New Physics in Supernovae and IceCube Flavor Ratios

based on :
VB, J. Kopp, J. Liu arXiv:1607.04278
VB, J. Kopp, X. Wang, in preparation

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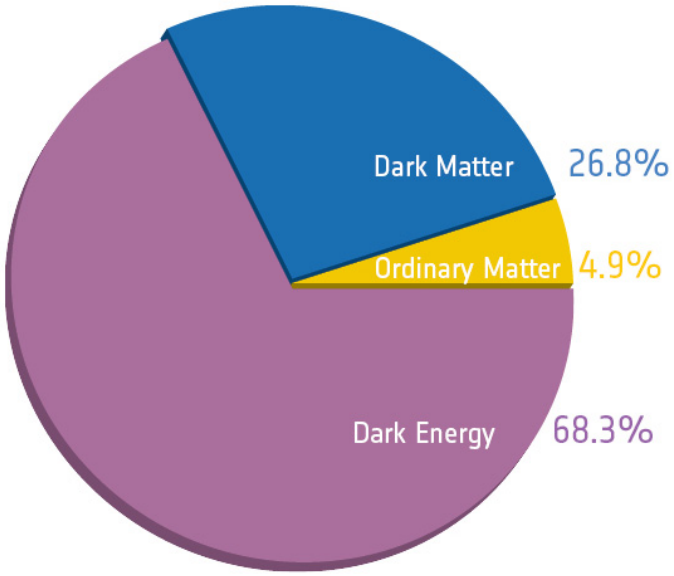
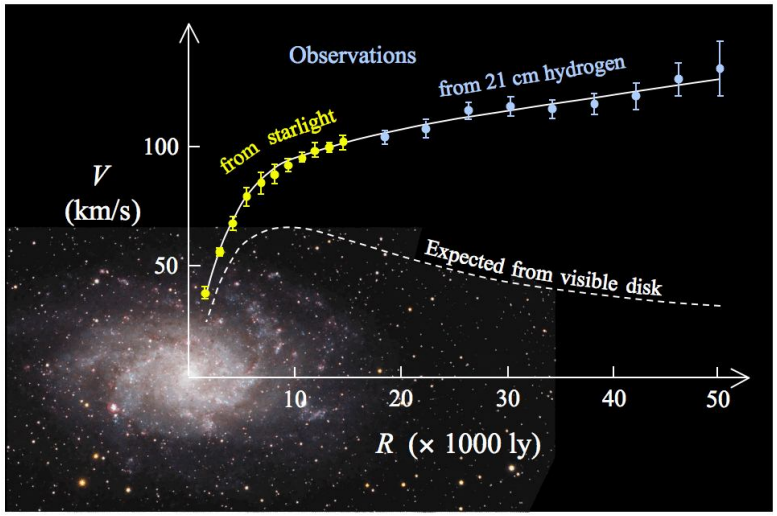
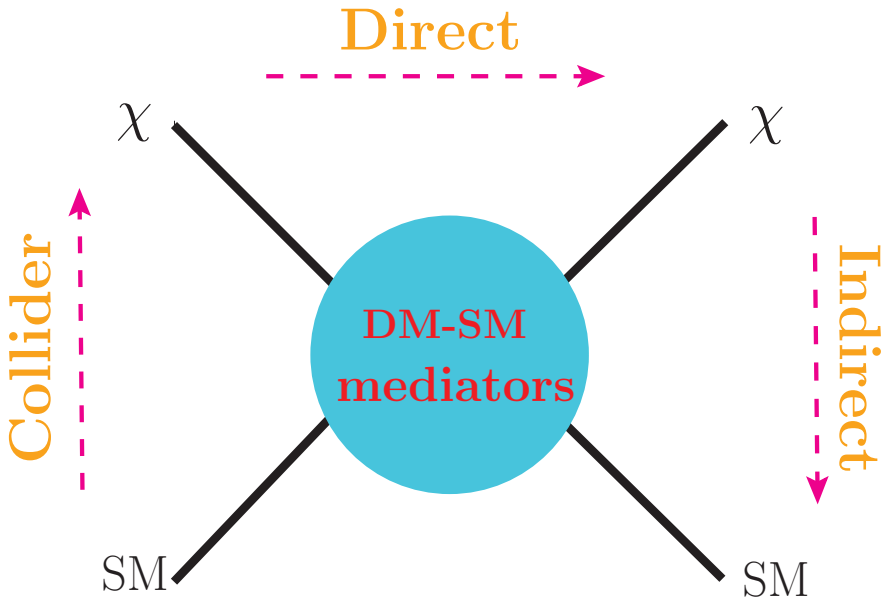
Dark Matter - the mystery of this century





- not charged under $U(1)_{EM}$ and $SU(3)_C$
- stable or long lived
- not in SM particle list

Dark Matter Searches



- Direct detection
  - nuclear recoils from DM scattering
- Collider searches
  - typical signal: missing energy + mono object
- Indirect detection
  - classified by annihilation product: γ, ν, e^+...

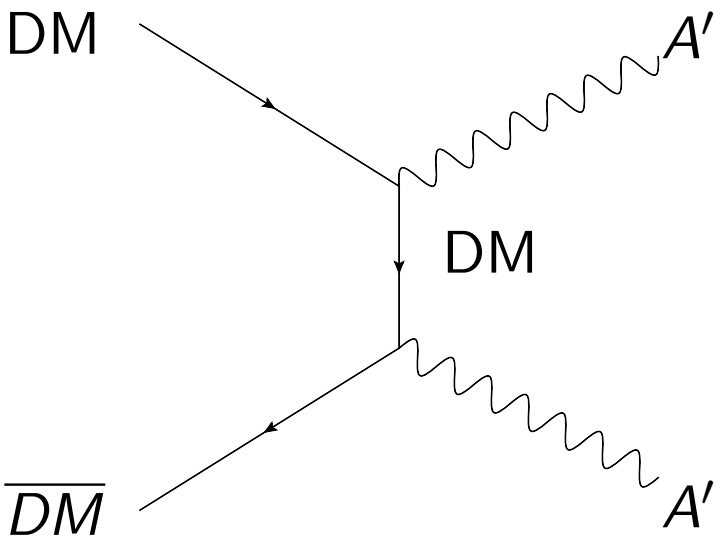
DM annihilation in the Sun

Capture and Annihilation ($dN/dt = C_{cap} - C_{ann}N^2$)

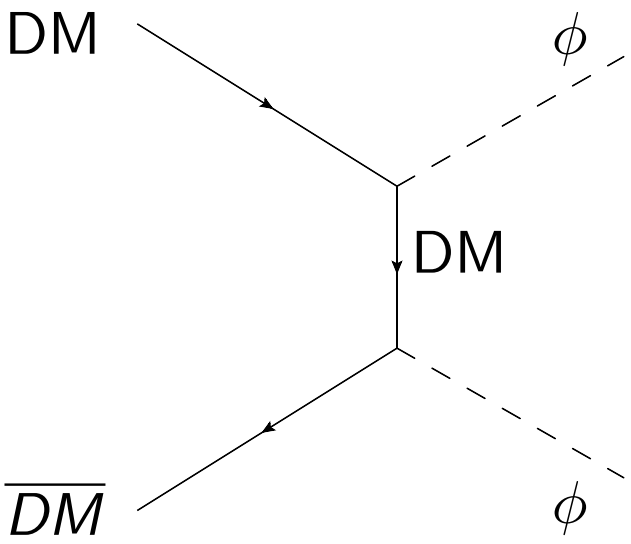
1. Conditions:
   - $C_{ann}^{\rm Sun} \equiv \frac{1}{N^2}\int d^3r\, \langle\sigma v_{\rm rel}\rangle\, n_{\rm DM}^2(r) \sim 10^{-53}s^{-1}$
   - $C_{cap} = \sum_i \int_0^{R_{\rm star}} dr\, 4\pi r^2\, \frac{dC_i(r)}{dV} \sim 10^{22}s^{-1}$
   - parameters: $m_{DM} = 100\,GeV$, $\sigma_{SD}^H = 10^{-40}cm^2$ and $\langle\sigma v_{\rm rel}\rangle = 3\times 10^{-26}cm^3s^{-1}$
2. Results:
   - $N(t) = \sqrt{\frac{C_{cap}}{C_{ann}}}\tanh\frac{t}{t_{eq}} \to \sqrt{\frac{C_{cap}}{C_{ann}}} \sim 10^{37}$
   - $t_{eq} \equiv 1/\sqrt{C_{cap}C_{ann}} \sim 10^{15}s$, $t_{Sun} = 10^{17}s$
   - $C_{ann}N^2 = C_{cap} = 10^{22}s^{-1}$
3. Conclusion: **For the case of the Sun, there is an equilibrium!**

BSM particle content

- fermionic (Dirac) DM $\sim$ (1,1,0)
- $\sim \mathcal{O}(1)$ GeV dark photon or scalar coupling to
  - DM
  - SM via kinetic mixing (vector) or higgs portal (scalar)

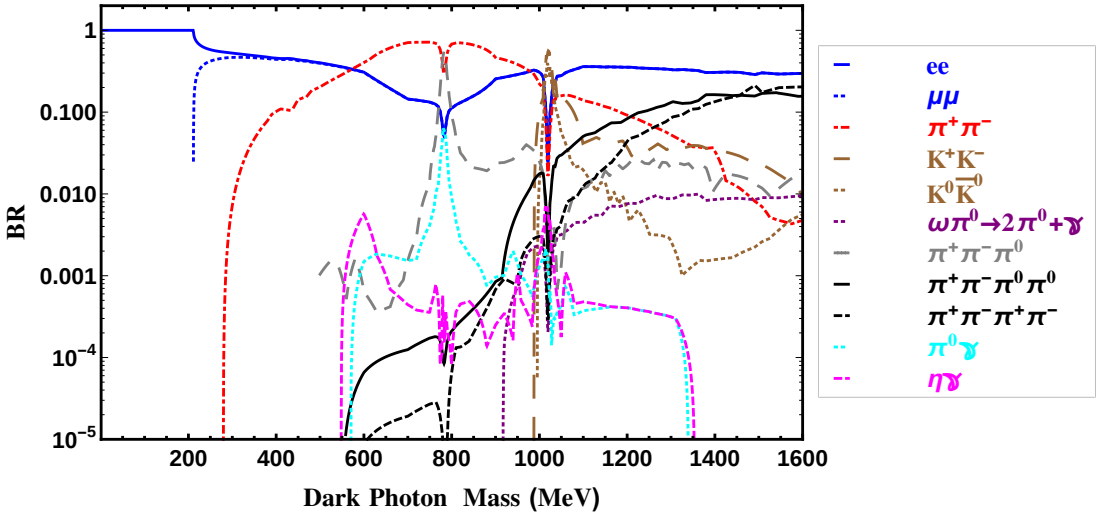


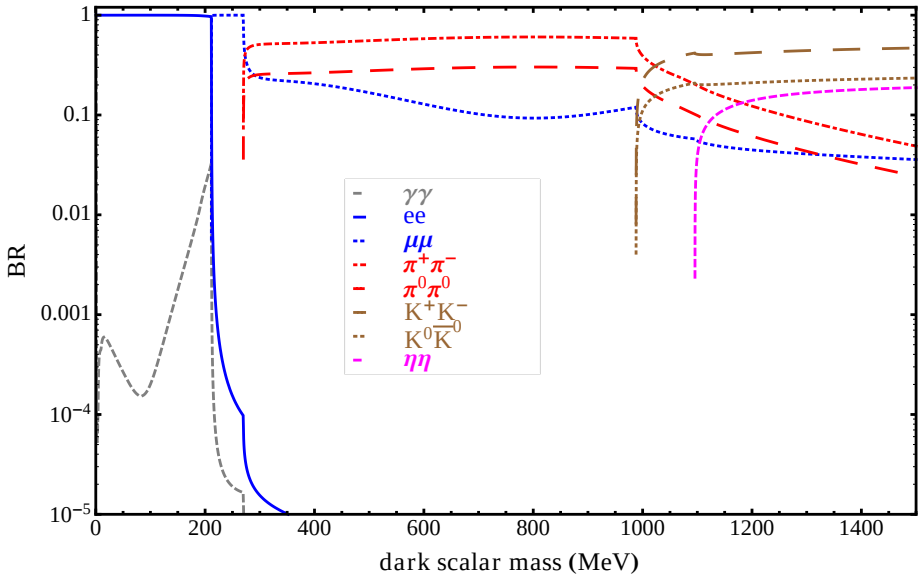
s-wave



p-wave

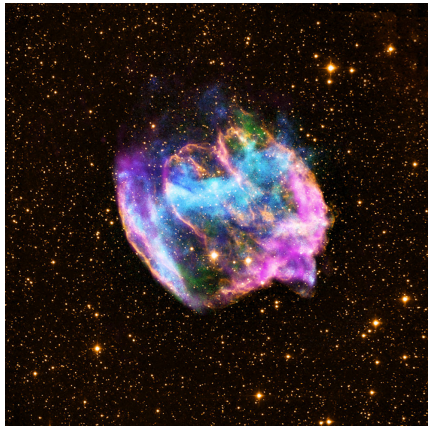
Decay modes of dark mediators





Liu,Weiner, Xue, arXiv:1412.1485

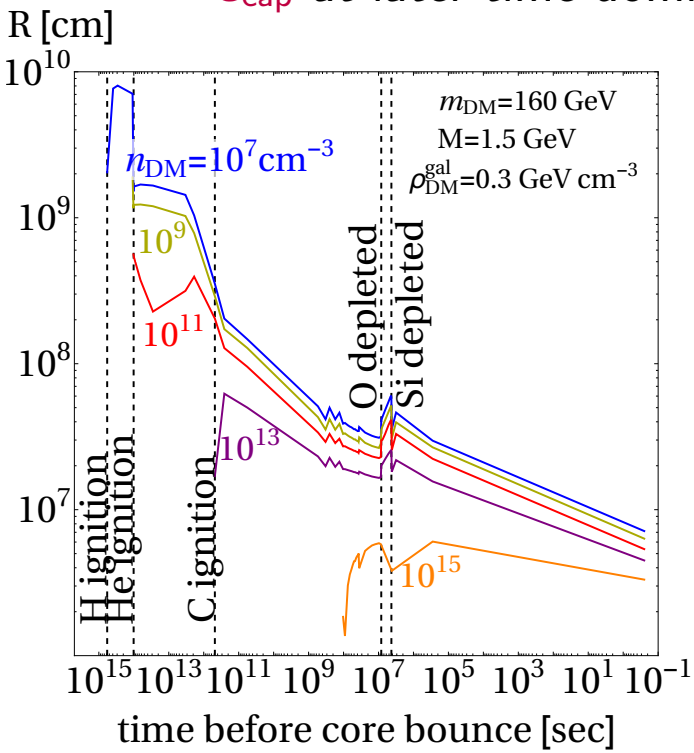
Supernova progenitors versus the Sun

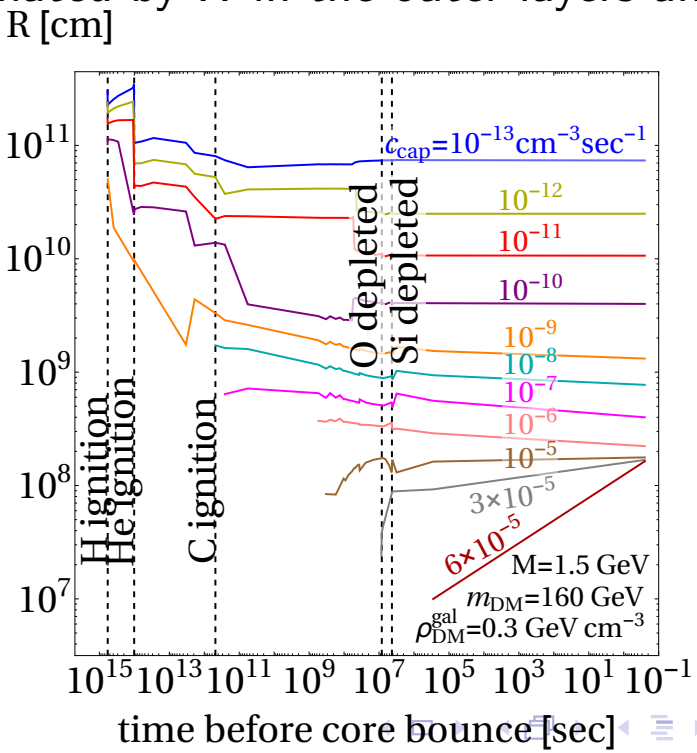


- $\mathcal{O}(10^8)$ further than the Sun, $\sim 1kpc$
- much heavier than the Sun, $\gtrsim 8M_{Sun}$
- $\mathcal{O}(10^{-2})$ shorter lifetime $\sim 10^{15}s$
- density, temperature and chemical composition change in time much faster
- End up with a core collapse Supernova
- Peak annihilation rate (dark gamma ray burst coincident with the supernova) $\mathcal{O}(10^{12})$ larger than the Sun!
- Capture and Annihilation *Not* in Equilibrium!

Capture Rates and DM Distribution in the Star

- $\rho_i(r,t), T(r,t)$ and chemical composition from Heger *et al.*
- $m_{DM} \in [10, 10^3]$ GeV, $\sigma^{SD} = 10^{-40} cm^2$, $\sigma^{SI} = 10^{-46} cm^2$
- DM core contracts along with the baryonic matter
- Quasi-instantaneous thermalization ($n_{\rm DM}(r) = n_0 \exp[-m_{\rm DM}\phi(r)/T_{\rm DM}]$)
- Large $C_{\rm cap}$ at early times due to large σ_{SD} on H
- $C_{\rm cap}$ at later time dominated by H in the outer layers and ^{14}N

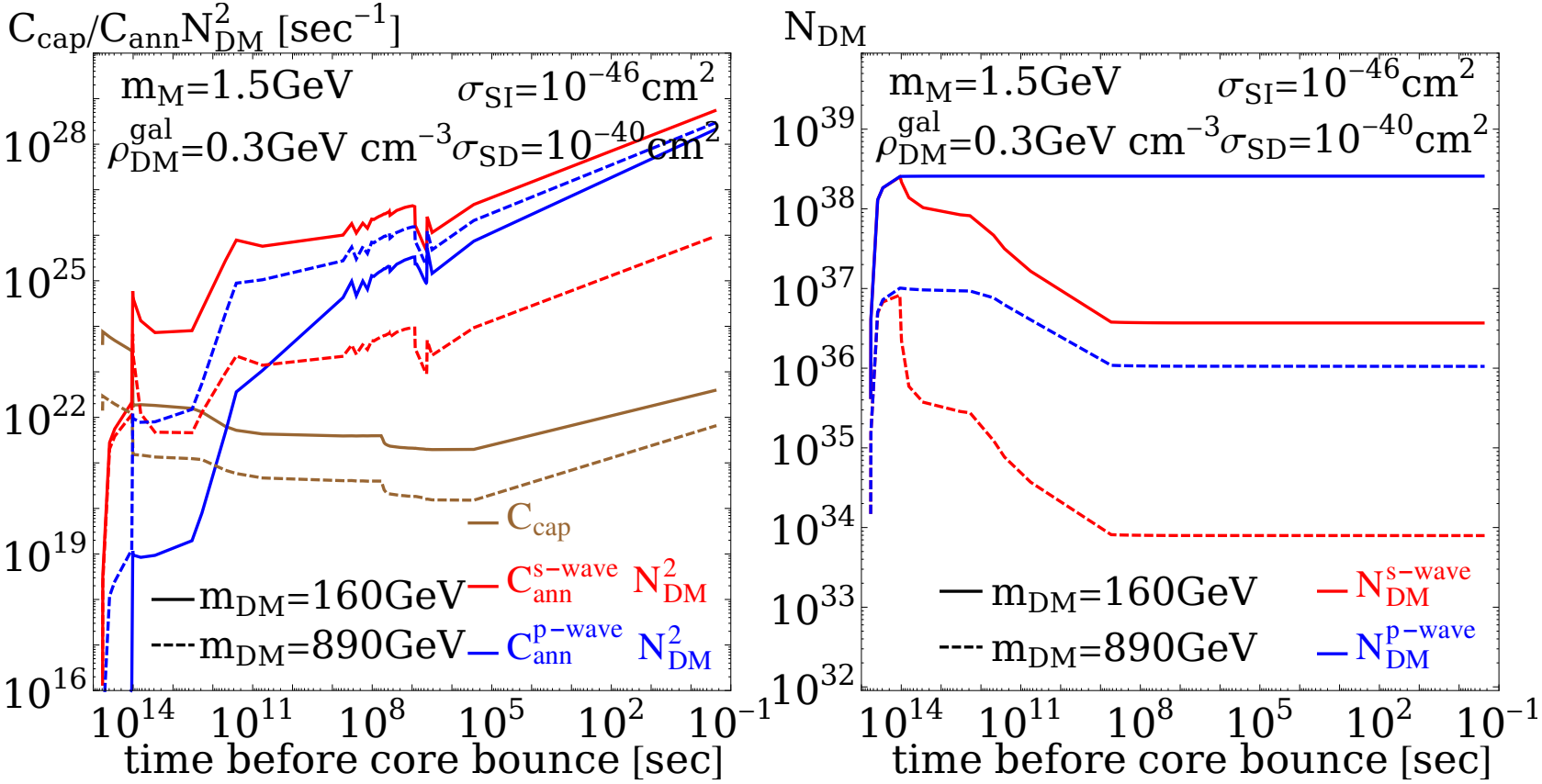




Capture and Annihilation Rates

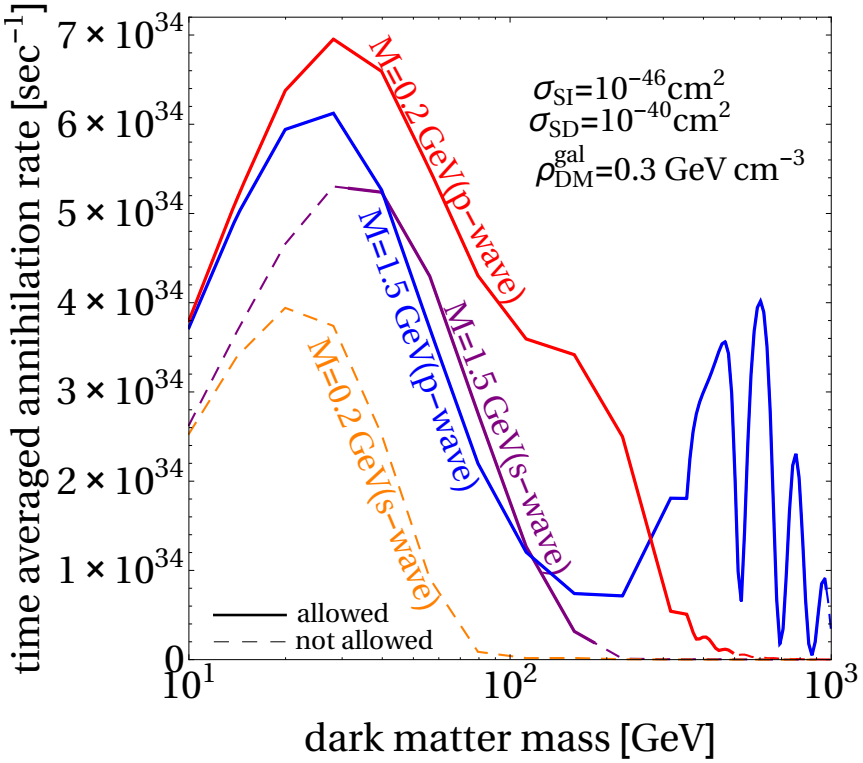
$$\dot{N}_{\rm DM}(t) = C_{\rm cap}(t) - C_{\rm ann}(t) N_{\rm DM}(t)^2 + C_{\rm self}(t) N_{\rm DM}(t)$$

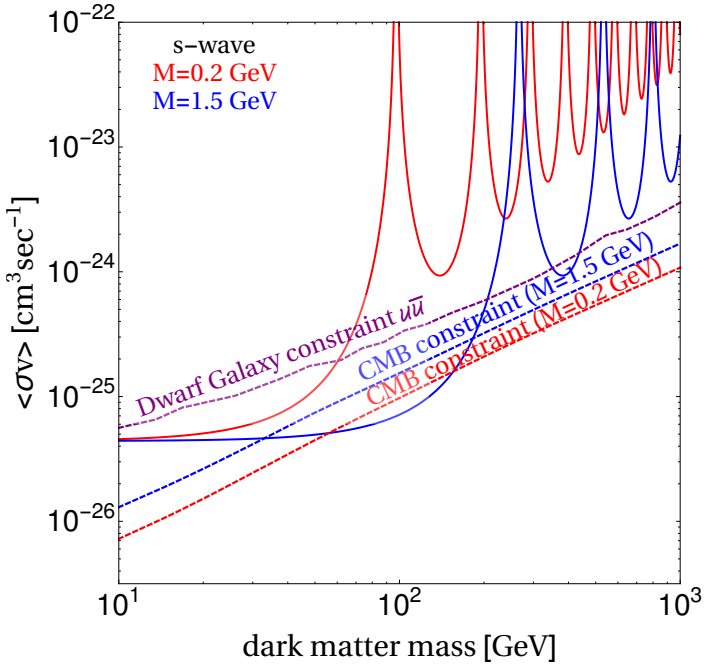
$$C_{\rm cap} = \sum_i \int_0^{R_{\rm star}} dr\, 4\pi r^2 \frac{dC_i(r)}{dV} \qquad C_{\rm ann} N_{\rm DM}^2 \equiv \int d^3 r\, \langle \sigma v_{\rm rel} \rangle\, n_{\rm DM}^2(r)$$



DM Annihilation Burst during Supernova cooling phase

- density and temperature fixed to 10^{14} g cm^{-3} and 3 MeV
- DM particles within $R_{core} \sim 30km$ (size of proto-neutron star)
- DM gets thermalized within $\sim 10^{-6}$ seconds
- $N_{\rm DM}(t) = \frac{N_0}{1+t\, C_{\rm ann}^{SN} N_0}$ $\quad \Delta t_{dur} \sim (C_{\rm ann}^{SN} N_0)^{-1}$ $\quad C_{\rm ann}^{SN} = \langle \sigma v_{\rm rel} \rangle \left(\frac{G_N m_{\rm DM} \rho_{\rm SN}}{3 T_{\rm SN}} \right)^{3/2}$

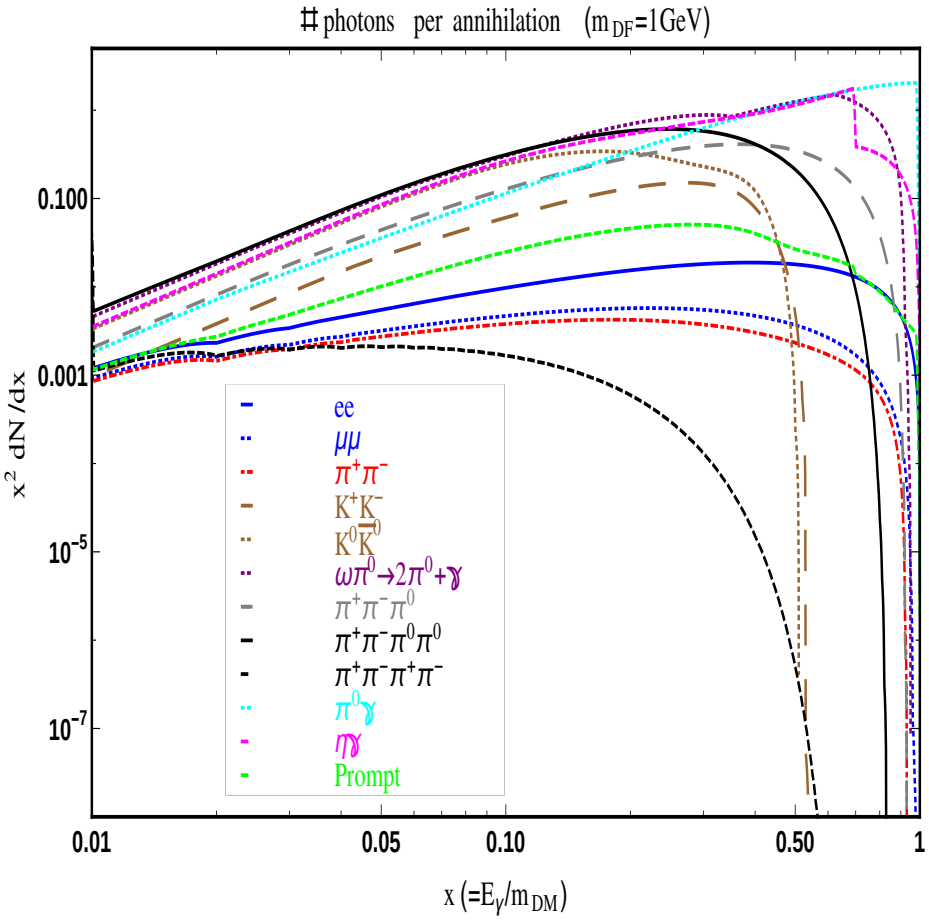




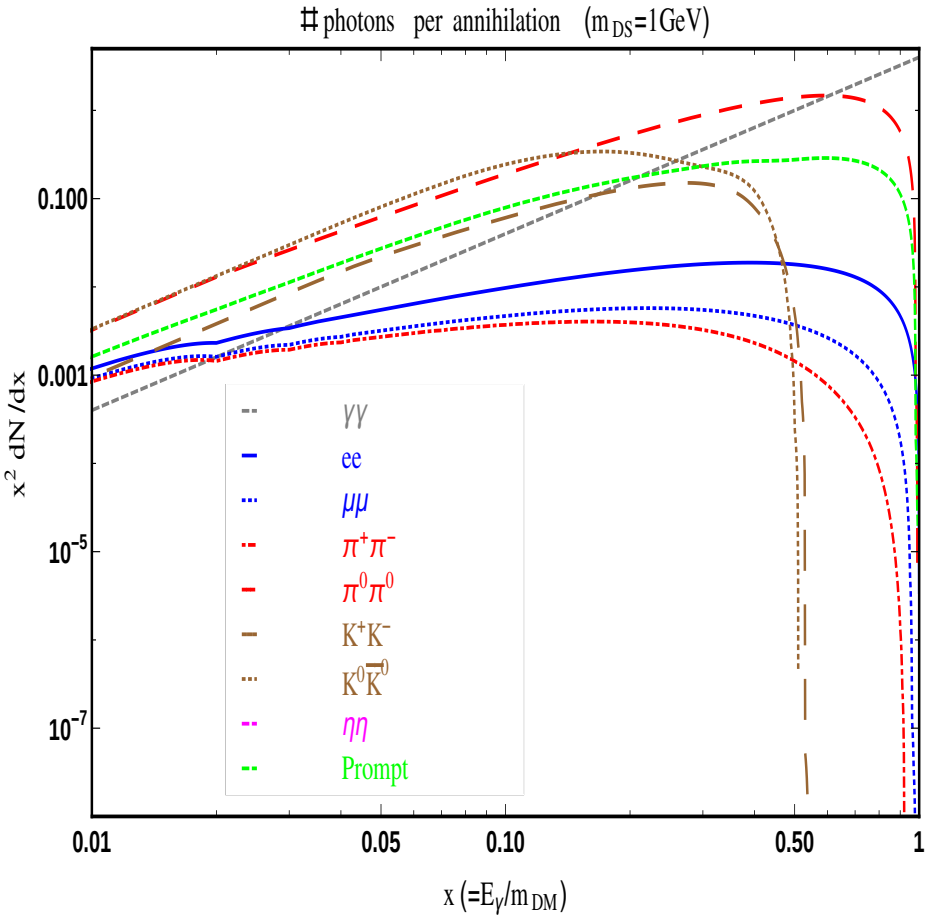
Photon Spectrum

Liu,Weiner, Xue, arXiv:1412.1485

dN/dx for dark photon



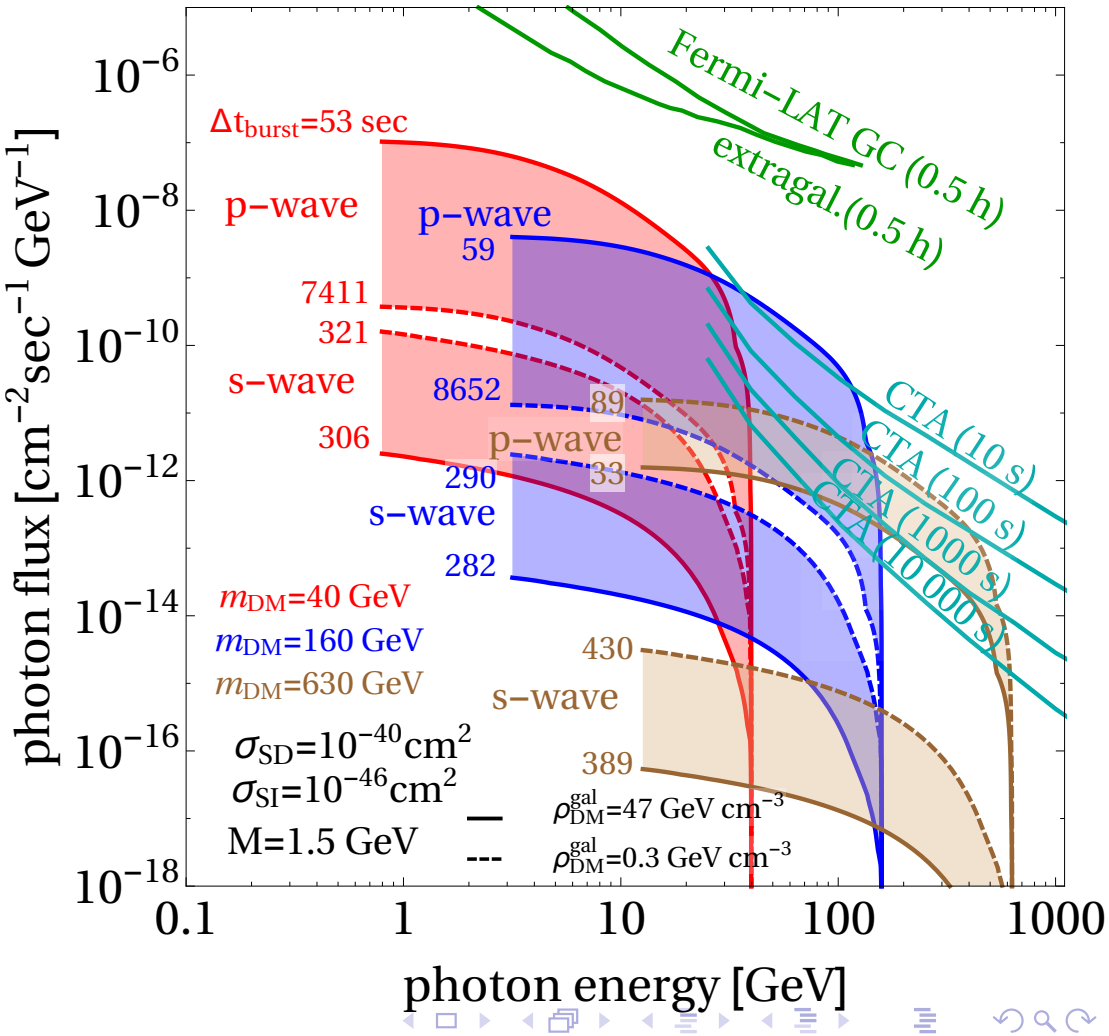
dN/dx for dark scalar



Dark Gamma Ray Burst

Properties

- An observable gamma ray signal after ν arrival
- $\Delta t_{burst} = (C_{\rm ann}^{SN} N_0)^{-1}$ related to sensitivity
- $\Delta t_{burst} \in [\mathcal{O}(10), \mathcal{O}(10^3)]$ sec for p-wave, $\mathcal{O}(10^2)$ sec for s-wave
- Benchmark locations: $0.1 kpc$ and $8 kpc$ from GC



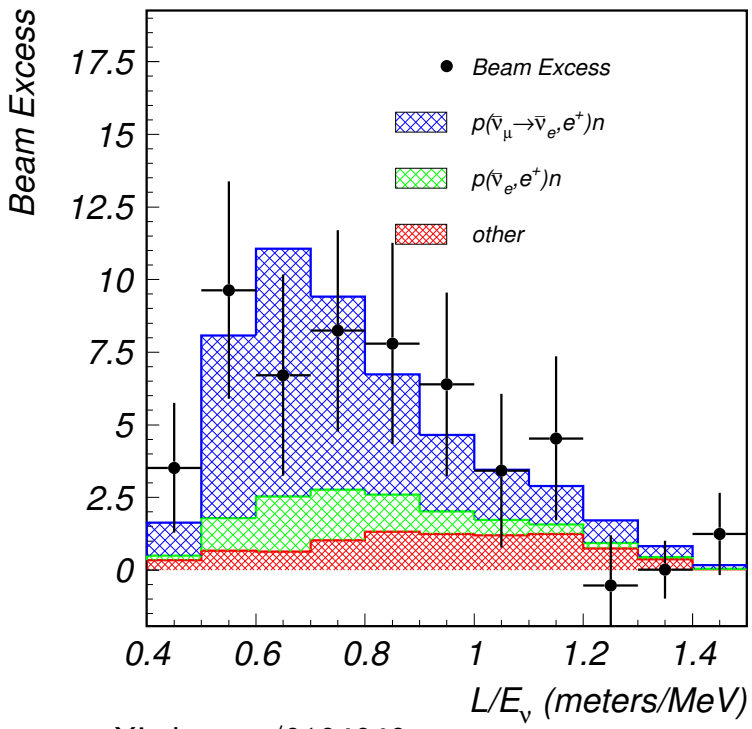
Summary I

- We have computed the evolution of the DM core in a massive star until core collapse
- If the DM annihilation products are able to leave the exploding star and decay to SM particles later, this may lead to an observable signal
- Such dark gamma ray burst can be detected by CTA for p-wave DM
- p-wave has larger photon flux than s-wave!

  This is a special feature since p-wave annihilation is generally harder to detect than s-wave ($< \sigma v >= \sigma_0 v^2$, with $v \sim 10^{-3}$ for galactic DM)
- The best signal is around $m_{\rm DM} \sim O(100)$ GeV

LSND and MiniBooNE

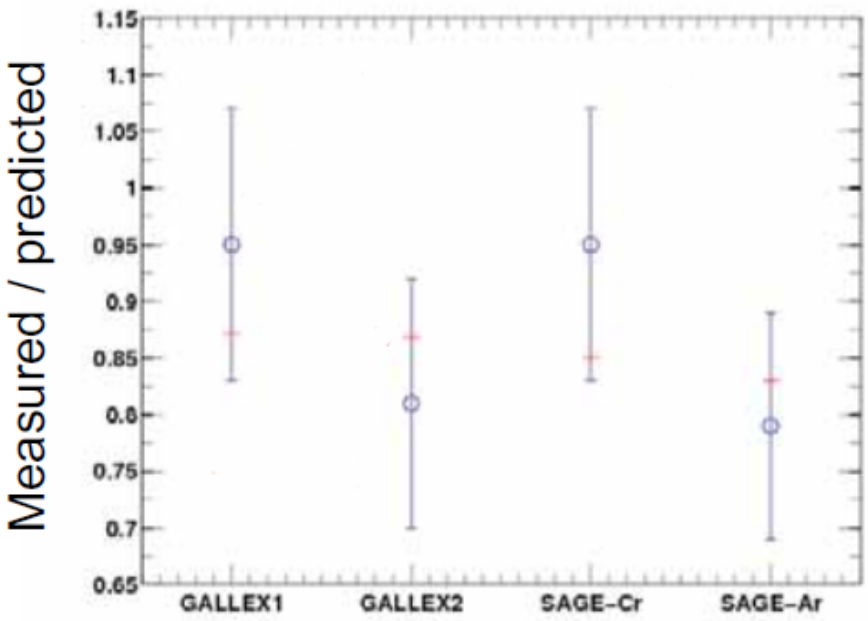
- Oscillation maxima for standard oscillations expected at
  - $L/E \sim 500$ km/GeV (from $\Delta m^2_{31} \sim 2.4 \times 10^{-3}\text{eV}^2$)
  - $L/E \sim 15000$ km/GeV (from $\Delta m^2_{21} \sim 7.5 \times 10^{-5}\text{eV}^2$)

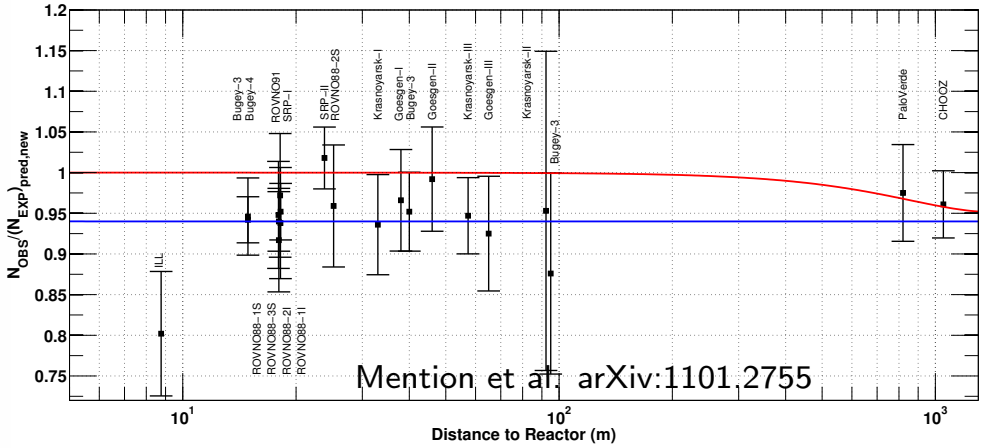


arXiv:hep-ex/0104049

- Explaining LSND and MiniBooNE requires an additional mass squared difference $\Delta m^2_{41} \sim 1\,\text{eV}^2$
- this requires an additional neutrino species
- number of active neutrinos is constrained by LEP measurements
- motivation for a sterile neutrino

Gallium and Reactor Anomaly



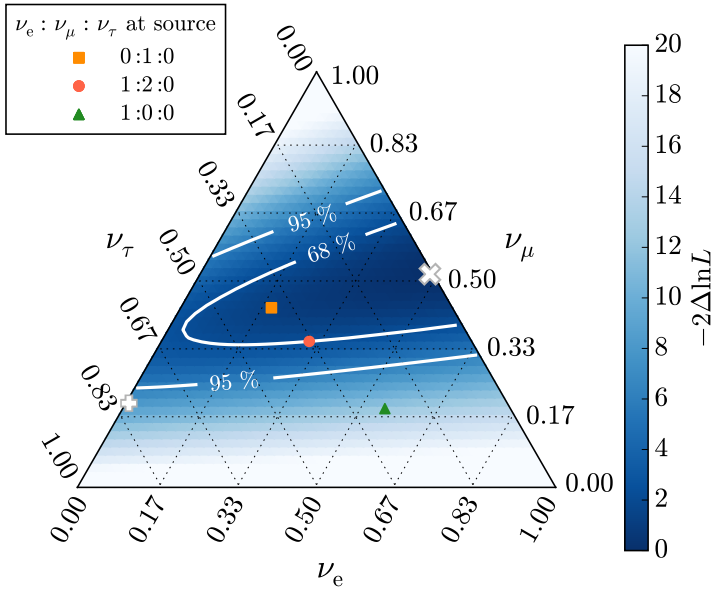


- GALLEX and SAGE solar neutrino detectors (detection via $^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + \mathrm{e}^-$)
- $\bar{\nu}_e$ deficit in short-baseline reactor experiments

Flavor ratios

- we use numerical fitting codes underlying the 4-flavor global fit from Kopp, Machado, Maltoni, Schwetz (arXiv:1303.3011)
- the goal is to explore neutrino flavor ratios with the presence of eV-scale sterile neutrino

arXiv:1507.03991



flavor ratios have been extensively explored in several classes of new physics models

Arguelles, Katori, Salvado 1506.02043

Bustamante, Beacom, Winter 1506.02645

Methods I

- the general formula for the conversion probability of high energy neutrinos in the presence of n flavors
  $P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 2\sum_{k>j} \mathrm{Re}\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] = \sum_{j=1}^{n} |U_{\alpha j}|^2 |U_{\beta j}|^2$
- we consider $n = 4$ case with the following PMNS matrix parametrization

$$U = R^{34}(\theta_{34})\tilde{R}^{24}(\theta_{24}, \delta_2) R^{23}(\theta_{23}) R^{14}(\theta_{14}) \tilde{R}^{13}(\theta_{13}, \delta) \tilde{R}^{12}(\theta_{12}, \delta_1)$$

- fluxes at Earth $\Phi^{\mathrm{det}}_{\nu_\alpha}$ are computed as $\Phi^{\mathrm{det}}_{\nu_\alpha} = \sum_\beta P_{\nu_\alpha \to \nu_\beta} \Phi^{\mathrm{prod}}_{\nu_\beta}$
- there are in total 12 parameters
  $\Theta \equiv (\theta_{12}, \theta_{13}, \theta_{23}, \delta_0, \theta_{14}, \theta_{24}, \theta_{34}, \delta_1, \delta_2, \Delta m^2_{21}, \Delta m^2_{31}, \Delta m^2_{41})$
- Δm^2_{21} and Δm^2_{31} fixed, Δm^2_{41} scanned between 0.1 and 10 eV^2
- mixing angles and phases taken to be distributed according to the Haar measure $dH =$
  $d(\sin^2\theta_{12})\, d(\sin^2\theta_{23})\, d(\cos^4\theta_{13})\, d(\cos^6\theta_{14})\, d(\cos^4\theta_{24})\, d(\sin^2\theta_{34})\, d\delta\, d\delta_1\, d\delta_2$

Haba,Murayama hep-ph/0009174

VB,Kopp,Koenig arXiv:1511.06371

Methods II

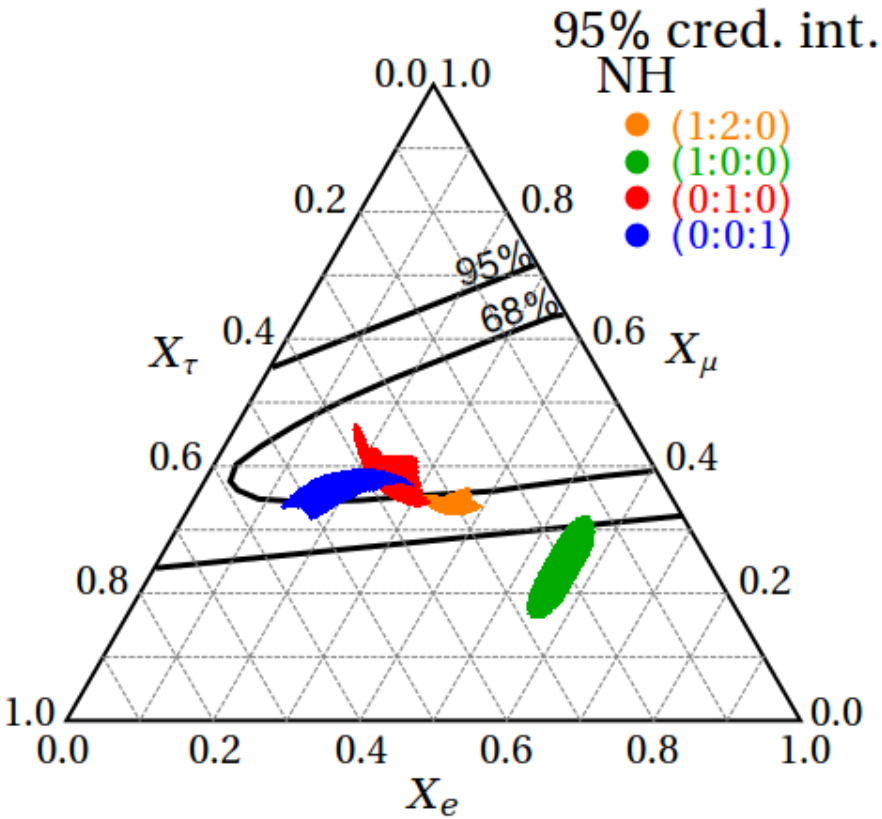
- all generated parameter sets are associated with a χ^2, obtained by summing the contribution from all experiments
- We then use Bayesian statistics to determine the credible intervals for the parameters
- prior $P(\Theta) \rightarrow$ Haar measure

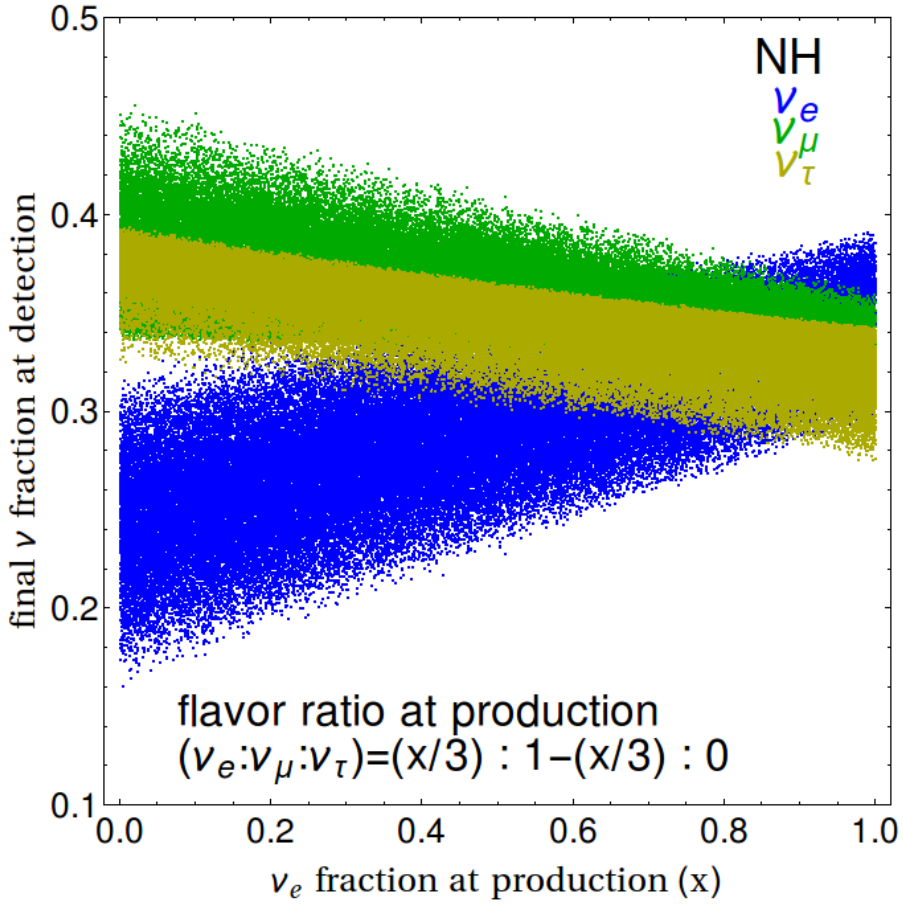
$$P(\text{data}|\Theta) = \exp\left[-\frac{\chi^2(\Theta)}{2}\right]$$

Bayes' theorem :

$$P(\Theta|\text{data}) = \frac{P(\text{data}|\Theta)\,P(\Theta)}{P(\text{data})}$$

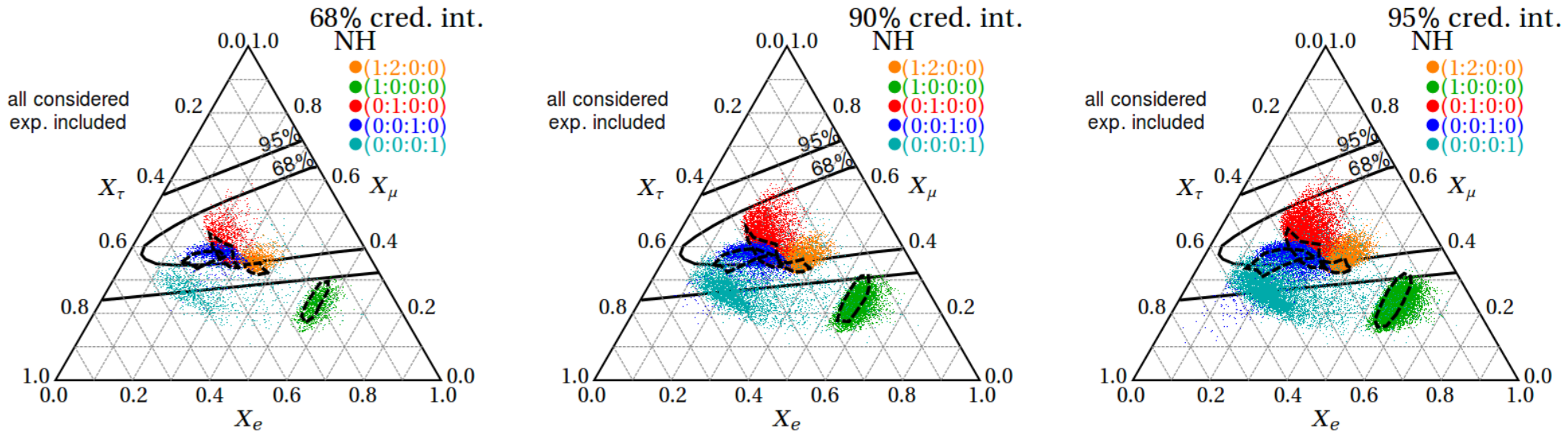
3 flavor case for several initial flavor ratios





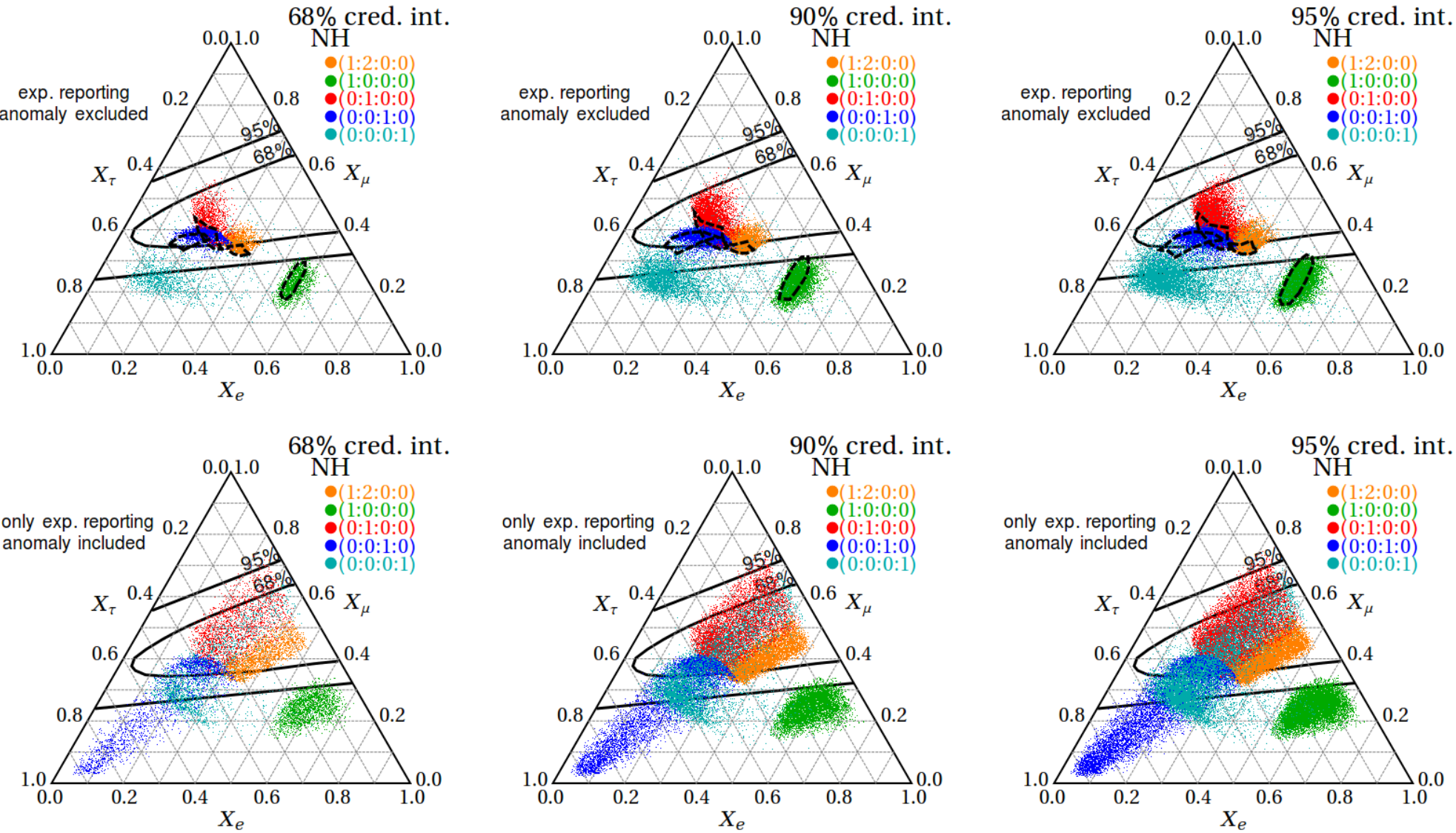
- assigning $\chi^2(\Theta)$ values based on the results of 3-flavor global fit (Gonzalez-Garcia et. al. 1409.5439)

4 Flavor Scenario

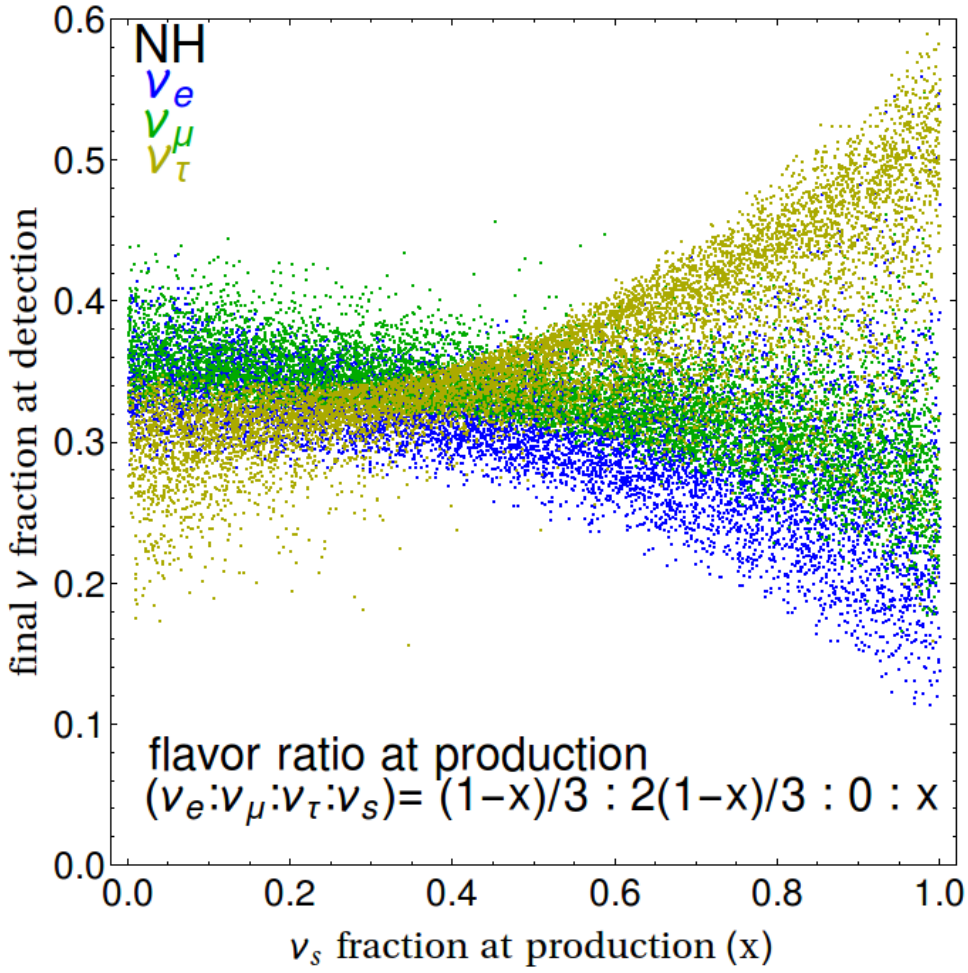


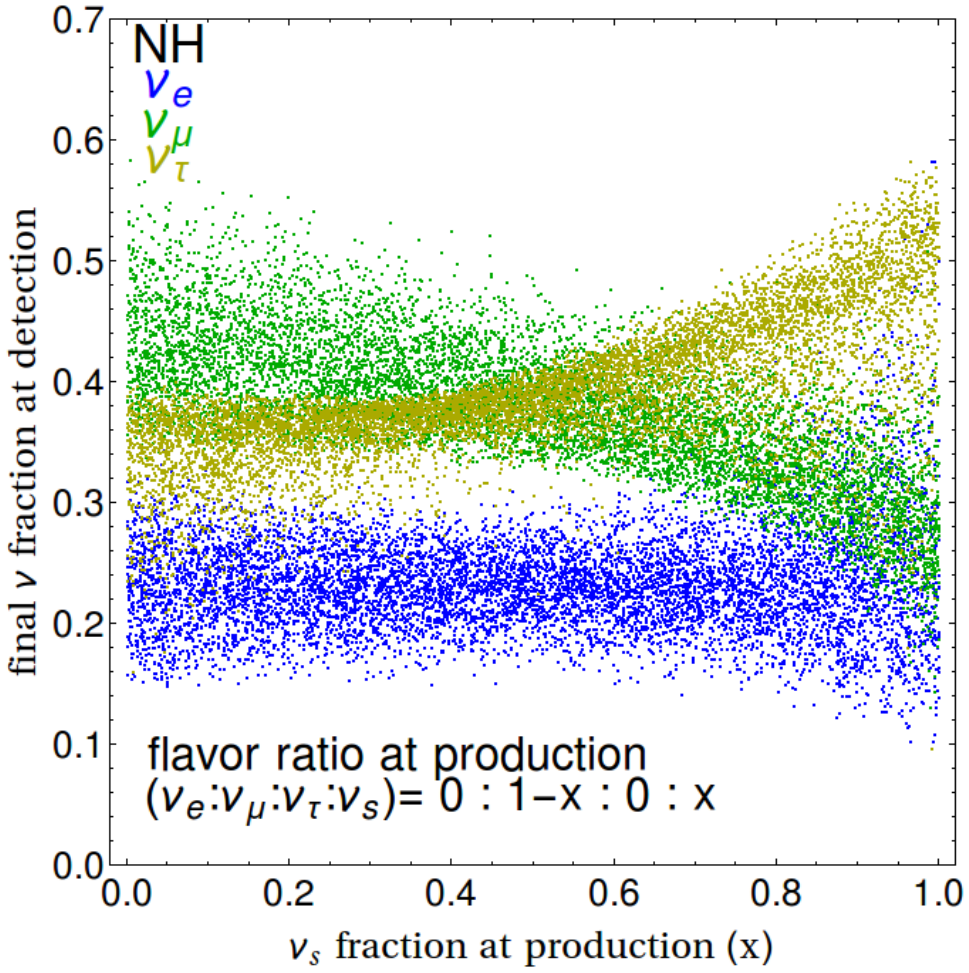
- no large deviations for the case of initial astrophysical flavor ratios
- on top of the astrophysical initial flavor ratio, we consider pure ν_τ (0:0:1:0) and pure ν_s flux at the production (0:0:0:1)$\rightarrow$ DM decay as a motivation?

4 Flavor Scenario II

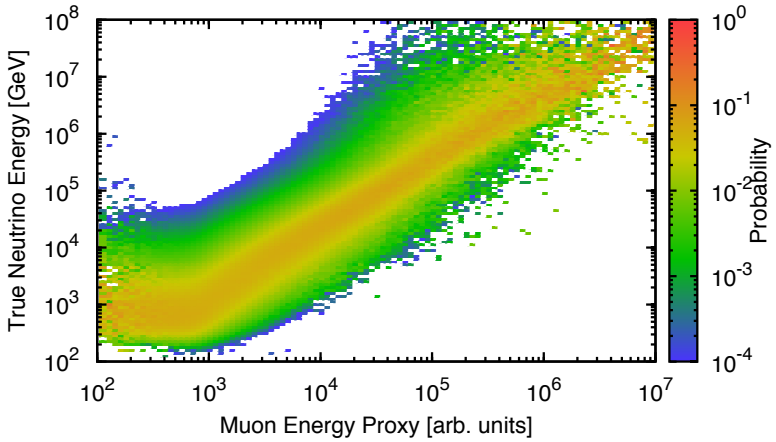


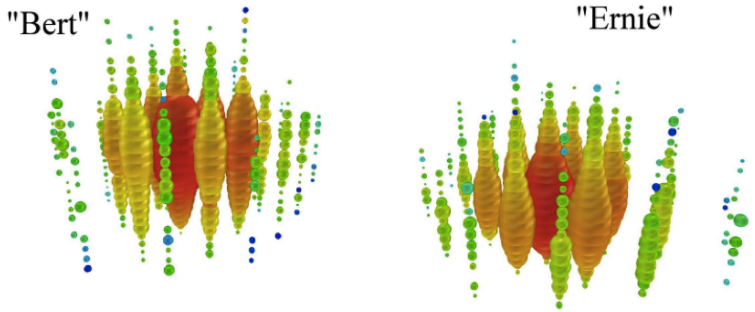
4 Flavor Scenario III





IceCube data–HESE and TGM





- 54 high-energy starting events (HESE) with deposited energies above 20 TeV
- First observed PeV-energy neutrinos in IceCube
- 14 muon tracks, 39 showers
- through-going muon events – complementary to HESE
- neutrino interactions both outside and inside of the detector considered $\rightarrow$ larger effective area
- atmospheric flux can not explain all observed events

Astrophysical flux and decaying DM

- **power law astrophysical flux**

$$\frac{dJ^{\rm PL}_{\rm astro}}{dE_\nu} = \Phi_0 \left(\frac{E_\nu}{100{\rm TeV}}\right)^{-\gamma}$$

- (1:1:1) flavor ratio at Earth assumed
- **Model 1: Heavy right-handed neutrino DM**

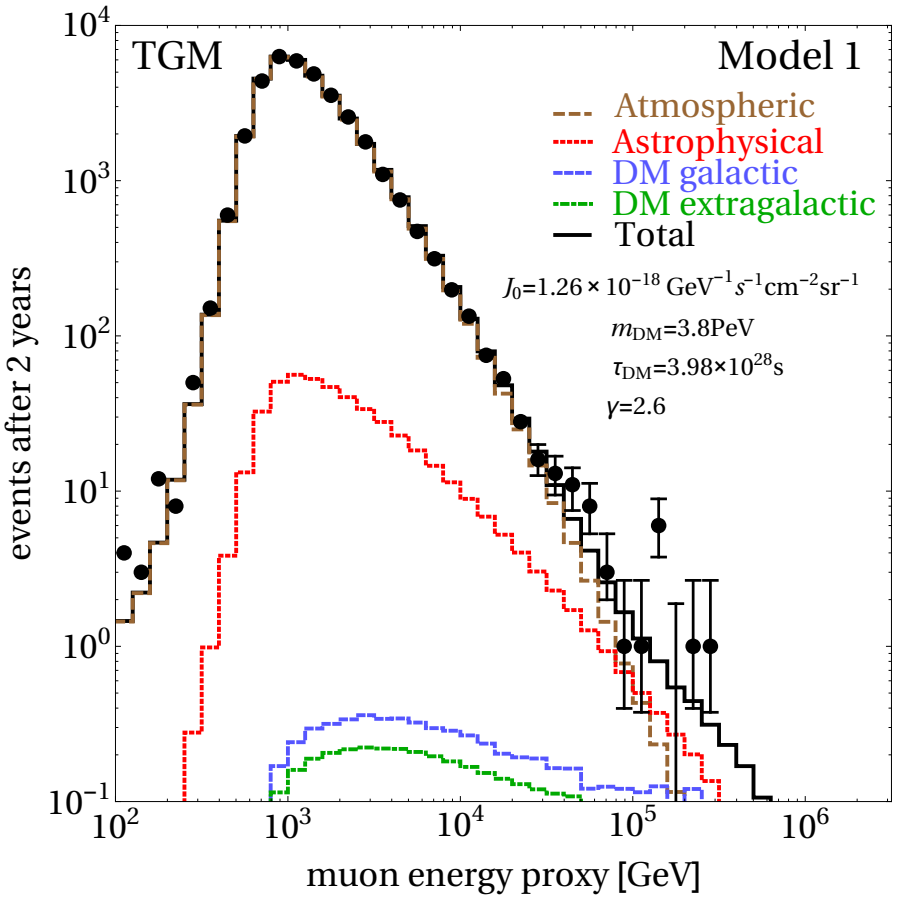
$$\mathcal{L}_{\rm int} \supset \sum_\alpha y_\alpha \bar{N}\, \tilde{H}^\dagger\, L_\alpha \,+\, {\rm h.c.}$$

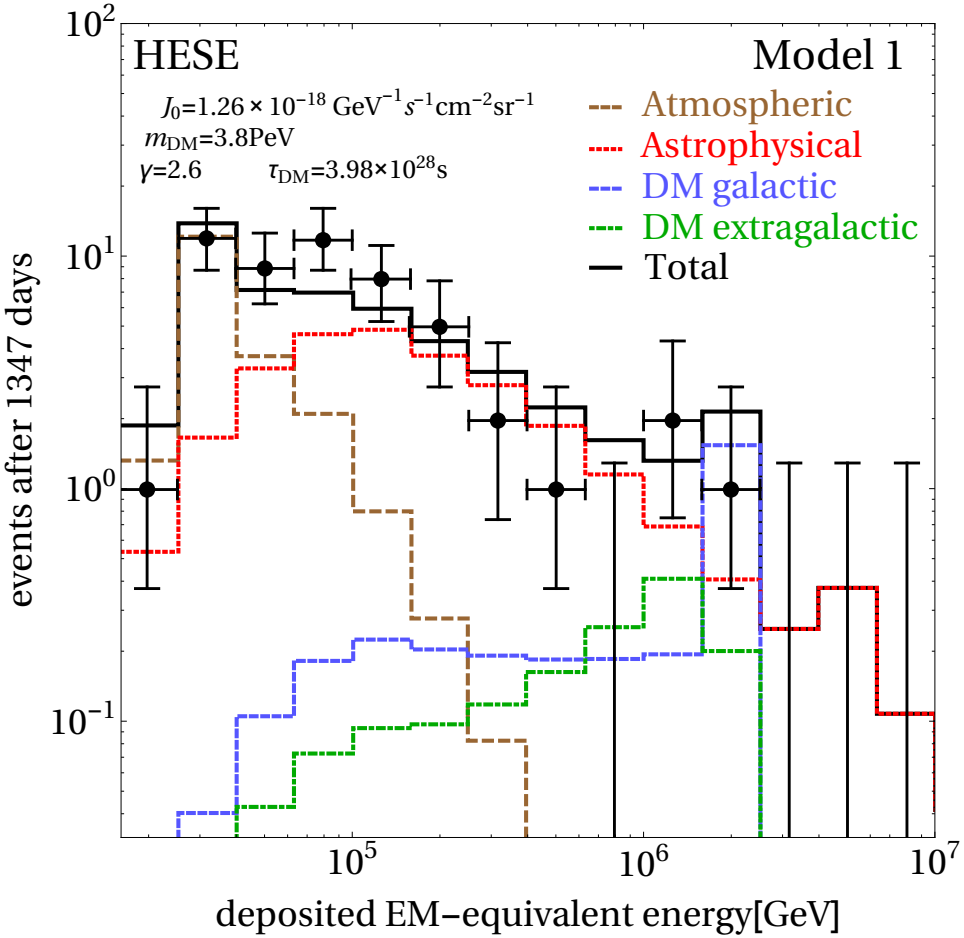
- $y_\tau \gg y_e, y_\mu$ – (0:0:1:0) at highest energies
- **Model 2: Scalar DM decaying to sterile neutrinos**

$$\mathcal{L}_{\rm int} \supset y_2\, \phi \bar{\nu}_s \nu_s \,+\, {\rm h.c.}$$

- for decaying DM case taking into account both galactic and extragalactic neutrino flux; oscillation effect considered

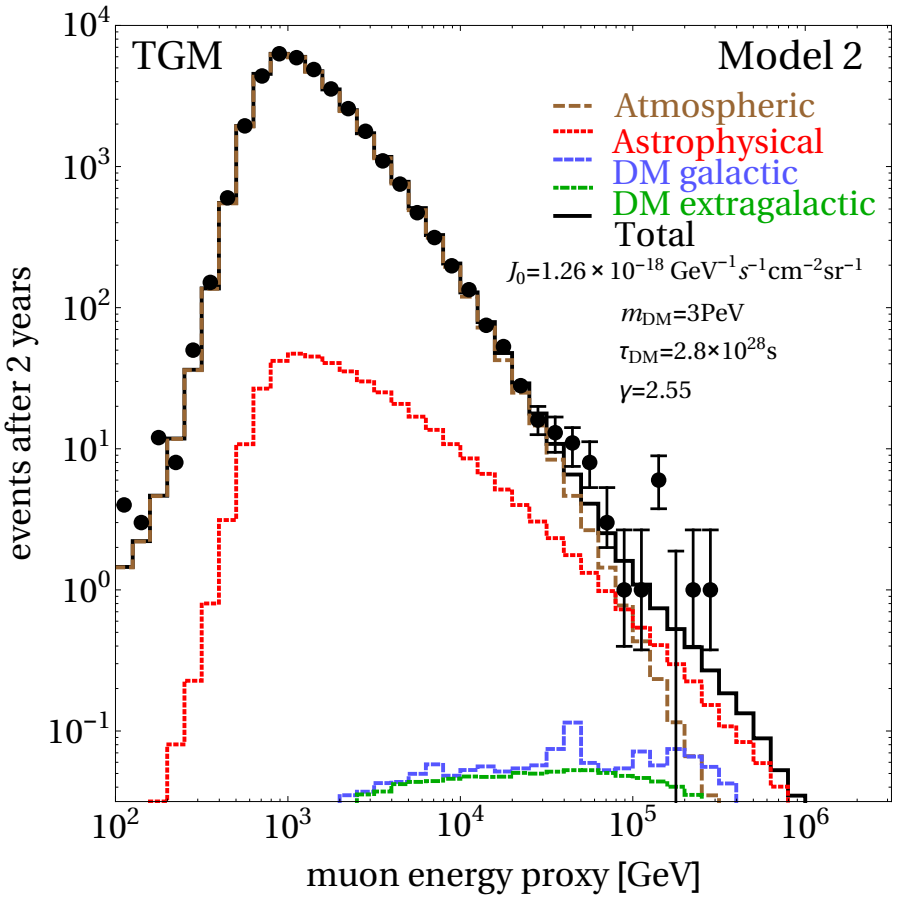
DM Model 1 with astro flux – combined HESE and TGM

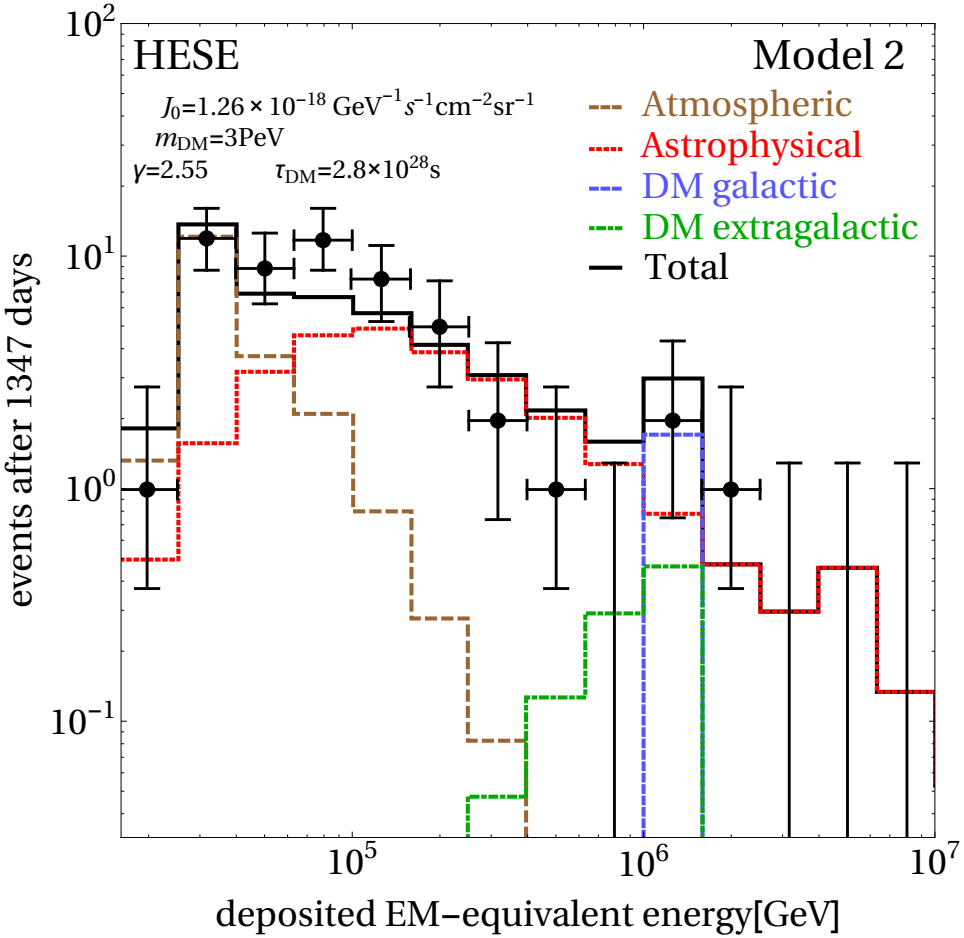




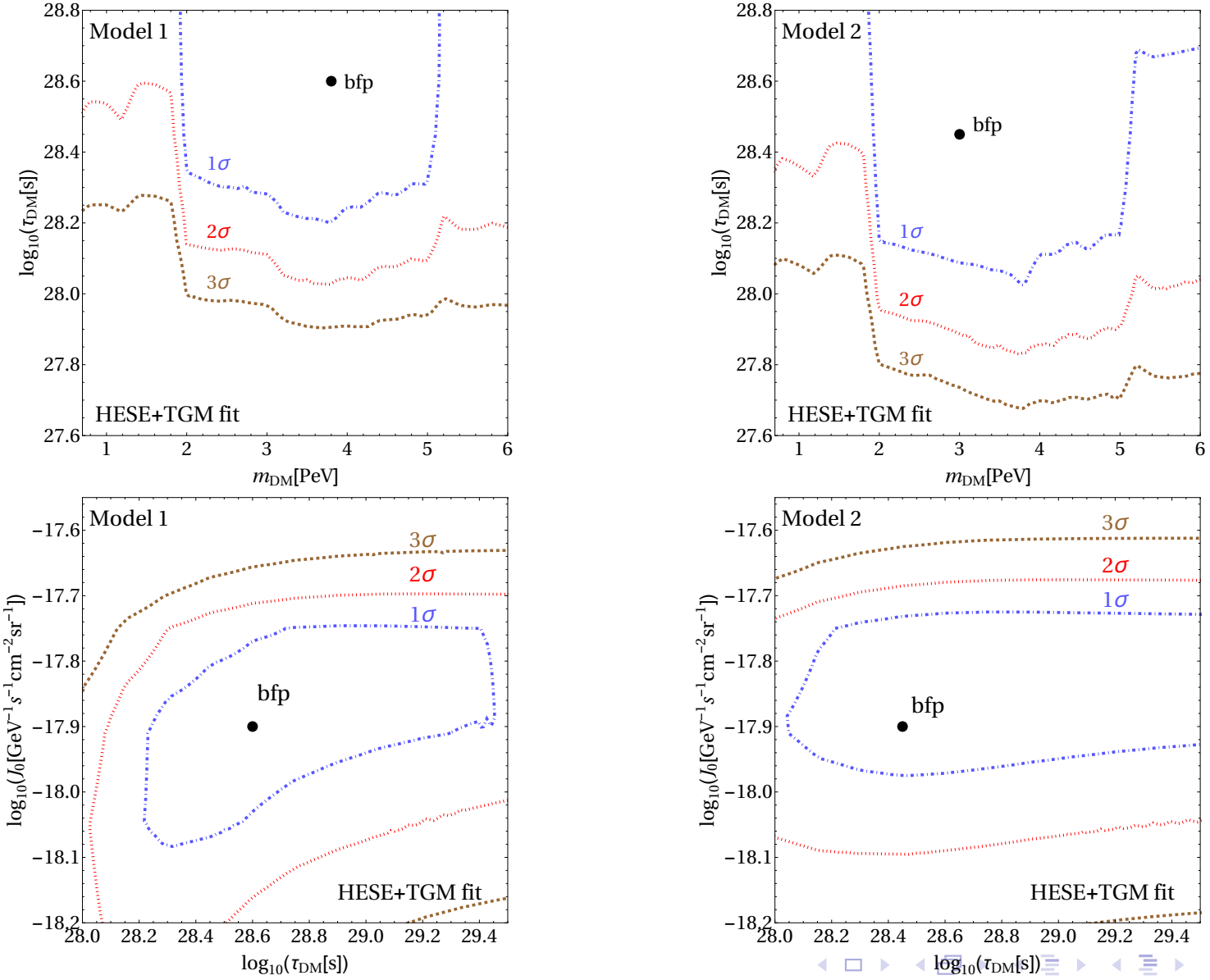
- only DM components can not successfully fit the full data

DM Model 2 with astro flux – combined HESE and TGM





Combined Fit



Summary II

- anomalies in several neutrino oscillation experiments provide a possible hint for eV sterile neutrino
- IC measured high energy neutrino events up to PeV scale

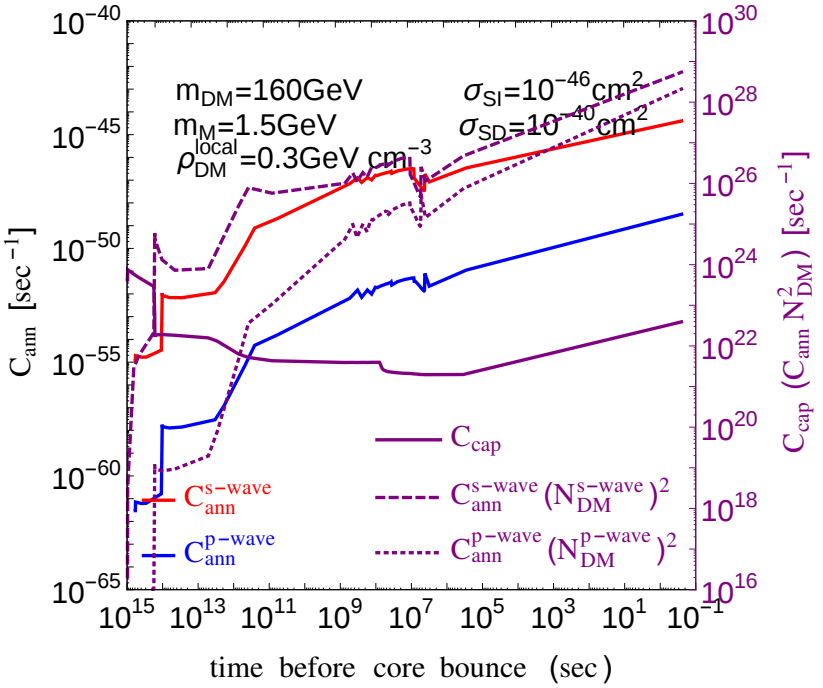
- we study flavor ratios at Earth assuming sterile neutrino both at the production & propagation
- fits with astrophysical and/or DM fluxes are performed
- probing the regions with unconventional flavor ratios possible with more statistics (Gen 2)

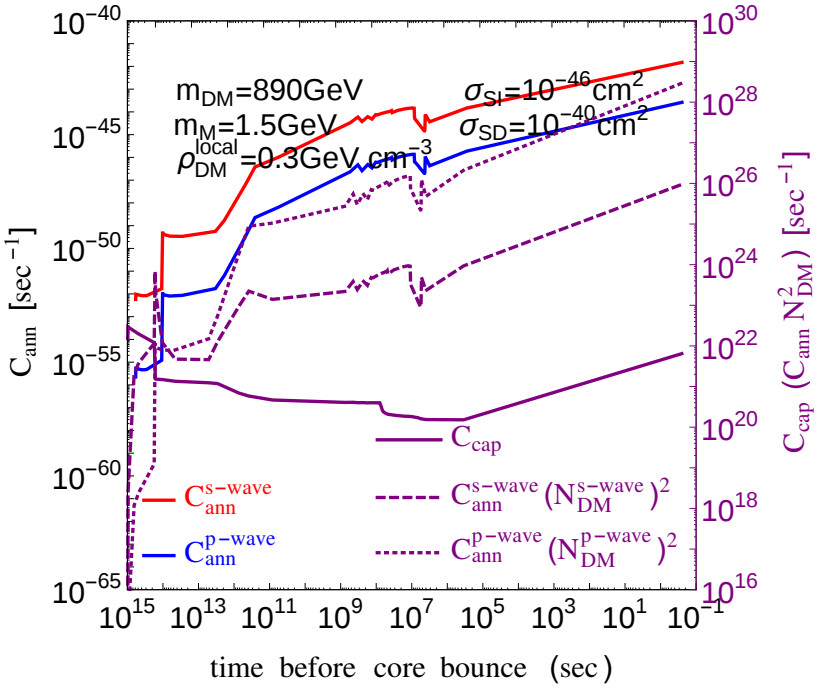
BACKUP SLIDES

Capture and Annihilation Rates

$$\dot{N}_{\rm DM}(t) = C_{\rm cap}(t) - C_{\rm ann}(t) N_{\rm DM}(t)^2 + C_{\rm self}(t) N_{\rm DM}(t)$$

$$C_{\rm cap} = \sum_i \int_0^{R_{\rm star}} dr\, 4\pi r^2 \frac{dC_i(r)}{dV} \qquad C_{\rm ann} N_{\rm DM}^2 \equiv \int d^3 r\, \langle \sigma v_{\rm rel} \rangle\, n_{\rm DM}^2(r)$$





Astrophysical and DM events

- broken power law (BPL) (1501.02615,1507.01000)

$$\frac{dJ^{\rm BPL}_{\rm astro}}{dE_\nu} = \Phi_0 \left(\frac{E_\nu}{100{\rm TeV}}\right)^{-\gamma} {\rm Exp}\left[\frac{E_\nu}{E_0}\right]$$

$$N^{\rm (B)PL}_{\rm astro}(E_a < E_\nu < E_b) = \int_{E_a}^{E_b} dE\, \frac{dJ^{\rm (B)PL}_{\rm astro}}{dE_\nu}\, \mathcal{E}(E) dE$$

- DM fluxes

$$\frac{dJ_{\rm gal}}{dE_\nu} \approx 1.7 \times 10^{-5}\,{\rm cm}^{-2}\,{\rm s}^{-1}\,{\rm sr}^{-1} \left(\frac{1\,{\rm GeV}}{m_{\rm DM}}\right)\left(\frac{10^{26}\,{\rm s}}{\tau_{\rm DM}}\right) \times \frac{dN_\nu(E_\nu)}{dE_\nu}$$

$$\frac{dJ_{\rm extragal}}{dE_\nu} = \frac{\Omega_{\rm DM}\rho_c}{4\pi m_{\rm DM}\tau_{\rm DM}} \int_0^\infty dz\, \frac{1}{H(z)} \frac{dN_\nu\big((1+z)E_\nu\big)}{dE_\nu}$$

$$\approx 1.4 \times 10^{-5}\,{\rm cm}^{-2}\,{\rm s}^{-1}\,{\rm sr}^{-1} \left(\frac{1\,{\rm GeV}}{m_{\rm DM}}\right)\left(\frac{10^{26}\,{\rm s}}{\tau_{\rm DM}}\right)$$

$$\times \int_0^{\frac{m_{\rm DM}}{2E_\nu}-1} dz\, \frac{1}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}} \frac{dN_\nu\big((1+z)E_\nu\big)}{dE_\nu}$$

Events and Fitting procedure

- HESE events in energy interval $[E_a, E_b]$

$$N_{\rm DM} = \int_{E_a}^{E_b} dE_\nu \, \Delta\Omega \, \Delta t \, A_{\rm eff}(E_\nu) \left(\frac{dJ^f_{\rm extragal}}{dE_\nu} + \frac{dJ^f_{\rm gal}}{dE_\nu} \right)$$

- TGM events in i-th reconstructed muon energy bin

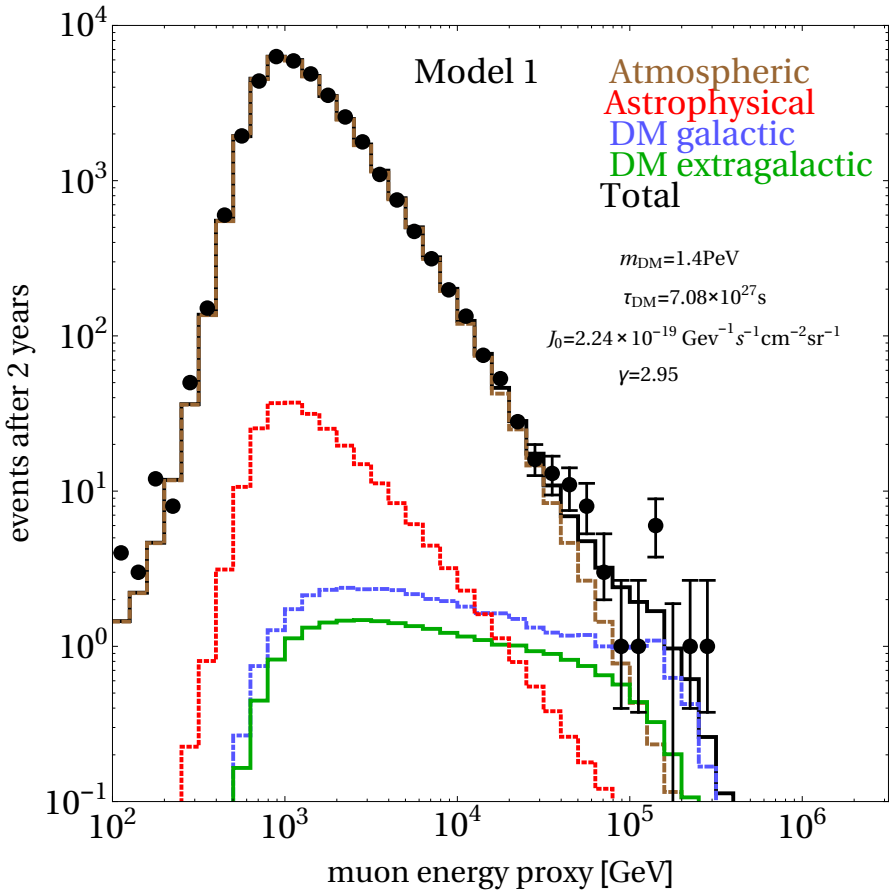
$$N^i = \sum_{j=2010,2011} \sum_{i=\mu,\bar{\mu},\tau,\bar{\tau}} A^{i,j}_{\rm eff} \Delta t \Delta\Omega \left[\int dE_\nu \left(\frac{dJ^f_{\rm extragal}}{dE_\nu} + \frac{dJ^f_{\rm gal}}{dE_\nu} \right) \right]^j$$

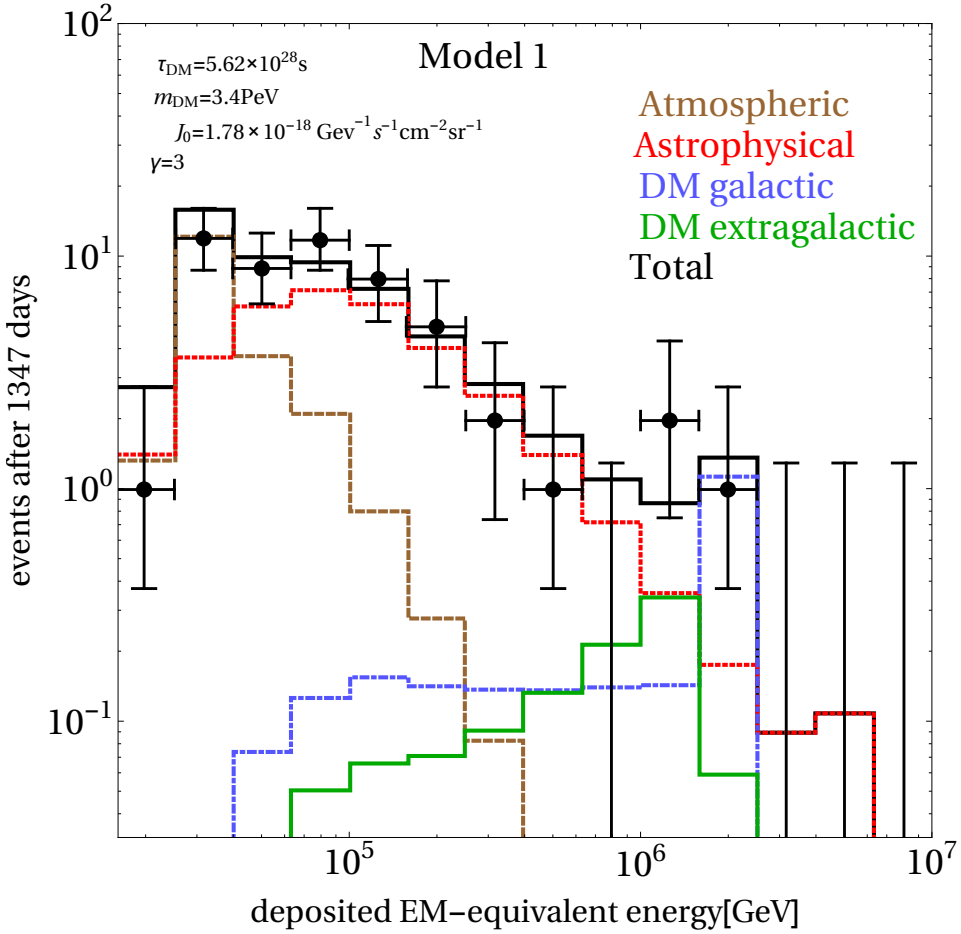
We use the log likelihood ratio (LLR) method to determine parameters in our models. The LLR is defined as

$$\mathrm{LLR}\Big(m_{\rm DM}, \tau_{\rm DM}, \phi_0, \gamma \Big)$$

$$= \log \left(\frac{\underset{x\in[-\infty,\infty]}{\mathrm{Max}} \left[f_{\rm Gauss}(x) \prod_i f_{\rm Poisson}\Big(S_i\Big(m_{\rm DM}, \tau_{\rm DM}, \phi_0, \gamma \Big) + B_i + x\,\Delta B_i \,\Big|\, O_i \Big) \right]}{\underset{x'\in[-\infty,\infty]}{\mathrm{Max}} \left[f_{\rm Gauss}(x') \prod_i f_{\rm Poisson}\big(B_i + x'\,\Delta B_i \big| O_i \big) \right]} \right)$$

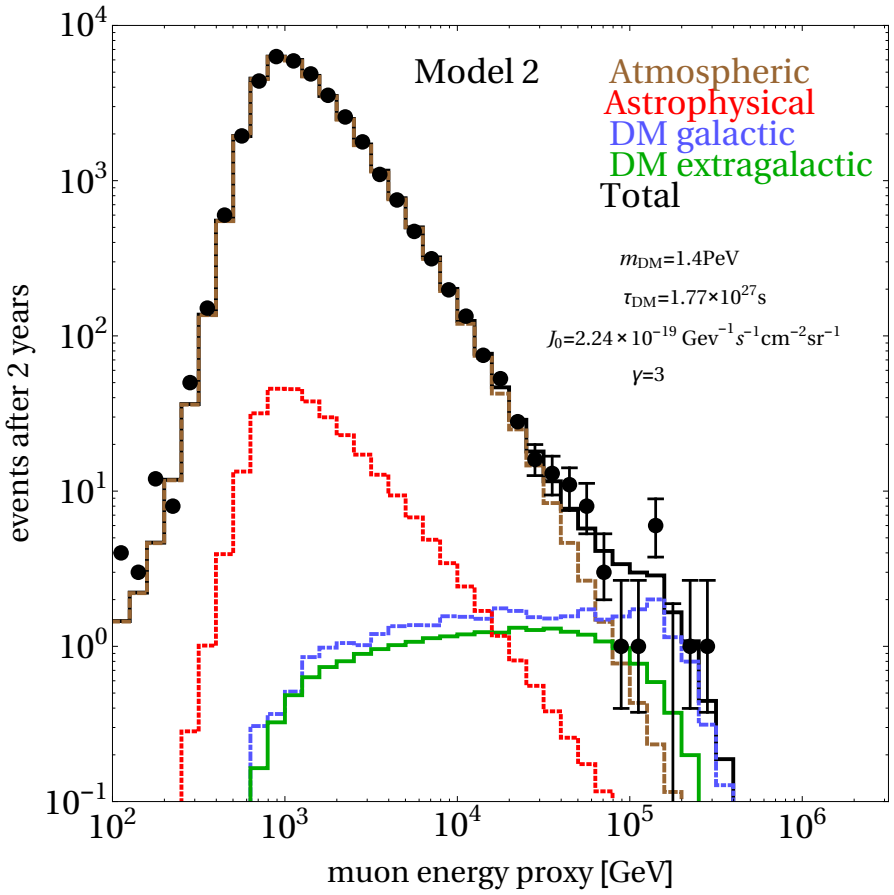
DM Model 1 with astro flux – HESE and TGM

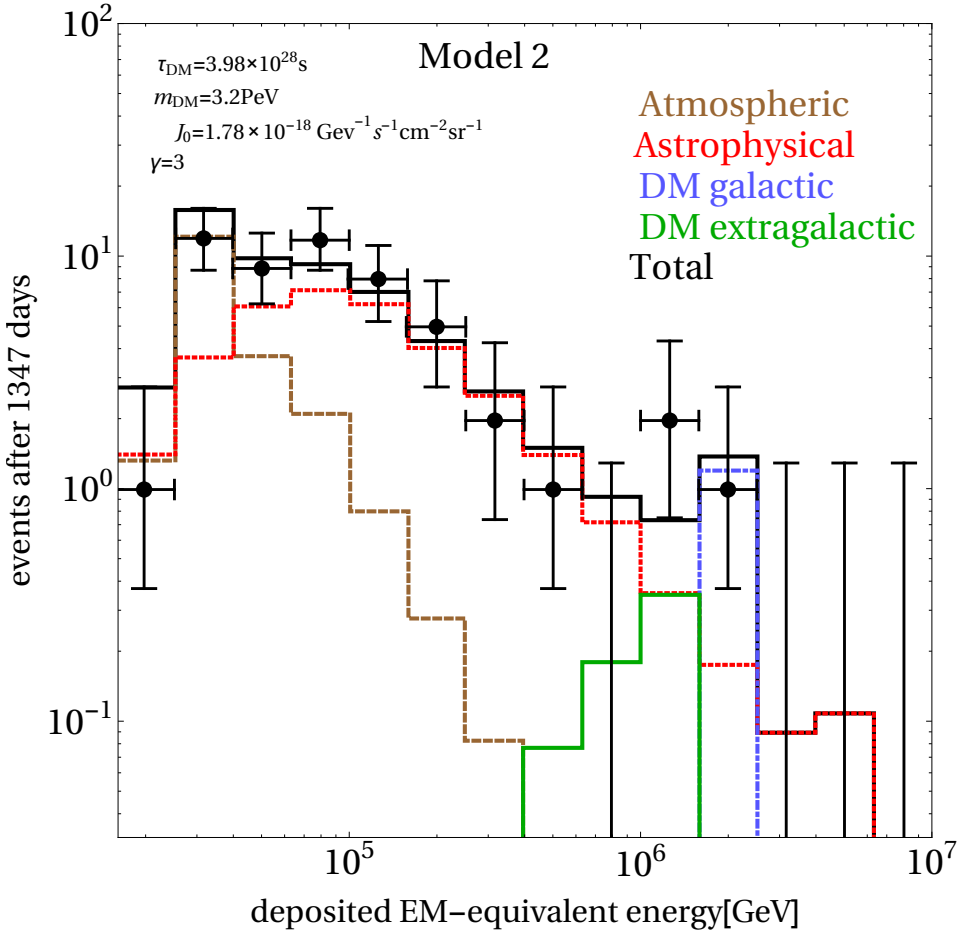
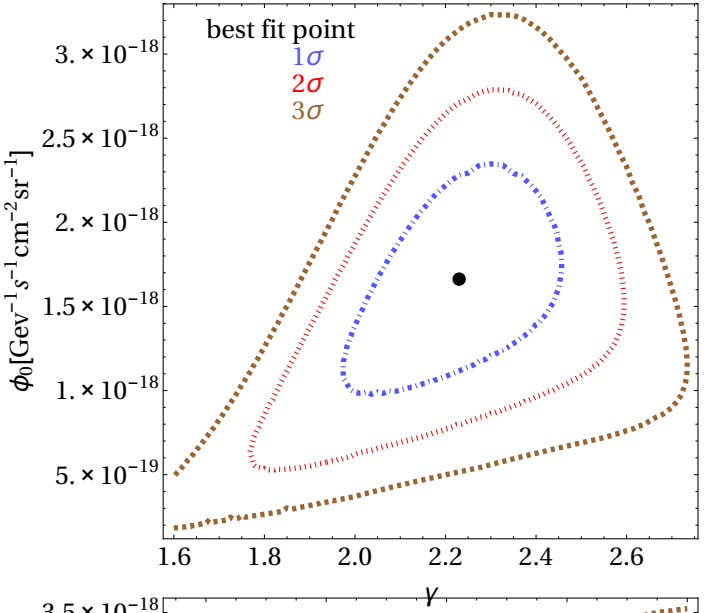
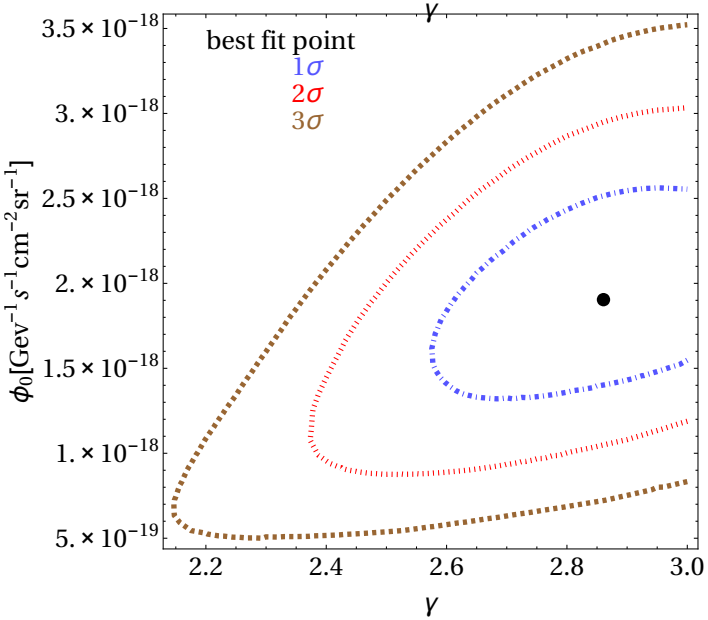
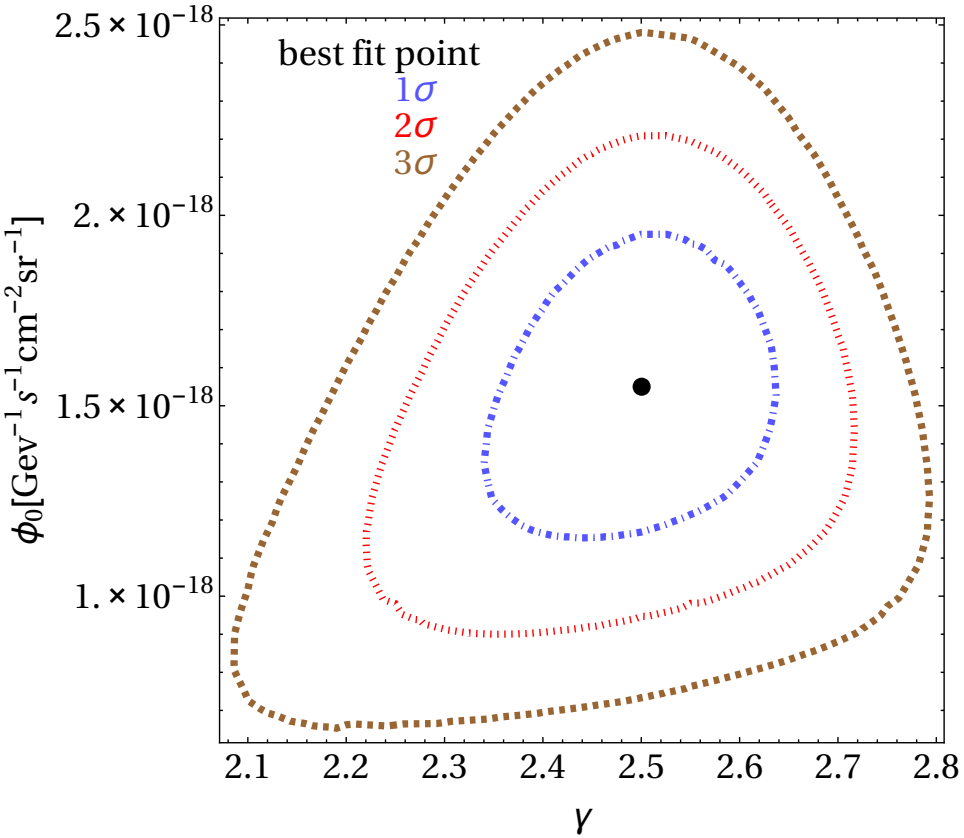




- only DM components can not successfully fit the full data

DM Model 2 with astro flux – HESE and TGM





TGM + HESE Combined Astrophysical Fit