Zee-Burst: Non-Standard Interactions in IceCube

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arXiv:1908.02779

Scalars in the Zee model

A. Zee Phys. Lett.95B,461(1980)

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Due to the structure of scalar potential, H_2^+ will mix with η^+

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As for the Yukawa sector, we have:

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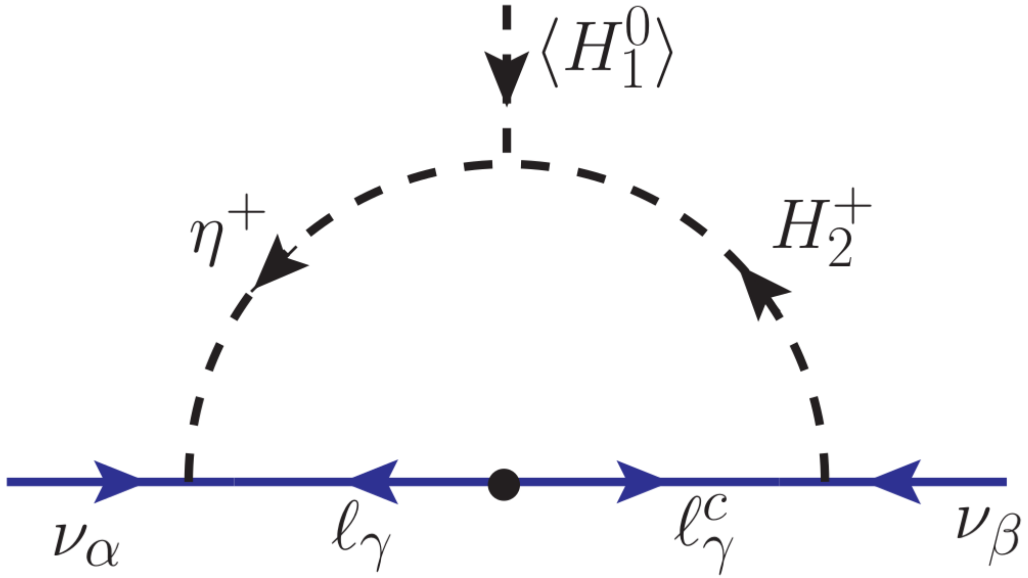

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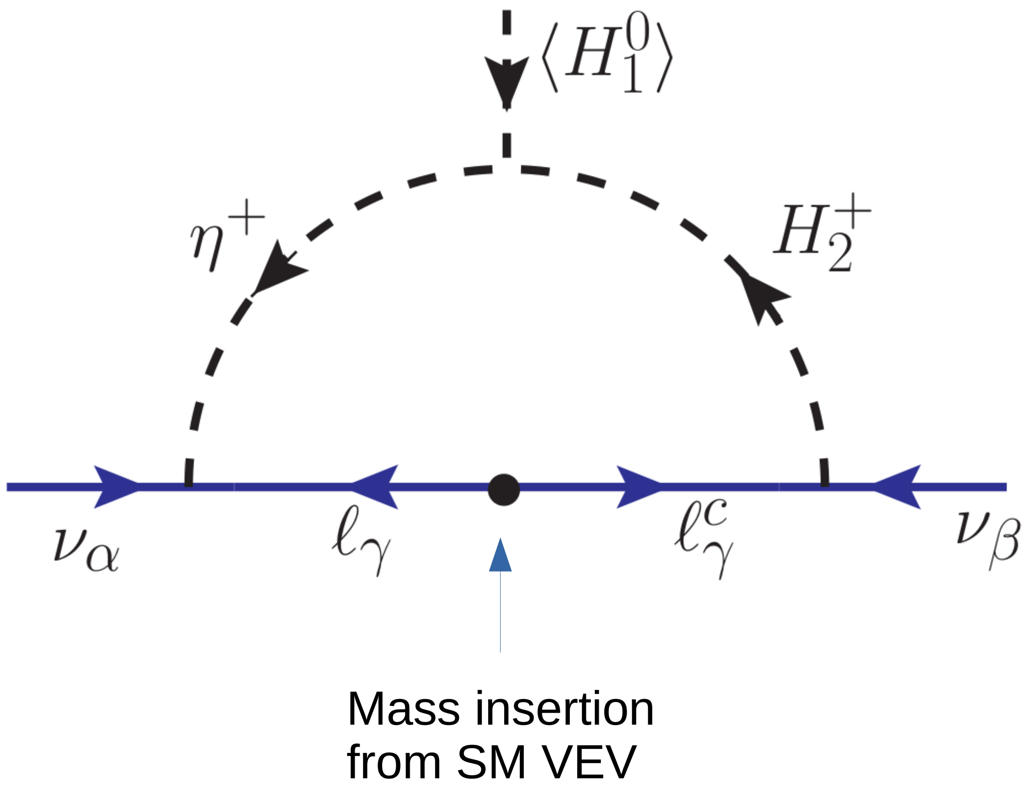

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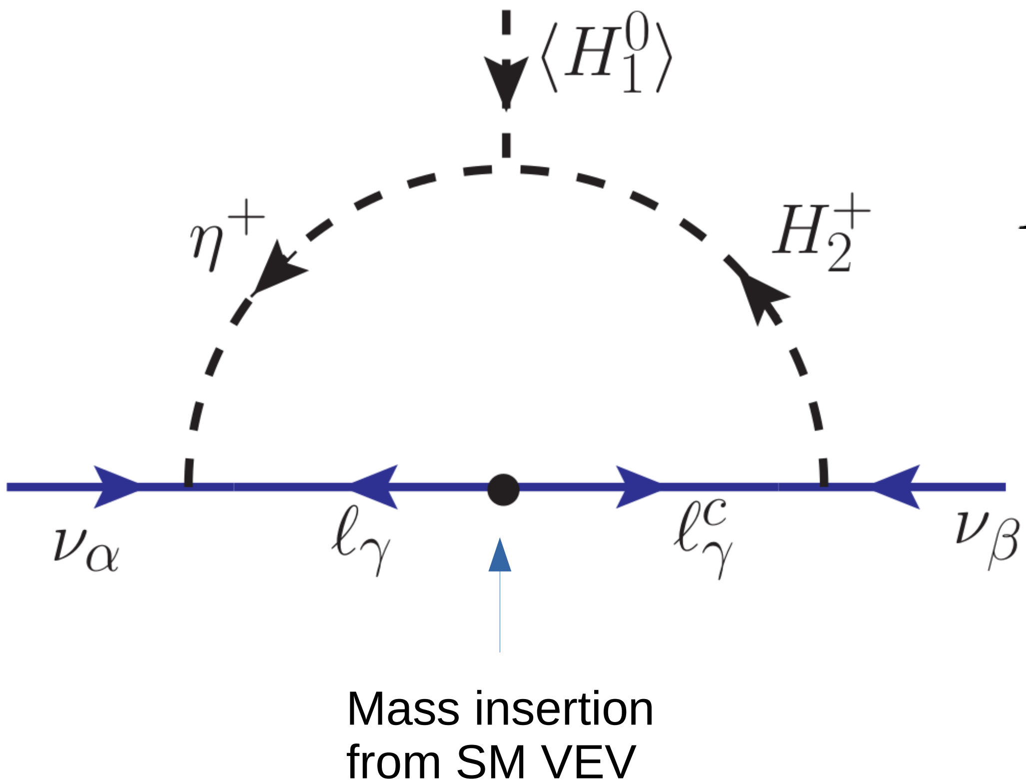

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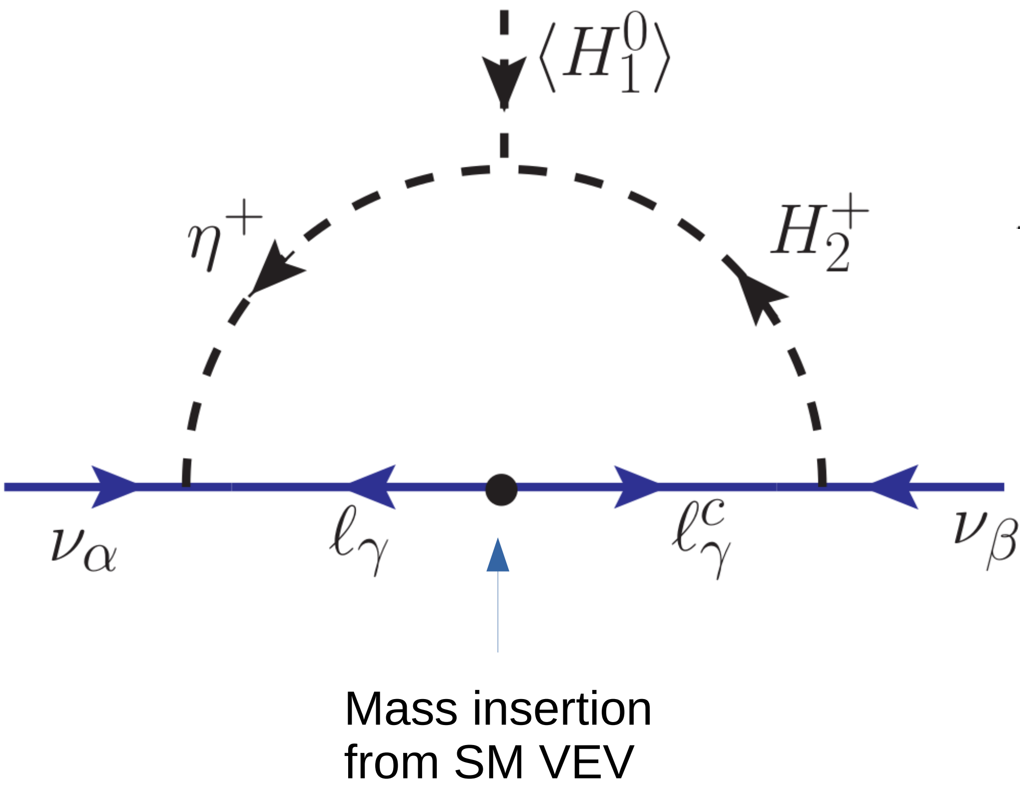

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$$M_\ell = \widetilde{Y} v/\sqrt{2}$$ Charged Lepton Mass Matrix

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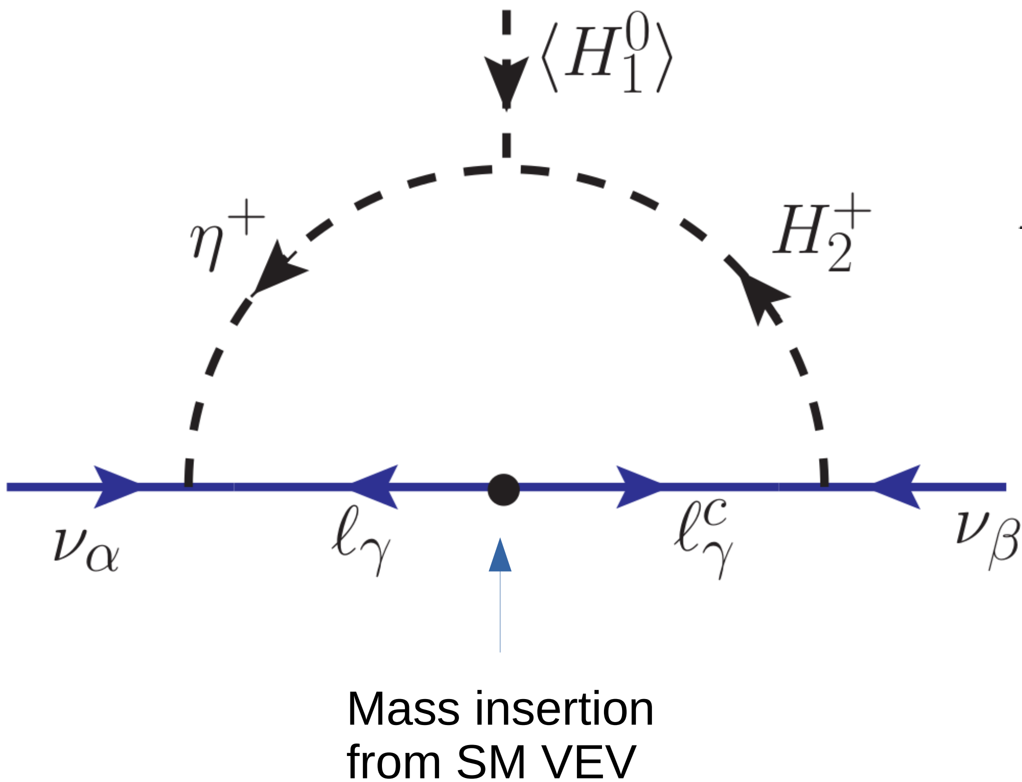

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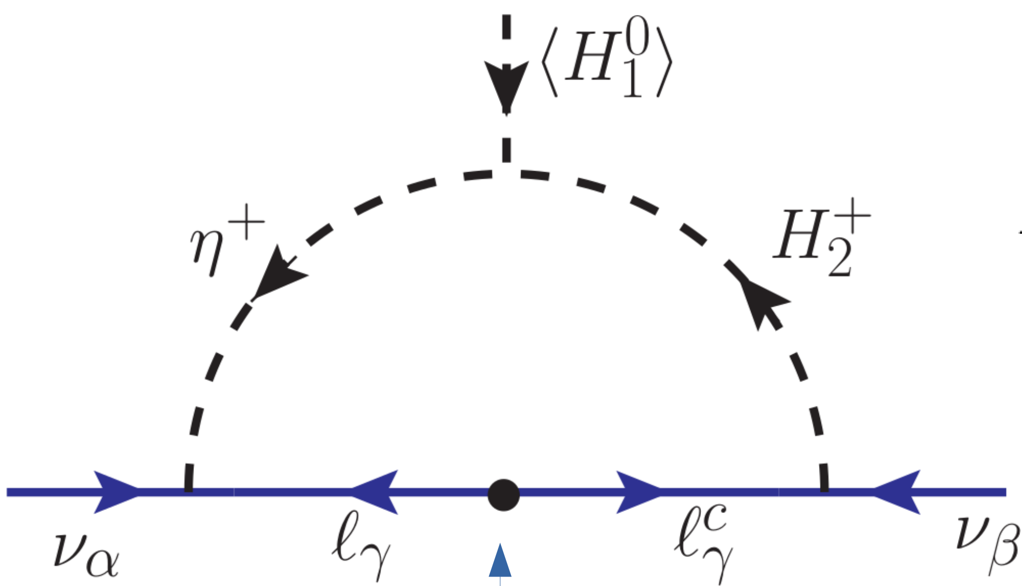

Mass insertion
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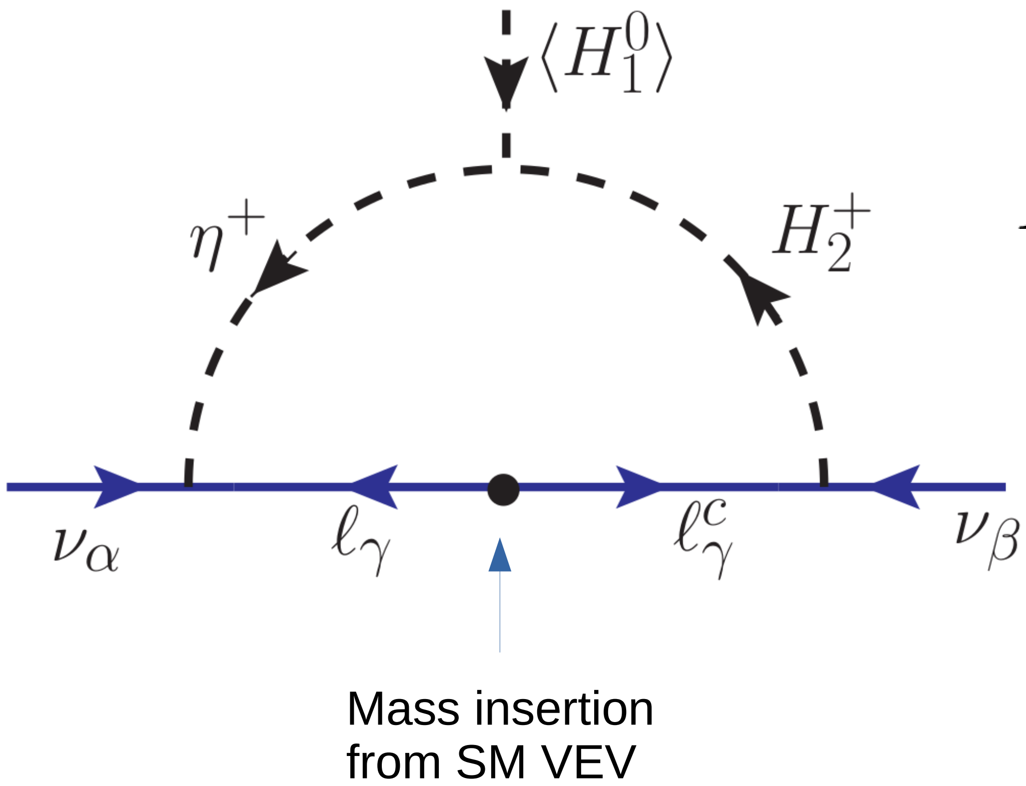

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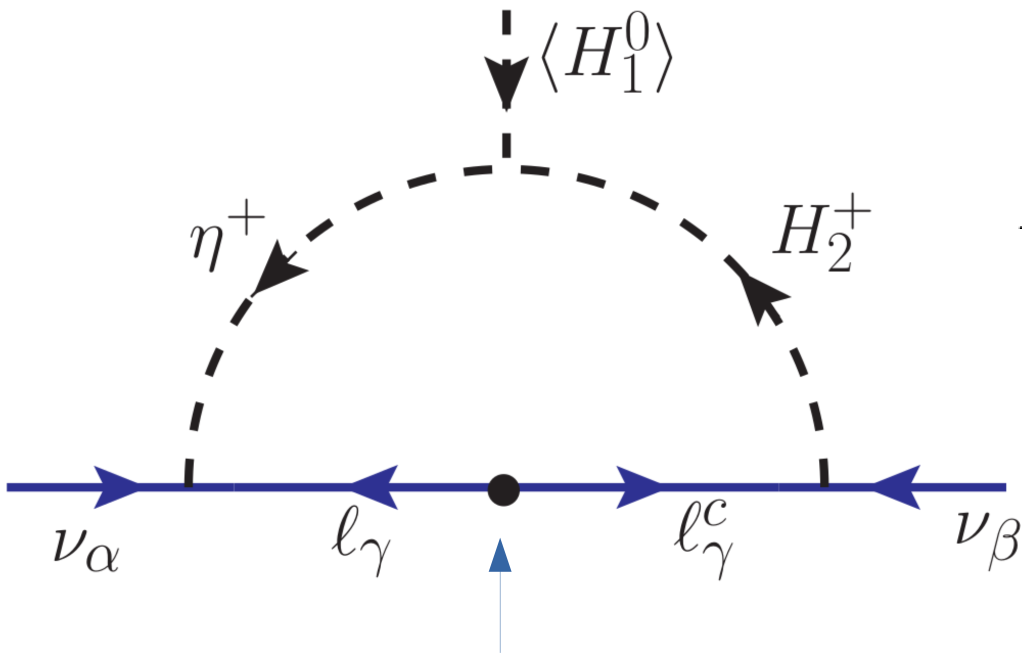
Herrero-Garcia, Ohlsson, Riad, Wiren, 2017'



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Glashow-Like Signatures

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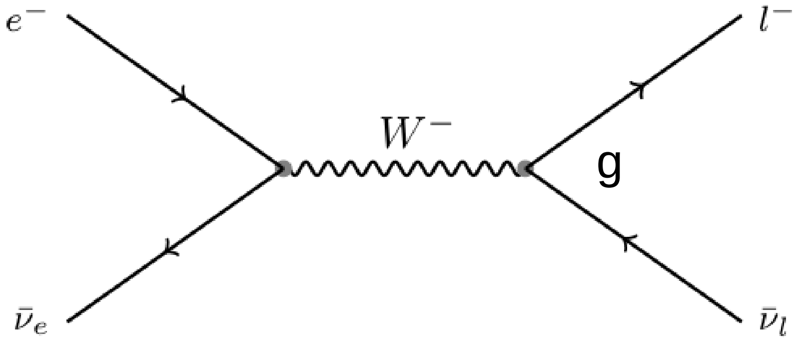

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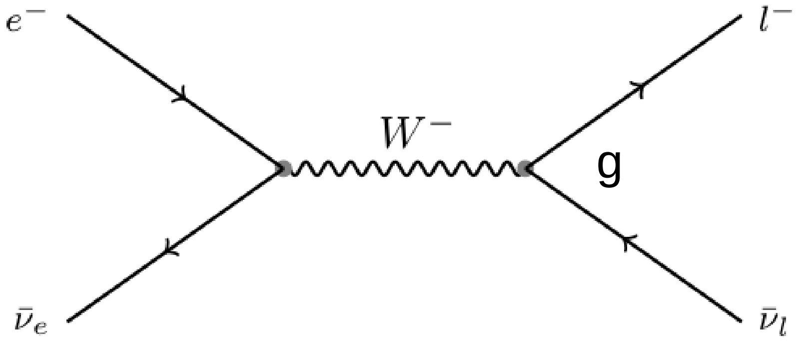

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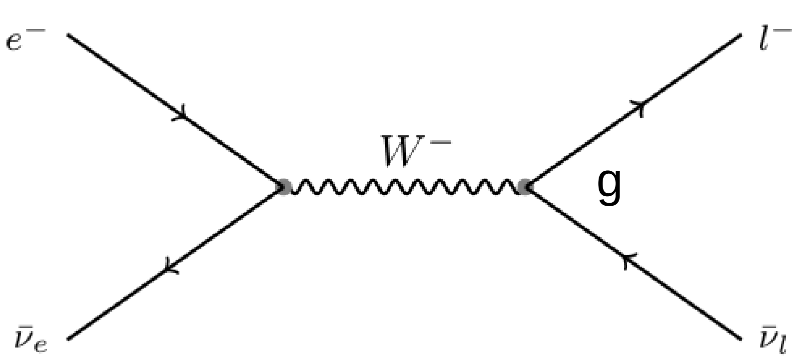

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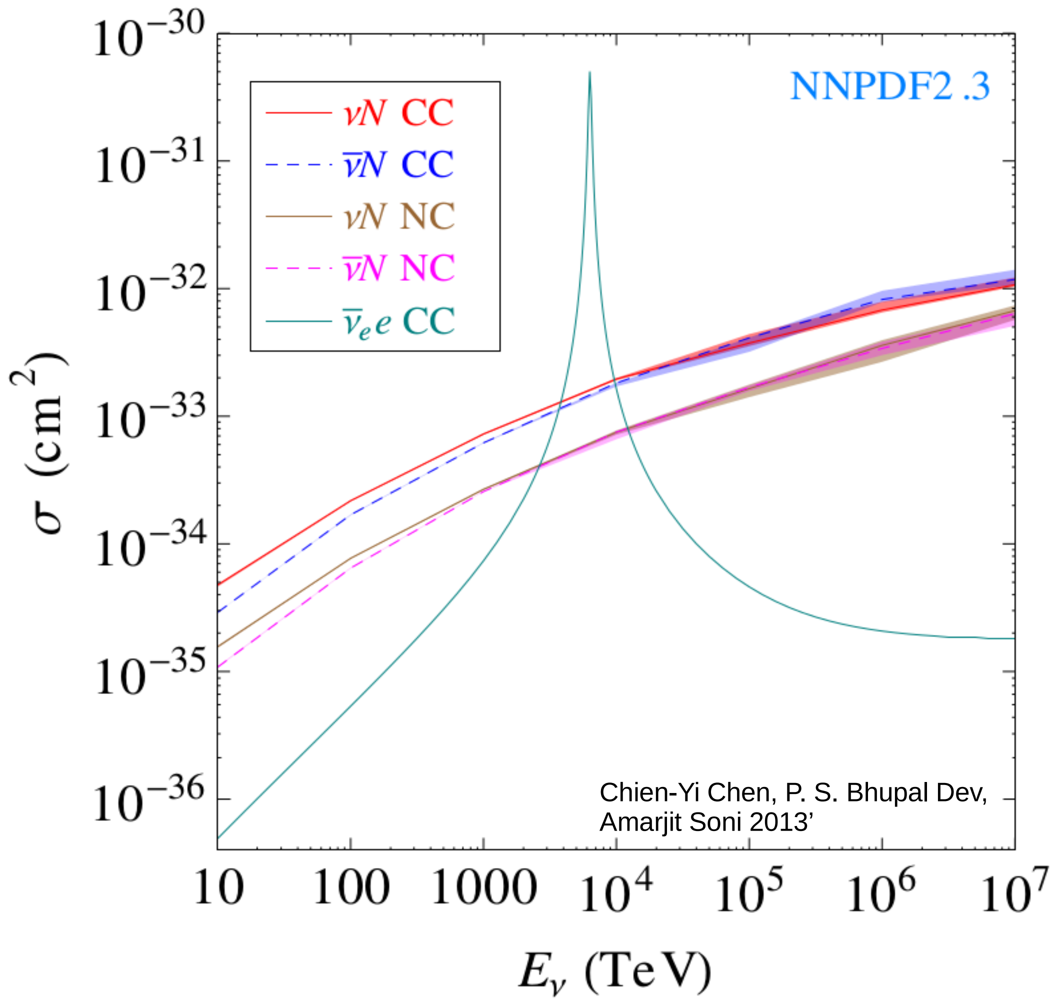

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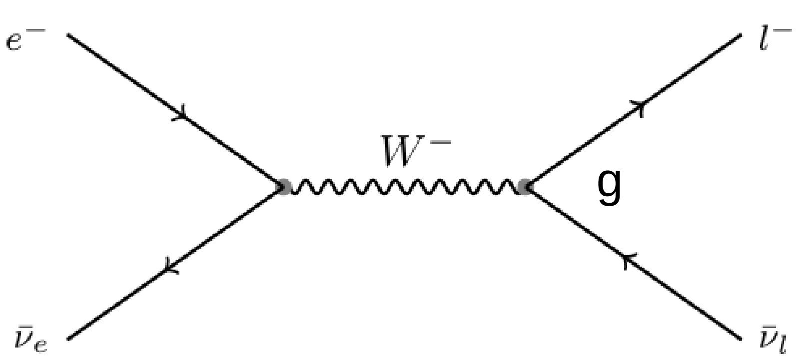

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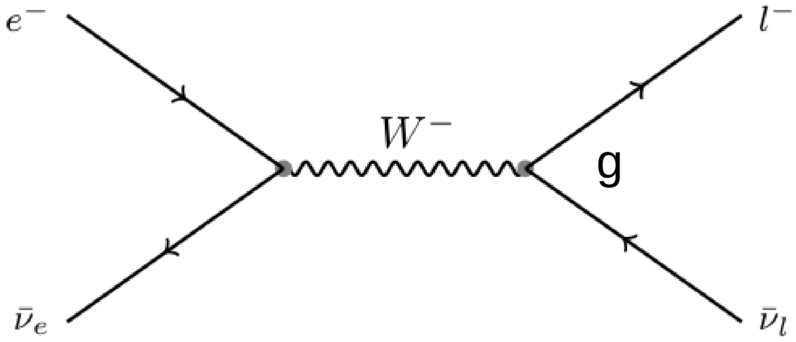

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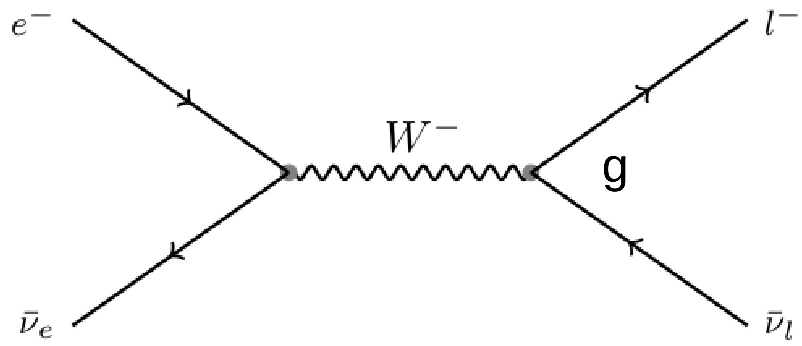

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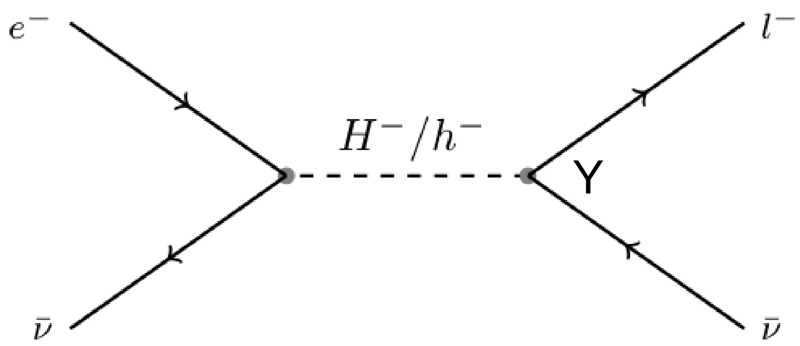
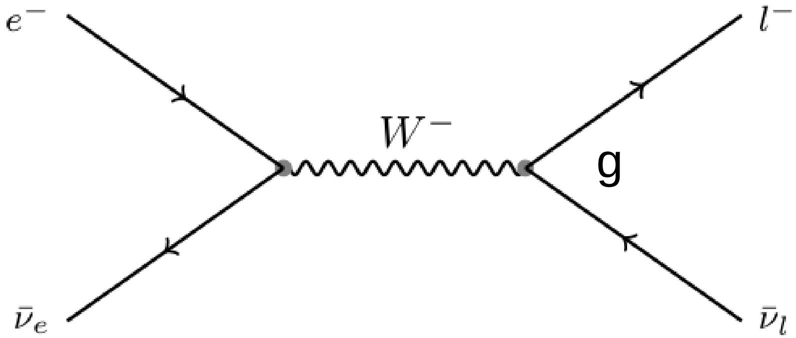


Zee burst

Glashow-Like Signatures



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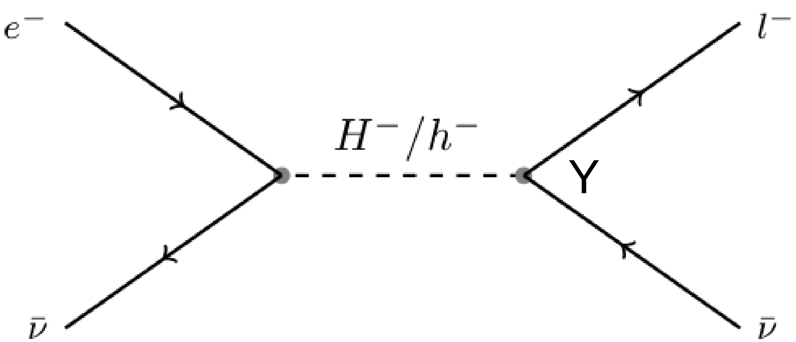

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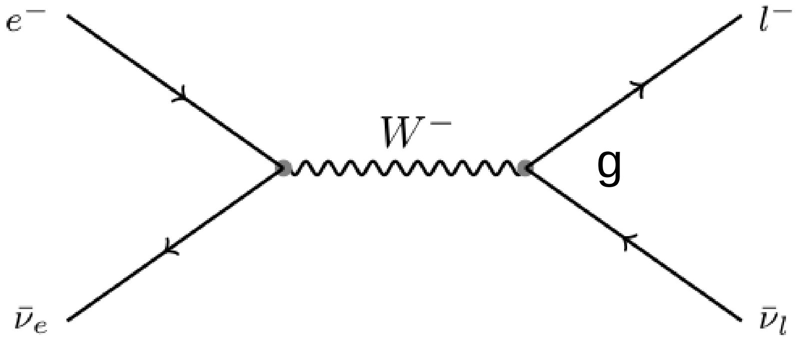

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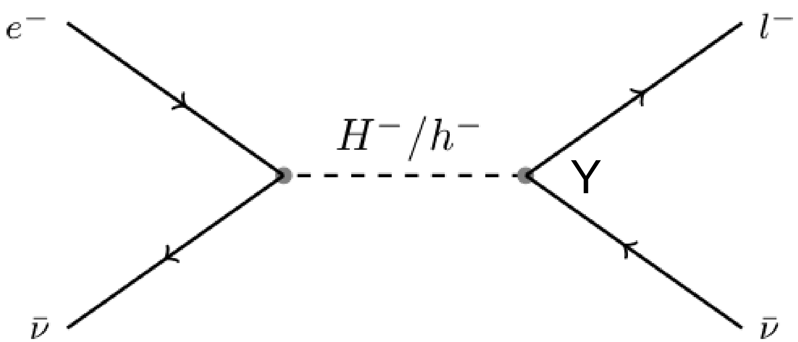

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$$\Gamma_X = \sum_{\alpha\beta} |Y_{\alpha\beta}|^2 \sin^2\varphi\, m_X/16\pi$$

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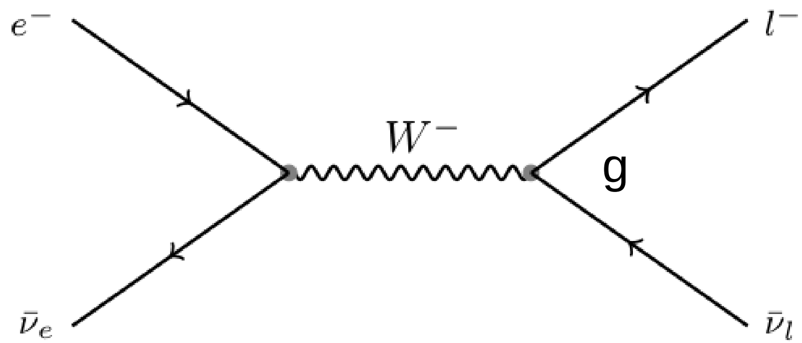

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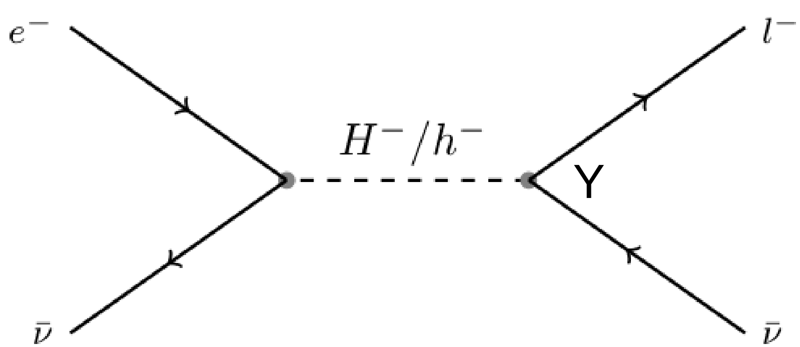

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$$E_\nu = m^2/2m_e \approx 6.3\ \text{PeV},\ 9.8\ \text{PeV}$$

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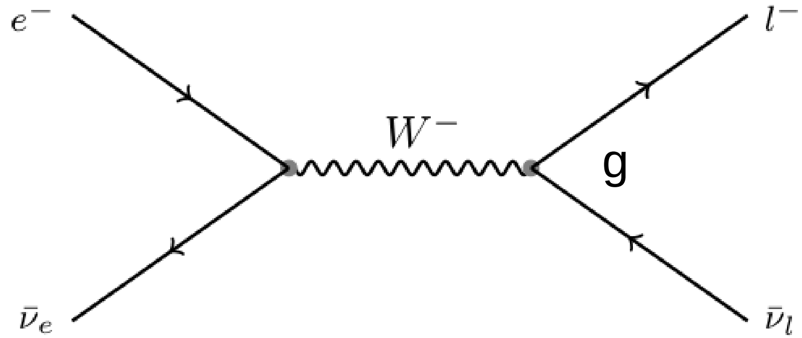

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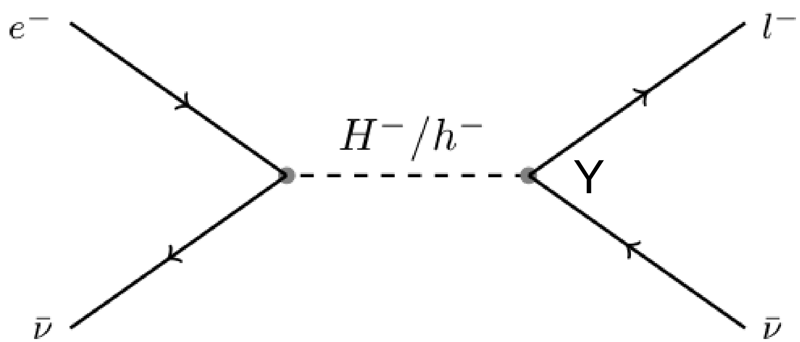


Zee burst

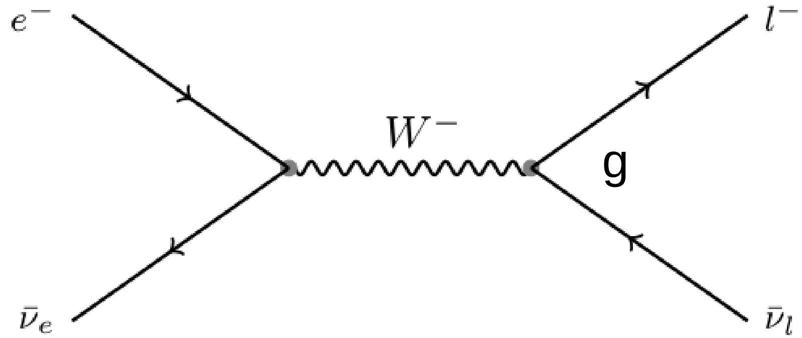
$$\sigma_{\text{Zee}}(s) \sim \Gamma_X^2 \, \text{BR}(X^- \to \bar{\nu}_\alpha e^-) \text{BR}(X^- \to \text{all}) \times \frac{s/m_X^2}{(s - m_X^2)^2 + (m_X \Gamma_X)^2}$$

$$\Gamma_X = \sum_{\alpha\beta} |Y_{\alpha\beta}|^2 \sin^2\varphi \, m_X / 16\pi$$

$$E_\nu = m^2 / 2m_e \approx 6.3 \text{ PeV}, \; 9.8 \text{ PeV}$$

m=80.4 GeV

Glashow-Like Signatures

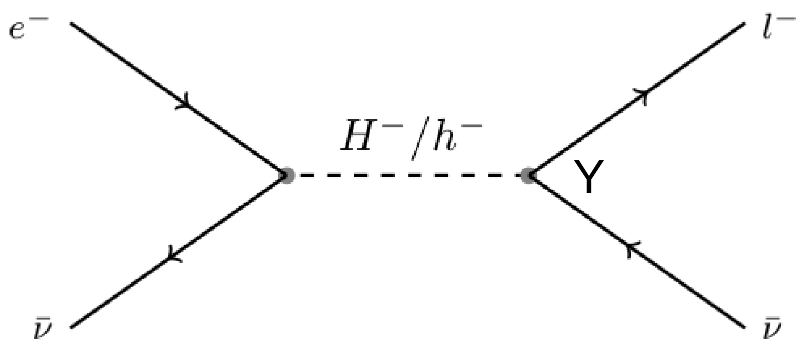


S. L. Glashow 1960

$$\sigma_{\text{Glashow}}(s) \sim \Gamma_W^2 \, \text{BR}(W^- \to \bar{\nu}_e e^-)\text{BR}(W^- \to \text{All}) \times \frac{s/m_W^2}{(s-m_W^2)^2 + (m_W \Gamma_W)^2}$$

@ resonance, becomes dominant

$$-\mathcal{L}_Y \supset f_{\alpha\beta} L^i_\alpha L^j_\beta \epsilon_{ij} \eta^+ + \widetilde{Y}_{\alpha\beta} \widetilde{H}^i_1 L^j_\alpha \ell^c_\beta \epsilon_{ij} + Y_{\alpha\beta} \widetilde{H}^i_2 L^j_\alpha \ell^c_\beta \epsilon_{ij} + \text{H.c.}$$



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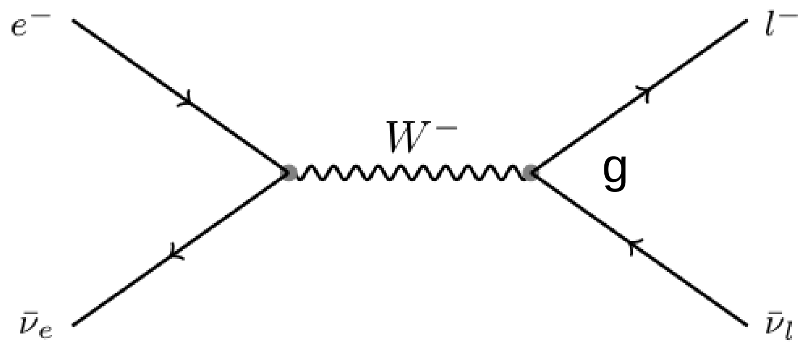
m=80.4 GeV

m=100 GeV

Glashow-Like Signatures



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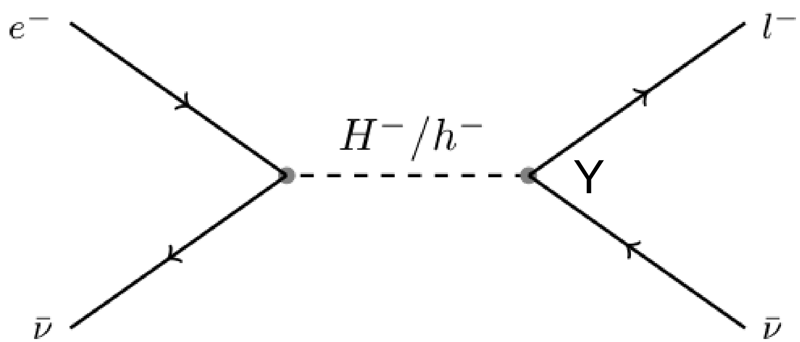

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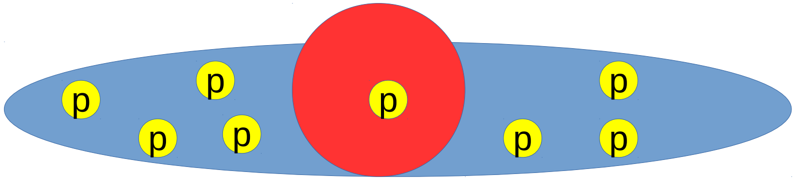
m=80.4 GeV   m=100 GeV

Where to find these High Energy neutrinos?

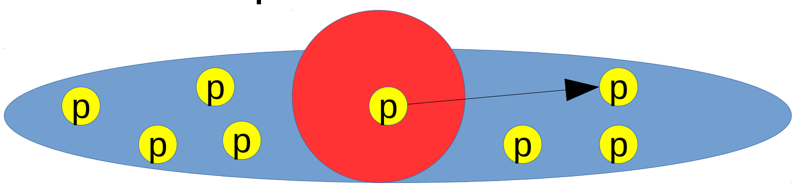
Astrophysical Neutrino Sources

Astrophysical Neutrino Sources

hadro-nuclear
production



Astrophysical Neutrino Sources



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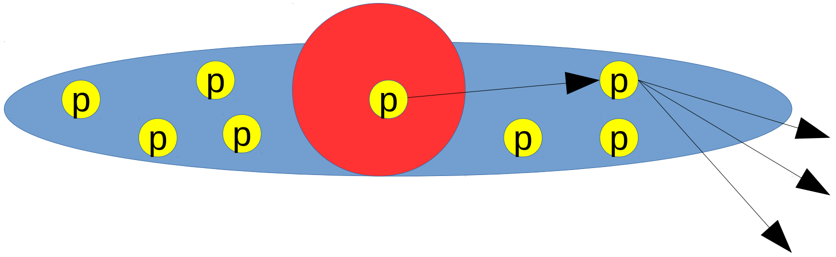

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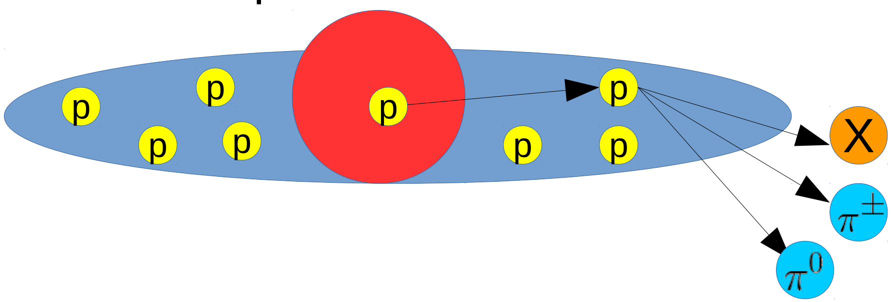

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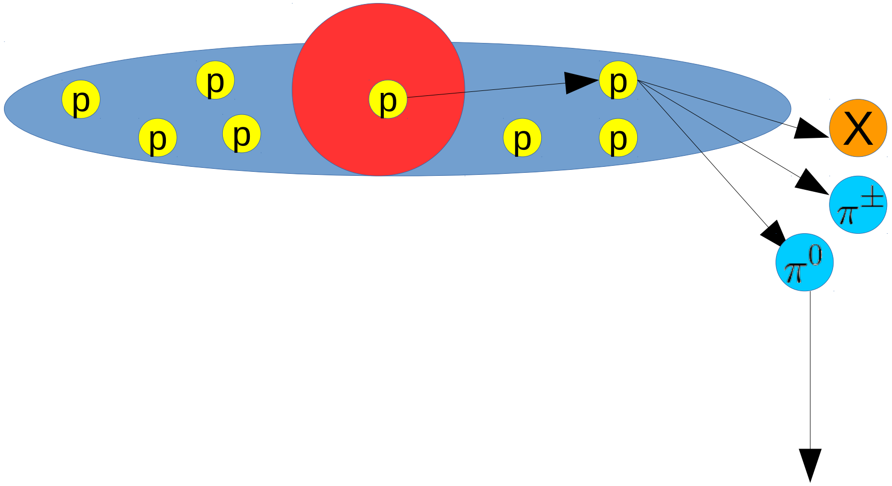

Astrophysical Neutrino Sources

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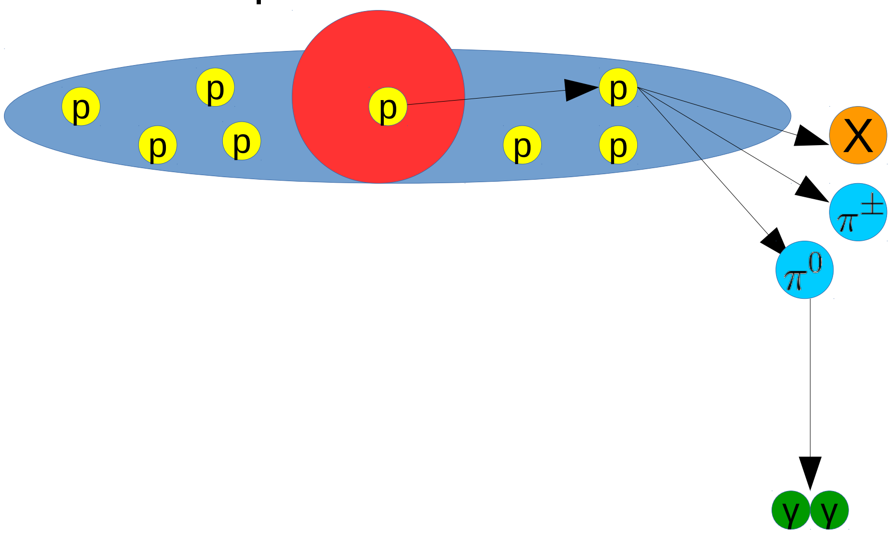

Astrophysical Neutrino Sources

hadro-nuclear
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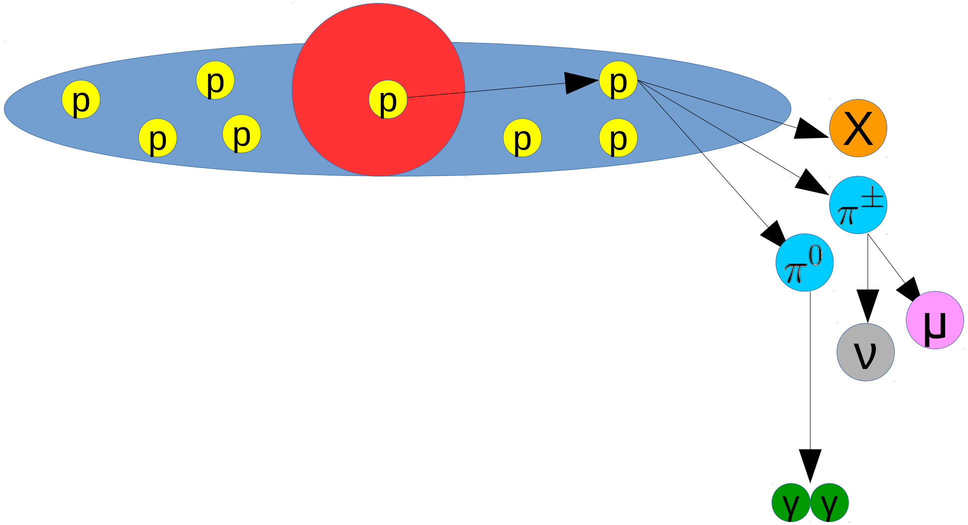
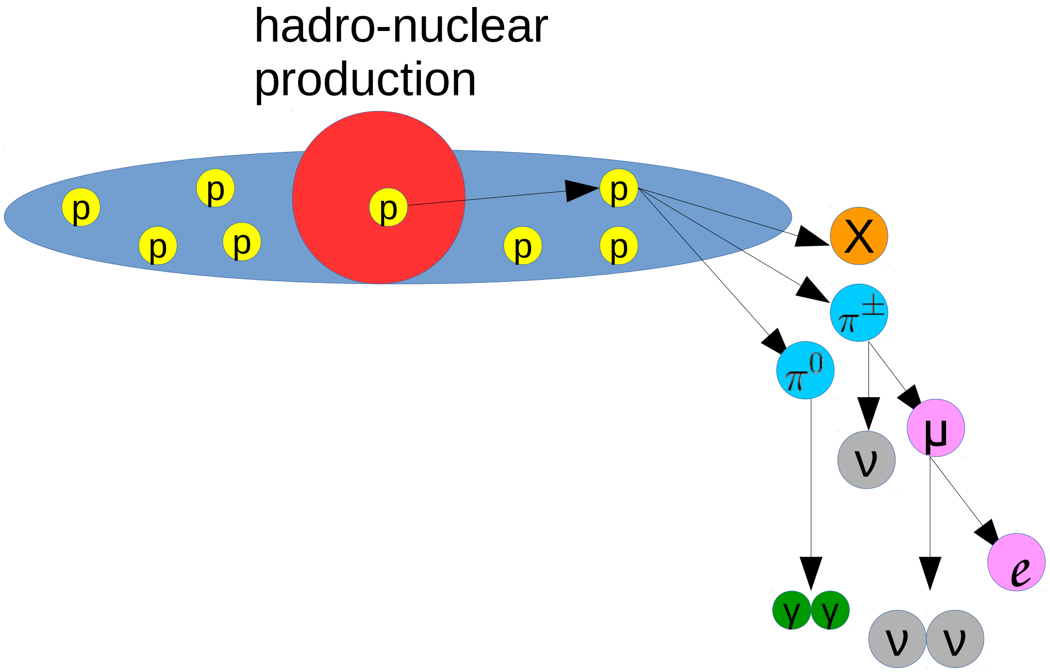
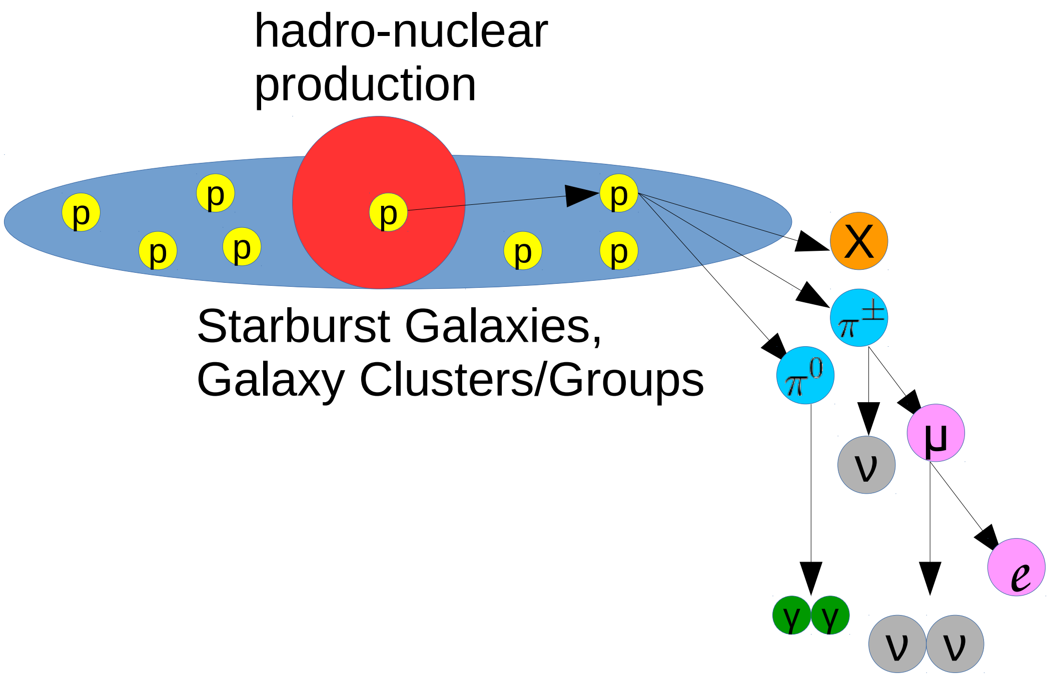


Astrophysical Neutrino Sources



Astrophysical Neutrino Sources



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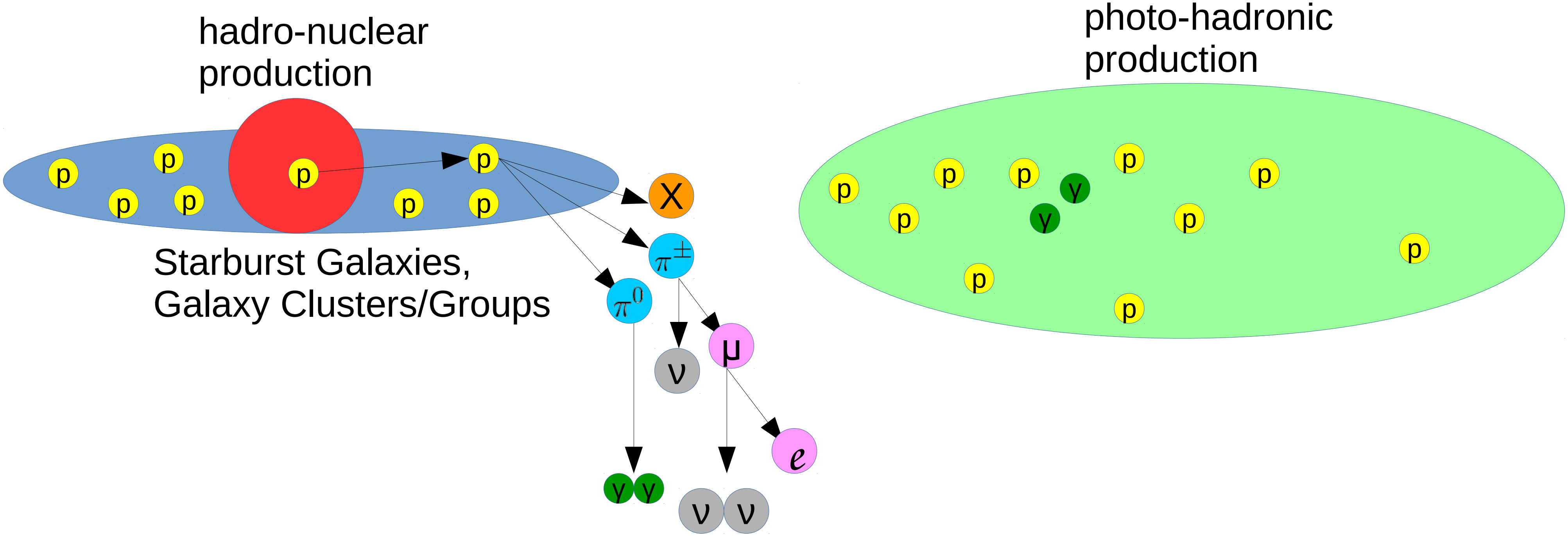
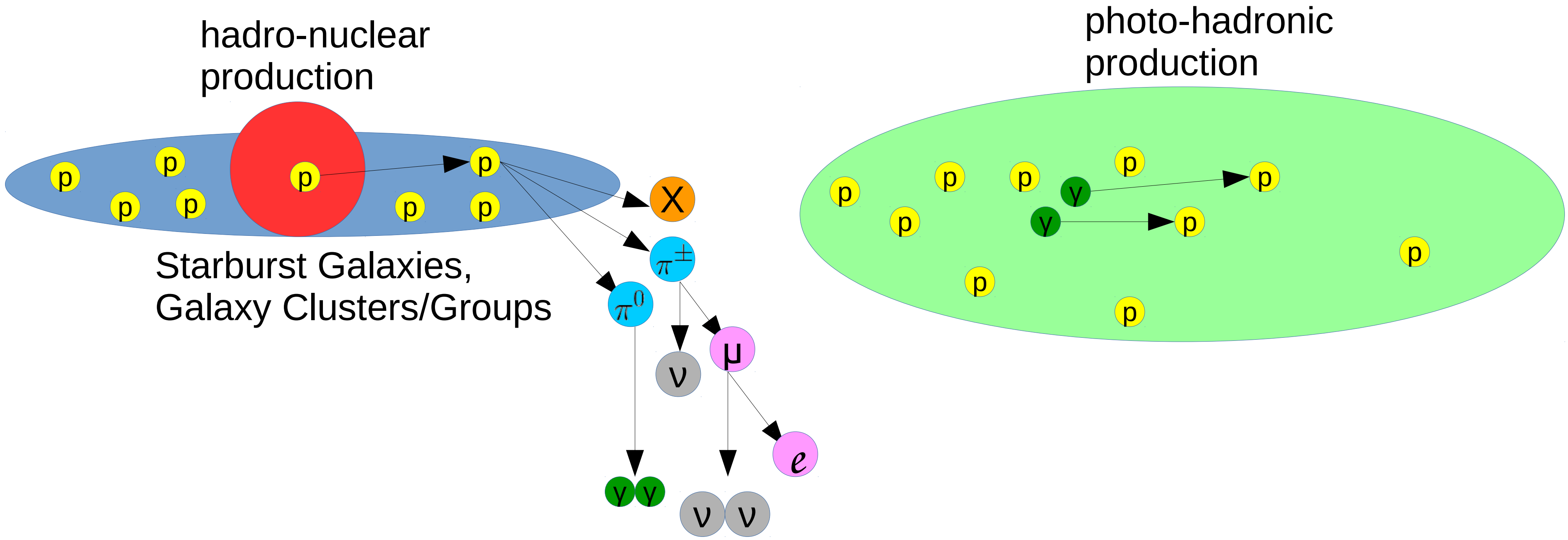
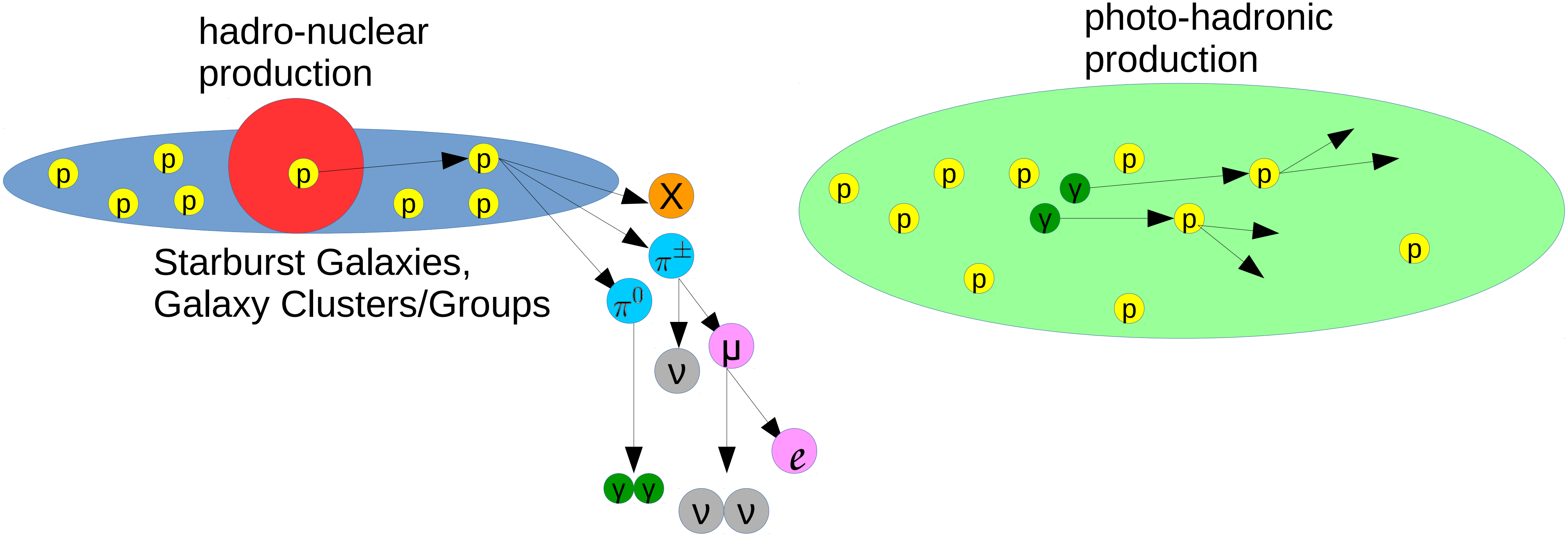


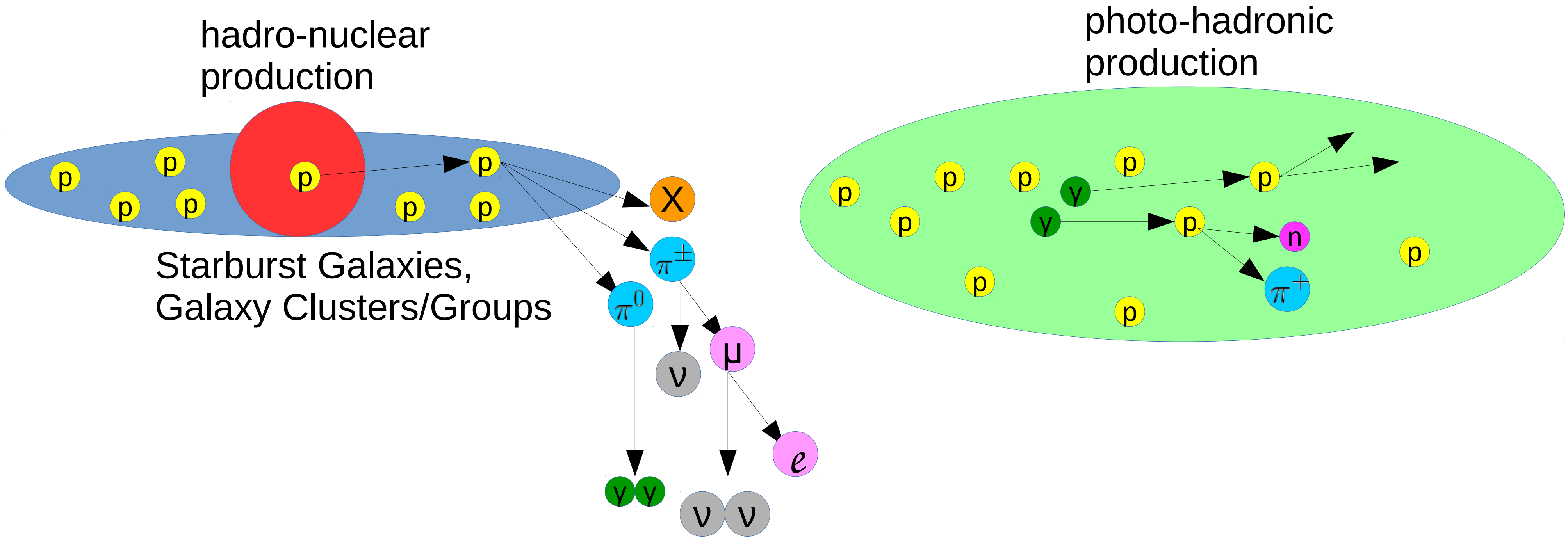
Astrophysical Neutrino Sources



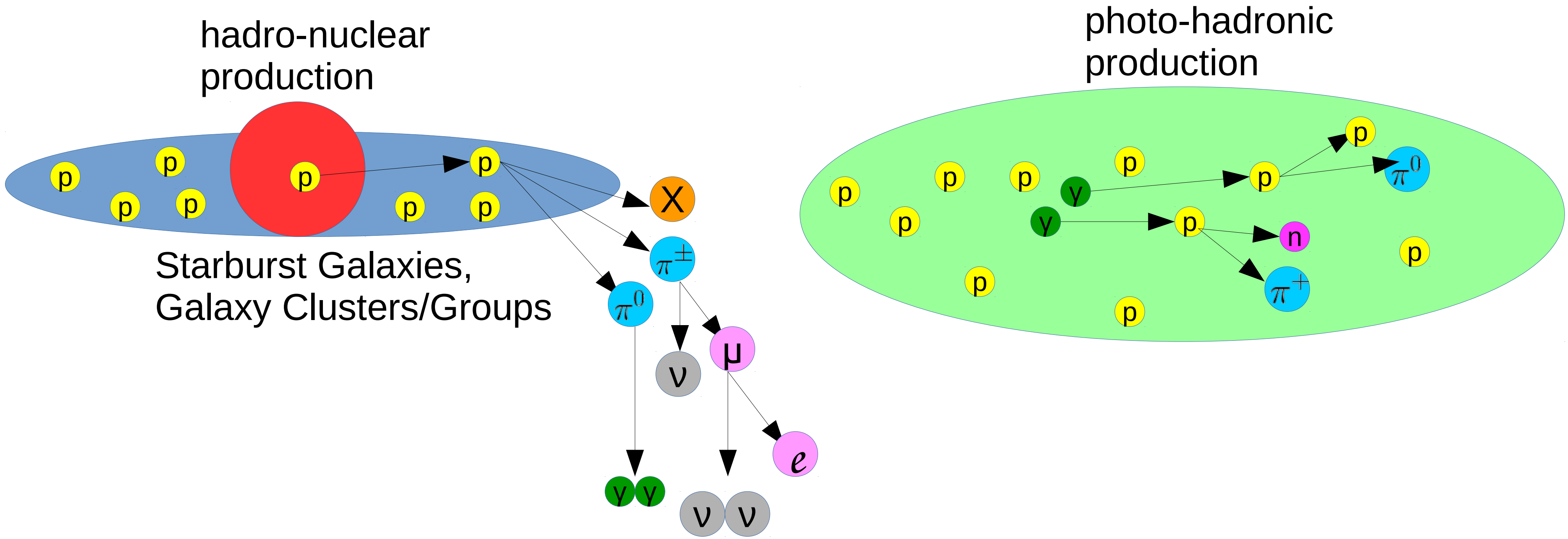
Astrophysical Neutrino Sources



Astrophysical Neutrino Sources



Astrophysical Neutrino Sources



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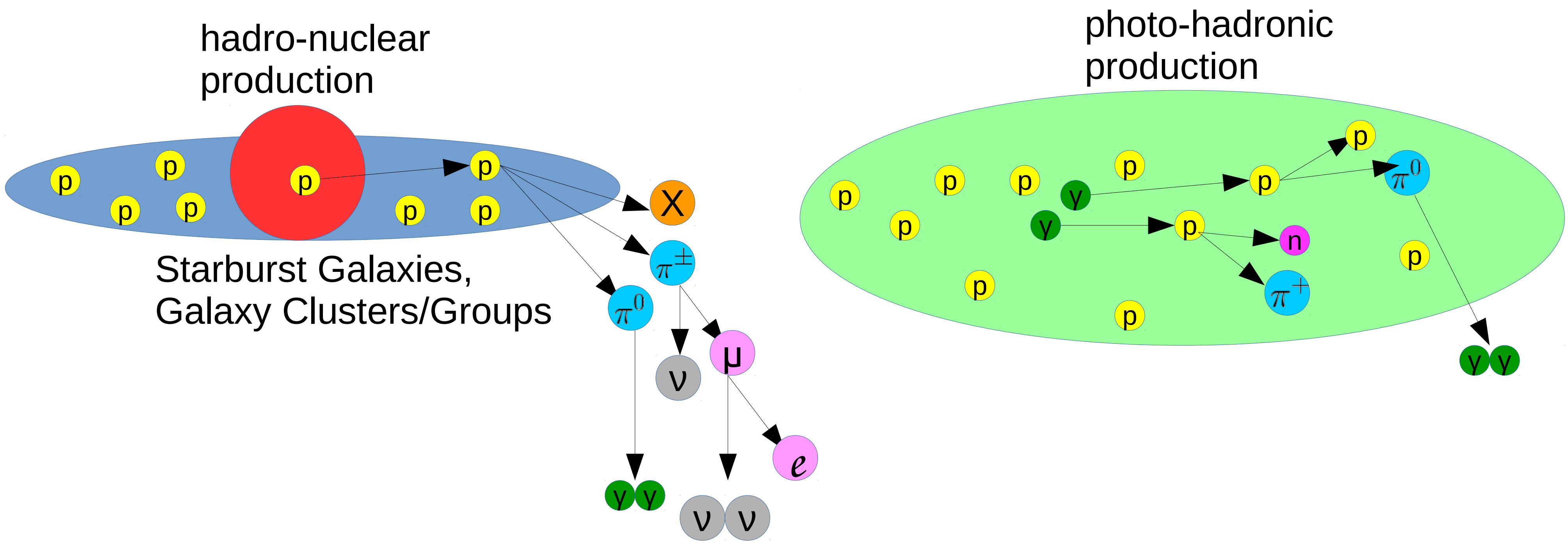
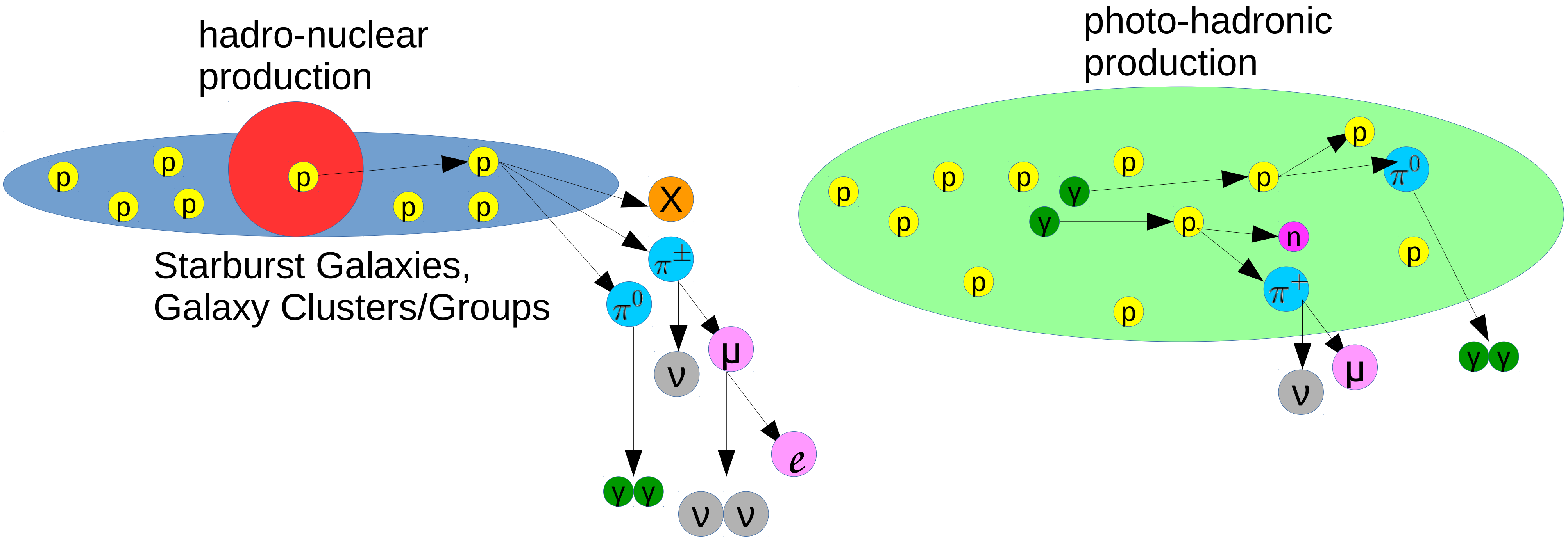


Astrophysical Neutrino Sources



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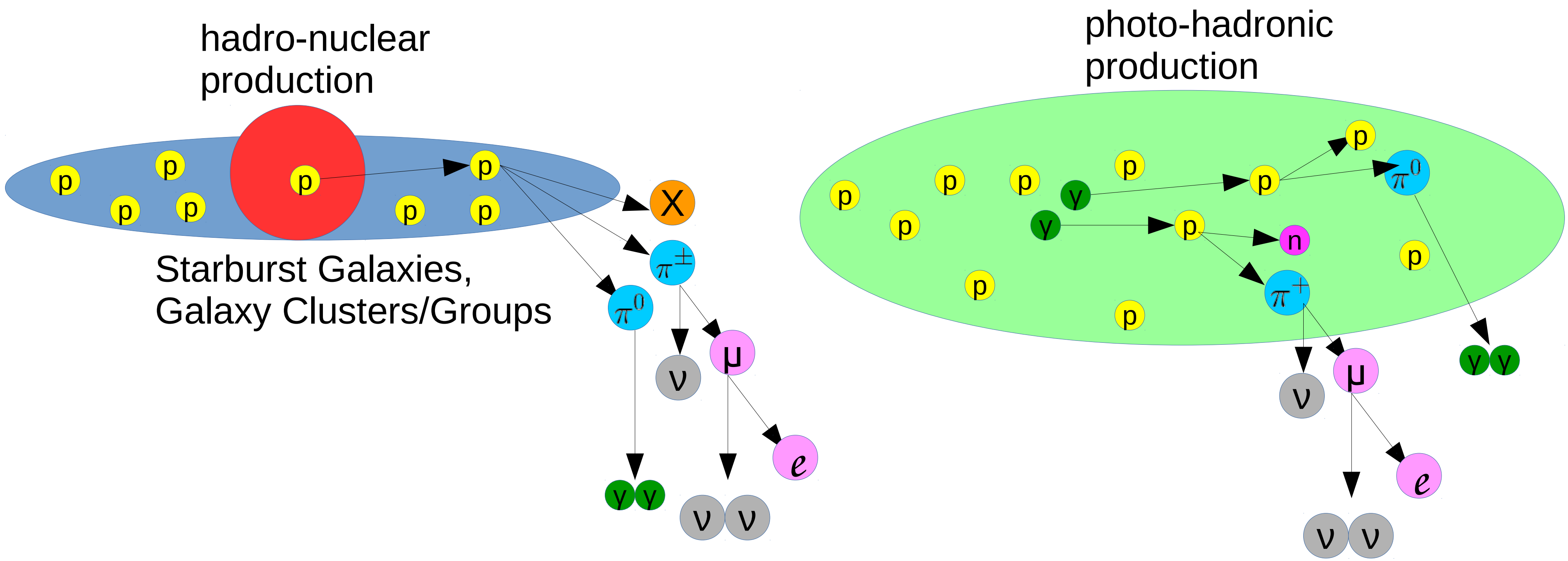

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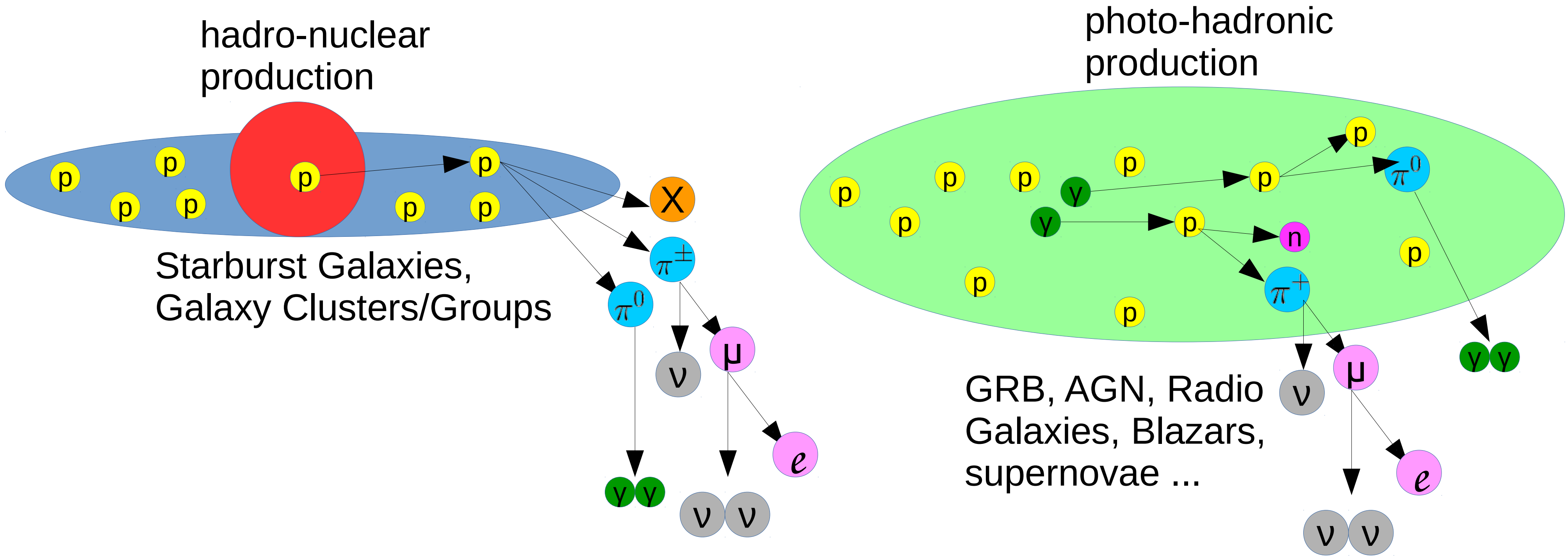
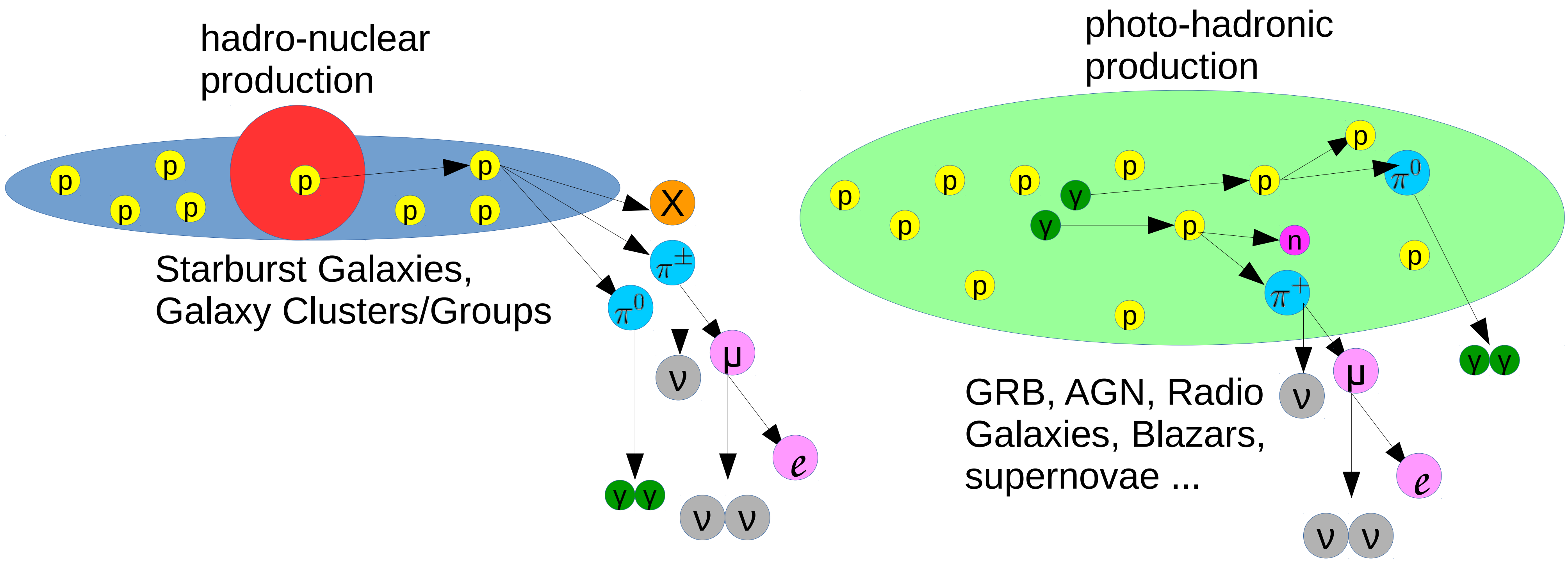


Astrophysical Neutrino Sources

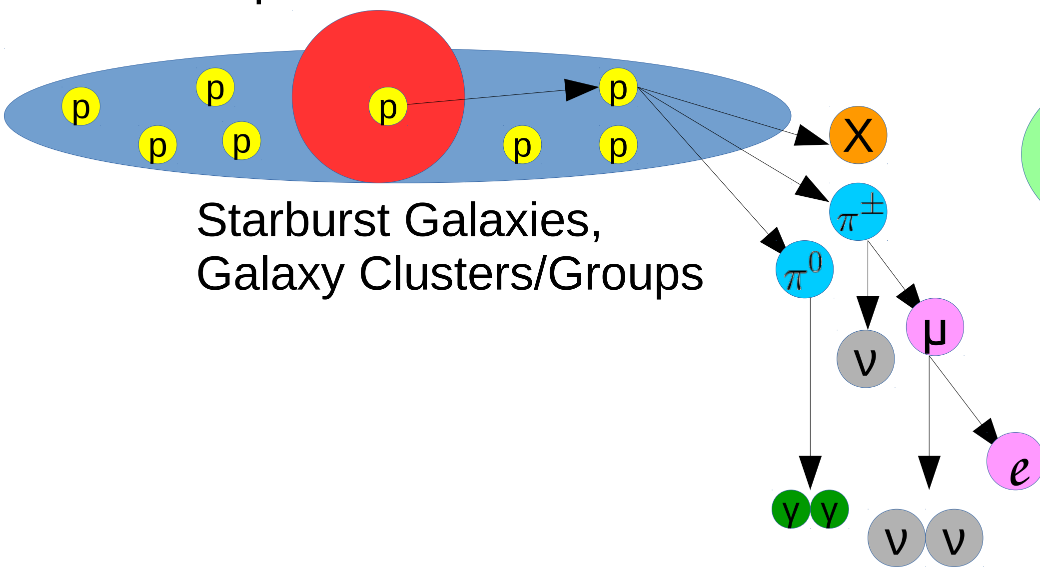


Charged Pions Decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

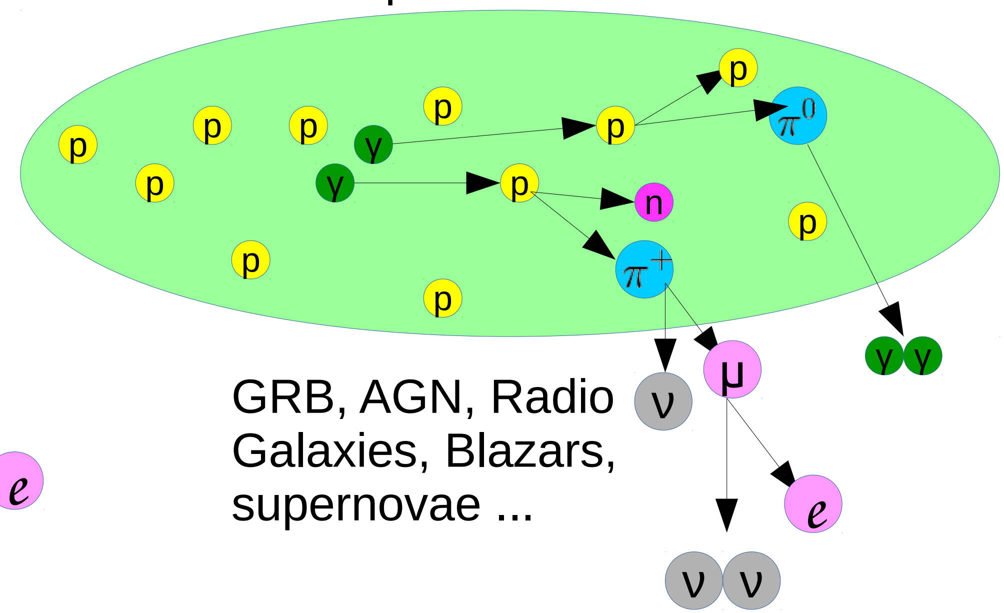
Astrophysical Neutrino Sources

hadro-nuclear
production



Starburst Galaxies,
Galaxy Clusters/Groups

photo-hadronic
production



GRB, AGN, Radio
Galaxies, Blazars,
supernovae ...

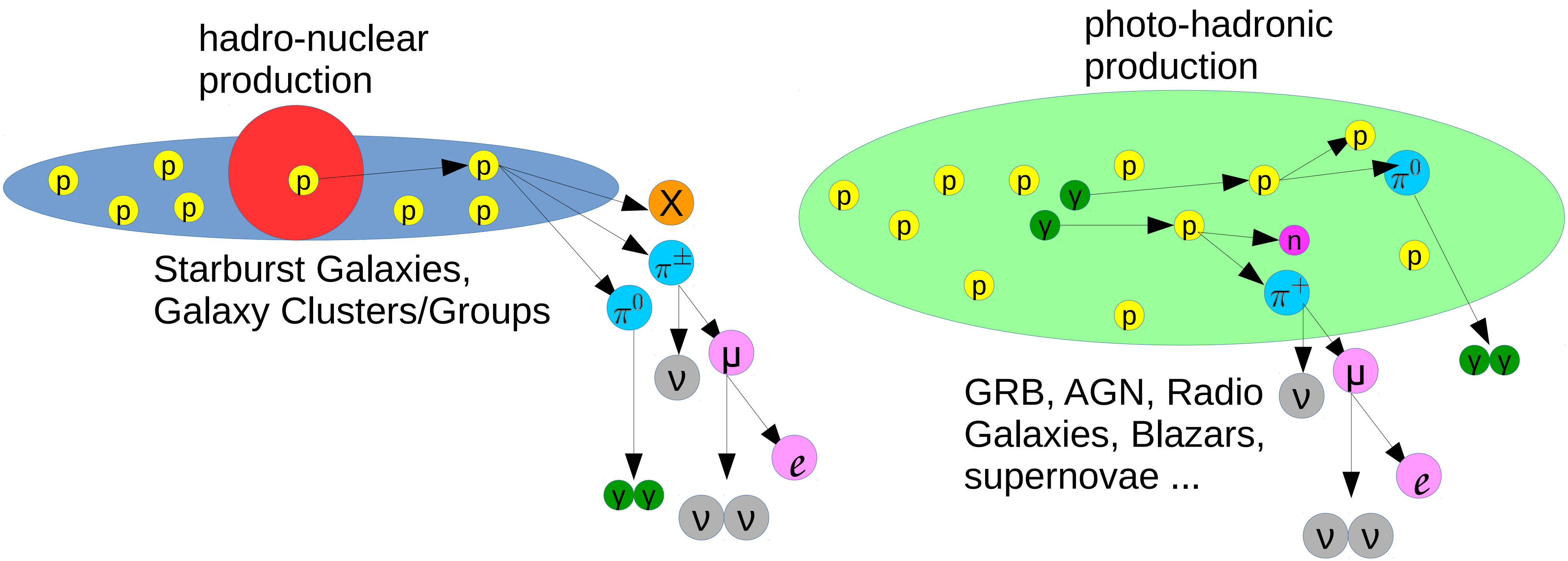
Charged Pions Decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

Neutrinos typically have 1-5% of proton energy

Maximally: $E_{\mathrm{GZK}} \sim 5 \times 10^4\ \mathrm{PeV}$

Astrophysical Neutrino Sources



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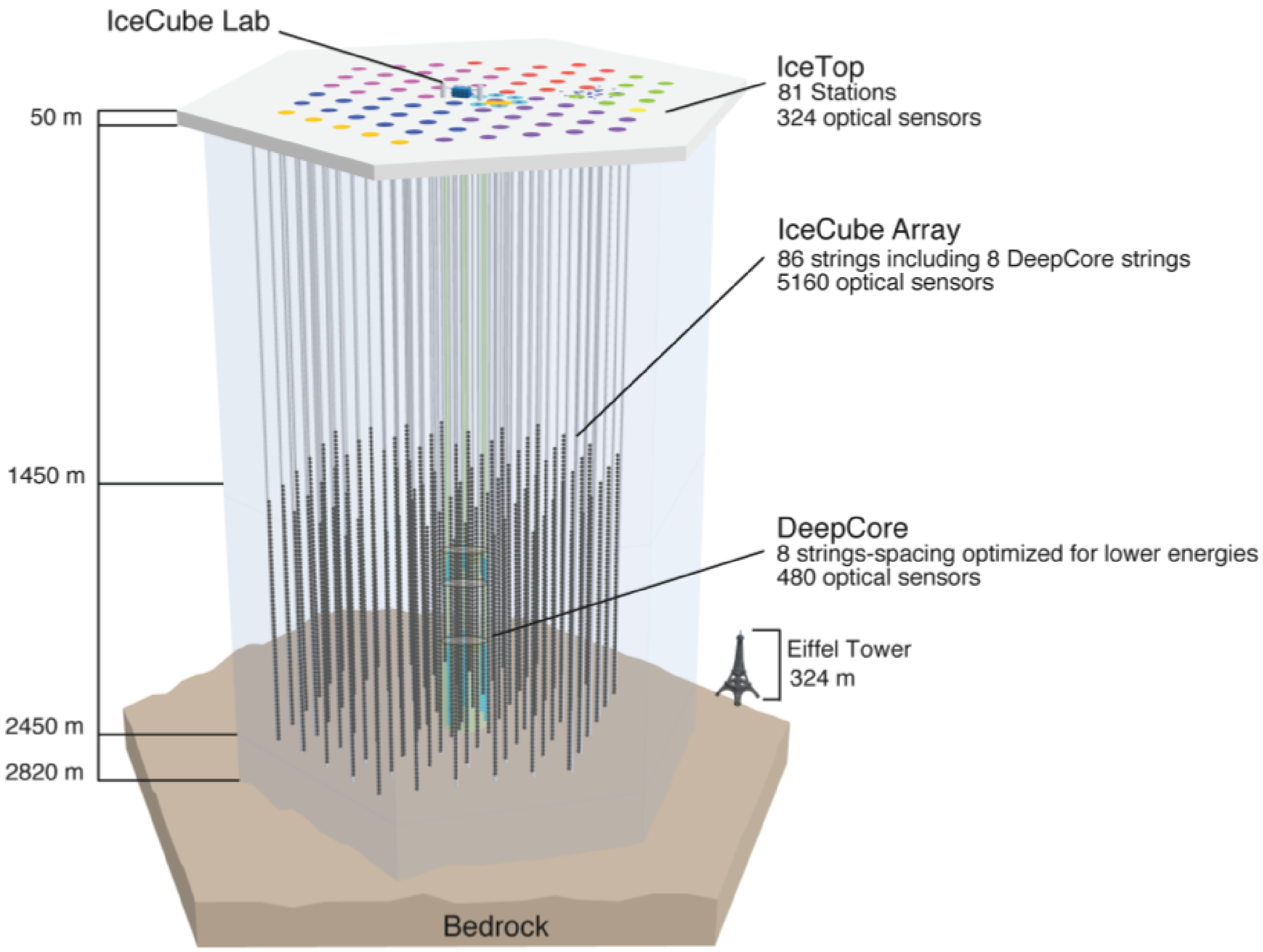
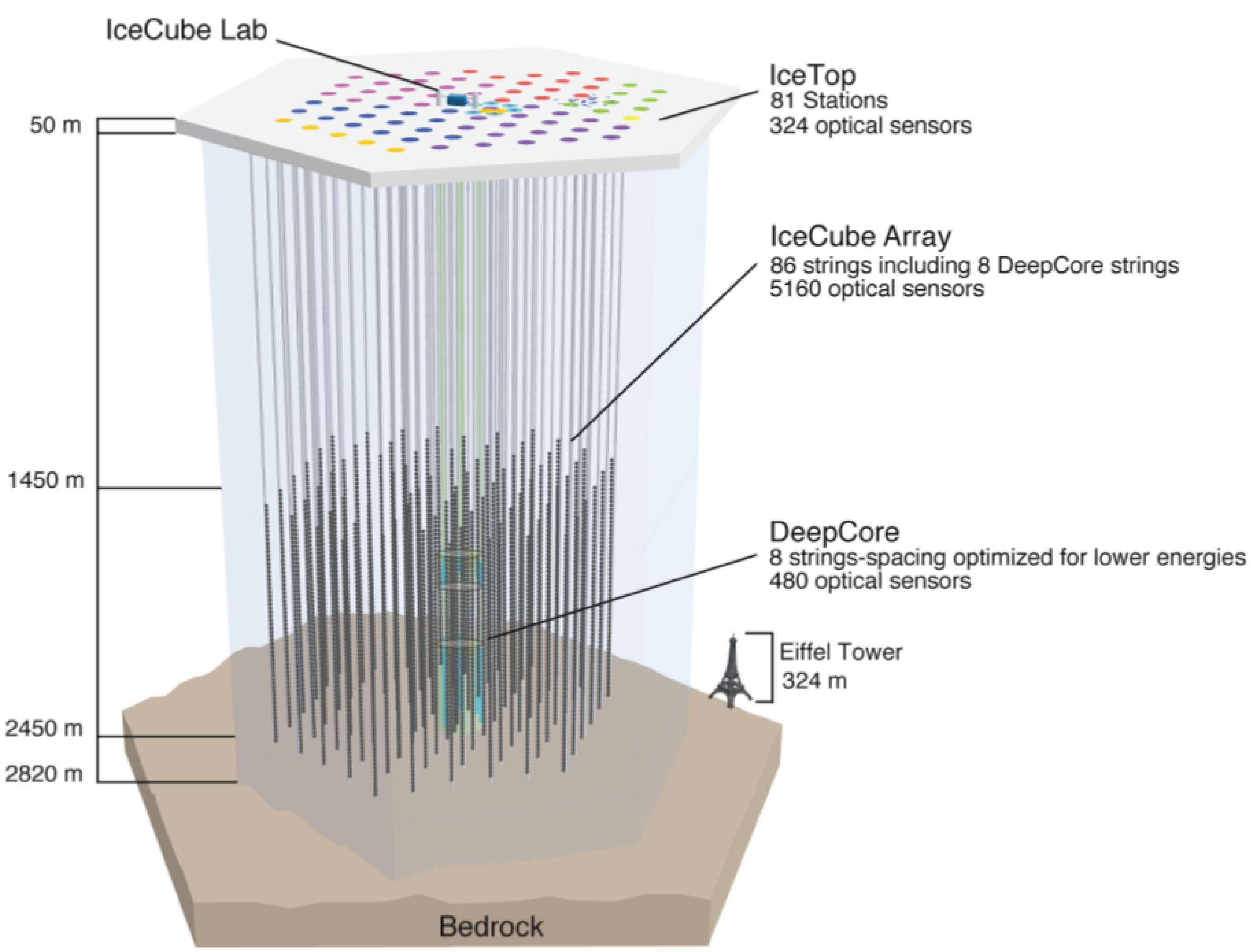
Maximally: $E_{\mathrm{GZK}} \sim 5 \times 10^4 \ \mathrm{PeV}$

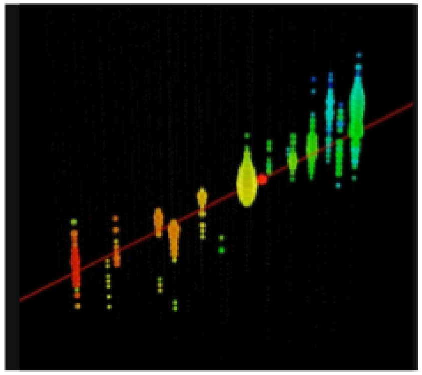
How do we detect them?

IceCube Detector



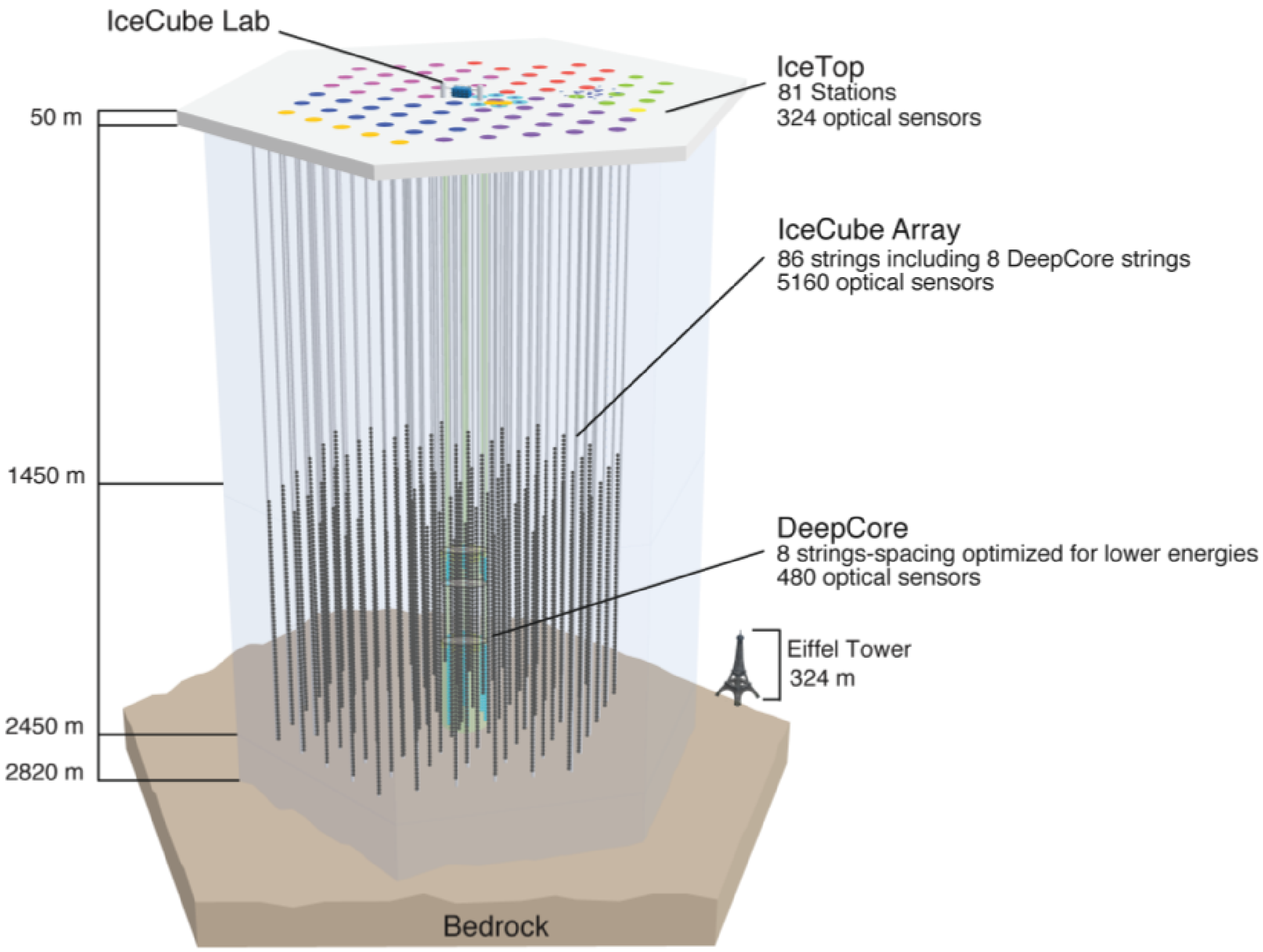
IceCube Detector

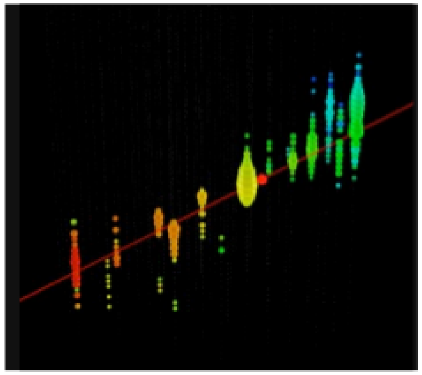




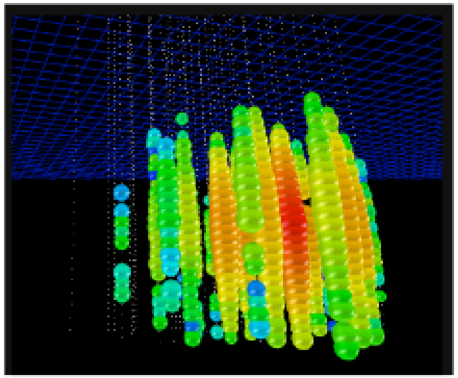
track

IceCube Detector



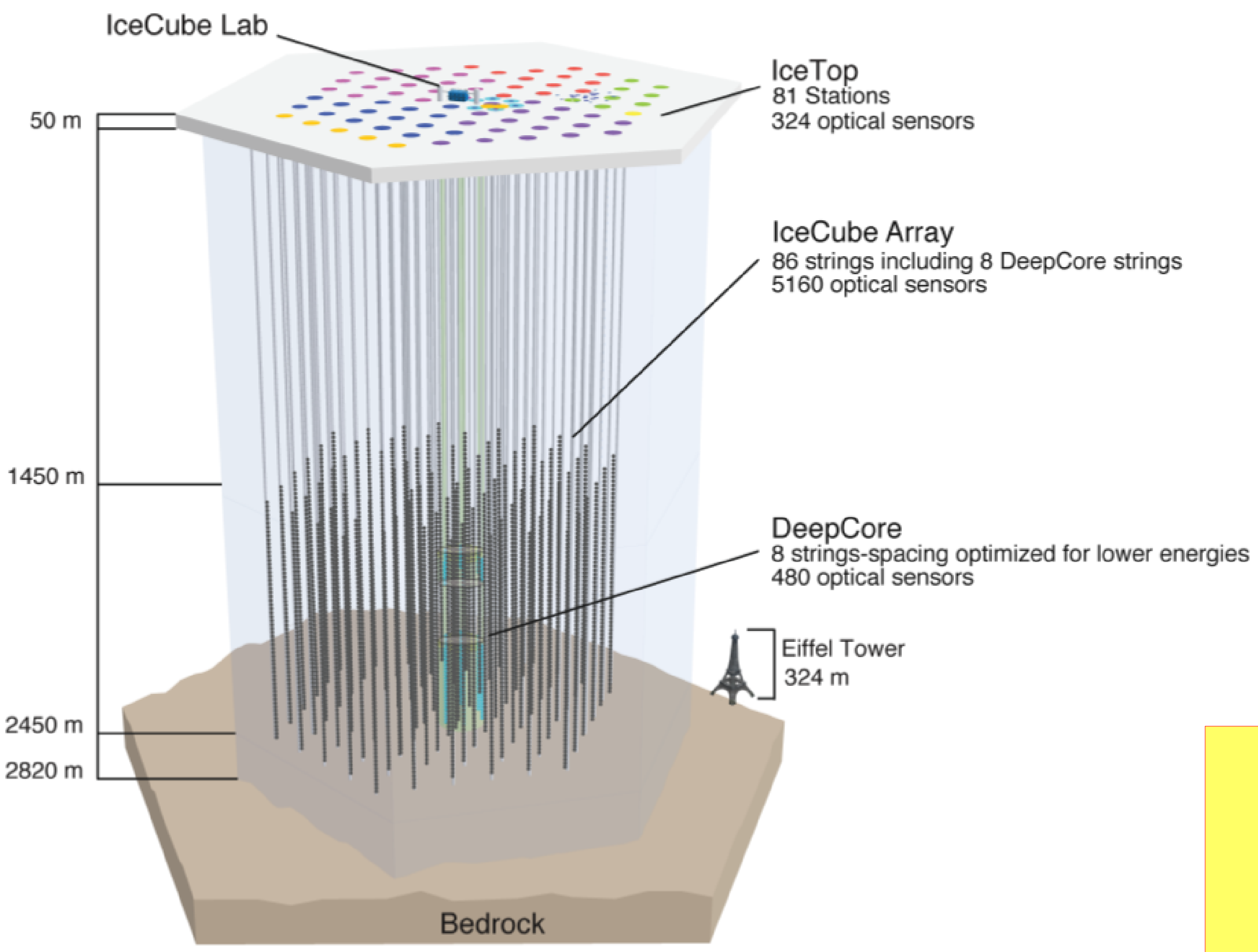


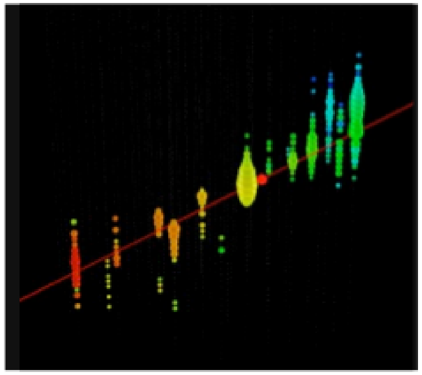
track



cascade

IceCube Detector





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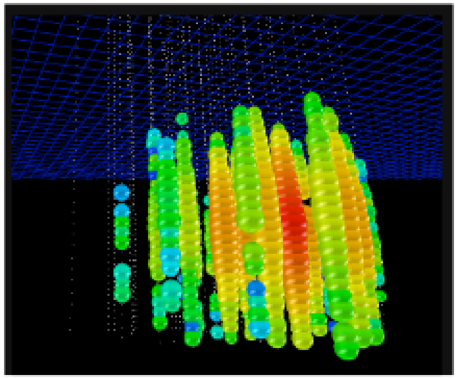


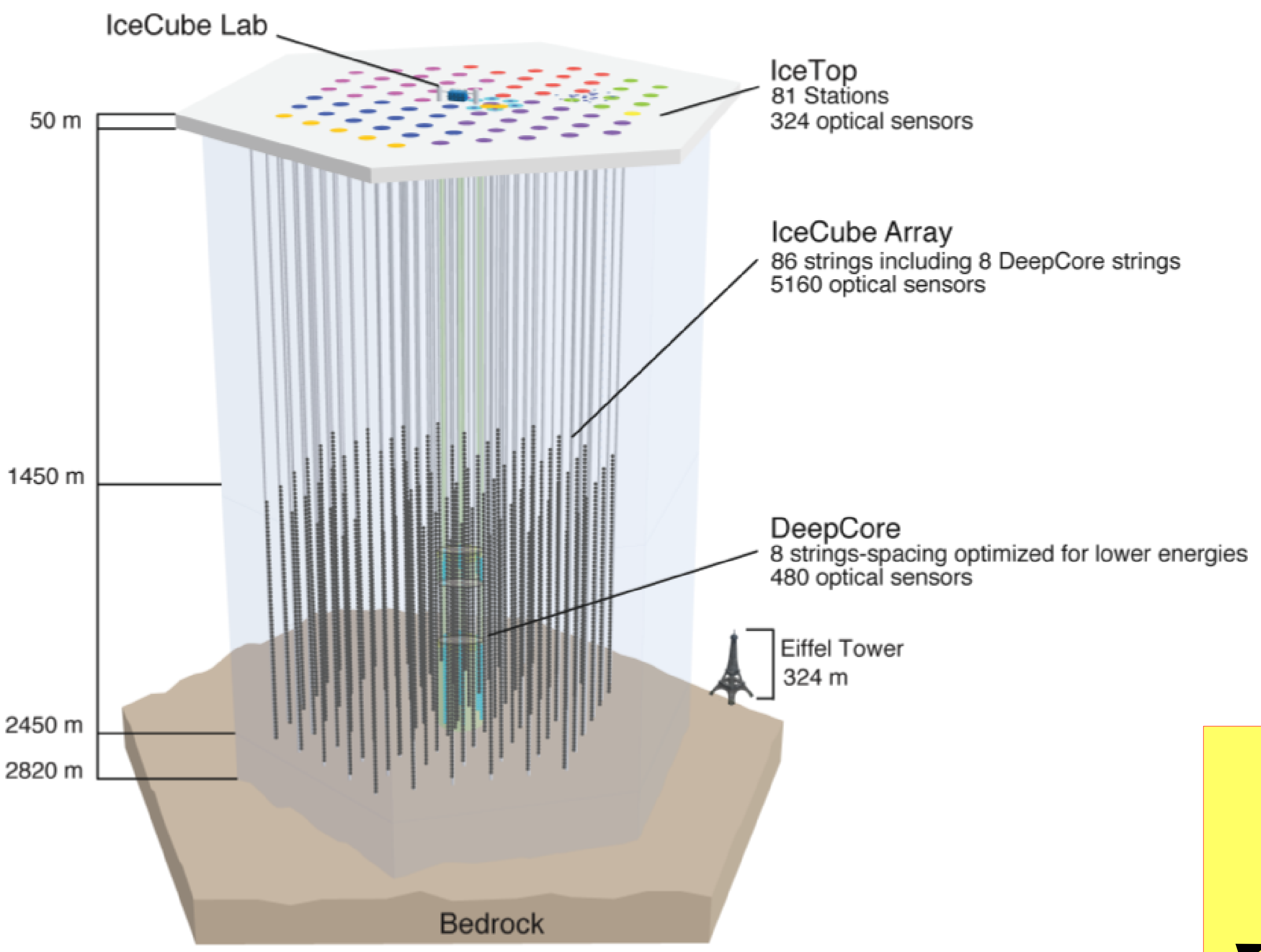
cascade

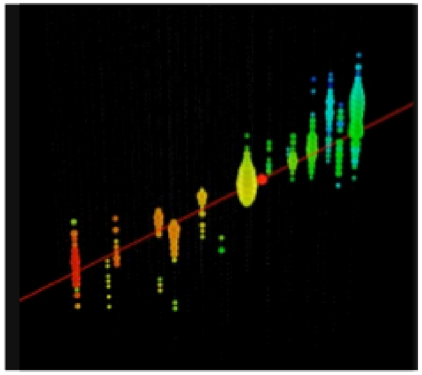
Mechanism:

$$\nu_l + N \rightarrow \begin{cases} l + X \ (CC) \\ \nu_l + X \ (NC) \end{cases}$$

Cherenkov radiation from interaction products: leptons and hadrons

IceCube Detector





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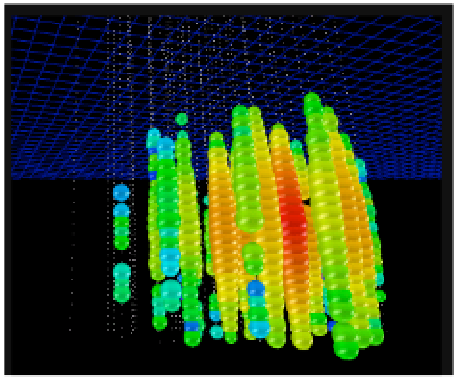

cascade

Mechanism:

$$\nu_l + N \rightarrow \begin{cases} l + X \ (CC) \\ \nu_l + X \ (NC) \end{cases}$$

Cherenkov radiation from interaction products: leptons and hadrons

nu e interactions dominates in special case

IC signal simulation

The IceCube Collaboration, 2017, 2019

IC signal simulation

$$N_i^{\mathrm{HESE}} = \int d\Omega \int_{E_{i,\mathrm{min}}}^{E_{i,\mathrm{max}}} dE \sum_{\ell=e,\mu,\tau} \Phi_{\nu_\ell}(E) \cdot T \cdot A_{\nu_\ell}(E,\Omega)$$

The IceCube Collaboration, 2017, 2019

IC signal simulation

$$N_i^{\mathrm{HESE}} = \int d\Omega \int_{E_{i,\min}}^{E_{i,\max}} dE \sum_{\ell=e,\mu,\tau} \Phi_{\nu_\ell}(E) \cdot T \cdot A_{\nu_\ell}(E,\Omega)$$

$A_{\nu_\ell}(E,\Omega)$: HESE effective area, sum of cross sections for all the particles in the detector, an effective total cross section

The IceCube Collaboration, 2017, 2019

IC signal simulation

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The IceCube Collaboration, 2017, 2019

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$$\Phi(E_\nu) = \Phi_0 (E_\nu / 100\ \mathrm{TeV})^{-\gamma}$$

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$$\Phi_0 = 6.45^{+1.46}_{-0.46}\ \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

$$\gamma = 2.89^{+0.20}_{-0.19}$$

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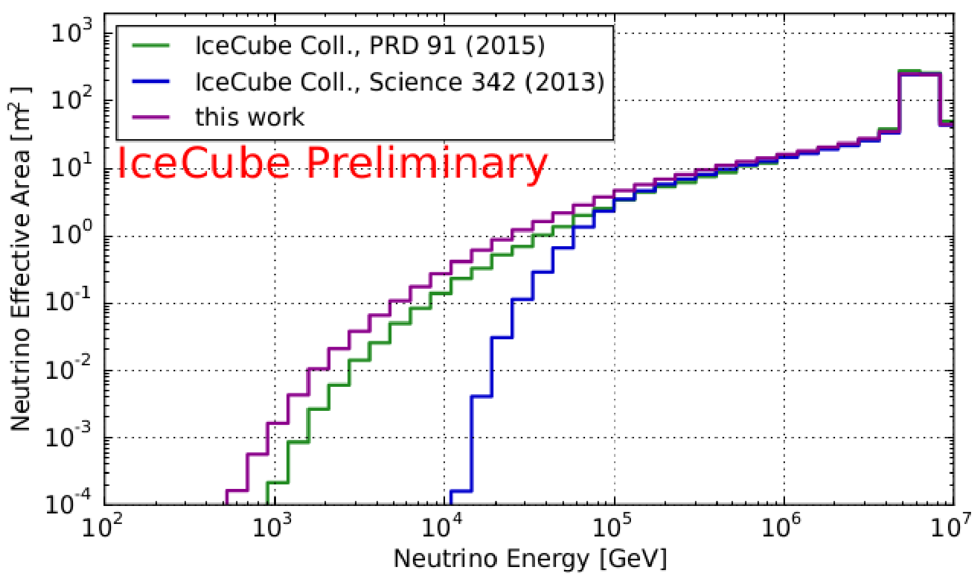
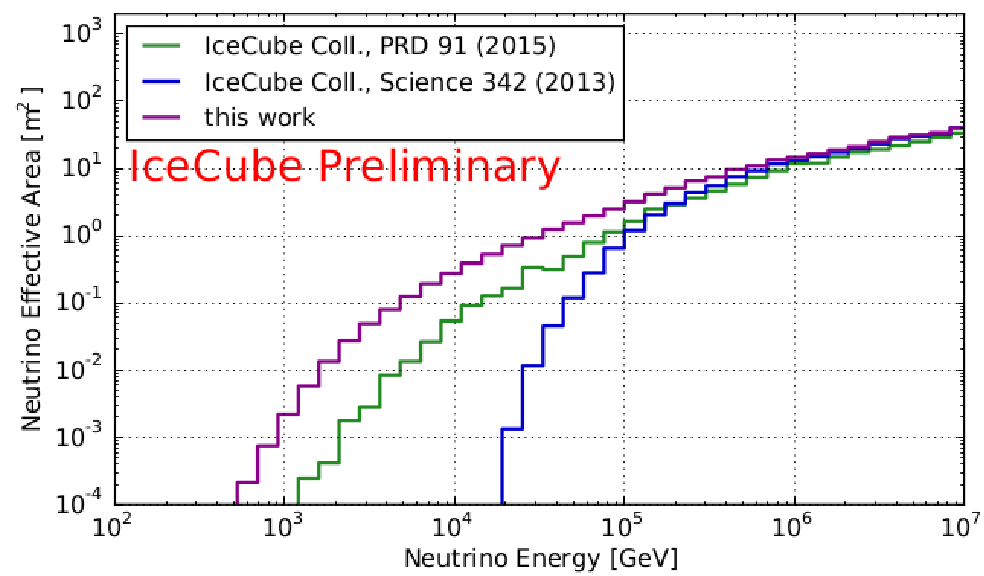
HESE e neutrino effective area



HESE muon neutrino effective area



The IceCube Collaboration, 2017, 2019

IC signal simulation

$$N_i^{\mathrm{HESE}} = \int d\Omega \int_{E_{i,\mathrm{min}}}^{E_{i,\mathrm{max}}} dE \sum_{\ell=e,\mu,\tau} \Phi_{\nu_\ell}(E) \cdot T \cdot A_{\nu_\ell}(E,\Omega)$$

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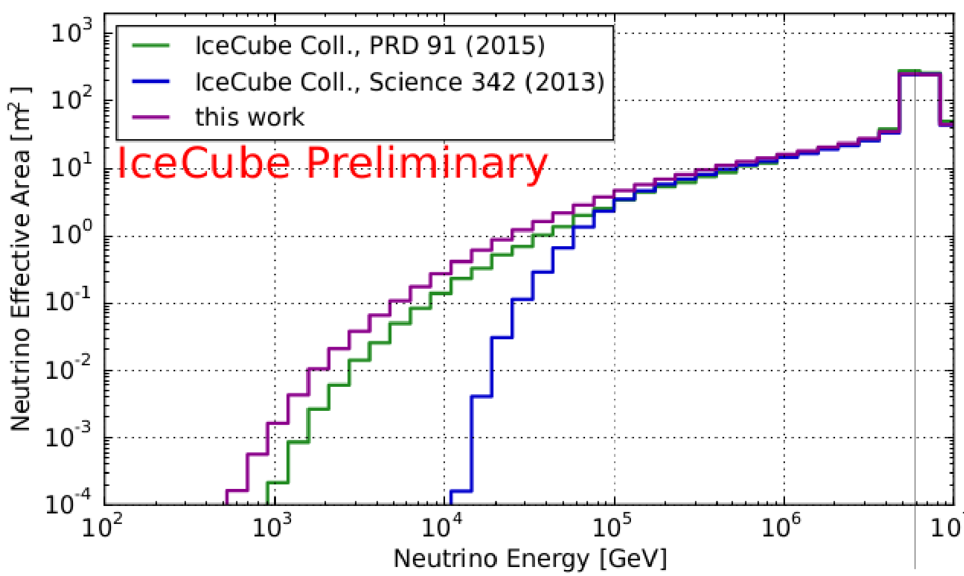
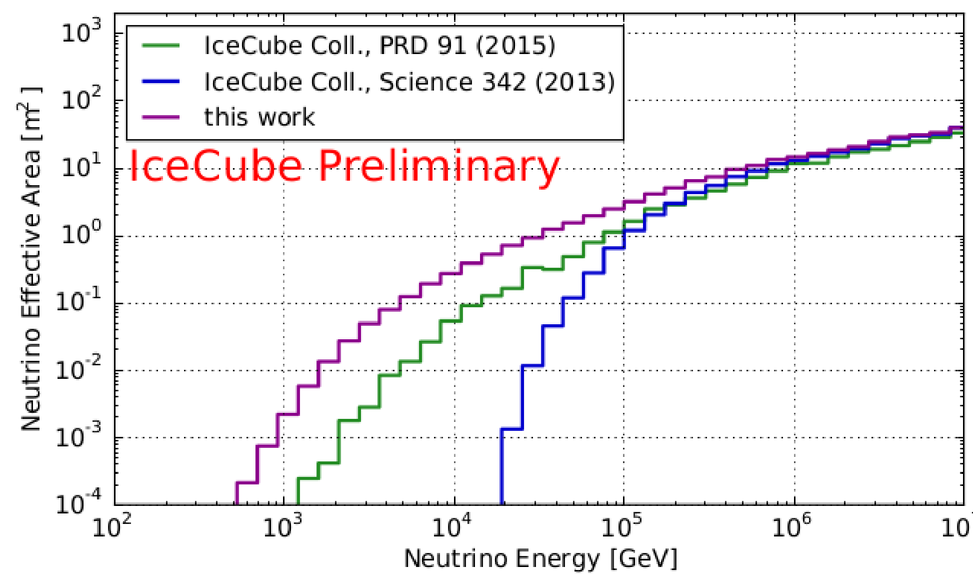


6.3 PeV

HESE muon neutrino effective area



The IceCube Collaboration, 2017, 2019

IC signal simulation

$$N_i^{\mathrm{HESE}} = \int d\Omega \int_{E_{i,\min}}^{E_{i,\max}} dE \sum_{\ell=e,\mu,\tau} \Phi_{\nu_\ell}(E) \cdot T \cdot A_{\nu_\ell}(E,\Omega)$$

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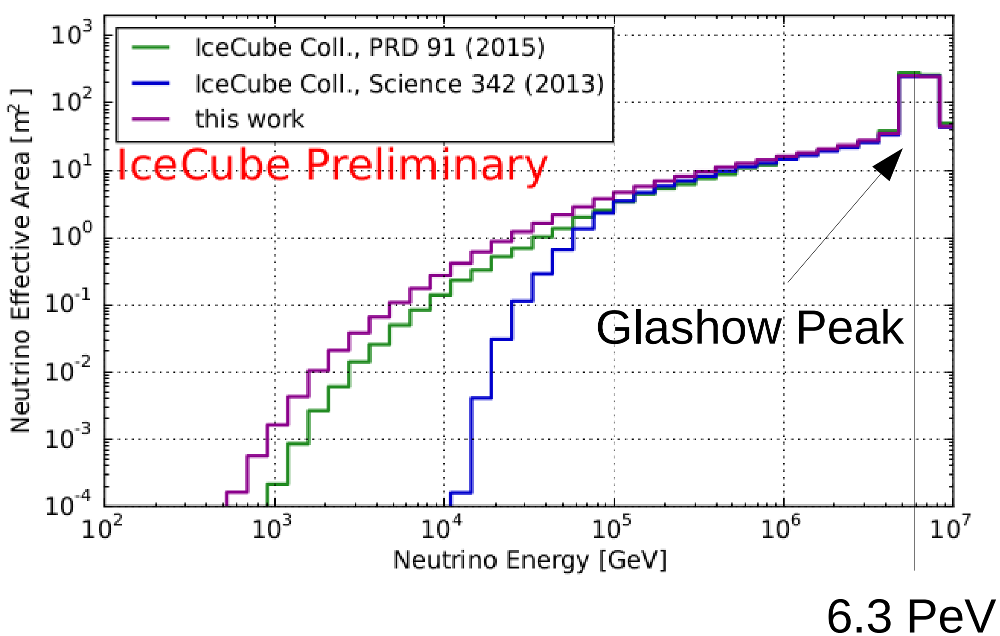
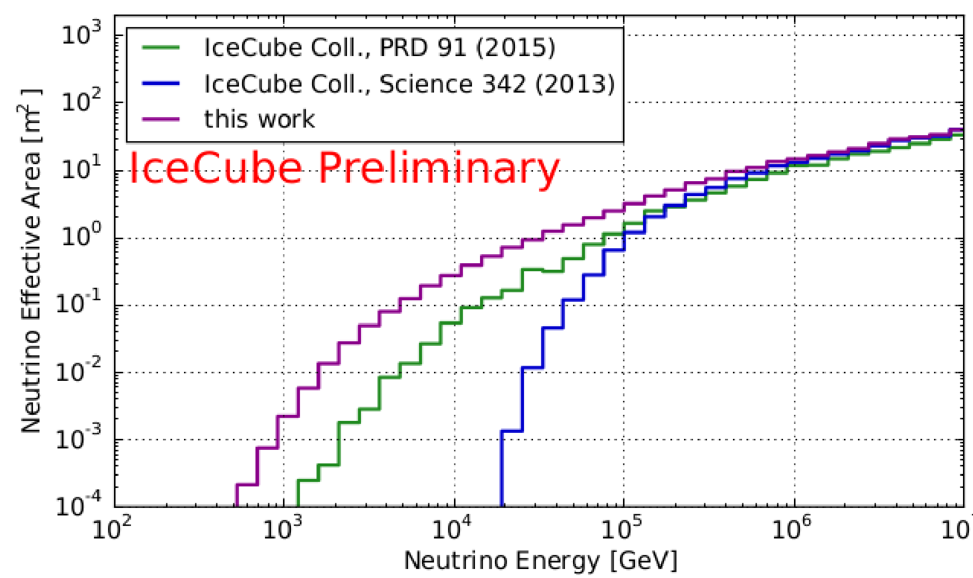
HESE e neutrino effective area

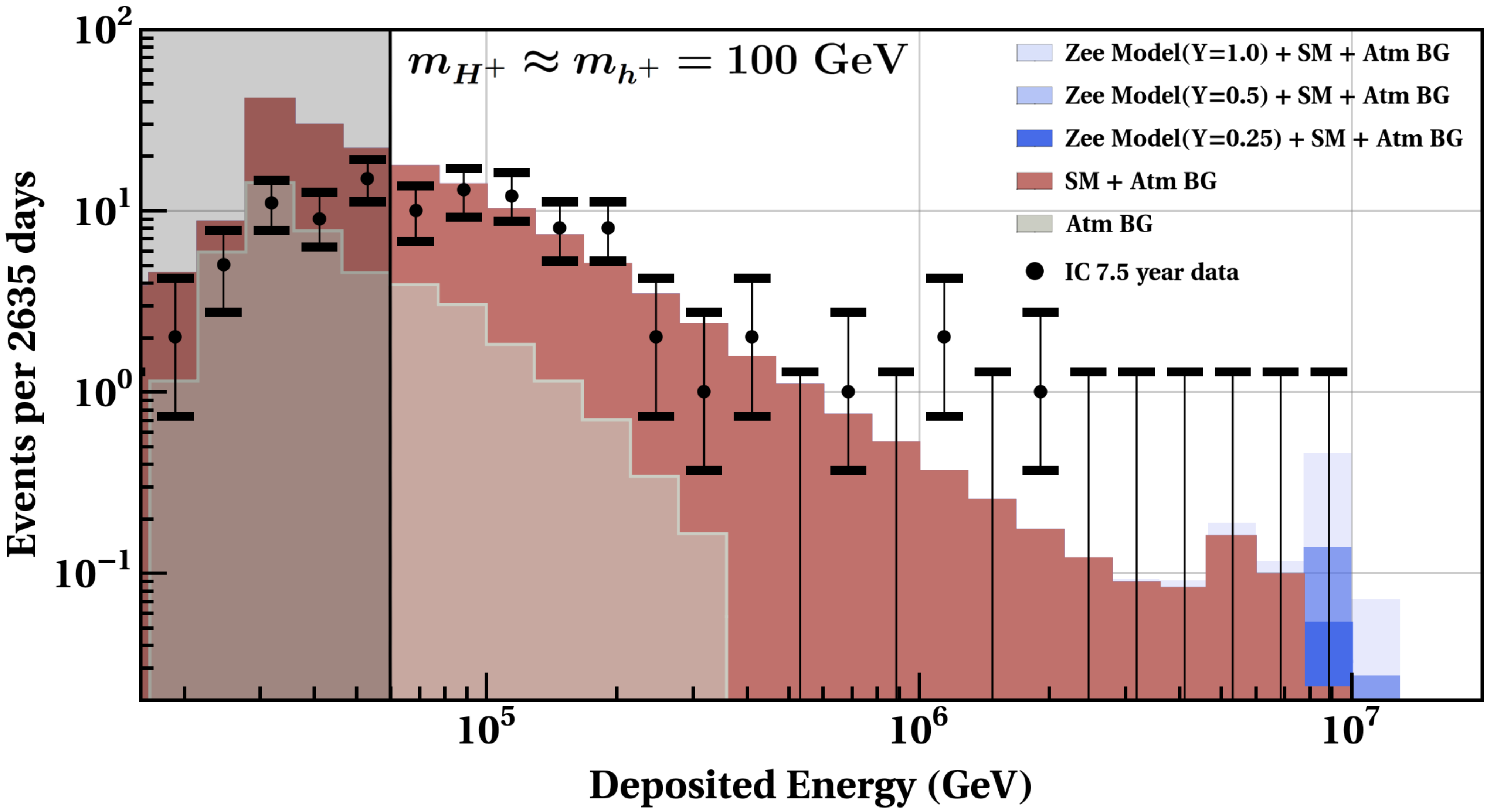


HESE muon neutrino effective area

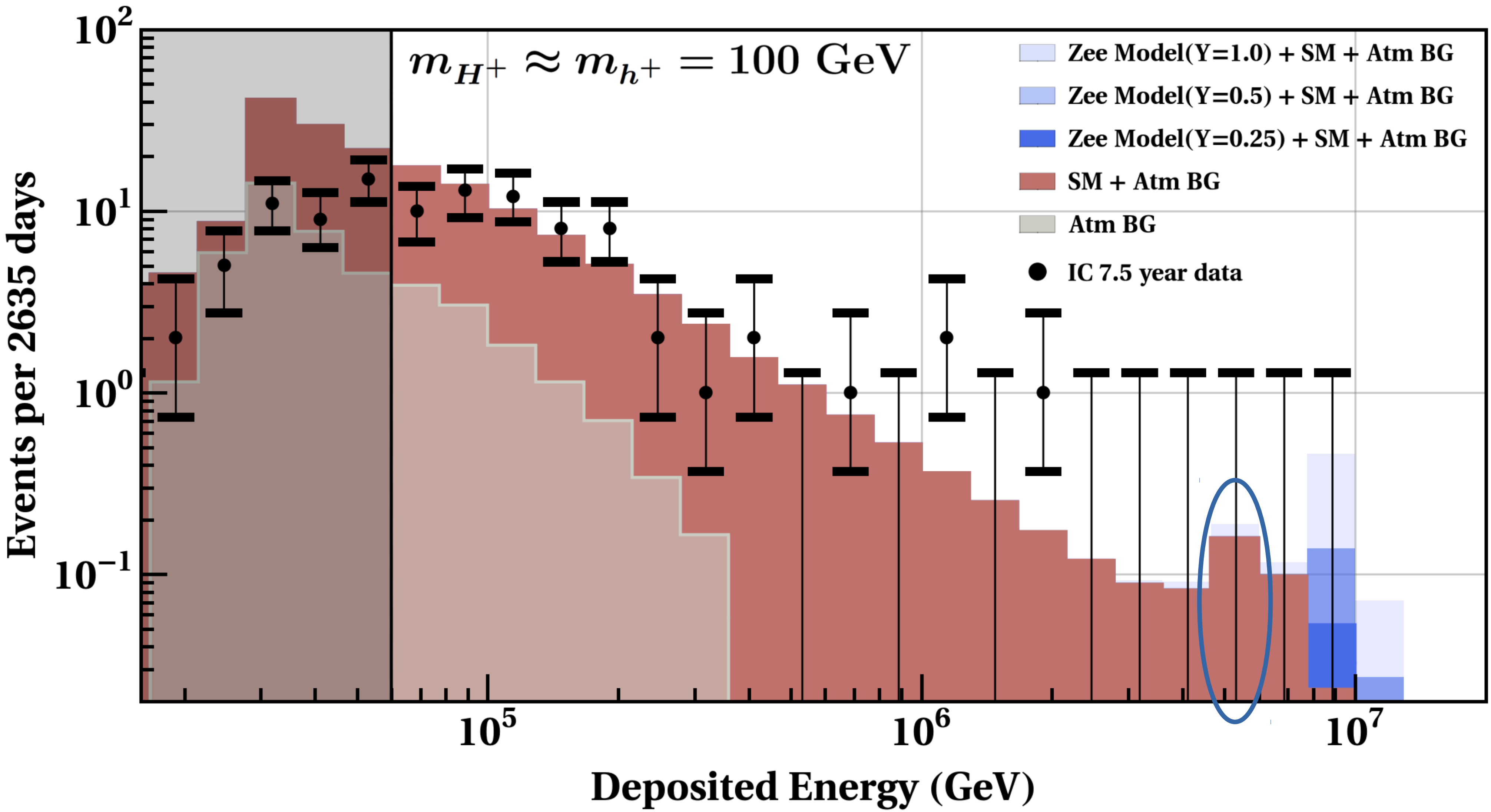


The IceCube Collaboration, 2017, 2019

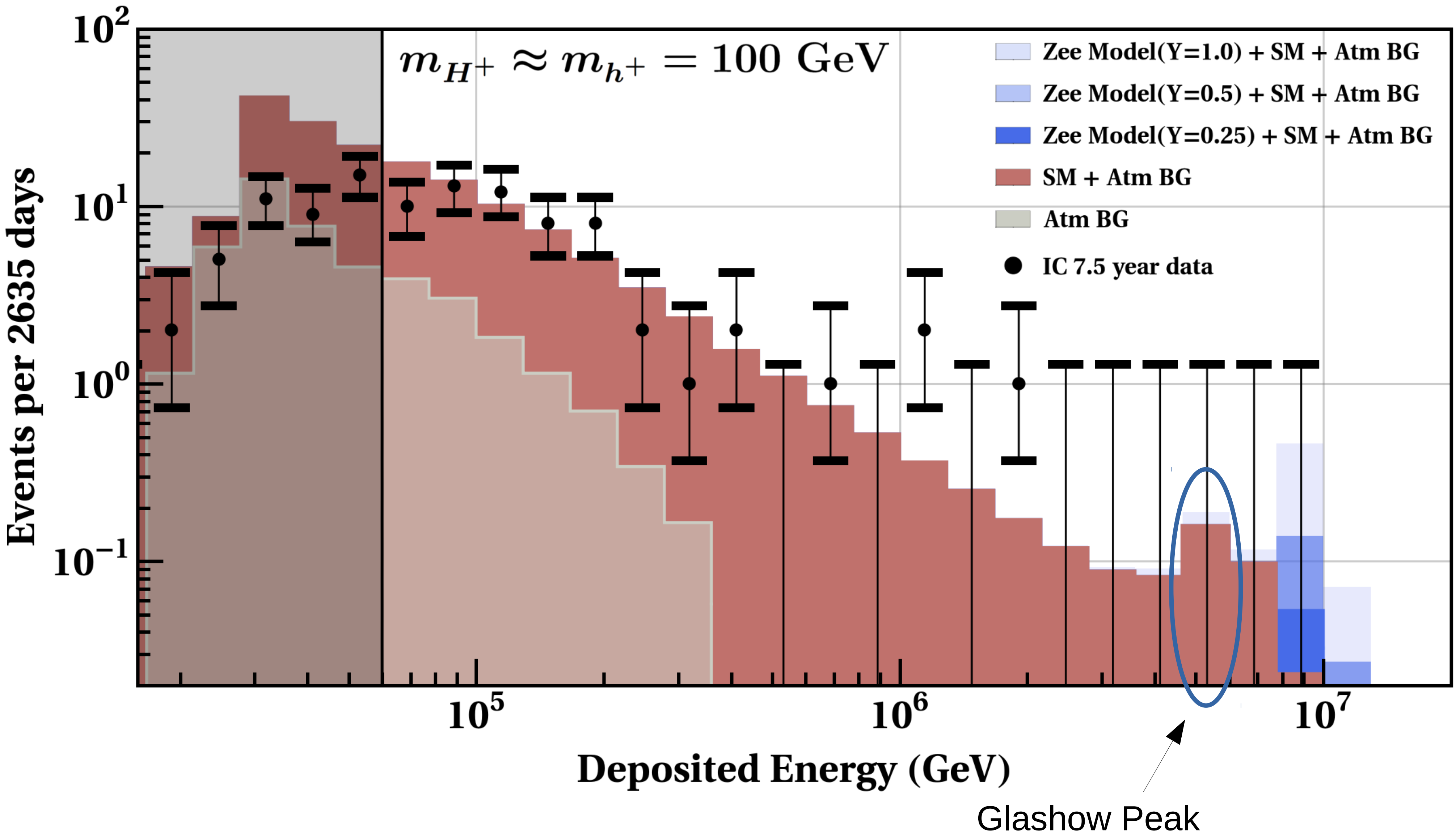
Spectrum plot



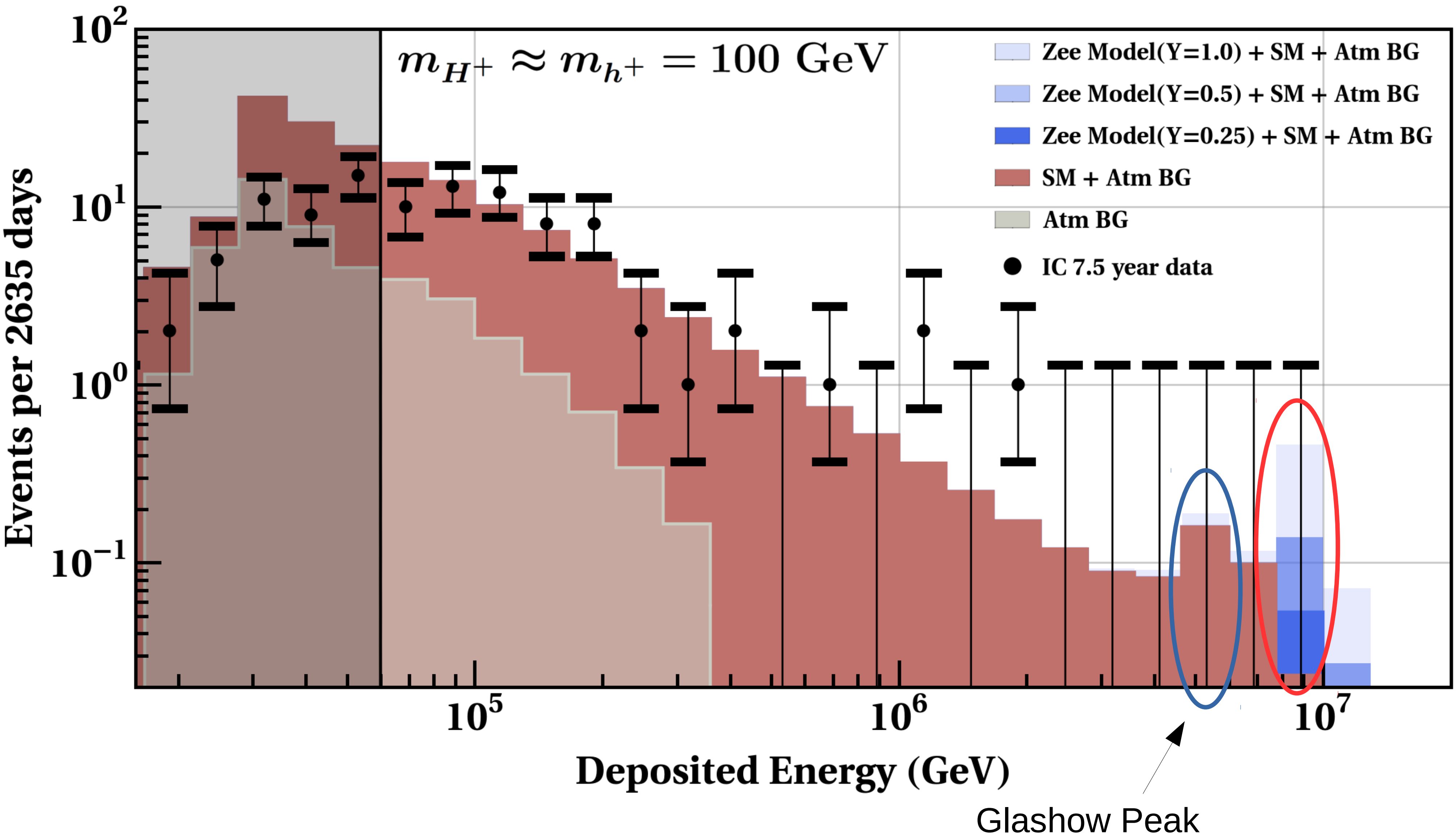
Spectrum plot



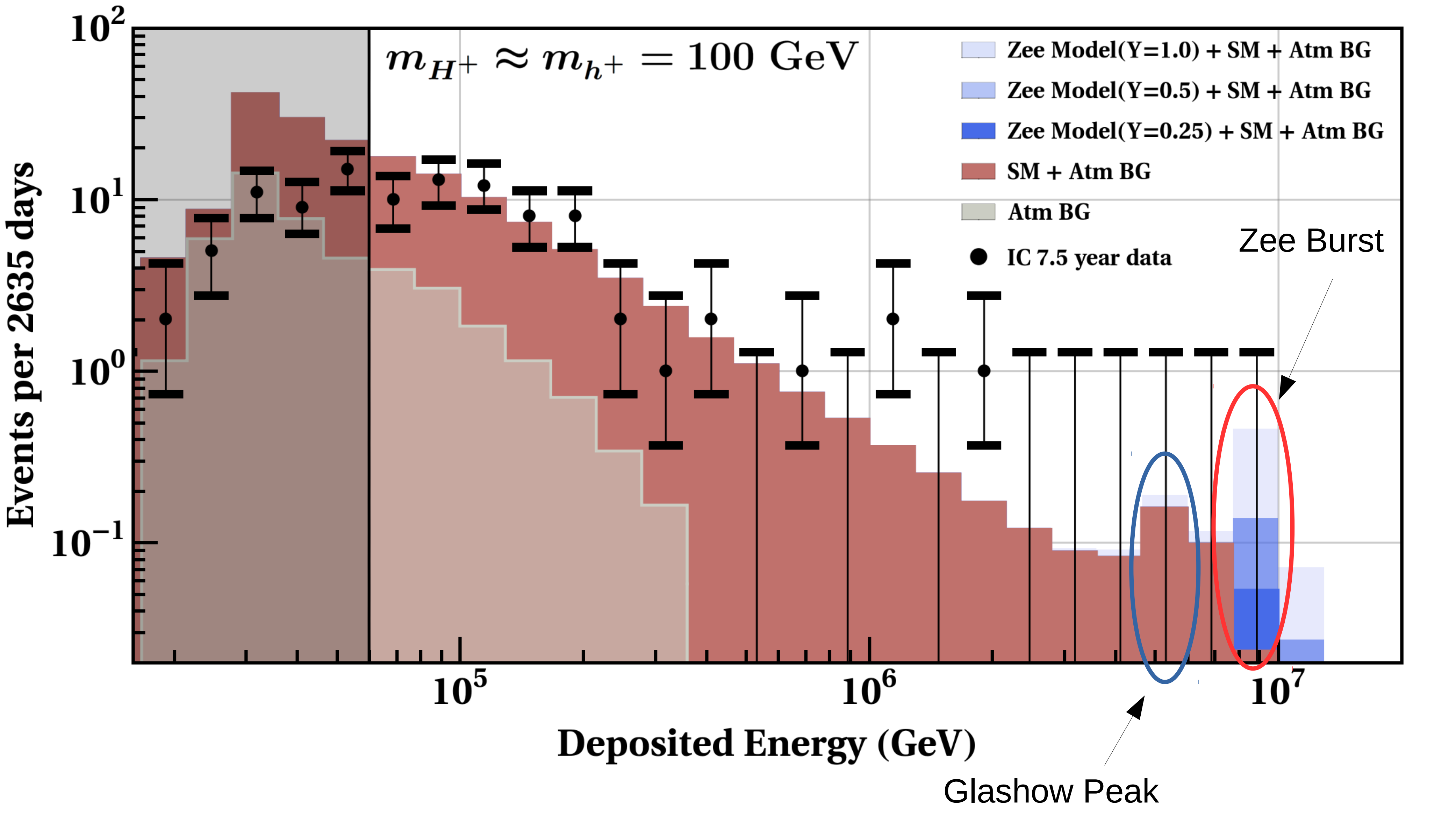
Spectrum plot



Spectrum plot



Spectrum plot



NSI from Zee Model

NSI from Zee Model

$$-\mathcal{L}_Y \supset f_{\alpha\beta} L^i_\alpha L^j_\beta \epsilon_{ij} \eta^+ + \widetilde{Y}_{\alpha\beta} \widetilde{H}^i_1 L^j_\alpha \ell^c_\beta \epsilon_{ij} + Y_{\alpha\beta} \widetilde{H}^i_2 L^j_\alpha \ell^c_\beta \epsilon_{ij} + \mathrm{H.c.}$$

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Effectively, we have:

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Effectively, we have:

$$\mathcal{L}_{\rm eff} = -\frac{1}{2} Y_{\alpha\rho} Y^\star_{\beta\sigma} \left(\frac{\sin^2\varphi}{m^2_{h^+}} + \frac{\cos^2\varphi}{m^2_{H^+}} \right) (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{\ell}_\sigma \gamma_\mu P_R \ell_\rho)$$

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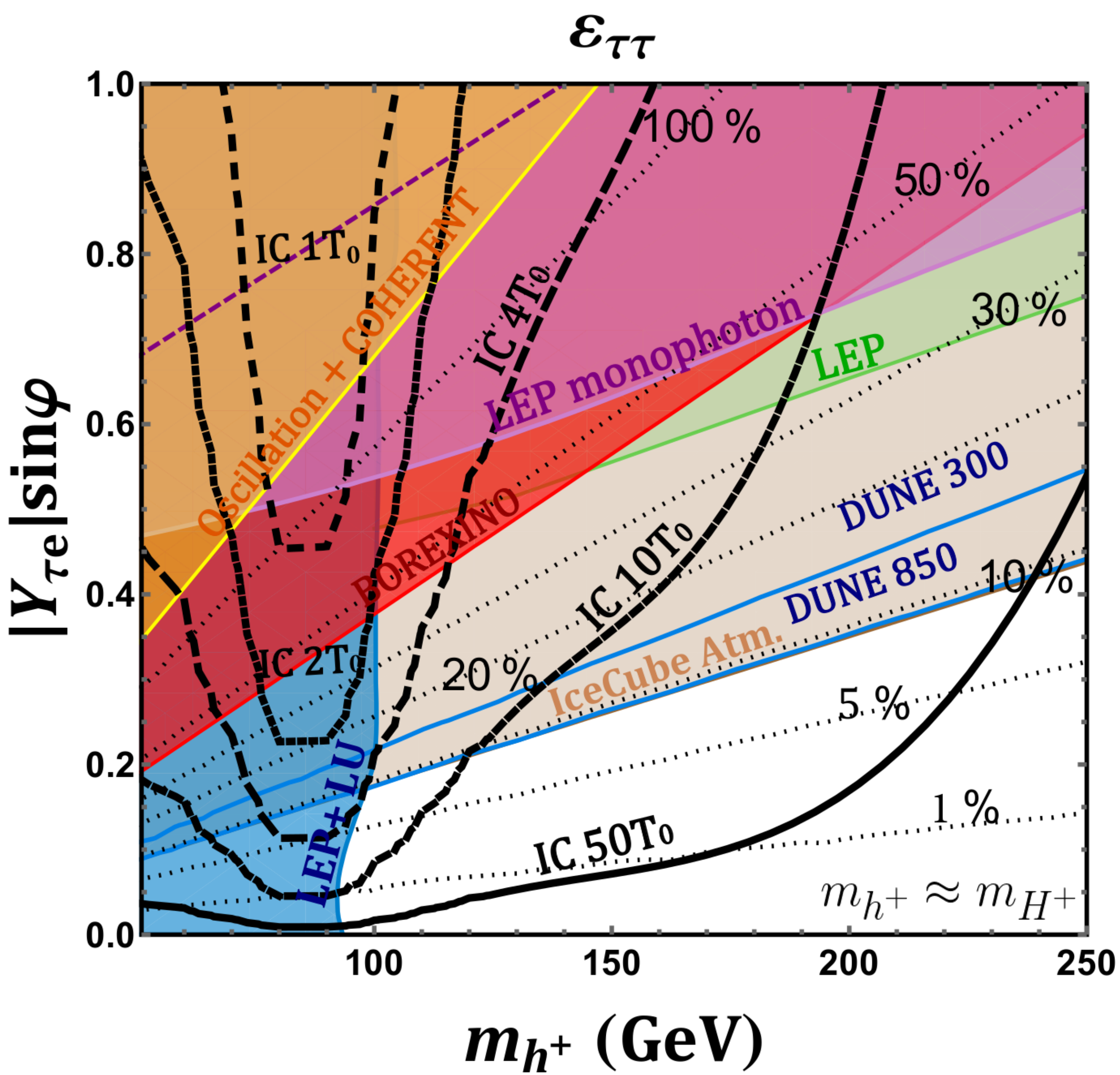
Condition for Maximum contribution to NSI and to Zee burst:

$$m_h^+ \approx m_H^+ \, , \; \sin\varphi = \cos\varphi$$

Sensitivity of IceCube and DUNE



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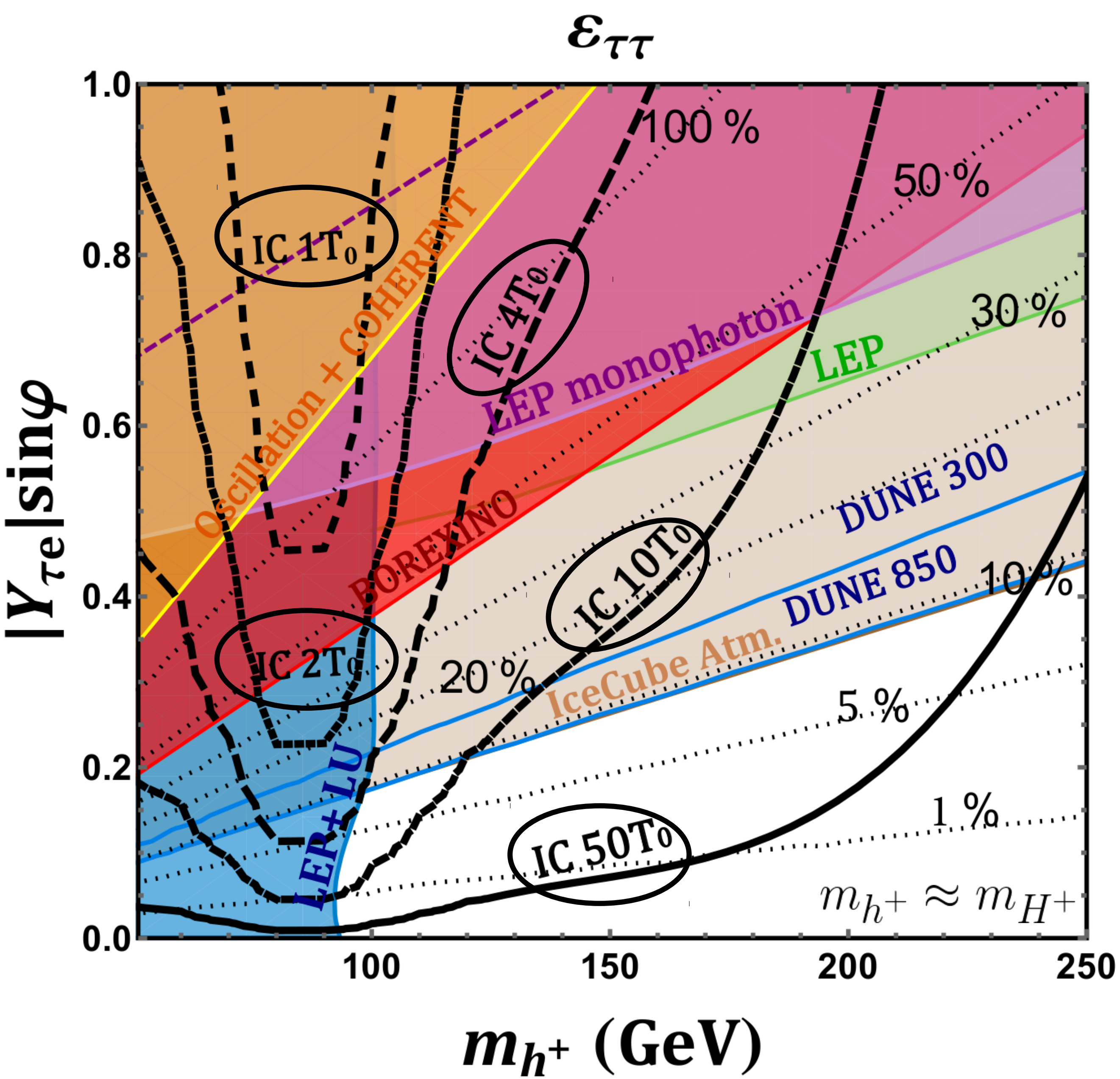

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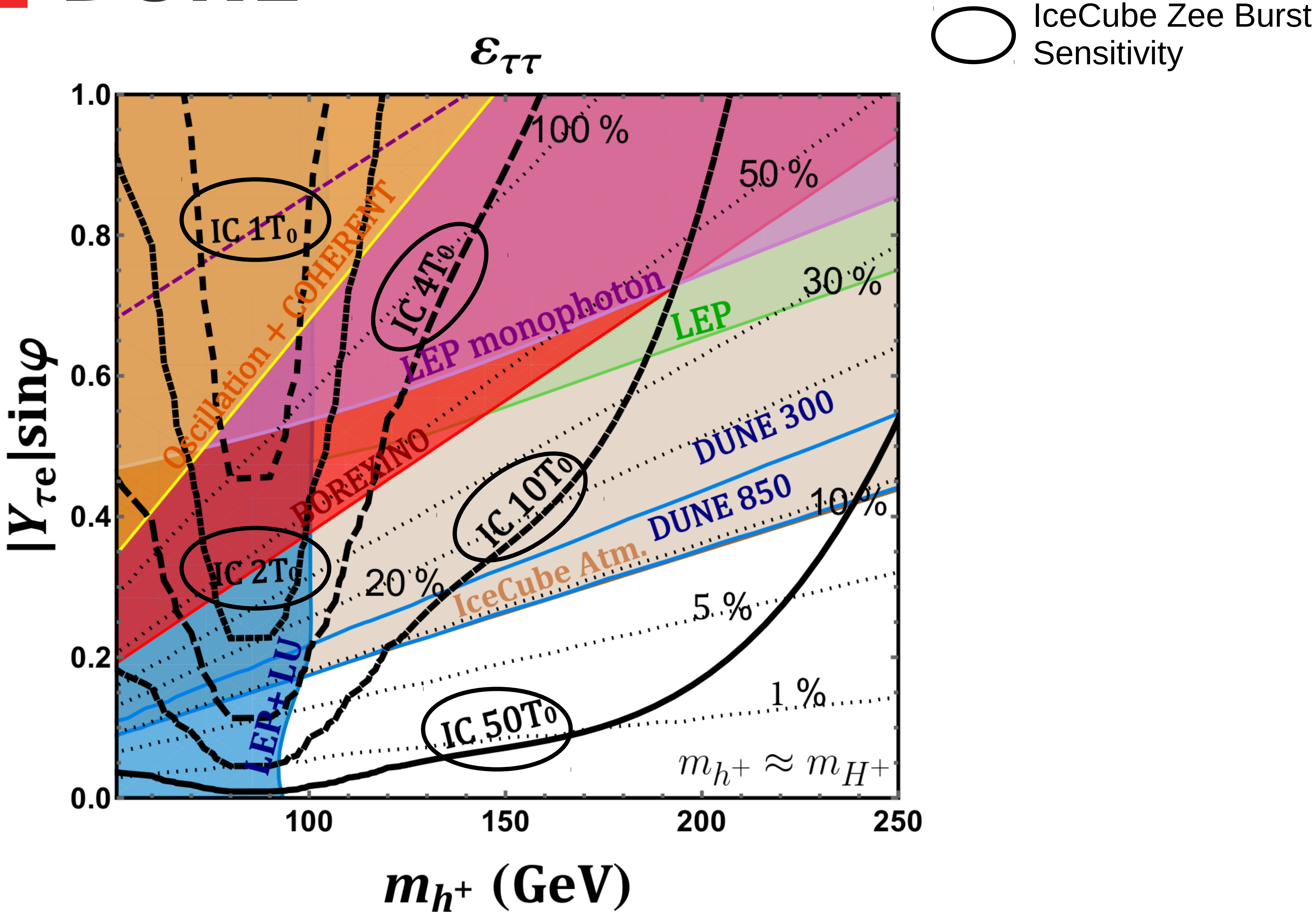

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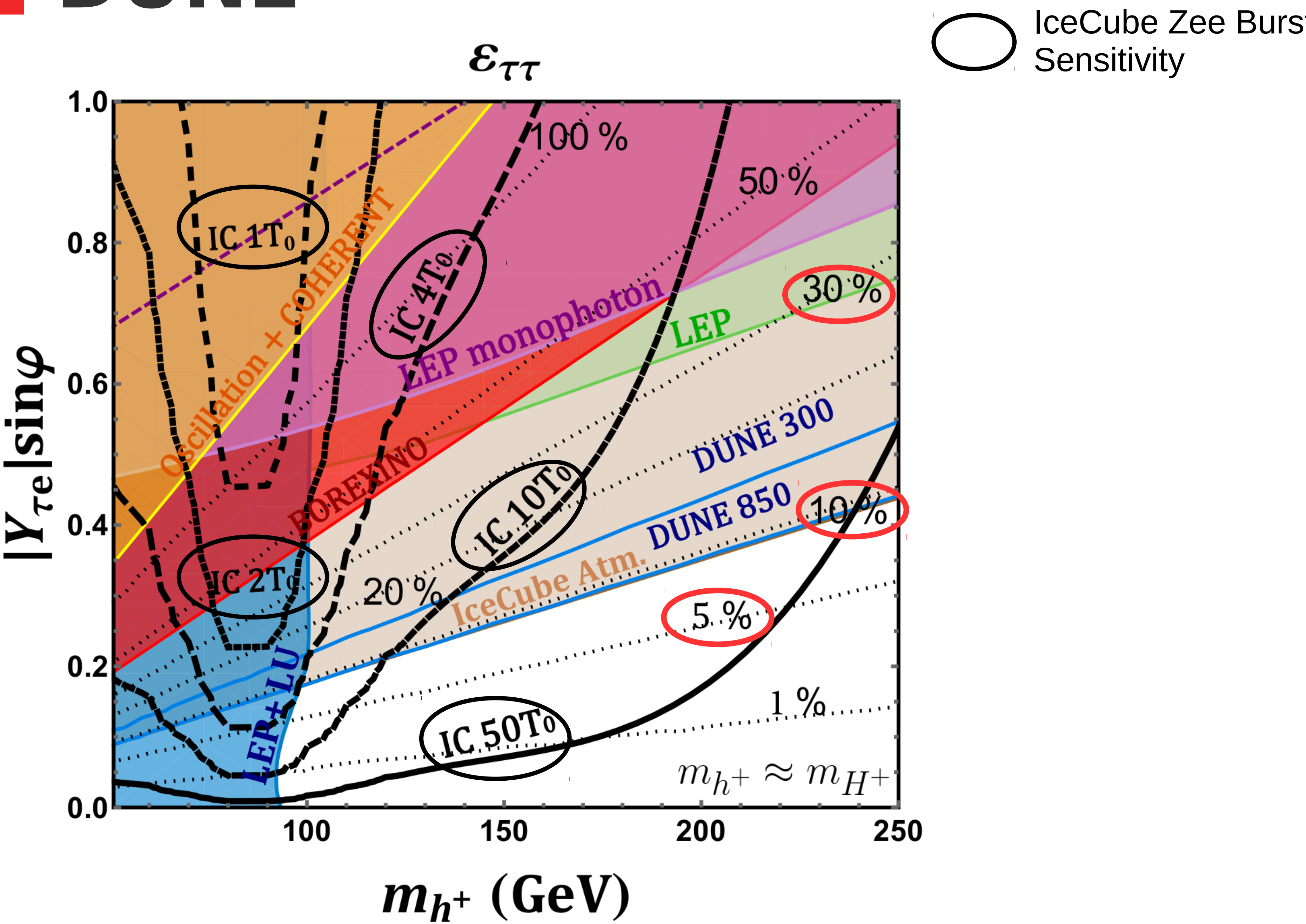
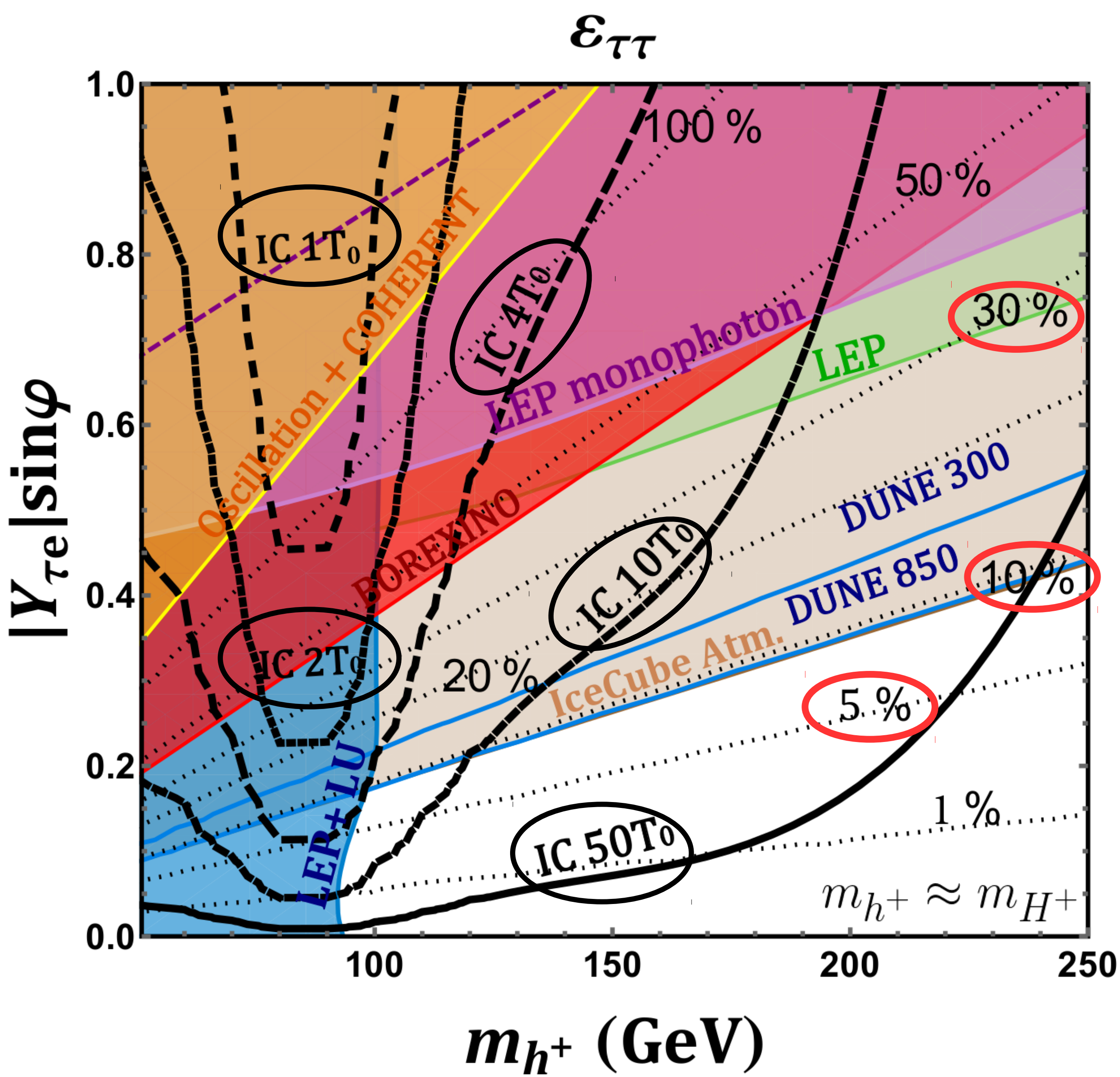
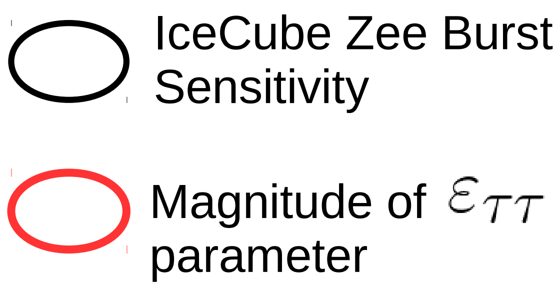


Sensitivity of IceCube and DUNE





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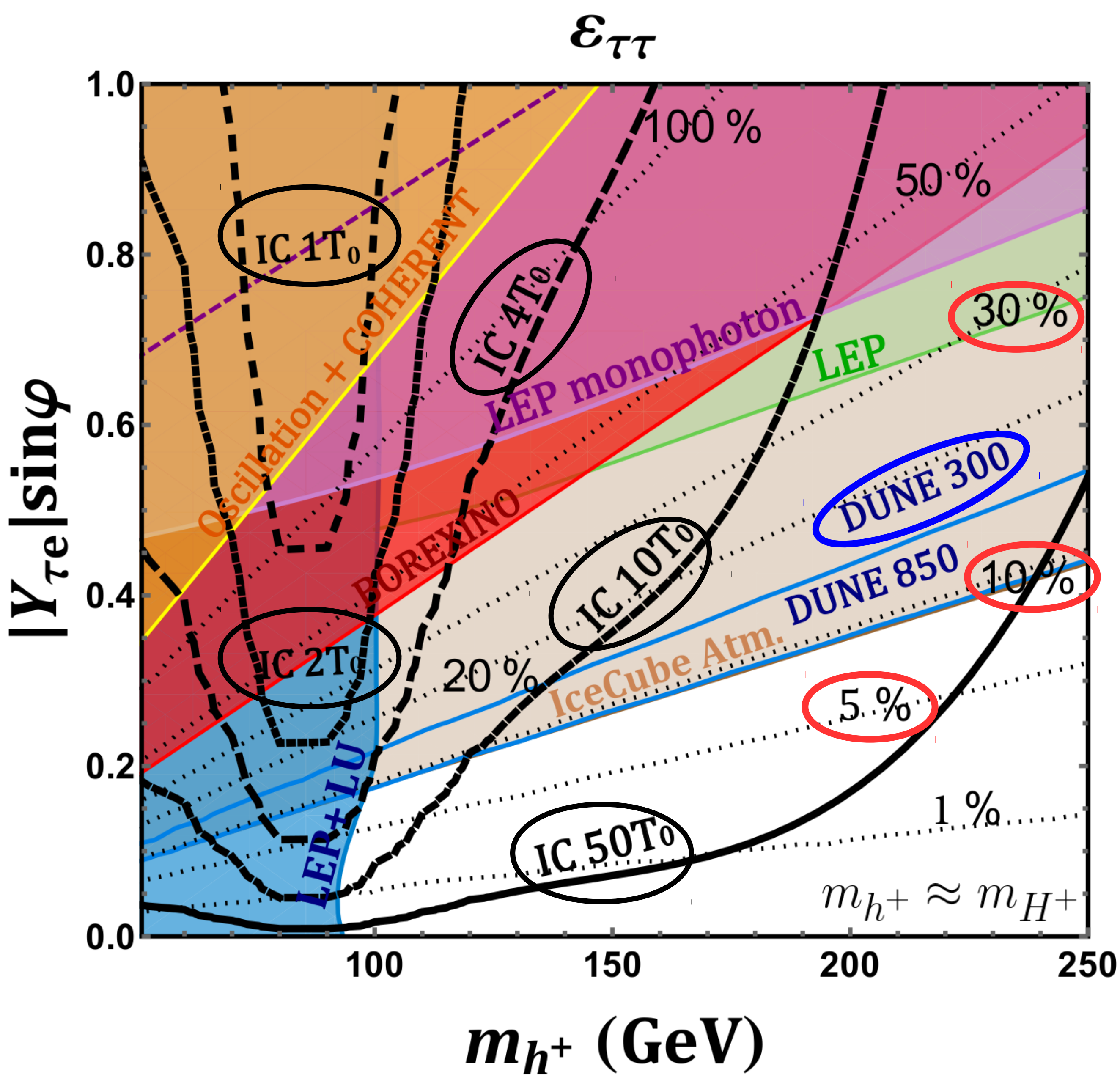
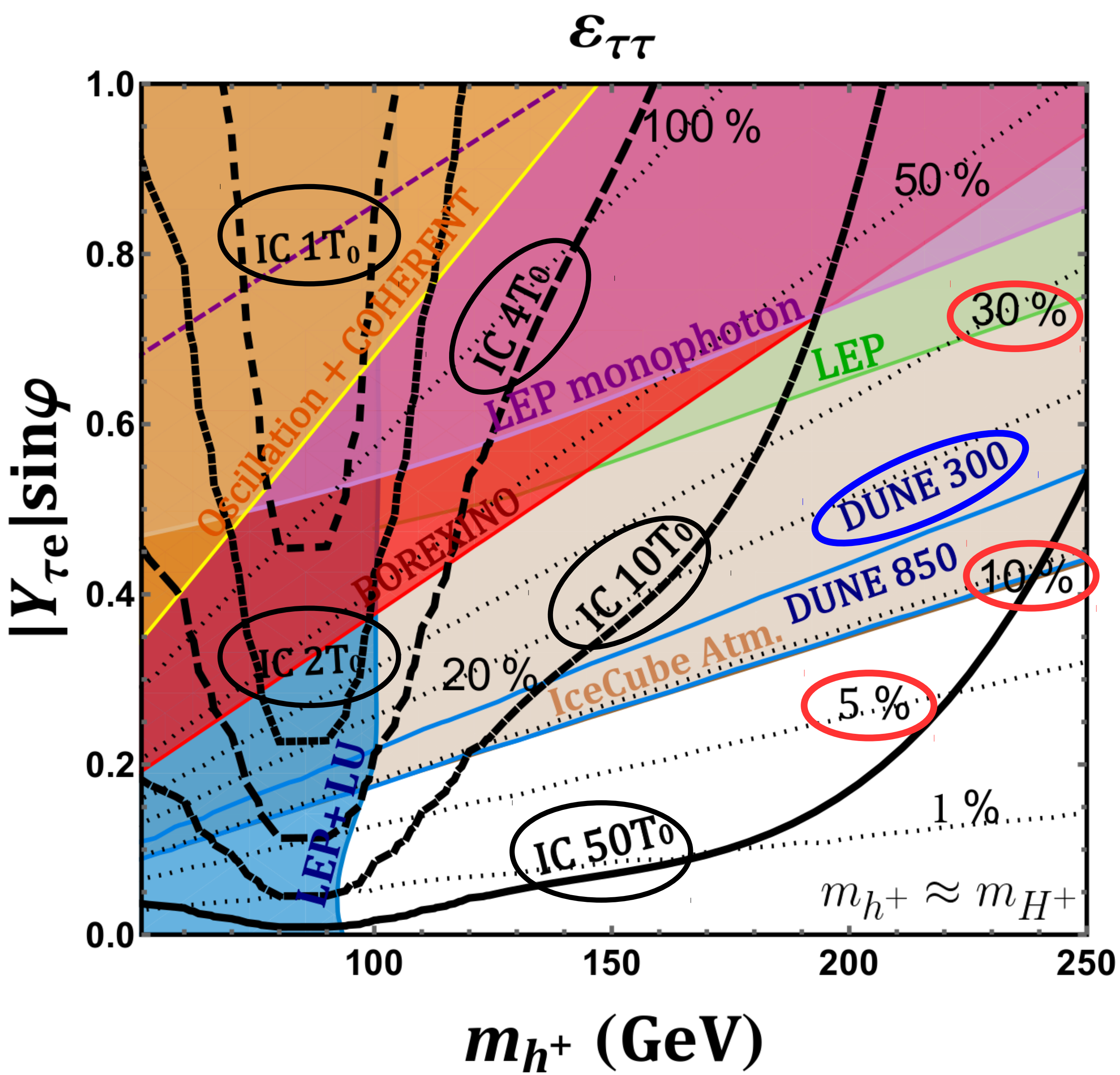


IceCube Zee Burst Sensitivity

Magnitude of $\varepsilon_{\tau\tau}$ parameter

Sensitivity of IceCube and DUNE

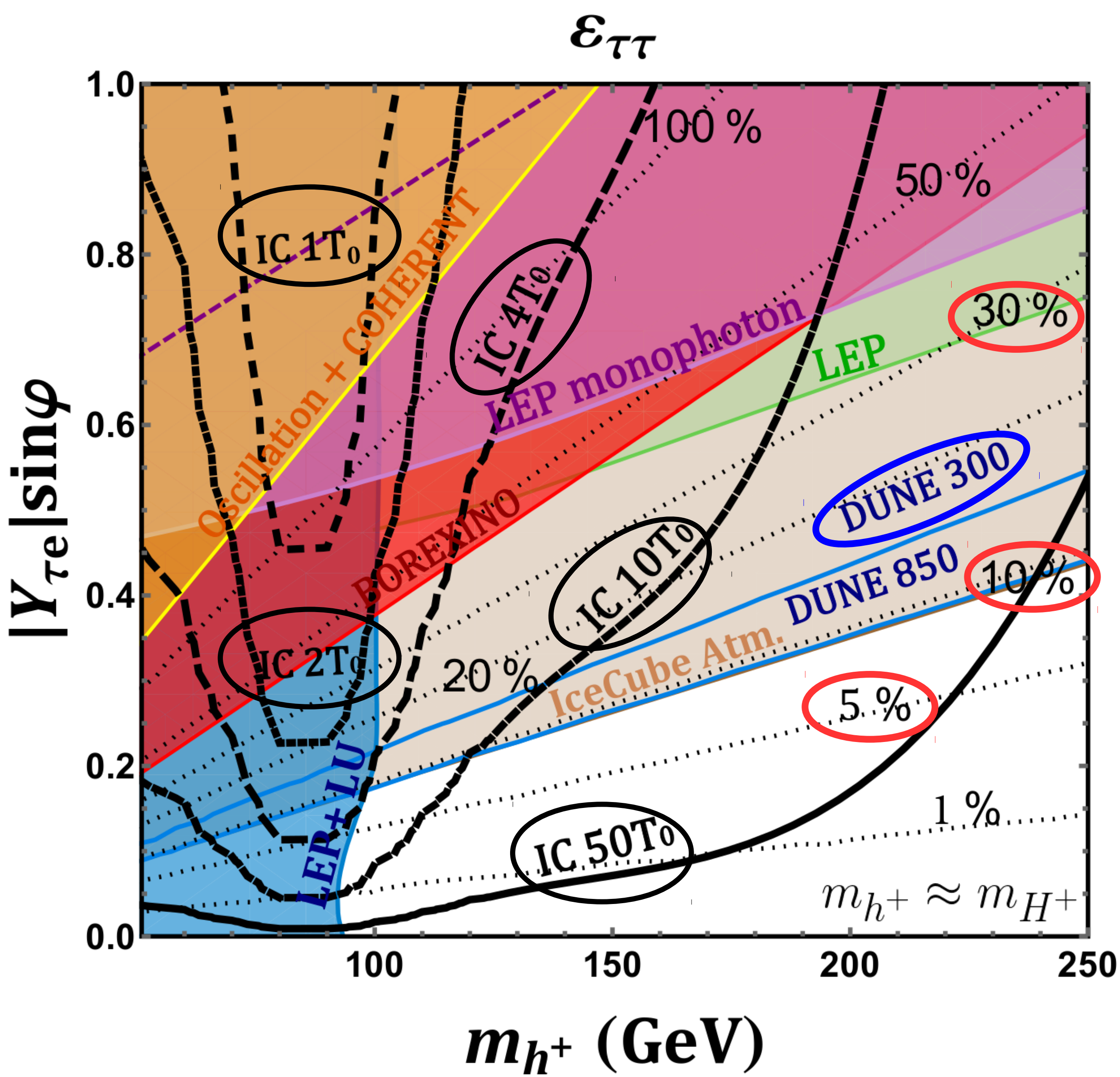


IceCube Zee Burst Sensitivity

Magnitude of $\varepsilon_{\tau\tau}$ parameter

DUNE sensitivity for NSI

Sensitivity of IceCube and DUNE



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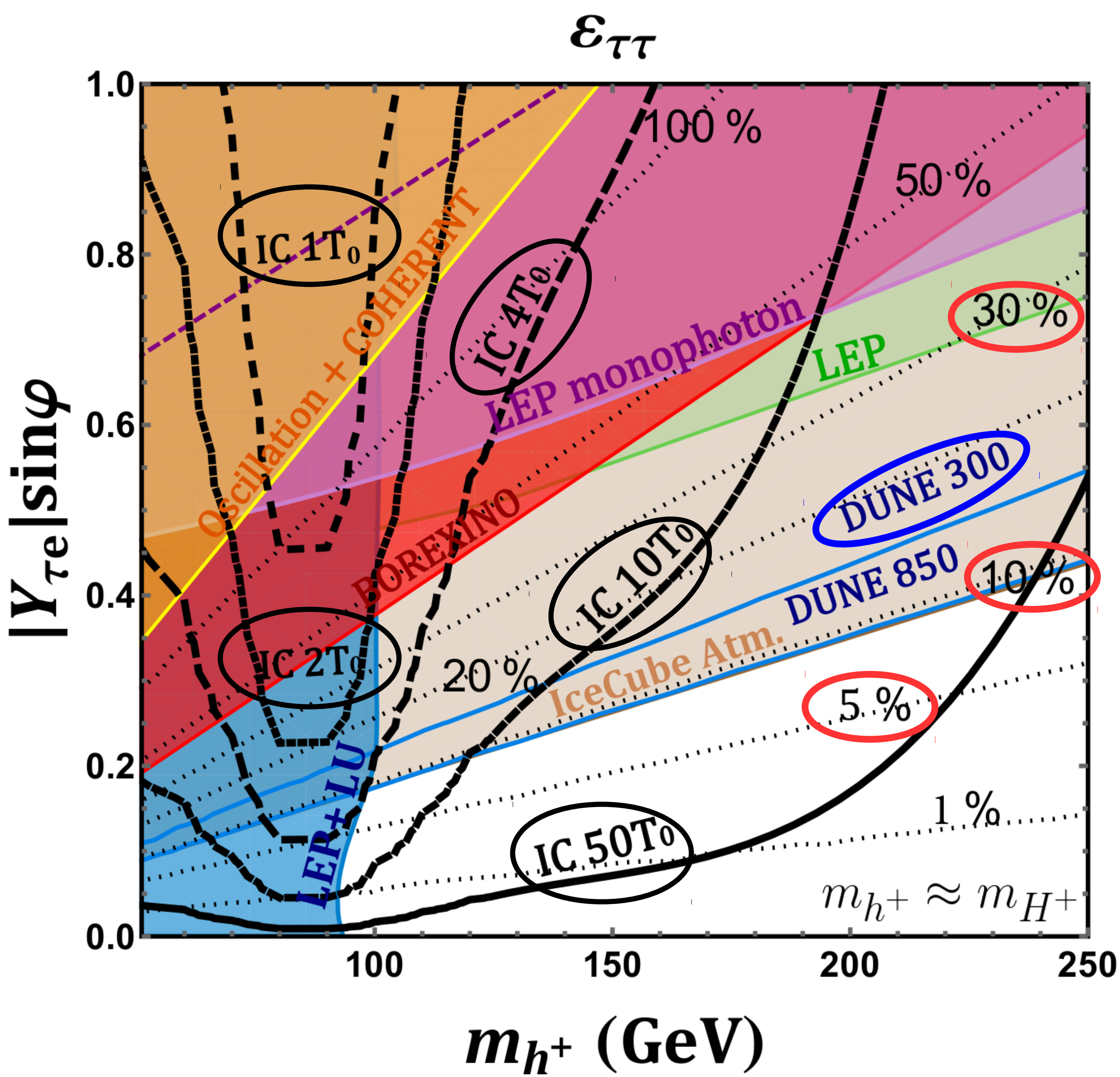


IceCube Zee Burst Sensitivity

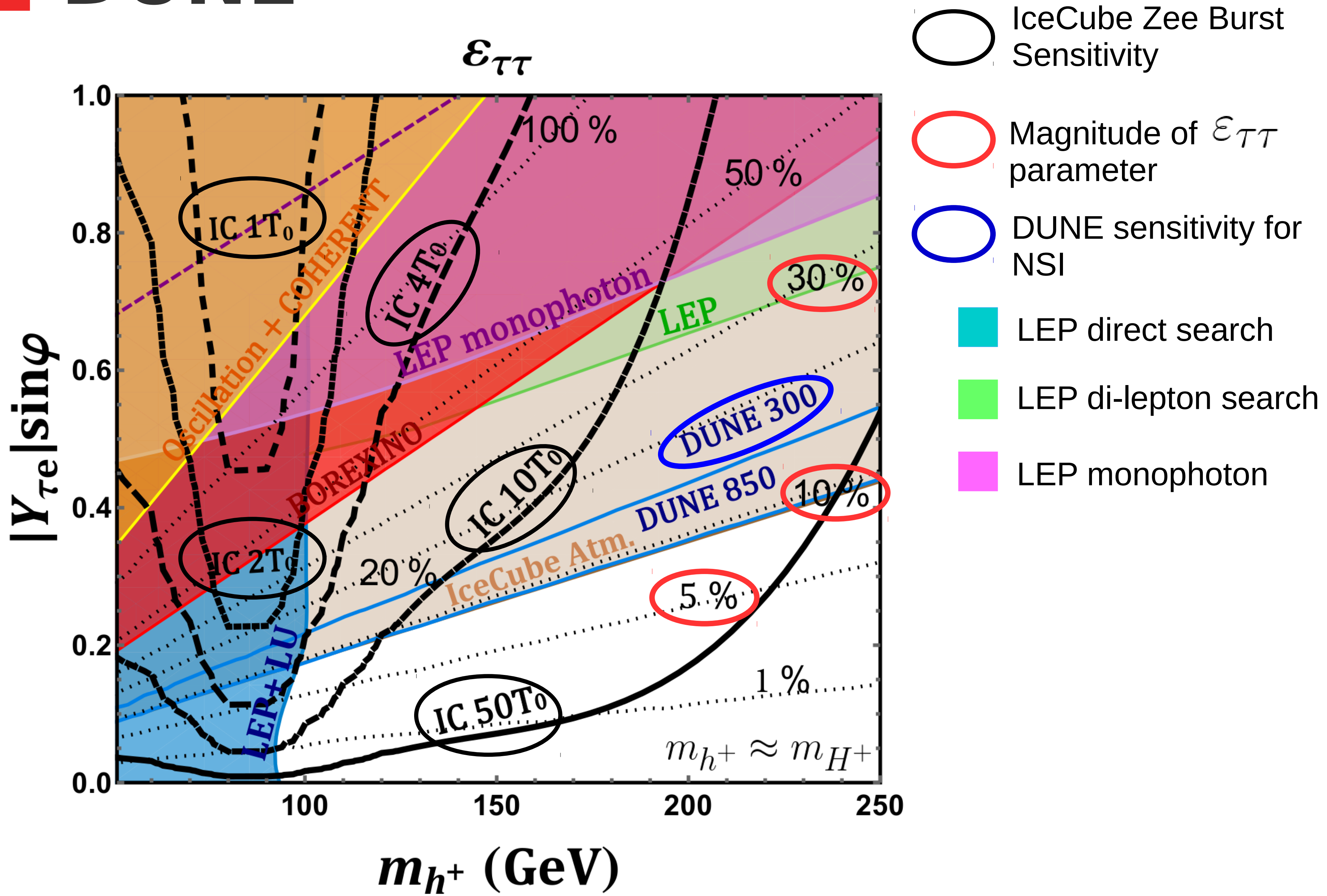
Magnitude of $\varepsilon_{\tau\tau}$ parameter

DUNE sensitivity for NSI

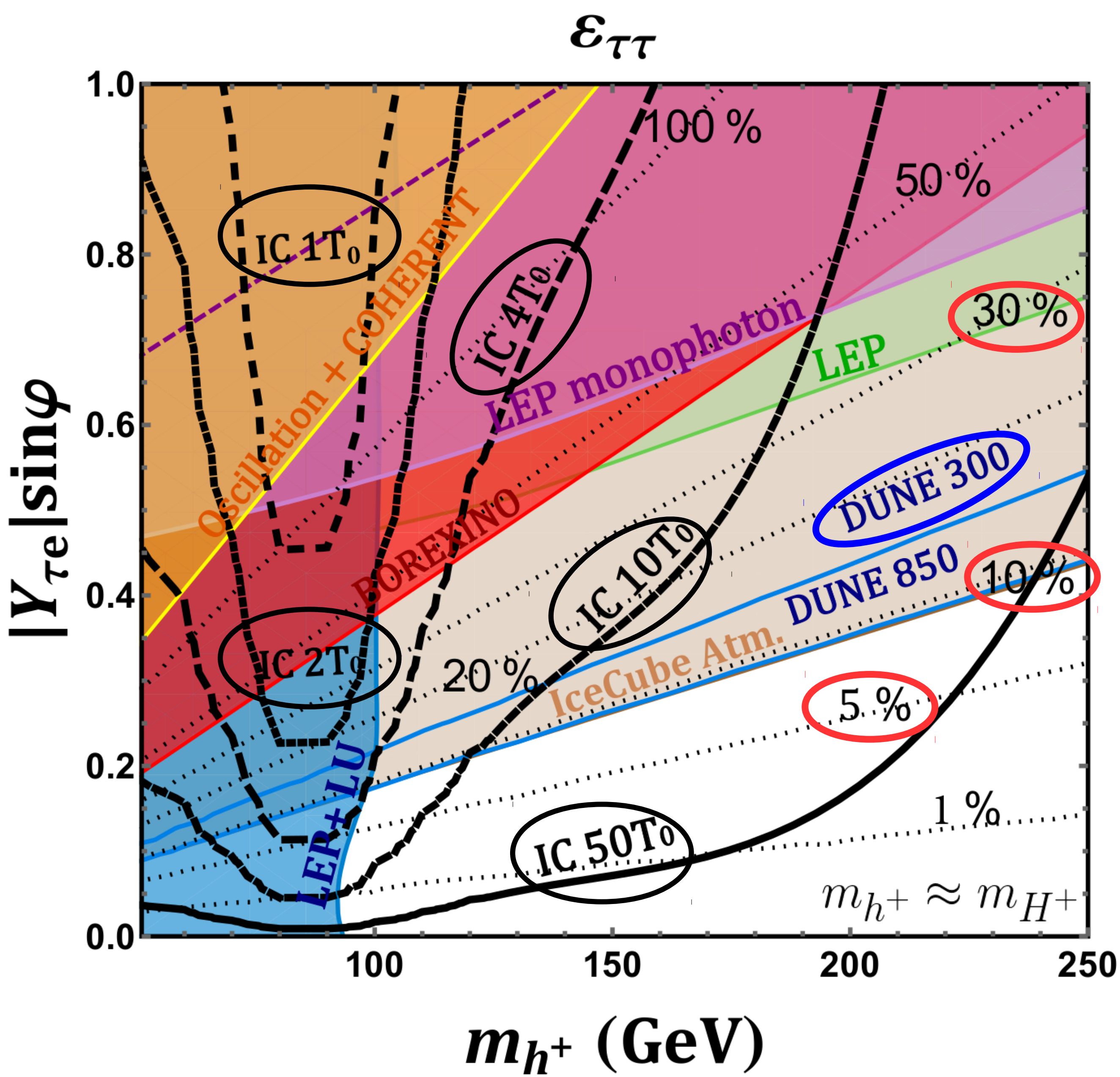
LEP direct search

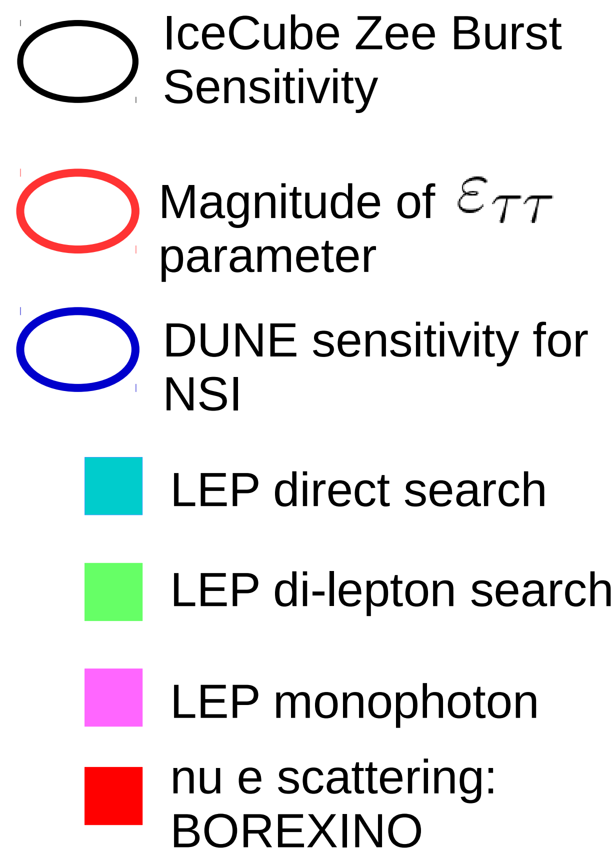
LEP di-lepton search

Sensitivity of IceCube and DUNE

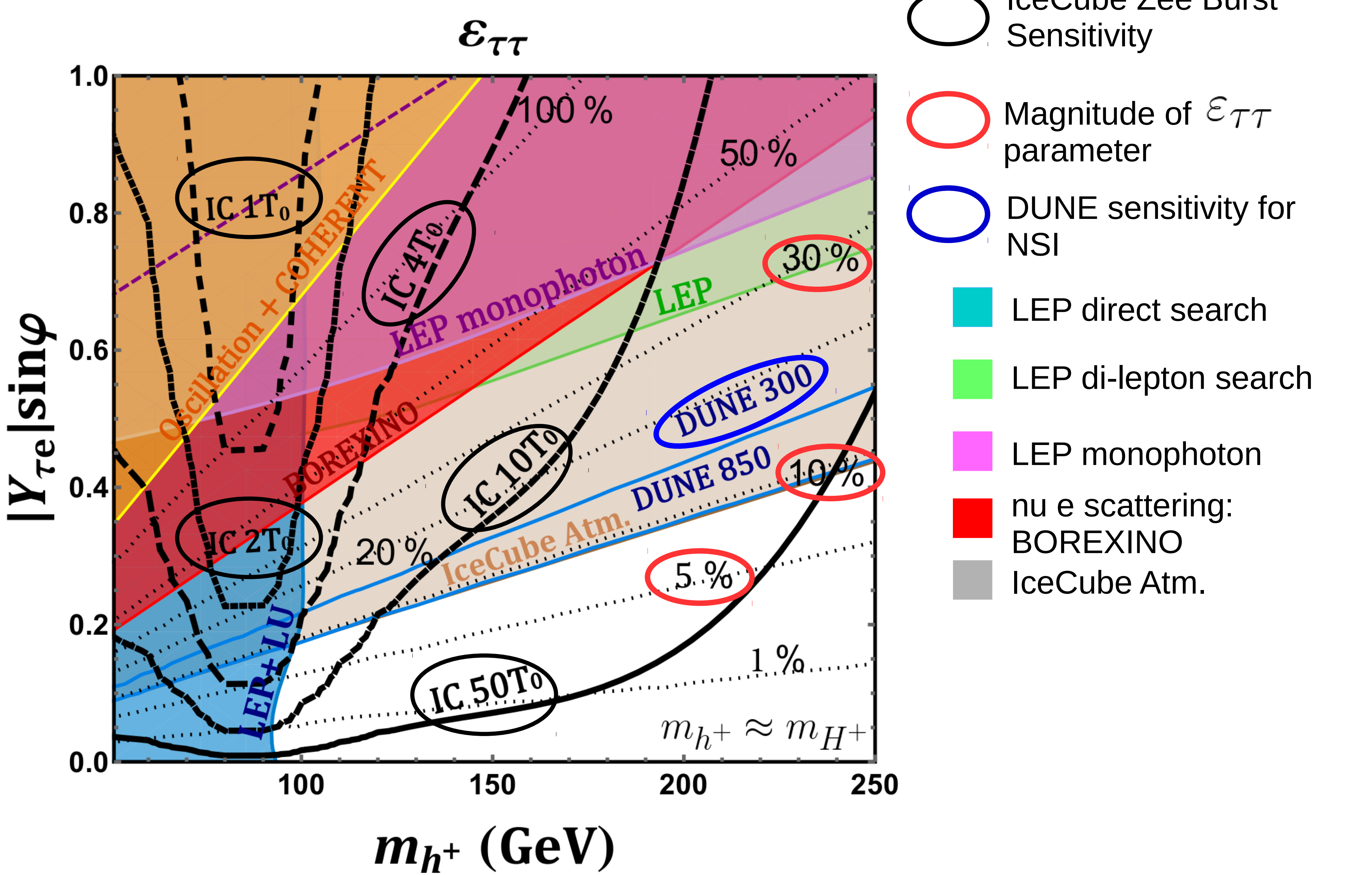


Sensitivity of IceCube and DUNE





Sensitivity of IceCube and DUNE



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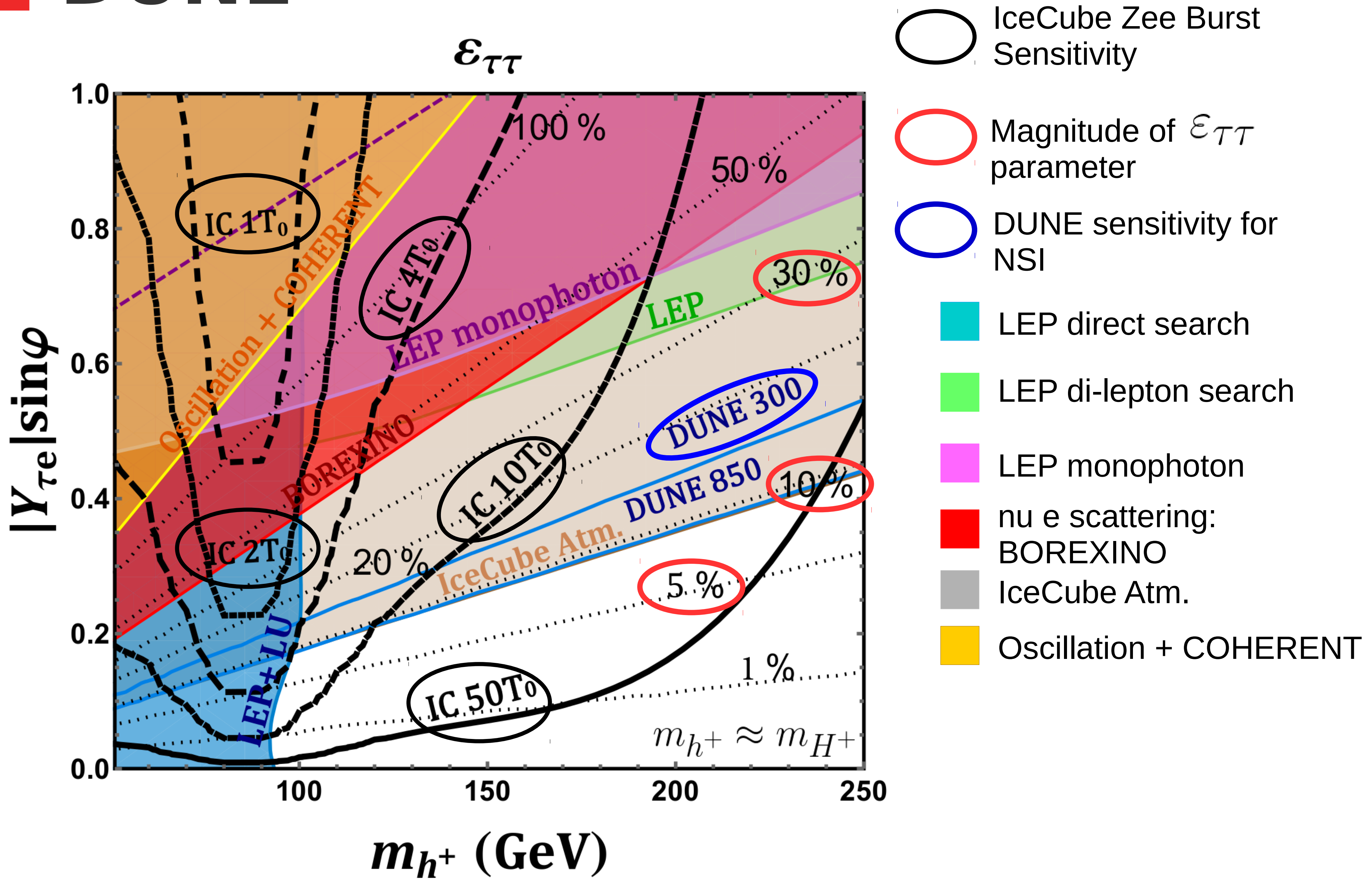

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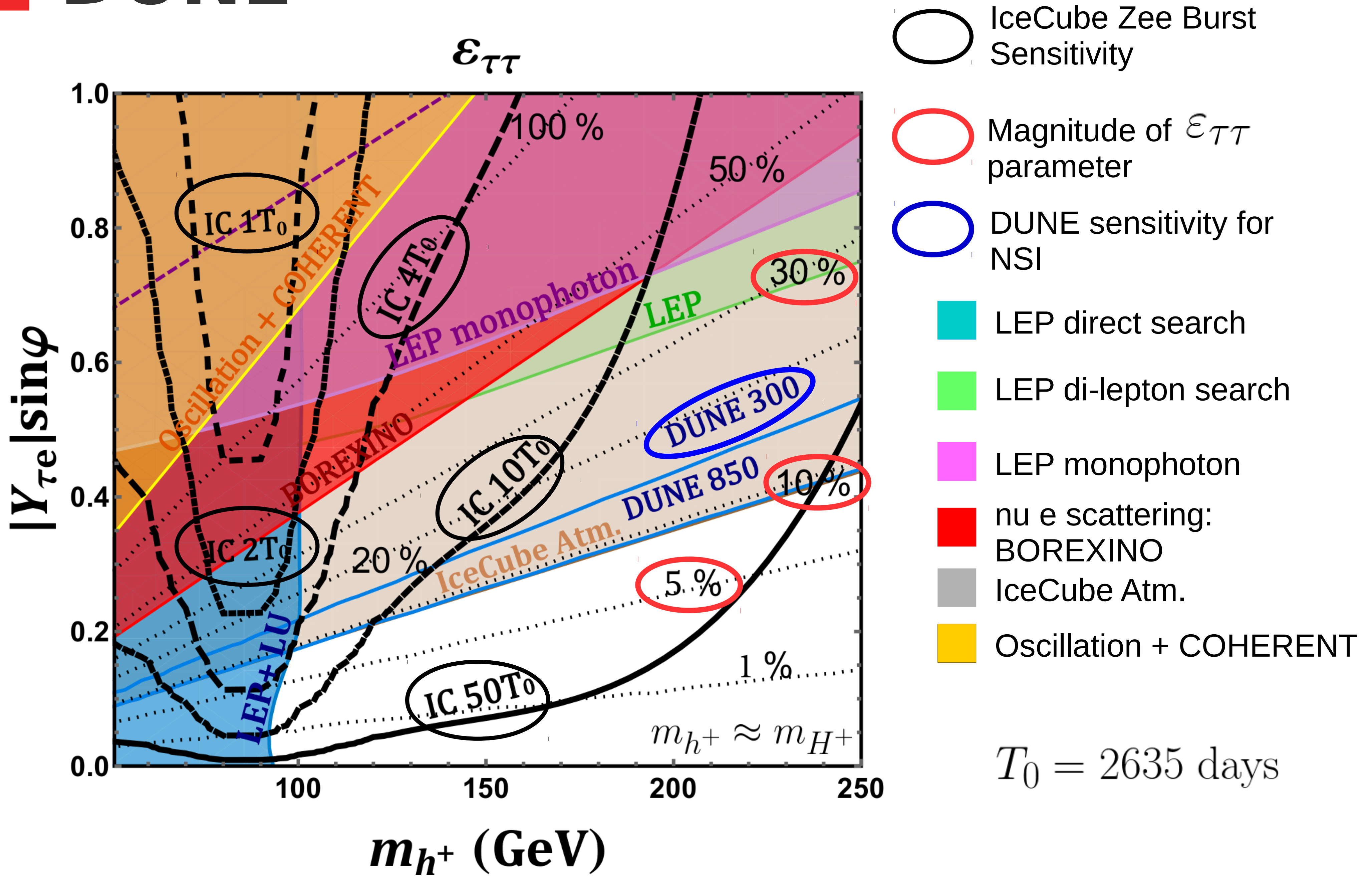

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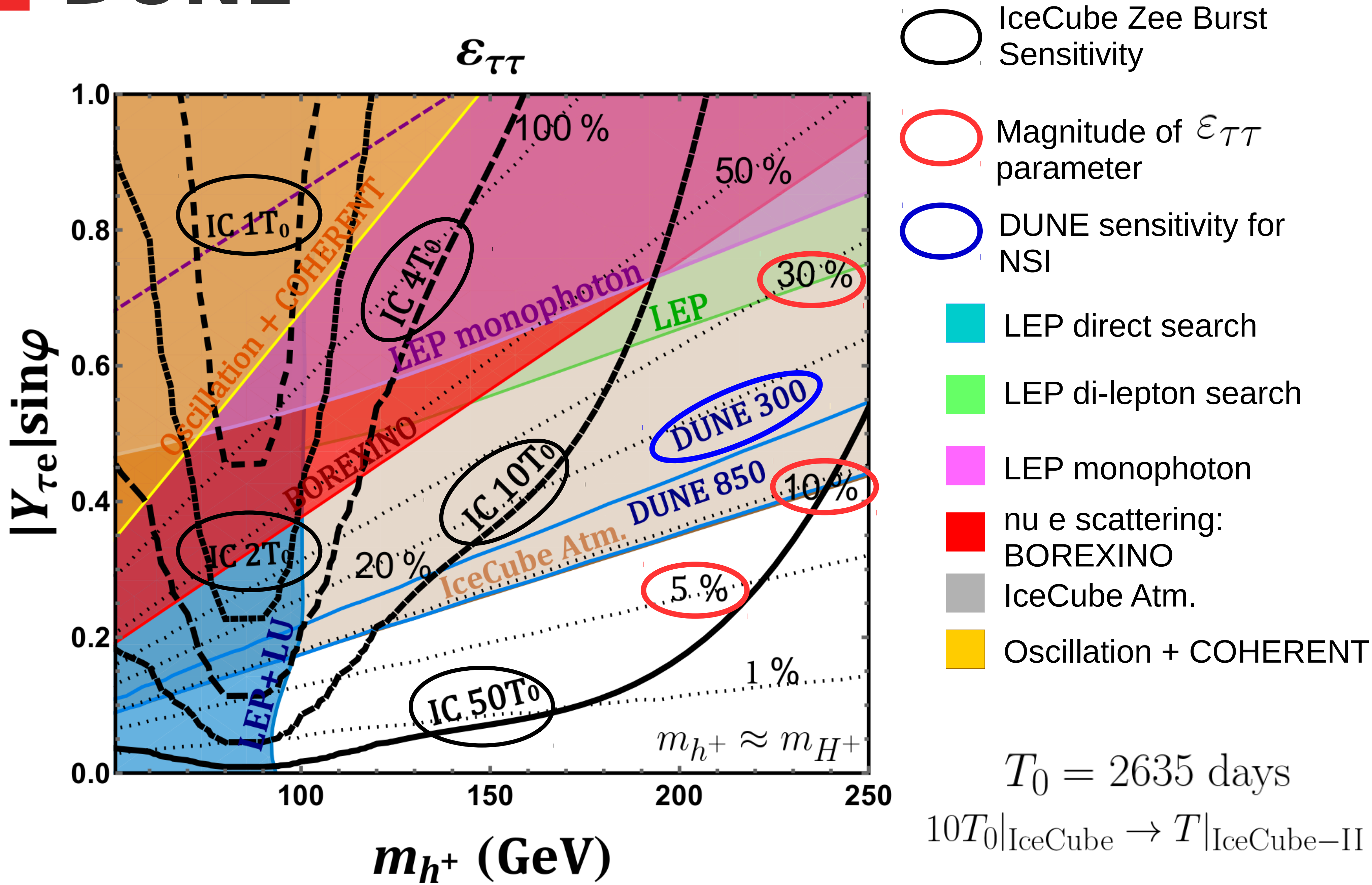

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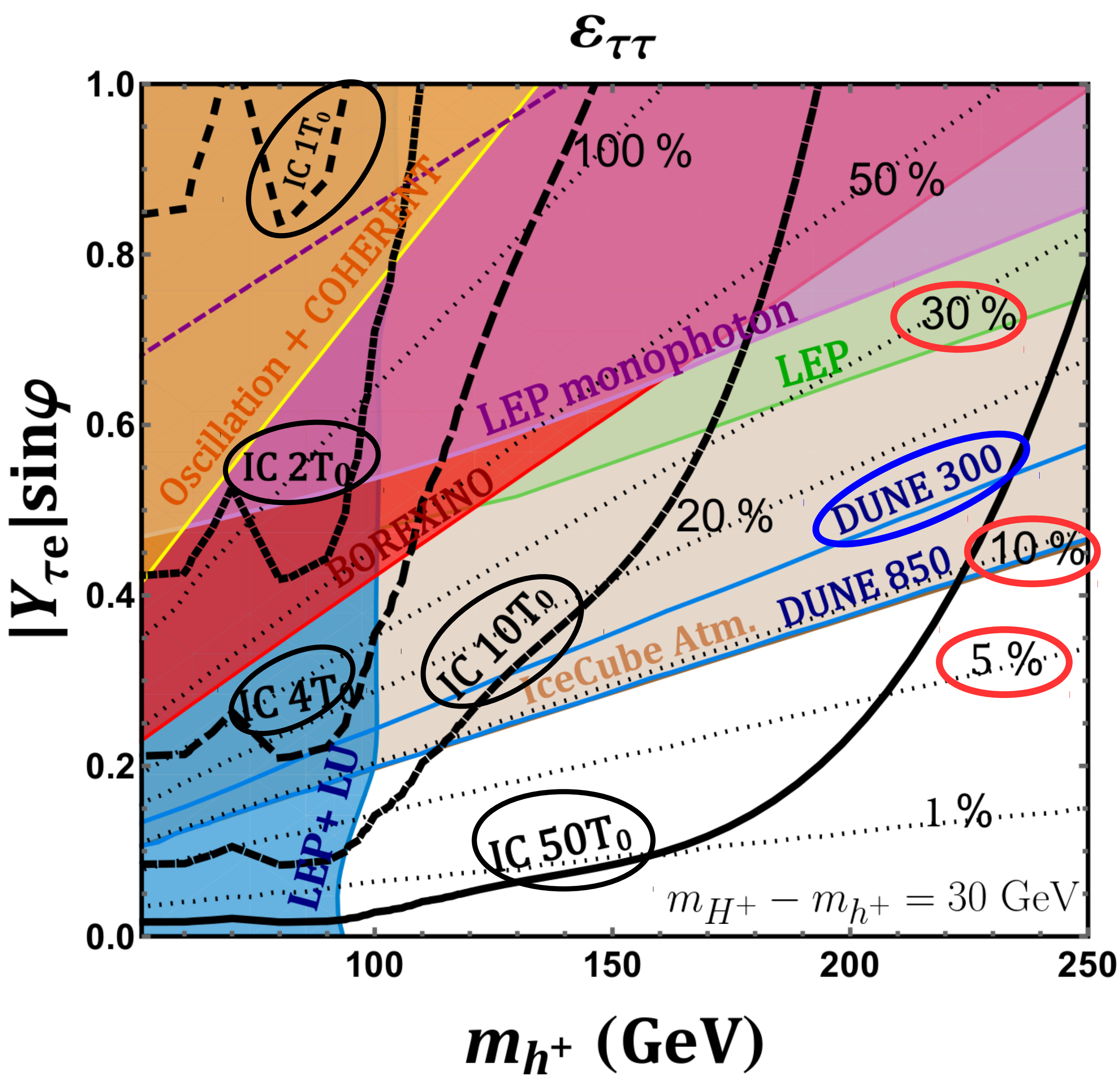
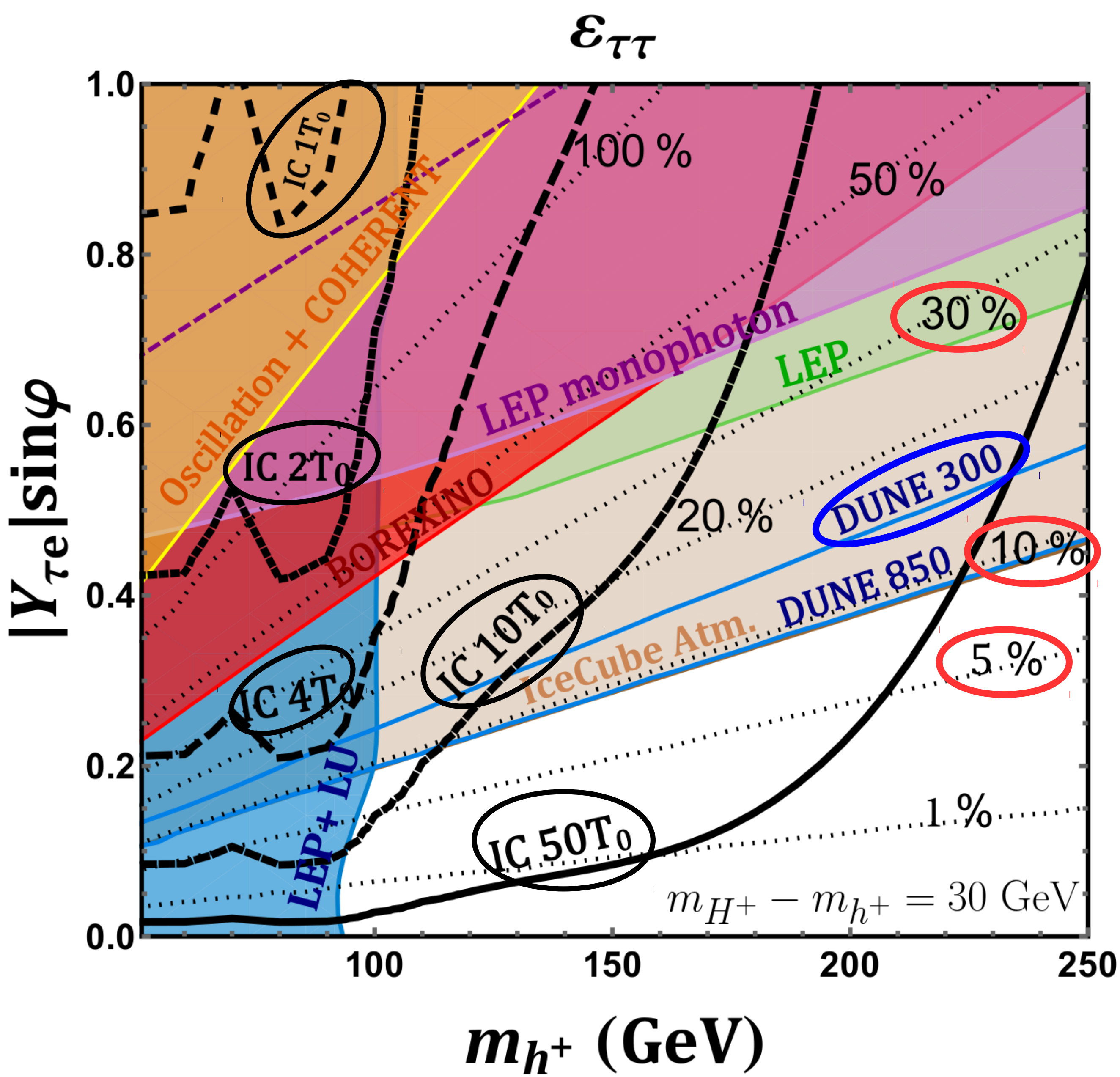


IceCube Zee Burst Sensitivity

Magnitude of $\varepsilon_{\tau\tau}$ parameter

DUNE sensitivity for NSI

Sensitivity of IceCube and DUNE



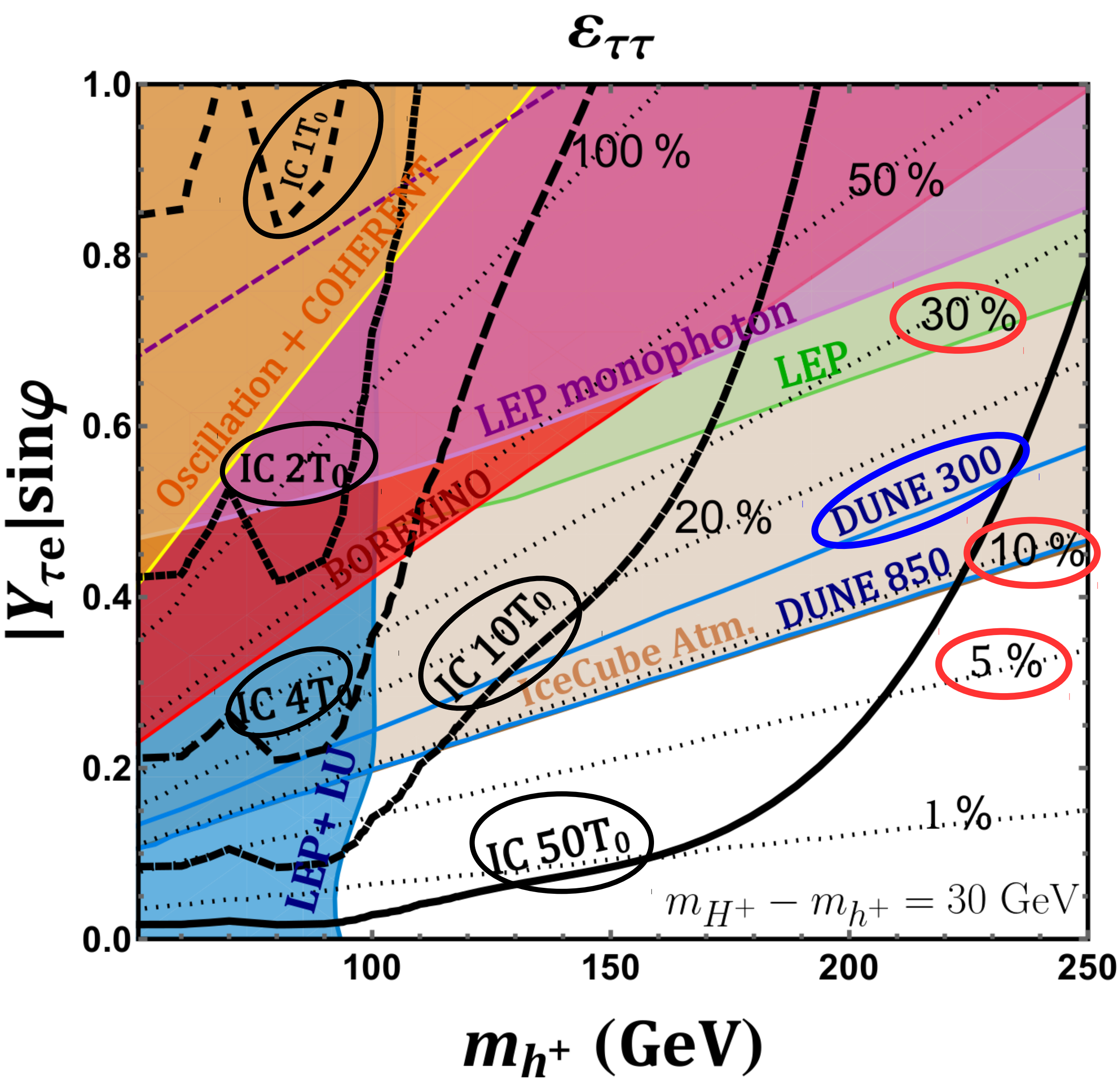
IceCube Zee Burst Sensitivity

Magnitude of $\varepsilon_{\tau\tau}$ parameter

DUNE sensitivity for NSI

Double-dip feature is due to the double peak cross section feature:

Sensitivity of IceCube and DUNE



IceCube Zee Burst Sensitivity

Magnitude of $\varepsilon_{\tau\tau}$ parameter

DUNE sensitivity for NSI

Double-dip feature is due to the double peak cross section feature:

mH – mh = 30 GeV

Conclusion

- We proposed a new way to probe light charged scalars using a Glashow-like resonance in the UHE neutrino data (IceCube).
- The same interactions for Glashow-like resonance also give rise to observable NSI effect.
- UHE neutrinos provide a complementary probe of NSI.
- We have used the popular Zee model of radiative neutrino mass as a demonstration.
- Further extensions to other models are possible and promising.

Thank you!