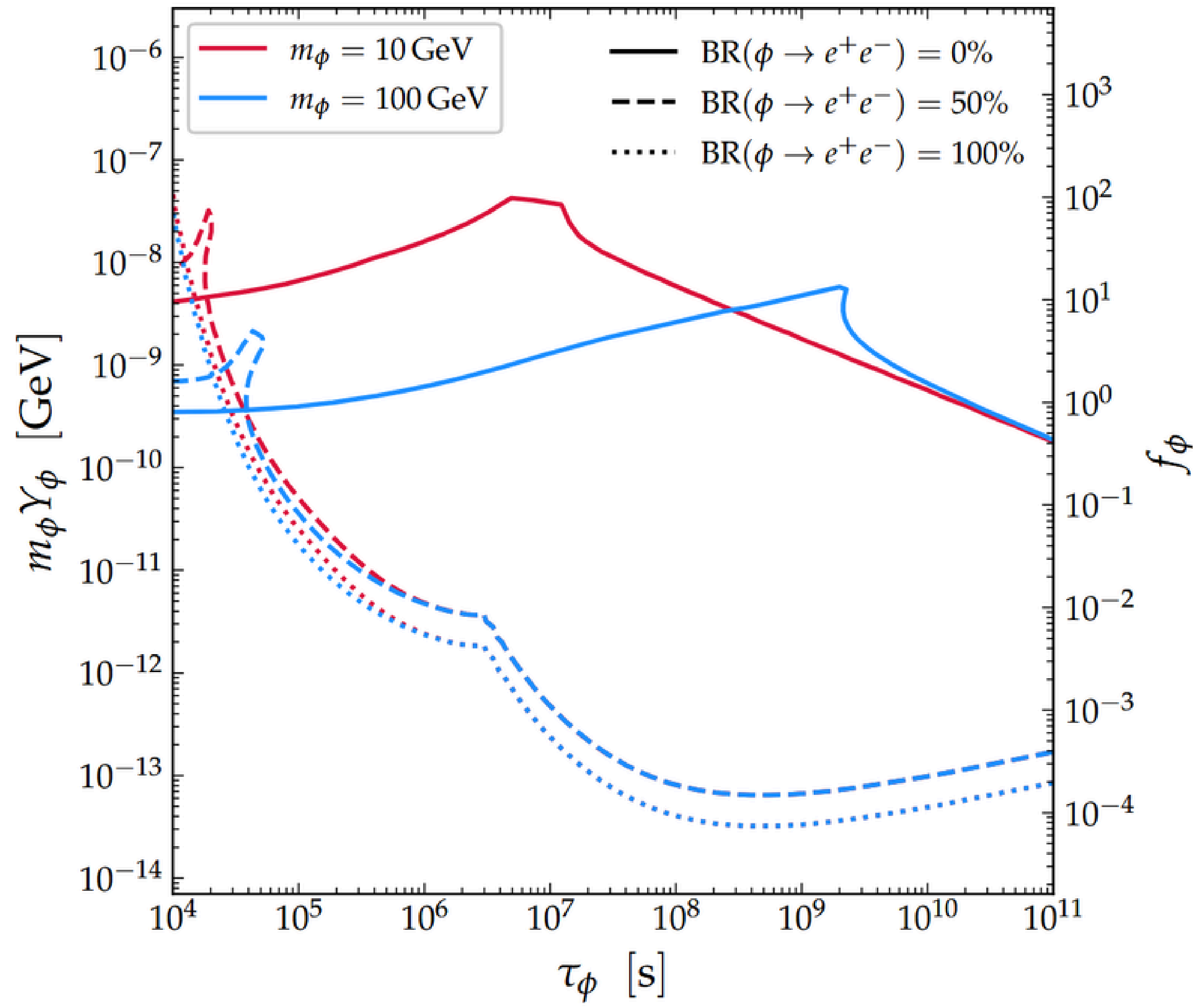
Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'

BBN constraints.

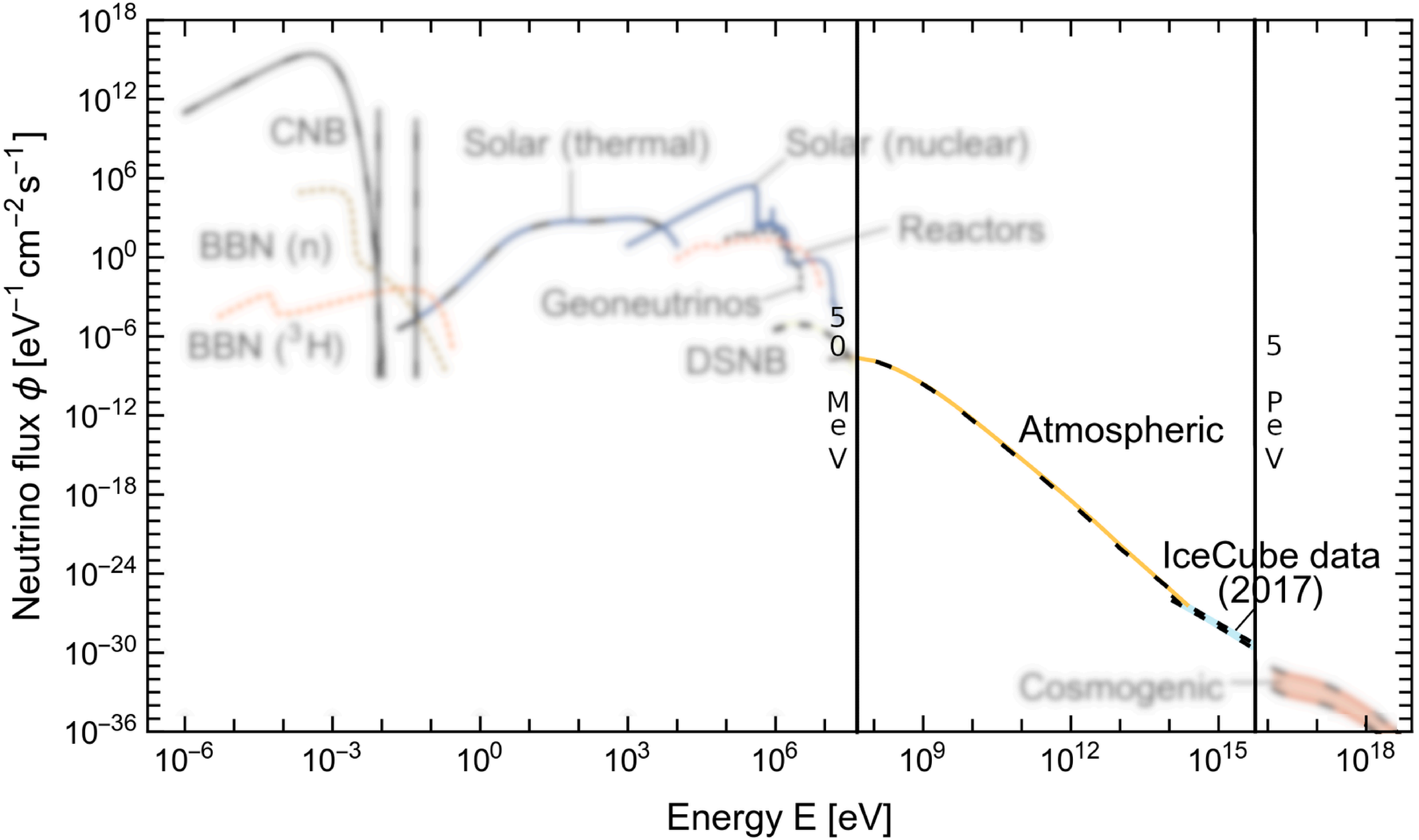


Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'

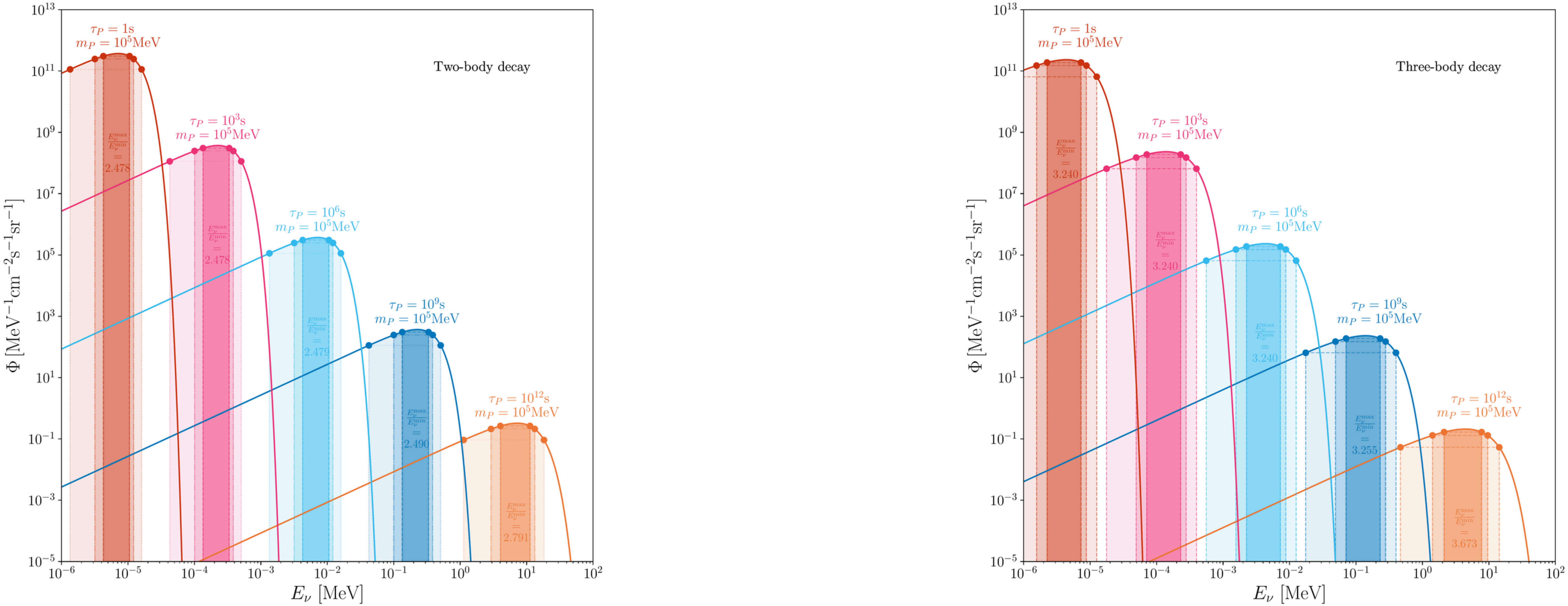
BBN constraints.



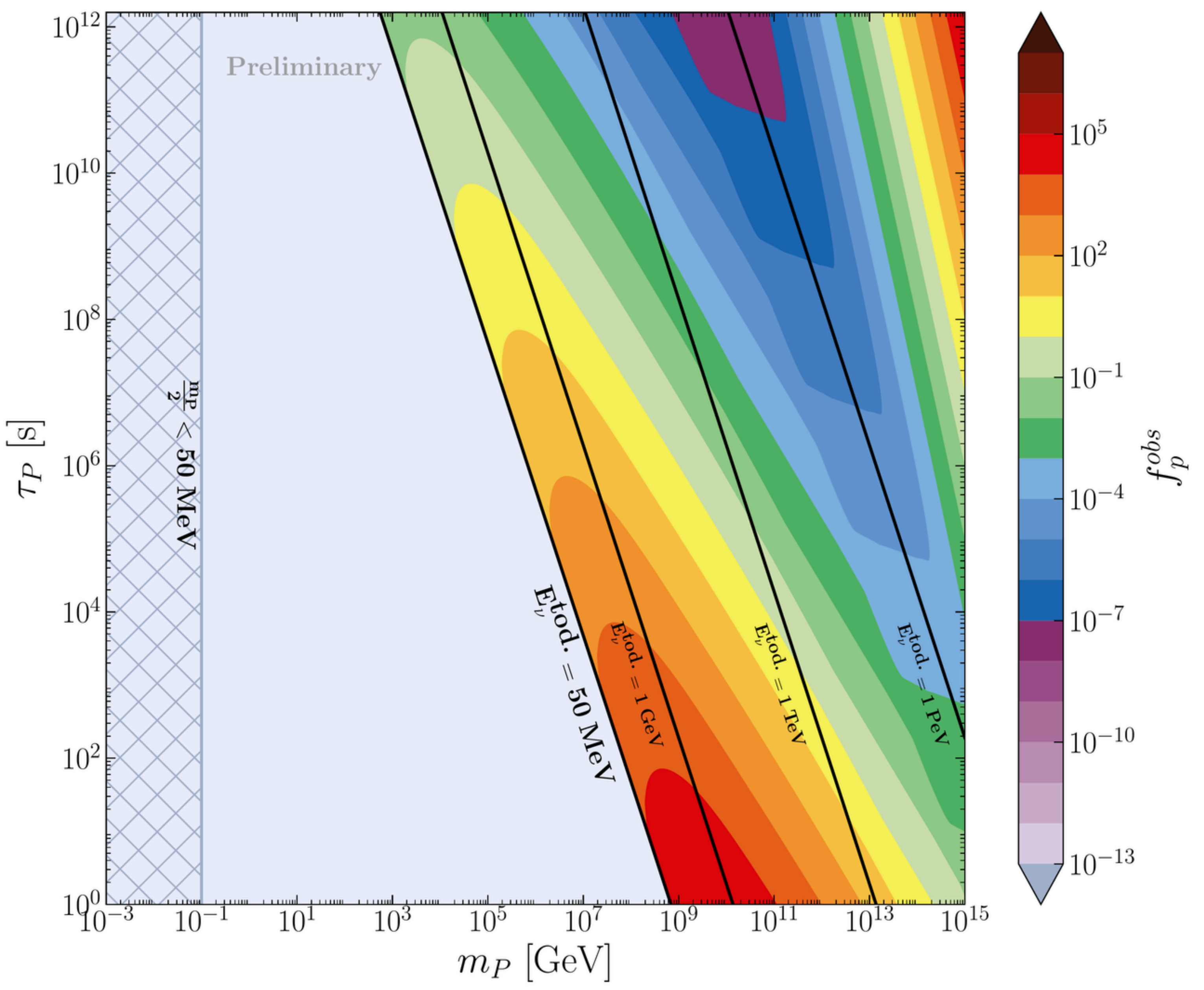
Bianco, Depta, Frerick, Hambye, Hufnagel,Scmidt-Hoberg 25'



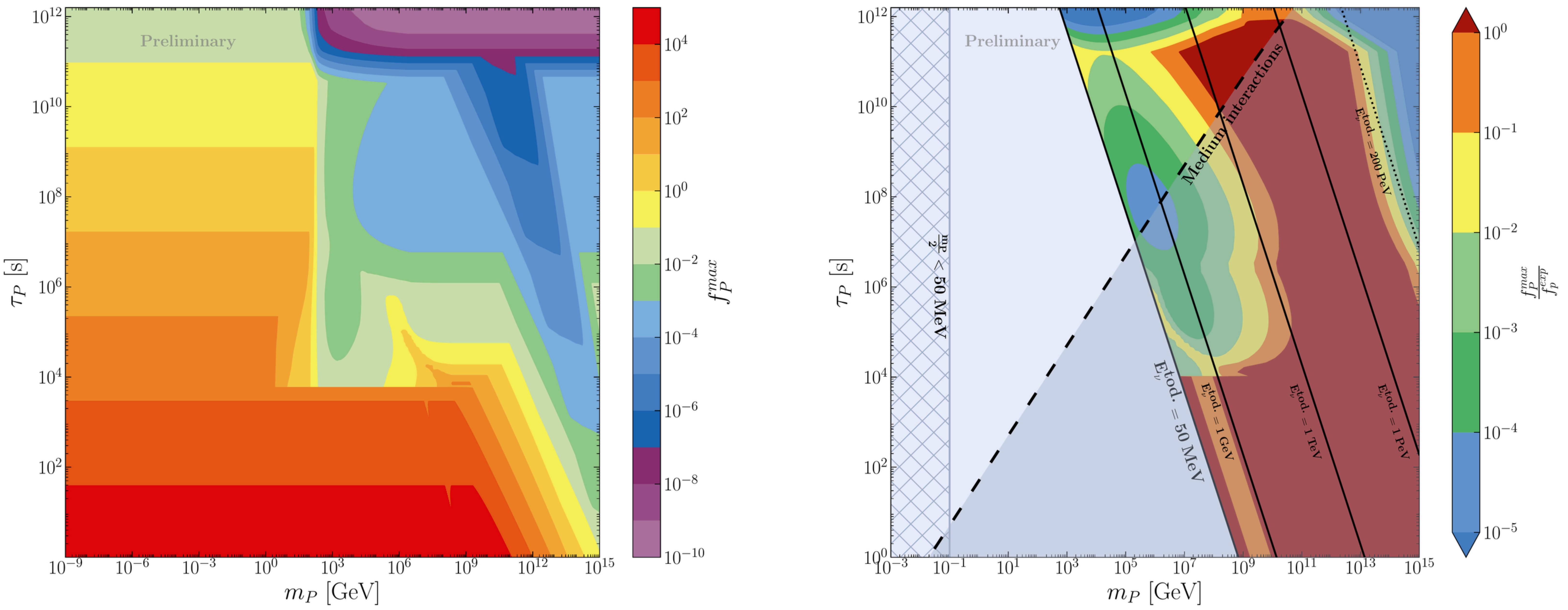
Vitagliano, Tamborra, Raffelt '19



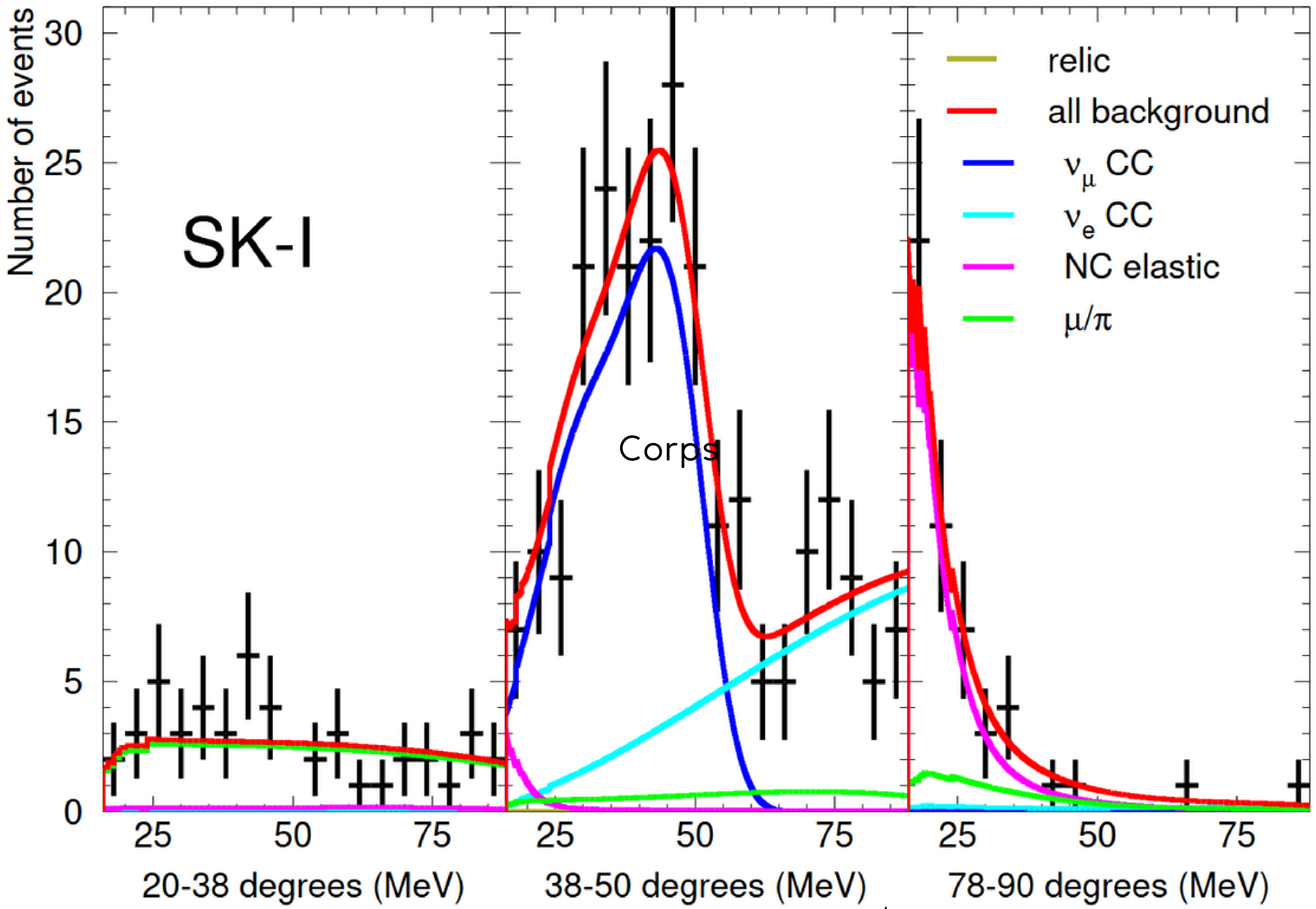
Two-body decay
Three-body decay
$\tau_P = 1$s
$m_P = 10^5$MeV
$\tau_P = 10^3$s
$m_P = 10^5$MeV
$\tau_P = 10^6$s
$m_P = 10^5$MeV
$\tau_P = 10^9$s
$m_P = 10^5$MeV
$\tau_P = 10^{12}$s
$m_P = 10^5$MeV
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.478$
$\frac{E_\nu^{\max}}{E_\nu^{\min}} = 2.478$
$\frac{E_\nu^{\max}}{E_\nu^{\min}}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



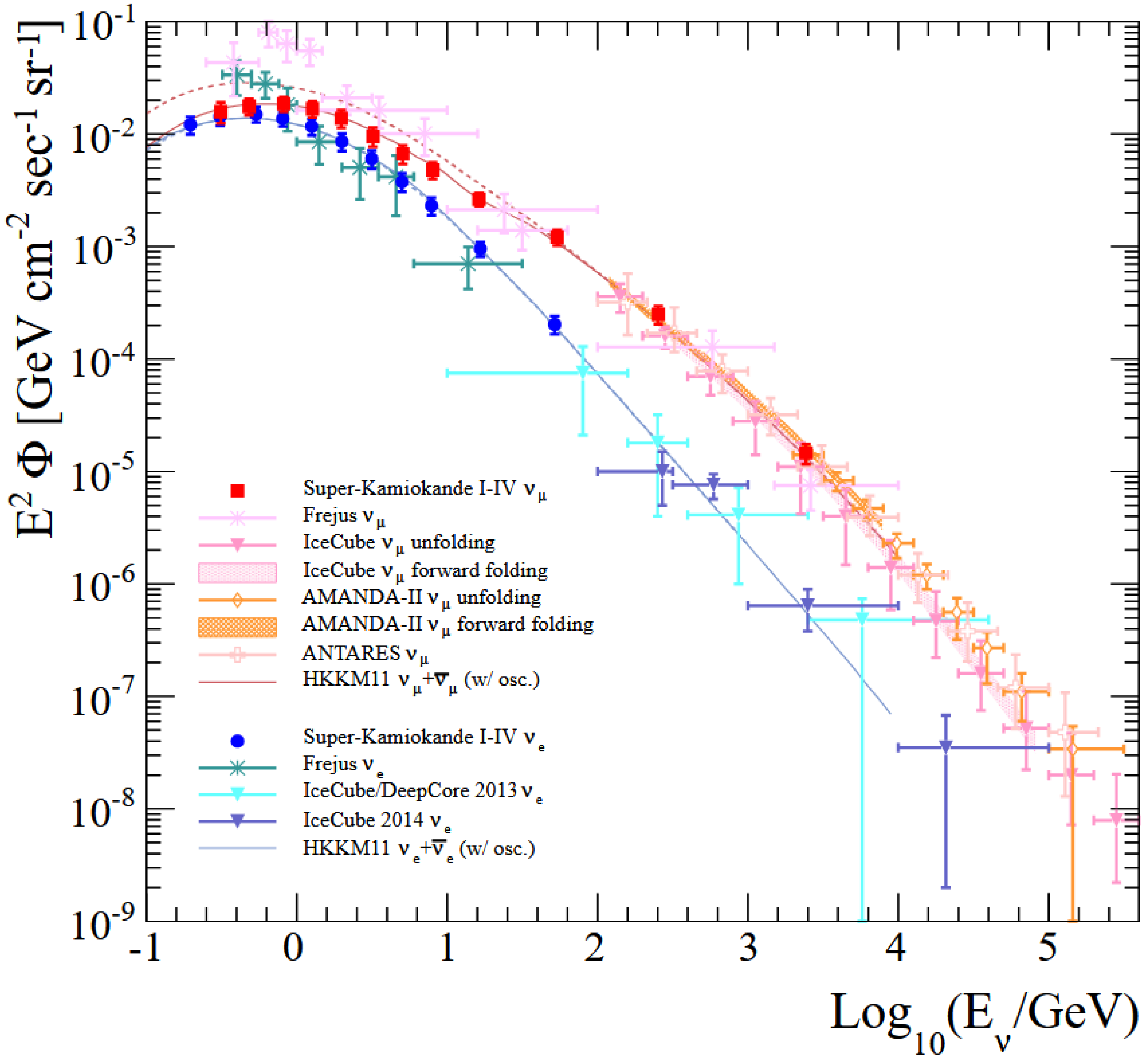
Preliminary
$\frac{m_P}{2} < 50$ MeV
$E_\nu^{\rm tod.} = 50$ MeV
$E_\nu^{\rm tod.} = 1$ GeV
$E_\nu^{\rm tod.} = 1$ TeV
$E_\nu^{\rm tod.} = 1$ PeV
τ_P [s]
m_P [GeV]
f_p^{obs}



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'

Models

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