A Combined Astrophysical and Dark Matter Interpretation of the IceCube HESE and Throughgoing Muon Events

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Washington University in St. Louis

Y. S, B. Dev, arXiv:1804.04919 [hep-ph]

Pheno2018
University of Pittsburgh
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Outline

- Introduction and Motivation
- 2 Comp Astro Flux
- DM + 1 Comp Astro Flux
- Gamma-Ray Constraint
- Conclusion

Introduction of Neutrino Flux

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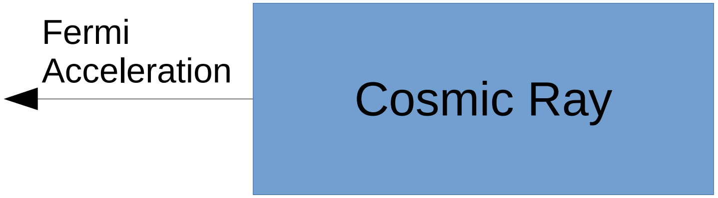
Cosmic Ray

Introduction of Neutrino Flux



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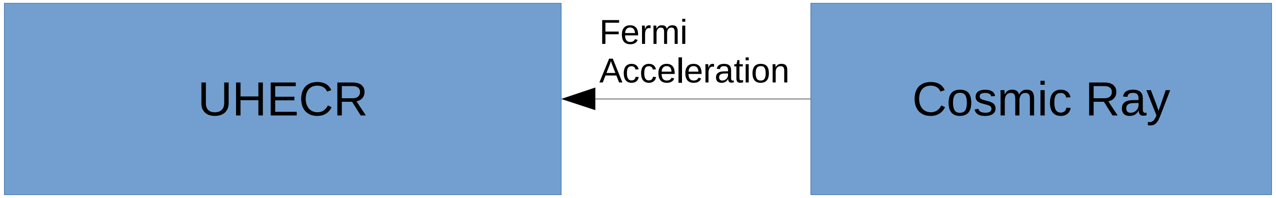

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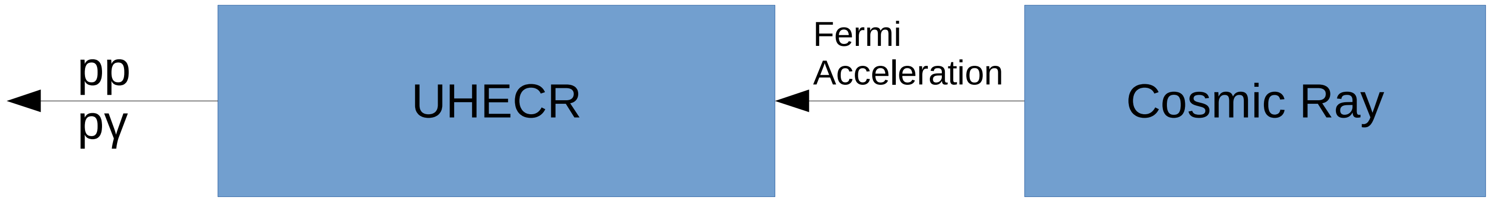

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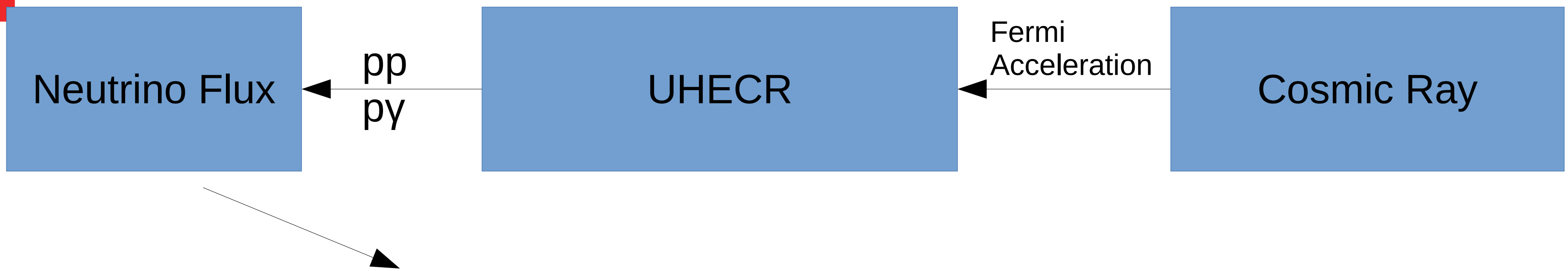

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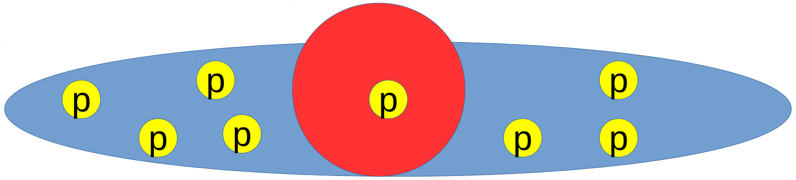

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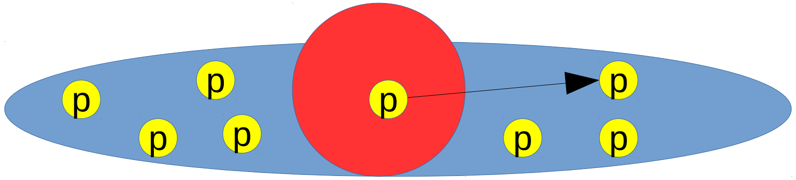

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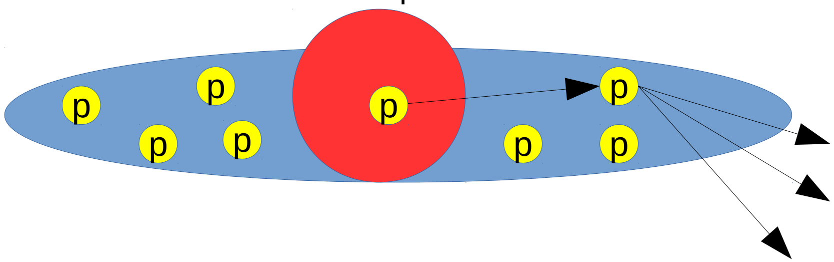

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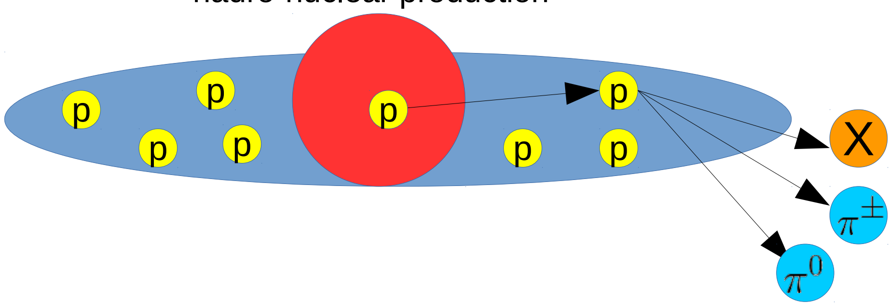

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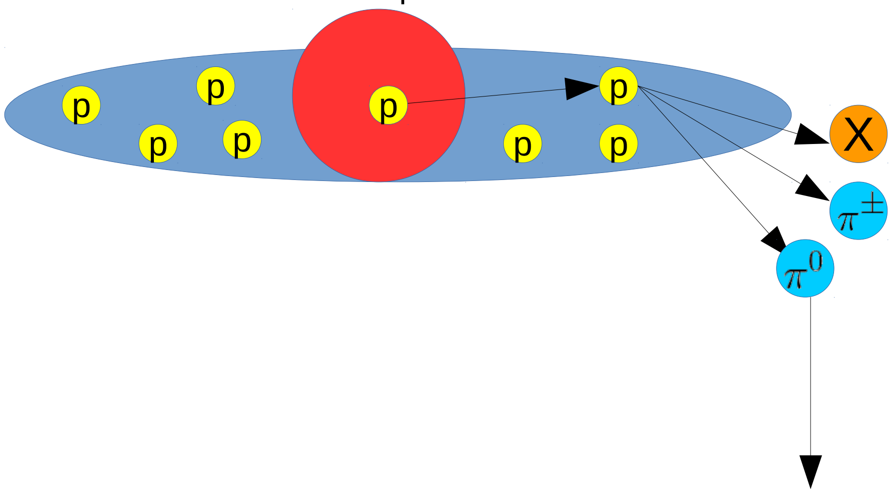

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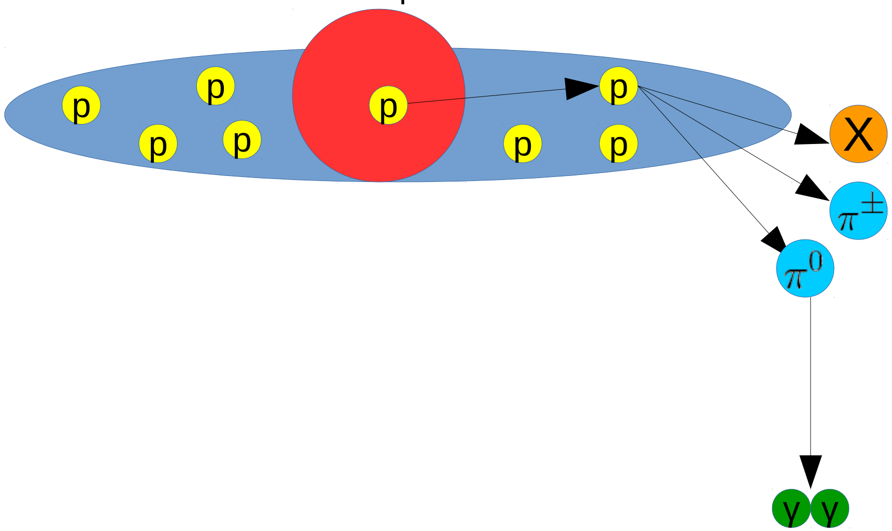

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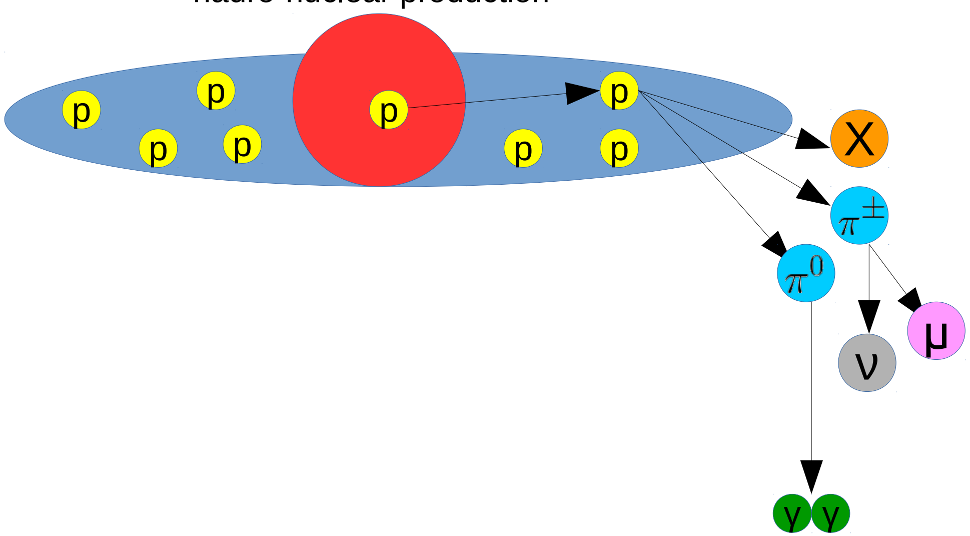

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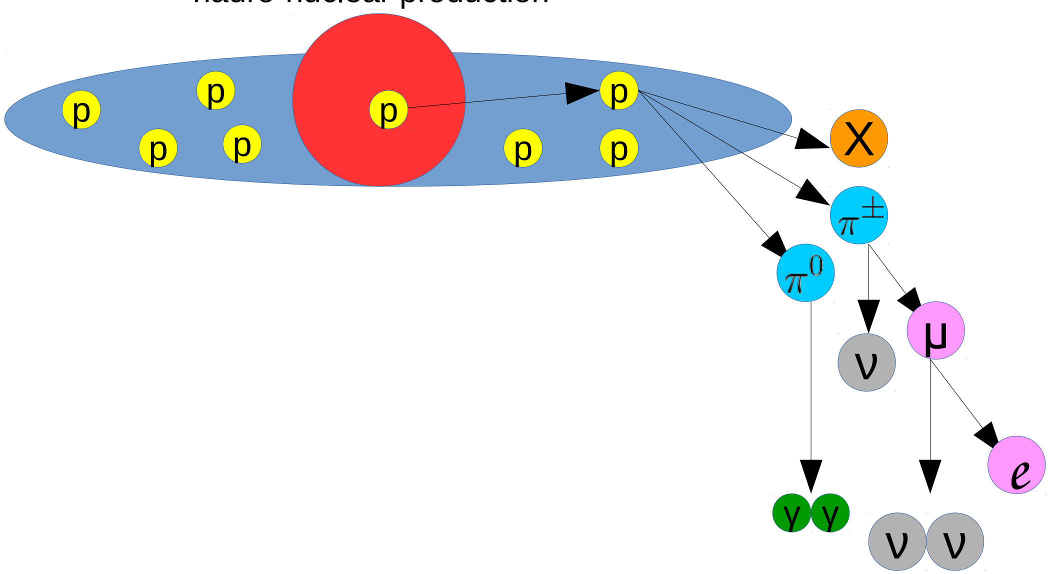

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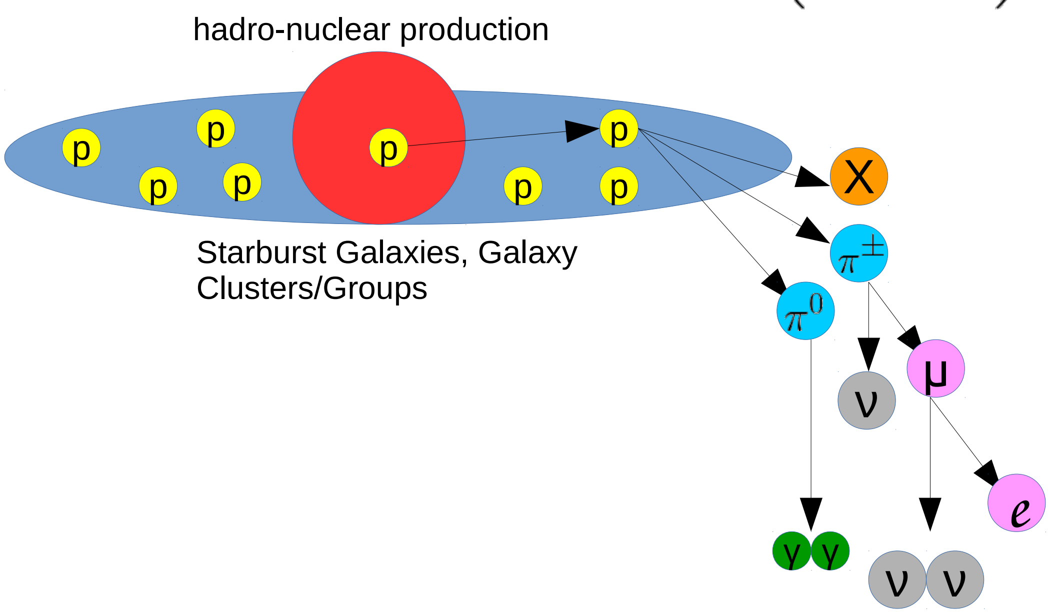

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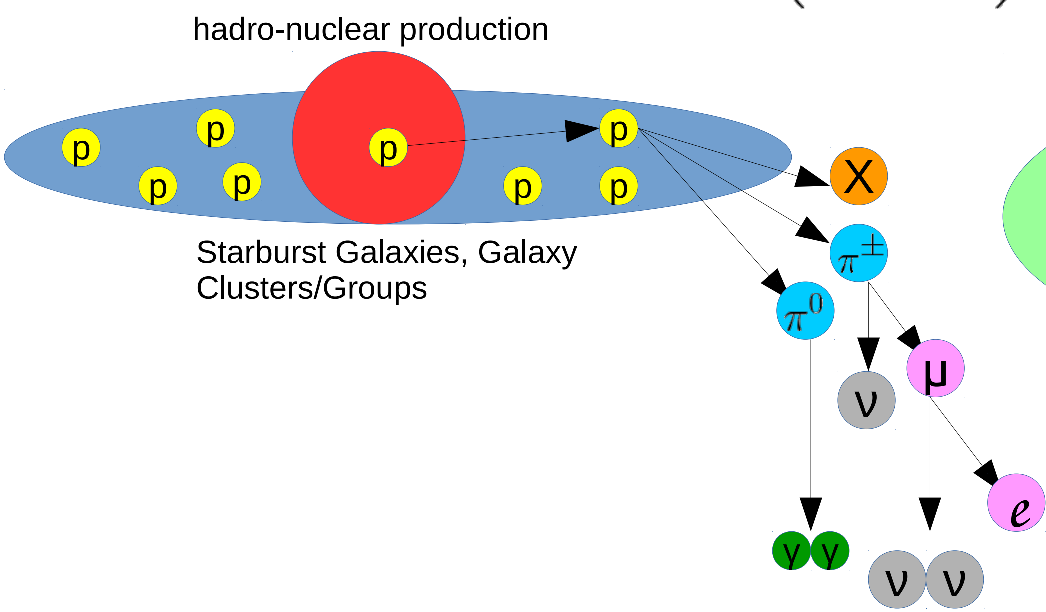

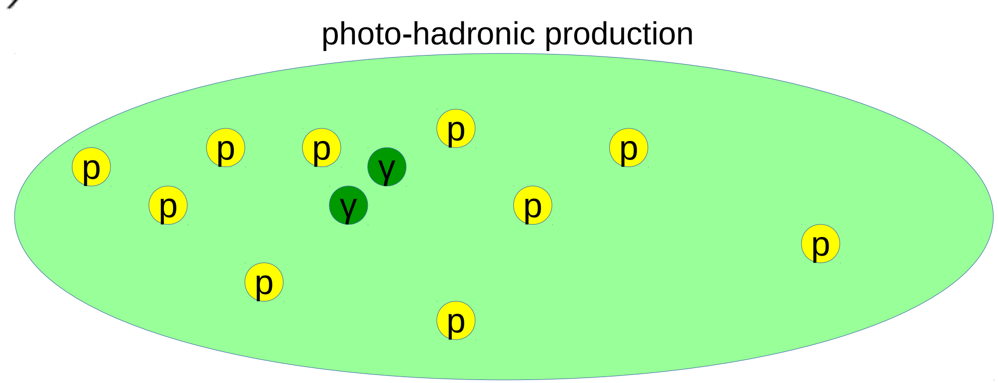

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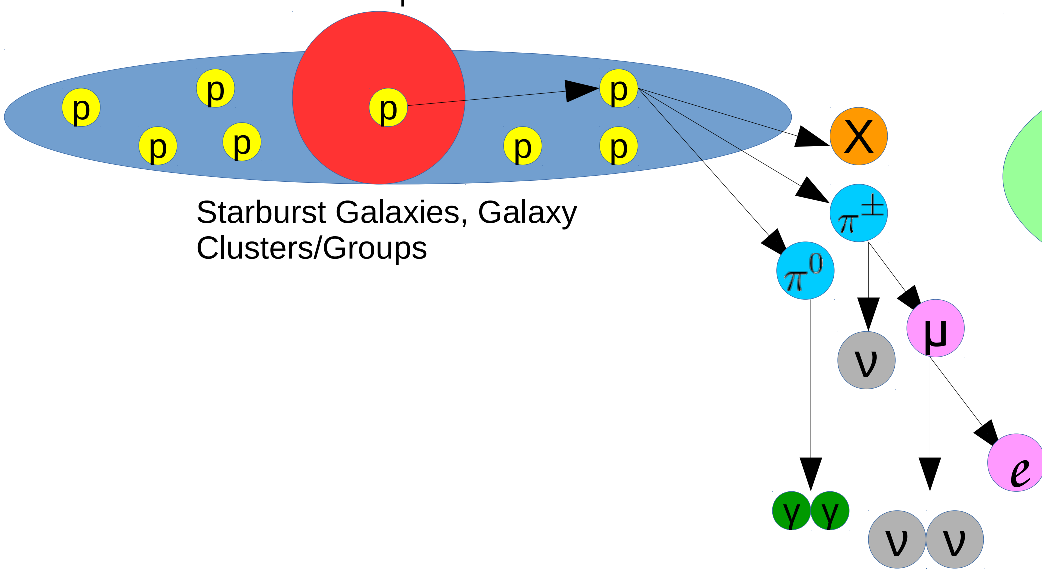
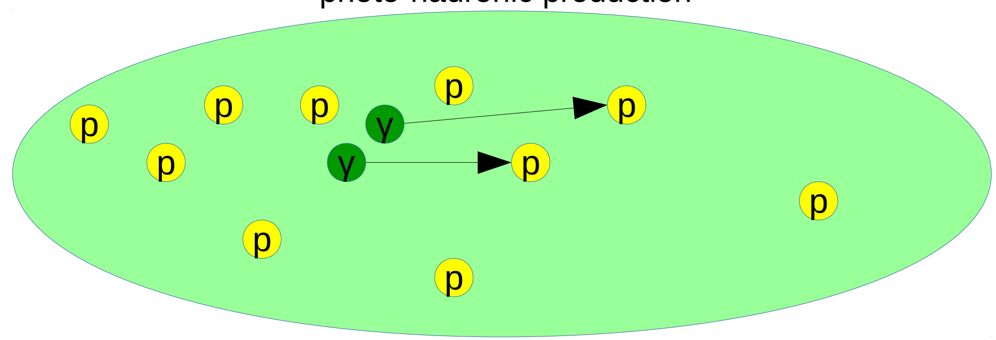


photo-hadronic production



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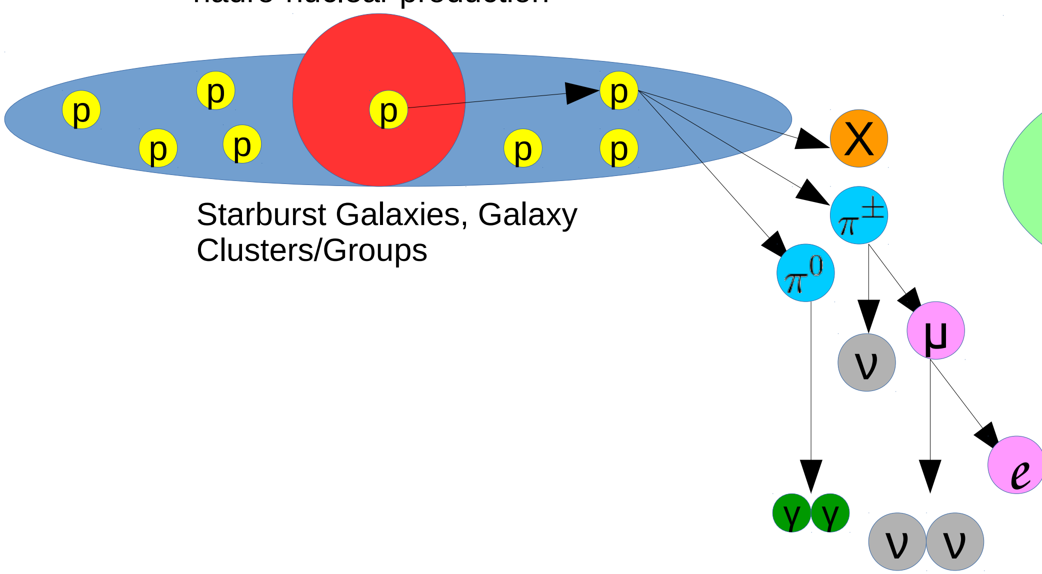

Starburst Galaxies, Galaxy Clusters/Groups

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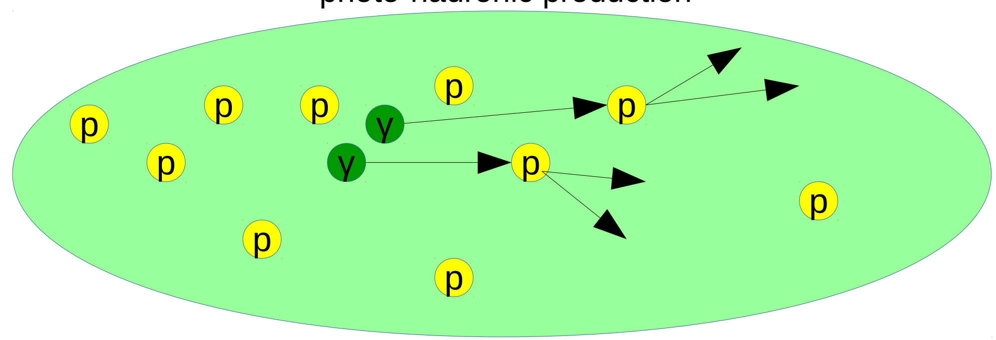

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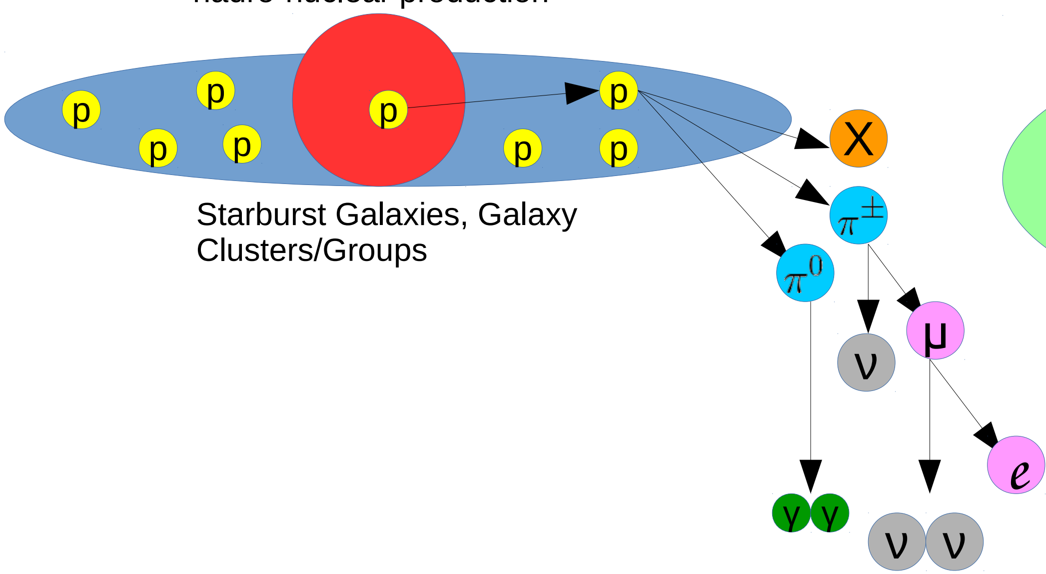

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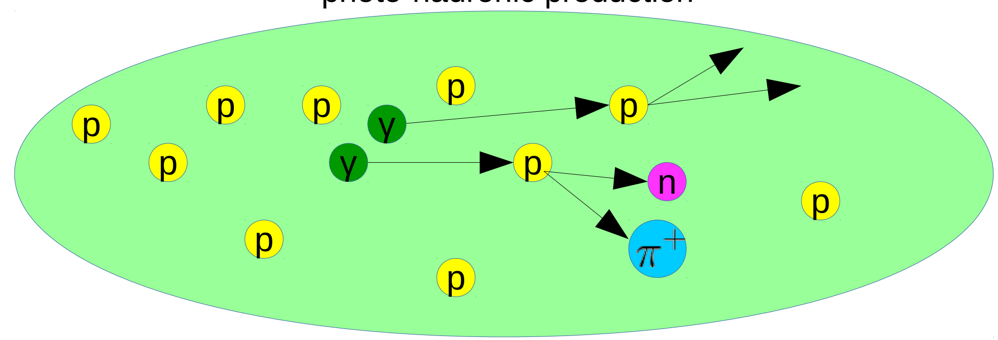

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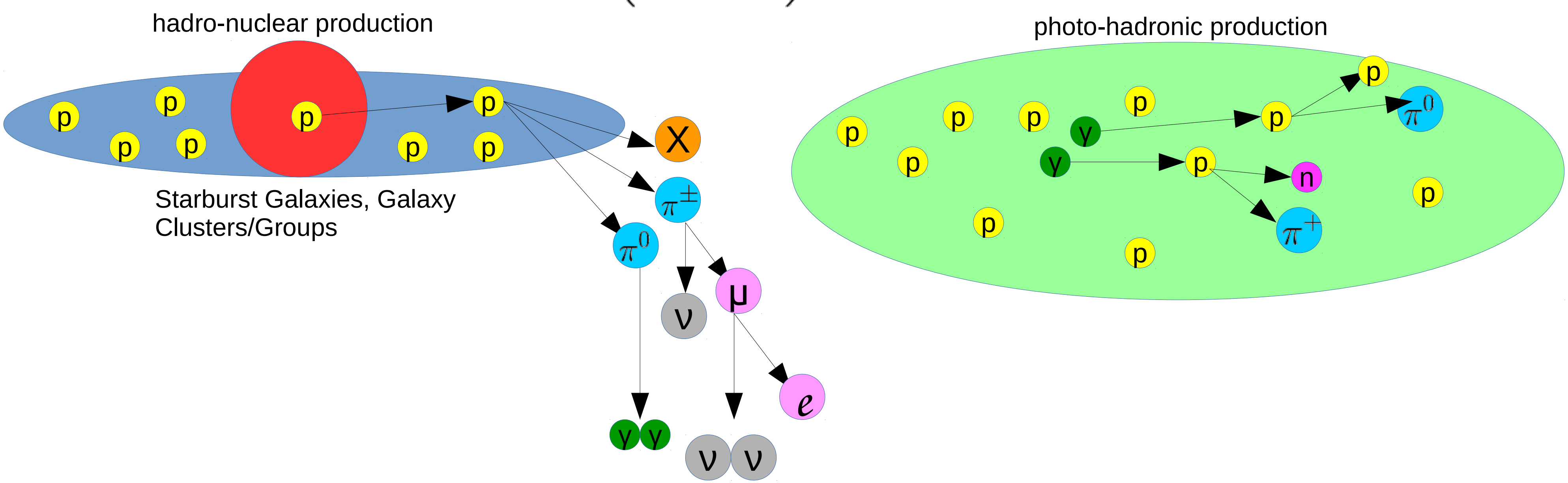

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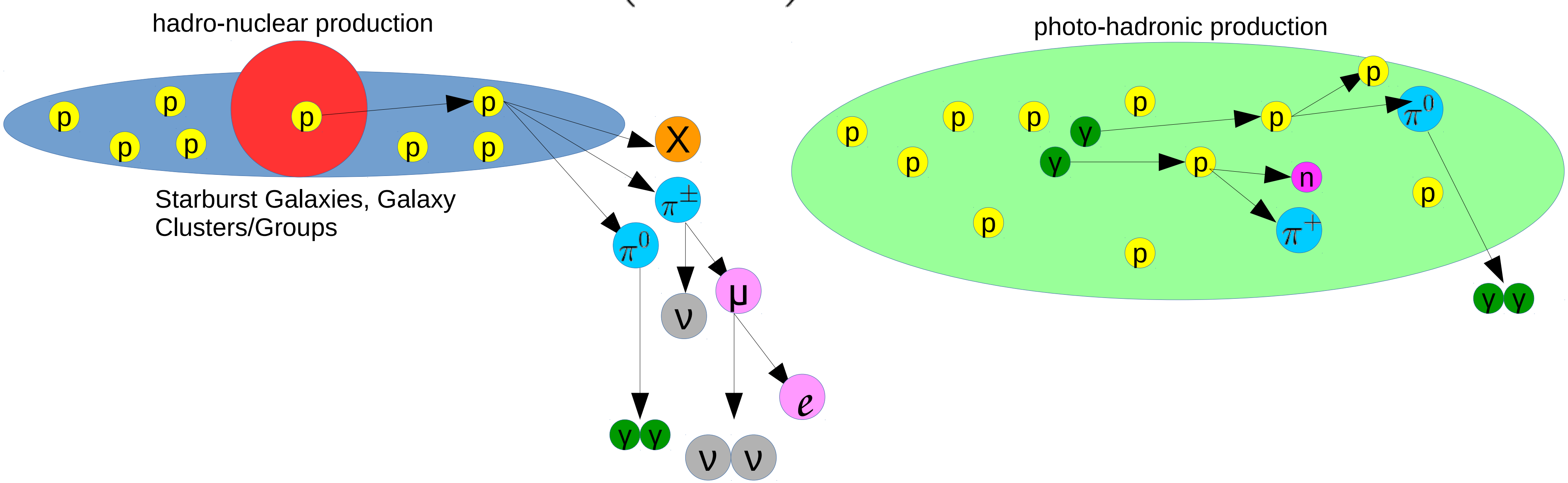

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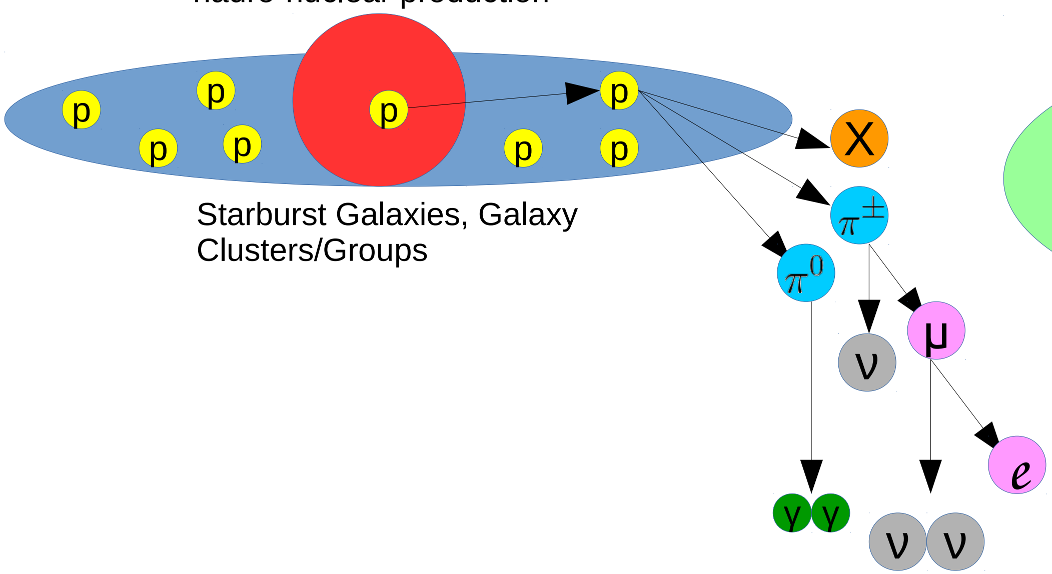

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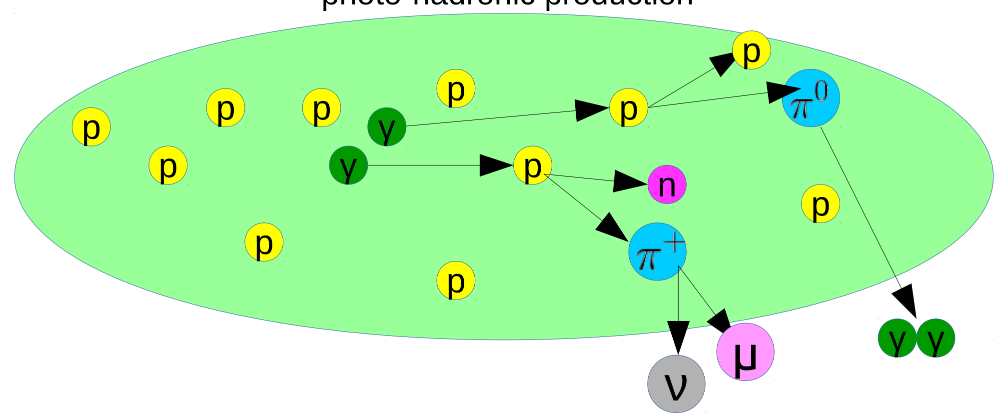

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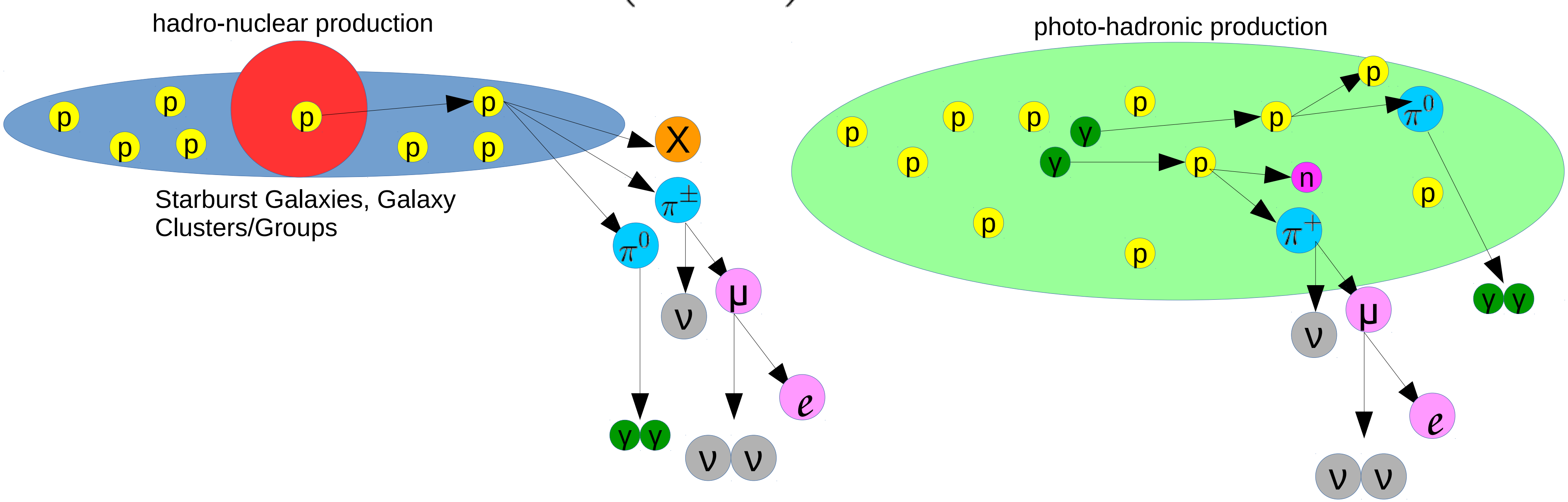

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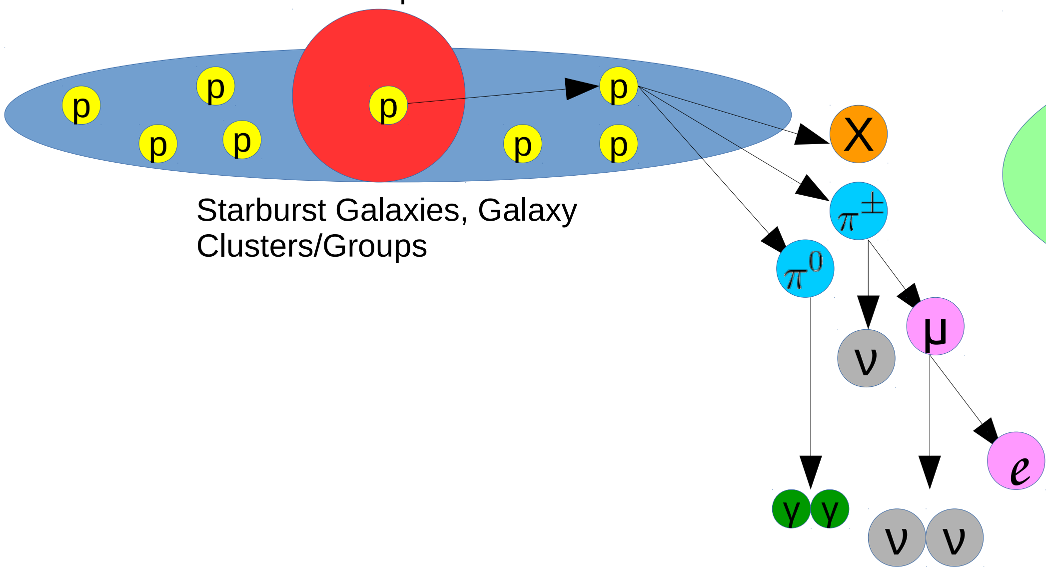

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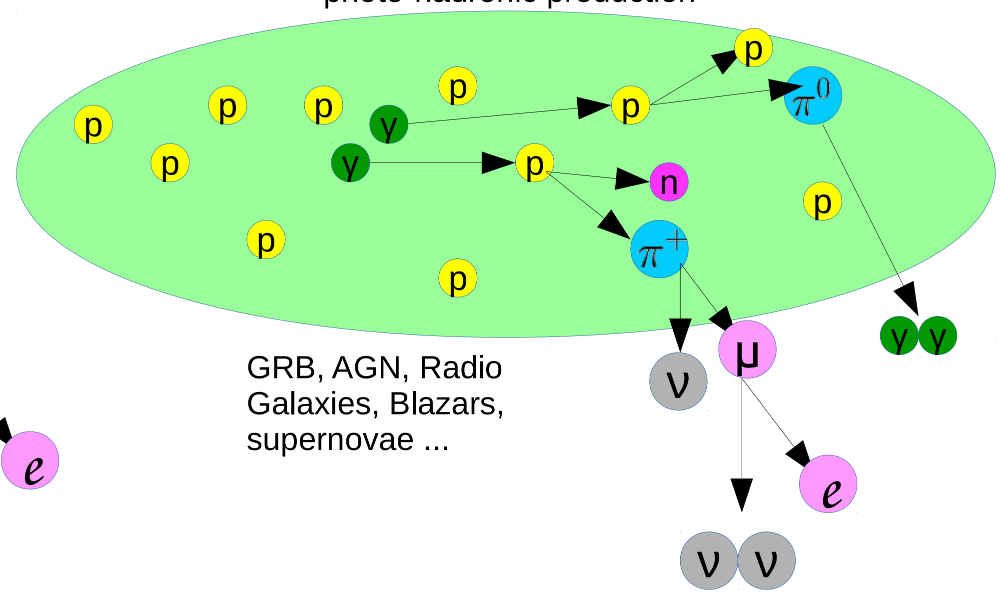

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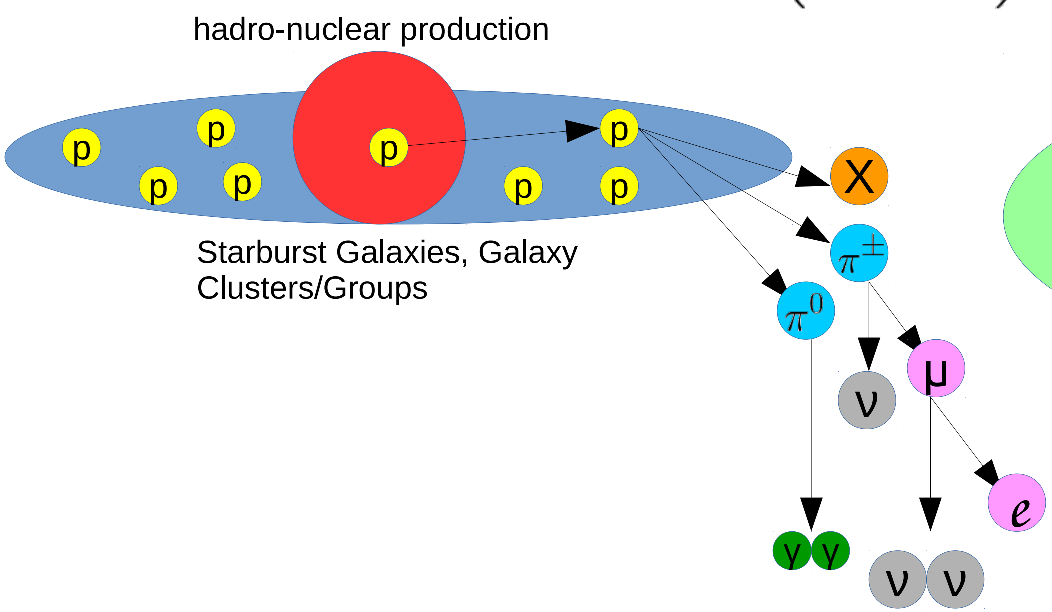

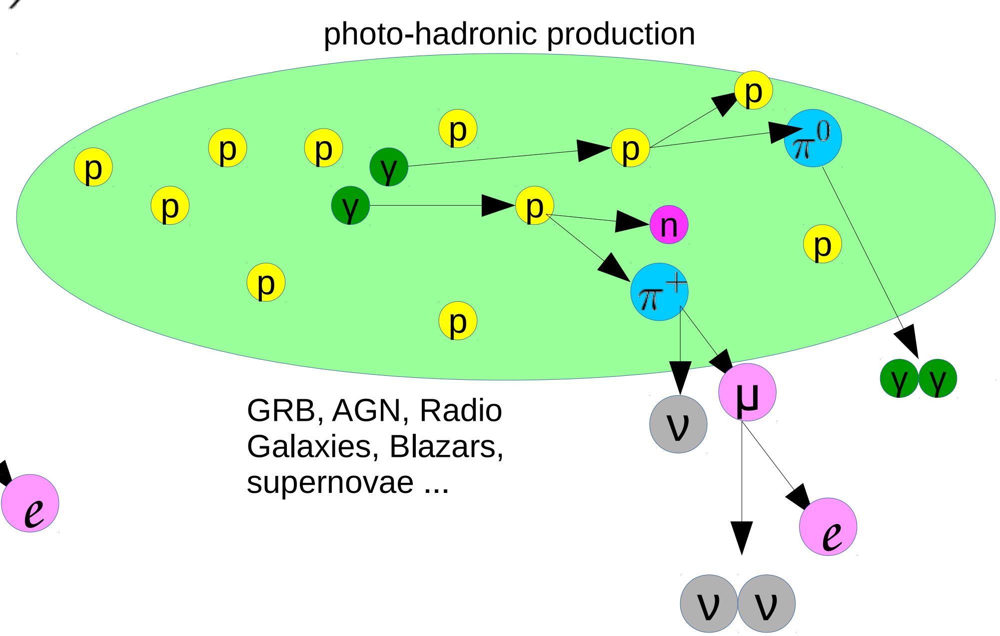

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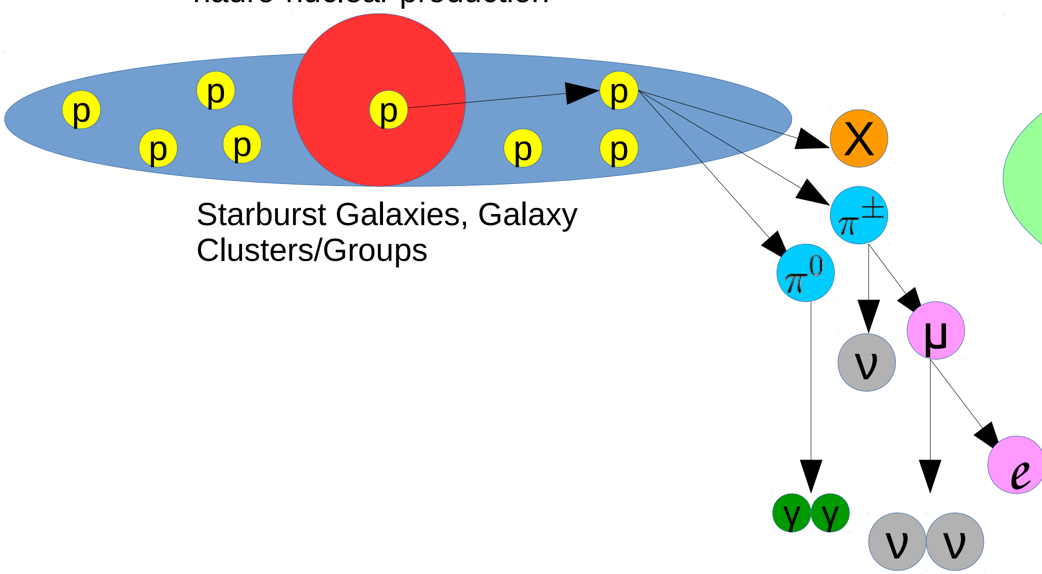

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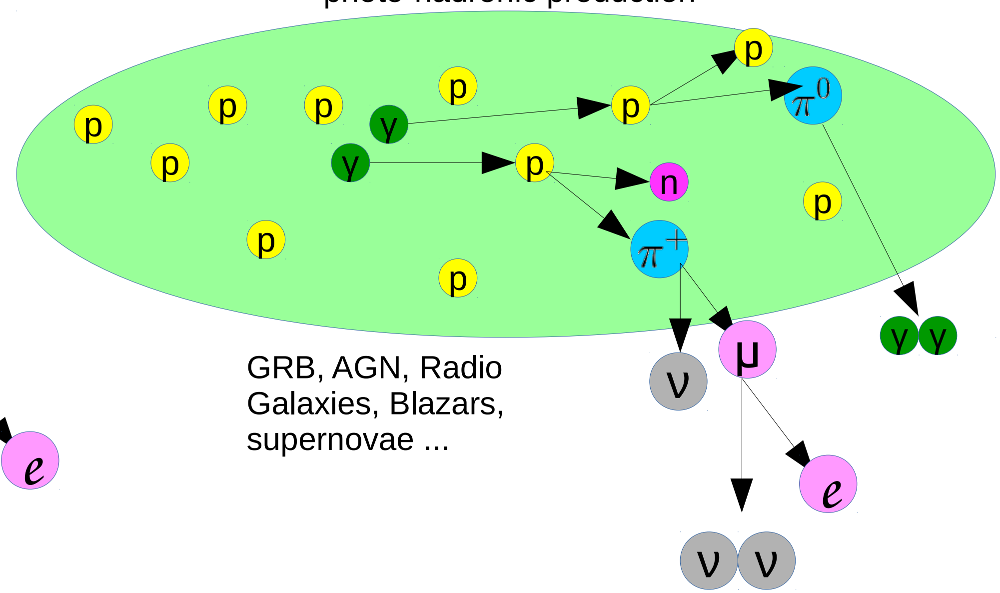

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	pp	pγ
Typical	(1 : 1 : 1)	(1 : 1 : 1)
μ damped	(4 : 7 : 7)	(4 : 7 : 7)

IceCube Detector

IceCube Detector

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

HESE

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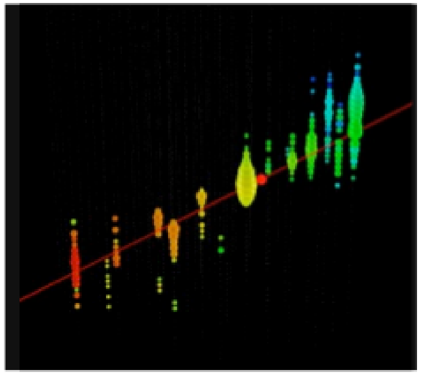

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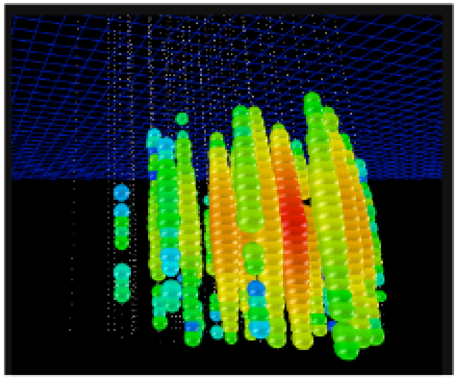

cascade

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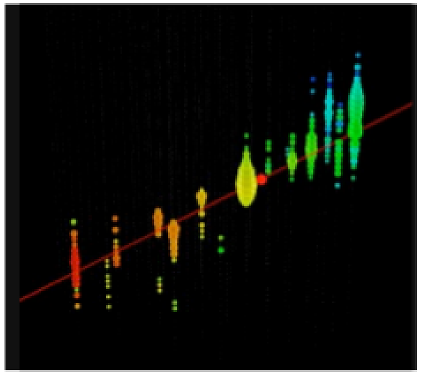

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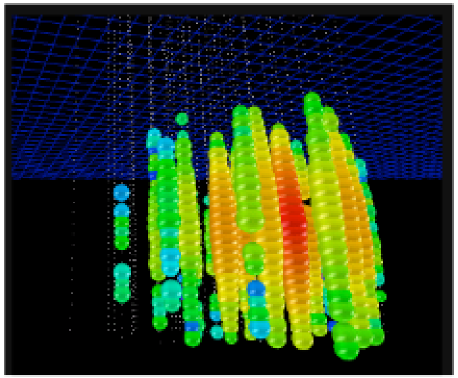

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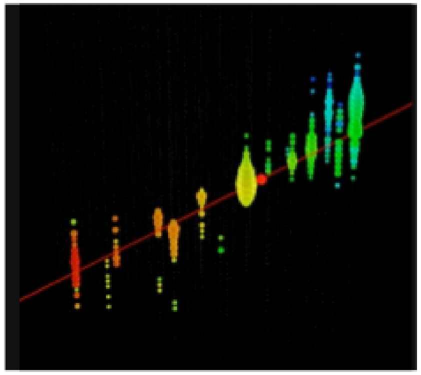

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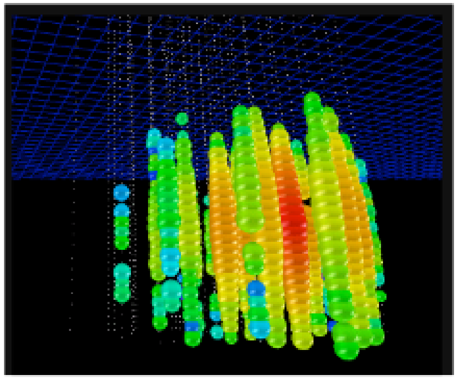

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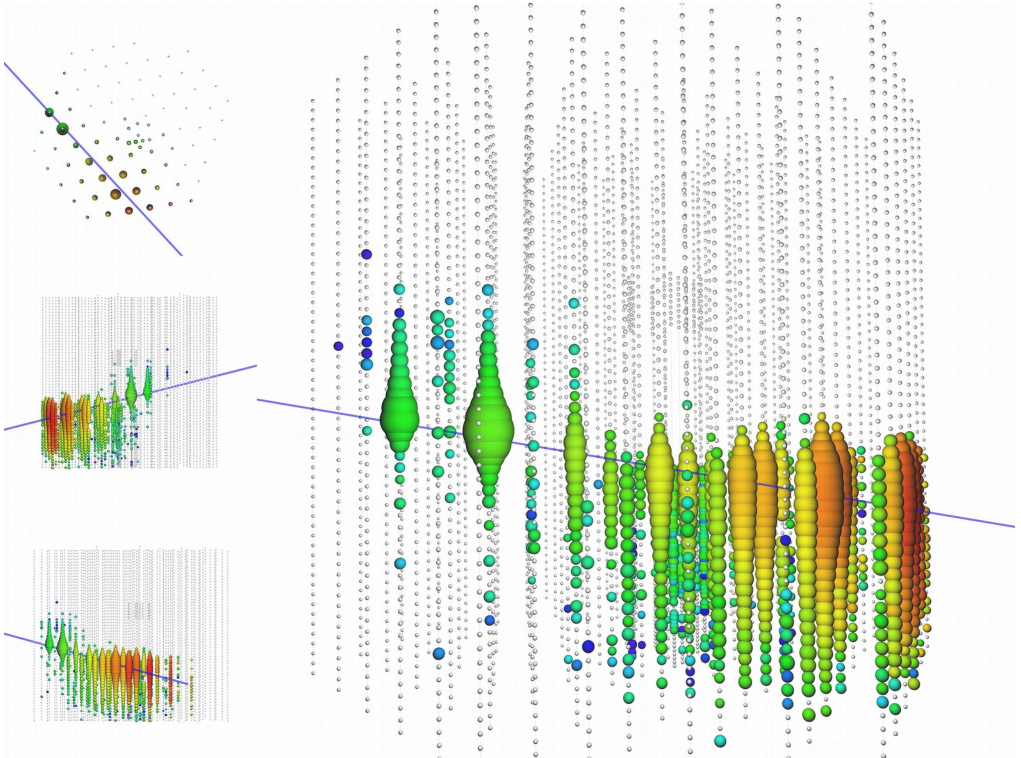

Motivations

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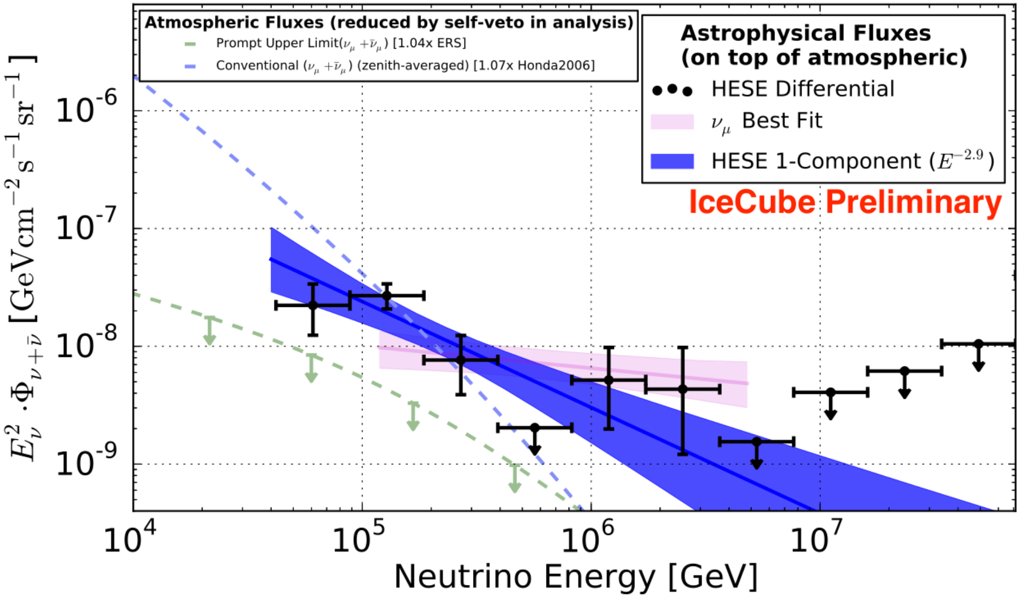

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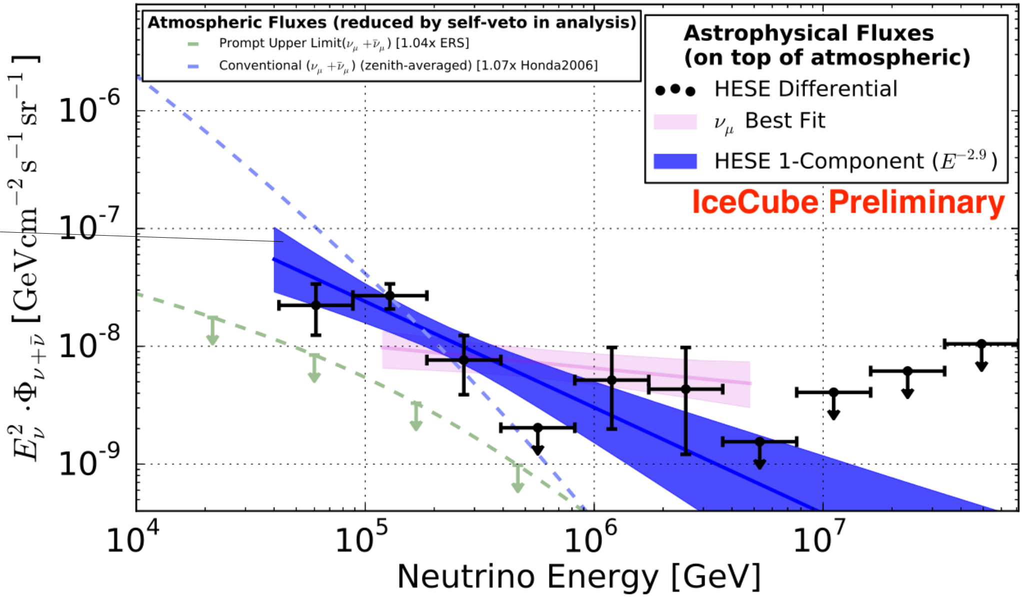

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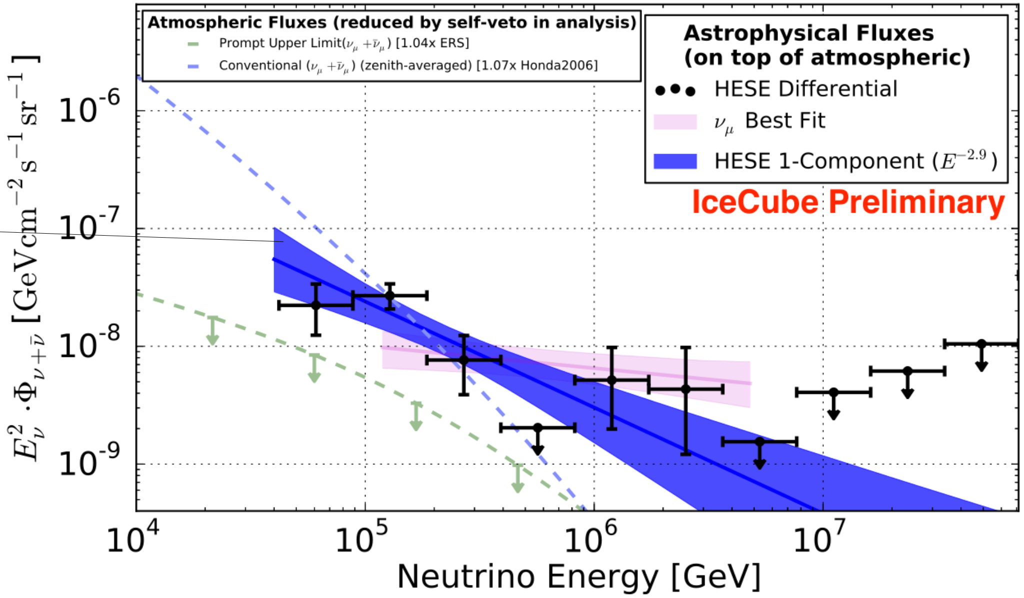

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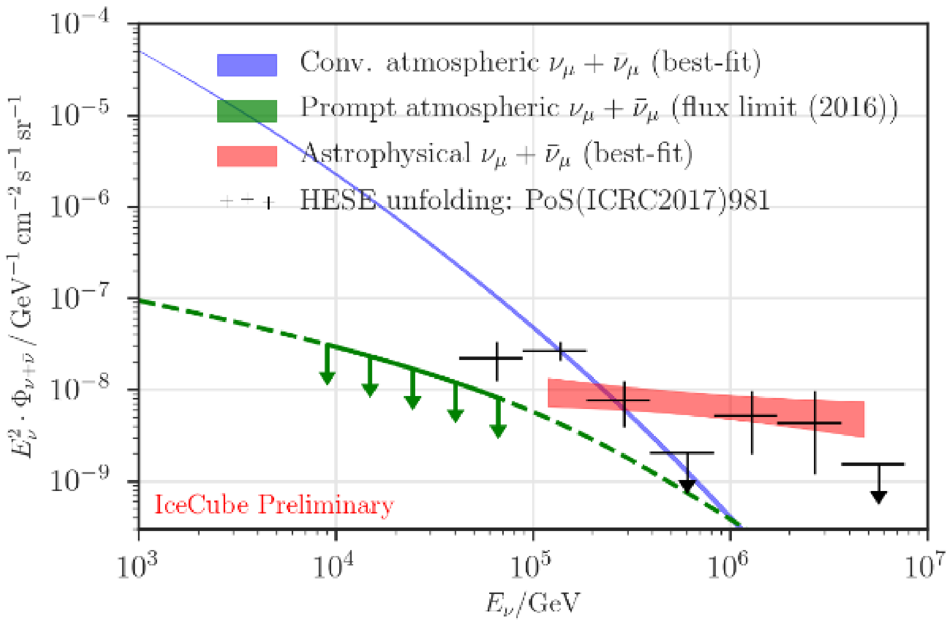

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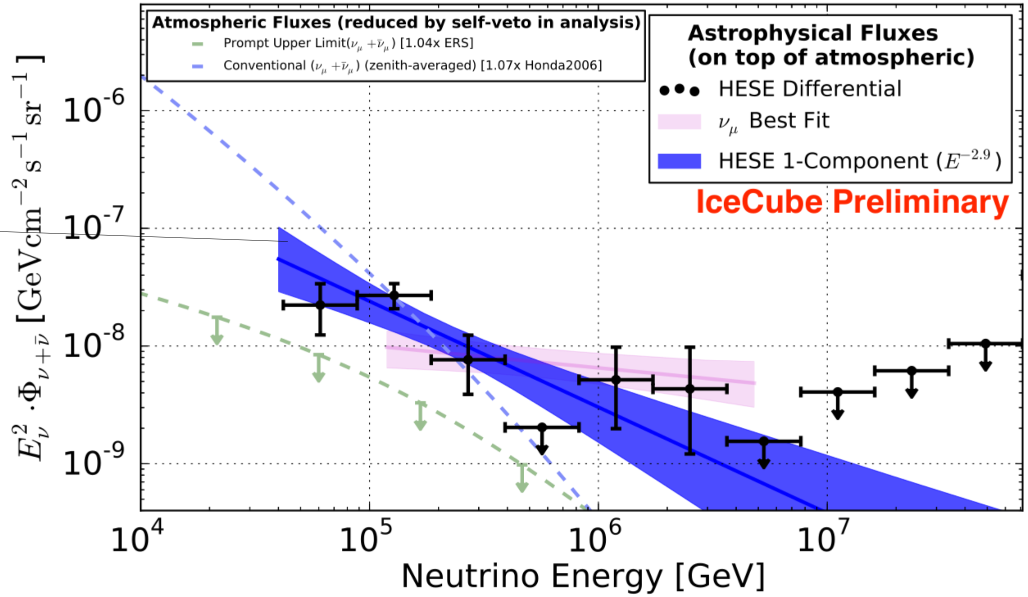

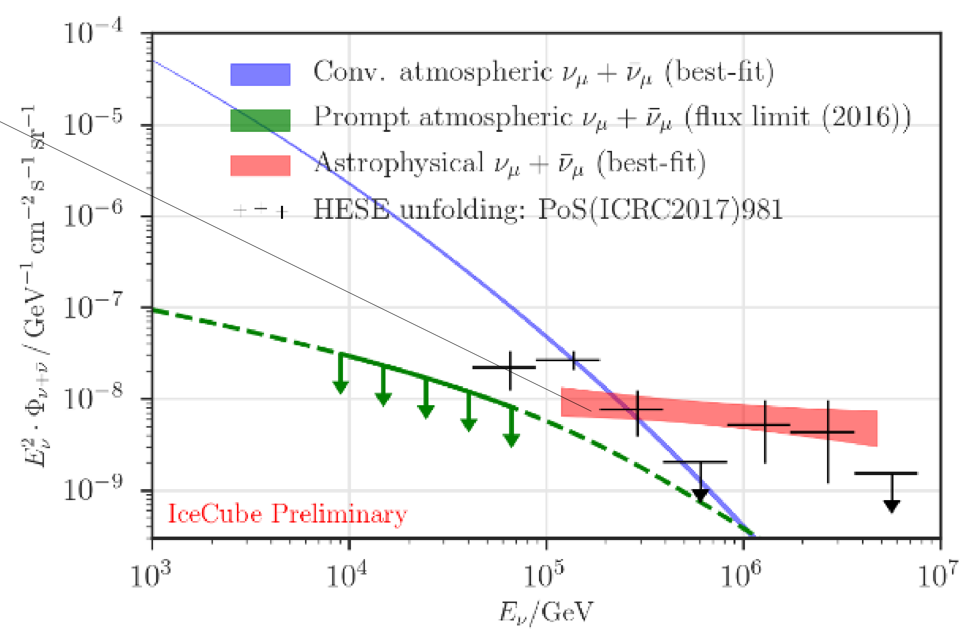

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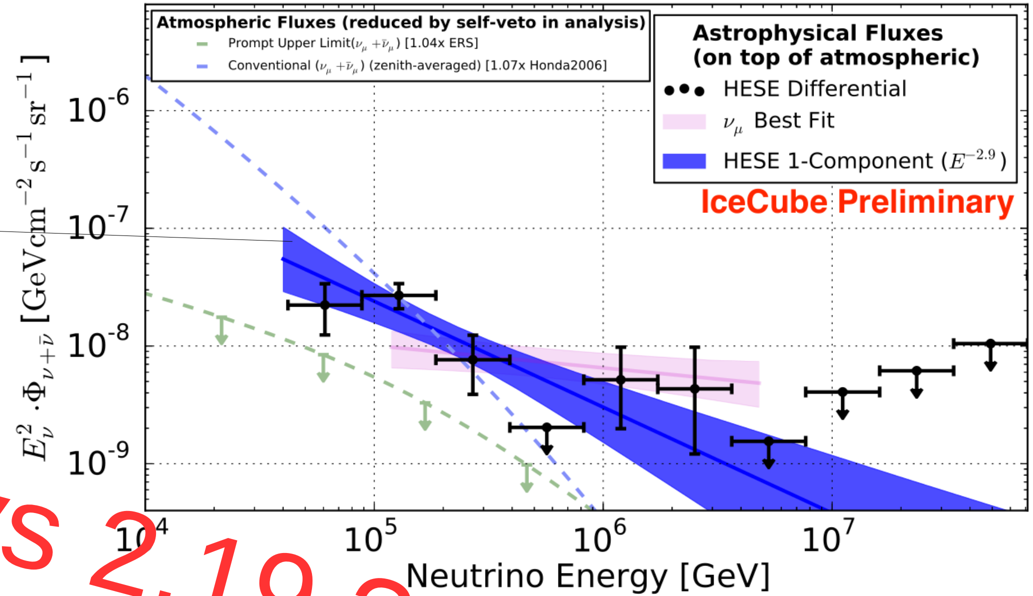

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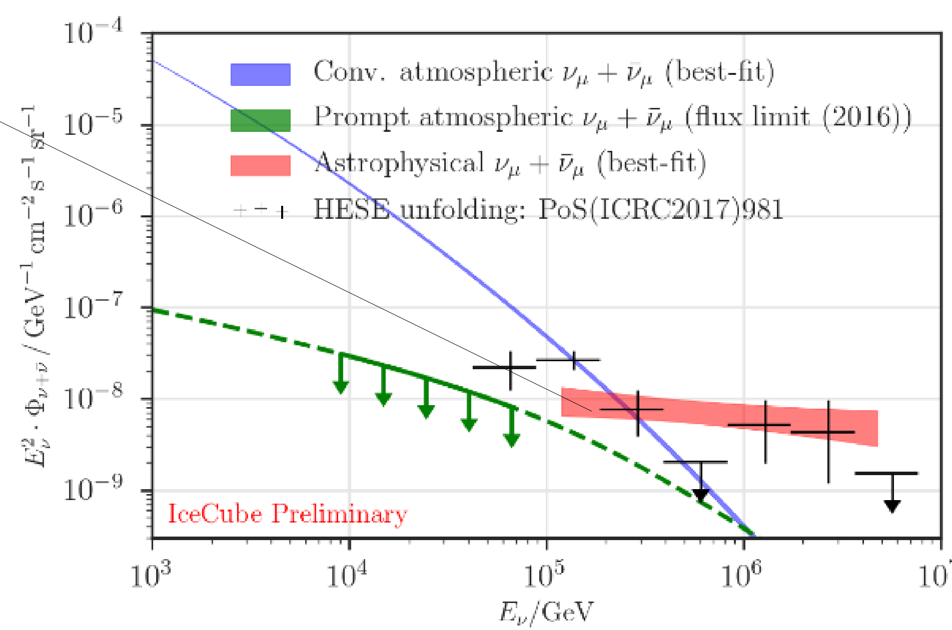
2.92 vs 2.19 ?



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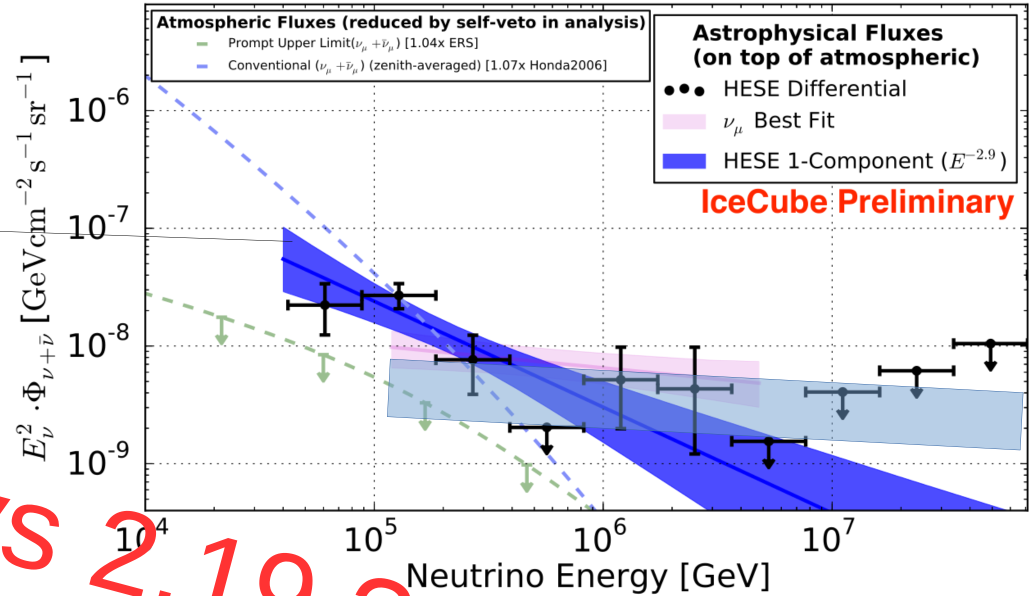

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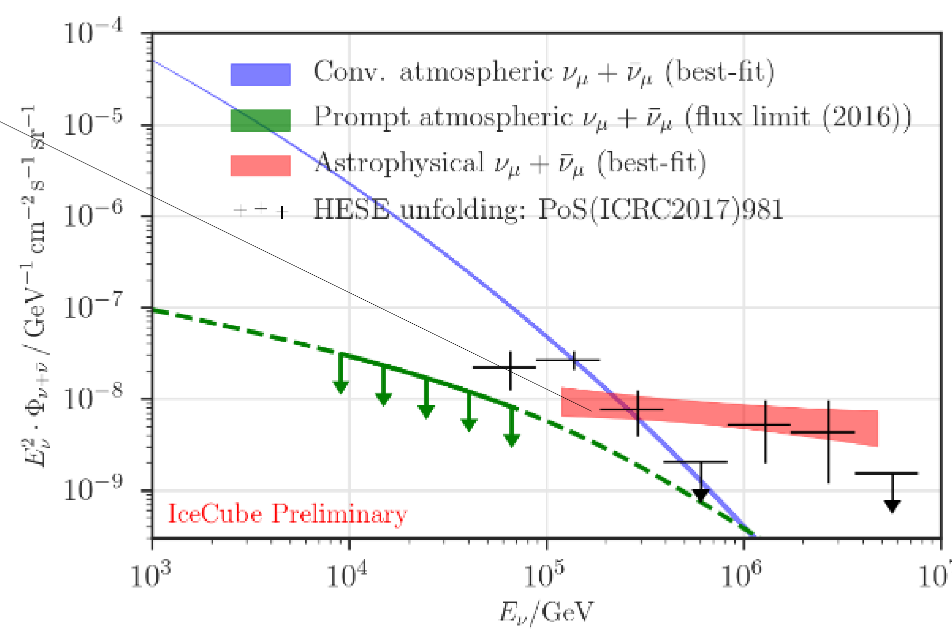

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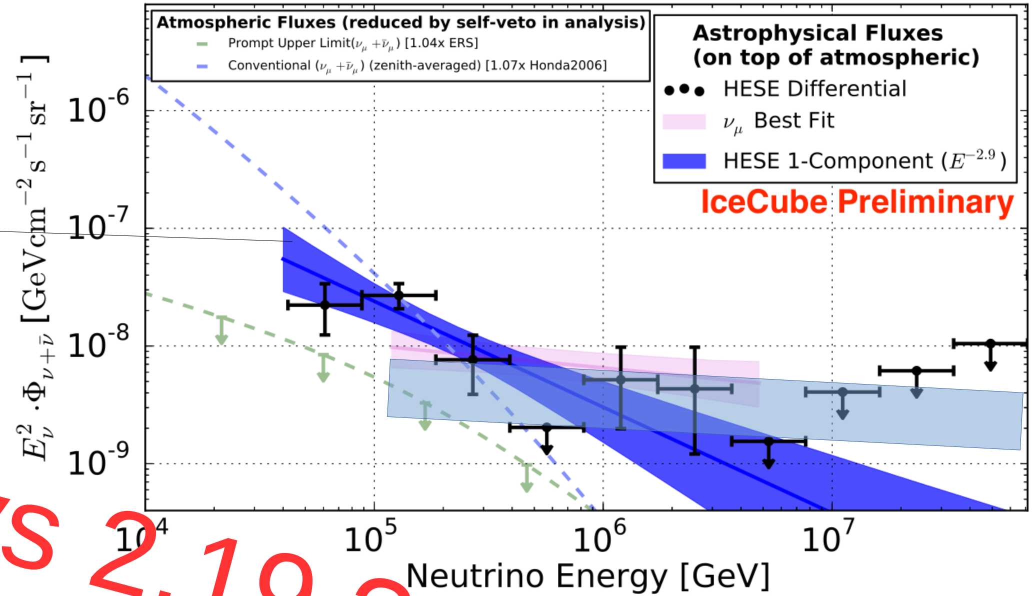

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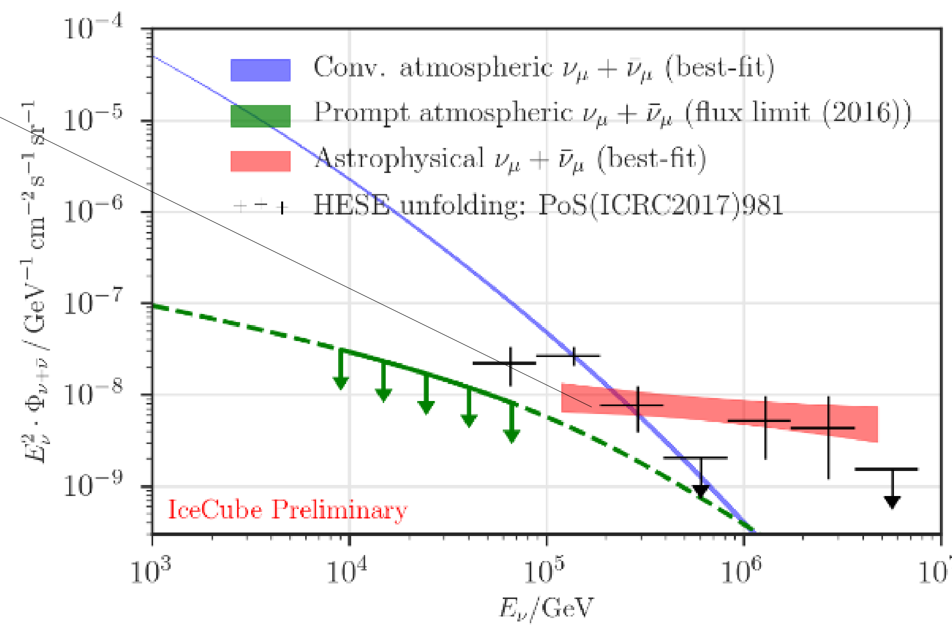
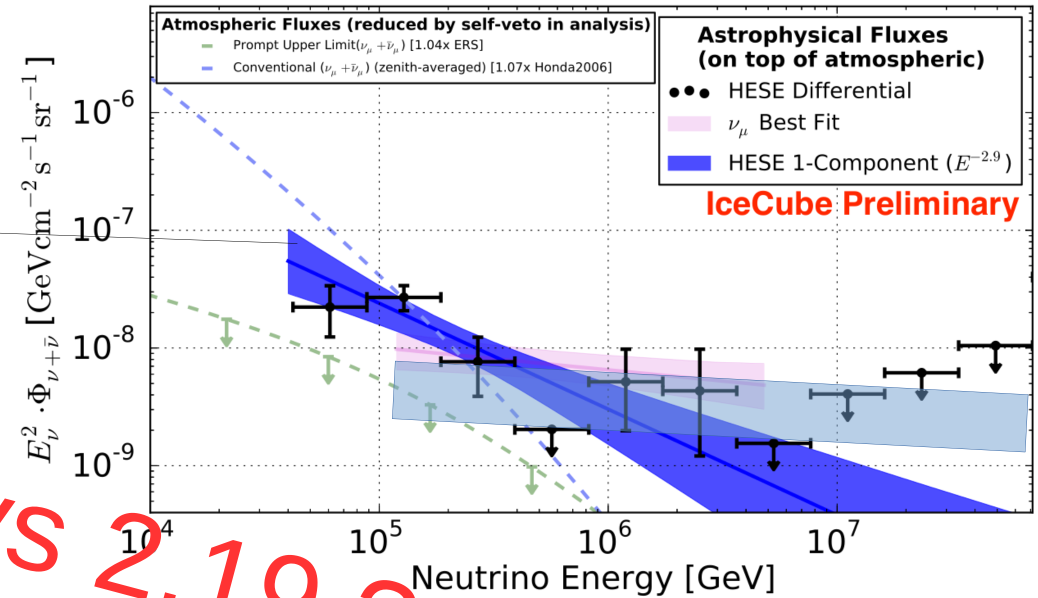


- Detected diffuse neutrino fluxes should follow a universal spectrum

Motivations

HESE:

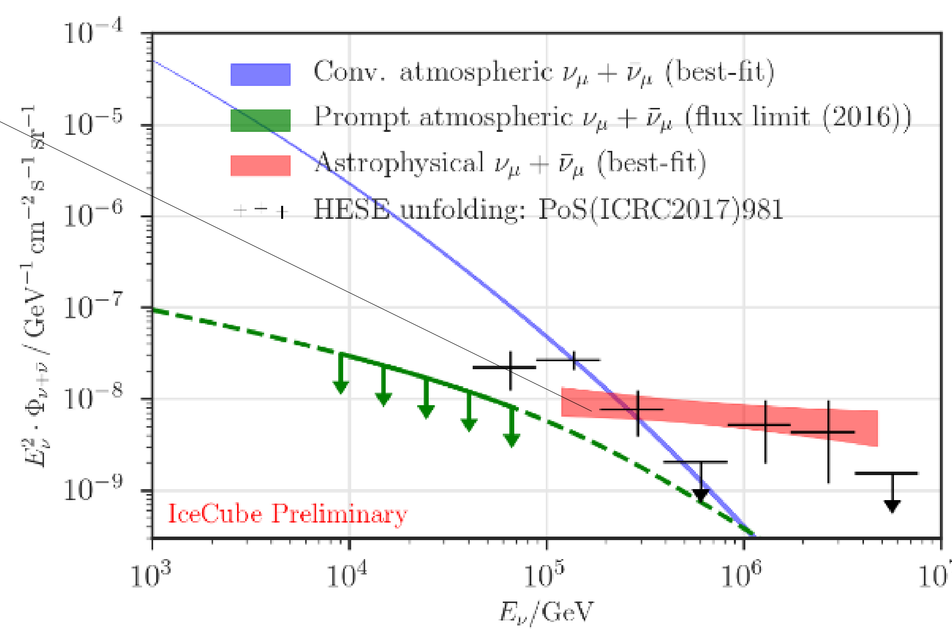
$$\Phi_\nu \sim E^{-2.92^{+0.33}_{-0.29}}$$



2.92 vs 2.19 ?

Throughgoing:

$$\Phi_\nu \sim E^{-2.19\pm0.10}$$



- Detected diffuse neutrino fluxes should follow a universal spectrum
- This spectrum might not be single component

The IceCube Collaboration, Pos(ICRC2017)1005,
The IceCube Collaboration, Pos(ICRC2017)981

2 Astro Comp Flux: Setup and Fitting

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1st component
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Cut off factor

2nd component
At all range

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(111)

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Flux

Reconstruction

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Flux → Reconstruction →

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Flux → Reconstruction → Best Fit

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Flux → Reconstruction → Best Fit

$$\theta = \{\Phi_{1_0}, \Phi_{2_0}, \gamma_1, \gamma_2, E_c\}$$

Fitting Results

1st Comp.	2nd Comp.	Φ_{1_0}	Φ_{2_0}	γ_1	γ_2	$E_c/100$ TeV	TS/dof
$(1:1:1)$	$(1:1:1)$	0.01	2.21	1.47×10^{-4}	2.08	0.10	1.91
$(1:1:1)$	$(4:7:7)$	17.18	0.88	3.19×10^{-10}	1.83	0.50	1.48

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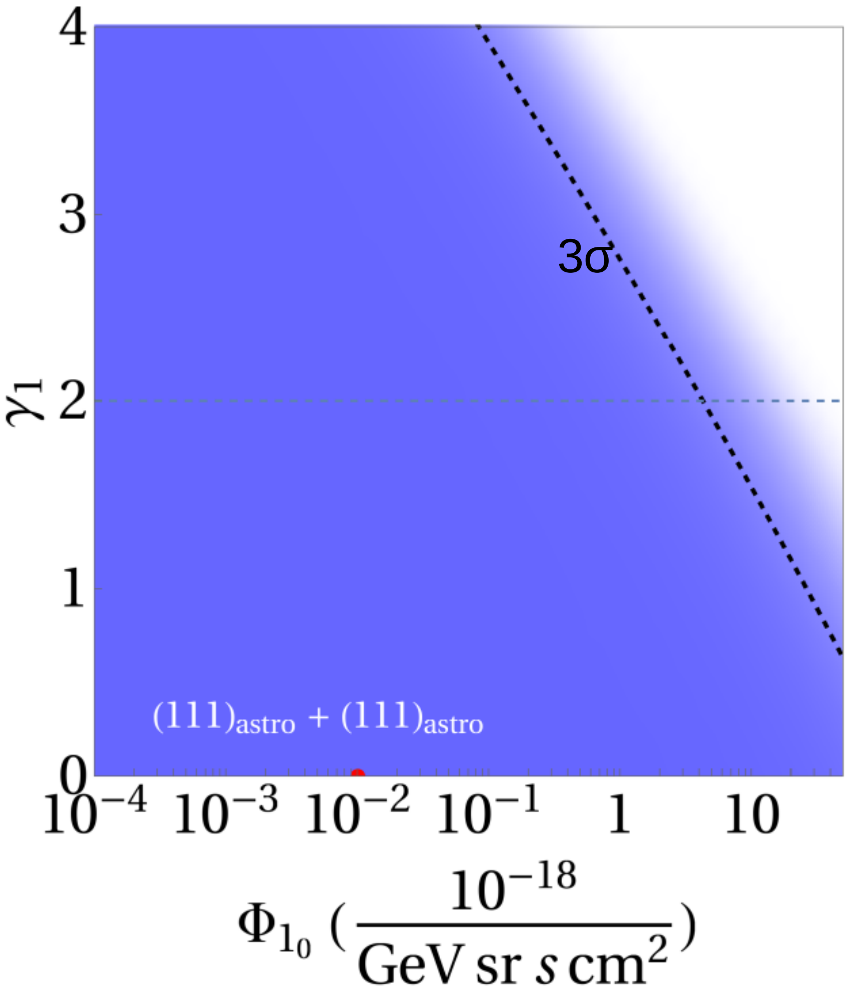

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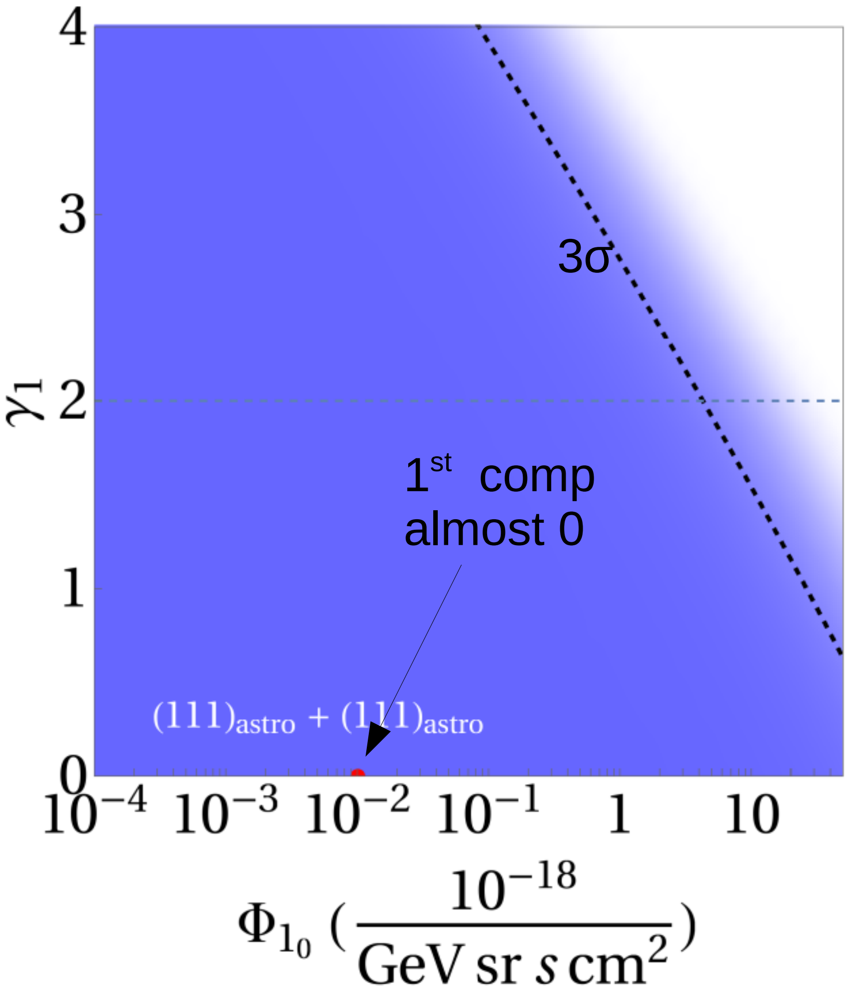

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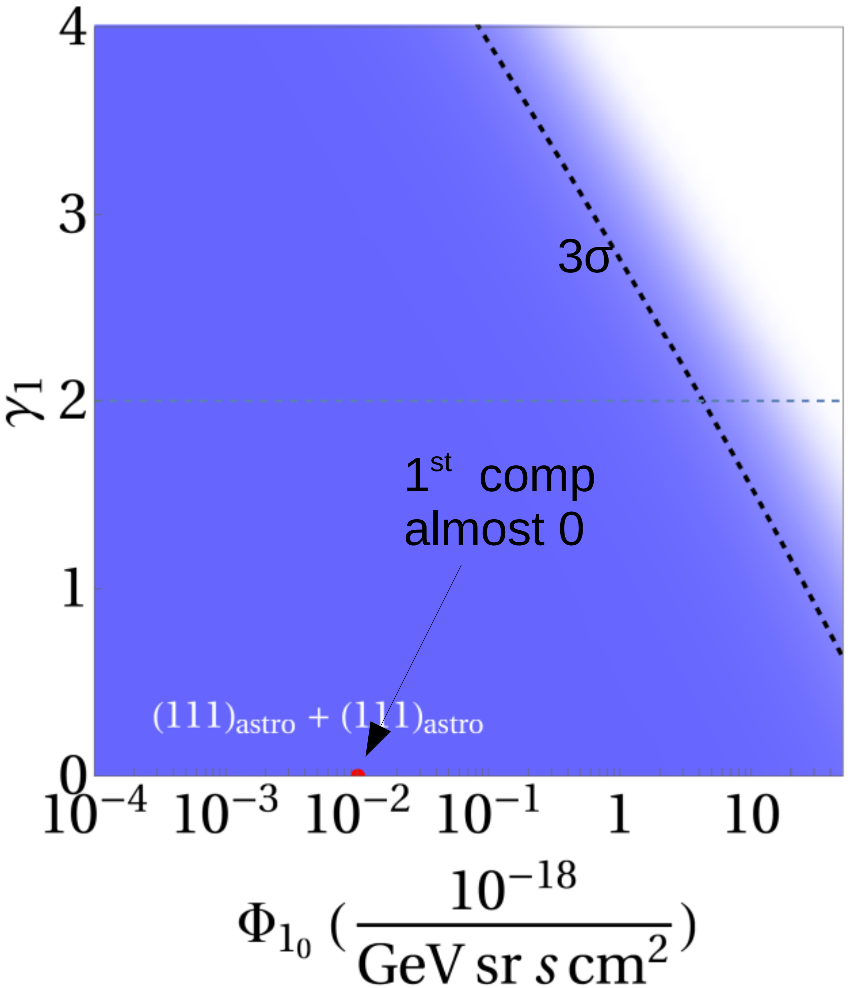

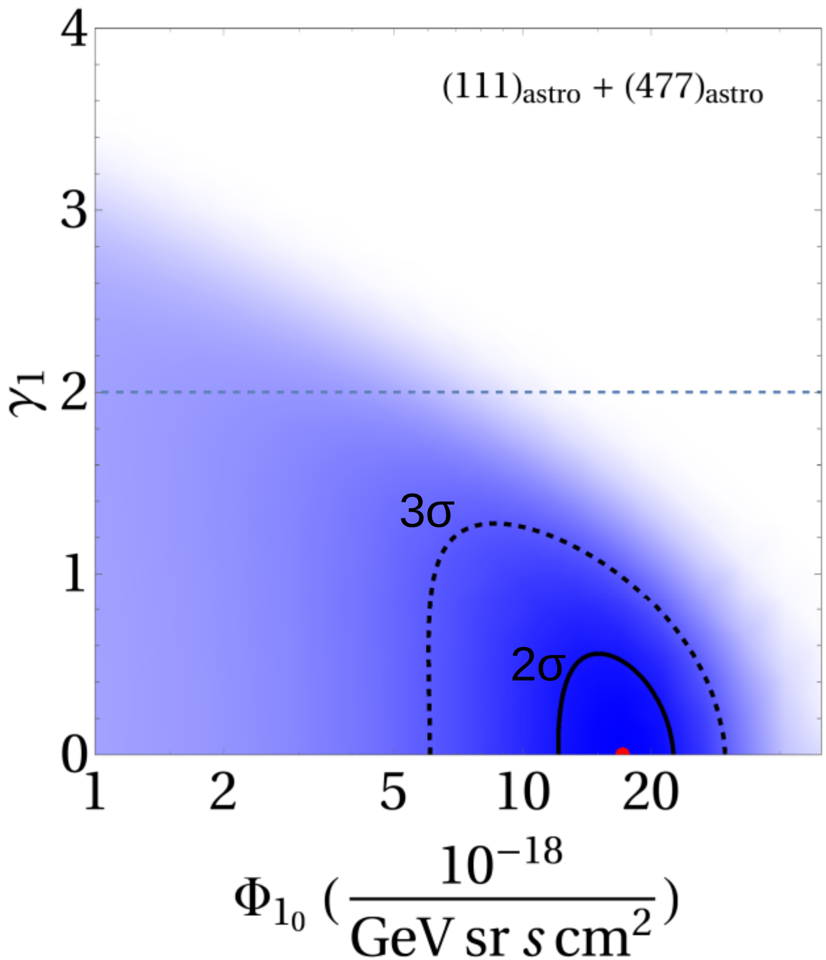

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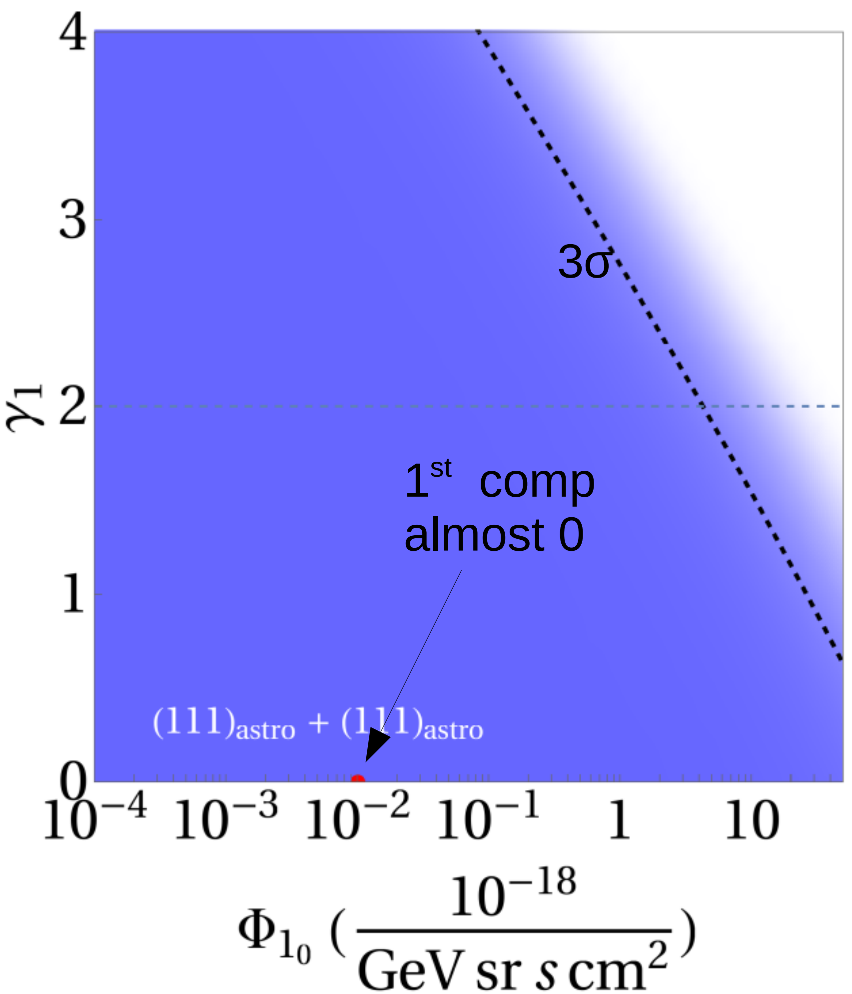

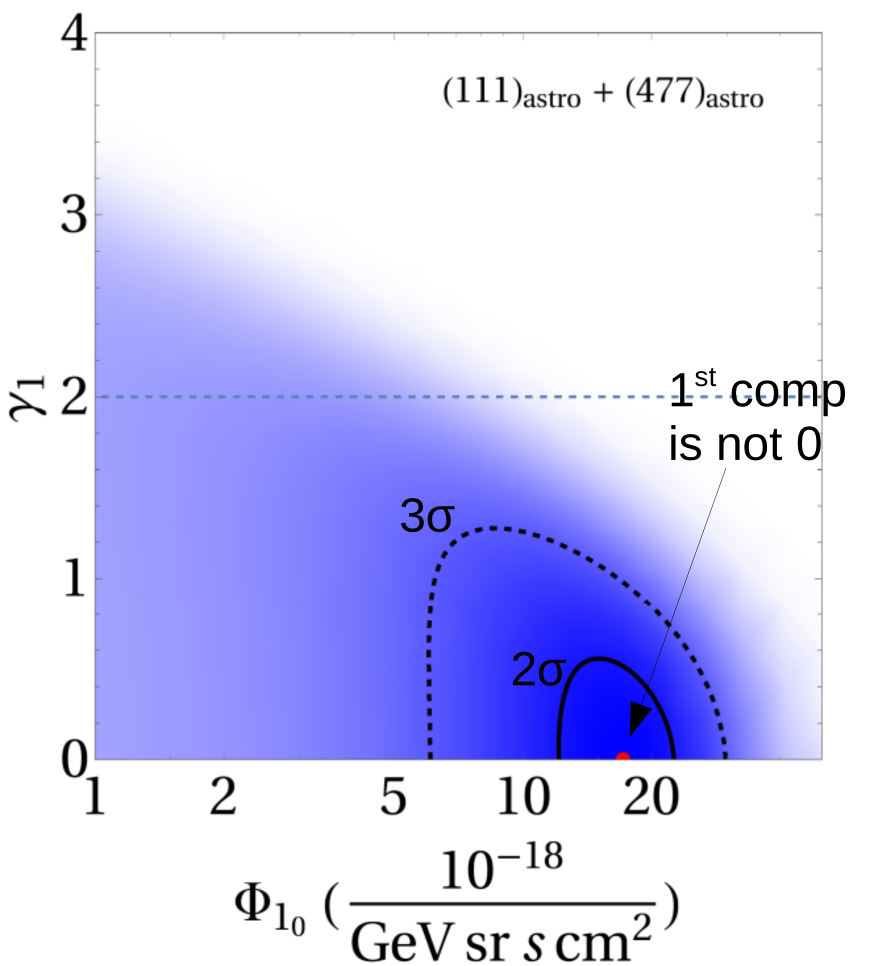

Best Fit Event Spectrum

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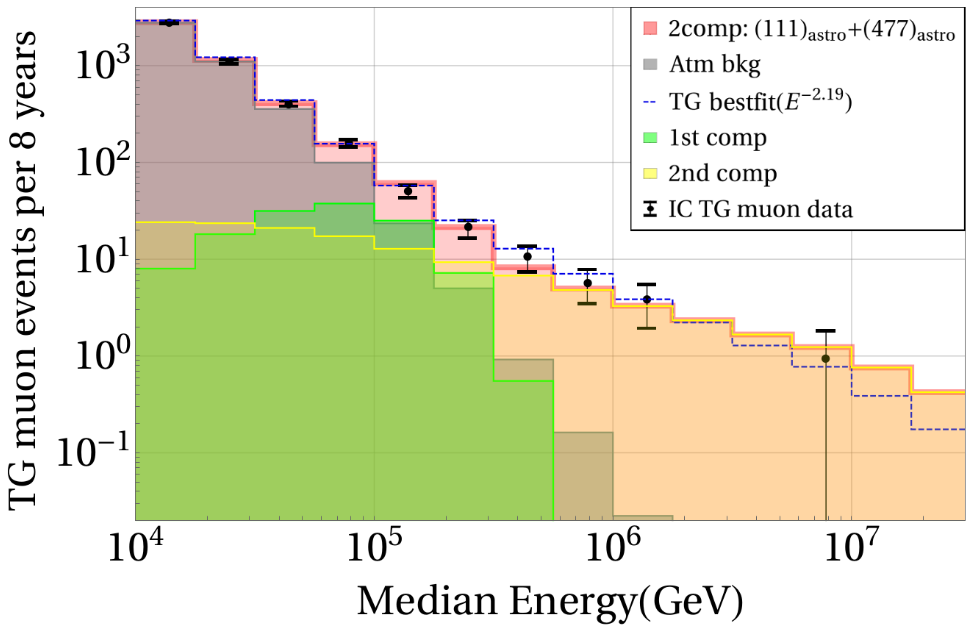

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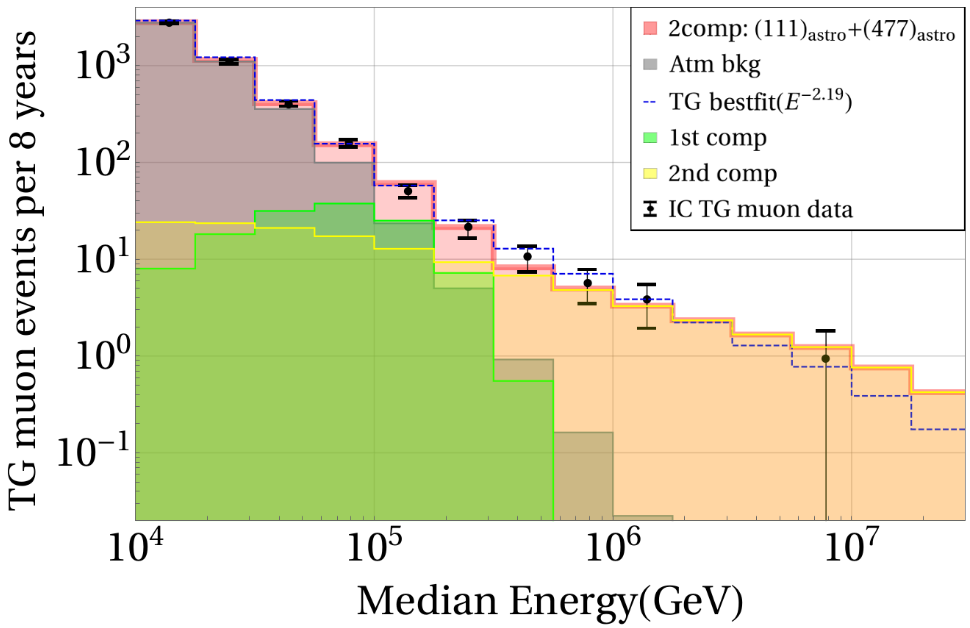

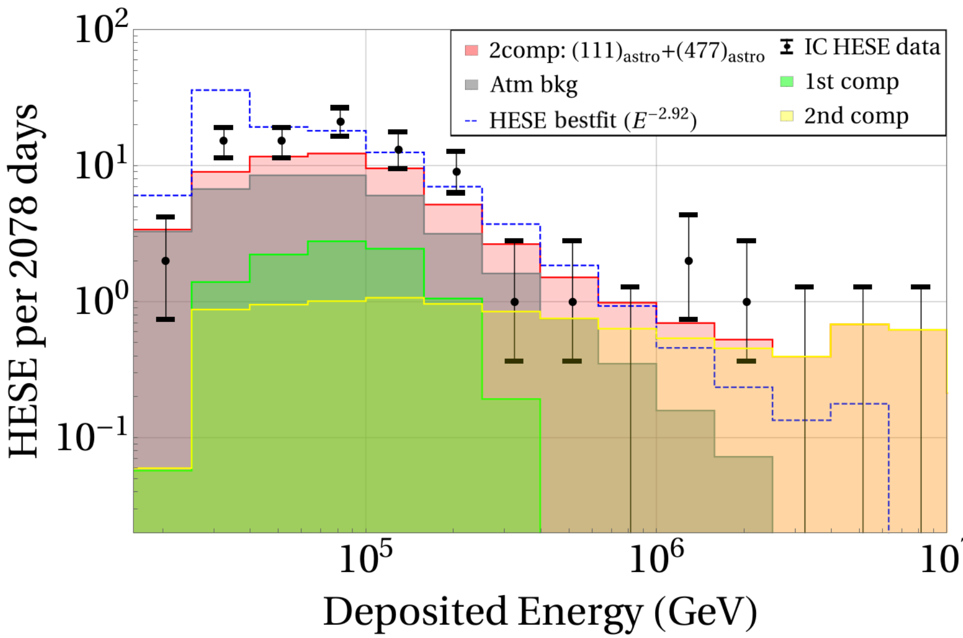

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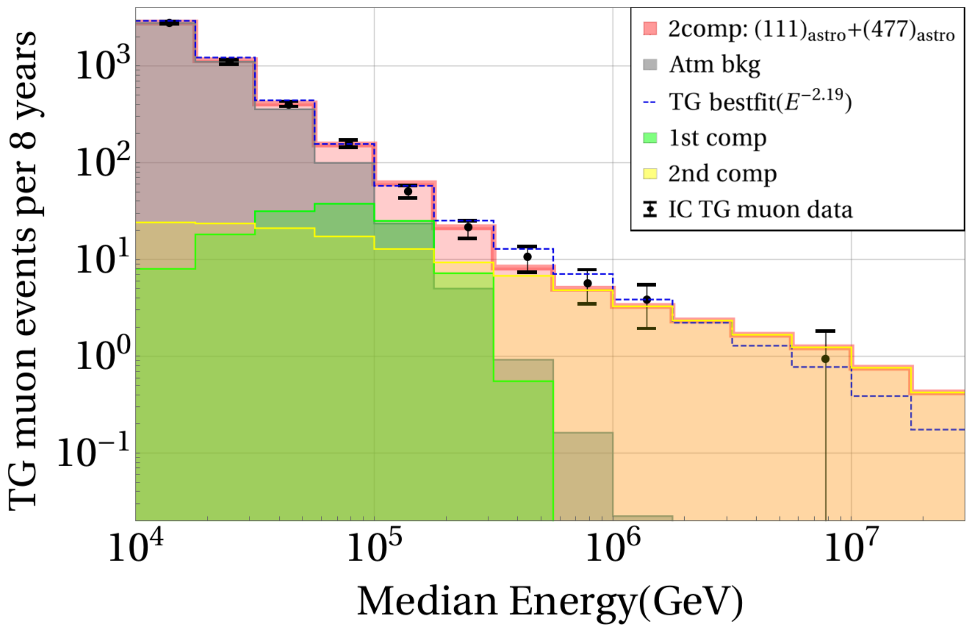

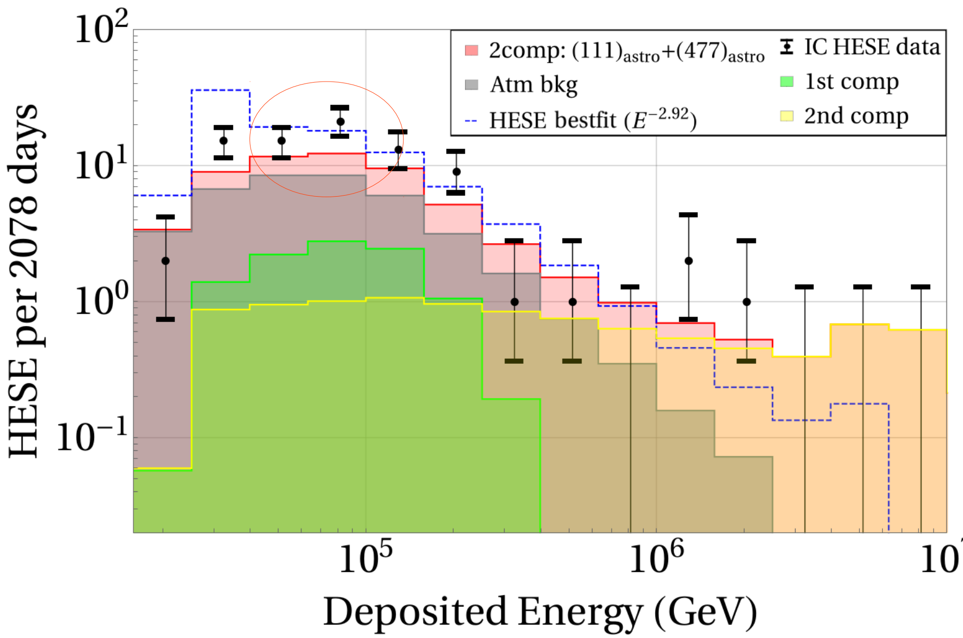

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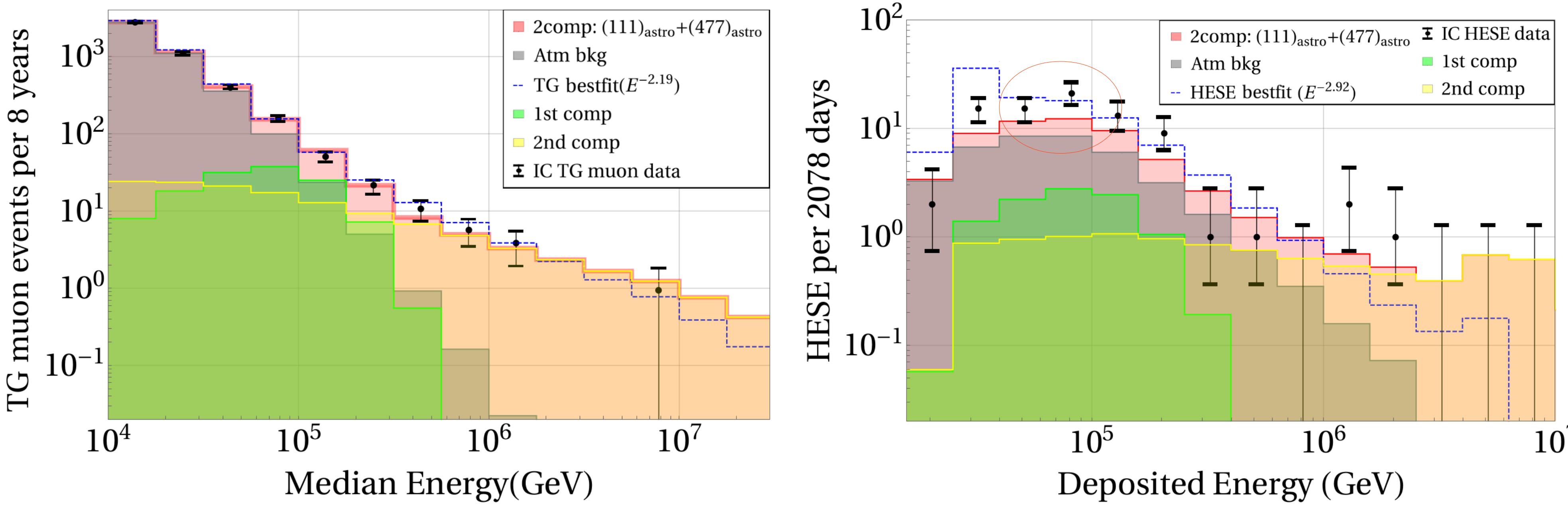

- Using 2 comp flux to fit both HESE and TG is doable but having discrepancy at bins ~ 100 TeV

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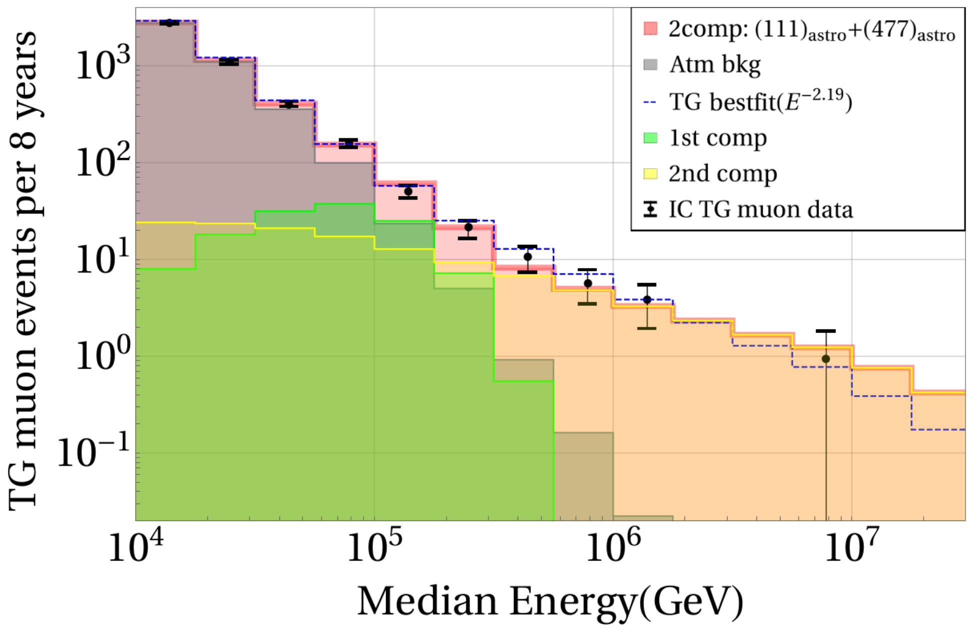

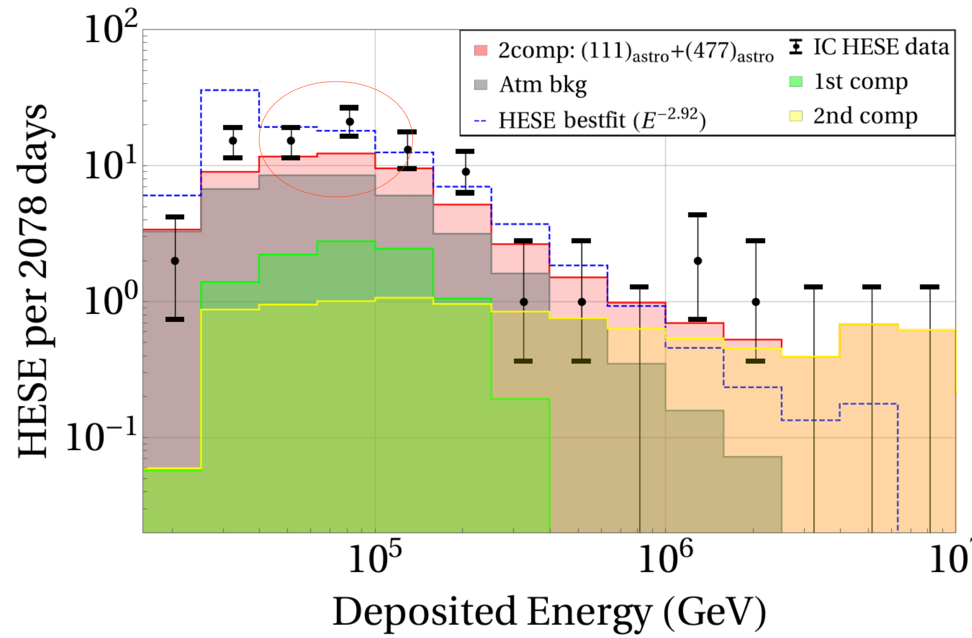

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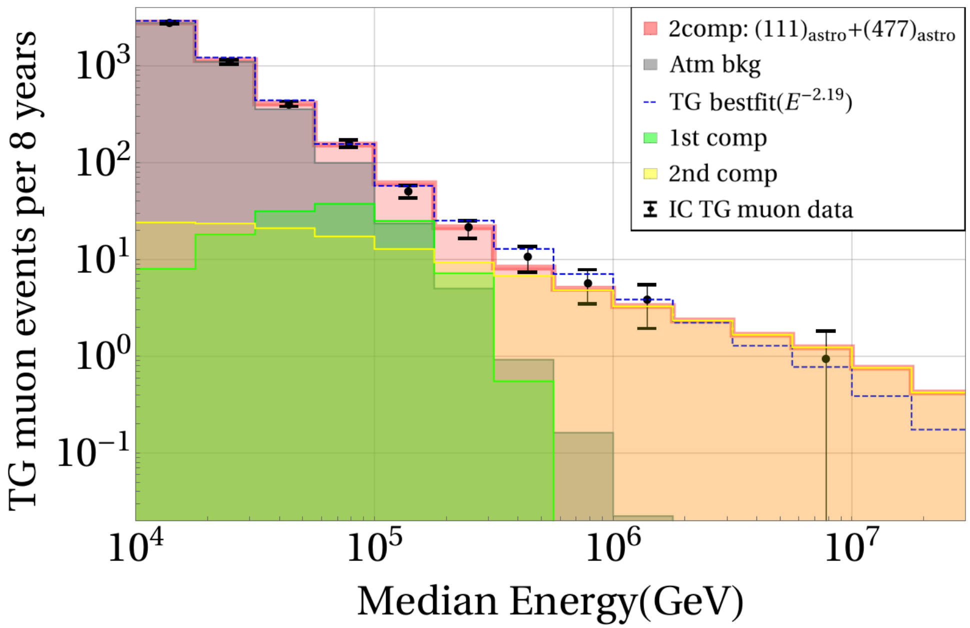
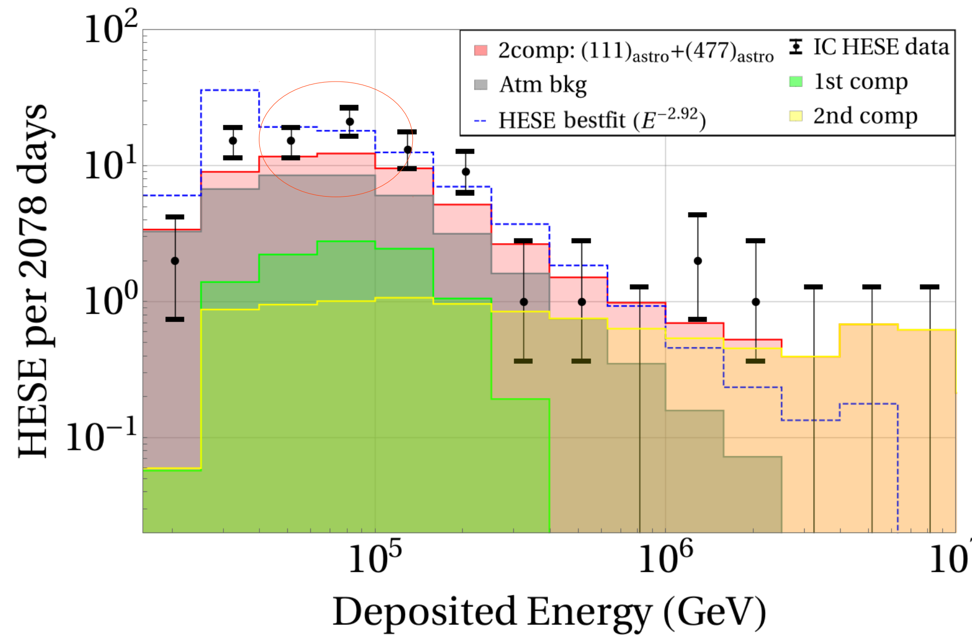
- 1st comp is not contributing in (111+111) case but contributes in (111+477)

Best Fit Event Spectrum





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Glashow Resonance

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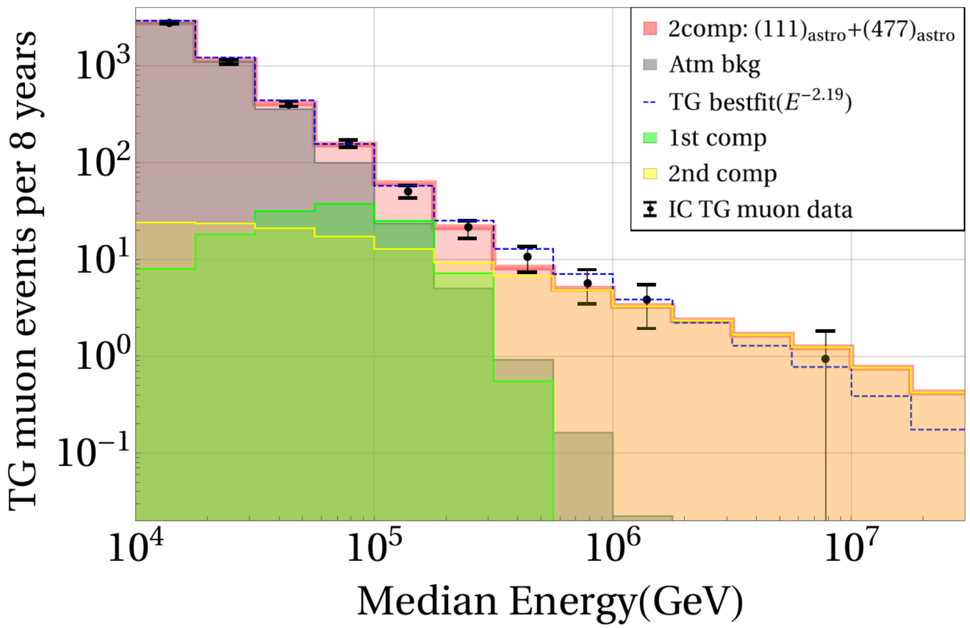

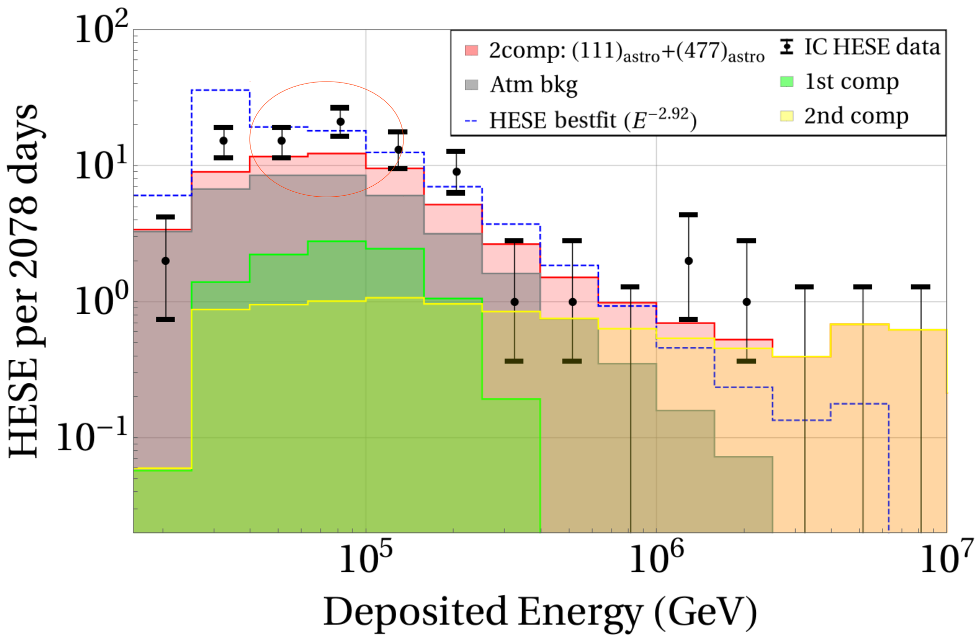

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   Glashow Resonance

- Statistically, (111+477) fit is slightly favored than (111+111)

DM+1Comp Flux: Model and Fitting

Feldstein et al (PRD '13); Esmaili, Serpico (JCAP '13); Murase et al (PRL '15); Boucenna et al (JCAP '15); Dev et al (JCAP '16); di Bari et al (JCAP '16); Cohen et al (PRL '17);

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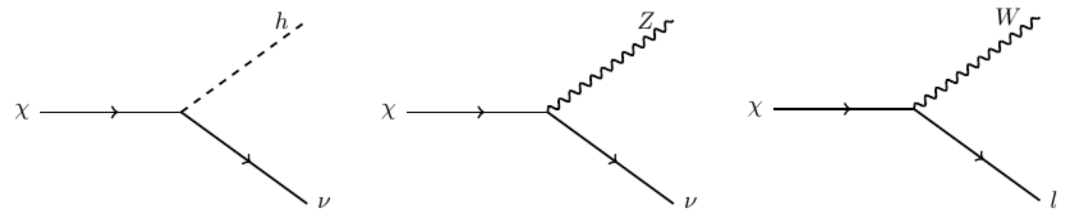

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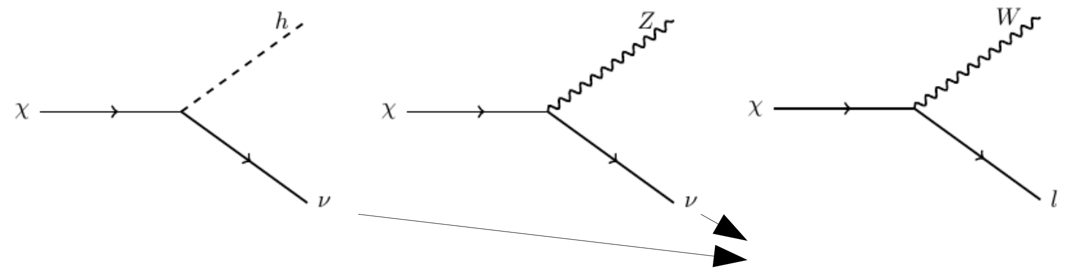

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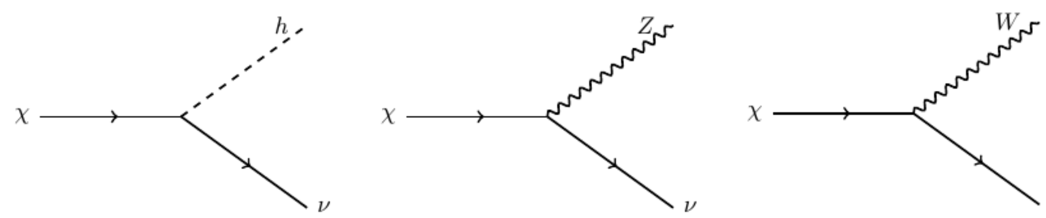

Almost monochromatic neutrinos

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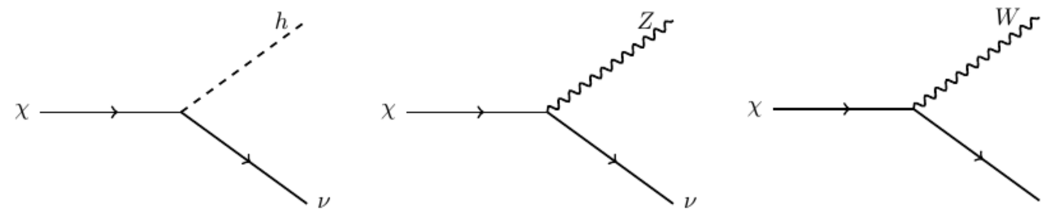

Almost monochromatic neutrinos

A.~Atre, T.~Han, S.~Pascoli and B.~Zhang, “The Search for Heavy Majorana Neutrinos”

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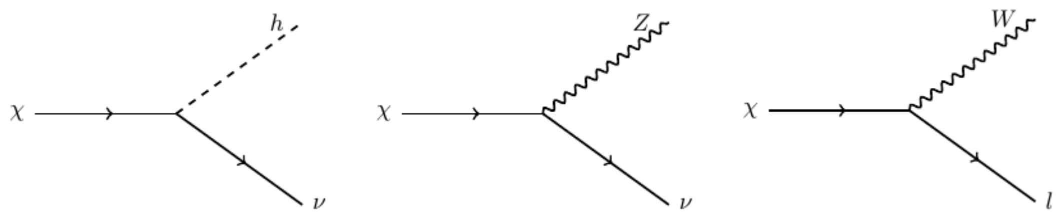

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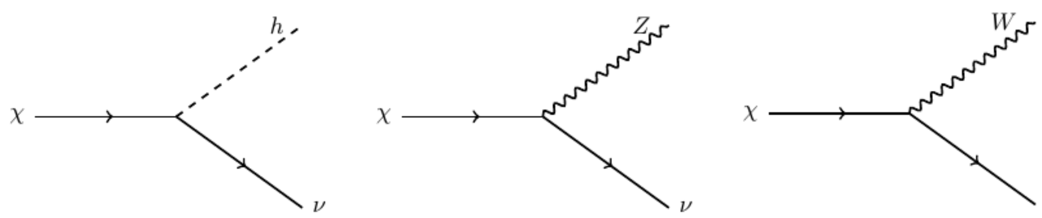

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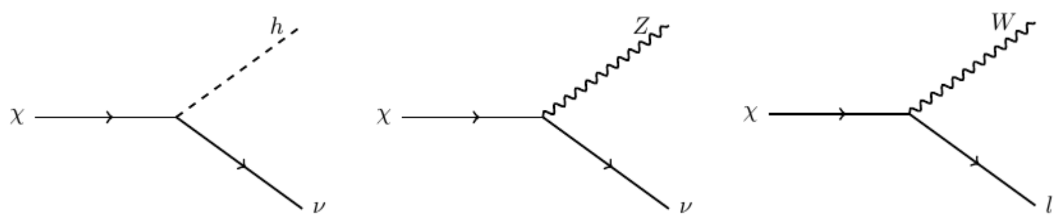

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Sum up contribution from all DM, galactically or extra-galactically

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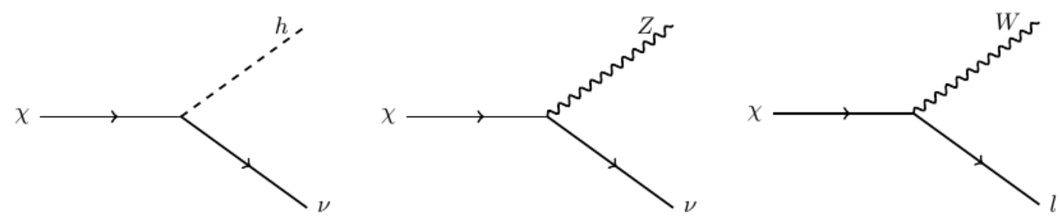

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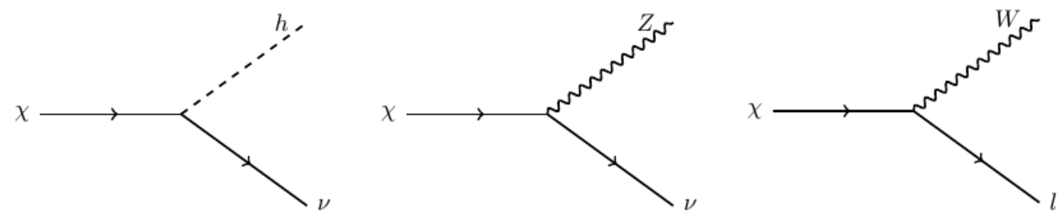

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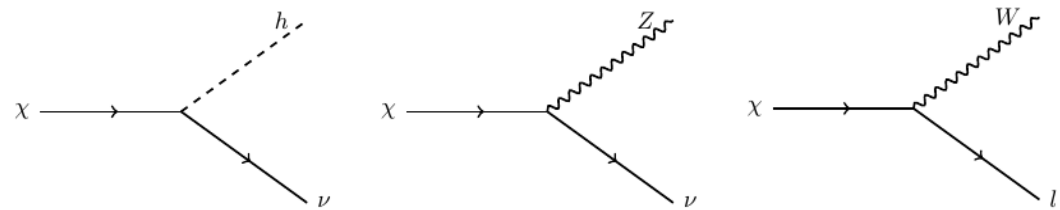

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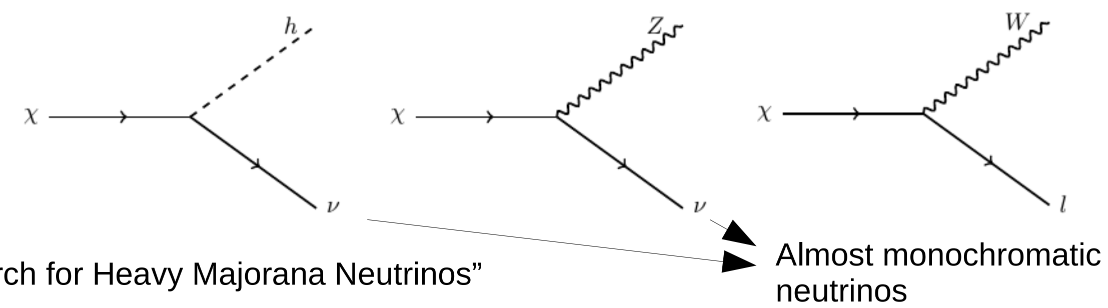

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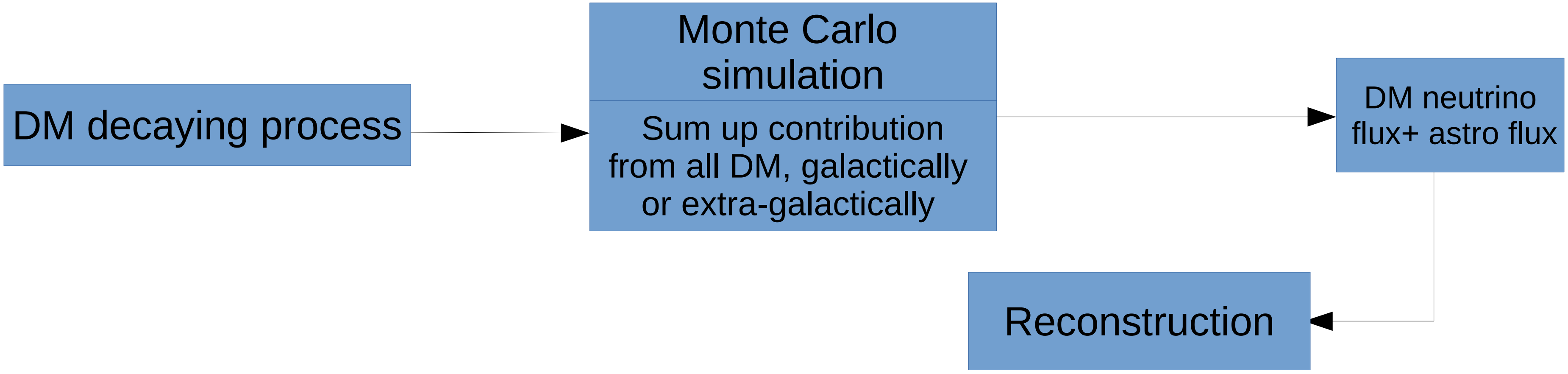

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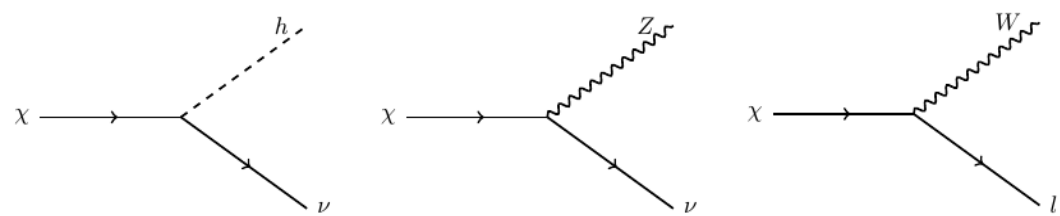

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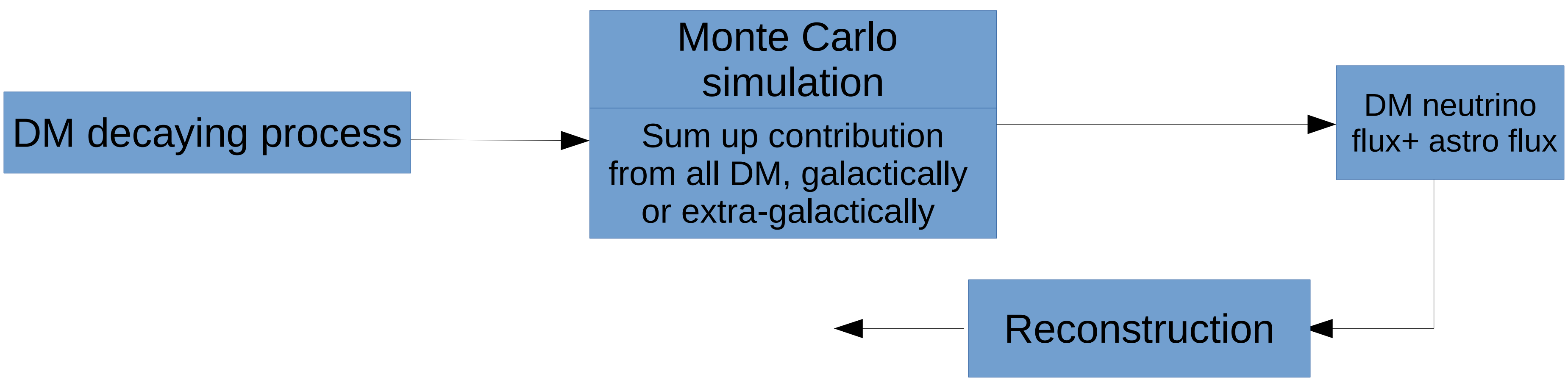

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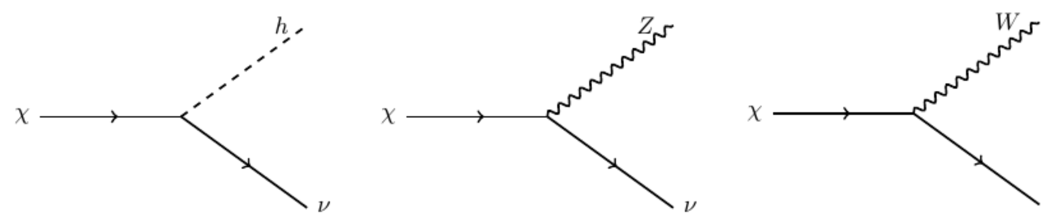

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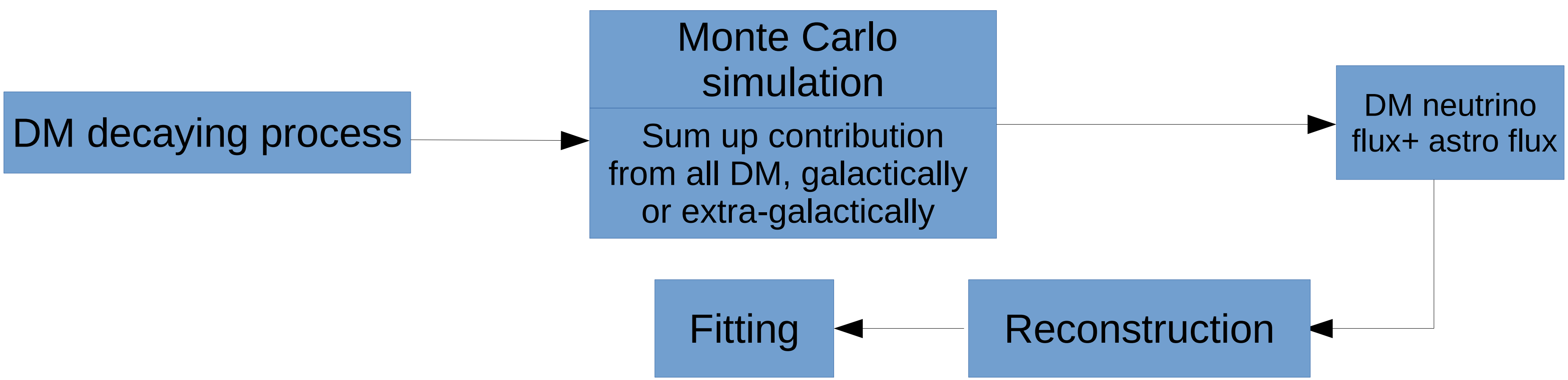

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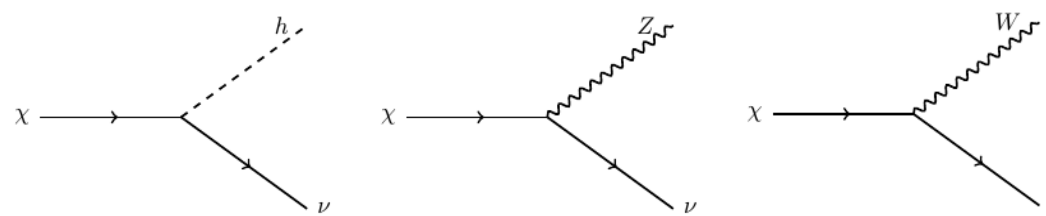

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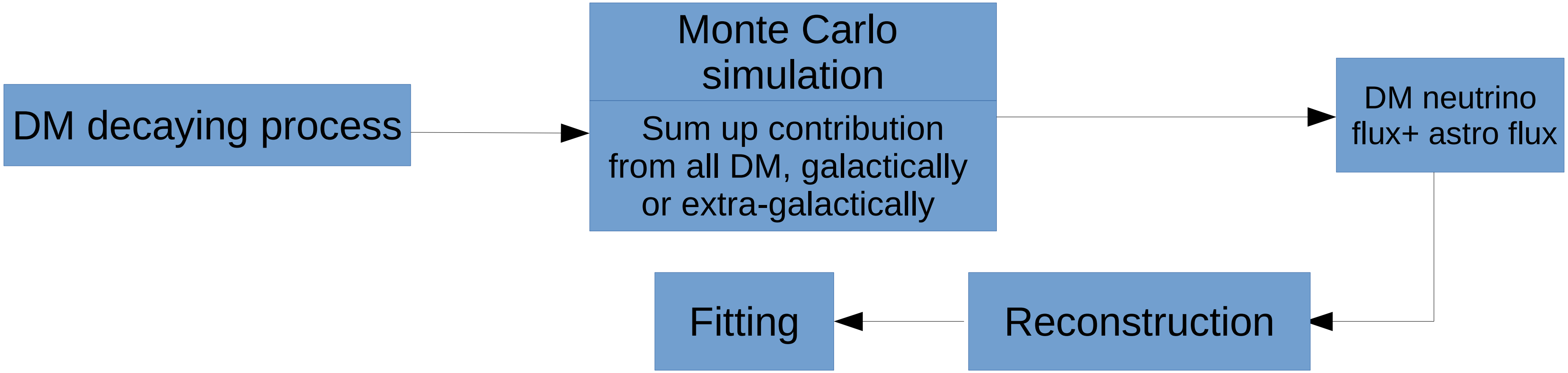

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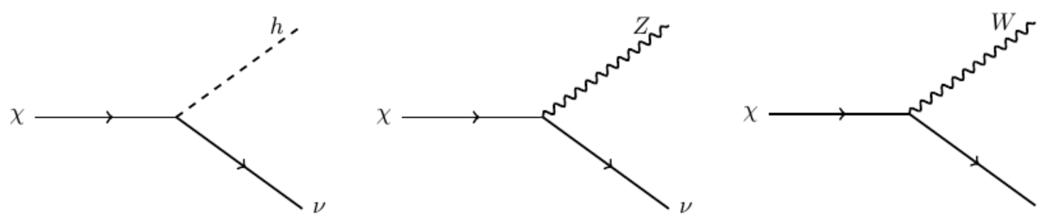

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Flavor composition for DM event: (111)

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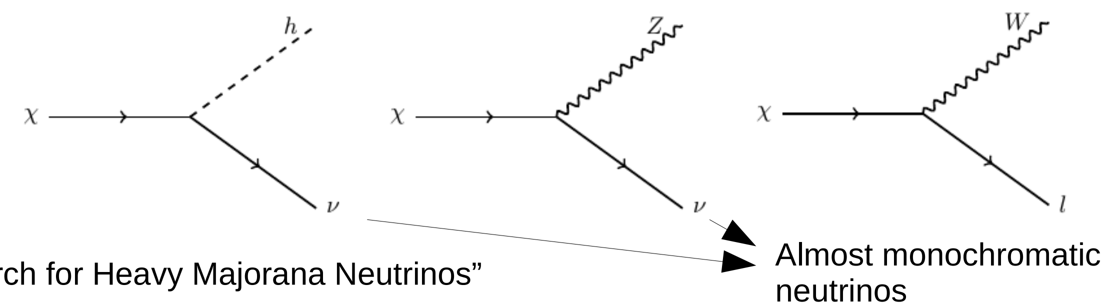

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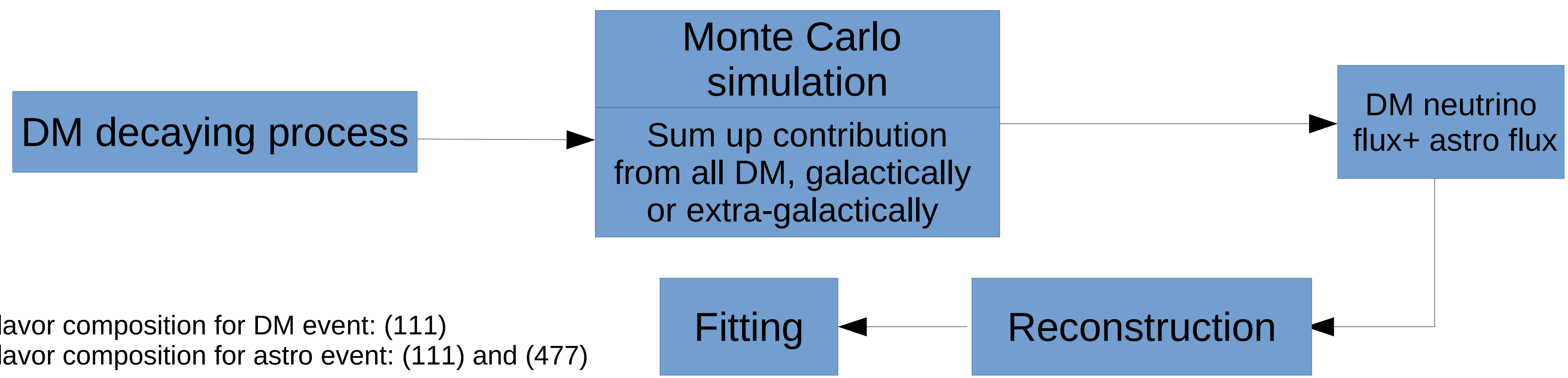

Flavor composition for DM event: (111)
Flavor composition for astro event: (111) and (477)

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Fitting Results

DM (1st comp.)	astro (2nd comp.)	Φ_0	γ_0	M_{DM} (TeV)	$\tau_{\mathrm{DM}}(10^{28}$ s)	TS/dof
$(1:1:1)$	$(1:1:1)$	1.62	2.00	316.23	6.31	1.38
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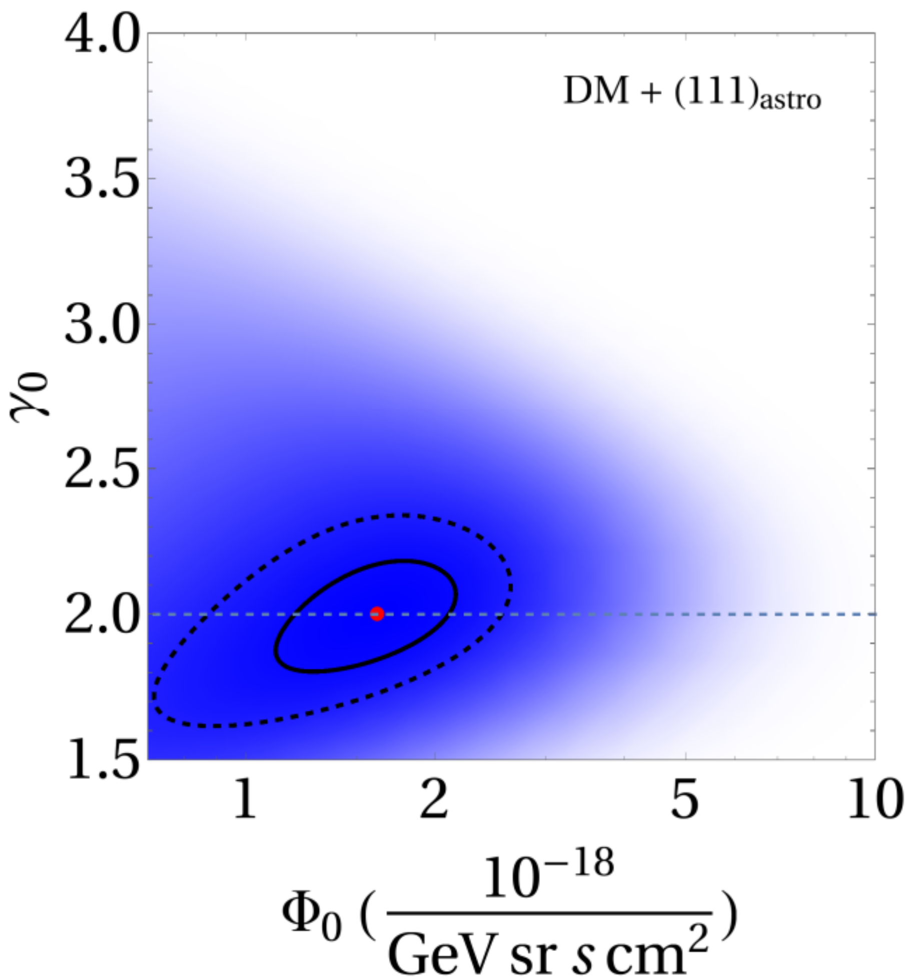

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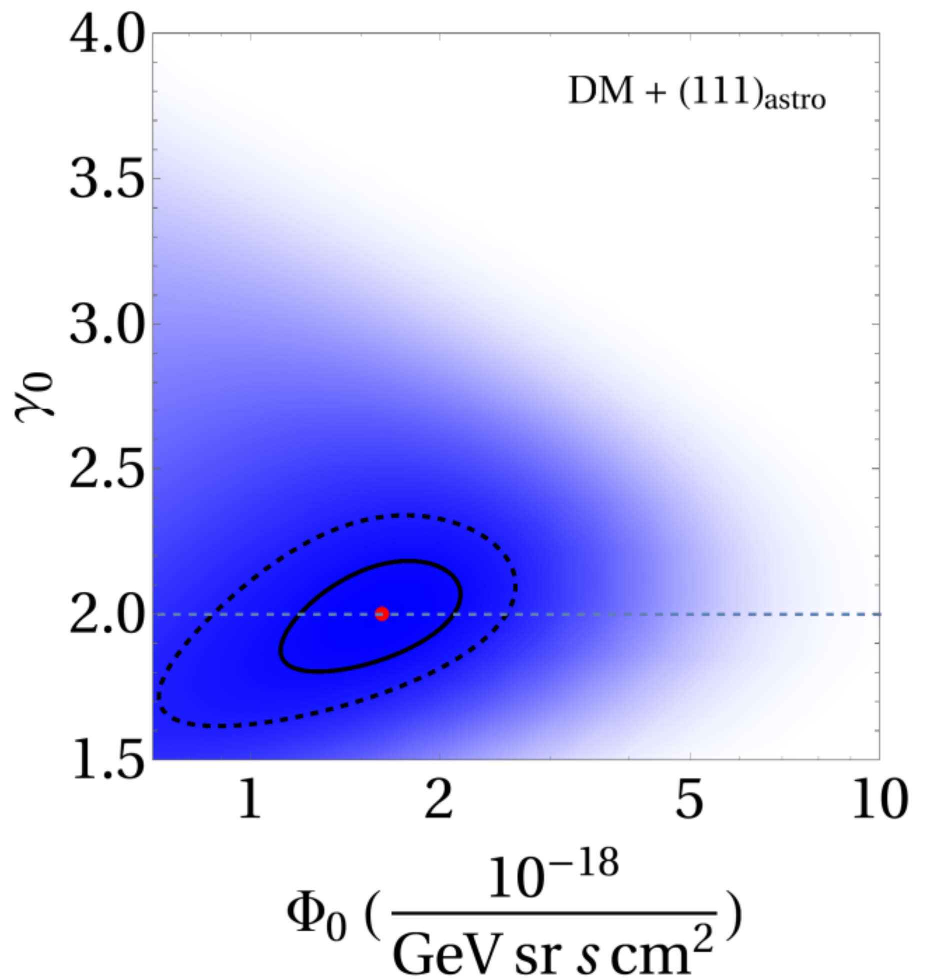

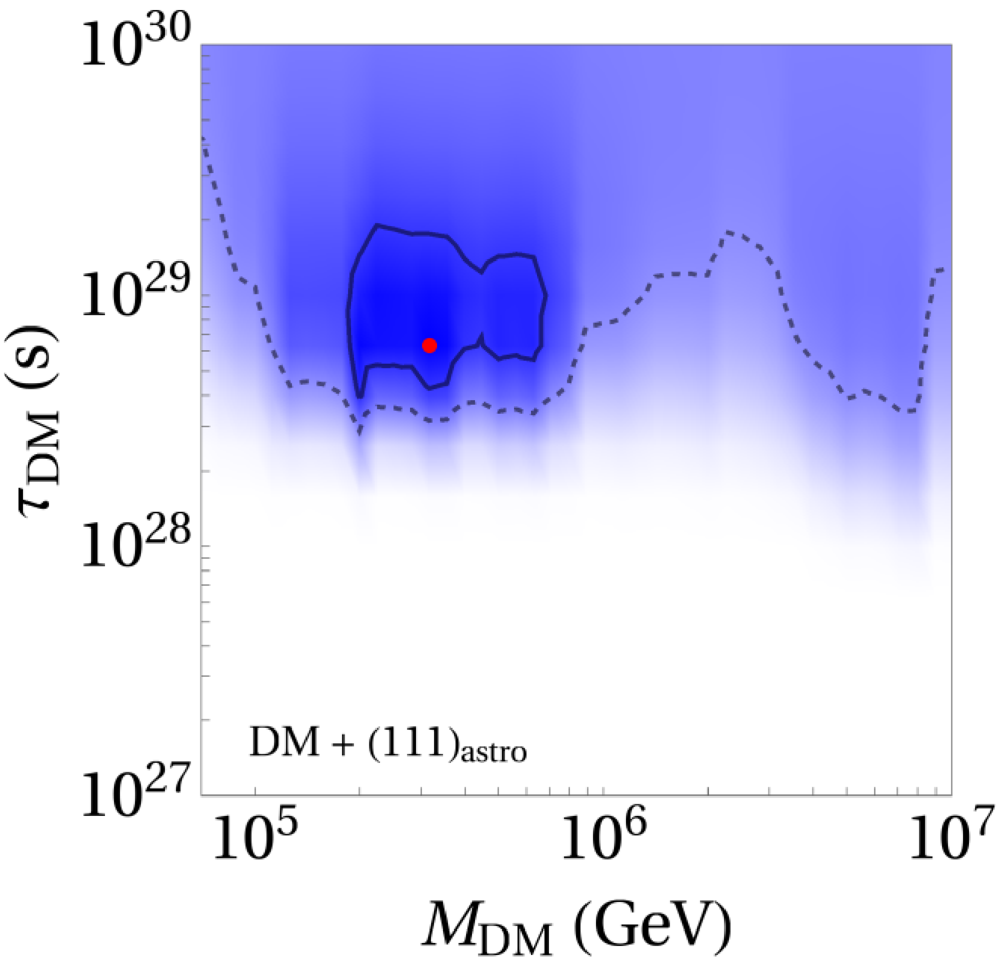

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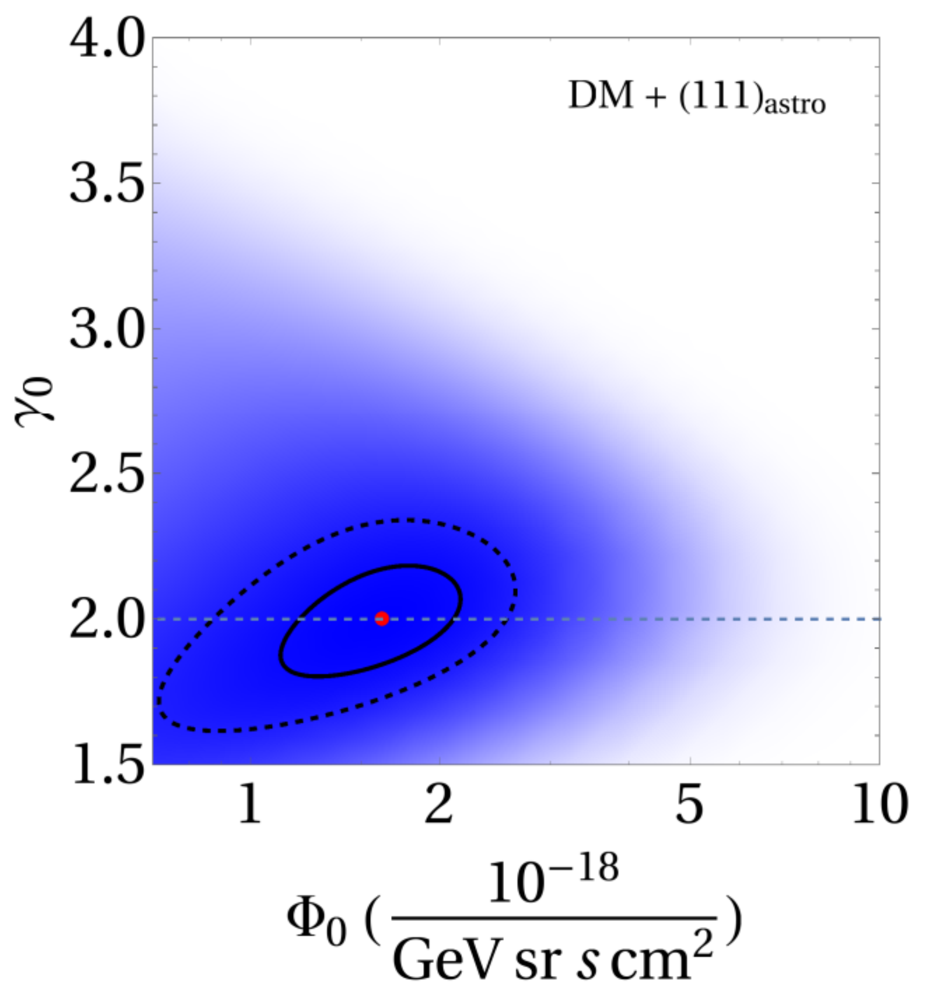
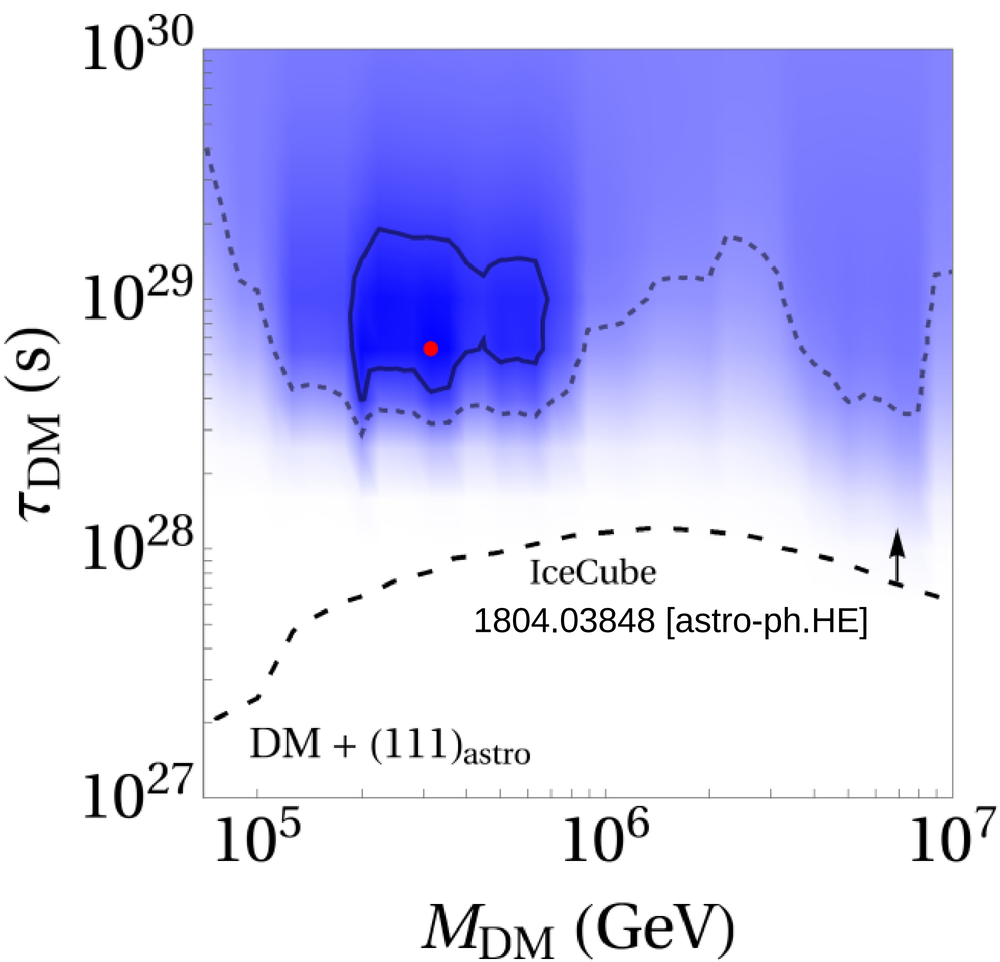
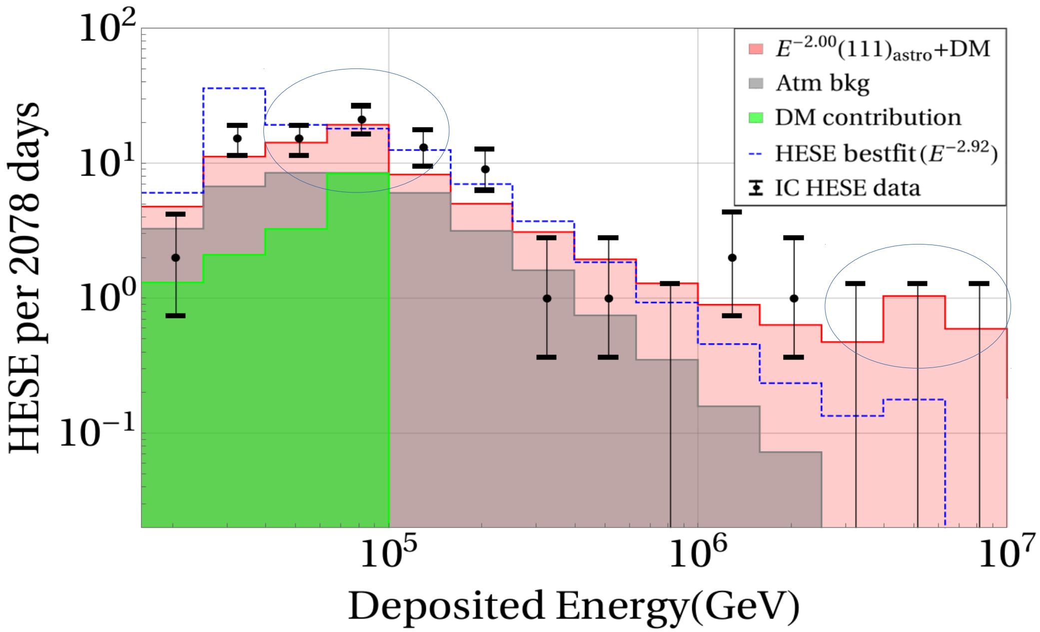
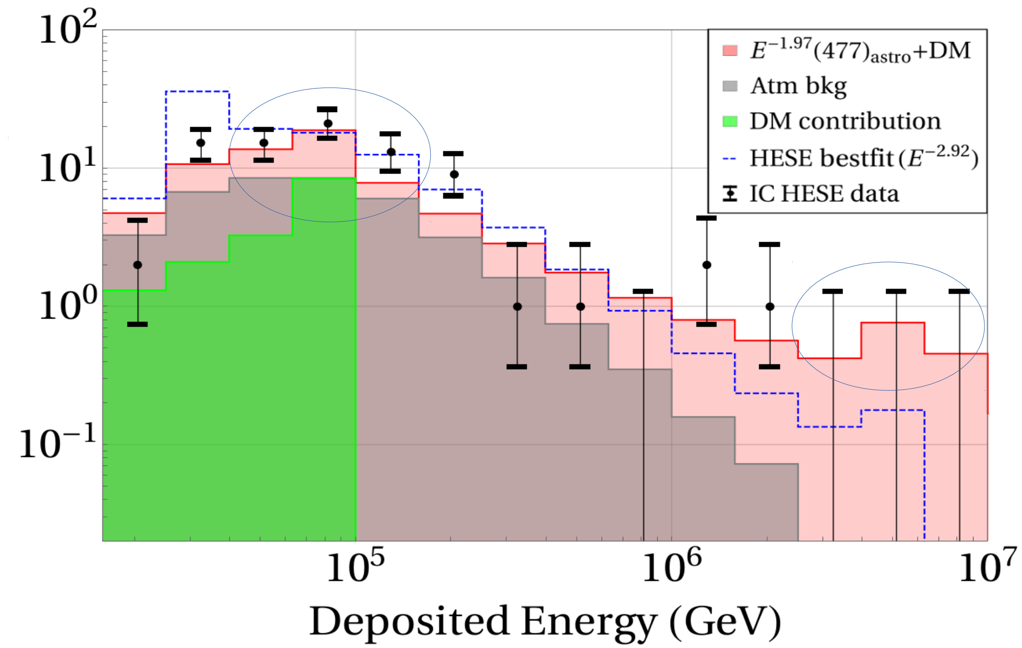




Best Fit Event Spectrum





1. A DM component with a power law astrophysical component together could fit both HESE and TG data, with $M_{\rm DM} = 316^{+335}_{-125}\,{\rm TeV},\ \tau_{\rm DM} = 6.3^{+12.7}_{-2.3} \times 10^{28}\,{\rm sec}$

2. Power law's index best fit is 2

3. Statistically, 477 case is slightly better than 111 case.

Multi-messenger Method

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Charged Pions Decay

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Charged Pions Decay

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Neutral Pions Decay

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Neutral Pions Decay

$$\pi^0 \rightarrow \gamma + \gamma$$

$$E_\gamma^2 \Phi_\gamma \simeq \frac{4}{K} E_\nu^2 \frac{\Phi_{(\nu+\bar{\nu})_{\mathrm{tot}}}}{3}\Bigg|_{E_\nu = 0.5 E_\gamma}$$

Typical case

Multi-messenger Method

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Muon-damped case

Multi-messenger Method

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K is the ratio between charged pions and neutral pions

Multi-messenger Method

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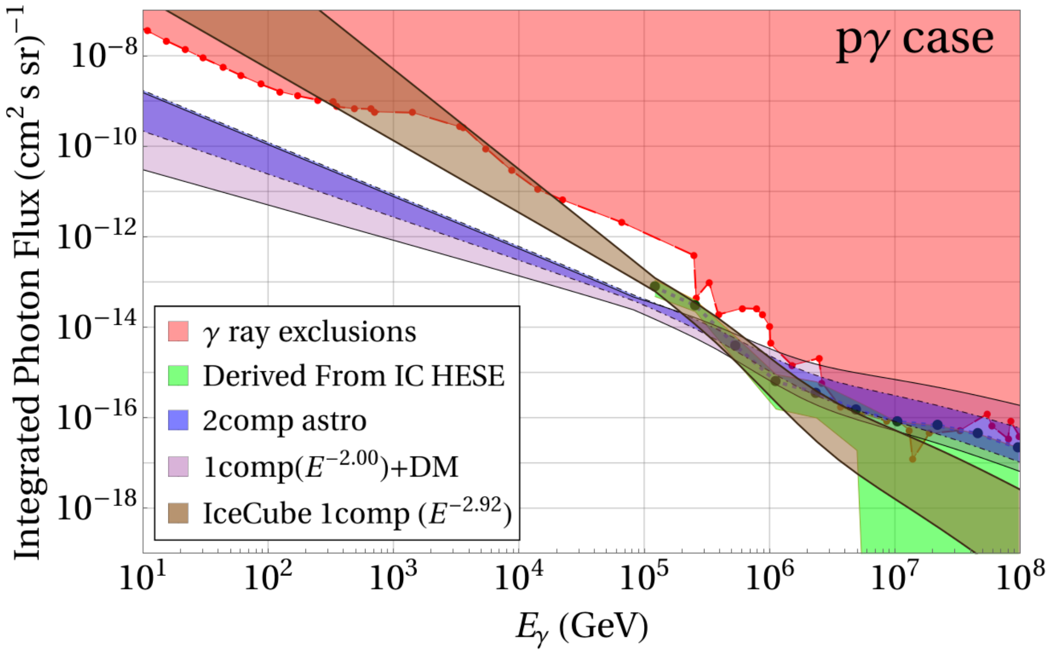
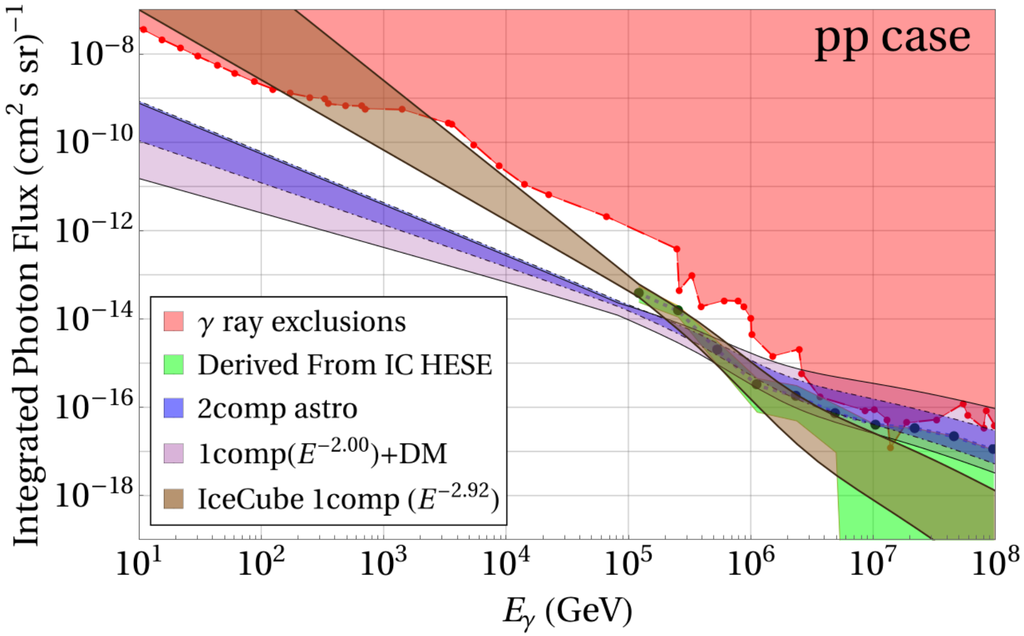
Estimation of photons flux could be made from neutrino flux

Kohta Murase, 1410.3680v2[hep-ph]

Verifying Best Fits with Photon Constraint

111 for both





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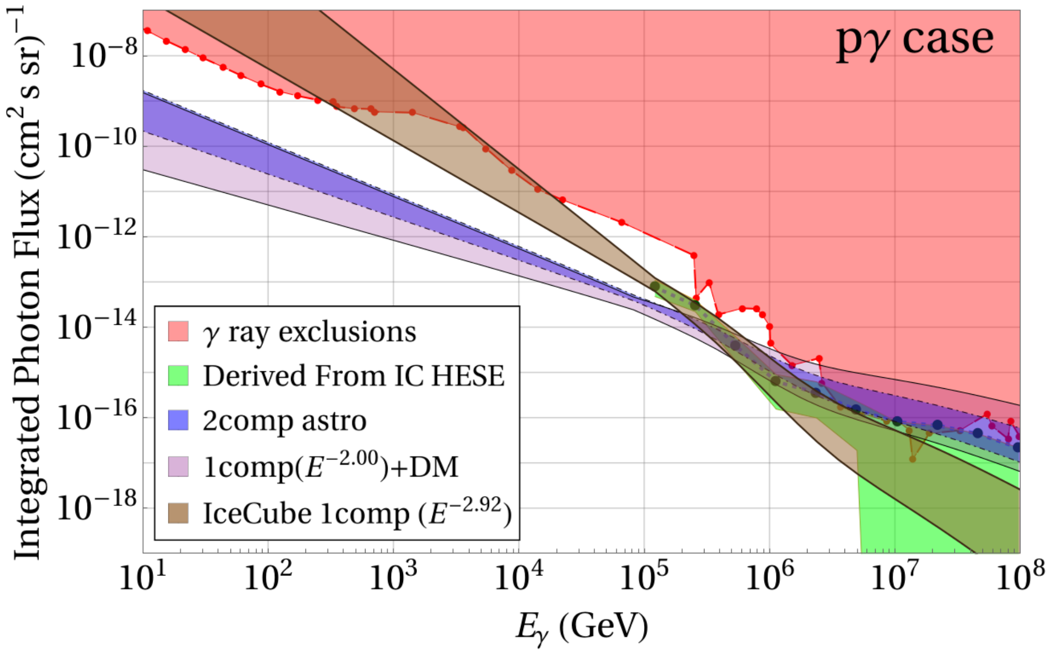

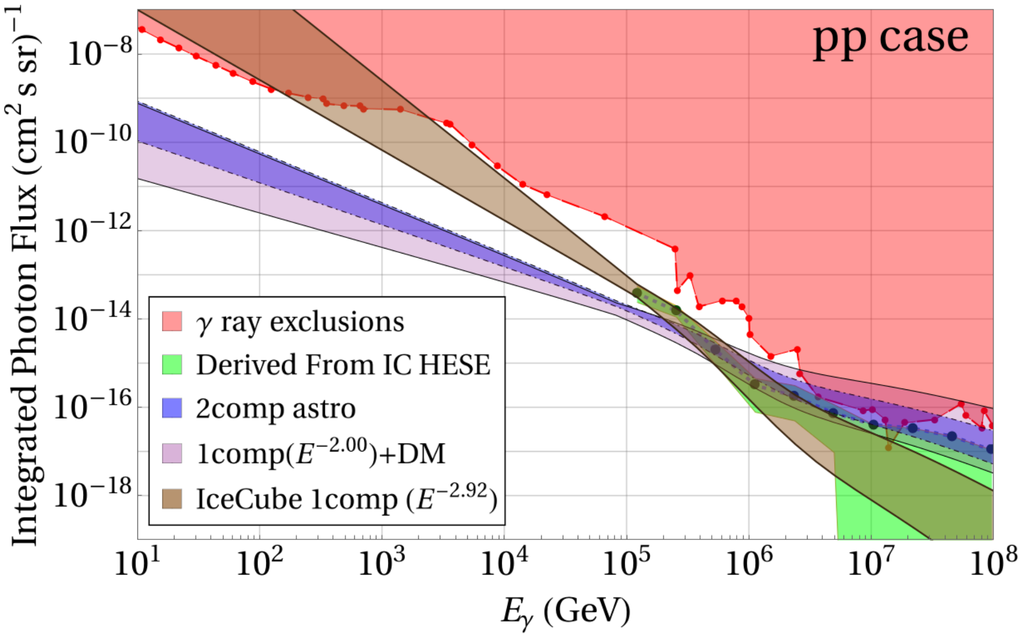

Comparing the photon estimated flux with gamma ray constraints from CASA-MIA, MILARGO, FERMI-LAT, GRAPES, KASCADE, ARGO, HAWC, HESS and VERITAS:

Verifying Best Fits with Photon Constraint

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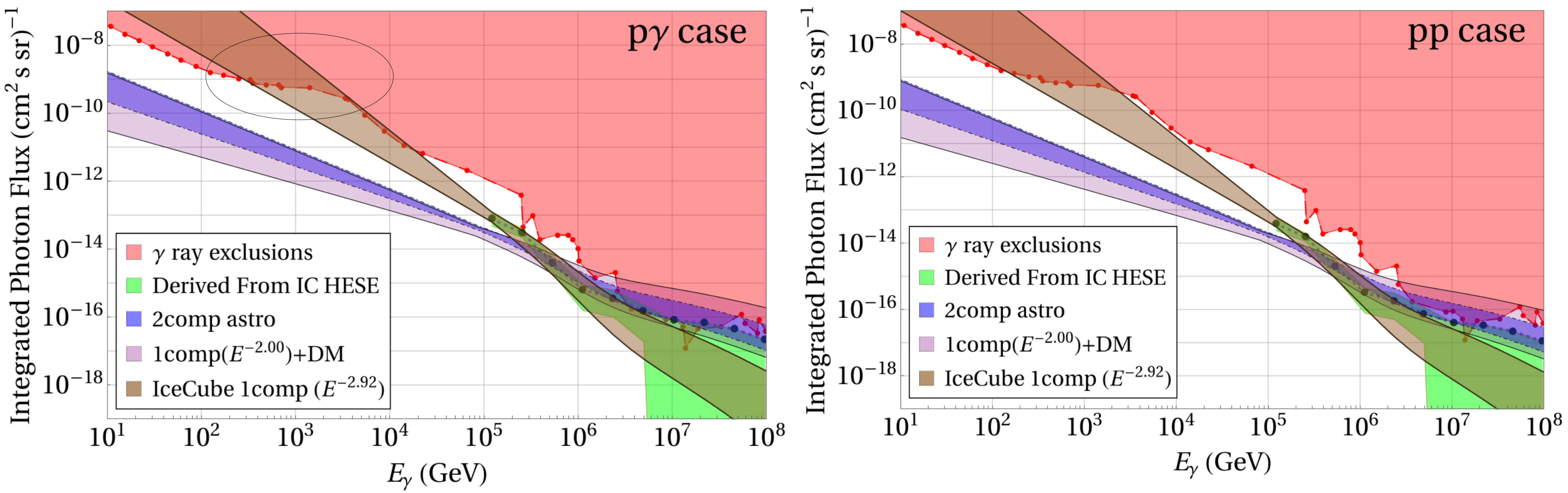

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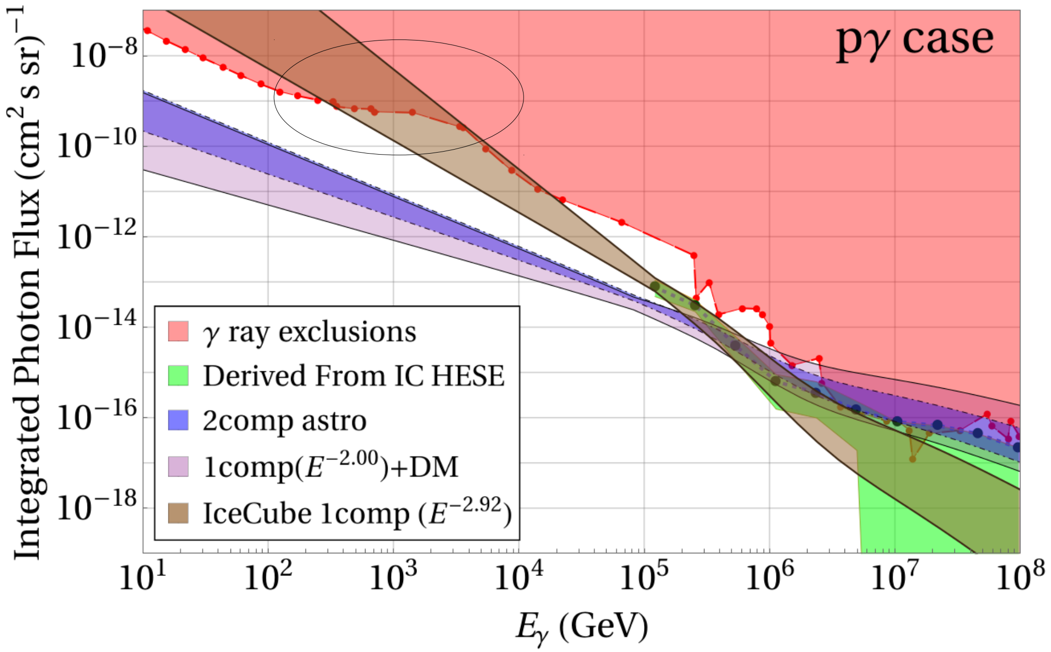

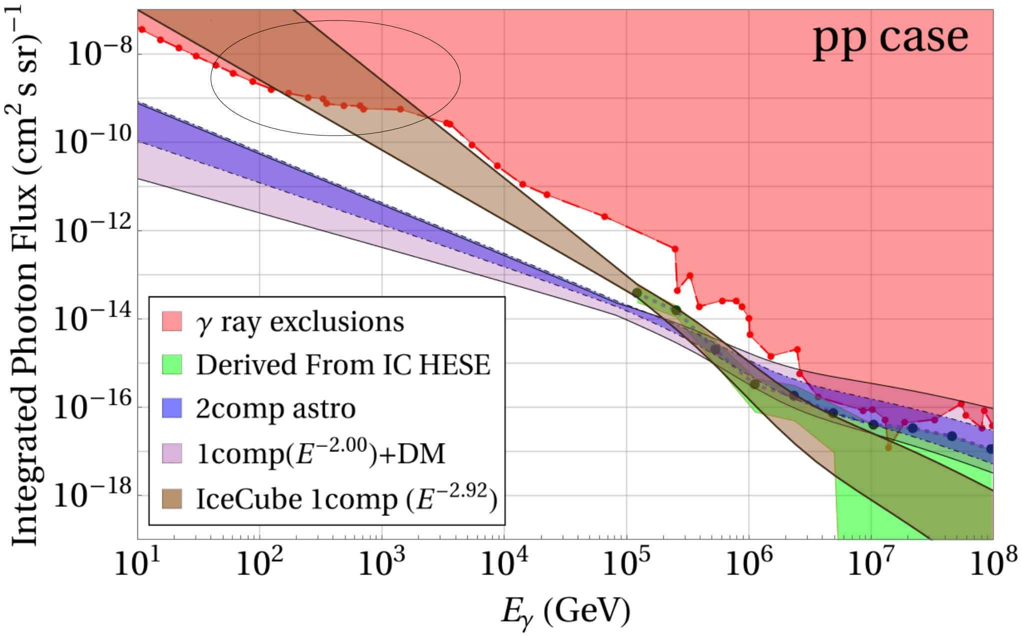

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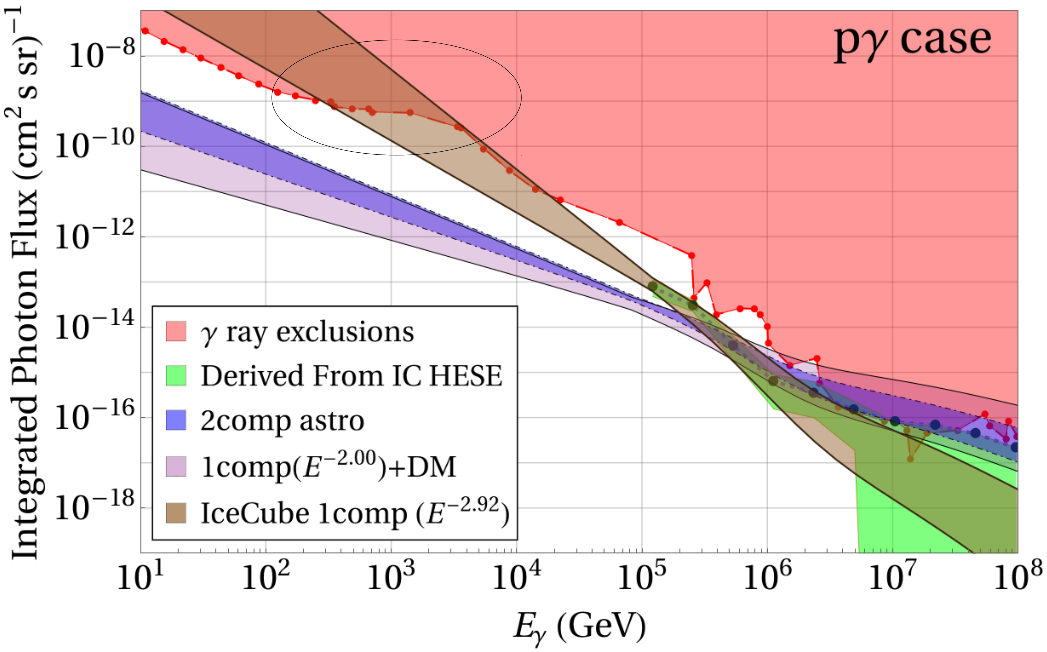

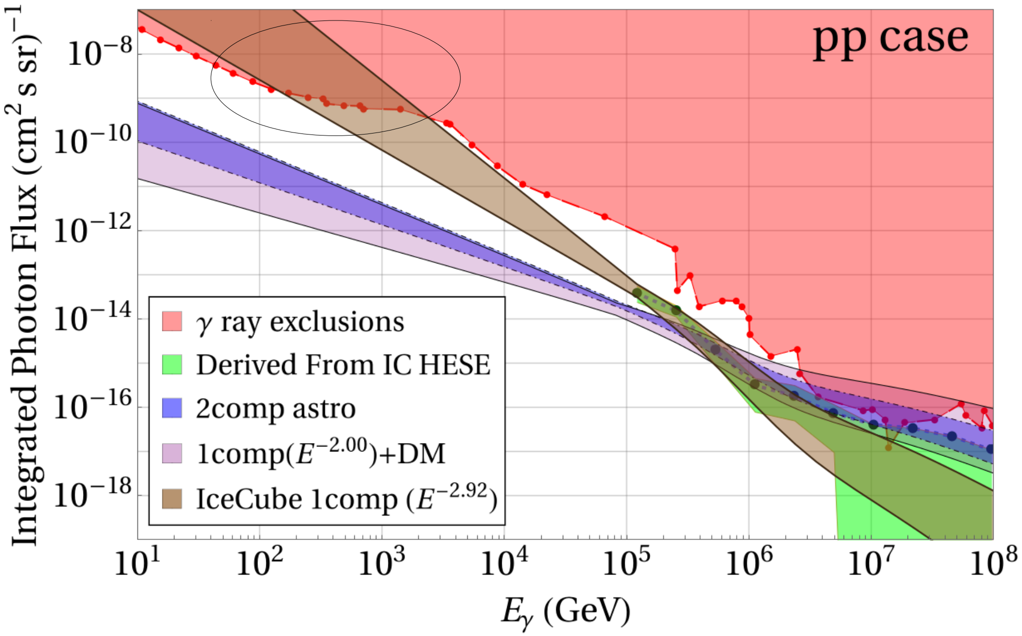

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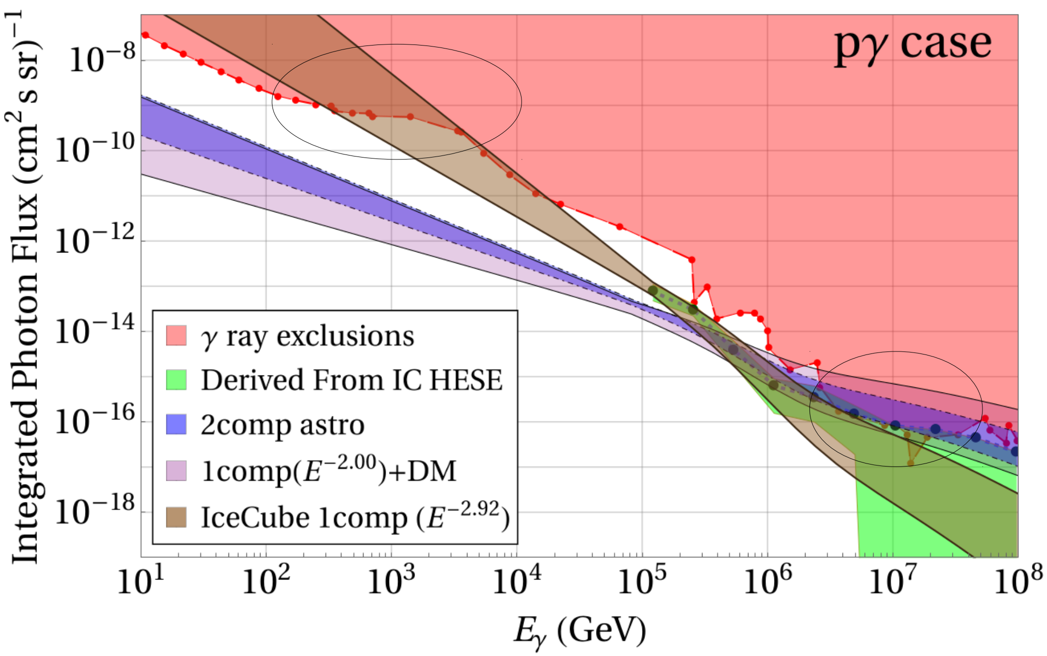

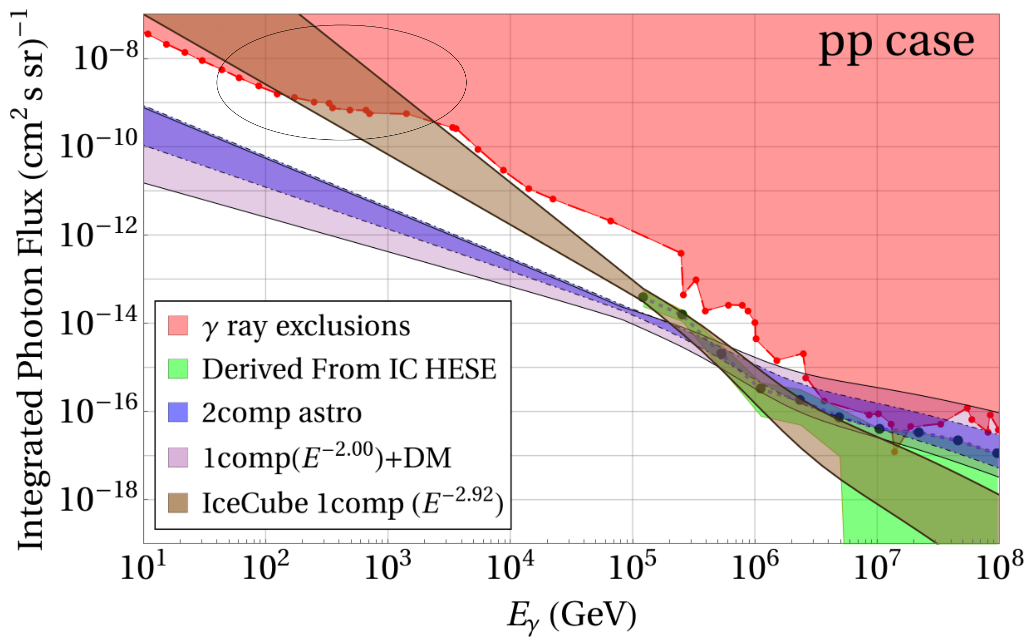

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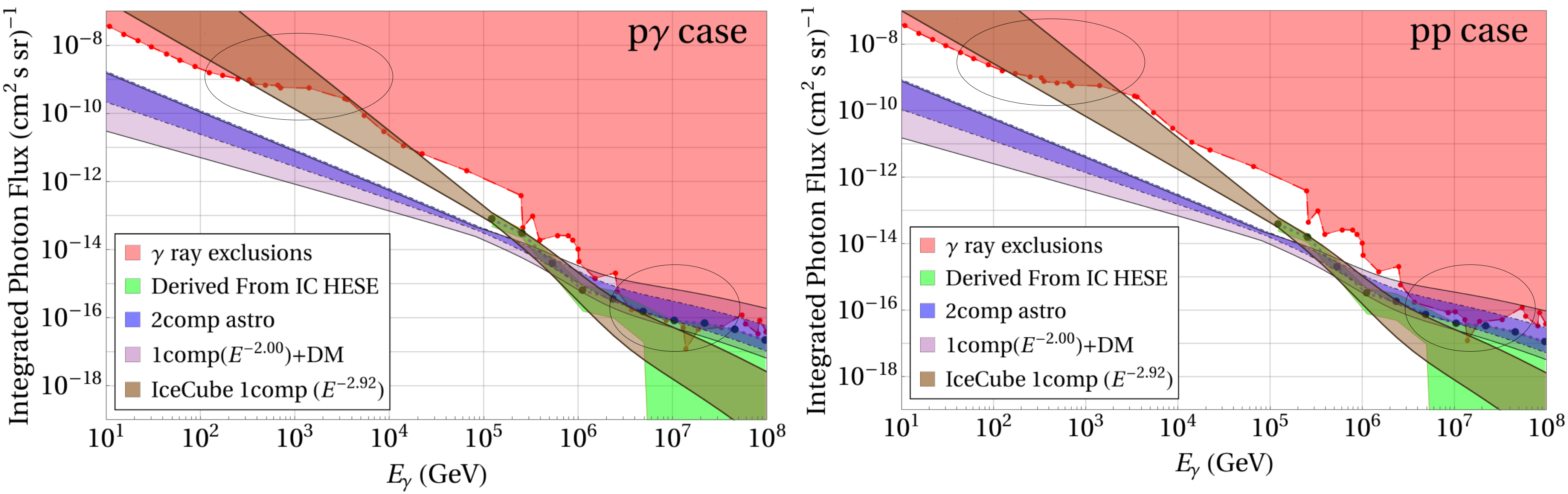

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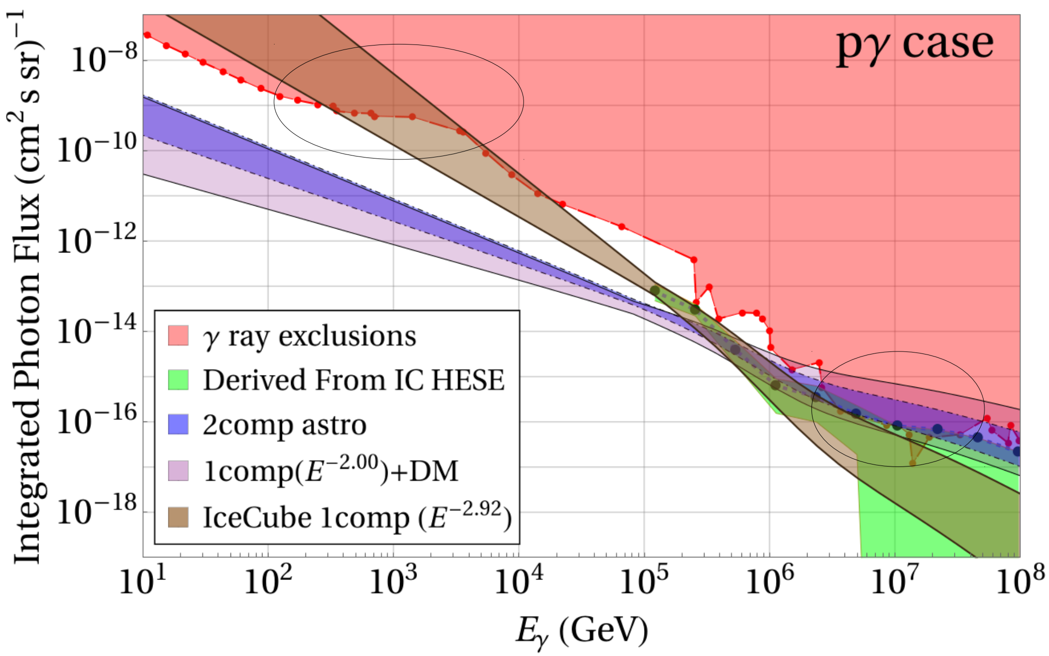

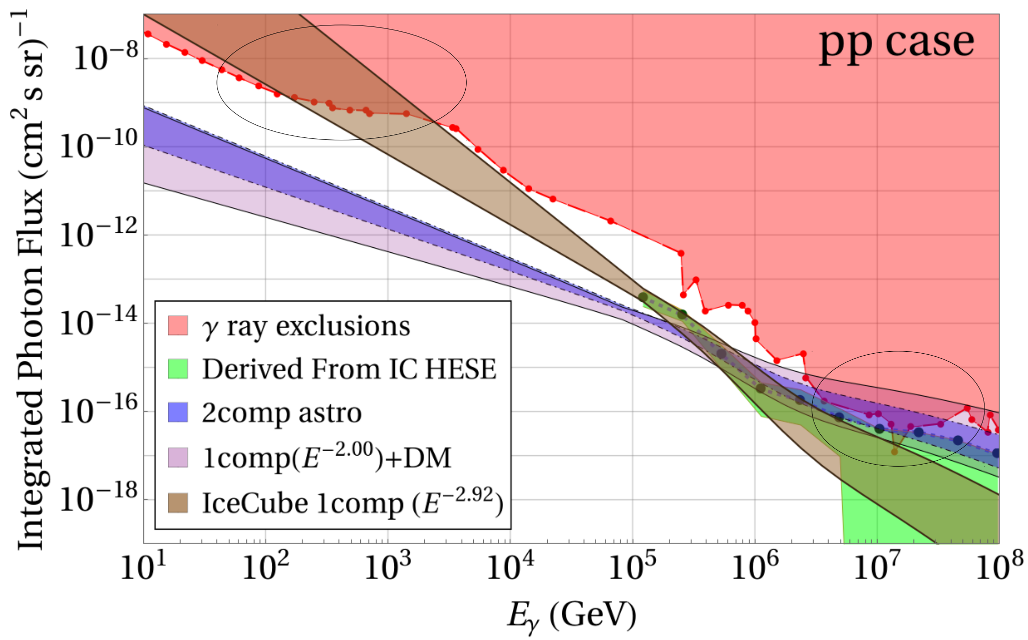

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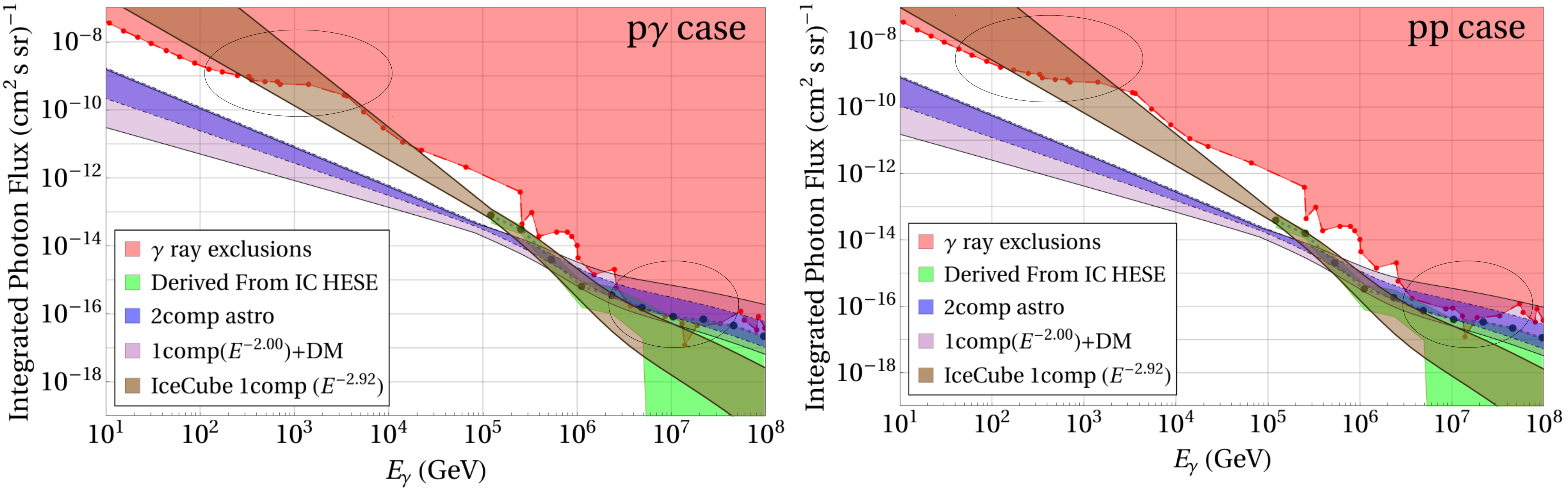
2. 2comp astro fit has some tension with the constraint, especially for p γ case

Verifying Best Fits with Photon Constraint

111 for both



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1. IceCube 1comp fit clearly violates the constraint

2. 2comp astro fit has some tension with the constraint, especially for p γ case

3. DM+1comp fit has more survival chance compared with 2comp astro fit

Conclusion

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1. It is possible to use 2 components flux to fit both HESE and TG data and we have considered two cases, each with 2 flavor compositions:

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Conclusion

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2. DM+1comp is more favored than 2comp case and, in each cases, (477) case is slightly favored than (111).

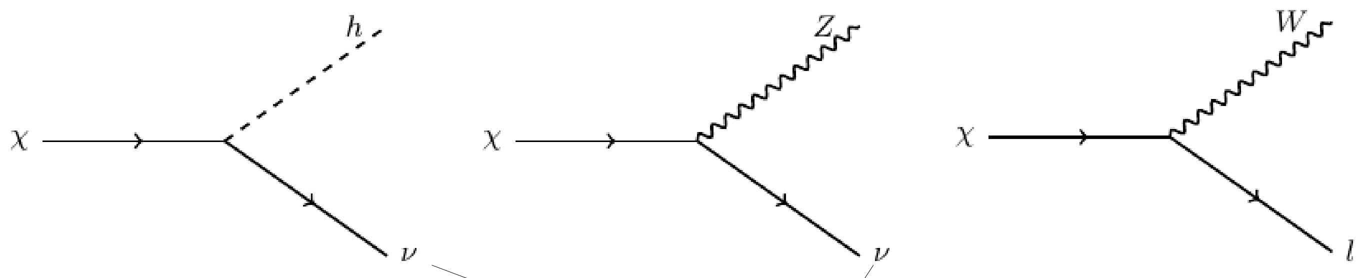
3. For DM+1comp, the astrophysical flux index comes out to be 2.

4. Compared with photon constraints, DM+1comp case also has more room to survive

Thank you!

Fermionic Dark Matter Decay

$$-\mathcal{L}_{\rm Y} \ = \ y_i \bar{L}_i \tilde{\phi} \chi + {\rm H.c}$$



Expand
after SSB

Providing almost monochromatic neutrinos

$$-\mathcal{L}_{\rm int} \ = V_{\ell\chi}\left(\frac{g}{\sqrt{2}}\,W^+_\mu\,\bar{\chi}\,\gamma^\mu P_L \ell^- + \frac{g}{2\,\cos\,\theta_w}\,Z_\mu\,\bar{\chi}\,\gamma^\mu P_L \nu_\ell + \frac{g \cdot M_{\rm DM}}{2\,M_W}\,h\,\bar{\chi} P_L \nu_\ell\right) + {\rm H.c.}$$

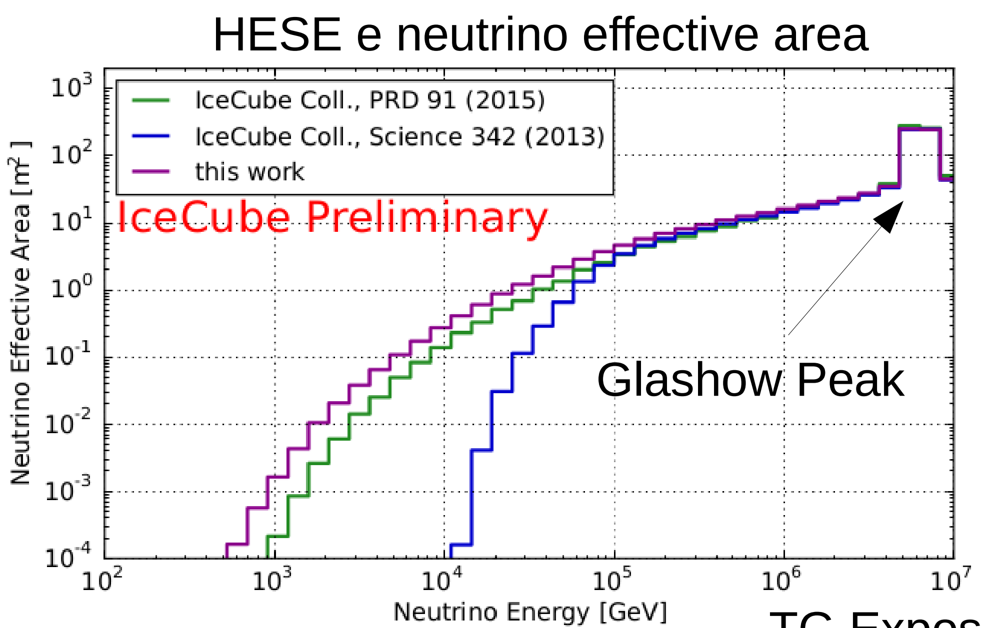
Neutrinos from the decay: Monochromatic parts $E_{\nu max} \approx \frac{M_{dm}}{2}$ + further decay products from h, Z and W

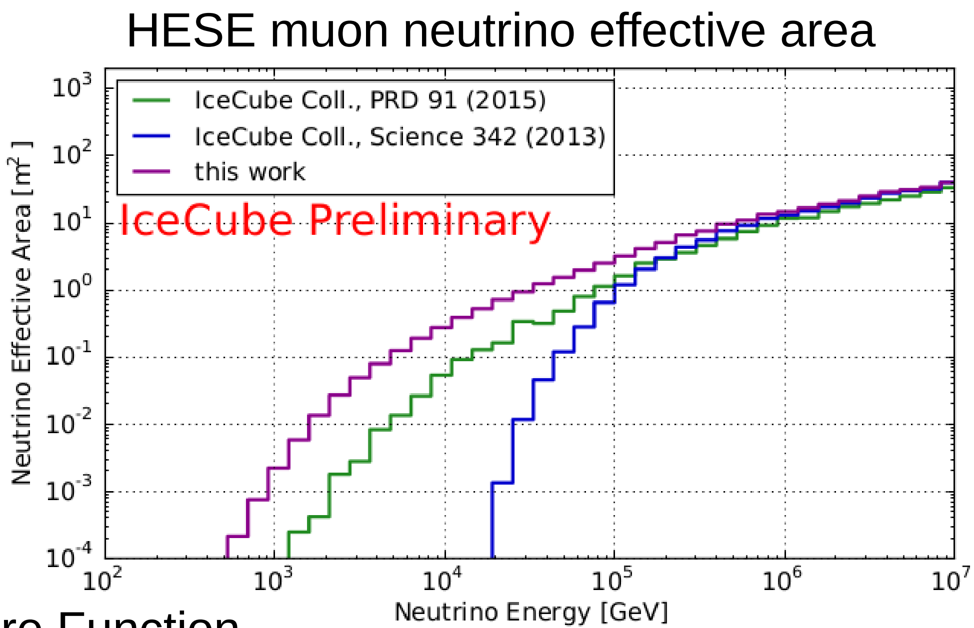
$$\Gamma_{\rm DM} \ \simeq \ \frac{3g^2}{16\pi}|V_{\ell\chi}|^2\frac{M_{\rm DM}^3}{M_W^2}$$

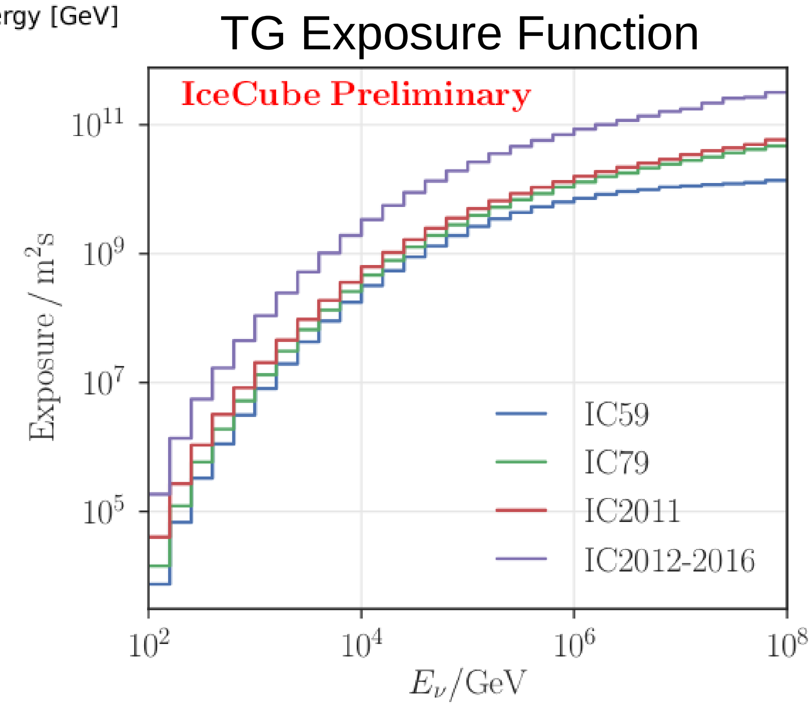
Mixing factors with different flavors, assumed to be the same for all flavors.

A.~Atre et al (JHEP '09)

Effective Area and Exposure Function







2 Comp Reconstruction

To simulate the IceCube data detecting process for our 2 comp neutrino flux, we need to reconstruct the neutrino flux into events.

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

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

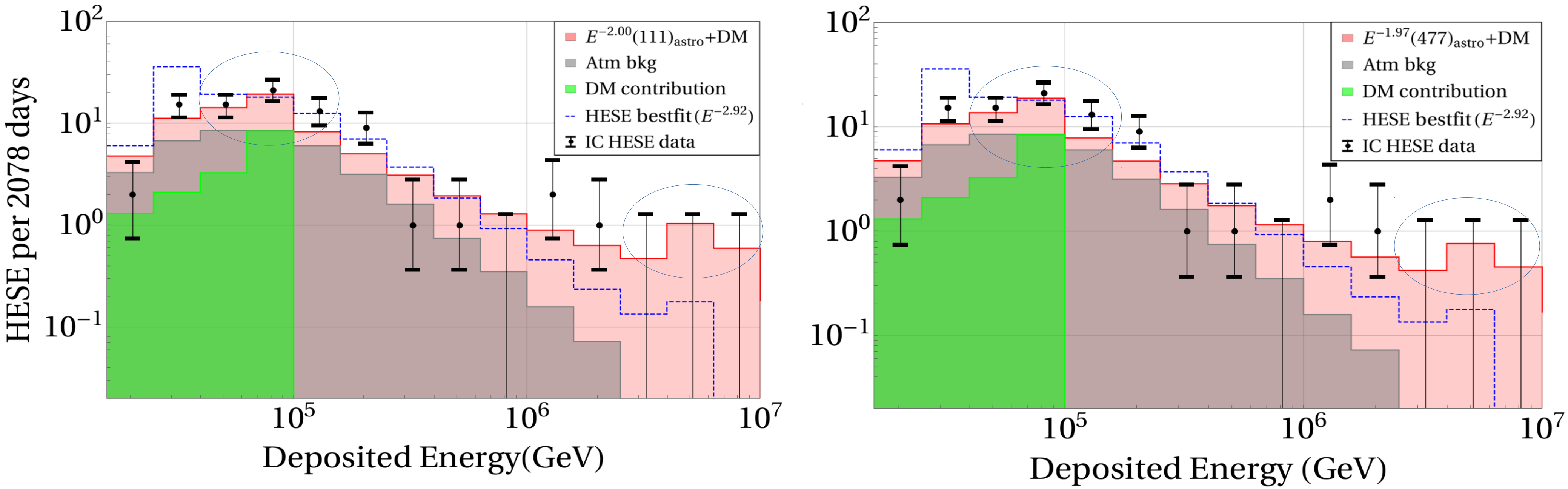
Decided by IceCube detector's configuration and run time

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

$F_{\nu_\ell}(E,\Omega)$: TG effective exposure function, effective area multiplied by time T

E for HESE is the deposited energy while E for TG is the median energy. Both are different but connected to real neutrino energy.

Best Fit Event Spectrum

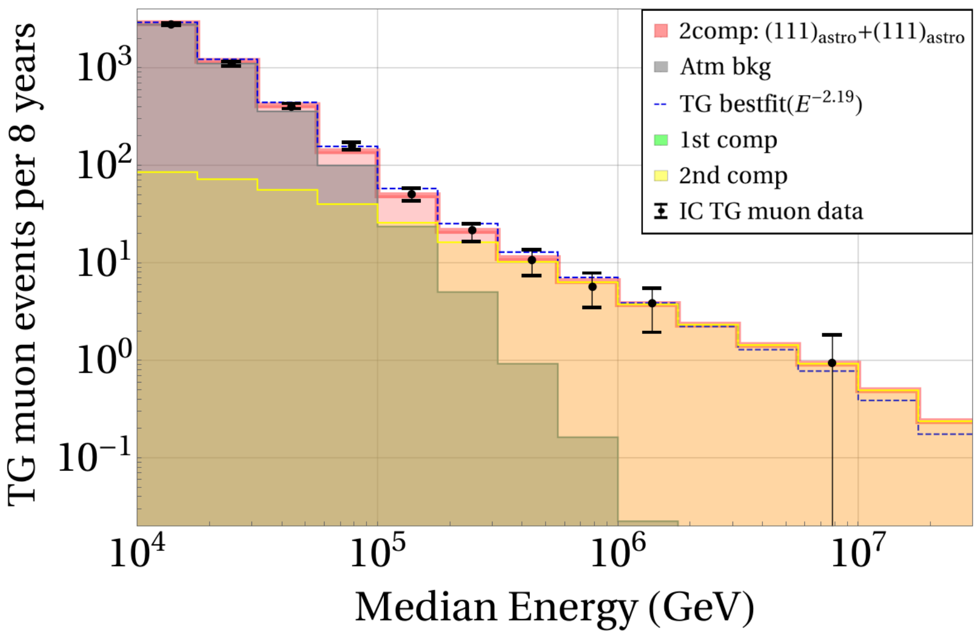


1. A DM component with a power law astrophysical component together could fit both HESE and TG data, with $M_{\rm DM} = 316^{+335}_{-125}\,\text{TeV}$, $\tau_{\rm DM} = 6.3^{+12.7}_{-2.3} \times 10^{28}\,\text{sec}$

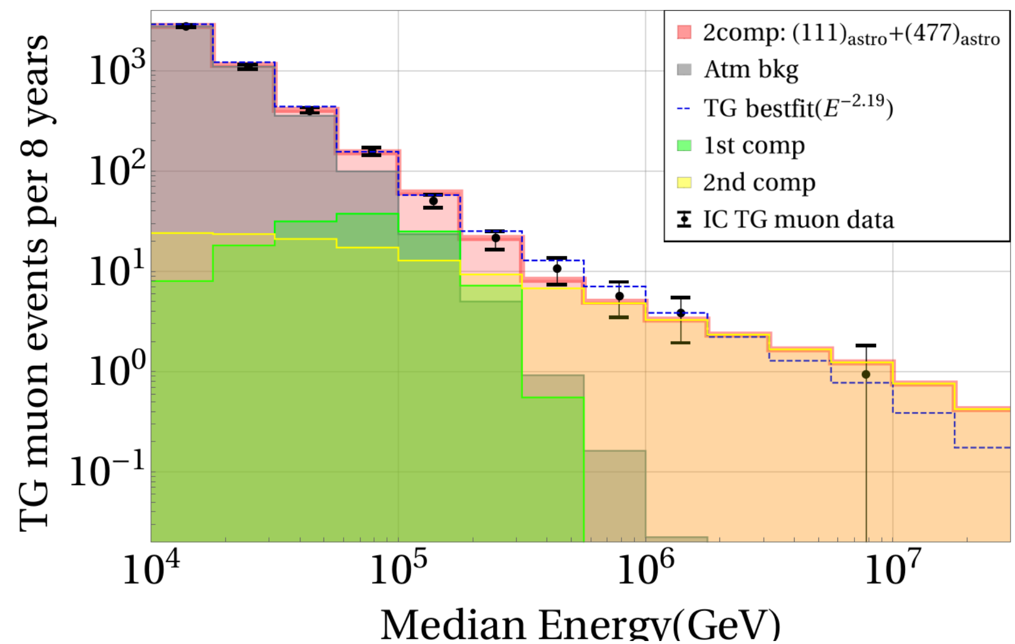
2. Power law's index best fit is 2

3. Statistically, 477 case is slightly better than 111 case.

TG Plots



2comp: $(111)_{astro}$+$(111)_{astro}$
Atm bkg
TG bestfit($E^{-2.19}$)
1st comp
2nd comp
IC TG muon data
TG muon events per 8 years
Median Energy (GeV)



2comp: $(111)_{astro}$+$(477)_{astro}$
Atm bkg
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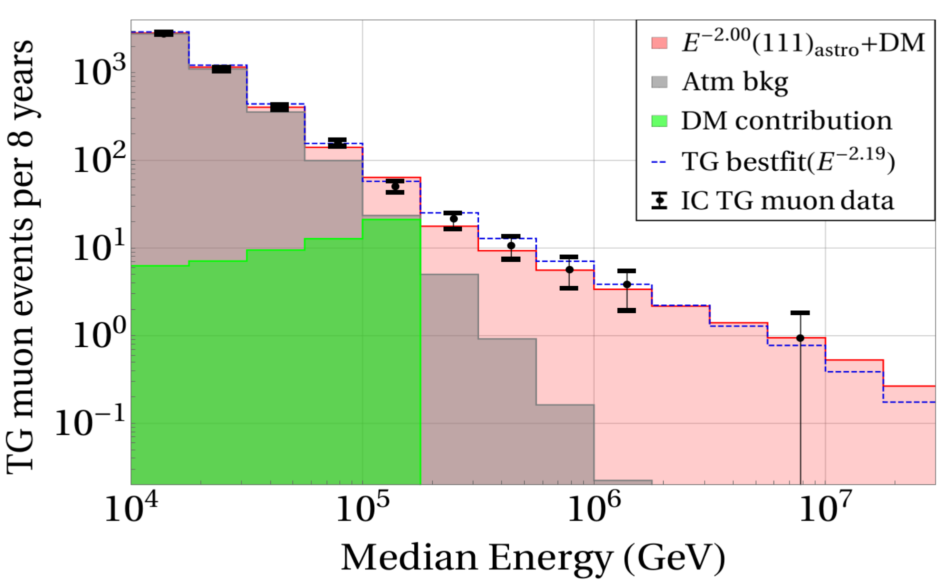
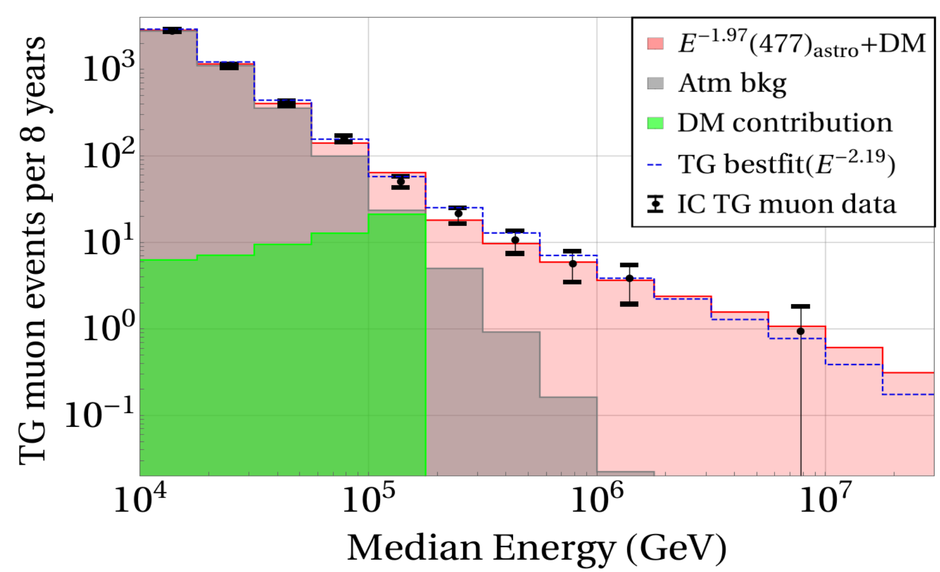


$E^{-2.00}(111)_{astro}$+DM
Atm bkg
DM contribution
TG bestfit($E^{-2.19}$)
IC TG muon data
TG muon events per 8 years
Median Energy (GeV)



$E^{-1.97}(477)_{astro}$+DM
Atm bkg
DM contribution
TG bestfit($E^{-2.19}$)
IC TG muon data
TG muon events per 8 years
Median Energy (GeV)

Neutrino Compositions At Source

	pp	pγ
Typical	$\nu_e : \nu_\mu : \nu_\tau : \bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau = \left(\frac{1}{6} : \frac{1}{3} : 0 : \frac{1}{6} : \frac{1}{3} : 0\right)$	$\nu_e : \nu_\mu : \nu_\tau : \bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau = \left(\frac{1}{3} : \frac{1}{3} : 0 : 0 : \frac{1}{3} : 0\right)$
μ damped	$\nu_e : \nu_\mu : \nu_\tau : \bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau = \left(0 : \frac{1}{2} : 0 : 0 : \frac{1}{2} : 0\right)$	$\nu_e : \nu_\mu : \nu_\tau : \bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau = (0 : 1 : 0 : 0 : 0 : 0)$

But, these are the ratios at source !!!

consider $f_e : f_\mu : f_\tau \equiv (\nu_e + \bar{\nu}_e) : (\nu_\mu + \bar{\nu}_\mu) : (\nu_\tau + \bar{\nu}_\tau)$

$$\begin{pmatrix} f_e \\ f_\mu \\ f_\tau \end{pmatrix}_{\oplus} = \frac{1}{18} \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix} \begin{pmatrix} f_e \\ f_\mu \\ f_\tau \end{pmatrix}_s$$

Assuming TBM Mixing, taking oscillation into account

	pp	pγ
Typical	(1 : 1 : 1)	(1 : 1 : 1)
μ damped	(4 : 7 : 7)	(4 : 7 : 7)

Propagation of Neutrinos in Vacuum

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle$$

PMNS Matrix, Similar to CKM matrix in quark mixing

$$|\nu_\alpha(L,T)\rangle = \sum_\beta \left(\sum_{k=1}^{3} U^*_{\alpha k} e^{-iE_k T + i p_k L} U_{\beta k} \right) |\nu_\beta\rangle$$

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2Re \sum_{k>j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E} \right)$$

Averaged out for large L

consider $f_e : f_\mu : f_\tau \equiv (\nu_e + \bar{\nu}_e) : (\nu_\mu + \bar{\nu}_\mu) : (\nu_\tau + \bar{\nu}_\tau)$

$$\begin{pmatrix} f_e \\ f_\mu \\ f_\tau \end{pmatrix}_{\oplus} = \frac{1}{18} \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix} \begin{pmatrix} f_e \\ f_\mu \\ f_\tau \end{pmatrix}_s$$

Assuming TBM Mixing

	pp	pγ
Typical	(1 : 1 : 1)	(1 : 1 : 1)
μ damped	(4 : 7 : 7)	(4 : 7 : 7)

Relation Between Ereal, Edep and Emedian

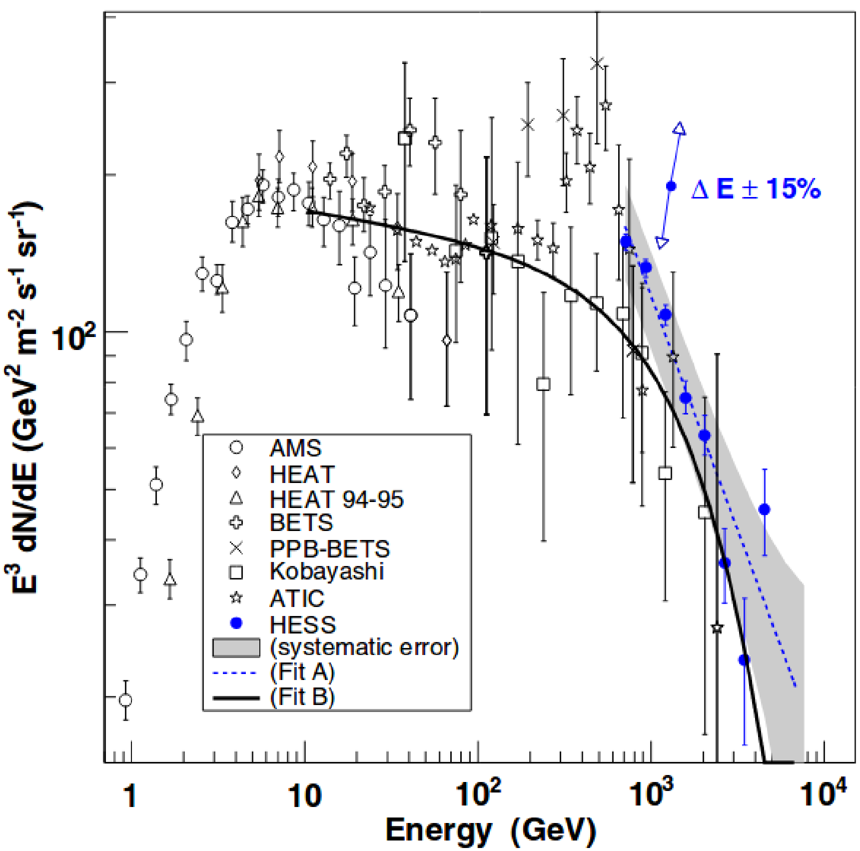
Ereal → Edep → Erec → E median

Ereal	Edep	Erec	E median
Real energy	This neutrino store this amount of energy in the facility	Using Edep and some technique to try to get the real energy, but this normally is different from real energy.	Median value of Erec

E real typically is linear to Edep and Erec. But for track, Erec could be very uncertain since the deposited energy for tracks are typically far less than real energy, so relation between E real and Erec is more of an estimation. Thus E real and Emedian’s relation is also a rough estimation

Constraints From H.E.S.S?

At around TeV level, the constraints from H.E.S.S is around 10^-5 E^2 * phi, while the constraints we have from Fermi LAT and HAWC is around 10^-6 to 10^-7, a better lower constraint than H.E.S.S



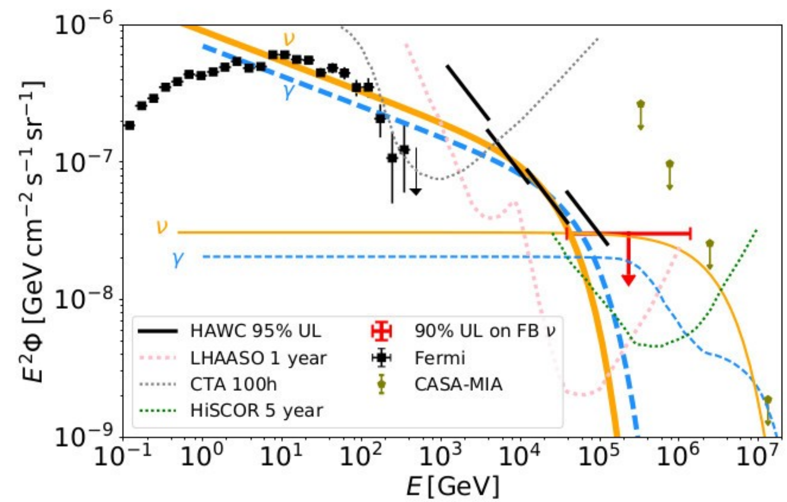


FIG. 3: The modeled intensity and spectrum of the neutrino and γ-ray emission produced by hadronic interactions in the *Fermi* bubbles. We show the predicted γ-ray (blue dashed) and all-flavor neutrino (orange solid) spectrum for our models of hadronic *Fermi* bubbles production (thick lines), as well as the hadronic fraction of our hybrid leptonic-hadronic model (thin lines). Details of the models are given in Section III. We note that the γ-ray spectrum in our leptonic-hadronic model receives additional contributions from the interactions of primary electrons, which are not shown here. We compare our results to γ-ray observations of the *Fermi* bubbles by the Fermi-LAT at GeV energies (black squares), the 95% confidence upper limits on the TeV γ-ray flux recorded by HAWC (black solid bars), the 90% confidence upper limits on ultrahigh-energy gamma rays by CASA-MIA scaled to the bubbles region (olive upper limits; [23, 32]), and the 90% confidence upper limit on the neutrino flux at TeV—PeV energies as calculated in this work (red upper limit). We additionally show the projected sensitivity from 100 hr of CTA observations (grey dotted; [33]), 5 yr of HiSCOR observations (green dotted; [34]), and 1 yr of LHASSO observations (pink dotted; [35]) in the region of the *Fermi* bubbles. In the hadronic scenario (thick lines), the maximum neutrino flux allowed by the Fermi-LAT and HAWC measurements does not produce a significant IceCube flux at high neutrino energies. However, in the hybrid leptonic-hadronic scenario (thin lines), the spectral index of the sub-dominant γ-ray component can be extremely hard, producing a bright neutrino flux detectable by IceCube. We note that the IceCube upper limit is calculated over a wide energy bin, and a significant number of neutrinos are observed at energies exceeding ~100 TeV where the flux in the pure hadronic model is negligible.

$$E_\gamma^2 \Phi_\gamma \approx \frac{4}{K}(E_\nu^2 \Phi_{\nu_i}) \mid_{E_\nu = 0.5 E_\gamma}$$

$$p\ p \to \pi^0\ \pi^+\ \pi^-$$

$$\pi^0 \to \gamma\ \gamma \qquad \pi^+ \to e\ 2\nu_\mu\ \nu_e \qquad \pi^- \to e\ 2\nu_\mu\ \nu_e$$

Same amount of 3 pions, and they have approximately same energy:

$$E_\gamma = 1/2 E_\pi \qquad \Delta N_\pi \doteq \Delta N_{\pi^+} = \Delta N_{\pi^-} = \Delta N_{\pi^0}$$

$$E_{\pi^+} = E_{\pi^-} = E_{\pi^0} = E_\pi$$

$$E_\nu = 1/4 E_\pi$$

1 pion goes to 4 leptons,share share the E

$$\Delta N_\pi = \int_{E_{\pi 1}}^{E_{\pi 2}} \frac{dN_\pi}{dE_\pi} \cdot dE_\pi$$

$$\frac{dN_\gamma}{dE_\gamma} \mid_{E_\gamma = E_\pi/2} = 4 \frac{dN_\pi}{dE_\pi} \mid_{E_\pi}$$

Derivative for Epi2

(1)

$$= 1/2 \Delta N_\gamma = 1/2 \int_{E_{\gamma 1} = 1/2 E_{\pi 1}}^{E_{\gamma 2} = 1/2 E_{\pi 2}} \frac{dN_\gamma}{dE_\gamma} \cdot dE_\gamma$$

(2)

$$N_{\nu_e} : N_{\nu_\mu} : N_{\nu_\tau} = 1 : 2 : 0$$

oscillation

$$N_{\nu_e} \mid_{earth} : N_{\nu_\mu} \mid_{earth} : N_{\nu_\tau} \mid_{earth} = 1 : 1 : 1$$

$$N_{\nu_e} \mid_{earth} = N_{\nu_\mu} \mid_{earth} = N_{\nu_\tau} \mid_{earth} \doteq N_\nu = N_{\nu_e}$$

$$\frac{dN_\nu}{dE_\nu} \mid_{E_\nu = 1/4 E_\pi} = 8 \frac{dN_\pi}{dE_\pi} \mid_{E_\pi}$$

Derivative for Epi2

$$2\Delta N_\pi = \Delta N_\nu$$

$$\frac{dN_\nu}{dE_\nu} \mid_{E_\nu = 1/4 E_\pi} = 2 \frac{dN_\gamma}{dE_\gamma} \mid_{E_\gamma = 1/2 E_\pi} \longrightarrow 2E_\nu^2 \frac{dN_\nu}{dE_\nu} \mid_{E_\nu = 1/4 E_\pi} = E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \mid_{E_\gamma = 1/2 E_\pi}$$

$$E_\gamma^2 \Phi_\gamma \approx \frac{4}{K}(E_\nu^2 \Phi_{\nu_i}) \,|_{E_\nu = 0.5 E_\gamma}$$

Same amount of 3 pions, and they have approximately same energy:

$$p\,\gamma \rightarrow \begin{cases} 2/3 \quad p\,\pi^0 \\ 1/3 \quad n\,\pi^+ \end{cases}$$

$$2\Delta N_{\pi^+} = \Delta N_{\pi^0}$$

$$E_\gamma = 1/2 E_\pi$$

$$E_{\pi^+} = E_{\pi^-} = E_{\pi^0} = E_\pi$$

$$E_\nu = 1/4 E_\pi$$

1 pion goes to 4 leptons,share share the E

$$\Delta N_{\pi^0} = \int_{E_{\pi 1}}^{E_{\pi 2}} \frac{dN_{\pi^0}}{dE_\pi} \cdot dE_\pi \quad (1)$$

$$= 1/2 \Delta N_\gamma = 1/2 \int_{E_{\gamma 1} = 1/2 E_{\pi 1}}^{E_{\gamma 2} = 1/2 E_{\pi 2}} \frac{dN_\gamma}{dE_\gamma} \cdot dE_\gamma \quad (2)$$

pi0

$$\frac{dN_\gamma}{dE_\gamma} \,|_{E_\gamma = E_{\pi^0}/2} = 4 \frac{dN_{\pi^0}}{dE_{\pi^0}} \,|_{E_\pi}$$

Derivative for Epi2

$$2\Delta N_{\pi^+} = \Delta N_{\pi^0}$$

$$N_{\nu_e} : N_{\nu_\mu} : N_{\nu_\tau} = 1 : 2 : 0$$

oscillation

$$N_{\nu_e} \,|_{earth} : N_{\nu_\mu} \,|_{earth} : N_{\nu_\tau} \,|_{earth} = 1 : 1 : 1$$

$$N_{\nu_e} \,|_{earth} = N_{\nu_\mu} \,|_{earth} = N_{\nu_\tau} \,|_{earth} \doteq N_\nu = N_{\nu_e}$$

Due to only pi+,no pi-

pi+

$$\frac{dN_\nu}{dE_\nu} \,|_{E_\nu = 1/4 E_{\pi^+}} = \boxed{4} \frac{dN_{\pi^+}}{dE_{\pi^+}} \,|_{E_\pi}$$

Derivative for Epi2

$$\Delta N_{\pi^+} = \Delta N_\nu$$

$$\boxed{2} \frac{dN_\nu}{dE_\nu} \,|_{E_\nu = 1/4 E_\pi} = \boxed{} \frac{dN_\gamma}{dE_\gamma} \,|_{E_\gamma = 1/2 E_\pi} \longrightarrow \boxed{8}$$

Twice more than Murase's Formula, I think he tokk pi0 and pi+ to have same amount

Details of goodness of fit

- goodness of fit test:

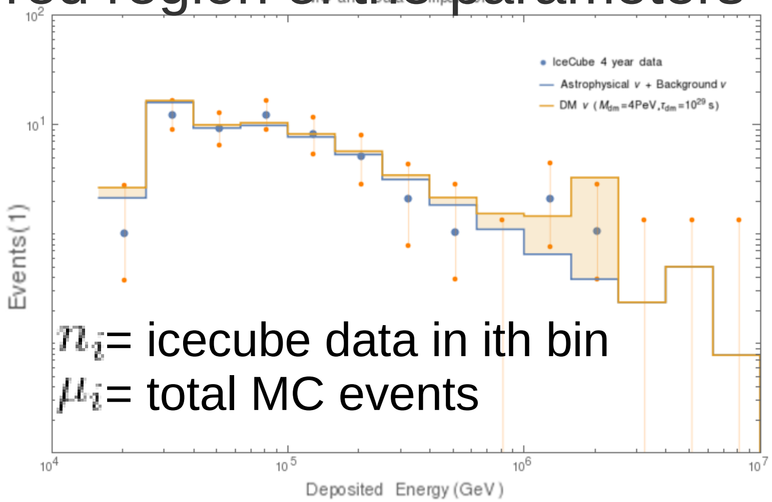
We use this statistical method to provide favored region of the parameters

For binned data, we could take it as Poisson distribution:

$$L(\theta) = f_P(n;\theta) = \prod_{i=1}^{n} \frac{\mu_i^{n_i}}{n_i!} e^{-\mu_i} \qquad \theta = (M_{dm}, \tau_{dm})$$

The likelihood ratio is:

$$\lambda(\theta) = \frac{f_P(n;\theta)}{f(n;\hat{\mu})} \qquad \text{where} \qquad \hat{\mu} = (n_1, n_2, ..., n_N)$$



n_i= icecube data in ith bin
μ_i= total MC events

We choose the test statistic as:

$$TS = -2ln(\lambda(\theta)) = 2\sum_{i=1}^{N}[\mu_i(\theta) - n_i + n_i ln\frac{n_i}{\mu_i(\theta)}]$$

TS will be a function of theta and thus we could find out the region that is statistically favored

To acquire the TS distribution of Mdm and tdm, we perform a grid calculation:

Mdm=(0.1, 0.2,…,10)PeV

Tdm=10^(1,1.03,1.06,…,3)*10^27 s