Constraining Dark Matter-Neutrino Interactions with Cosmic Neutrinos

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in collaboration with
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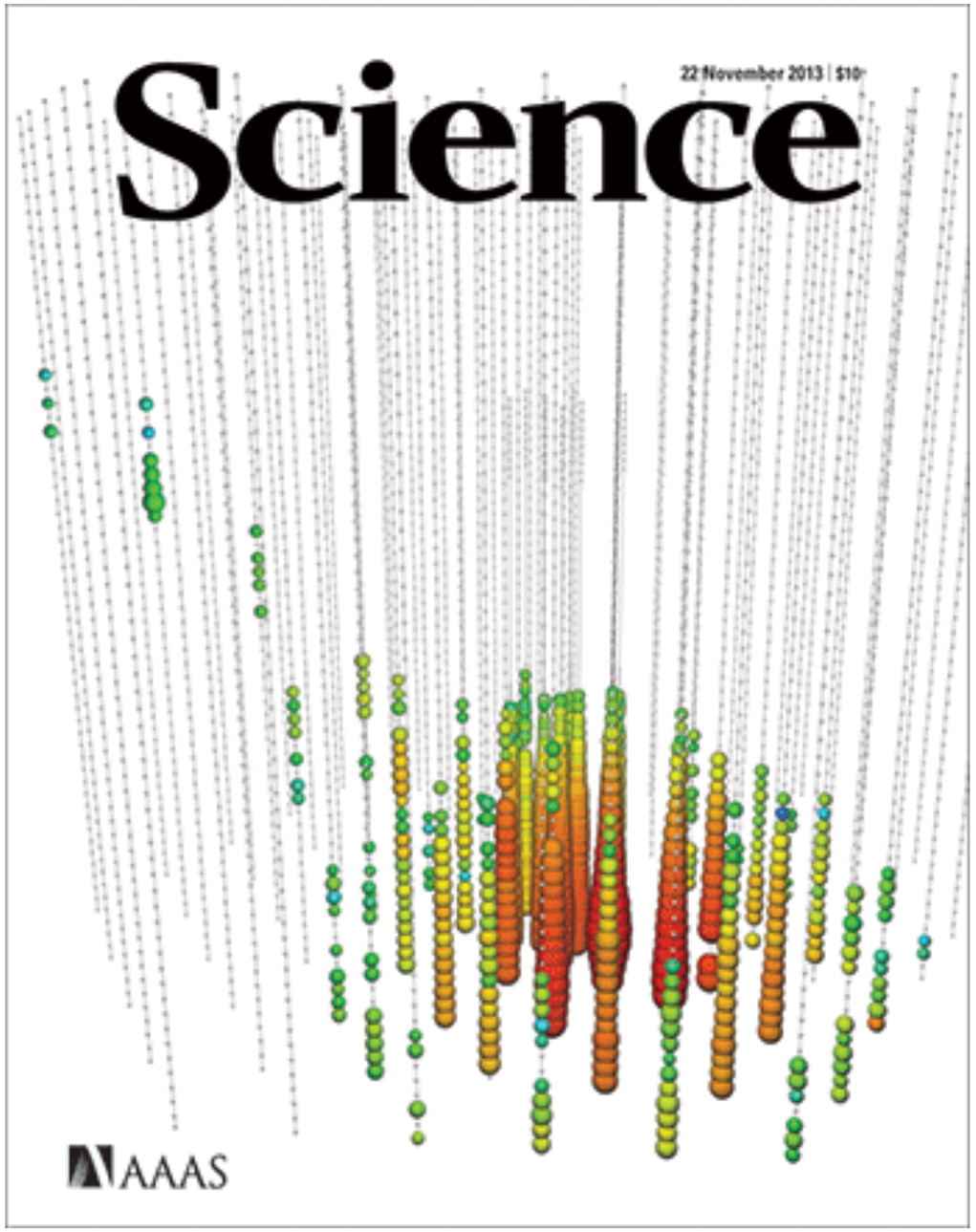
Outline

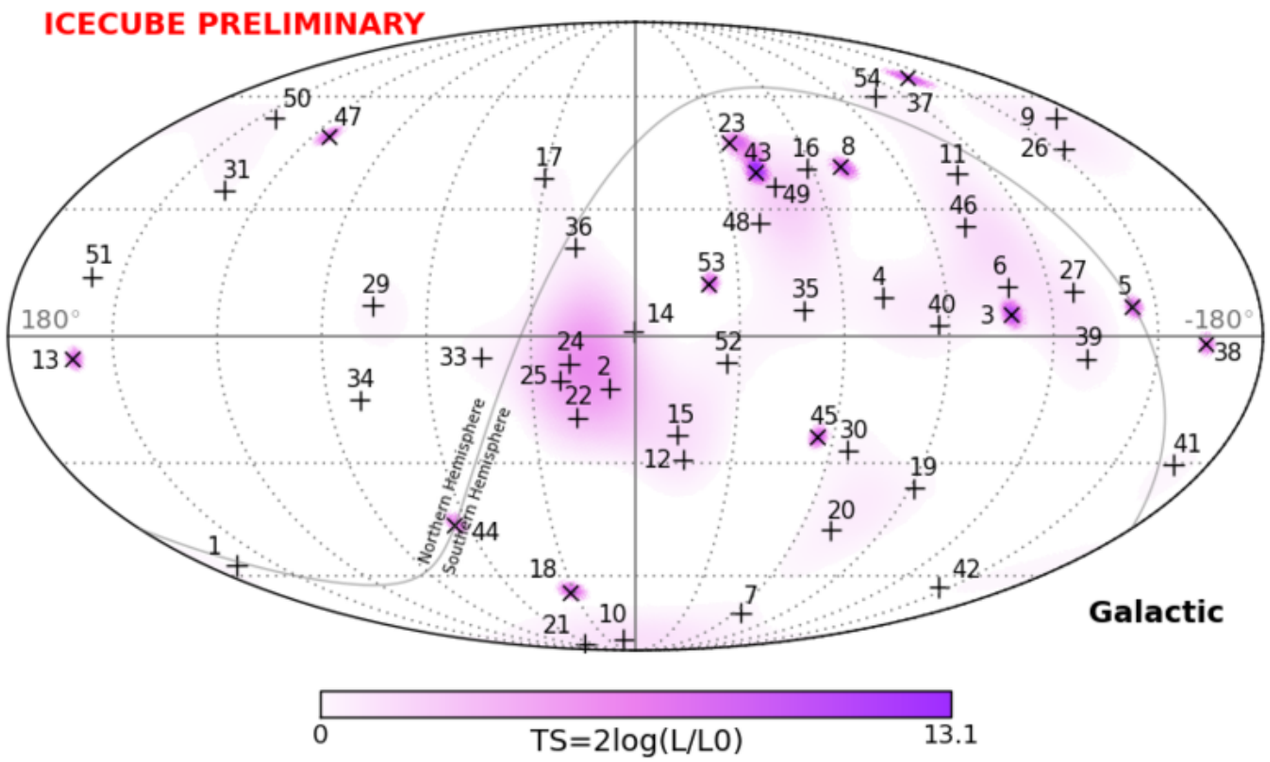
- IceCube high energy astrophysical neutrinos
- Dark matter-neutrino interactions
- Scattering of diffuse high energy neutrinos propagating through dark matter
- Analysis method
- Upper limits and cosmology

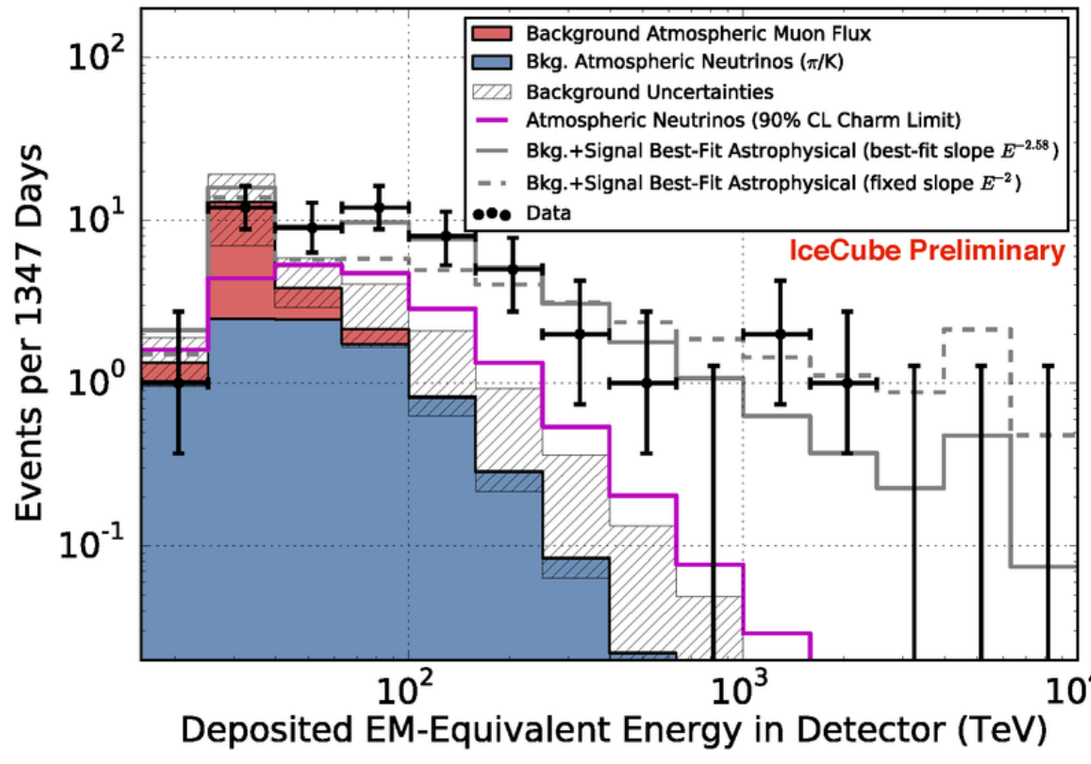
High energy cosmic neutrinos: Discovery



- IceCube discovered neutrinos with astrophysical origin in 2013.
- Since the discovery IceCube has been observing cosmic neutrinos continuously.
- Source of HE neutrinos still unknown.

High Energy Neutrinos: flux properties





$$E^2\phi(E) = 2.2 \pm 0.7 \times 10^{-8} (E/100\text{TeV})^{-0.58} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

- 54 Events in 4 years.
- Events spatial distribution compatible with **isotropic** hypothesis.
- **No correlation** with Galactic plane.
- Event distribution suggests extragalactic origin for the majority of the events.
- **Flavor ratio** is consistent with 1:1:1 ratio. **arXiv:1510.05223.**

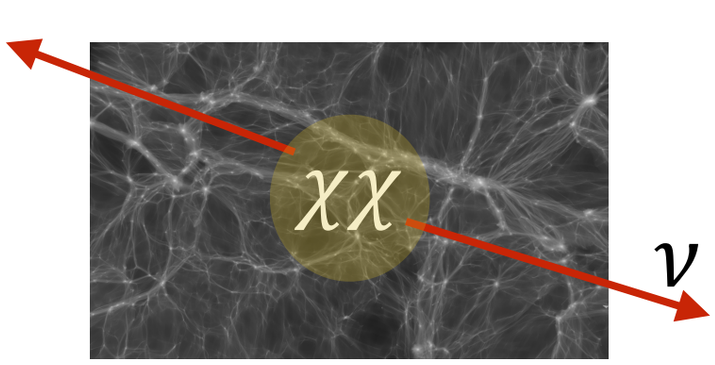
Dark matter neutrino interactions

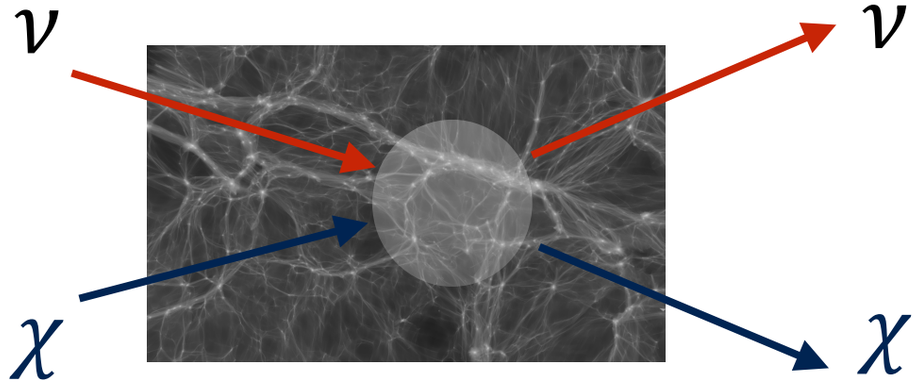
DM annihilation near Weak Scale: **WIMP Miracle**

DM-DM → SM-SM ◀ · · · · ▶ SM-DM → DM-SM

basis of direct underground DM experiments searching for DM-q

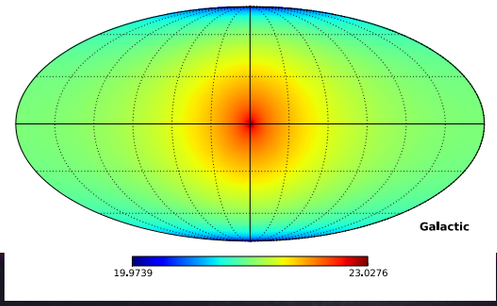
$\overline{\nu}$





DM-ν interaction motivated by light DM scenarios and appears e.g. in models where dark matter is sneutrino.

DM density is largest in center of the galaxy.



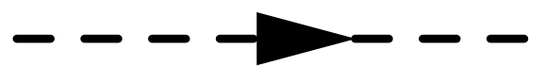
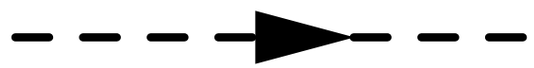
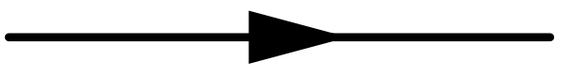
ν

χ

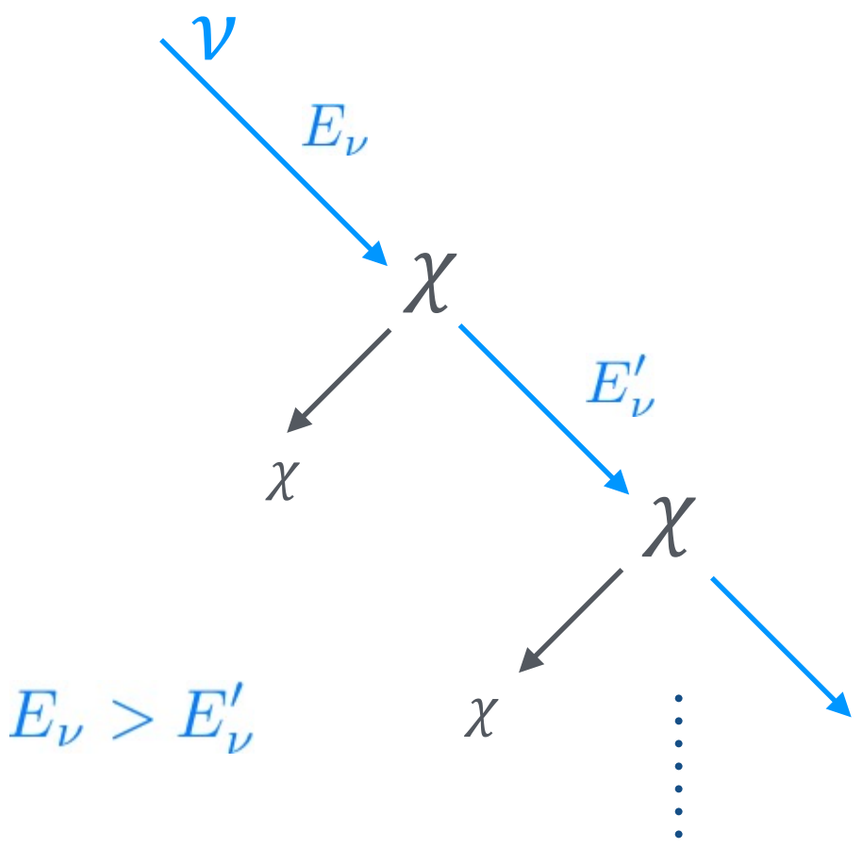
ν

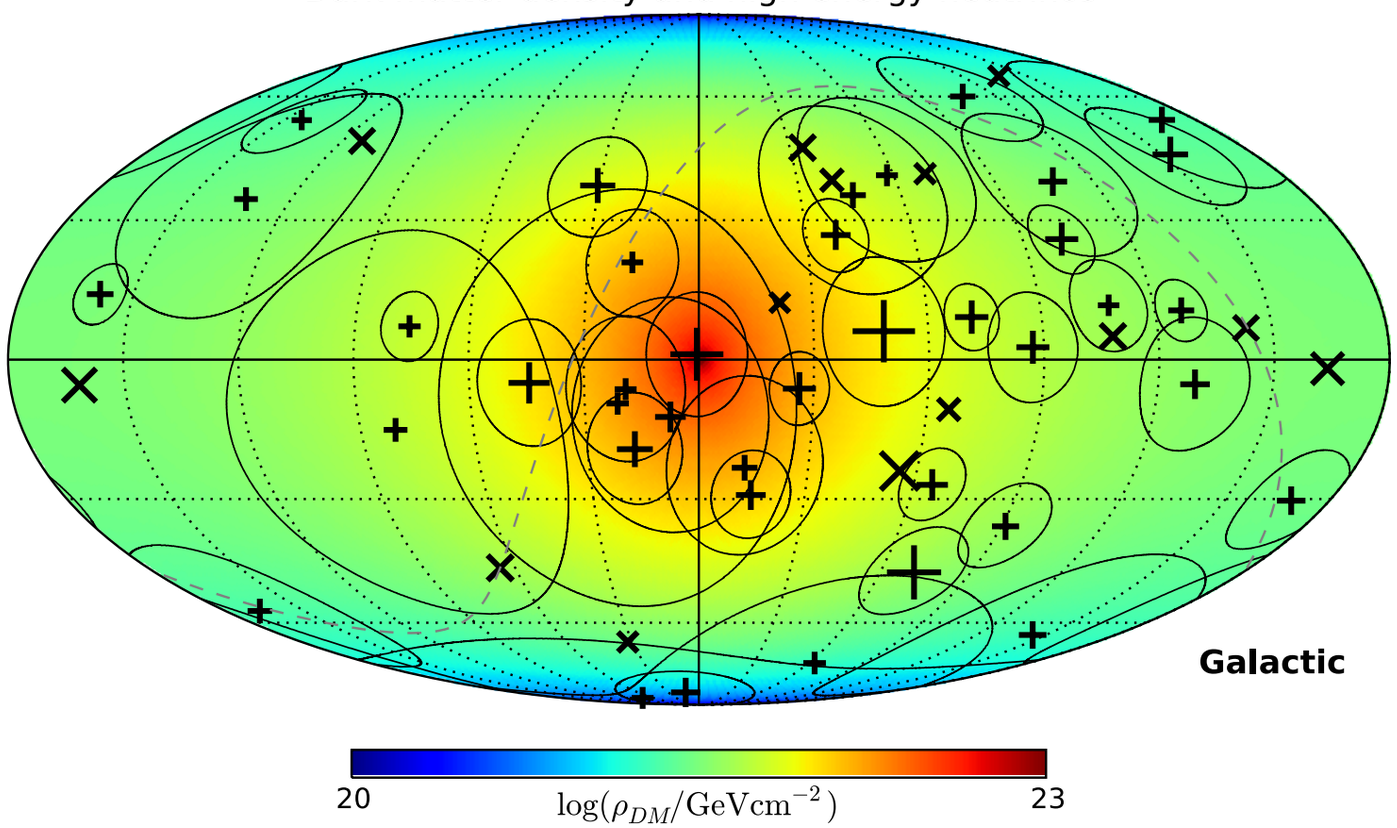
DM-ν interaction will result in scattering of neutrinos from extragalactic sources, leading to *anisotropy* of diffuse neutrino flux.

Simplified models of interactions

DM particle	mediator	couplings
 scalar	 scalar	$g_\nu g_\chi$ scalar/scalar fermion/scalar fermion/vector
 fermion	 fermion	g^2 scalar/fermion
	 vector	

Neutrino-dark matter interaction





$$\frac{d\phi(E)}{d\tau} = -\sigma(E)\phi(E) + \int d\tilde{E}\frac{d\sigma(\tilde{E},E)}{dE}\phi(\tilde{E})$$

flux loss

flux gain

$$\tau(b,l) = \int_{l.o.s} n_\chi(x;b,l)dx$$

integrated column density

DM profile: Einasto

Analysis method

Full Unbinned likelihood based on IceCube's event *energies* and *arrival direction*

$$\log \mathcal{L}(\{t, E, \vec{x}\}|\vartheta) = \sum_i \log \sum_{f=e,\mu,\tau} P^{astro}_{i,f}(t_i, E, \vec{x}) P(t_i|f, E) \phi(E, b, l|\vartheta)$$

- topology
- energy
- arrival direction
- model parameters
- events
- astrophysical-ness
- probability of an event yielding observed topology

We establish a limit based on Markov Chain Monte Carlo search of the parameter space of each interaction model: DM mass, mediator mass, and the coupling strength.

The model dependence of the likelihood thus comes from the directional *backscattering* with respect to the isotropic hypothesis.

Cosmological constrains

Cosmological limits on the DM-ν scattering cross section are obtained for two forms of the low-energy cross section:

- constant with temperature $\sigma_{const.} < 6 \times 10^{-31} \left(\frac{m_\chi}{\mathrm{GeV}}\right) \ \mathrm{cm}^2$
- proportional to T^2 $\sigma_{T^2} < 2 \times 10^{-40} \left(\frac{m_\chi}{\mathrm{GeV}}\right) \left(\frac{T}{T_0}\right)^2 \ \mathrm{cm}^2$

$T_0 = (4/11)^{1/3} T_{CMB} = 1.95K$ cosmological neutrino temperature today

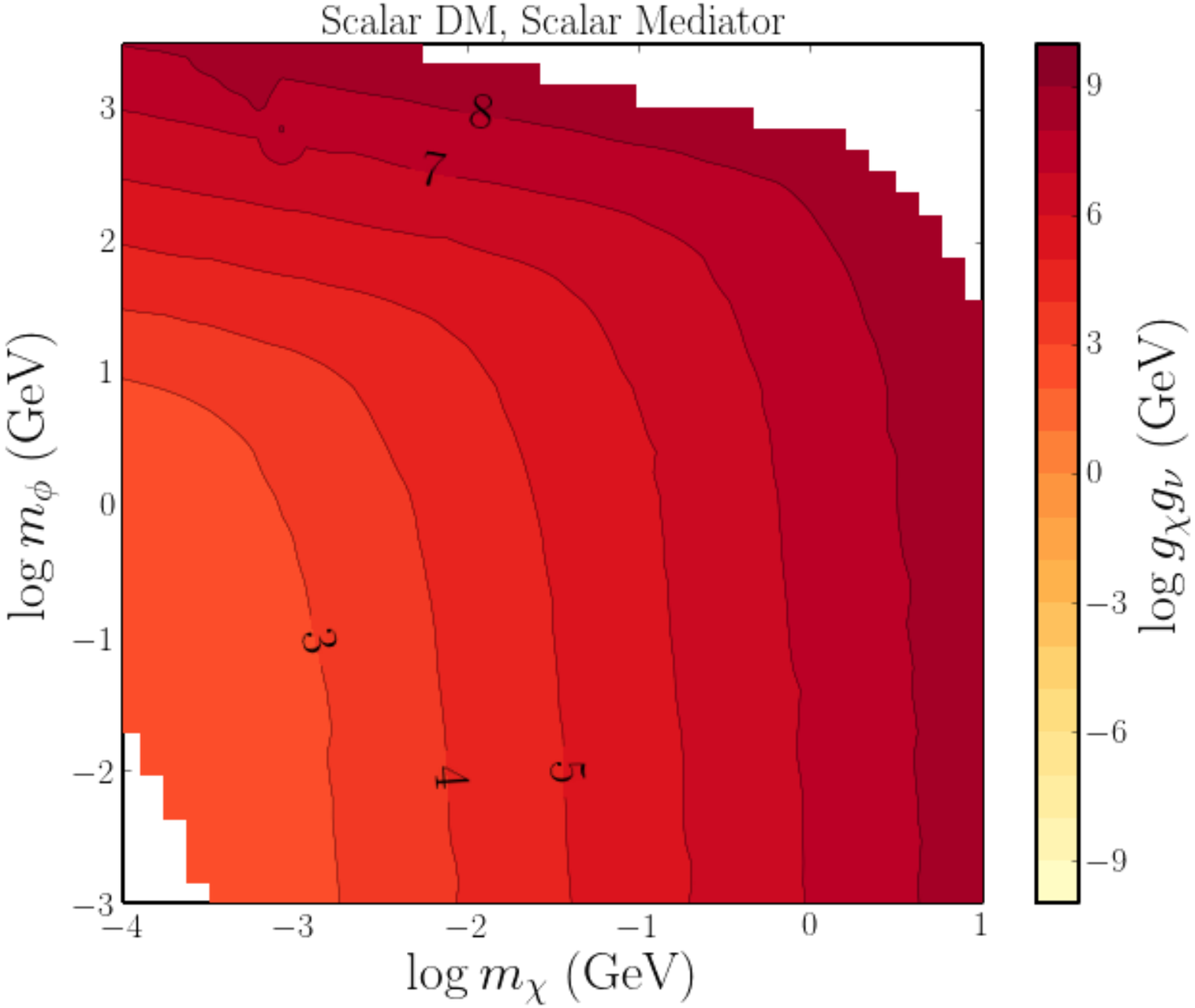
$\langle E_\nu^2 \rangle \propto T^2$ average energy per neutrino in a Fermi-Dirac distribution

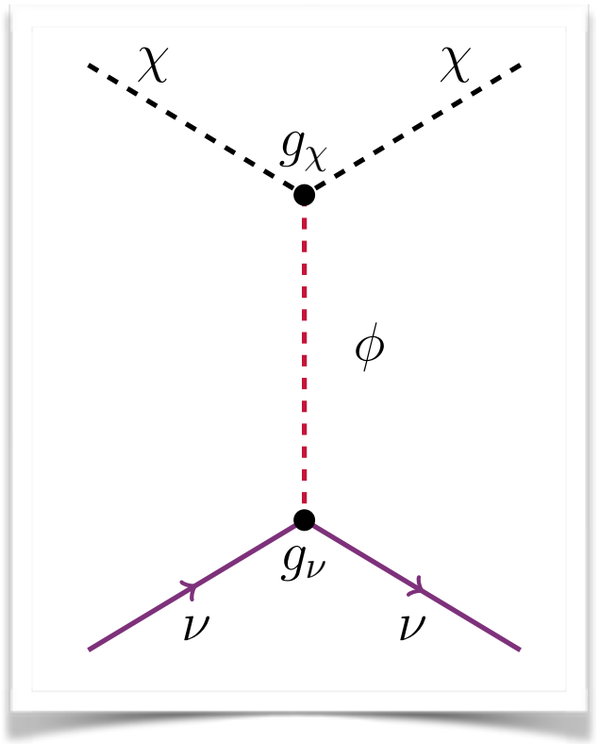
arXiv:1505.06735

If the cross section is proportional to E^2, then the we could look at high energy regimes to constrain the parameter space.

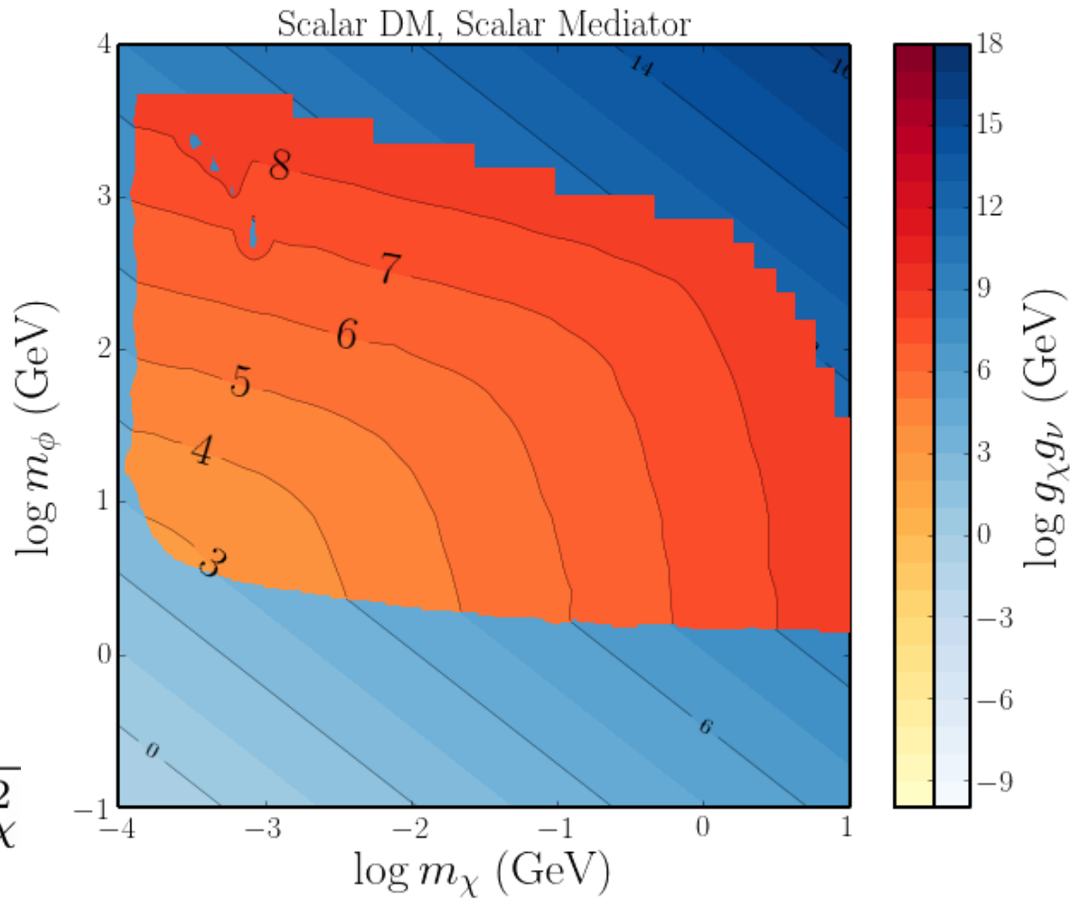
Scalar DM, Scalar Med.

our bound



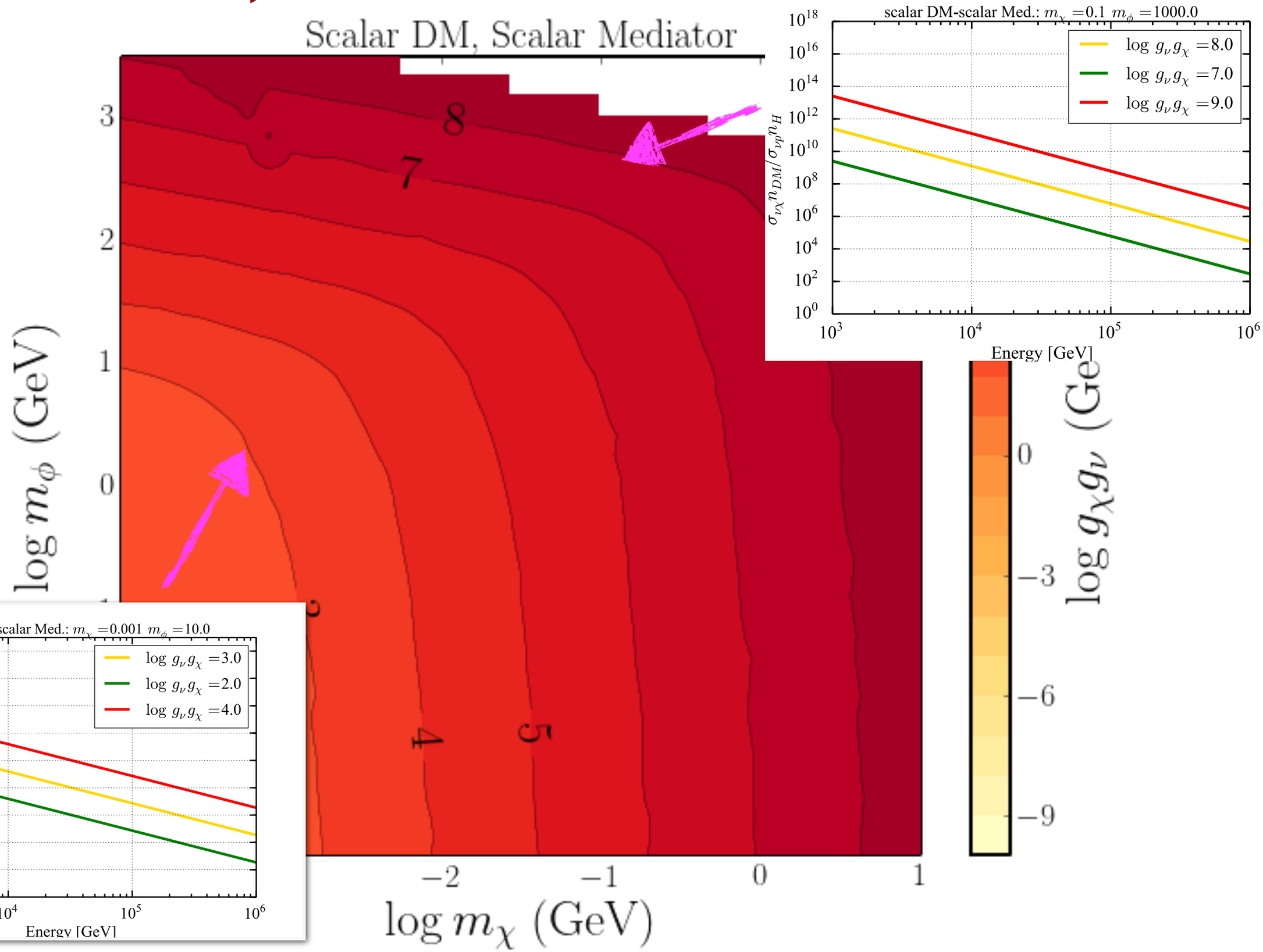


cosmology+our bound

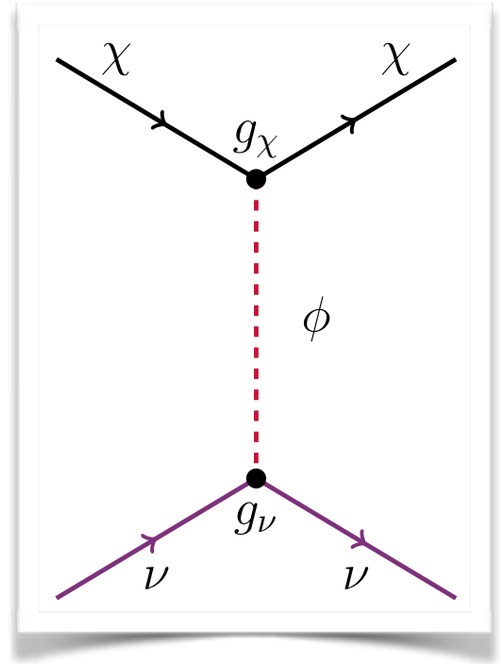


low energy limit: $\sigma \simeq \dfrac{g_\nu^2 g_\chi^2 E^2}{16\pi m_\phi^4 m_\chi^2}$

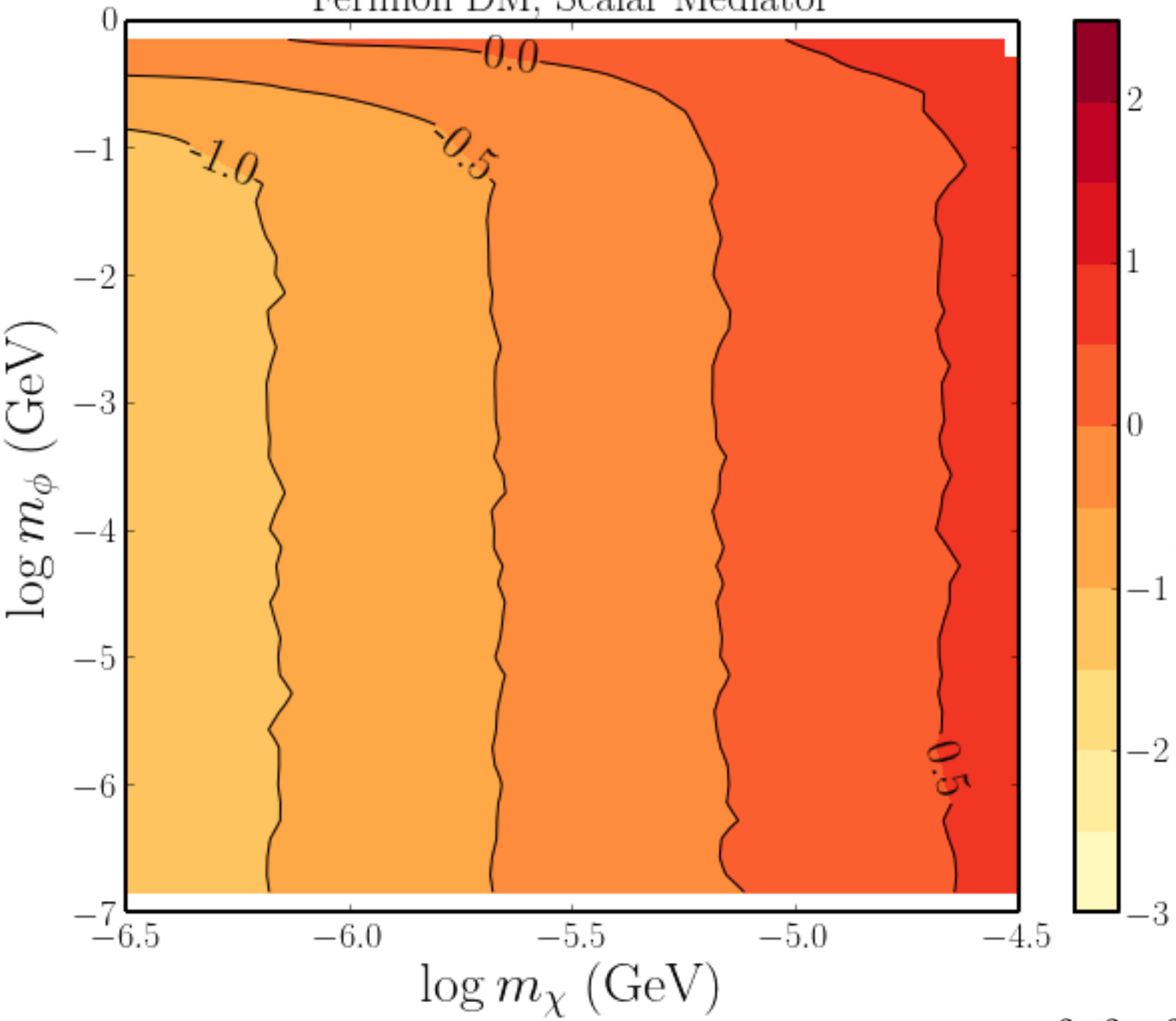
Scalar DM, Scalar Med.



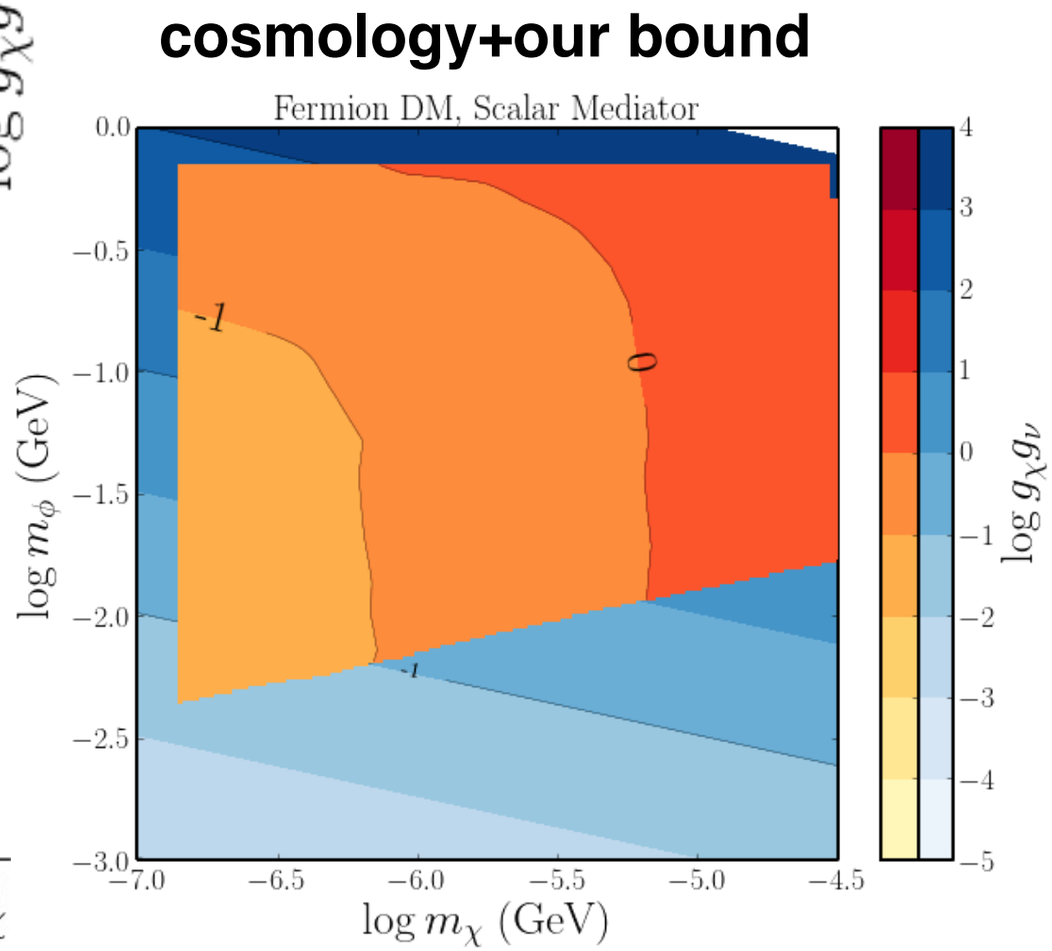
Fermion DM, Scalar Med.



our bound

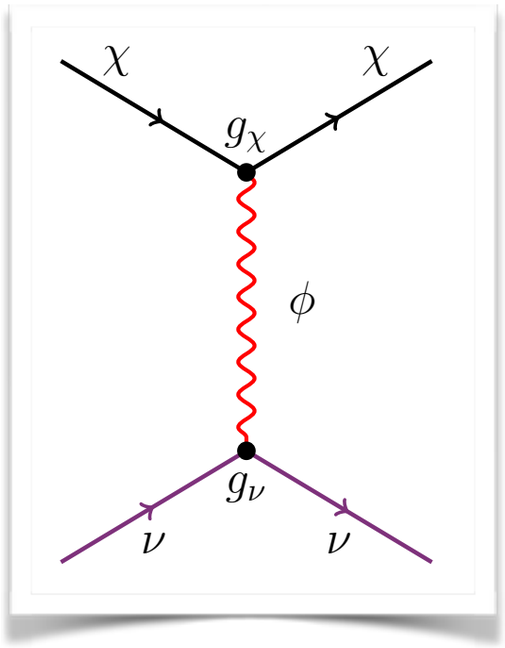


cosmology+our bound

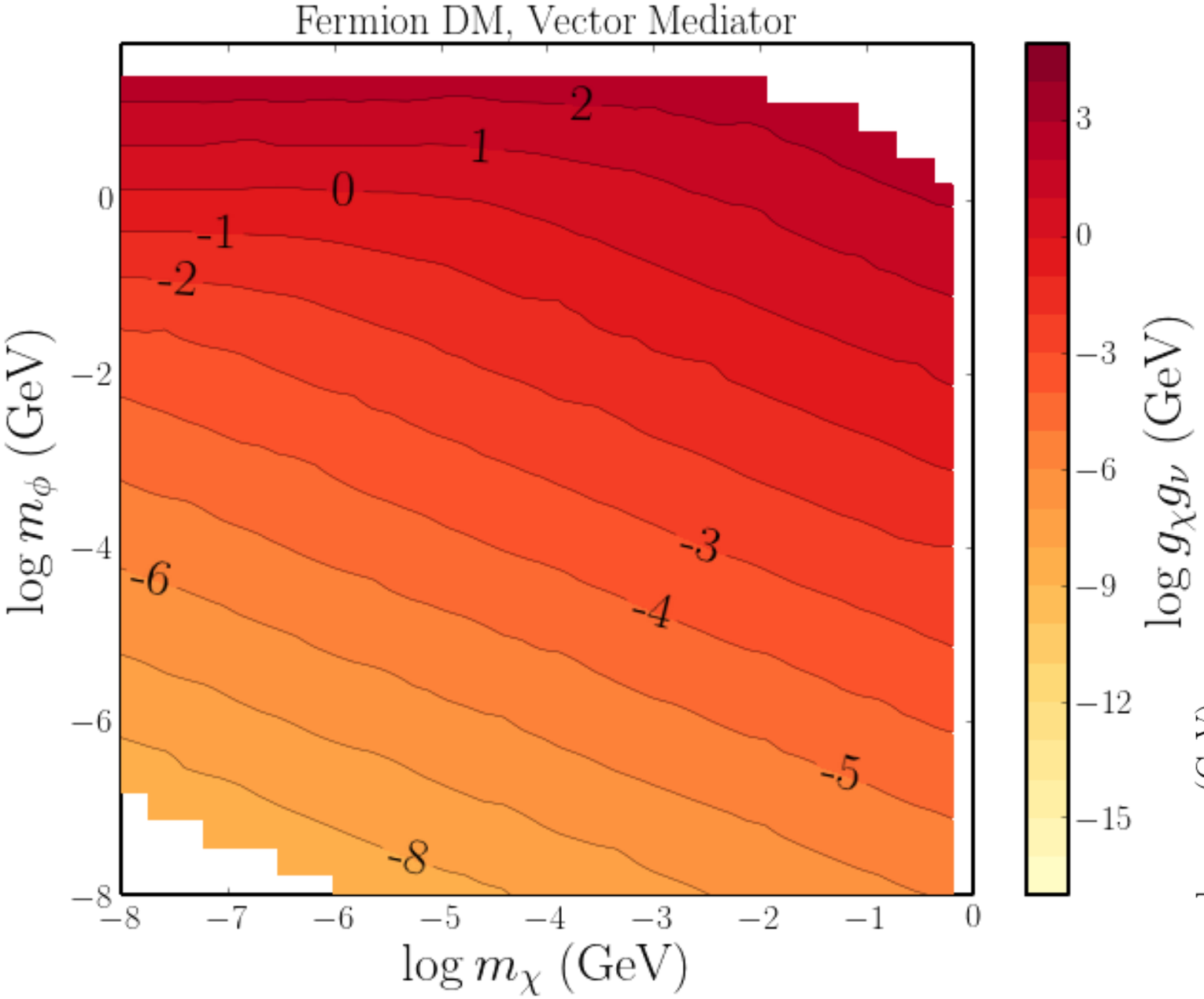


low energy limit: $\sigma \simeq \dfrac{g_\nu^2 g_\chi^2 E^2}{16\pi m_\phi^4 m_\chi^2}$

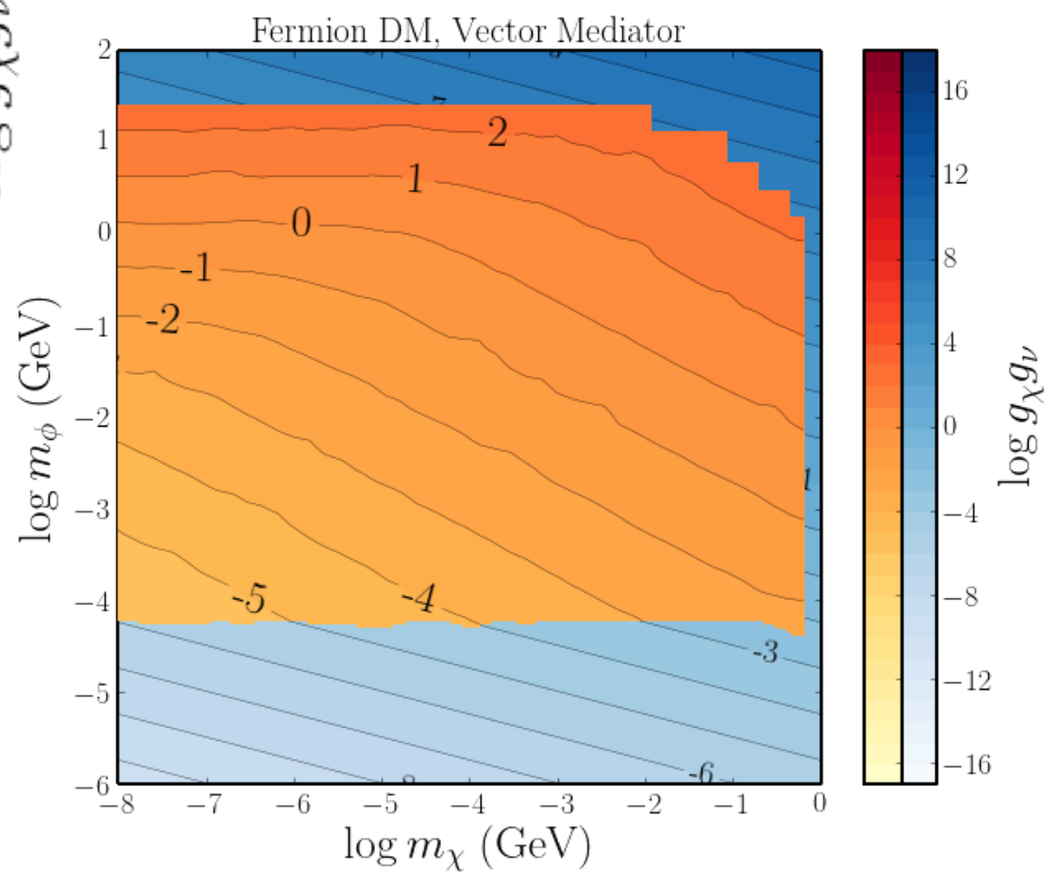
Fermion DM, Vector Med.



our bound



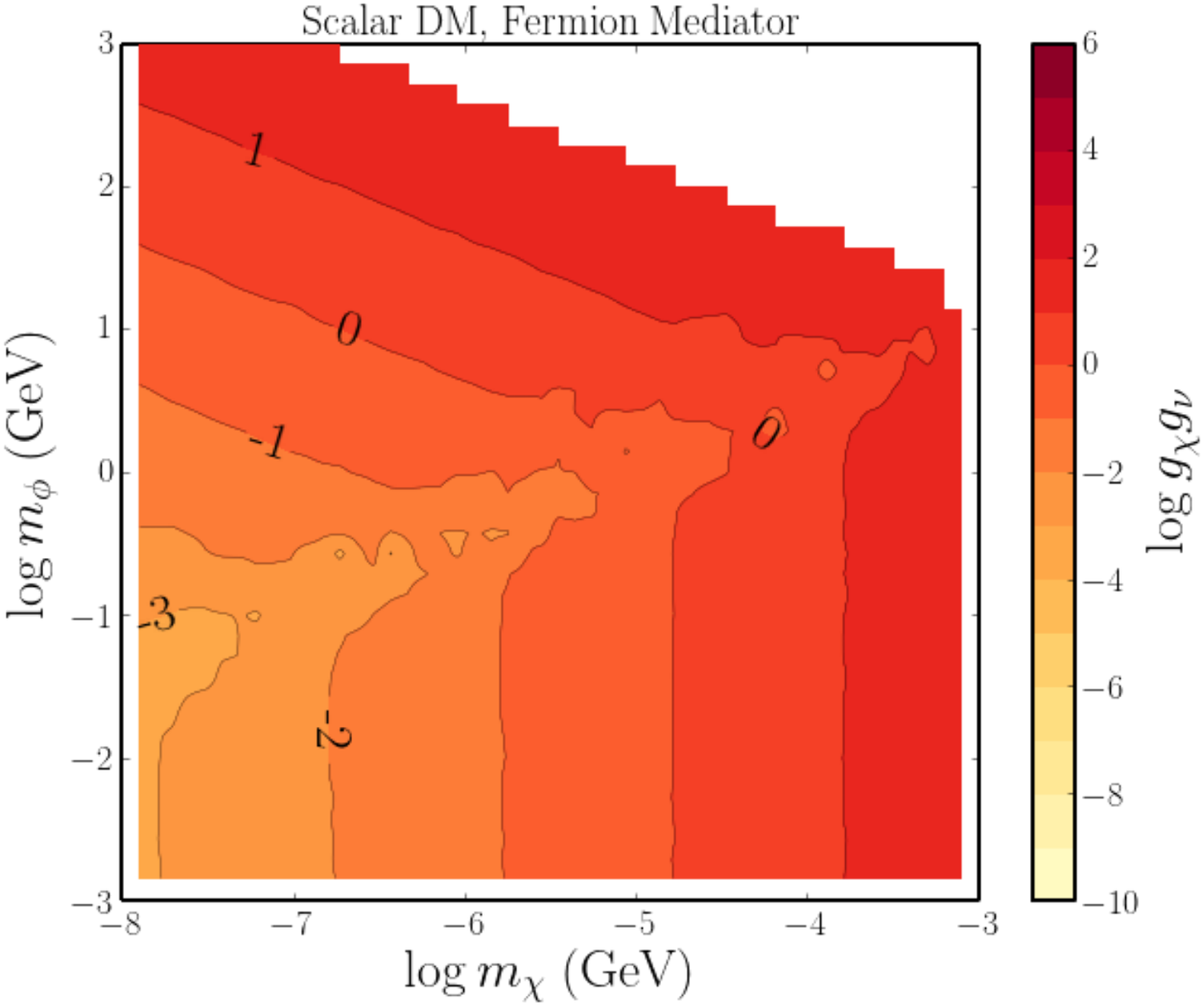
cosmology+our bound

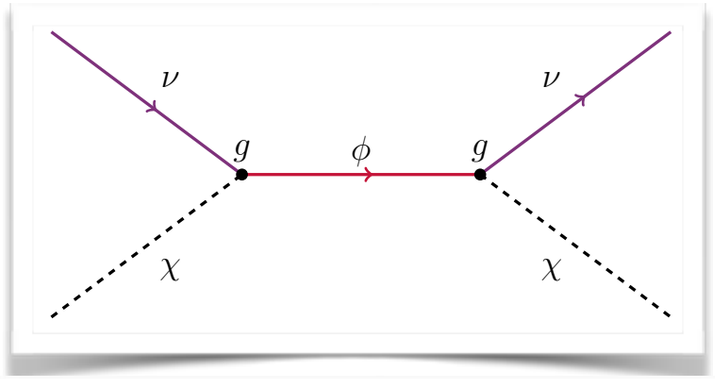


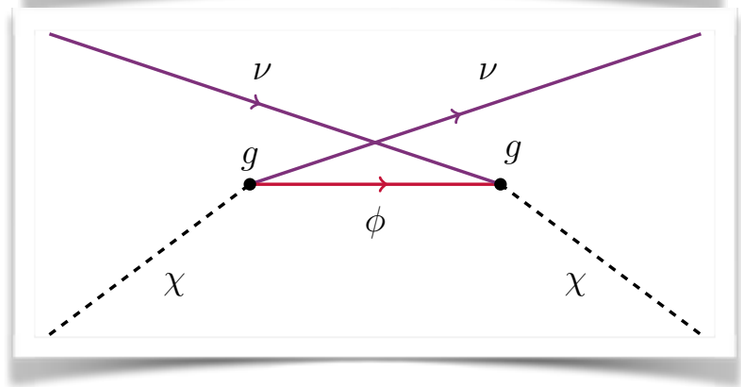
low energy limit: $\sigma \simeq \dfrac{g_\chi^2 g_\nu^2 E_\nu^2}{2\pi m_\phi^4}$

Scalar DM, Fermion Med.

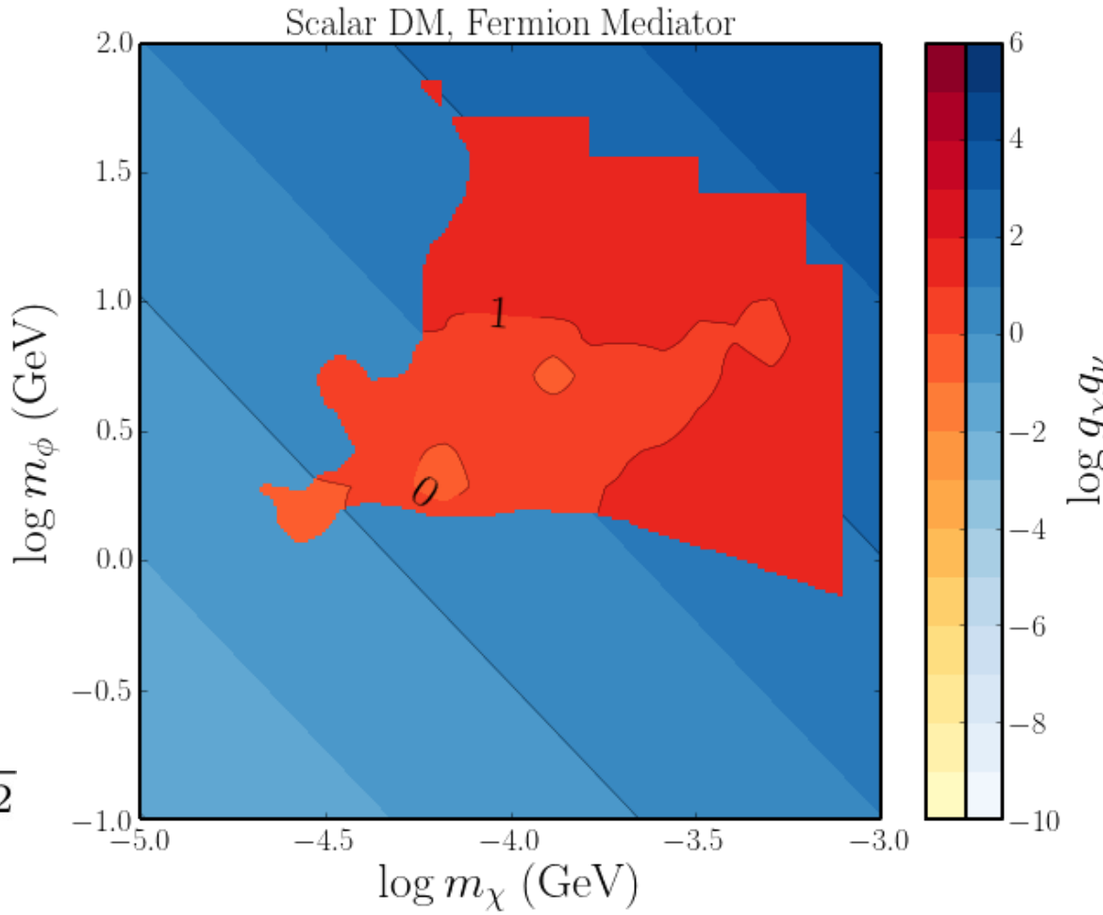
our bound







cosmology+our bound

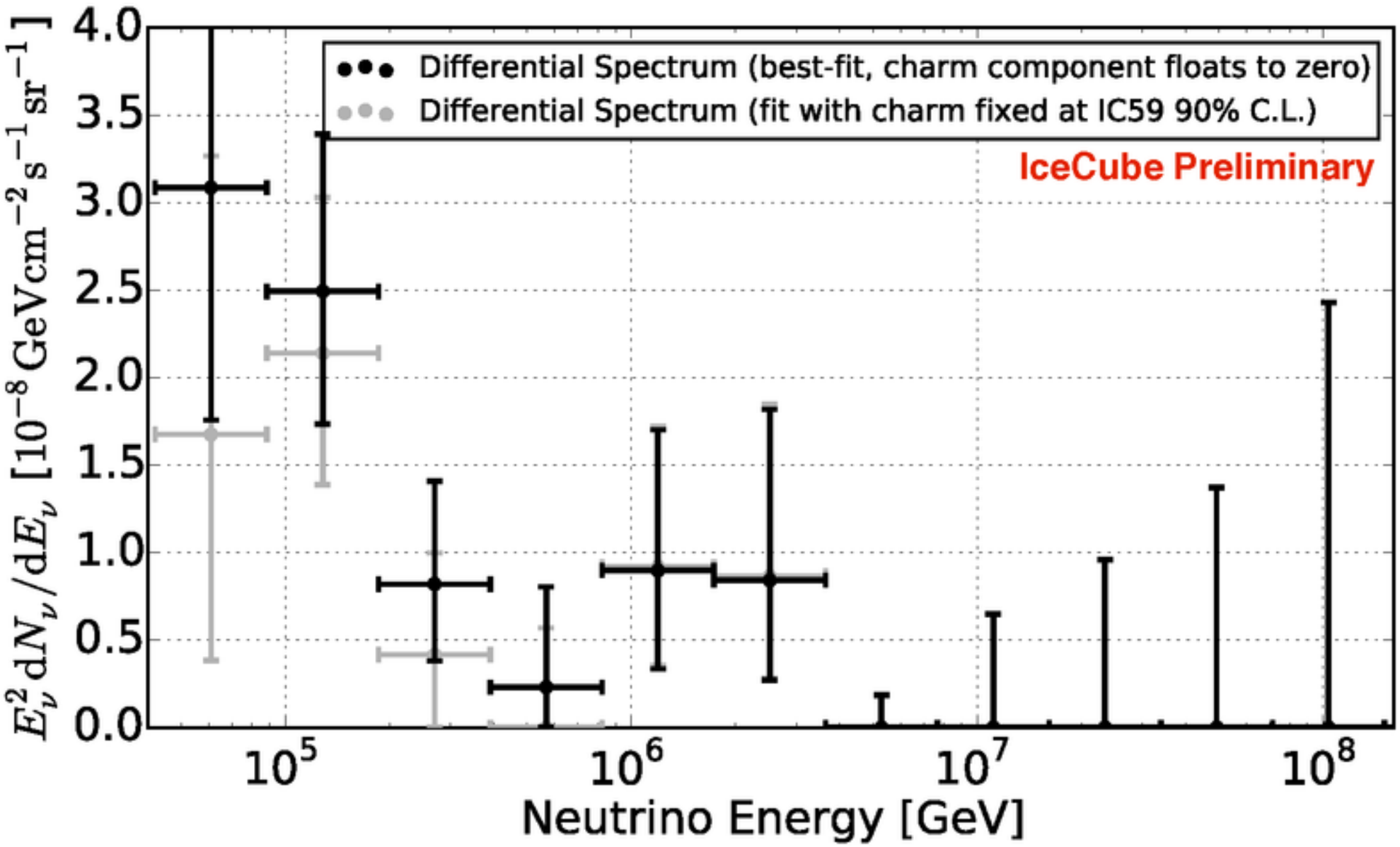


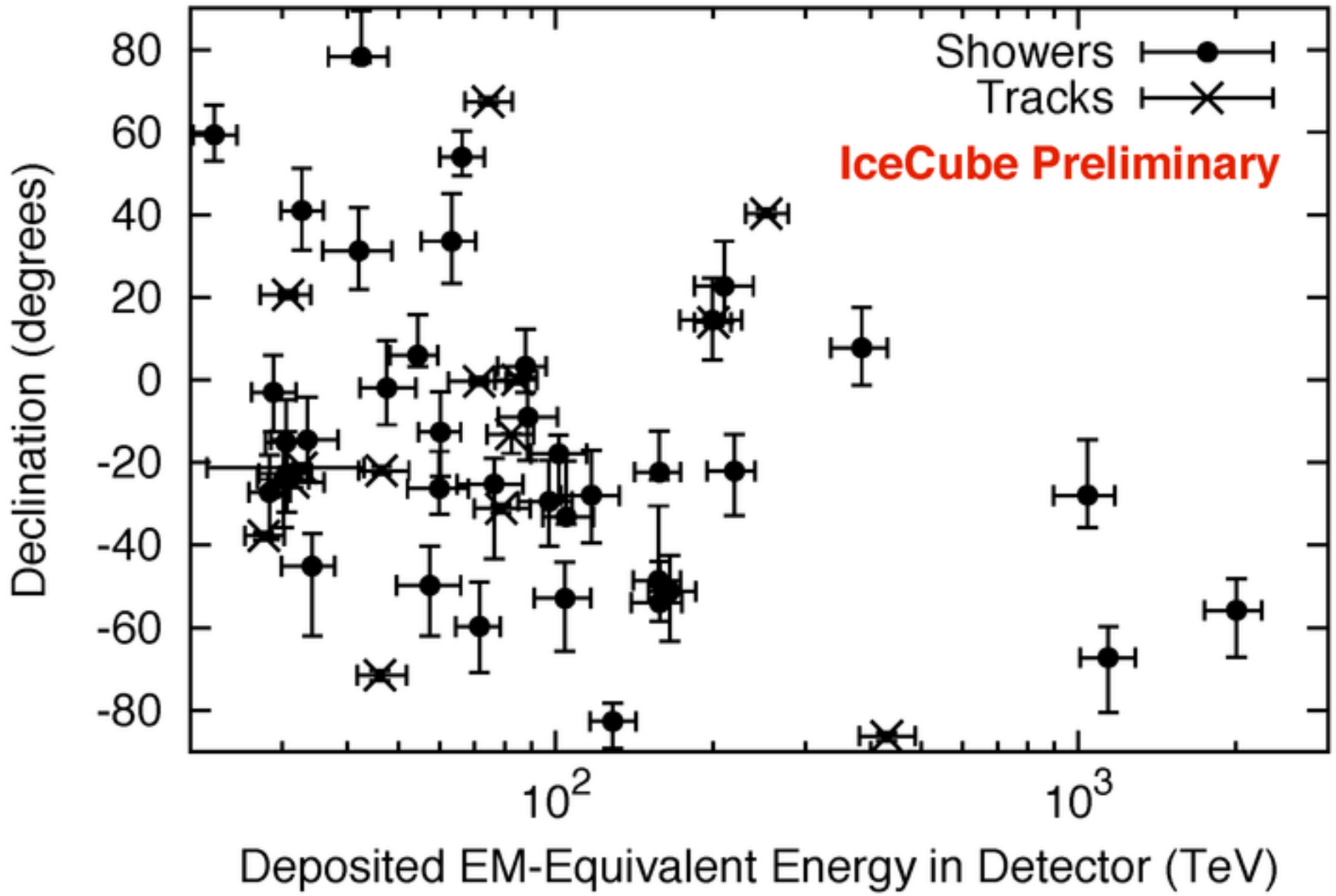
low energy limit: $\sigma \simeq \dfrac{g^4 m_\phi^2 E_\nu^2}{2\pi m_\chi^2 (m_\chi^2 - m_\phi^2)^2}$

Summary

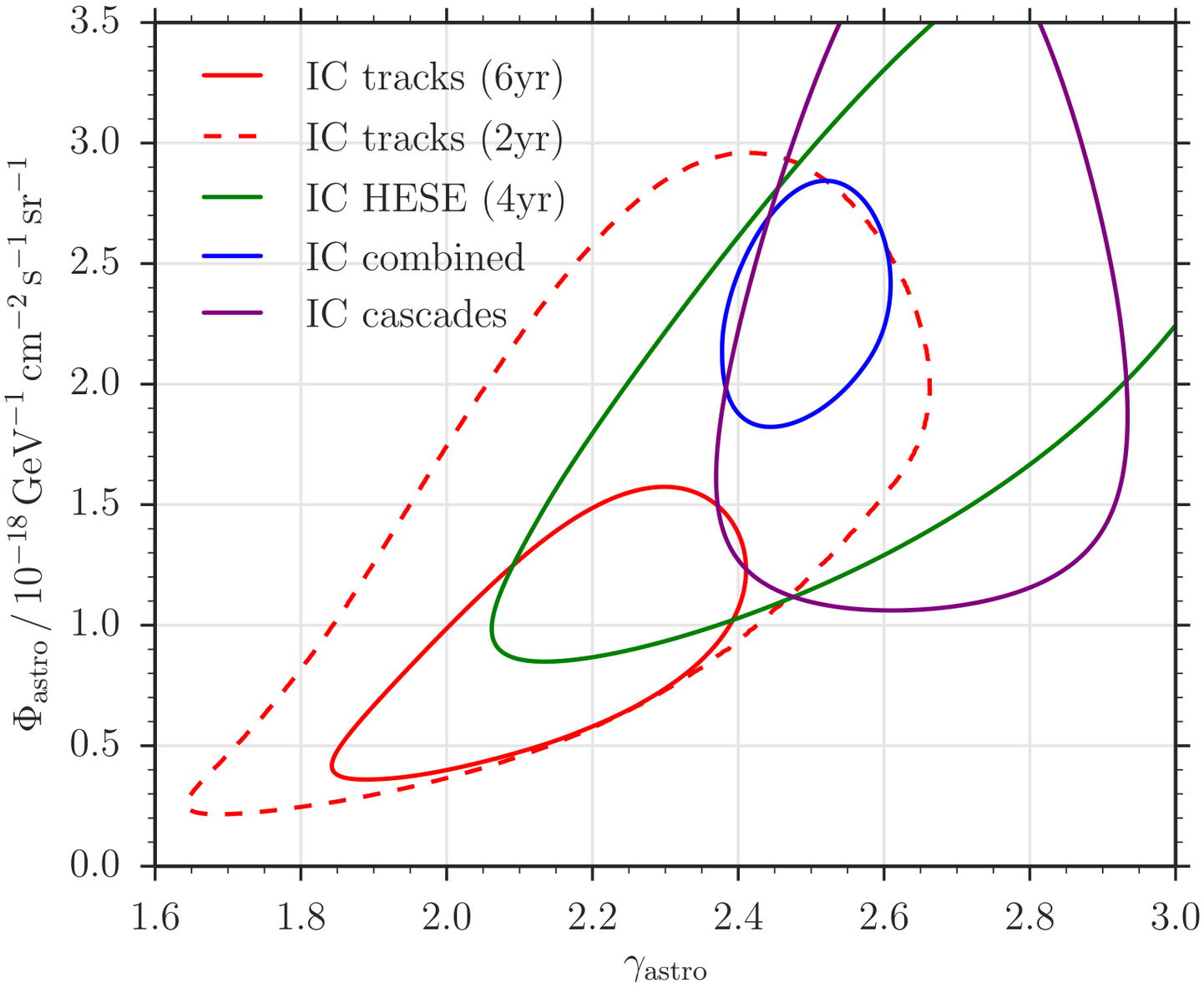
- Dark Matter-Neutrino interactions are motivated in beyond standard models.
- The discovery of high energy cosmic neutrinos allows us to investigate DM-neutrino interactions.
- The upper limits found on the model parameters are **stronger** than cosmological constraints in parts of the parameter space.
- Observation of more events would provide stronger constraints, and allow for discovery of this interaction for large part (low DM + med mass) of the parameter space.

Bonus Slides


Differential Spectrum (best-fit, charm component floats to zero)
Differential Spectrum (fit with charm fixed at IC59 90% C.L.)
IceCube Preliminary
$E_\nu^2 \mathrm{d}N_\nu/\mathrm{d}E_\nu$ [10^{-8} GeV cm^{-2} s^{-1} sr^{-1}]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^5
10^6
10^7
10^8
Neutrino Energy [GeV]


Showers
Tracks
IceCube Preliminary
80
60
40
20
0
-20
-40
-60
-80
Declination (degrees)
10^2
10^3
Deposited EM-Equivalent Energy in Detector (TeV)

Fit of Power-Law Spectrum



- update of $\nu_\mu + \bar{\nu}_\mu$ search ("IC tracks") [PRL 115 (2015) 081102; arXiv:1607.08006]

➜ mild tension with cascade-dominated samples: **indication of spectral features?**

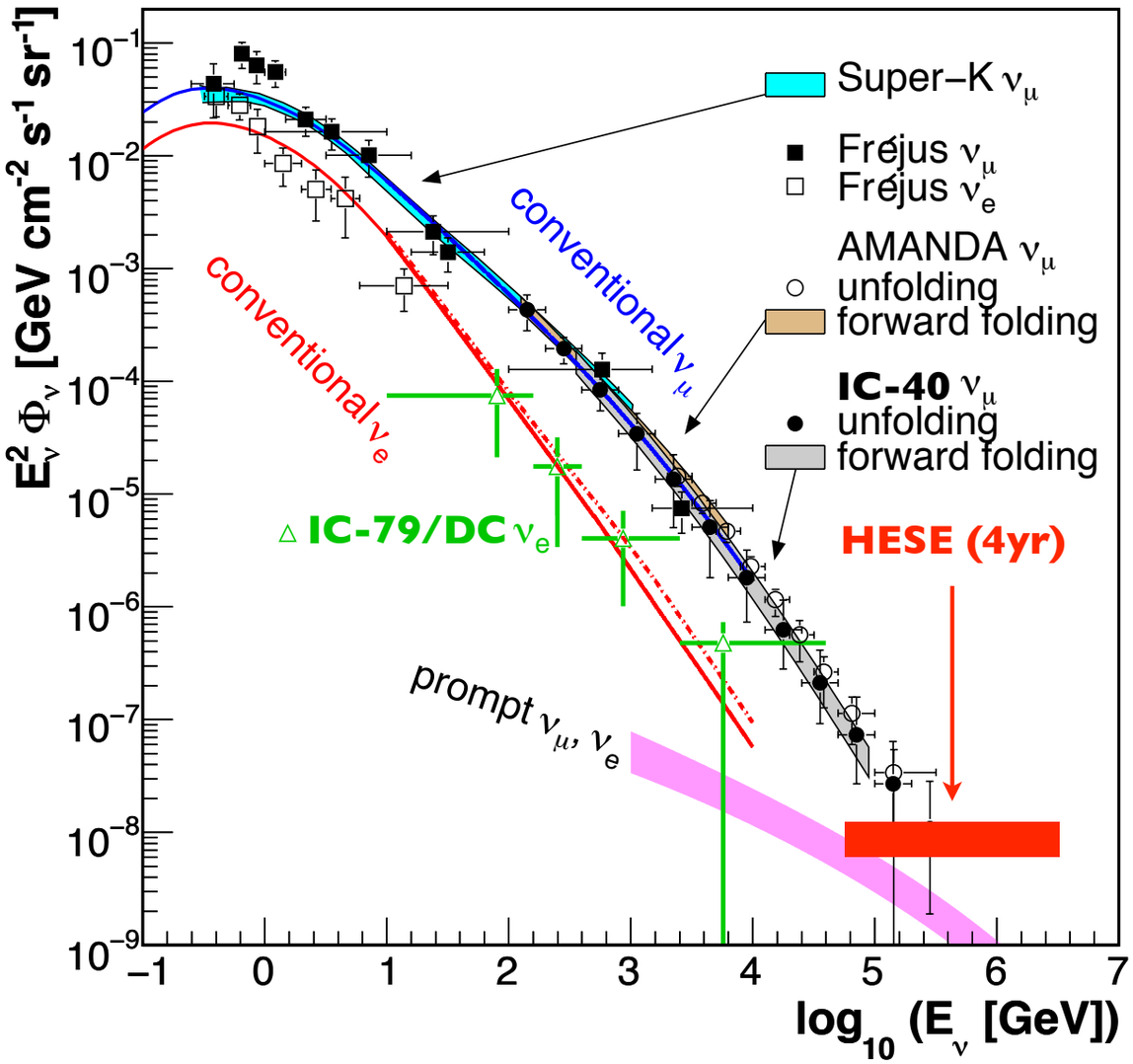
Credit: Markus Ahlers

IceCube HESE (4yr)

- **High-Energy Starting Event (HESE)** sample: [IceCube Science 342 (2013)]
  - bright events ($E_{\rm th} \gtrsim 30$TeV) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer

- 54 events in about four years: [IceCube ICRC'15]
  - 39 **cascades** events
  - 14 **track** events
  - 1 **composite** event (removed)
- expected background events:
  - $9.0^{+8.0}_{-2.2}$ **atmospheric neutrinos**
  - 12.6 ± 5.1 **atmospheric muons**
- best-fit E^{-2}-flux 60TeV-3PeV (6.5σ):

$$E_\nu^2 \phi_{\nu_\alpha} \simeq (0.84 \pm 0.3) \times 10^{-8} \frac{\rm GeV}{\rm s\,cm^2\,sr}$$

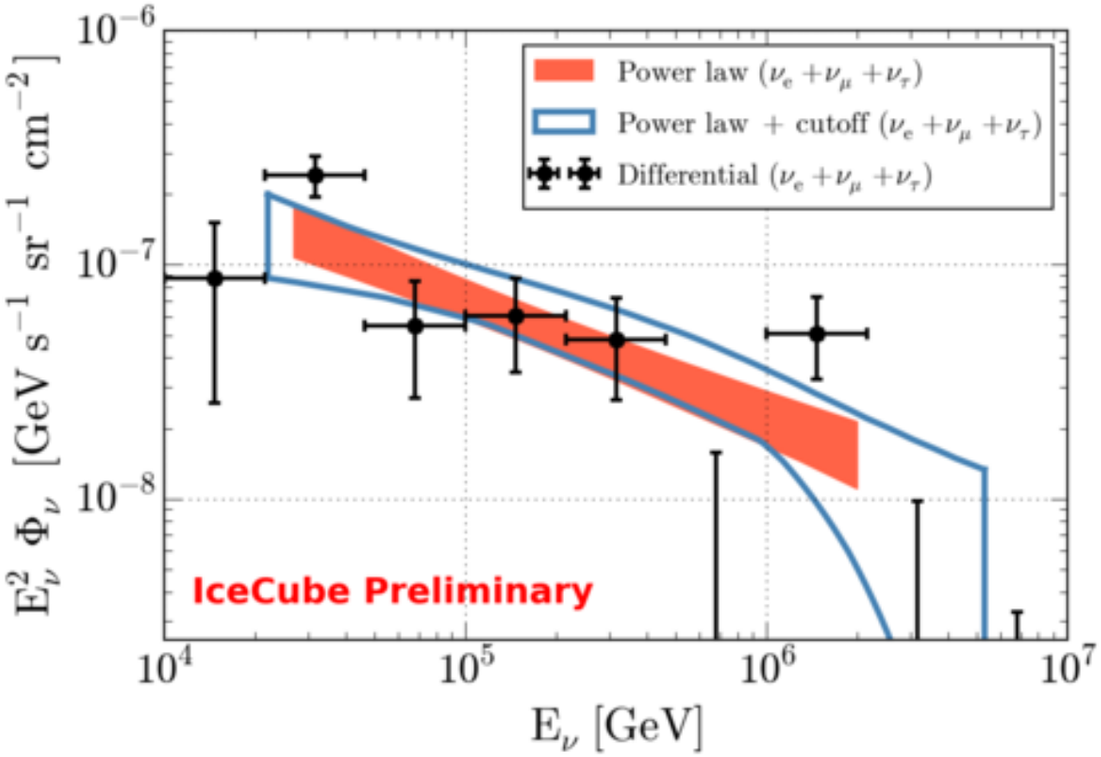


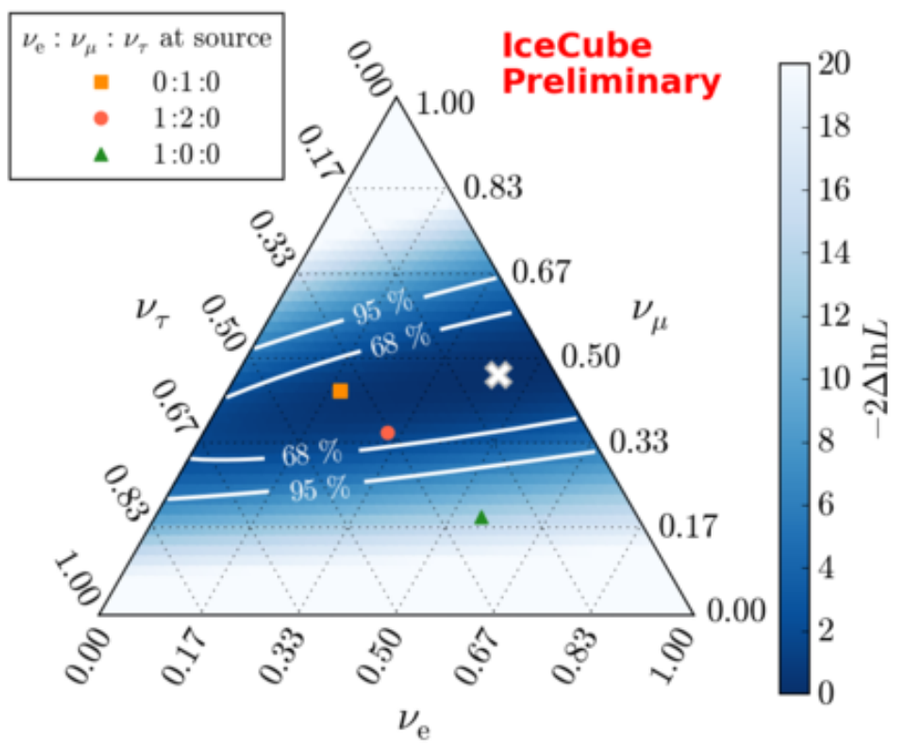
Credit: Markus Ahlers

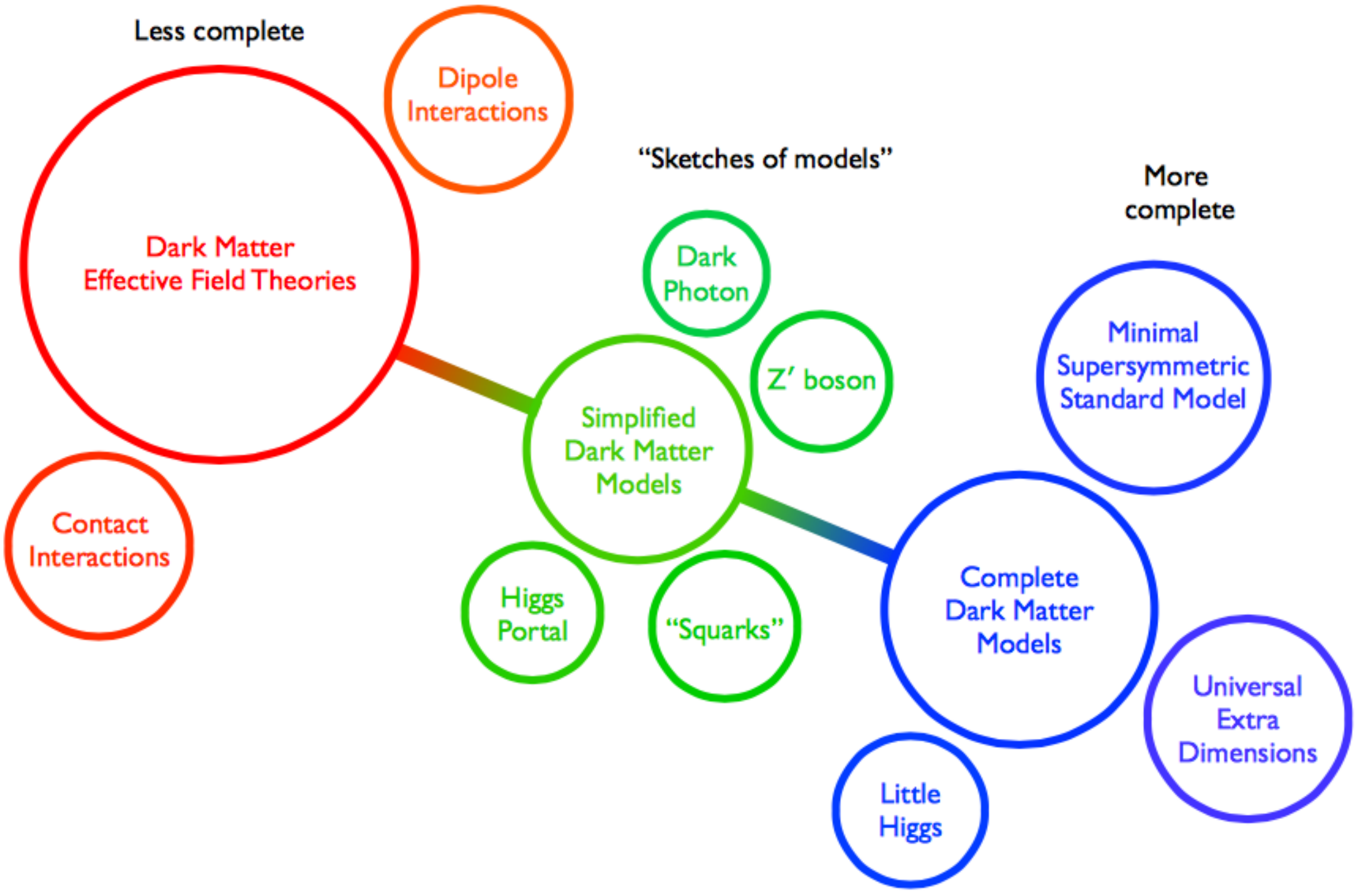
High Energy Neutrinos: Samples

- High Energy Starting Events
  whole sky, 4 years, all flavors, veto
- Through going tracks
  northern sky, 6 years, muons
- Medium Energy Starting Events
  whole sky, 2 years, cascades, veto

Global Fit

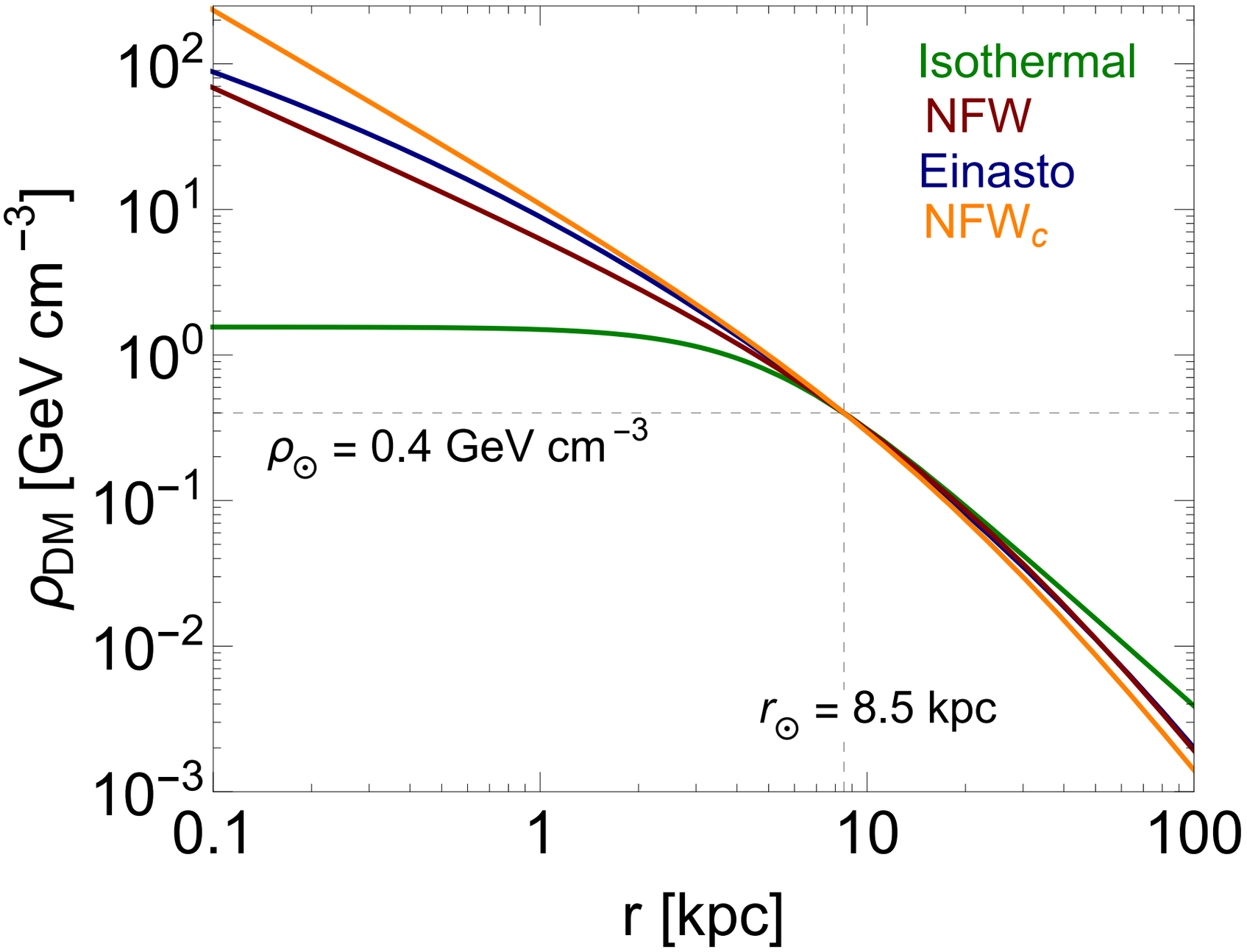




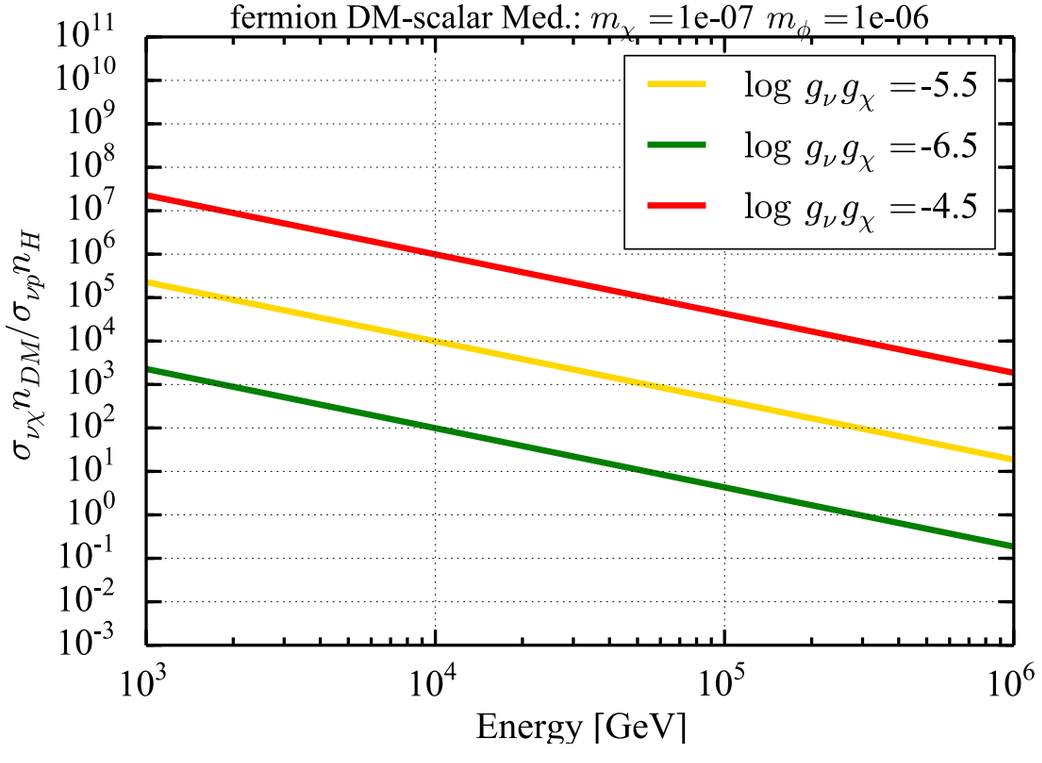


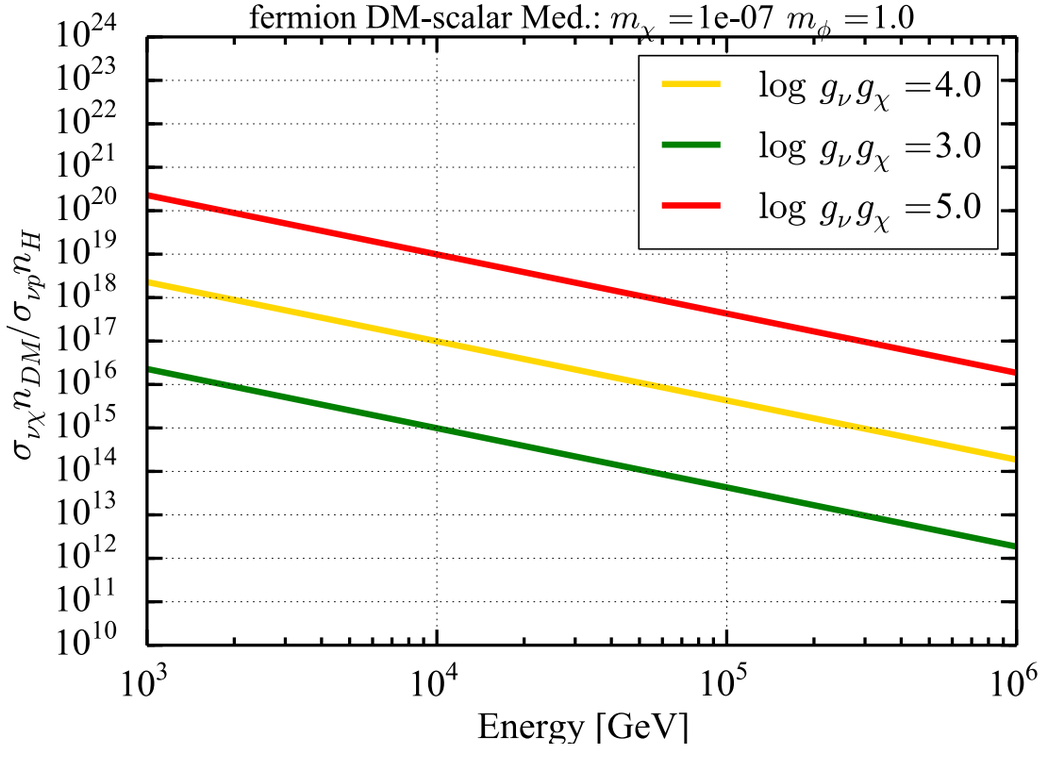
Abdallah et al 2015

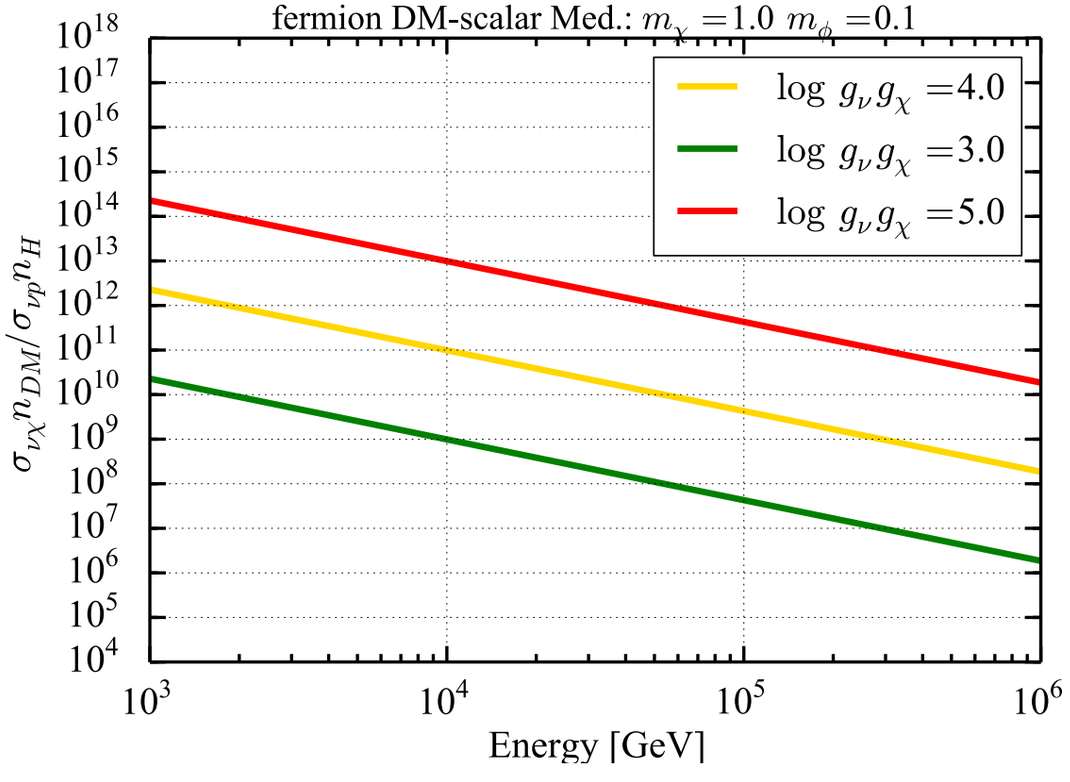
DM profiles

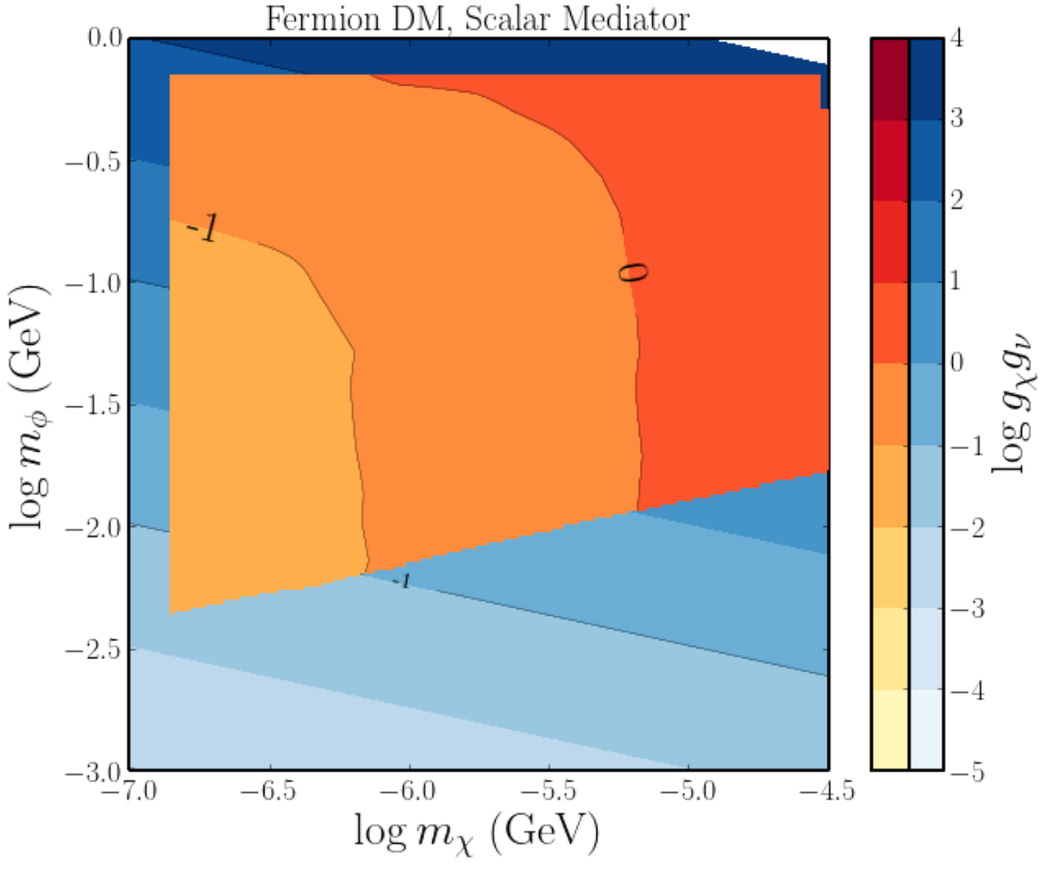


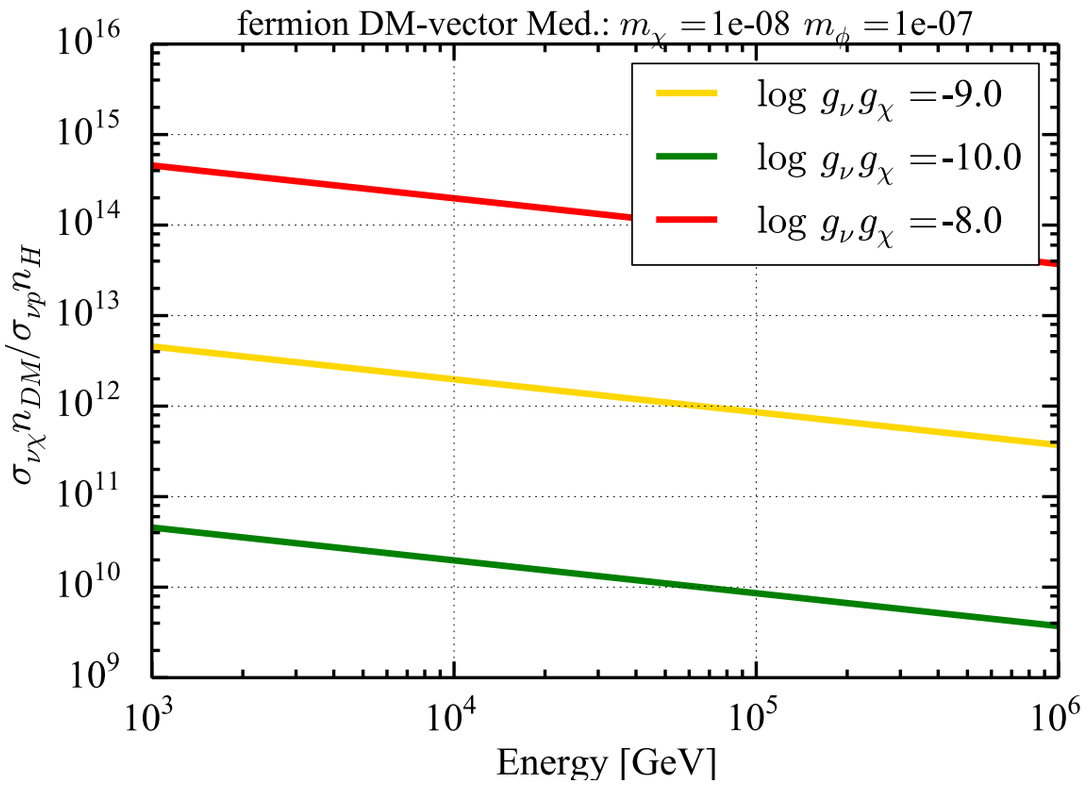
arXiv:1503.07169

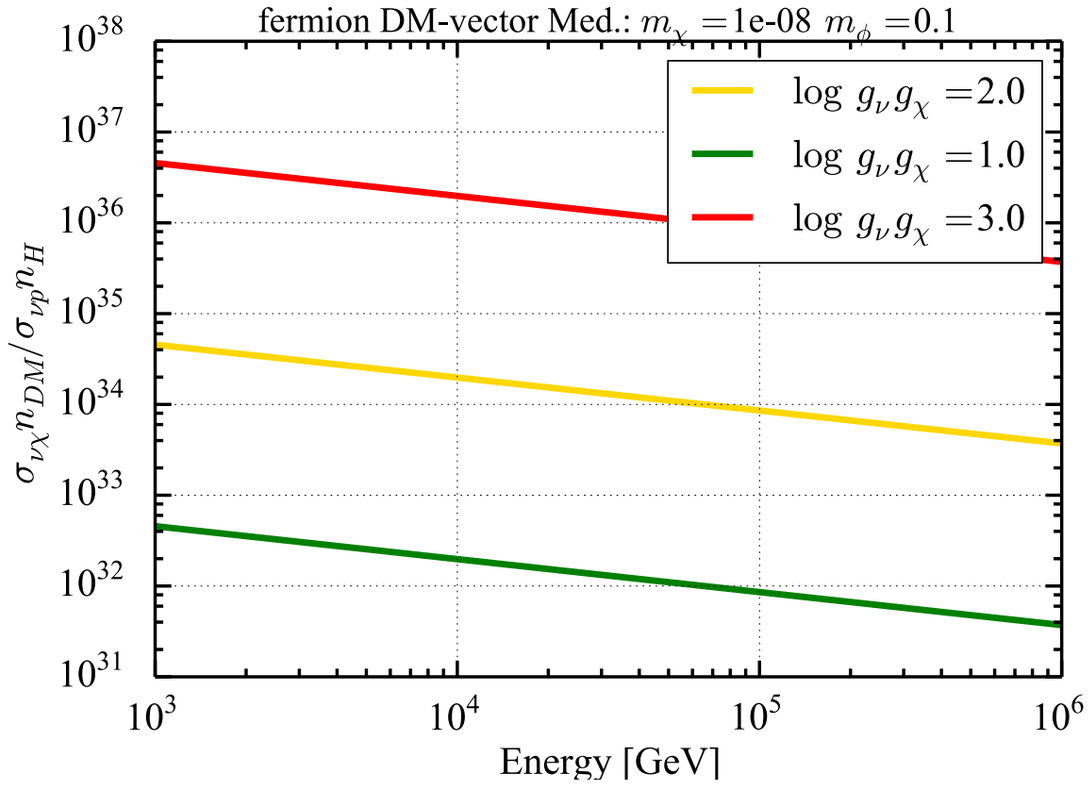

fermion DM-scalar Med.: m_χ =1e-07 m_ϕ =1e-06
log $g_\nu g_\chi$ =-5.5
log $g_\nu g_\chi$ =-6.5
log $g_\nu g_\chi$ =-4.5
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]

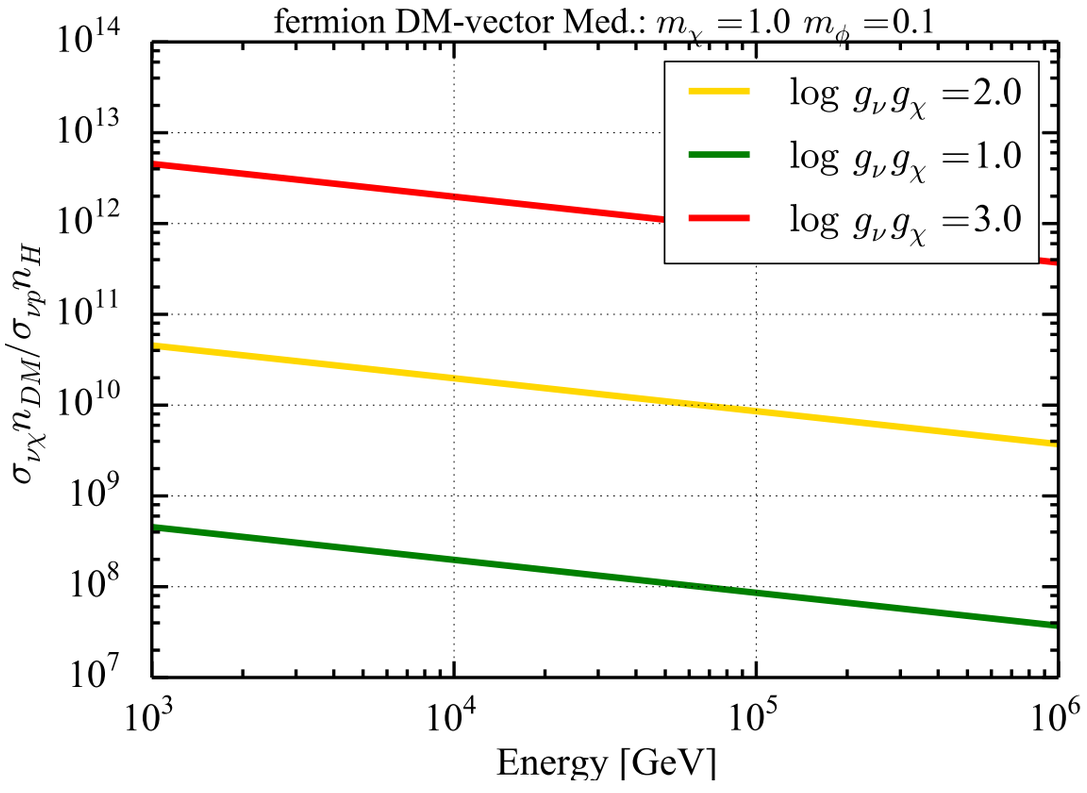

fermion DM-scalar Med.: m_χ =1e-07 m_ϕ =1.0
log $g_\nu g_\chi$ =4.0
log $g_\nu g_\chi$ =3.0
log $g_\nu g_\chi$ =5.0
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]

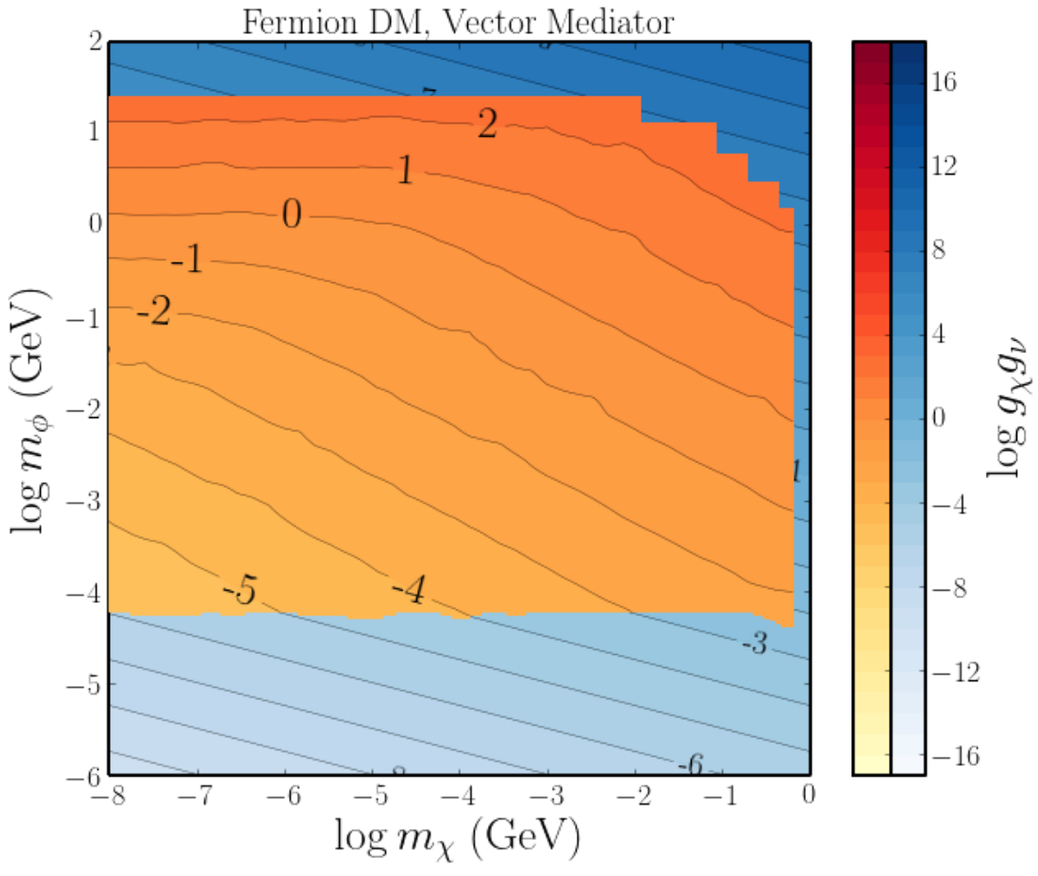

fermion DM-scalar Med.: m_χ =1.0 m_ϕ =0.1
log $g_\nu g_\chi$ =4.0
log $g_\nu g_\chi$ =3.0
log $g_\nu g_\chi$ =5.0
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]

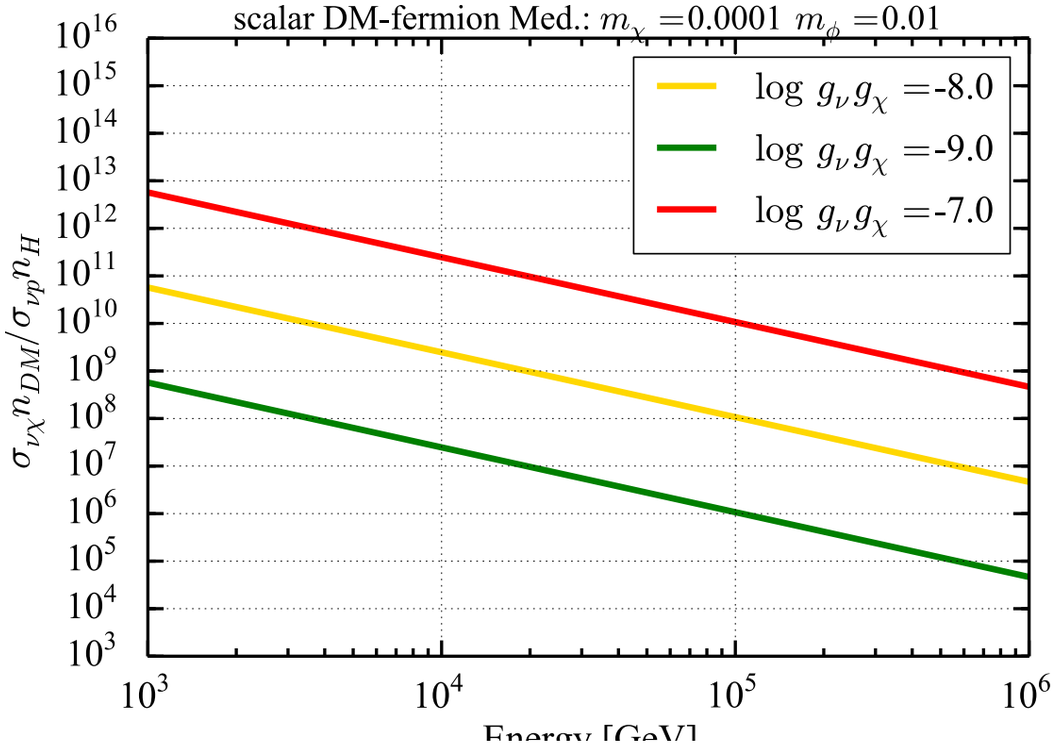

Fermion DM, Scalar Mediator
-1
0
-1
log m_ϕ (GeV)
log m_χ (GeV)
log $g_\chi g_\nu$

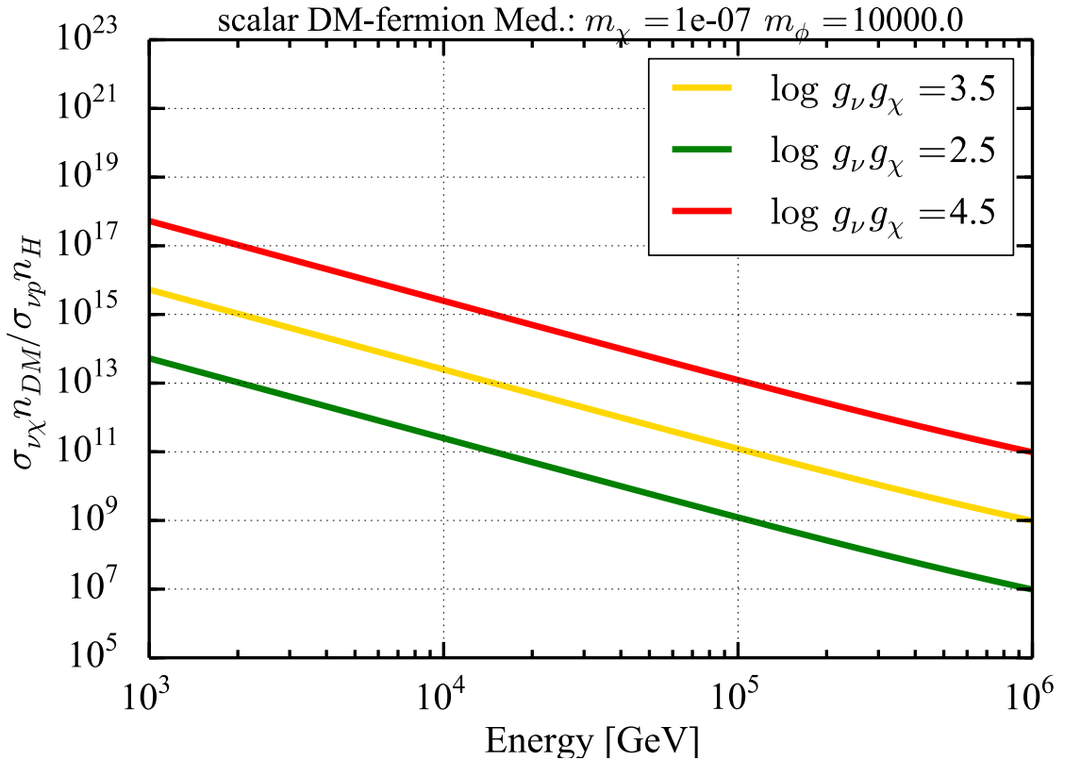

fermion DM-vector Med.: m_χ =1e-08 m_ϕ =1e-07
log $g_\nu g_\chi$ =-9.0
log $g_\nu g_\chi$ =-10.0
log $g_\nu g_\chi$ =-8.0
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]

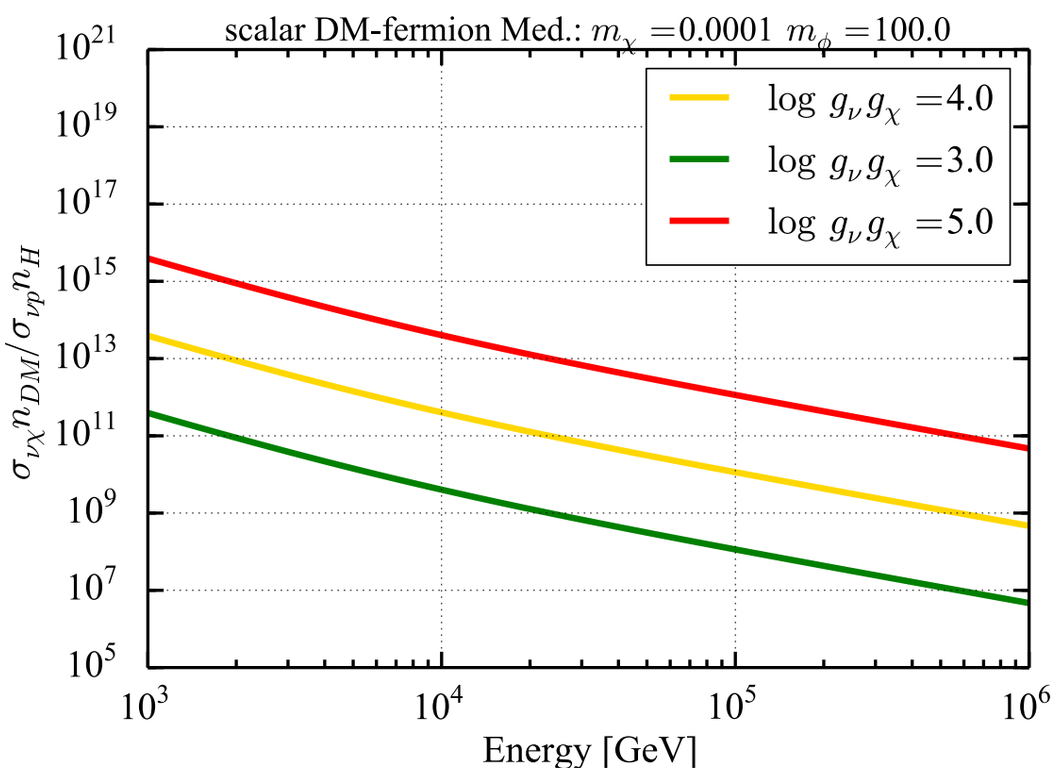

fermion DM-vector Med.: m_χ =1e-08 m_ϕ =0.1
log $g_\nu g_\chi$ =2.0
log $g_\nu g_\chi$ =1.0
log $g_\nu g_\chi$ =3.0
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]

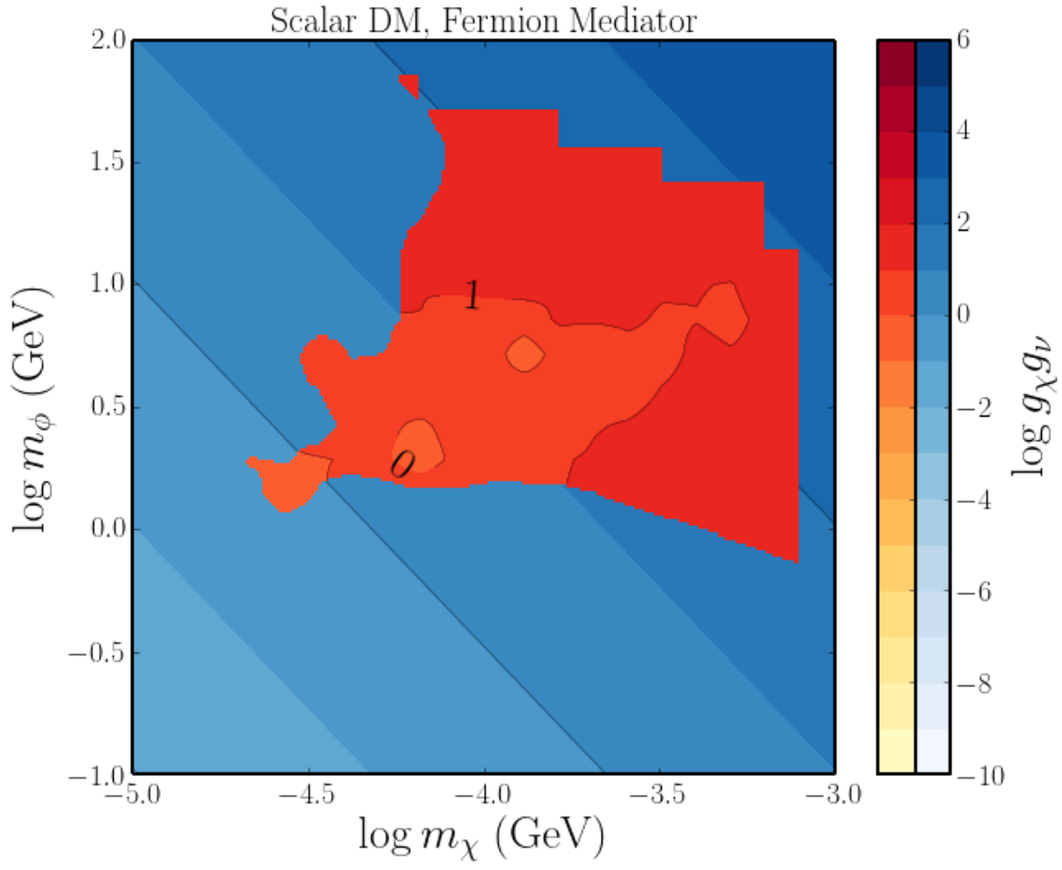

fermion DM-vector Med.: m_χ =1.0 m_ϕ =0.1
log $g_\nu g_\chi$ =2.0
log $g_\nu g_\chi$ =1.0
log $g_\nu g_\chi$ =3.0
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]

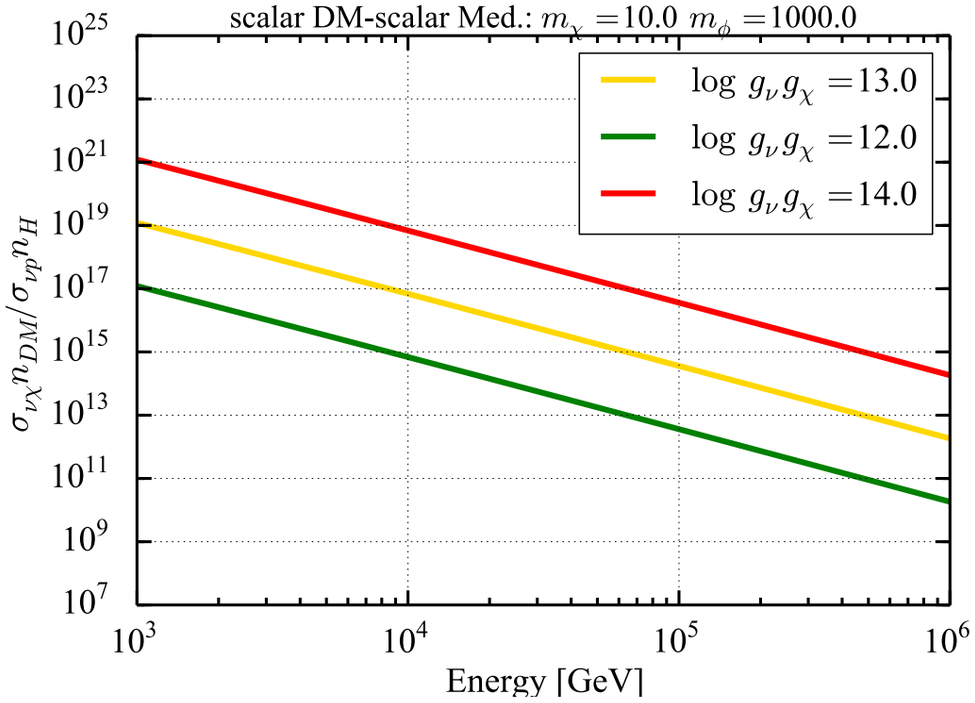

Fermion DM, Vector Mediator
log m_ϕ (GeV)
log m_χ (GeV)
log $g_\chi g_\nu$

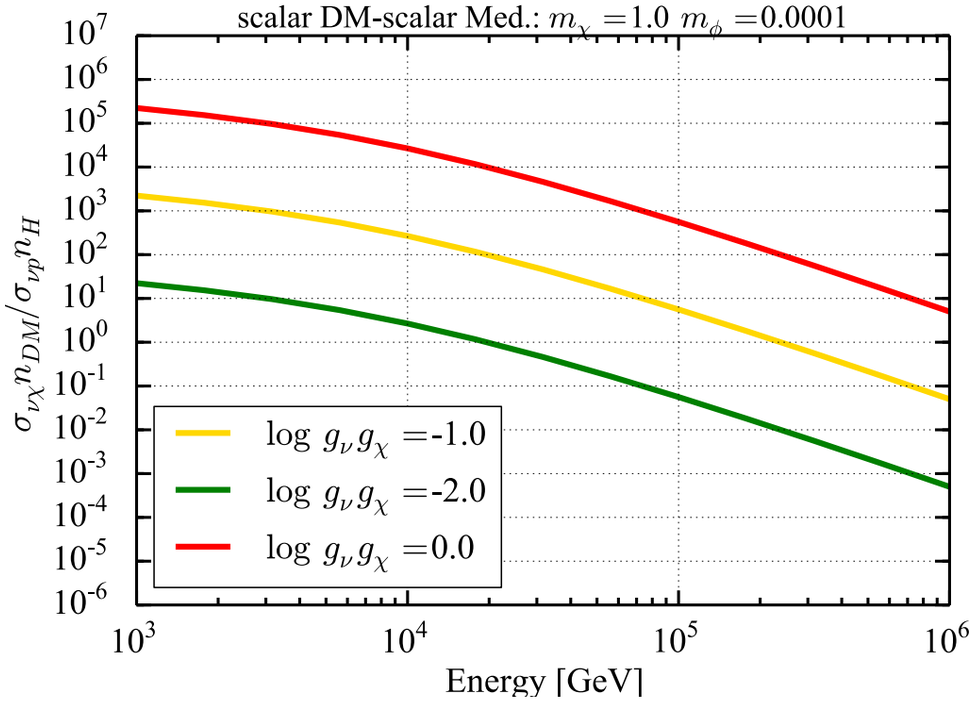

scalar DM-fermion Med.: m_χ =0.0001 m_ϕ =0.01
log $g_\nu g_\chi$ =-8.0
log $g_\nu g_\chi$ =-9.0
log $g_\nu g_\chi$ =-7.0
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]

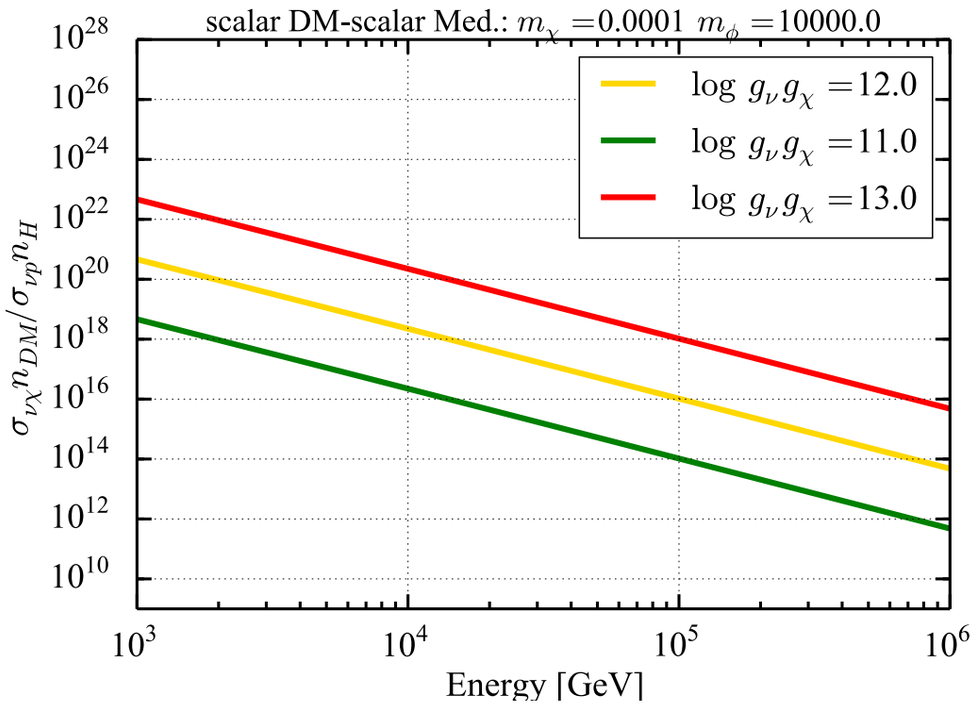

scalar DM-fermion Med.: m_χ =1e-07 m_ϕ =10000.0
log $g_\nu g_\chi$ =3.5
log $g_\nu g_\chi$ =2.5
log $g_\nu g_\chi$ =4.5
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]

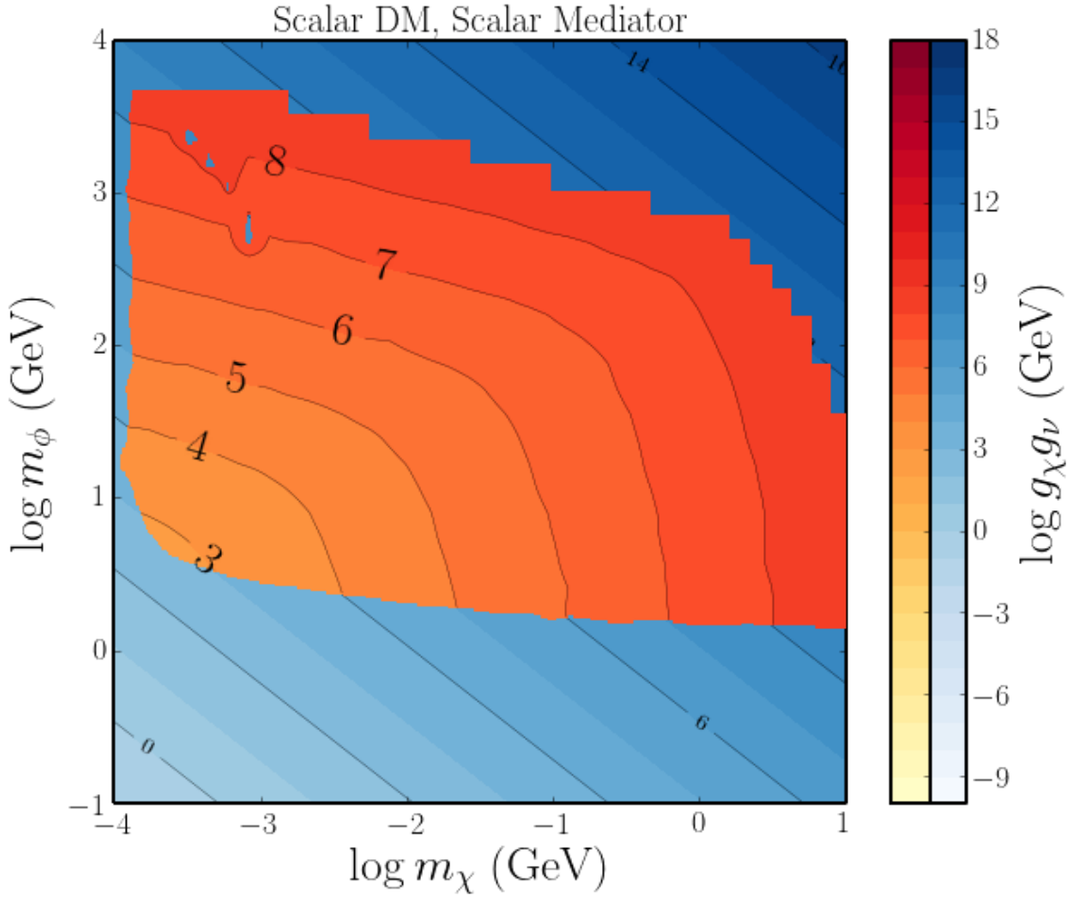

scalar DM-fermion Med.: m_χ =0.0001 m_ϕ =100.0
log $g_\nu g_\chi$ =4.0
log $g_\nu g_\chi$ =3.0
log $g_\nu g_\chi$ =5.0
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]


Scalar DM, Fermion Mediator
log m_ϕ (GeV)
log m_χ (GeV)
log $g_\chi g_\nu$
1
0


scalar DM-scalar Med.: m_χ =10.0 m_ϕ =1000.0
log $g_\nu g_\chi$ =13.0
log $g_\nu g_\chi$ =12.0
log $g_\nu g_\chi$ =14.0
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]


scalar DM-scalar Med.: m_χ =1.0 m_ϕ =0.0001
log $g_\nu g_\chi$ =-1.0
log $g_\nu g_\chi$ =-2.0
log $g_\nu g_\chi$ =0.0
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]


scalar DM-scalar Med.: m_χ =0.0001 m_ϕ =10000.0
log $g_\nu g_\chi$ =12.0
log $g_\nu g_\chi$ =11.0
log $g_\nu g_\chi$ =13.0
$\sigma_{\nu\chi} n_{DM}/\sigma_{\nu p} n_H$
Energy [GeV]


Scalar DM, Scalar Mediator
log m_ϕ (GeV)
log m_χ (GeV)
log $g_\chi g_\nu$ (GeV)