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Picturing Dark Matter from its Neutrinos

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hep-ph/0506298

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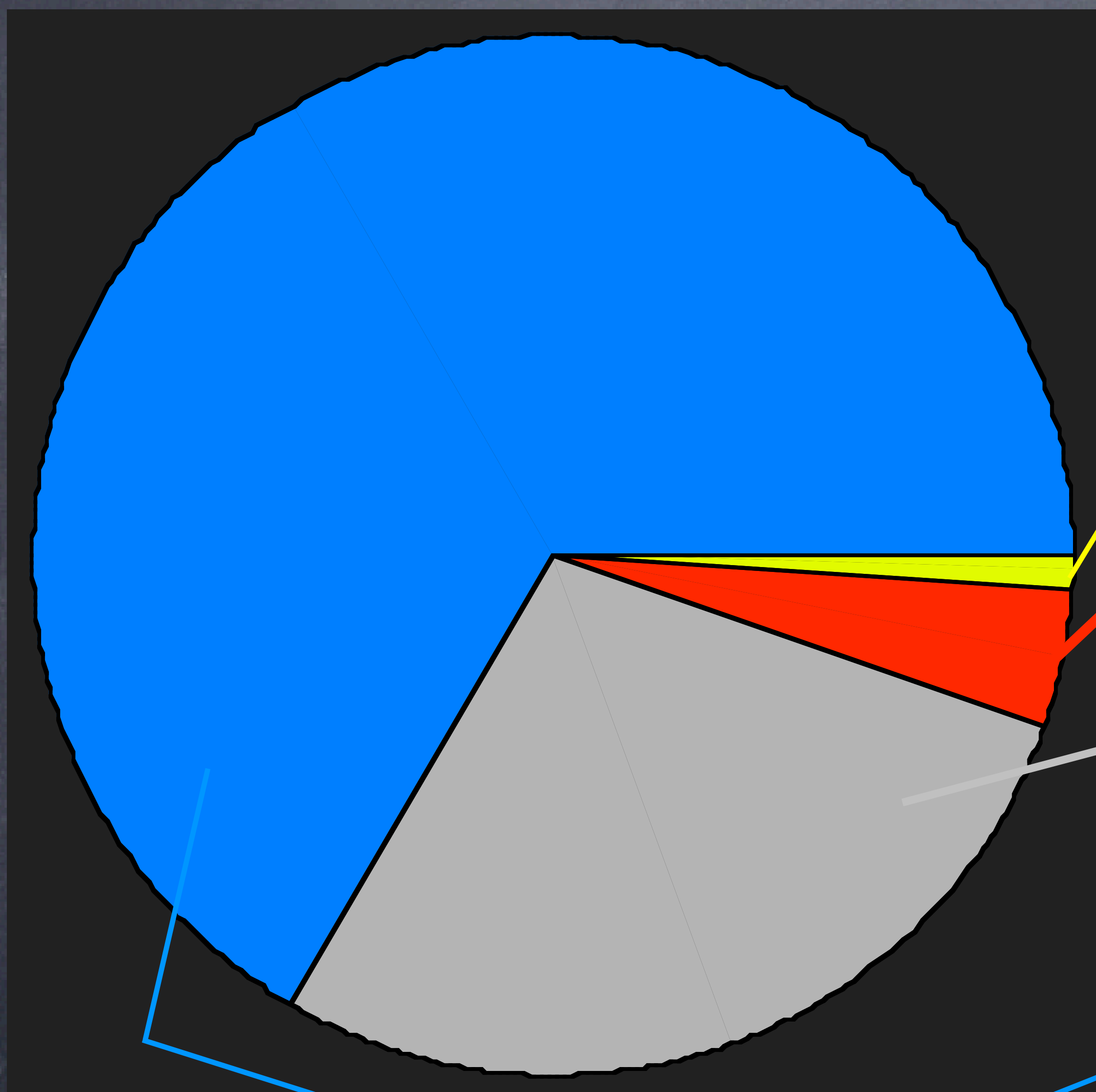
- Key Points of this work 1 slide
- procedure and results a lot of slides

The cosmic inventory

most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

-mass to light ratio in typical systems

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$

-BBN
-CMB

$\Omega_{\rm DM} \sim 0.29$

$\Omega_{\rm de} \sim 0.7$

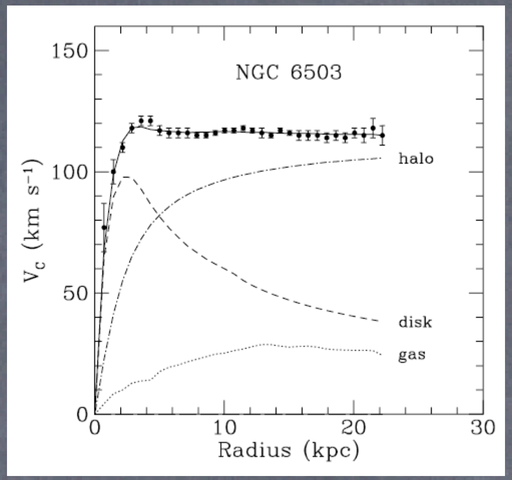
- CMB + SNIa
- CMB - DM
- acoustic peak in baryons

$\left(\Omega_x = \frac{\rho_x}{\rho_c}; \text{ CMB first peak} \Rightarrow \Omega_{\rm tot} = 1 \text{ (flat)}; \right.$

$\left. \text{HST } h = 0.71 \pm 0.07 \right)$

The Evidence for DM

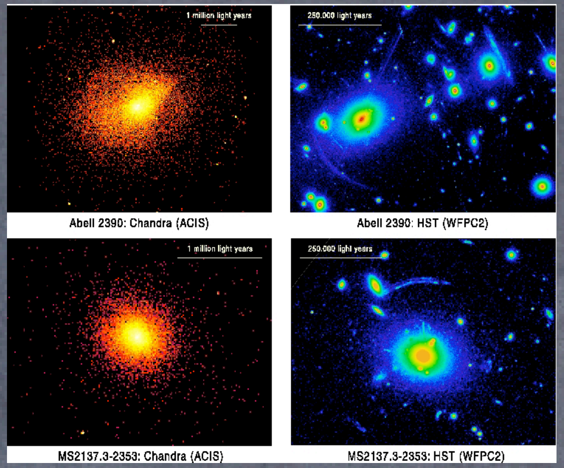
1) galaxy rotation curves



details

$\Omega_\mathrm{M} \gtrsim 0.1$

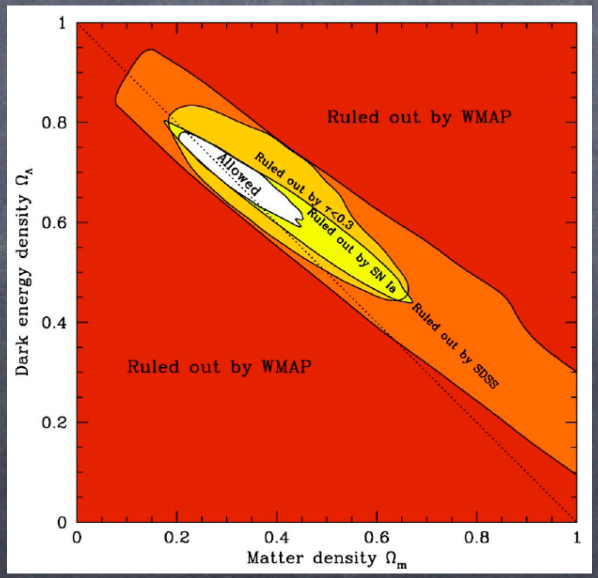
2) clusters of galaxies



details

$\Omega_\mathrm{M} \sim 0.2 \div 0.4$

3) CMB+LSS+SNIa



details

$\Omega_\mathrm{M} \approx 0.30 \pm 0.04$

DM is there.

What is DM?

The case for a WIMP

A Weakly Interacting, Massive Particle

has

the correct relic abundance today!

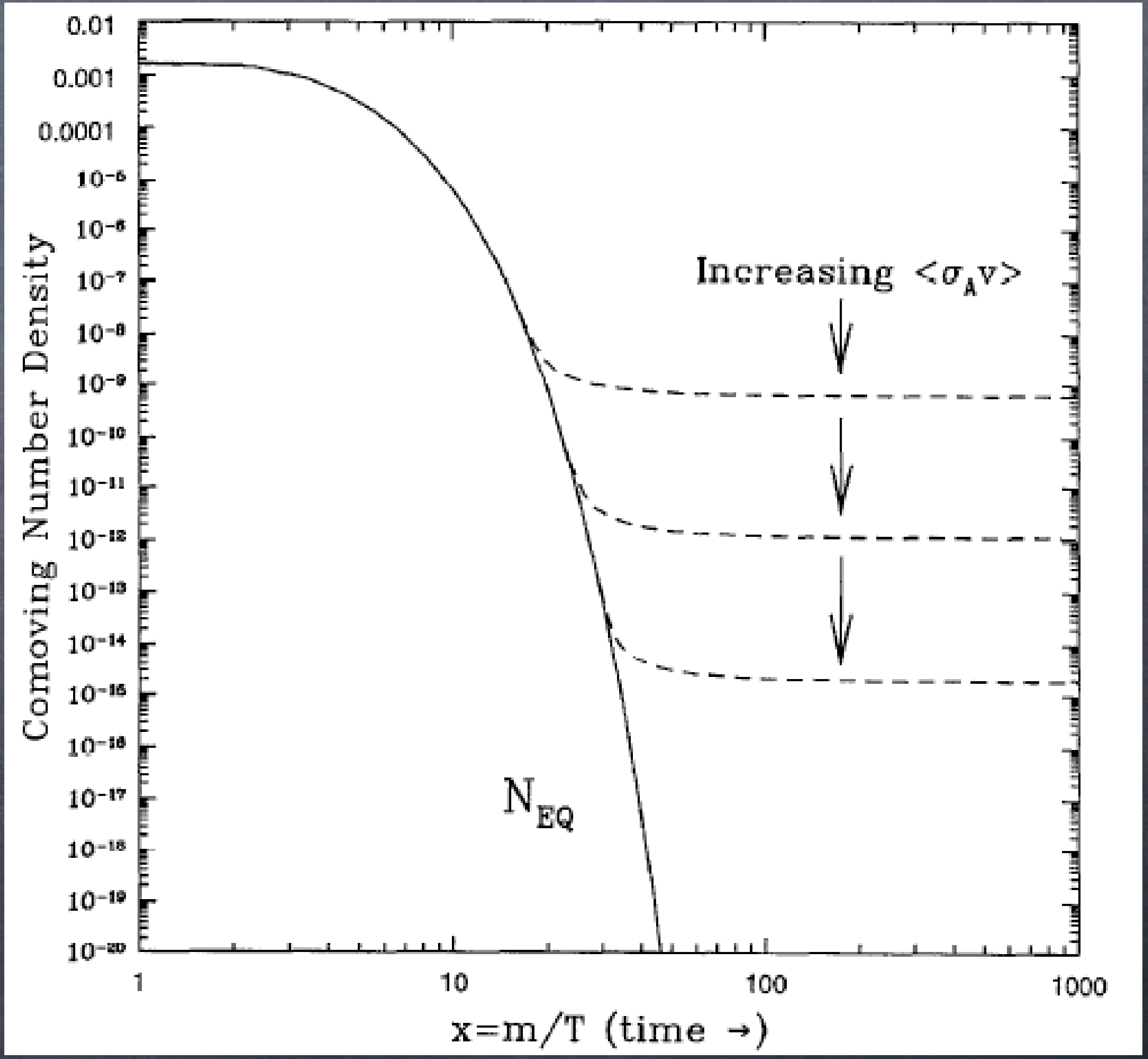
Boltzmann equ. in the Early Universe

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

Weak cross section:

$$\langle \sigma_{\mathrm{ann}} v \rangle \approx \frac{\alpha_w^2}{M_w^2} \approx \frac{\alpha_w^2}{100\ \mathrm{GeV}^2}$$

$$\Omega_X \sim \mathcal{O}(\mathrm{few}\ 0.1)$$



Kolb,Turner, The Early Universe, 1995

The case for SUSY neutralino

- with R-parity, SUSY naturally provides a stable massive WIMP
- in most realizations it is a neutralino

[details]

$$\chi \equiv \chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

gauginos

gaugino fraction:

$$f_g = |N_{11}|^2 + |N_{12}|^2$$

higgsinos

higgsino fraction:

$$f_h = |N_{13}|^2 + |N_{14}|^2$$

and $m_\chi \approx \mathcal{O}(100 \text{ GeV})$

But other possibilities are open

(SUSY: sneutrino...)

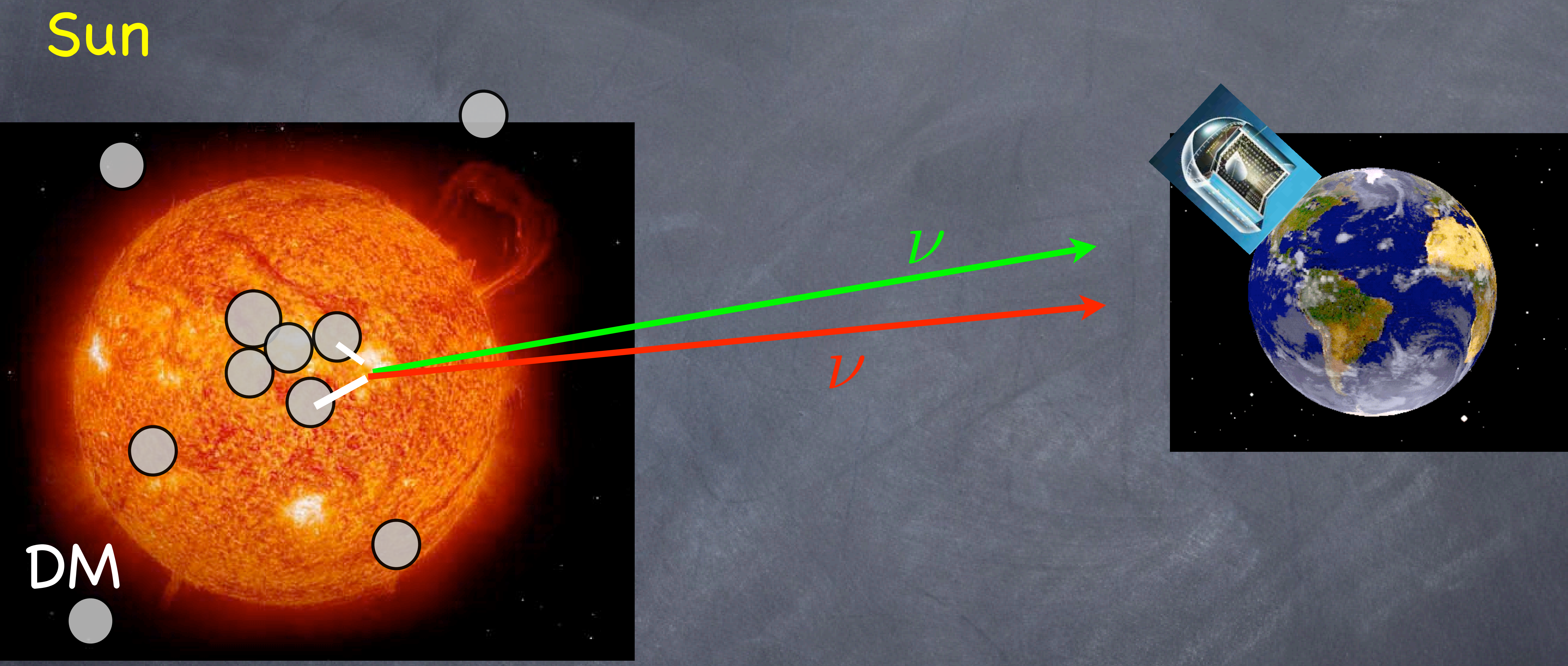
(KK DM, superHeavy DM, technibaryon.....)

DM detection

- production at colliders
- direct detection DAMA
- indirect
  - γ from annihil in galactic halo or center
    (line + continuum) EGRET, WMAP
  - e^+ from annihil in galactic halo or center HEAT
  - $\bar{p}$ from annihil in galactic halo or center
  - $\nu, \bar{\nu}$ from annihil in massive bodies

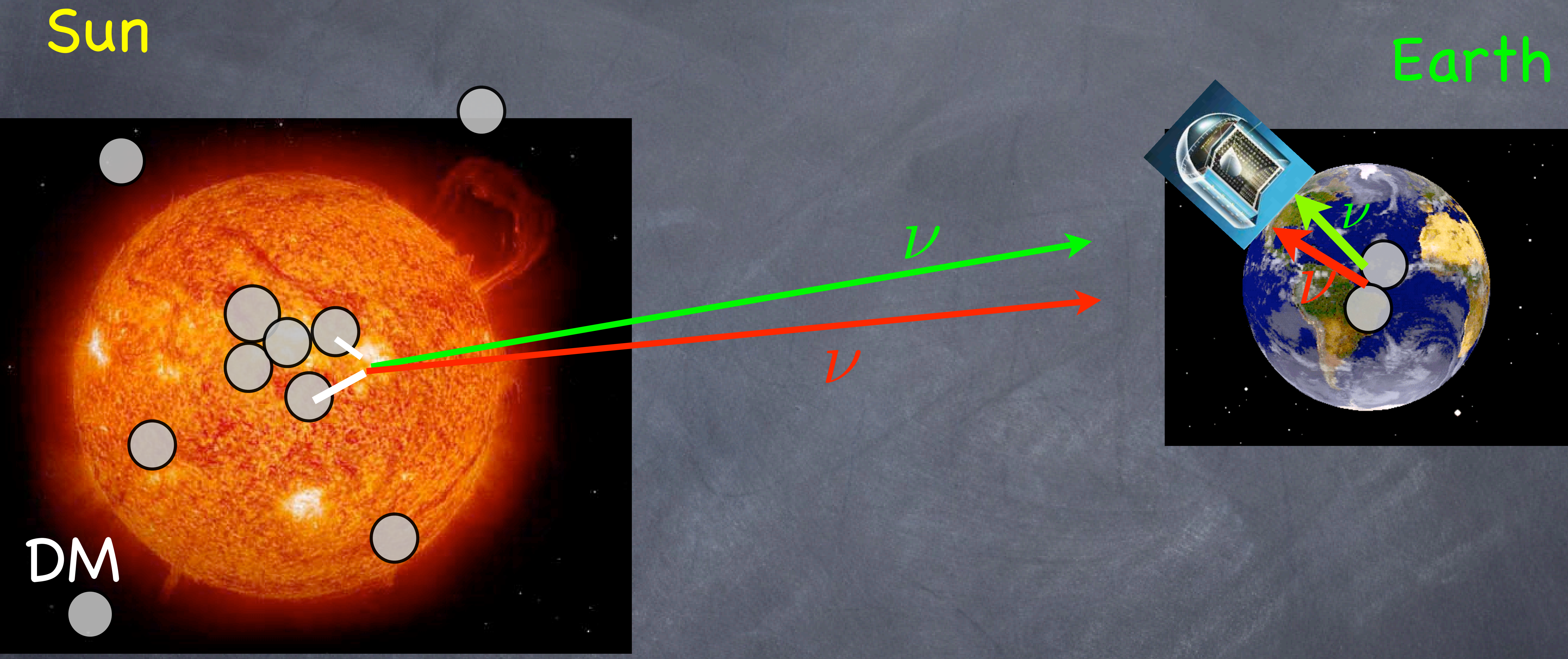
    NB: - a clean channel (γ, e, p are deviated/absorbed...;
    we know the physics of ν
    and of the source)
    - complementary to collider production!

Neutrinos from DM



Capture rates

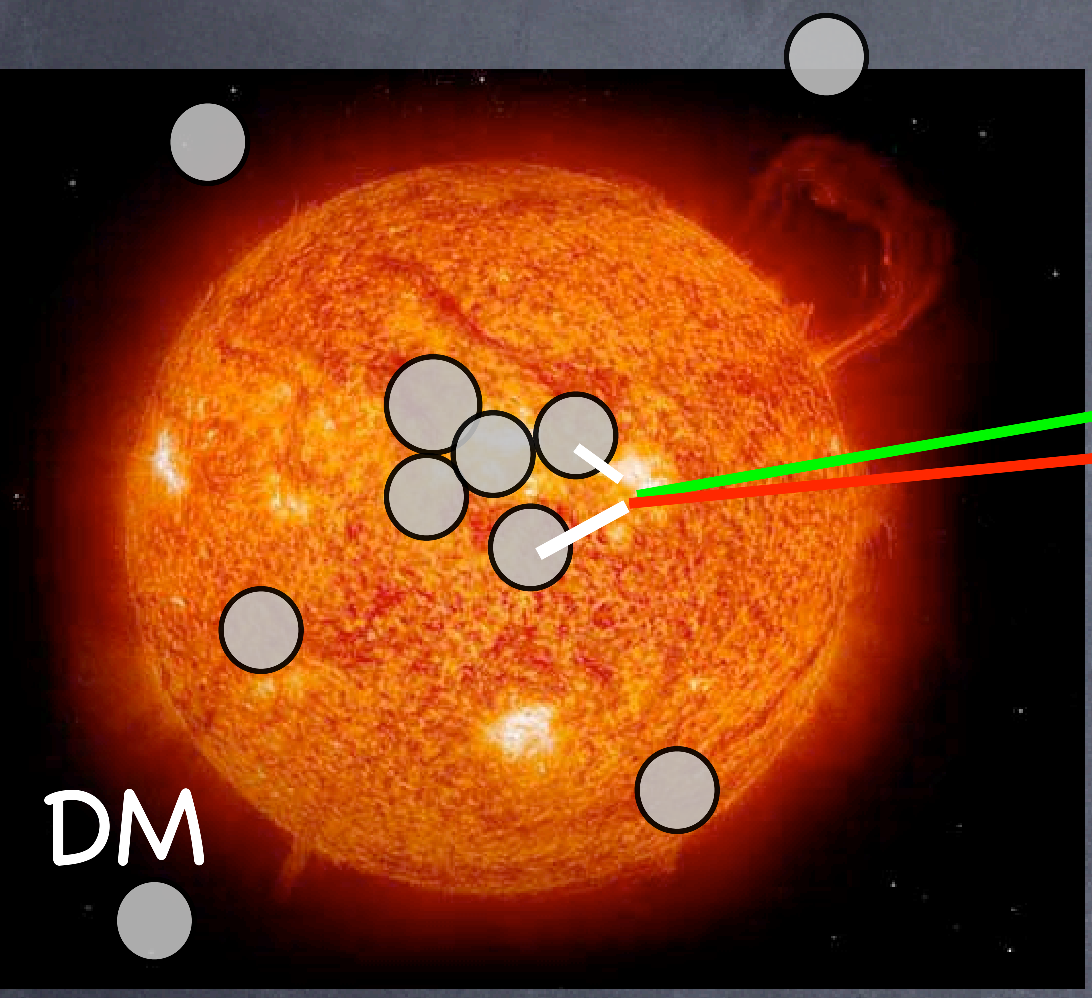
Neutrinos from DM



Capture rates

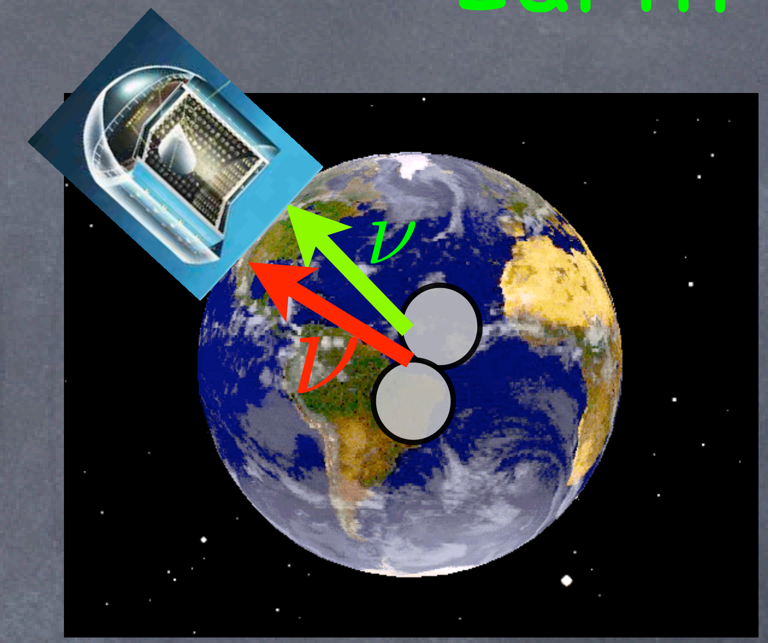
Neutrinos from DM

Sun

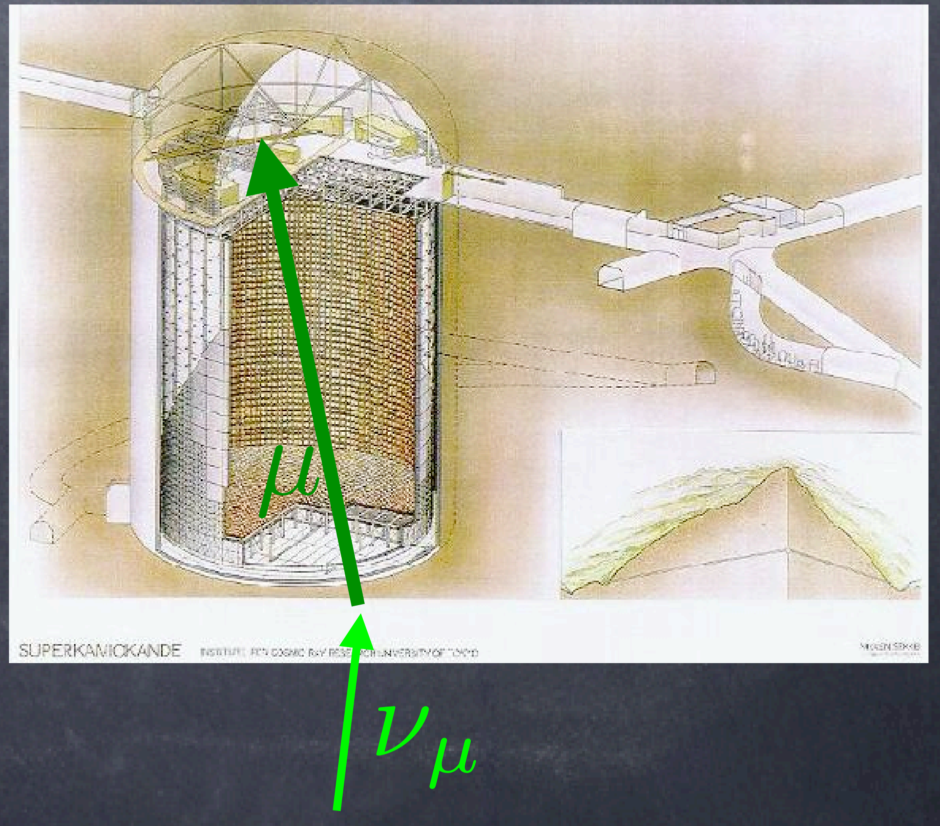


DM

Earth



up-going muons:



Capture rates

Key Points of this work

So far, no events seen; but they are ``around the corner”.

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For discovery, you need a reliable prediction of how the neutrino signal looks like.

After discovery, you want to reconstruct DM properties from its neutrinos.

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For these purposes:

(A) oscillations + interactions

(B) neutrino spectra, not only rates

(C) ν_e, ν_μ and ν_τ , not only ν_μ

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So far, no events seen; but they are ``around the corner''.

For discovery, you need a reliable prediction of how the neutrino signal looks like.

After discovery, you want to reconstruct DM properties from its neutrinos.

For these purposes:

(A) oscillations + interactions

astrophysical uncertainties!

(B) neutrino spectra, not only rates

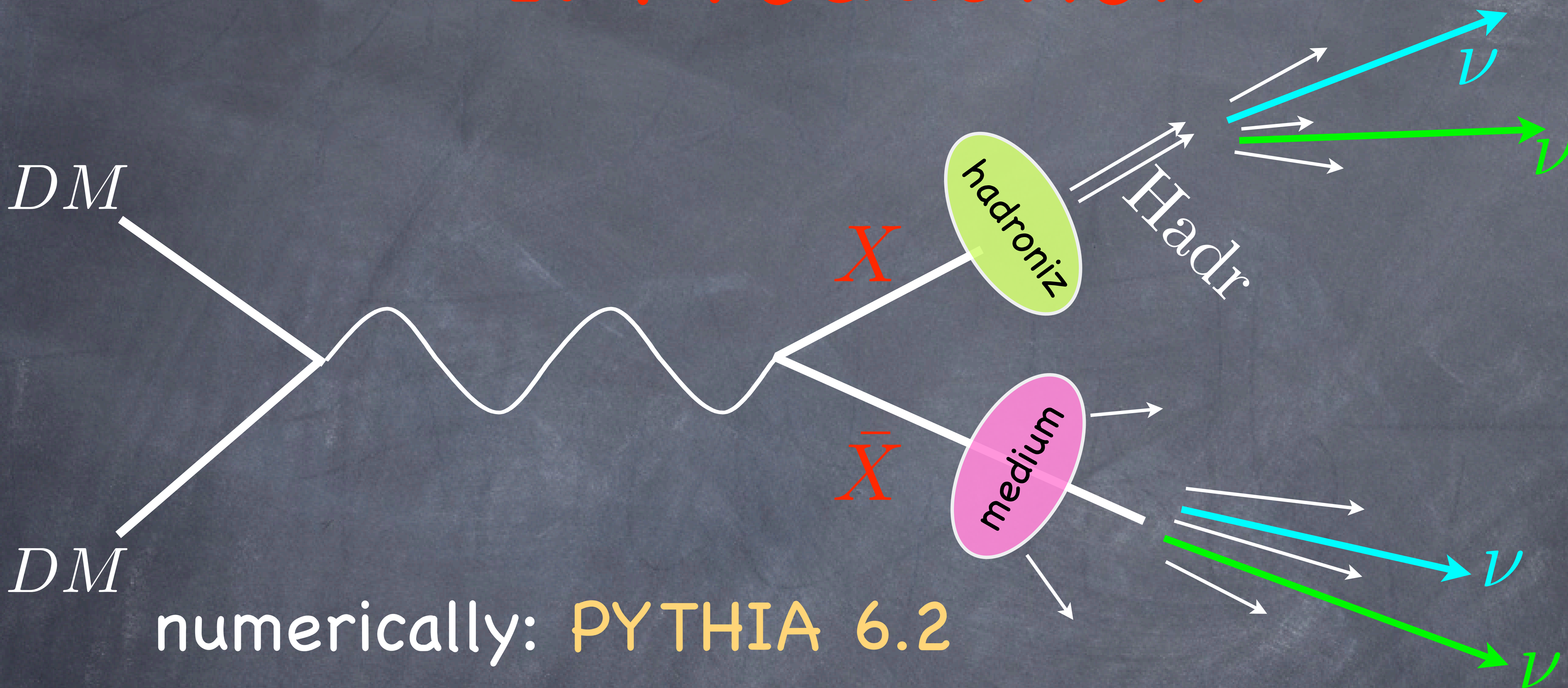
(C) ν_e, ν_μ and ν_τ, not only ν_μ

1. Production

2. Propagation

3. Detection

1. Production



numerically: PYTHIA 6.2

$\mathcal{O}(100\ \mathrm{GeV})$ $\mathcal{O}(\mathrm{tens\ GeV})$

Main variables of the game:

- $m_{\rm DM}$
- BR in primary channels $X\bar{X}$ $(=\tau\bar{\tau}, b\bar{b}, \nu\bar{\nu}, ZZ, W^+W^- \ldots)$

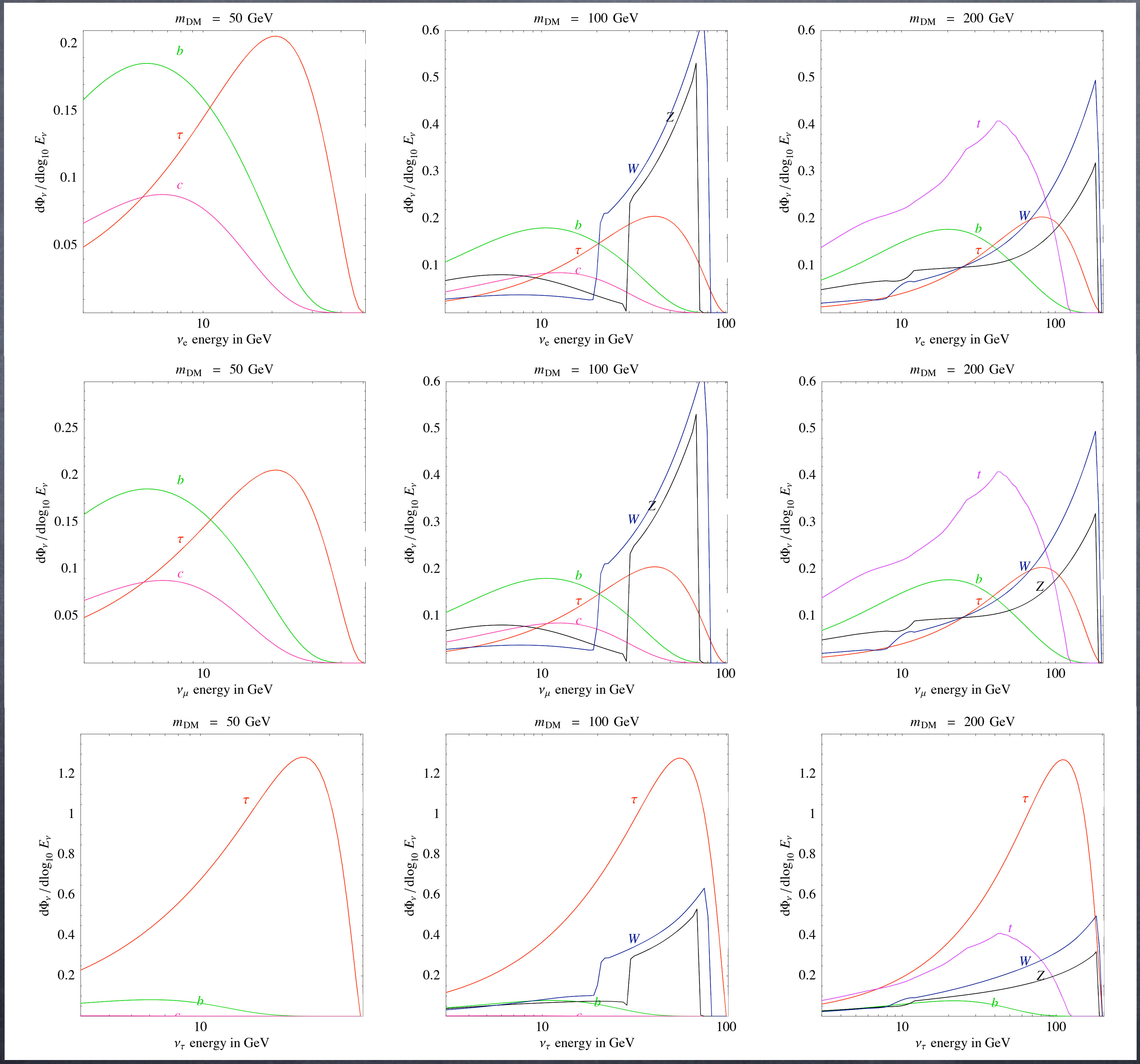
1. Production

$m_{\rm DM} = 50$ GeV $m_{\rm DM} = 100$ GeV $m_{\rm DM} = 200$ GeV

ν_e

ν_μ

ν_τ



1. Production

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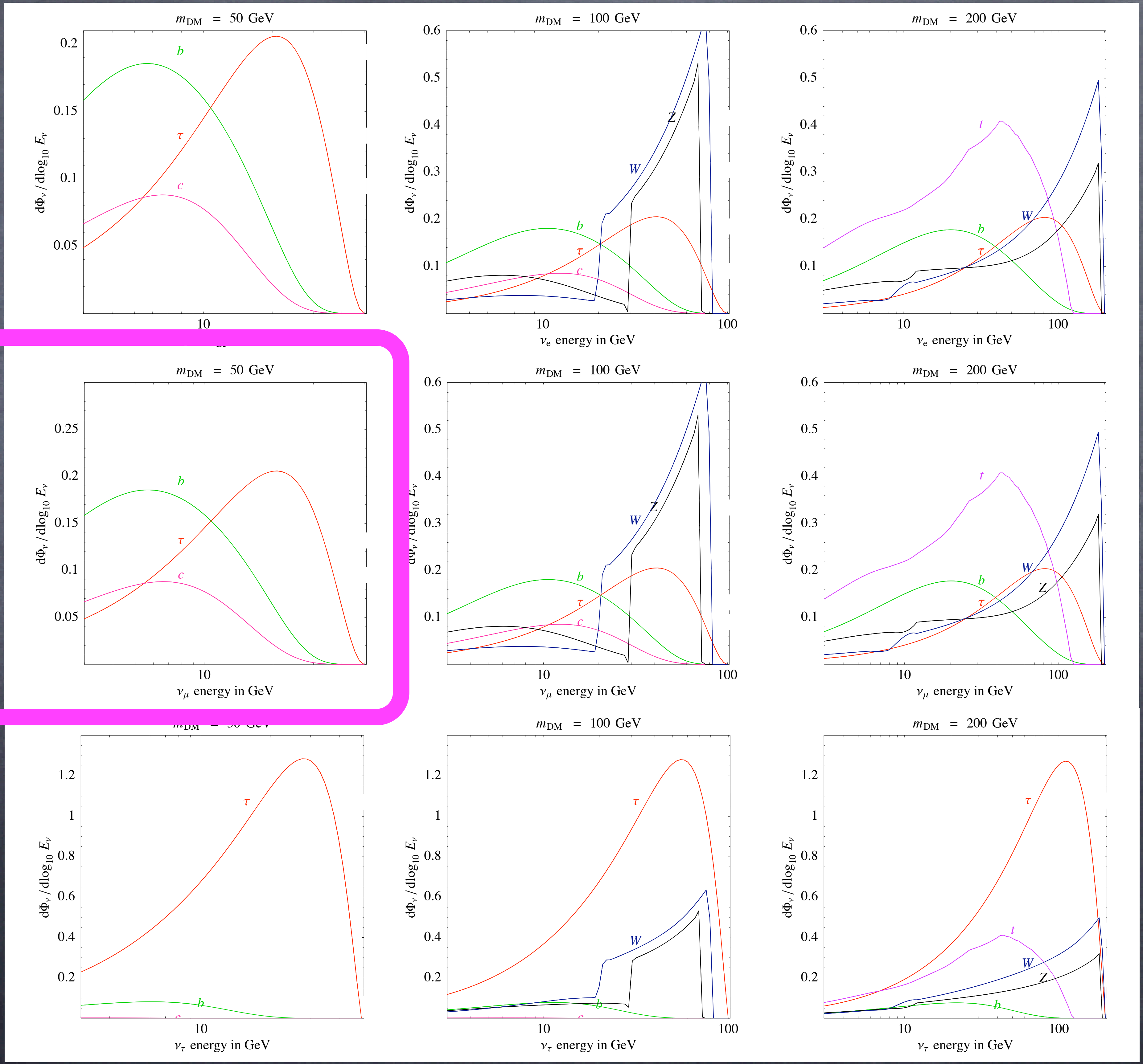
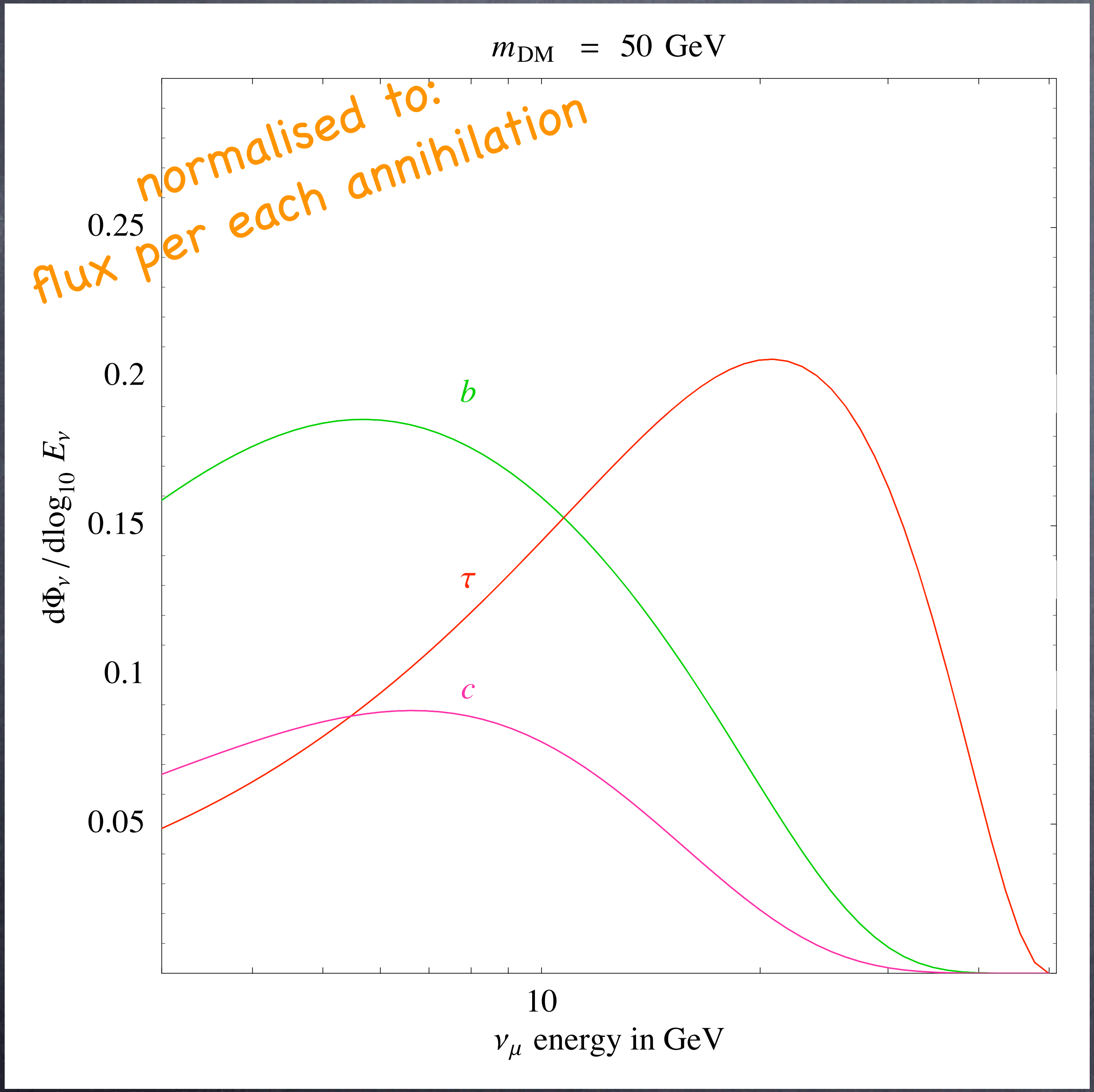


1. Production

ν_μ from 50 GeV $\chi\bar{\chi}$ annihilations



- $\chi\bar{\chi} \to f\bar{f}$ [diagrams]
- proportional to m_f
- av. energy set by $m_{\rm DM}$
- hard spectrum from $\tau\bar{\tau}$
  soft spectrum from $b\bar{b}$

footnote:
for h-mediated channels
$BR(b\bar{b})/BR(\tau\bar{\tau}) = 3m_b^2/m_\tau^2 \approx 20$
but in general independent

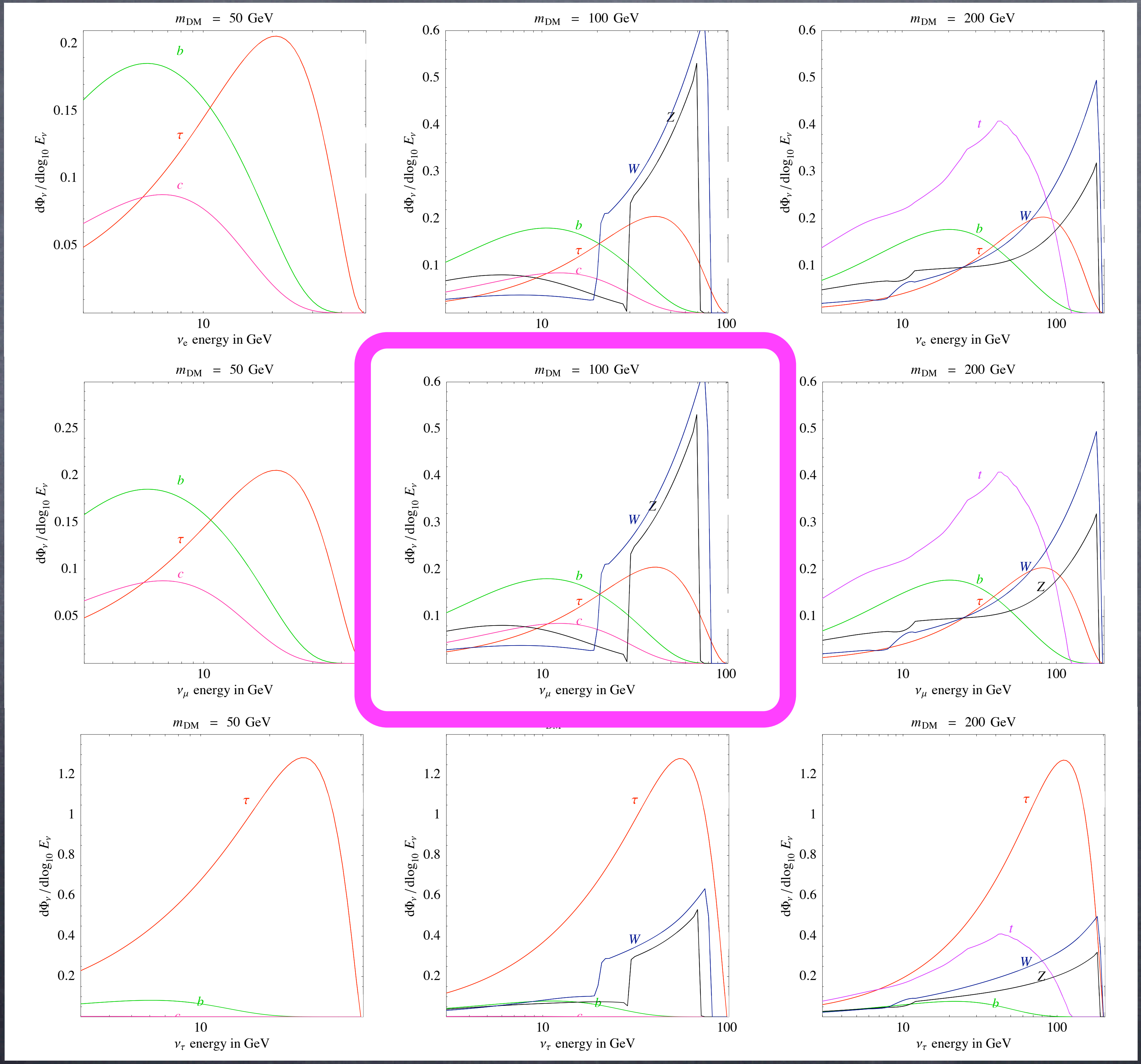
1. Production

$m_{\rm DM} = 50$ GeV $m_{\rm DM} = 100$ GeV $m_{\rm DM} = 200$ GeV

ν_e

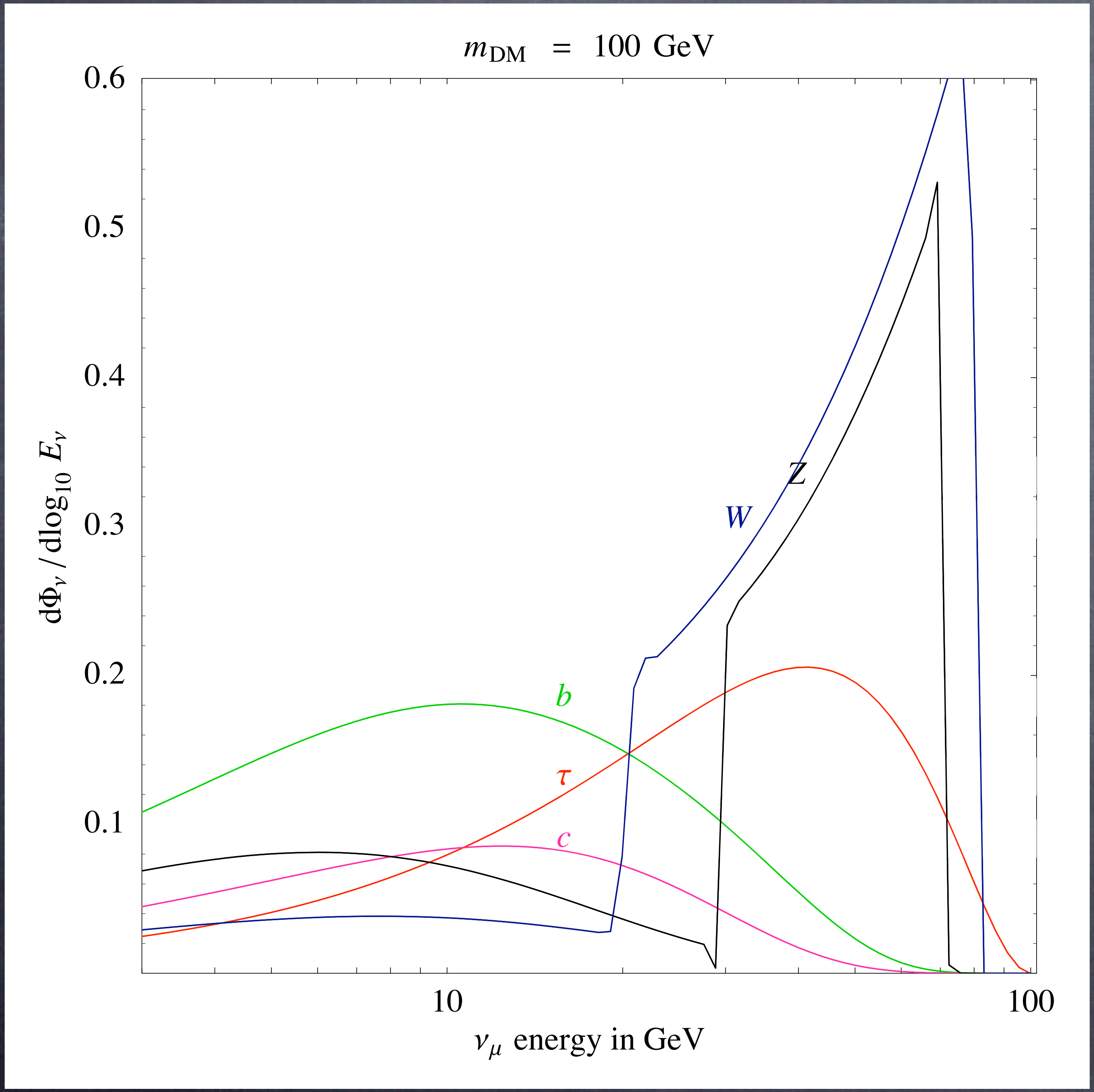
ν_μ

ν_τ



1. Production

ν_μ from 100 GeV $\chi\bar{\chi}$ annihilations



- $\chi\bar{\chi} \to f\bar{f}$

  $\chi\bar{\chi} \to ZZ, W^+W^-$

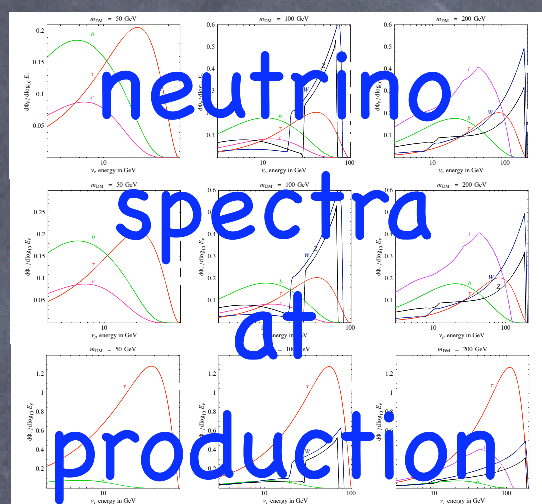
[diagrams]

- "prompt" ν + "secondary" ν

m_{DM}	a_0	a_1	a_2	a_3	a_4	a_5	b	c_0	c_1	c_2
DM annihilations into $b\bar{b}$										
10	34.5/55.7	4.15/4.34	7.47/8.03	6.83/7.52	3.16/3.55	0.594/0.677	7.98/8.75	0/0	0/0	0/0
30	10.1/16.6	3.27/3.43	4.99/5.25	3.69/3.95	1.34/1.46	0.192/0.214	7.13/8.18	0/0	0/0	0/0
50	7.17/9.60	3.01/3.00	4.40/4.27	3.04/2.90	1.01/0.962	0.132/0.126	6.96/8.00	0/0	0/0	0/0
70	4.46/7.42	2.76/2.85	4.07/3.98	2.70/2.58	0.848/0.803	0.104/0.097	6.49/7.99	0/0	0/0	0/0
100	6.07/8.28	2.87/2.77	4.12/3.68	2.74/2.26	0.878/0.657	0.110/0.072	7.05/8.67	0/0	0/0	0/0
200	1.82/3.28	2.46/2.90	4.26/4.56	2.75/2.87	0.830/0.838	0.098/0.094	5.74/7.90	0/0	0/0	0/0
300	1.61/2.36	2.37/2.79	4.17/4.45	2.61/2.45	0.770/0.613	0.089/0.058	5.73/9.12	0/0	0/0	0/0
500	0.918/10.9	1.73/2.87	4.08/3.74	2.54/2.22	0.770/0.635	0.092/0.071	5.62/12.3	0/1.20	0/1.72	0/8.06
700	0.893/4.21	1.68/3.64	4.12/5.23	2.62/2.93	0.827/0.772	0.101/0.079	5.78/8.99	0/0	0/0	0/0
1000	0.779/31.3	1.39/2.76	4.13/2.99	2.77/1.47	0.934/0.345	0.117/0.032	5.99/18.7	0/1.20	0/1.72	0/8.06
DM annihilations into $\tau\bar{\tau}$										
10	1.09/0.903	1.33/0.654	0.795/−0.946	−0.404/−2.42	−0.728/−1.80	−0.253/−0.462	2.11/2.02	0/0	0/0	0/0
30	1.07/0.839	1.48/0.763	1.54/−0.058	0.926/−0.687	0.312/−0.460	0.046/−0.096	2.07/1.95	0/0	0/0	0/0
50	1.17/0.994	1.72/1.30	2.06/1.13	1.41/0.499	0.519/0.105	0.078/0.0070	2.12/2.03	0/0	0/0	0/0
70	1.10/0.962	1.56/1.20	1.68/0.942	1.01/0.353	0.323/0.060	0.043/0.0036	2.09/2.01	0/0	0/0	0/0
100	1.03/1.25	1.40/1.81	1.35/2.12	0.715/1.35	0.203/0.446	0.024/0.059	2.06/2.16	0/0	0/0	0/0
200	0.895/1.25	1.08/1.80	0.781/2.08	0.257/1.30	0.029/0.412	−0.0010/0.052	1.97/2.18	0/0	0/0	0/0
300	1.09/0.378	1.48/−1.73	1.45/−3.67	0.744/−2.90	0.195/−1.00	0.020/−0.128	2.11/1.53	0/0	0/0	0/0
500	1.04/1.09	1.39/1.46	1.30/1.39	0.639/0.701	0.162/0.183	0.017/0.019	2.08/2.11	0/0	0/0	0/0
700	0.958/1.13	1.23/1.53	1.05/1.55	0.469/0.826	0.107/0.225	0.0099/0.024	2.02/2.13	0/0	0/0	0/0
1000	1.01/0.686	1.32/0.526	1.18/0.057	0.548/−0.146	0.129/−0.066	0.012/−0.0084	2.06/1.81	0/0	0/0	0/0
DM annihilations into $c\bar{c}$										
10	0.703/0.654	−1.66/−1.46	−2.96/−1.06	−1.68/1.55	−0.408/1.79	−0.058/0.492	6.27/6.40	0/0	0/0	0/0
30	0.233/0.674	−7.56/−3.07	−8.62/−5.38	−3.09/−3.29	0.353/−0.691	0.297/0.0012	6.35/7.86	0/0	0/0	0/0
50	0.513/0.828	−2.06/−2.93	−2.90/−5.87	−1.62/−4.35	−0.323/−1.38	−0.0032/−0.154	6.81/8.84	0/0	0/0	0/0
70	0.328/0.962	−2.66/−3.78	−0.903/−8.23	1.82/−6.68	1.66/−2.40	0.388/−0.324	6.55/9.91	0/0	0/0	0/0
100	0.685/1.60	−1.92/−1.70	−4.19/−4.59	−3.65/−3.87	−1.42/−1.39	−0.208/−0.185	7.57/11.1	0/0.160	0/6.11	0/12.8
200	0.532/1.41	−2.17/−2.30	−3.51/−4.73	−2.49/−3.42	−0.727/−1.06	−0.074/−0.120	7.58/12.9	0/0.158	0/6.11	0/12.8
300	0.279/1.72	−3.52/−2.68	−2.93/−4.98	−1.03/−3.28	0.118/−0.919	0.072/−0.094	6.98/16.8	0/0.153	0/6.11	0/12.8
500	0.363/1.35	−3.02/−3.24	−3.31/−4.89	−1.61/−2.74	−0.136/−0.613	0.029/−0.045	7.56/17.5	0/0.153	0/6.11	0/12.8
700	0.476/2.90	−1.60/−3.10	−1.64/−5.64	−0.663/−3.50	0.088/−0.909	0.044/−0.085	7.77/23.4	0/0.152	0/6.11	0/12.8
1000	0.420/2.19	−2.08/−3.80	−1.65/−5.49	−0.195/−2.84	0.408/−0.584	0.095/−0.040	8.01/26.4	0/0.151	0/6.11	0/12.8
DM annihilations into $q\bar{q}$										
10	0.0024/0.919	−2.17/1.04	−4.97/1.73	−6.24/5.85	−4.68/6.21	−1.38/2.00	16.0/42.2	0/0.025	0/2.59	0/11.2
30	0.038/0.871	−0.632/3.50	−5.46/4.96	−7.21/3.52	−3.64/1.26	−0.649/0.183	17.3/20.4	0/0	0/0	0/0
50	0.020/0.405	2.78/3.44	5.17/4.79	5.22/3.18	3.26/1.03	0.771/0.132	12.0/20.4	0/0	0/0	0/0
70	0.017/0.0057	2.28/−2.11	5.65/−0.717	5.80/−1.42	3.44/0.398	0.733/0.208	14.2/15.5	0/0	0/0	0/0
100	0.019/0.017	2.25/−0.973	6.88/−2.07	8.24/−0.842	5.16/1.31	1.10/0.494	14.6/15.3	0/0	0/0	0/0
200	0.017/0.012	2.28/−0.863	6.86/−1.64	7.97/−1.60	5.49/1.65	1.14/0.561	14.3/15.4	0/0	0/0	0/0
300	0.015/0.041	2.05/−1.38	6.28/−2.16	7.67/0.967	6.01/2.60	1.23/0.635	14.3/17.3	0/0	0/0	0/0
500	0.065/0.047	3.44/−1.73	7.82/−1.49	8.11/2.53	4.25/3.41	0.708/0.747	15.5/19.7	0/0	0/0	0/0
700	0.093/0.043	3.57/−1.50	7.95/−1.57	8.14/2.47	4.04/3.63	0.638/0.754	15.7/19.7	0/0	0/0	0/0
1000	0.061/0.050	2.90/−2.07	8.48/−2.74	10.2/1.18	5.57/2.90	0.873/0.579	16.3/23.5	0/0	0/0	0/0
DM annihilations into gluons										
10	0.050/0.017	−0.286/0.645	−1.43/7.23	−2.12/1.20	−0.727/−4.95	−0.011/−2.21	9.31/9.15	0/0	0/0	0/0
30	0.042/0.012	−2.49/0.394	−0.522/8.54	3.44/−2.01	5.60/−1.81	2.00/0.043	8.88/7.62	0/0	0/0	0/0
50	0.011/0.802	−4.03/0.211	3.80/−2.76	−0.409/−3.88	4.15/−1.88	1.90/−0.310	7.10/14.5	0/0	0/0	0/0
70	0.013/0.532	−0.695/0.030	3.66/−2.72	−3.72/−3.74	2.55/−1.73	1.56/−0.271	6.06/13.8	0/0	0/0	0/0
100	0.353/1.01	−2.00/−0.413	−6.65/−3.37	−6.74/−3.66	−2.61/−1.47	−0.352/−0.205	13.1/17.4	0/0	0/0	0/0
200	0.082/0.555	−4.58/−0.850	−6.82/−3.38	−5.00/−3.39	−0.326/−1.18	0.207/−0.139	11.1/17.4	0/0	0/0	0/0
300	0.052/0.227	−4.17/−2.12	−6.56/−3.38	−5.60/−2.52	0.399/−0.196	0.433/0.073	8.88/17.9	0/0.090	0/2.57	0/8.13
500	0.063/0.814	−5.59/−1.86	−6.83/−4.34	−3.22/−3.20	1.88/−0.802	0.619/−0.062	10.4/23.9	0/1.43	0/2.41	0/13.6
700	0.069/0.453	−3.50/−2.42	0.232/−4.26	4.58/−2.75	5.20/−0.358	1.05/0.023	11.0/24.0	0/59.7	0/4.77	0/16.4
1000	0.235/0.328	3.74/−2.99	8.11/−4.19	7.39/−2.08	3.63/0.246	0.561/0.123	9.14/24.0	0/481.	0/5.52	0/20.6

Table 1: *Fit parameters for the expression $g(x)$ in eq. (7). Give the $\nu_e = \nu_\mu = \bar{\nu}_e = \bar{\nu}_\mu$ spectra at production from annihilations in the Earth/Sun. DM masses are in* GeV. *These data are available at [30].*

http://pantheon.yale.edu/~mc654/DMnu.html



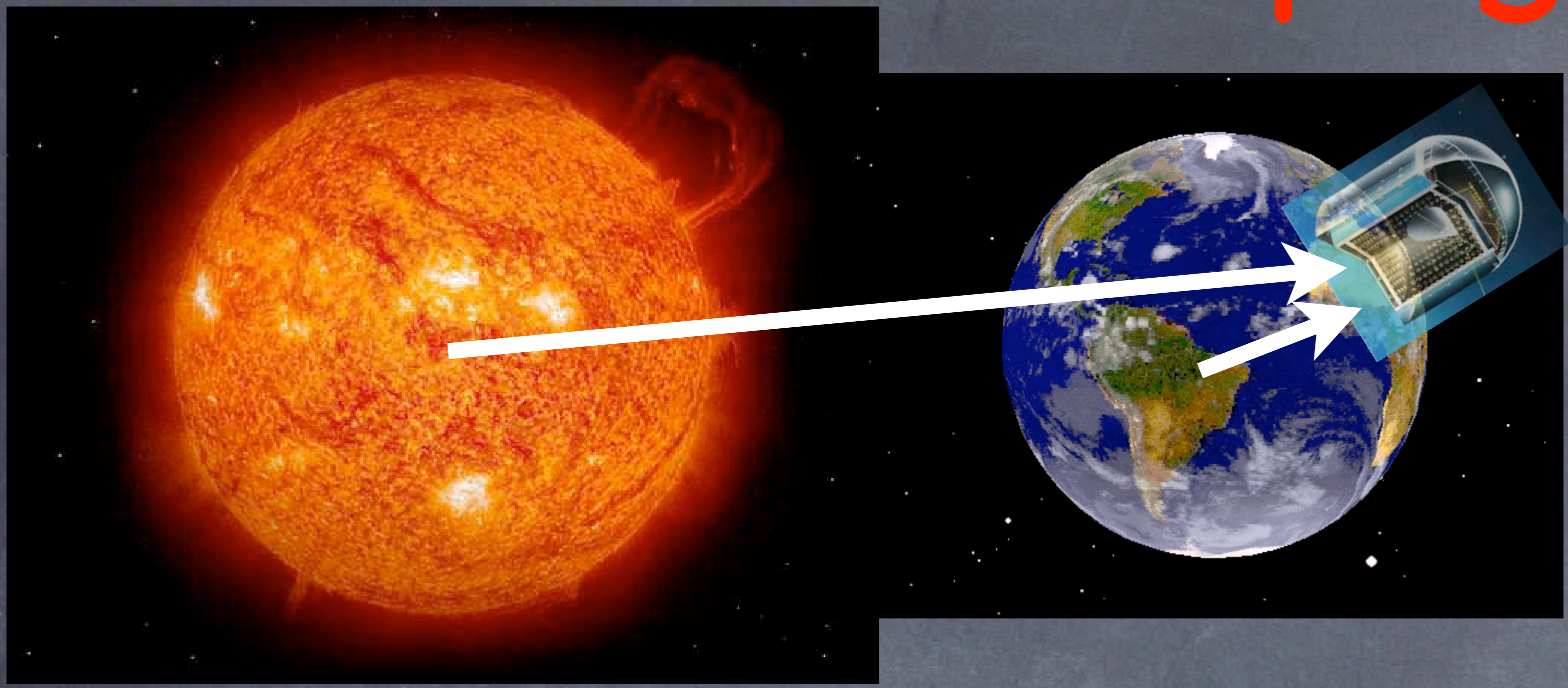
neutrino spectra at production

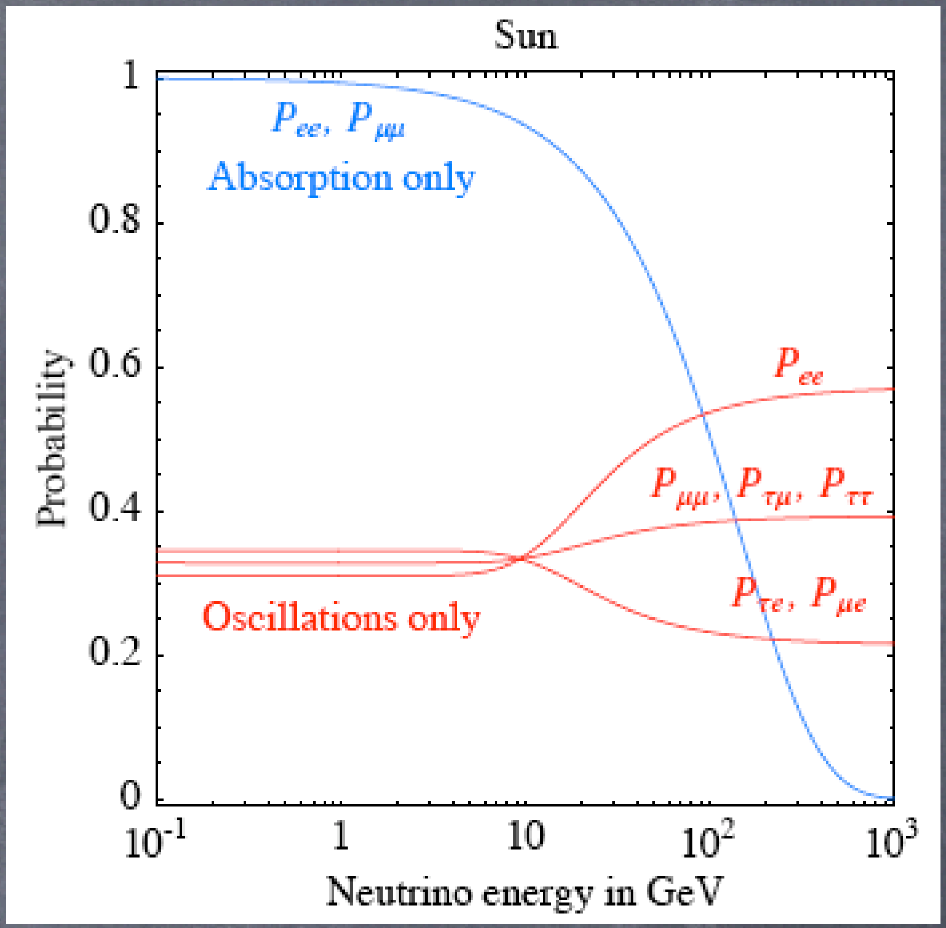
1. production

neutrino spectra arriving to us

2. propagation

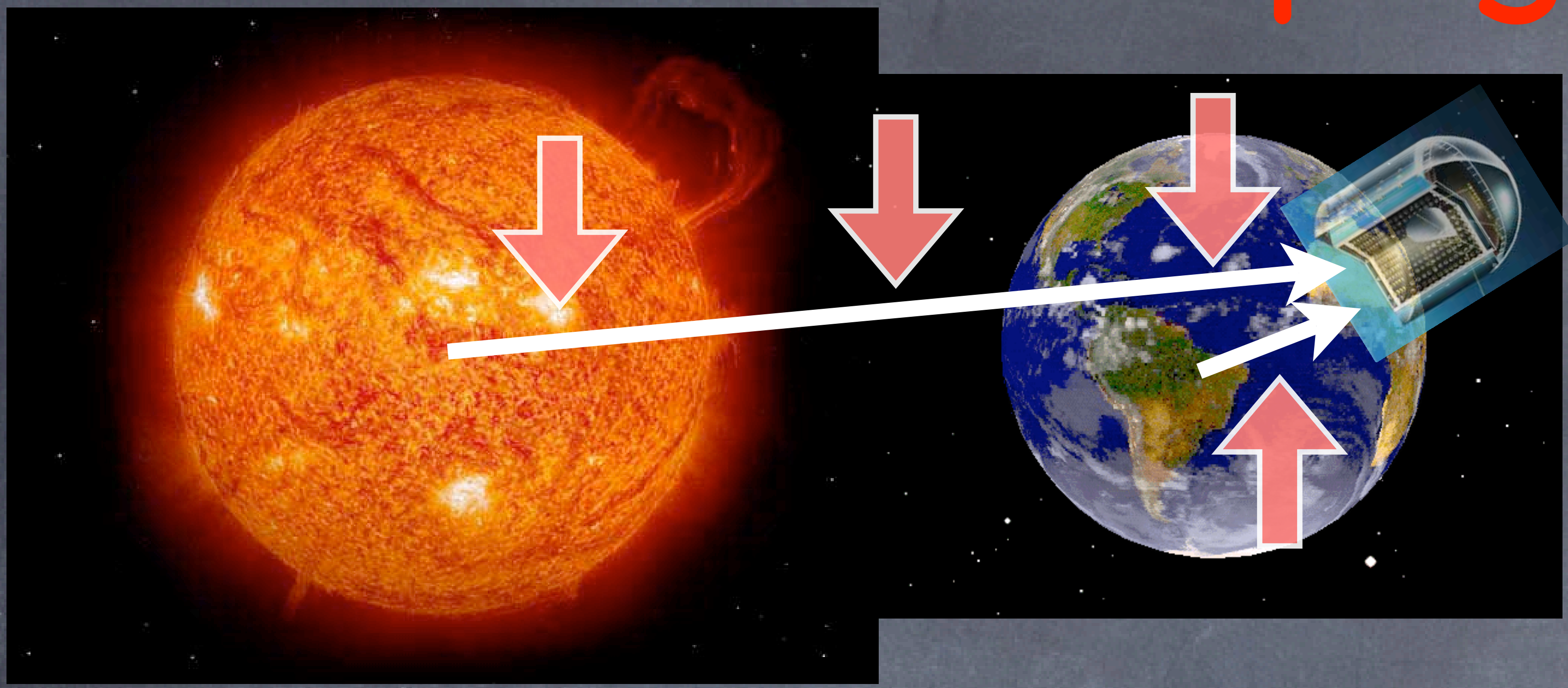
2. Propagation

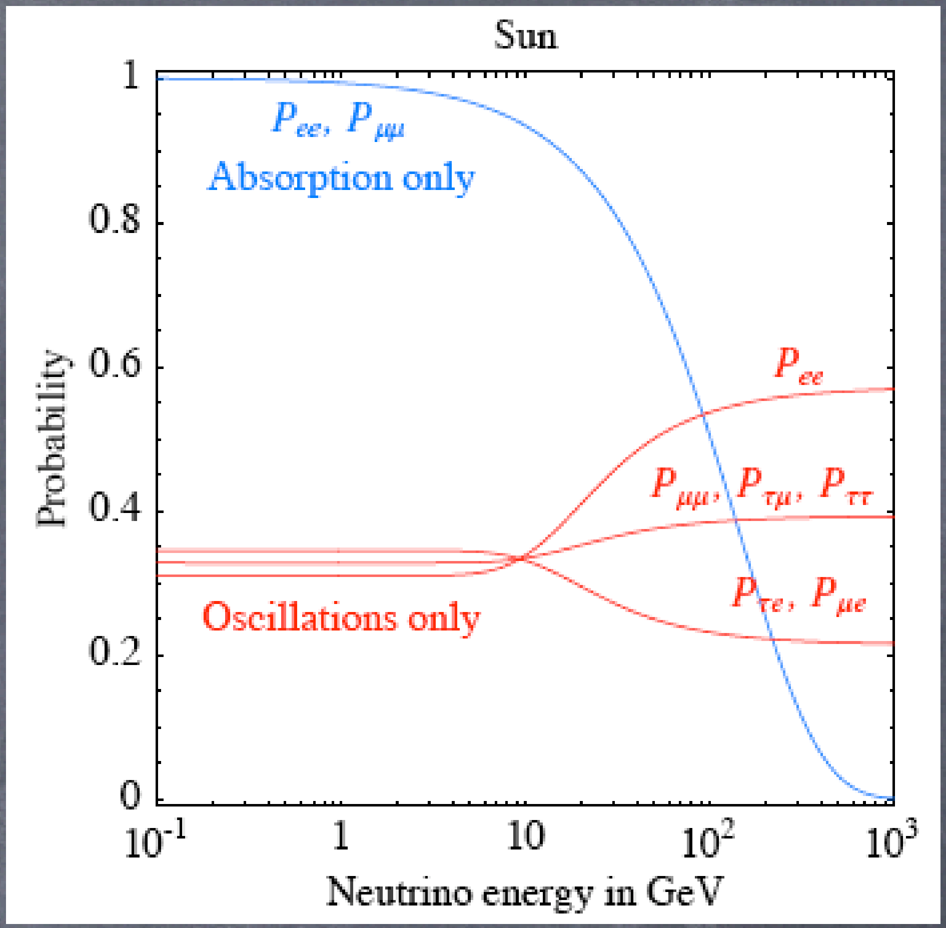




oscillations + interactions

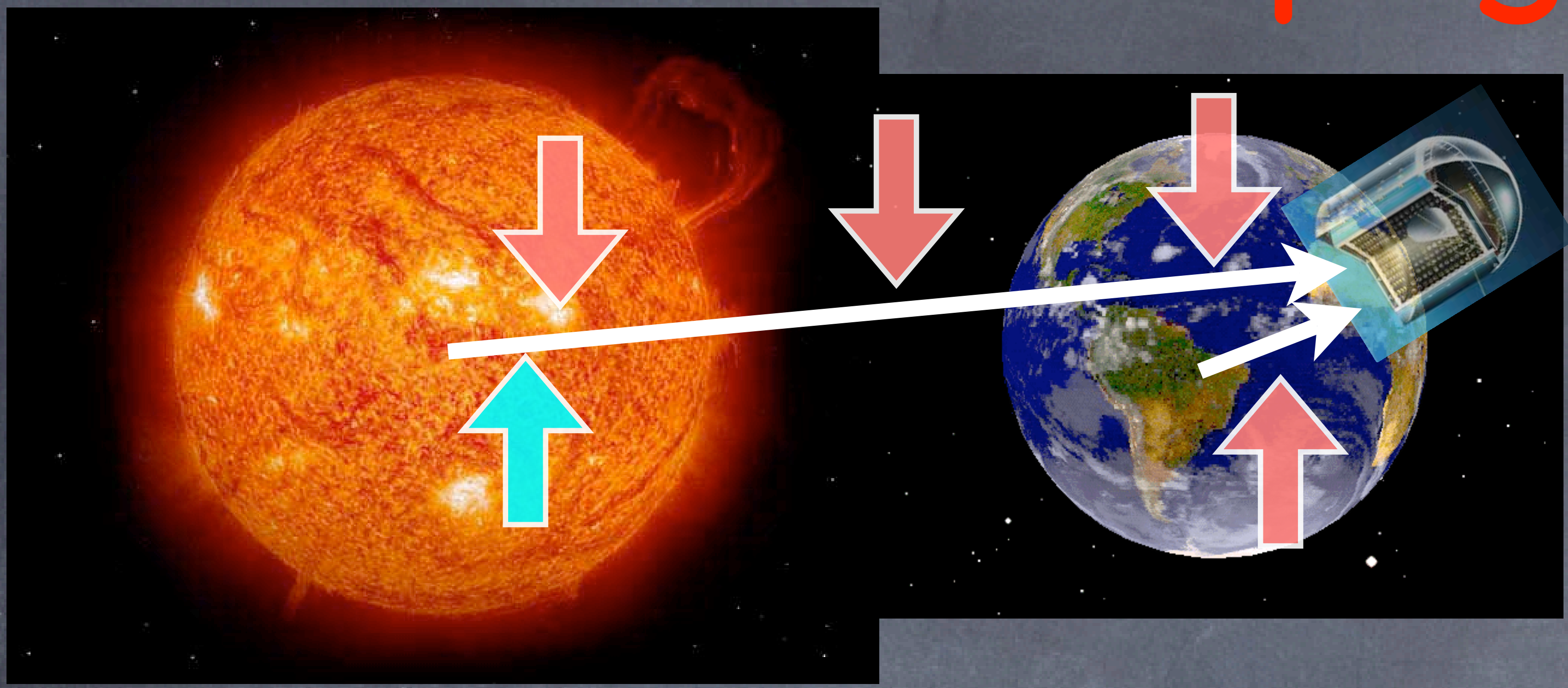
2. Propagation

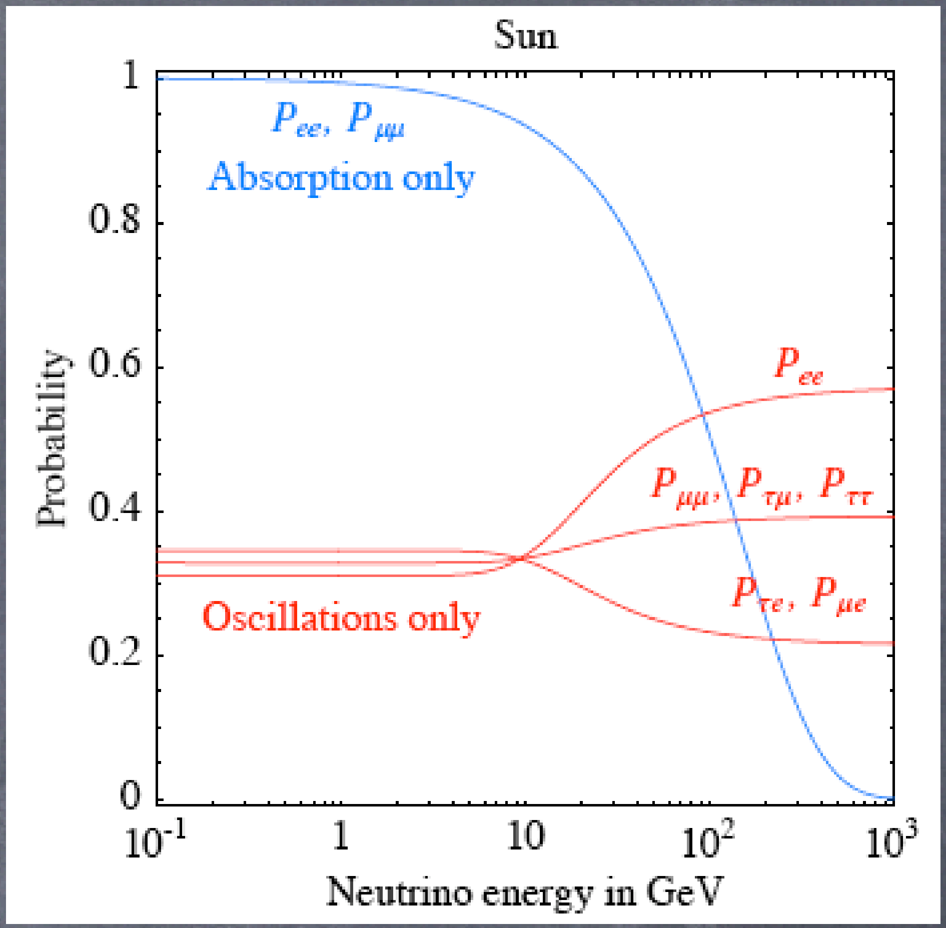




oscillations + interactions

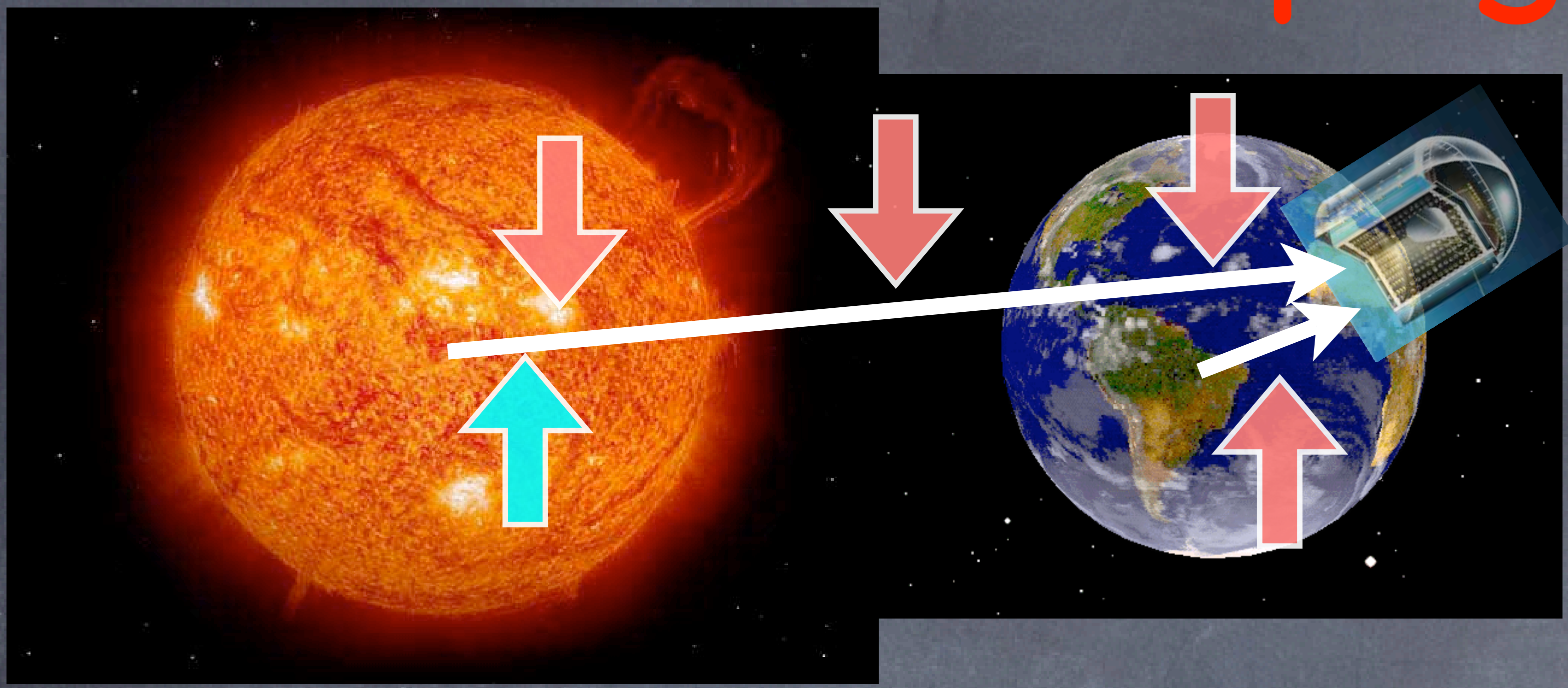
2. Propagation

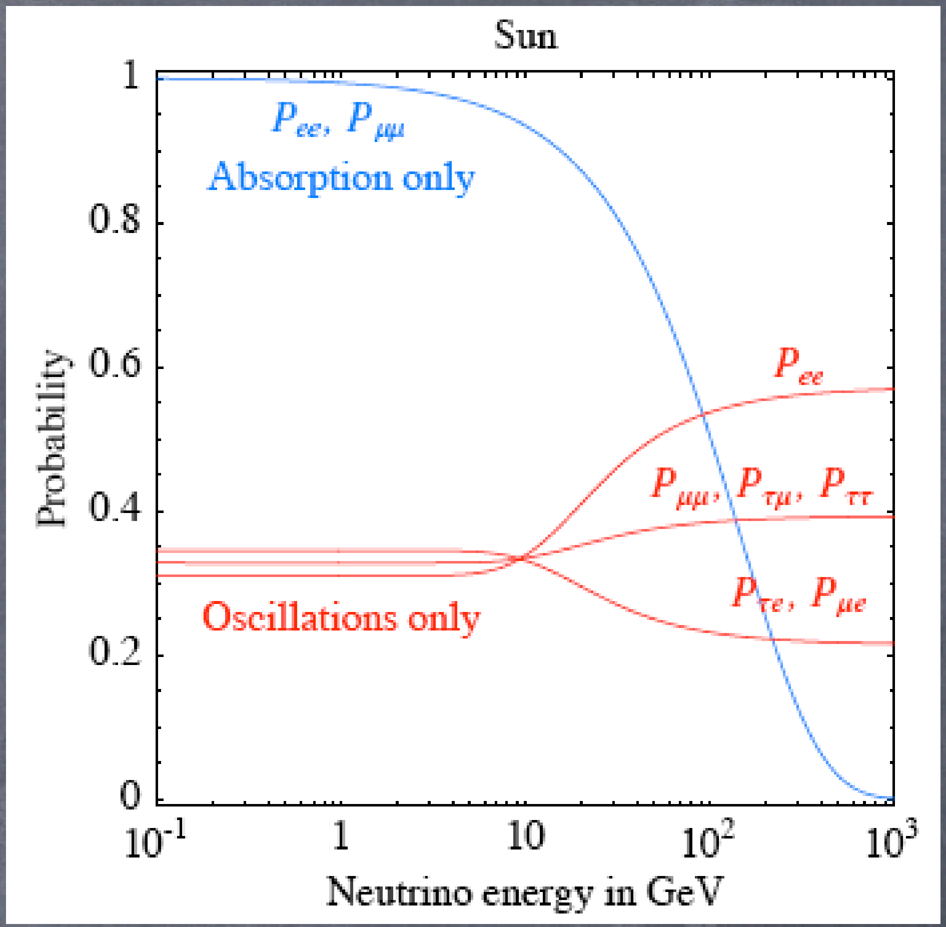




oscillations + interactions

2. Propagation

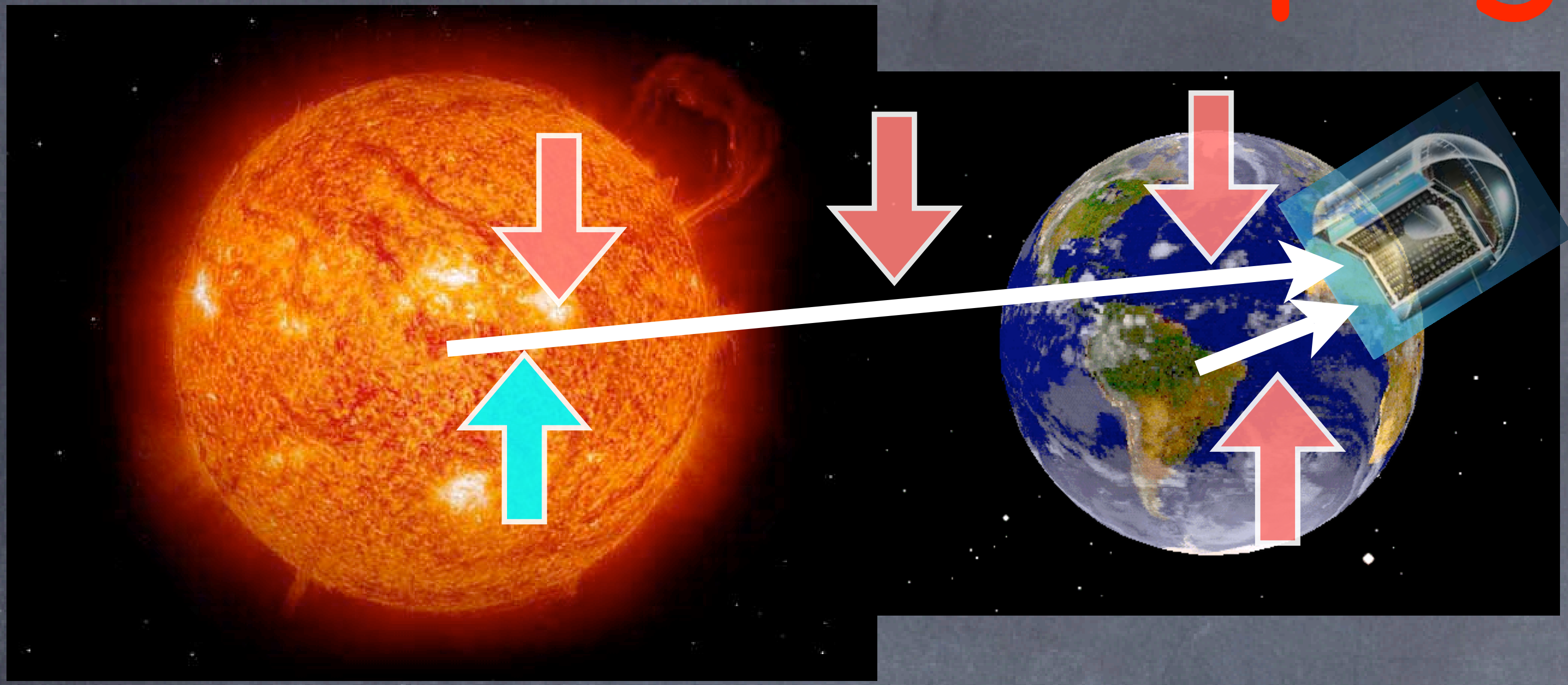


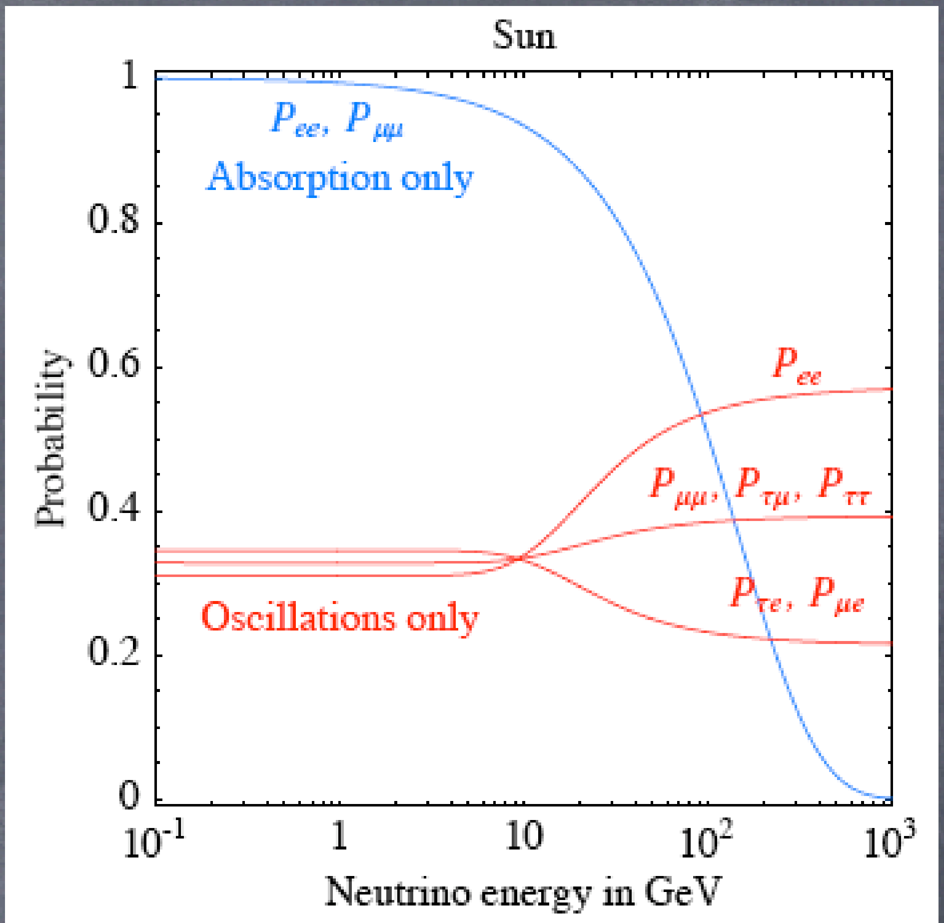


oscillations + interactions

$$\text{production} \longrightarrow \begin{pmatrix} \Phi_{\nu_e} & & \\ & \Phi_{\nu_\mu} & \\ & & \Phi_{\nu_\tau} \end{pmatrix} \longrightarrow \text{detection}$$

2. Propagation





oscillations + interactions

density matrix

$$\boldsymbol{\rho} = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

full evolution equation:

$$\boxed{\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}] + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm NC} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm in}}$$

2. Propagation: oscillations

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}]$$

$$\boldsymbol{H} = \frac{\boldsymbol{m}^\dagger \boldsymbol{m}}{2E_\nu} + \sqrt{2}G_{\mathrm{F}} \left[N_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} - \frac{N_n}{2} \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} \right]$$

2. Propagation: oscillations

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}]$$

$$\boldsymbol{H} = \frac{\boldsymbol{m}^\dagger \boldsymbol{m}}{2E_\nu} + \sqrt{2}G_{\rm F}\left[N_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} - \frac{N_n}{2}\begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}\right]$$

vacuum mixing:

$$\boldsymbol{m}^\dagger \boldsymbol{m} = \boldsymbol{V}\cdot\begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix}\cdot\boldsymbol{V}^\dagger$$

$$\begin{aligned}
&\theta_{\rm sun} = 32^\circ\\
&\theta_{\rm atm} = 45^\circ\\
&\theta_{13} = 0\\
&\Delta m^2_{\rm sun} = 8.0\ 10^{-5}{\rm eV}^2\\
&|\Delta m^2_{\rm atm}| = 2.5\ 10^{-3}{\rm eV}^2
\end{aligned}$$

2. Propagation: oscillations

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}]$$

$$\boldsymbol{H} = \frac{\boldsymbol{m}^\dagger \boldsymbol{m}}{2E_\nu} + \sqrt{2}G_{\rm F}\left[N_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} - \frac{N_n}{2}\begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}\right]$$

vacuum mixing:

$$\boldsymbol{m}^\dagger \boldsymbol{m} = \boldsymbol{V} \cdot \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix} \cdot \boldsymbol{V}^\dagger$$

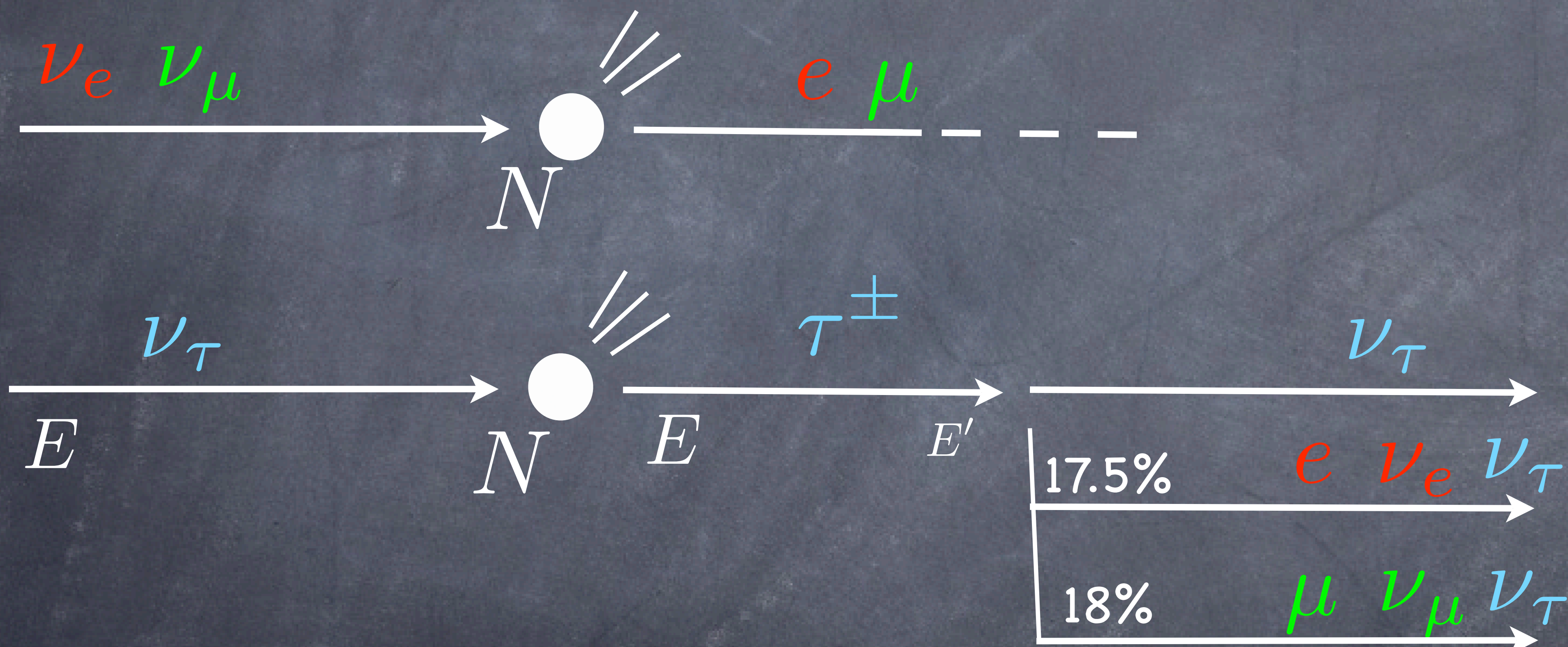
$$\begin{aligned} &\theta_{\rm sun} = 32^\circ \\ &\theta_{\rm atm} = 45^\circ \\ &\theta_{13} = 0 \\ &\Delta m^2_{\rm sun} = 8.0\ 10^{-5}{\rm eV}^2 \\ &|\Delta m^2_{\rm atm}| = 2.5\ 10^{-3}{\rm eV}^2 \end{aligned}$$

matter effect (MSW):

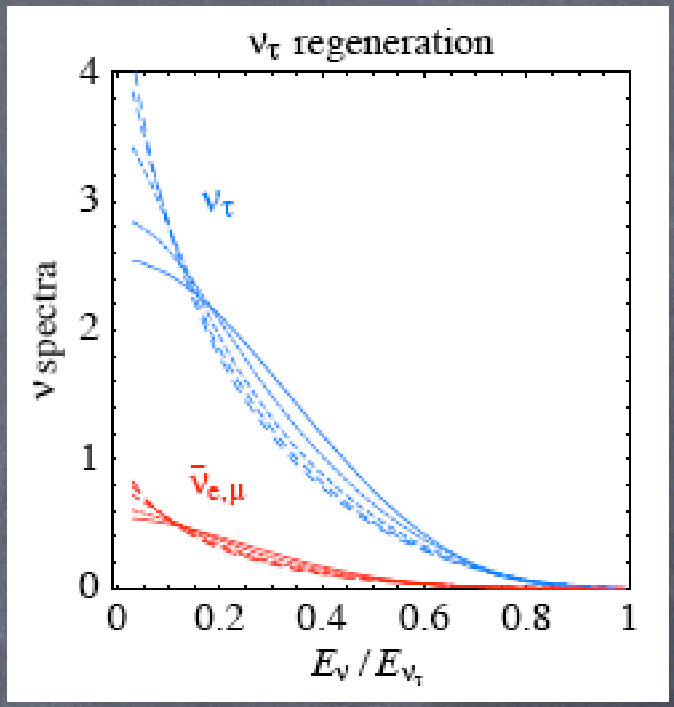
$N_e(r), N_n(r)$ from solar/ Earth models

2. Propagation: CC absorption and tau regeneration

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}] + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC}$$



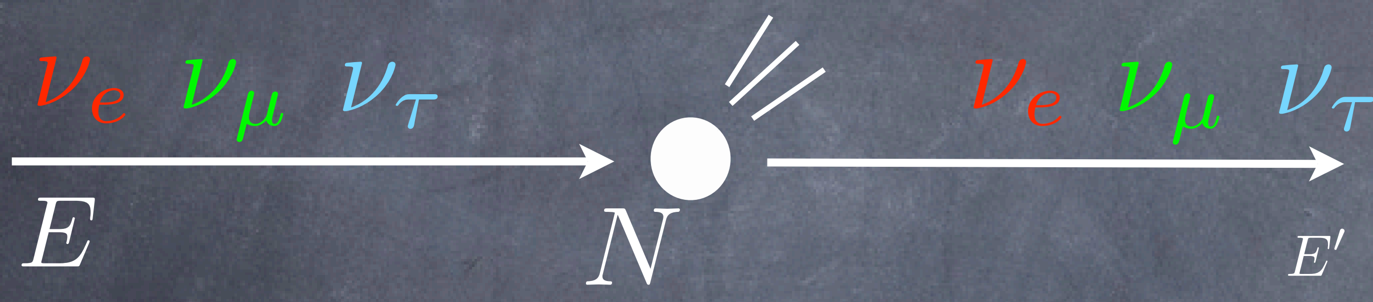
(re)generation!

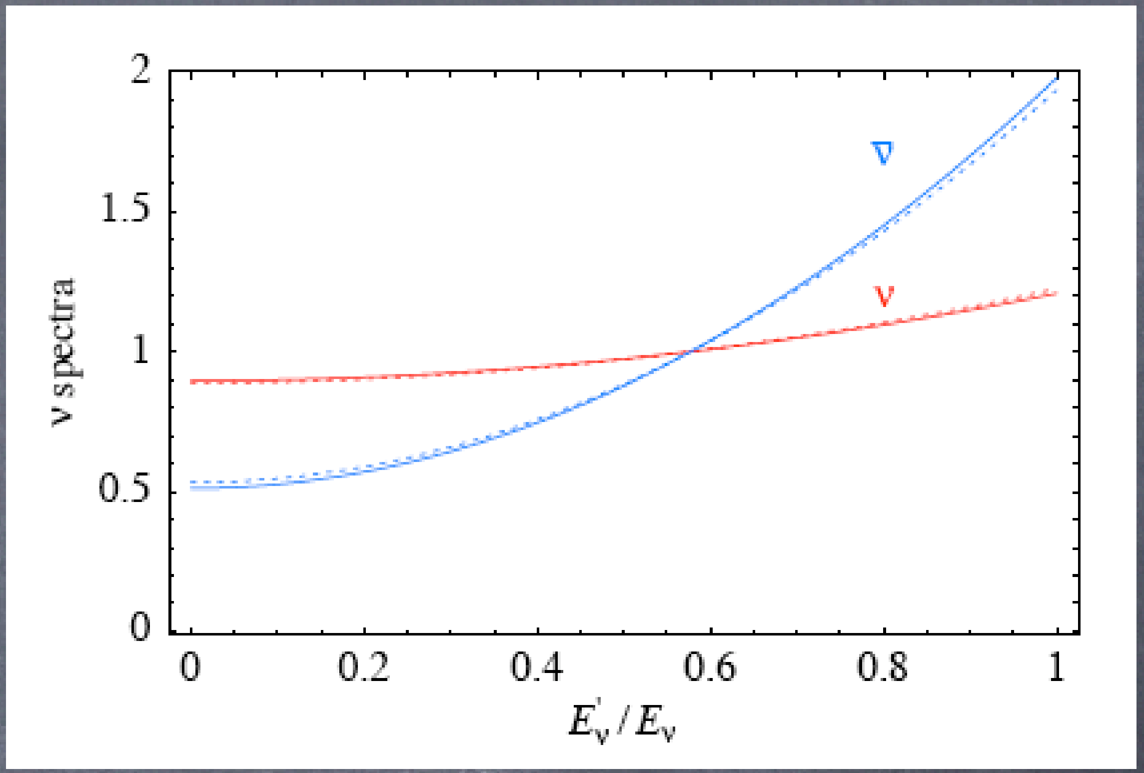


$$\left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC} = -\frac{\{\boldsymbol{\Gamma}_{\rm CC}, \boldsymbol{\rho}\}}{2} + \int \frac{dE_\nu^{\rm in}}{E_\nu^{\rm in}} \Big[\boldsymbol{\Pi}_\tau \rho_{\tau\tau}(E_\nu^{\rm in}) \Gamma^\tau_{\rm CC}(E_\nu^{\rm in}) f_{\tau\to\tau}(E_\nu^{\rm in}, E_\nu) + \boldsymbol{\Pi}_{e,\mu} \bar{\rho}_{\tau\tau}(E_\nu^{\rm in}) \bar{\Gamma}^\tau_{\rm CC}(E_\nu^{\rm in}) f_{\bar{\tau}\to e,\mu}(E_\nu^{\rm in}, E_\nu) \Big]$$

2. Propagation: NC scatterings

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}] + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm NC}$$





$$\left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm NC} = -\int_0^{E_\nu} dE'_\nu \frac{d\Gamma_{\rm NC}}{dE'_\nu}(E_\nu, E'_\nu)\boldsymbol{\rho}(E_\nu) + \int_{E_\nu}^{\infty} dE'_\nu \frac{d\Gamma_{\rm NC}}{dE_\nu}(E'_\nu, E_\nu)\boldsymbol{\rho}(E'_\nu)$$

2. Propagation: summary

Effects of oscillations and interactions:

- reshuffle of the 3 flavors (oscillations and regeneration)

- attenuation of the fluxes

- degradation of energy (distortion of spectra)

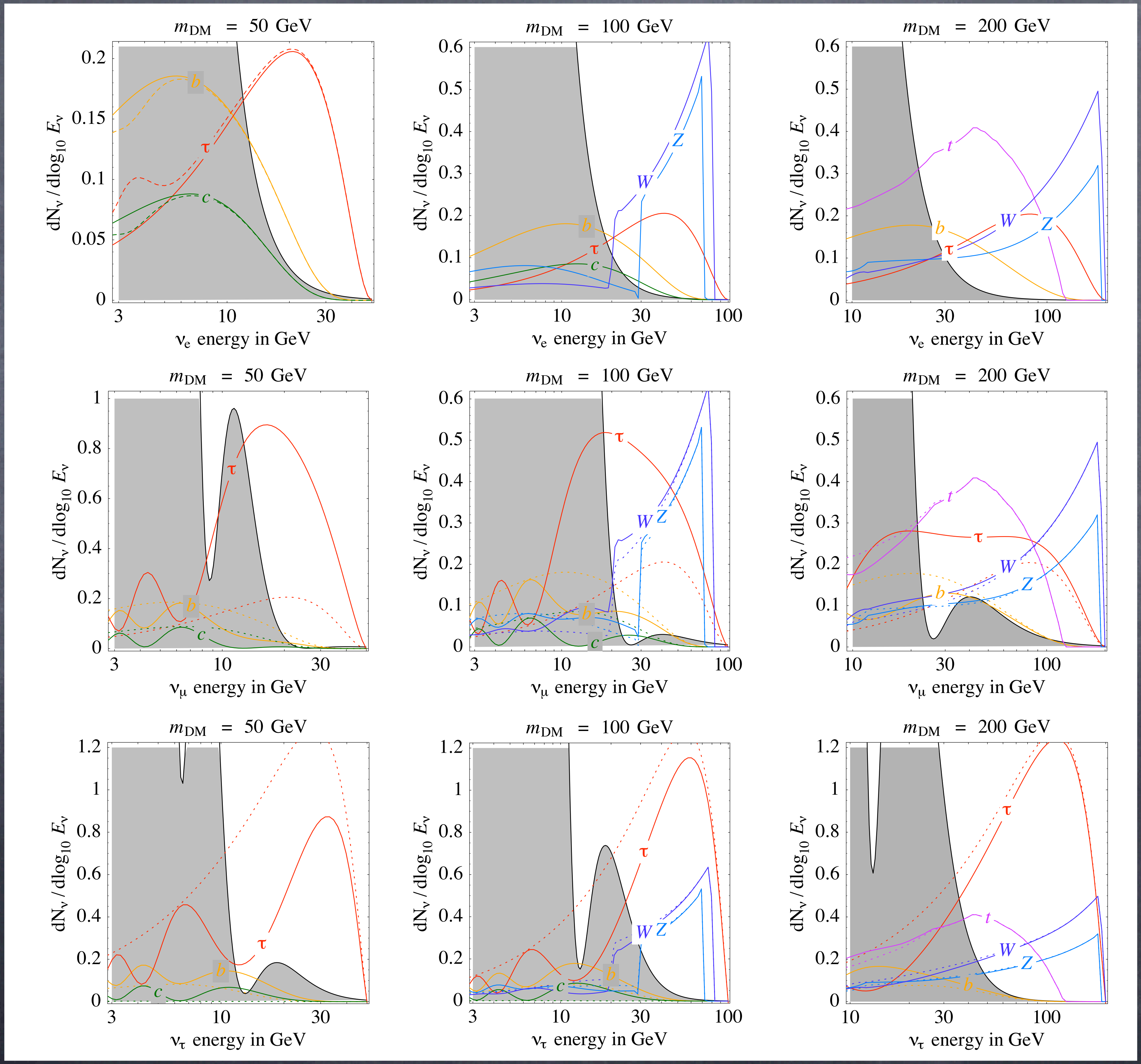
2.Final ν fluxes from Earth

$m_{\rm DM} = 50$ GeV $\quad m_{\rm DM} = 100$ GeV $\quad m_{\rm DM} = 200$ GeV

ν_e

ν_μ

ν_τ



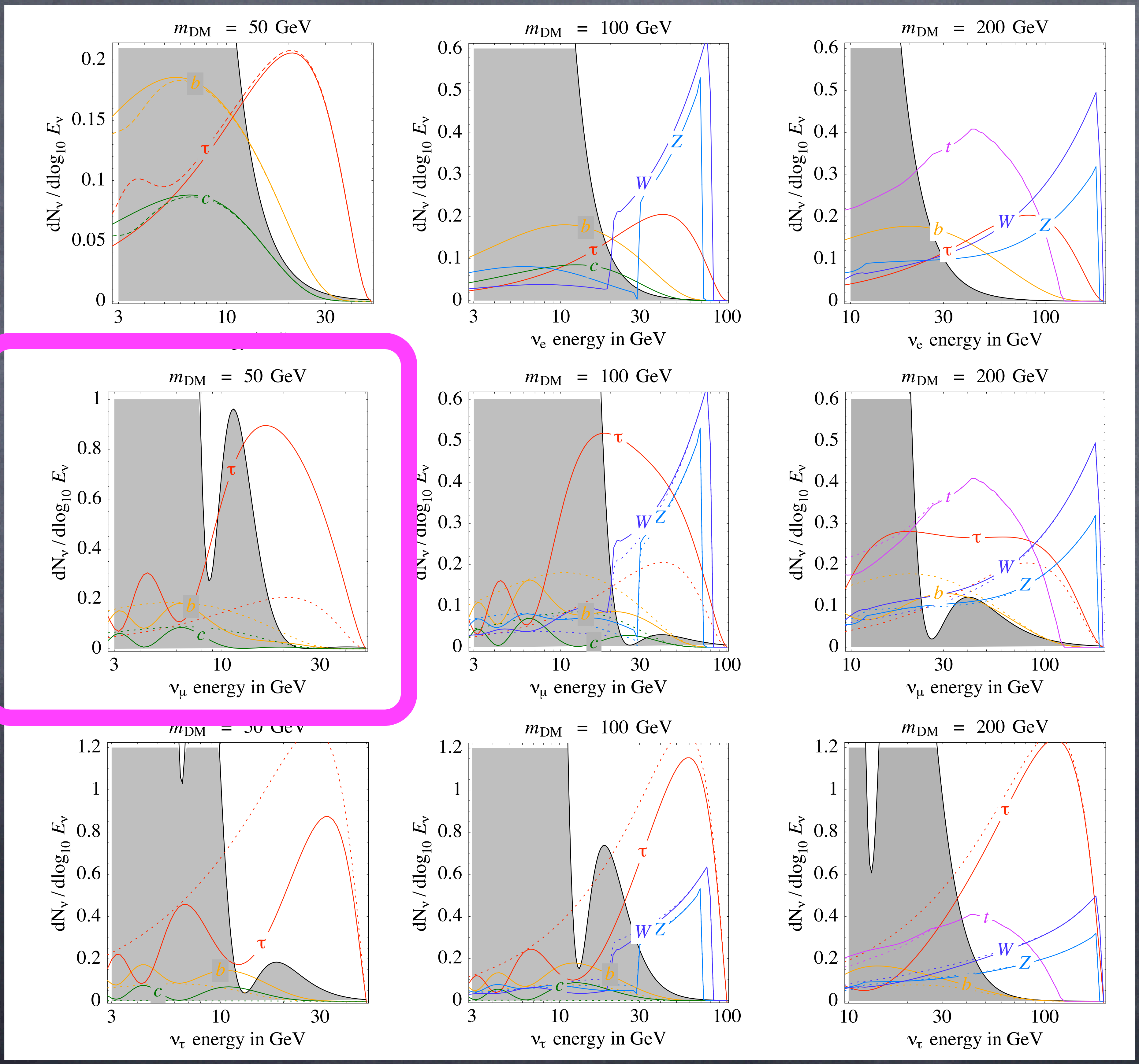
2.Final ν fluxes from Earth

$m_{\rm DM} = 50$ GeV $m_{\rm DM} = 100$ GeV $m_{\rm DM} = 200$ GeV

ν_e

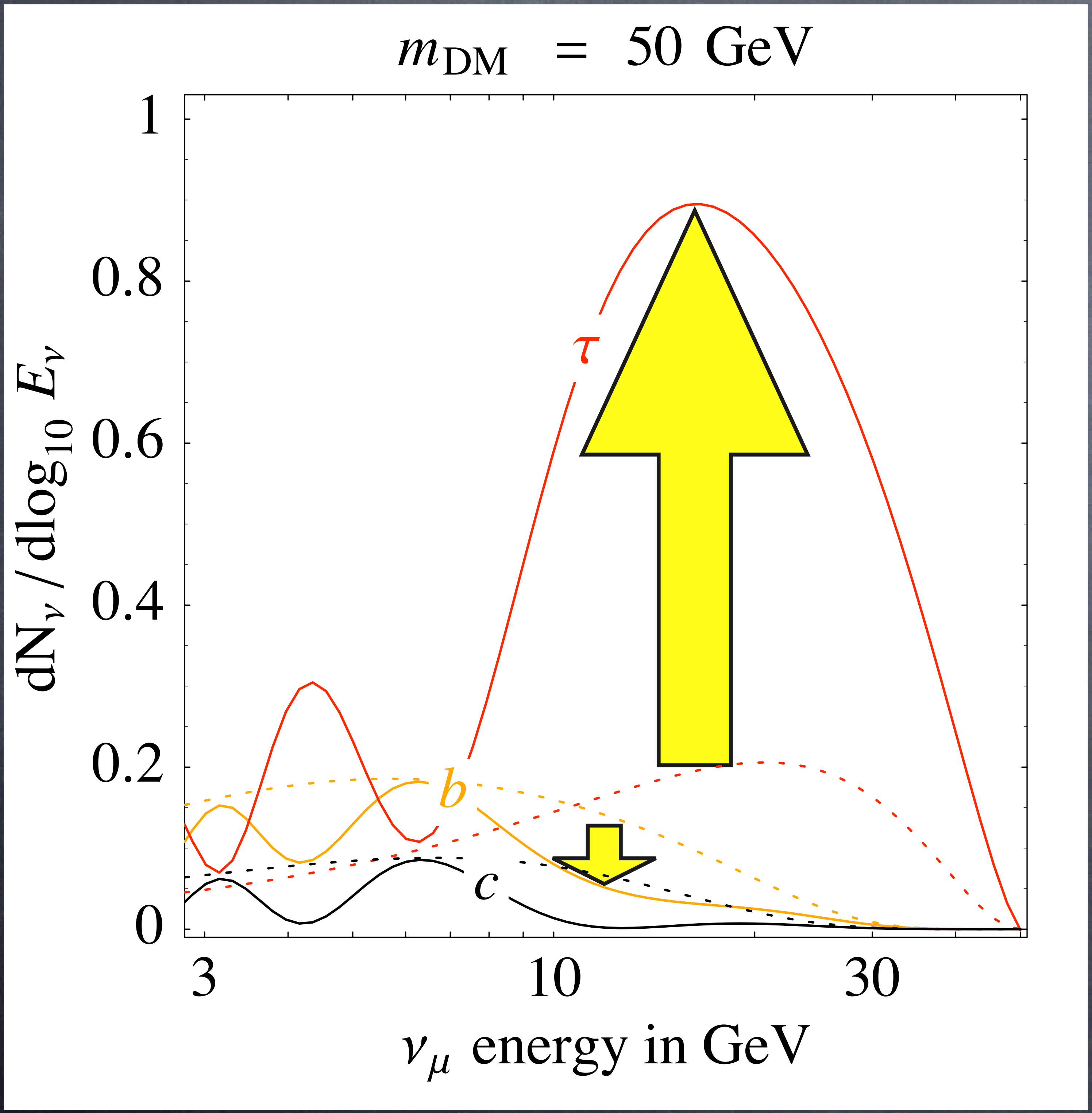
ν_μ

ν_τ



2. Final fluxes

ν_μ from 50 GeV $\chi\bar{\chi}$ annihilations in Earth's core



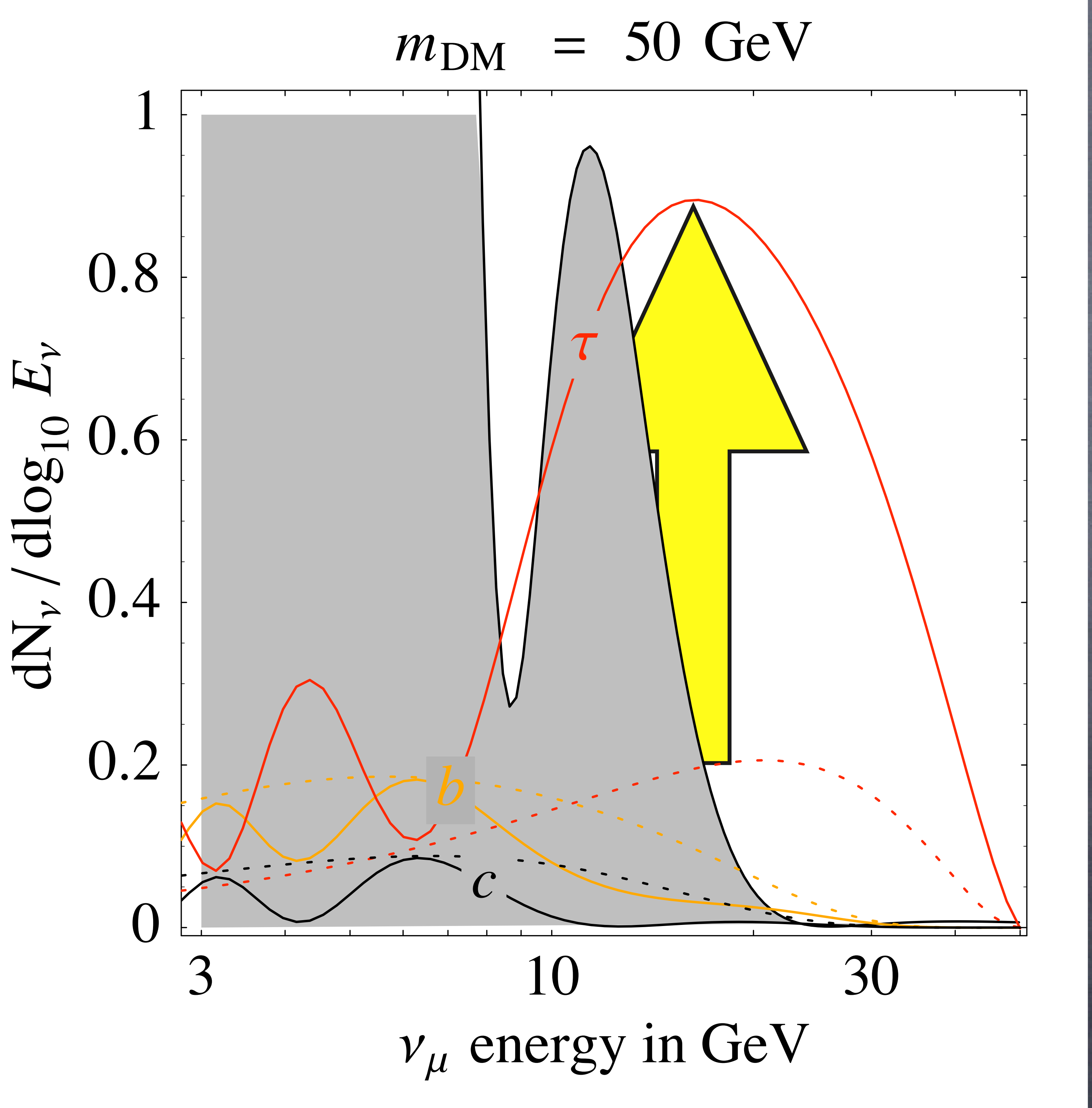
- OSCILLATIONS!

  atmospheric oscillations with

$$\lambda_{\rm atm} = \frac{4\pi E_\nu}{|\Delta m^2_{\rm atm}|} \approx 10^5 \mathrm{km} \frac{E_\nu}{100\ \mathrm{GeV}}$$

2. Final fluxes

ν_μ from 50 GeV $\chi\bar{\chi}$ annihilations in Earth's core



- OSCILLATIONS!

  atmospheric oscillations with

$$\lambda_{\rm atm} = \frac{4\pi E_\nu}{|\Delta m^2_{\rm atm}|} \approx 10^5 {\rm km} \frac{E_\nu}{100 \text{ GeV}}$$

- BACKGROUND: from atmospheric neutrinos!
  - smaller at large E
  - known angular extrapolation
  - relative normalisation assuming

$$10^{14} \left(\frac{100 \text{ GeV}}{m_{\rm DM}}\right)^2$$ annihil/sec

(FLUKA)

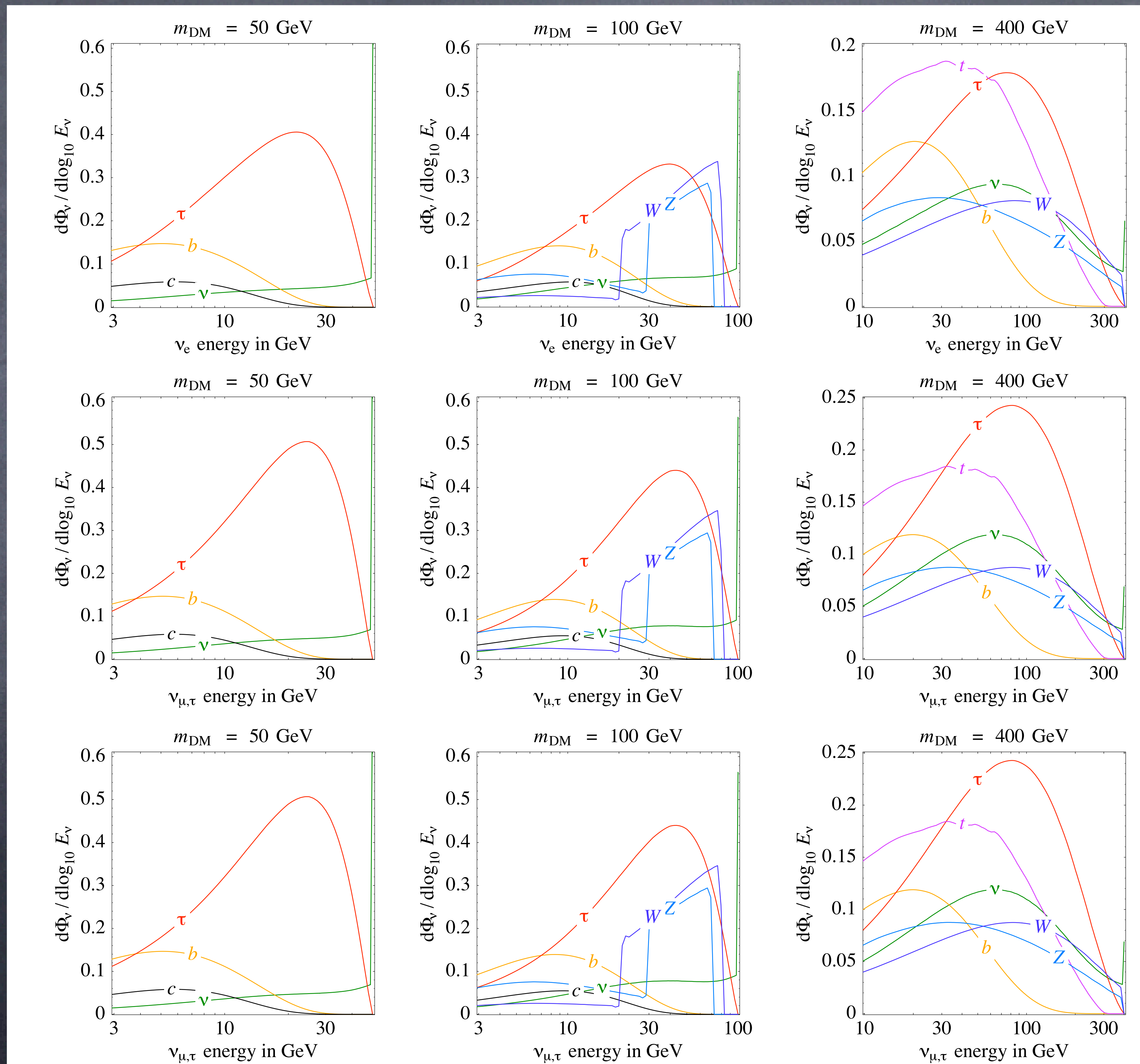
2.Final ν fluxes from Sun

$m_{\rm DM} = 50$ GeV $\quad m_{\rm DM} = 100$ GeV $\quad m_{\rm DM} = 400$ GeV

ν_e

ν_μ

ν_τ



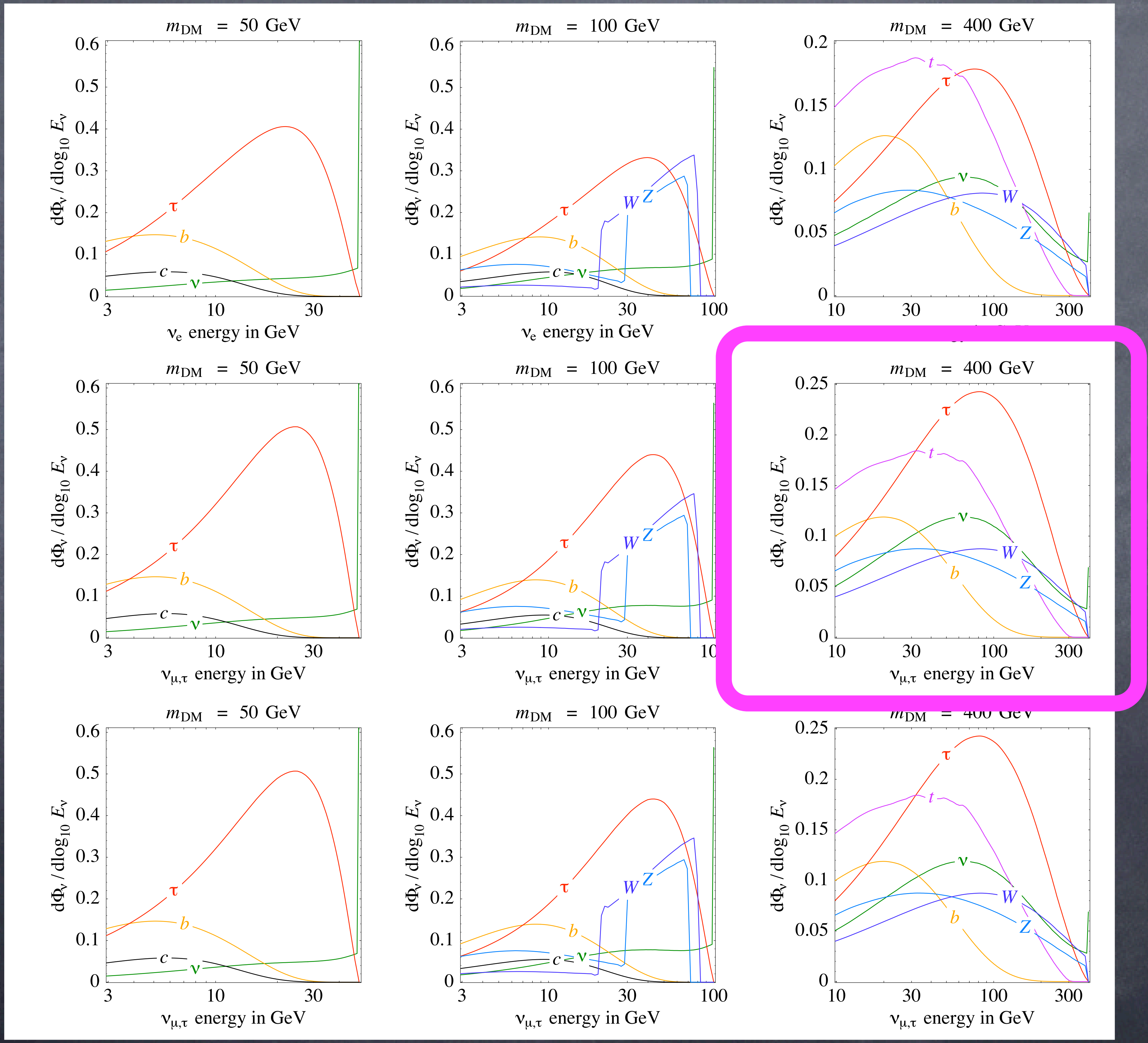
2.Final ν fluxes from Sun

$m_{\mathrm{DM}} = 50$ GeV $\quad m_{\mathrm{DM}} = 100$ GeV $\quad m_{\mathrm{DM}} = 400$ GeV

ν_e

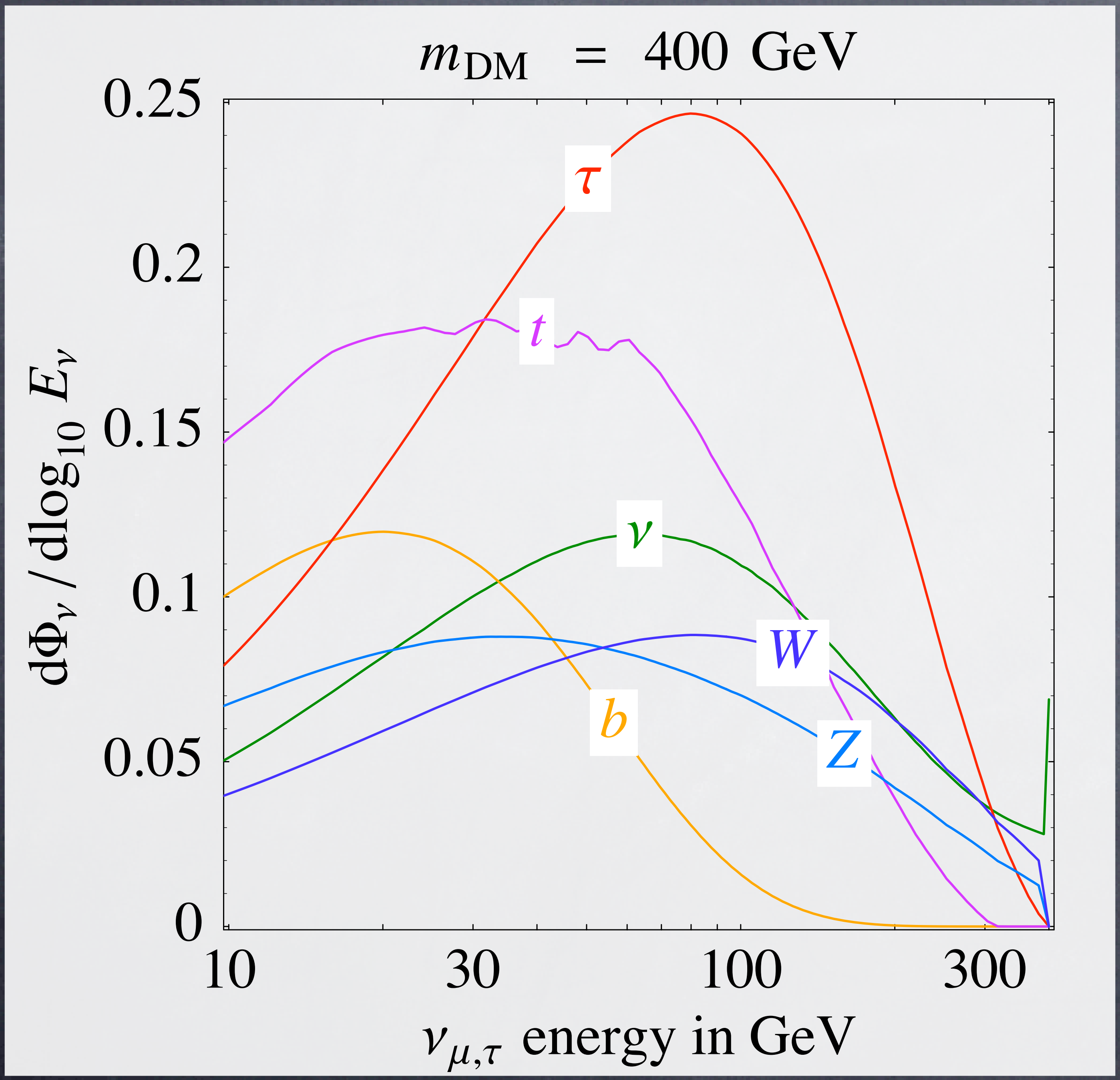
ν_μ

ν_τ

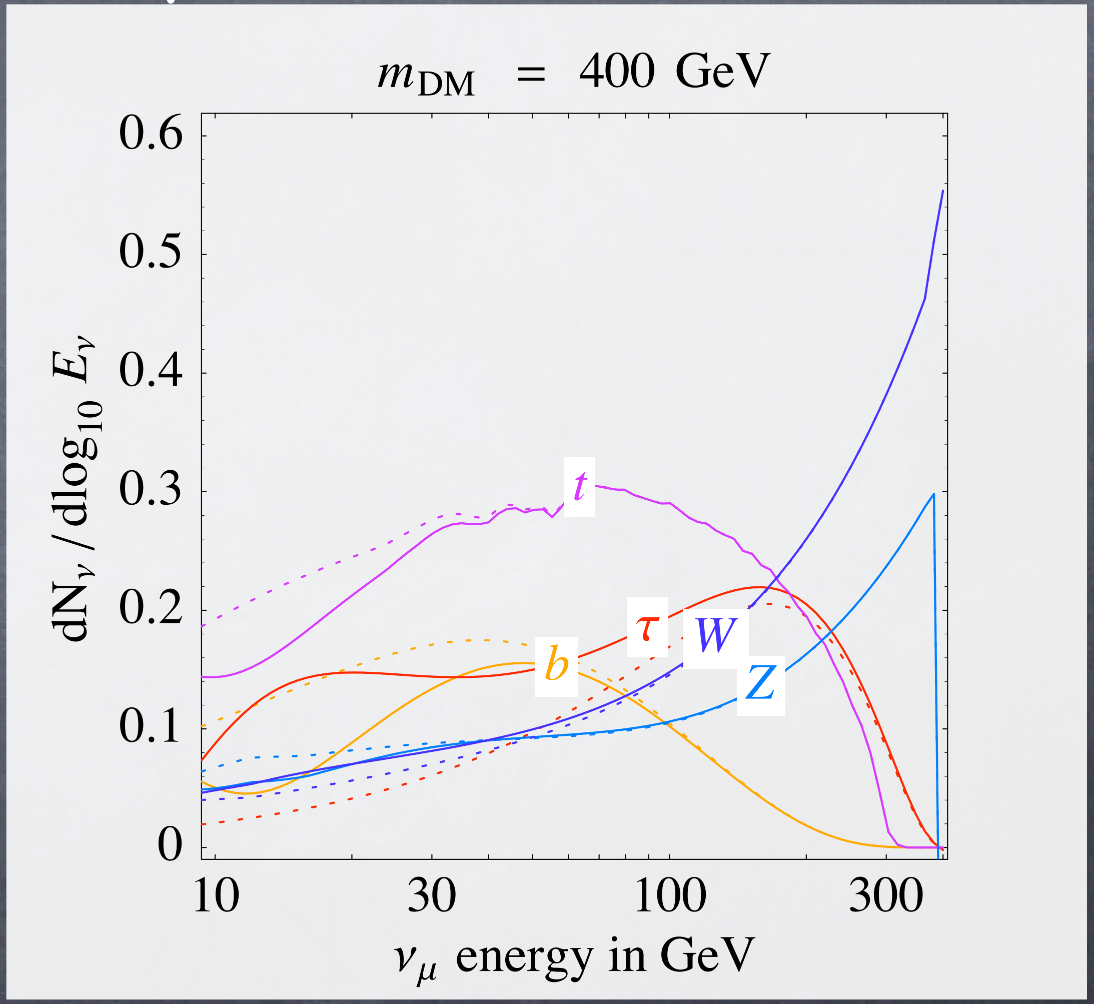


2. Final fluxes

ν_μ from 400 GeV $\chi\bar{\chi}$ annihilations in Sun's core



compare with Earth's case:



- interactions degrade and smoothen spectrum, approach "limit spectrum"

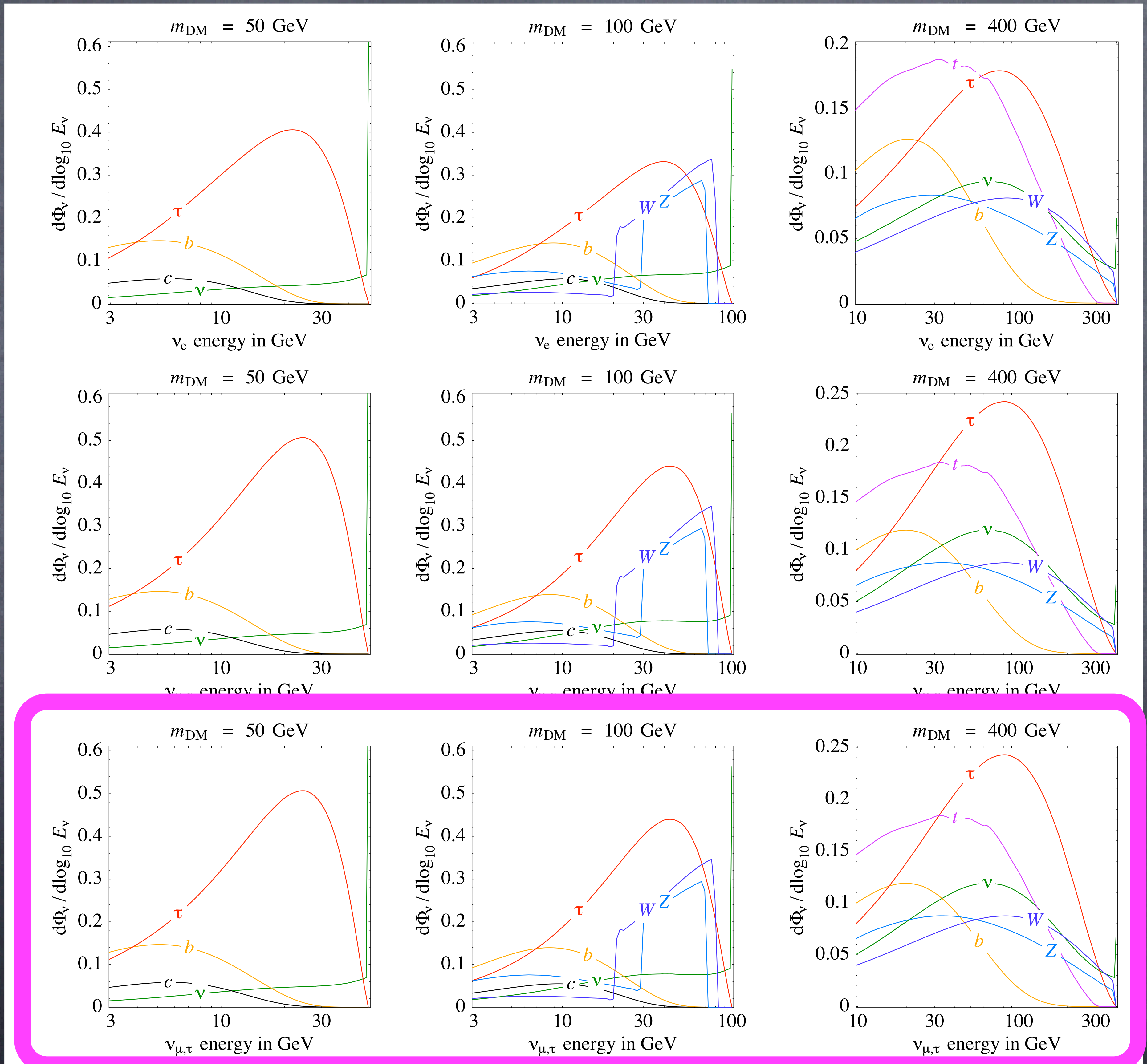
2.Final ν fluxes from Sun

$m_{\rm DM} = 50$ GeV $\quad m_{\rm DM} = 100$ GeV $\quad m_{\rm DM} = 400$ GeV

ν_e

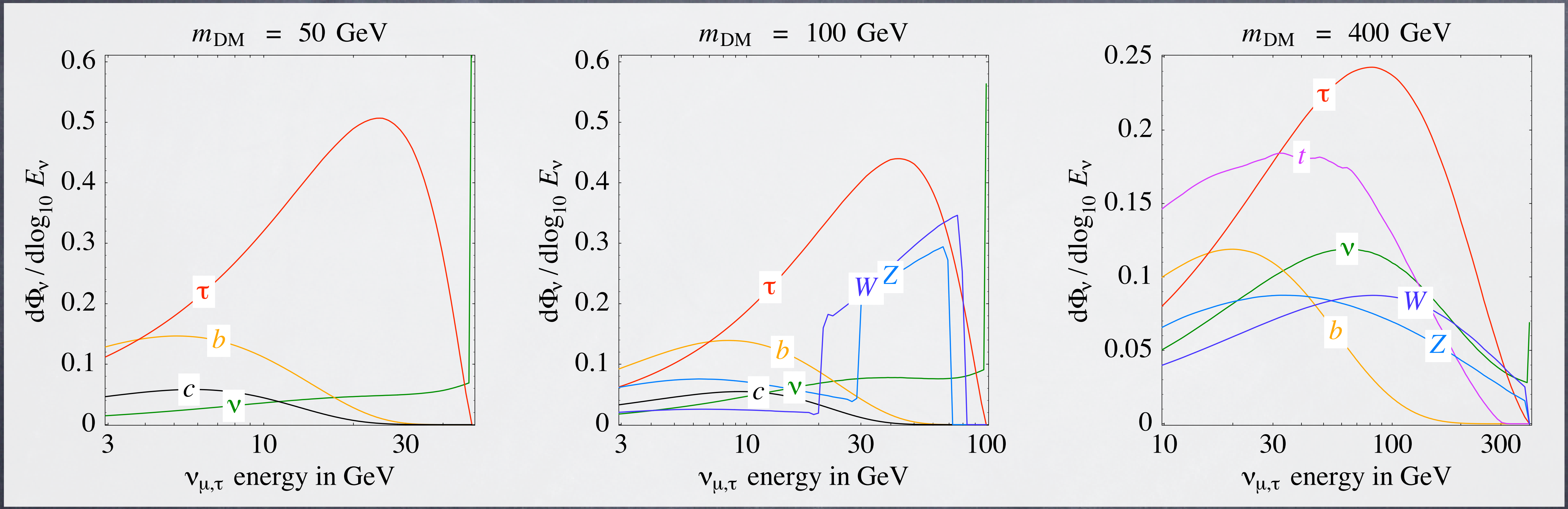
ν_μ

ν_τ



2. Final fluxes

ν_τ from above: **NO BACKGROUND !**



- atmo ν_τ: little production ($D_s \to \tau\nu_\tau$), no from oscillations $(\sim 10^{-3})$
- ν_τ from solar corona: small
- ν_τ from other astrophysical sources: directional and negligible

700	0.12	0.608978	0.341566	0.288158	0.00732825	1.01016	0.329712	0.325684
700	0.13	0.549979	0.338742	0.261576	0.00587295	0.938862	0.306415	0.314678
700	0.14	0.497406	0.335783	0.237414	0.00472903	0.879793	0.28655	0.305119
700	0.15	0.45023	0.332688	0.215358	0.00380882	0.814194	0.269374	0.296714
700	0.16	0.407863	0.329461	0.195214	0.00307157	0.79659	0.254494	0.289315
700	0.17	0.369843	0.326101	0.176844	0.00248237	0.753636	0.24159	0.282798
700	0.18	0.335522	0.322618	0.160047	0.00200452	0.716648	0.230284	0.277002
700	0.19	0.304578	0.31901	0.14472	0.00162001	0.675494	0.220381	0.271845
700	0.2	0.276564	0.315279	0.130711	0.00130737	0.637912	0.211633	0.26723
700	0.21	0.251174	0.311436	0.117905	0.00105404	0.604016	0.203894	0.263081
700	0.22	0.228188	0.307472	0.10625	0.000849125	0.572074	0.19704	0.259361
700	0.23	0.207361	0.30339	0.0956315	0.000683914	0.540172	0.190963	0.25601
700	0.24	0.188471	0.299207	0.0859745	0.00055027	0.514165	0.185543	0.25298
700	0.25	0.171298	0.29493	0.0771891	0.000442236	0.490279	0.180708	0.250232
700	0.26	0.155638	0.290551	0.0691846	0.00035443	0.46804	0.176369	0.247734
700	0.27	0.141436	0.28608	0.0619432	0.000283948	0.449289	0.172486	0.245459
700	0.28	0.12846	0.281519	0.0553506	0.000226624	0.425593	0.168987	0.243375
700	0.29	0.116646	0.276873	0.0493849	0.00018028	0.402885	0.165838	0.241472
700	0.3	0.105937	0.272149	0.044022	0.000143647	0.385856	0.163012	0.239737
700	0.31	0.0961617	0.267351	0.0391701	0.00011413	0.370693	0.160458	0.238141
700	0.32	0.0872398	0.262489	0.0347864	0	0.356329	0.158152	0.236669
700	0.33	0.0791152	0.257559	0.0308456	0	0.342135	0.156067	0.235315
700	0.34	0.0716946	0.252566	0.0272953	0	0.327646	0.154173	0.234065
700	0.35	0.0649382	0.247521	0.0241132	0	0.313854	0.15246	0.232911
700	0.36	0.0587938	0.242423	0.0212697	0	0.302327	0.150908	0.231843
700	0.37	0.053184	0.237281	0.0187219	0	0.292082	0.149494	0.230853
700	0.38	0.0480605	0.232096	0.0164396	0	0.280878	0.148205	0.229935
700	0.39	0.0433863	0.226871	0.0144014	0	0.26817	0.14703	0.229083
700	0.4	0.0391341	0.221616	0.0125922	0	0.255281	0.145962	0.228293
700	0.41	0.0352722	0.216337	0.0109905	0	0.246658	0.144988	0.227559
700	0.42	0.0317531	0.211032	0.00956675	0	0.237501	0.1441	0.226875
700	0.43	0.0285549	0.205707	0.00830948	0	0.227852	0.143291	0.22624
700	0.44	0.0256505	0.200367	0.00720247	0	0.218472	0.142555	0.225648
700	0.45	0.0230042	0.195016	0.00622261	0	0.211149	0.14188	0.225094
700	0.46	0.0206088	0.189659	0.00536784	0	0.203462	0.141266	0.224579
700	0.47	0.0184371	0.184305	0.00461755	0	0.193263	0.140705	0.224098
700	0.48	0.0164685	0.178953	0.00395984	0	0.184528	0.140192	0.223651
700	0.49	0.0146954	0.173603	0.00339197	0	0.17742	0.139723	0.223235
700	0.5	0.0130821	0.168269	0.00289159	0	0.1702	0.139291	0.222845
700	0.51	0.0116199	0.162952	0.00245495	0	0.162878	0.138894	0.222479
700	0.52	0.0103006	0.157653	0.00207853	0	0.155461	0.138529	0.222137
700	0.53	0.0091172	0.152373	0.00175797	0	0.14865	0.138198	0.221818
700	0.54	0.00804896	0.147125	0.00147903	0	0.142326	0.137896	0.221523
700	0.55	0.00708584	0.141913	0.00123738	0	0.135811	0.137616	0.221247
700	0.56	0.00622815	0.136728	0.00103514	0	0.128866	0.13736	0.22099
700	0.57	0.00545587	0.131592	0.000859692	0	0.122174	0.137124	0.22075
700	0.58	0.00476481	0.126503	0.000709713	0	0.115727	0.136909	0.220526
700	0.59	0.00415106	0.121462	0.000583949	0	0.109512	0.136713	0.220318
700	0.6	0.00361091	0.116466	0.000481224	0	0.103521	0.136535	0.220125
700	0.61	0.00313234	0.111516	0.000395915	0	0.0987924	0.136371	0.219943
700	0.62	0.00270273	0.106636	0.000321888	0	0.0940419	0.136217	0.219773
700	0.63	0.00232052	0.101826	0.000258944	0	0.0888425	0.136075	0.219615
700	0.64	0.0019903	0.0970669	0.000209454	0	0.0824631	0.135944	0.219471
700	0.65	0.0016971	0.09239	0.000167397	0	0.0763778	0.135822	0.219336
700	0.66	0.00143827	0.0877947	0.00013201	0	0.0706895	0.13571	0.219209
700	0.67	0.00121235	0.0832786	0.000103	0	0.0653816	0.135606	0.219089
700	0.68	0.00101793	0.0788391	0	0	0.0604386	0.13551	0.218977
700	0.69	0.000853677	0.0744738	0	0	0.0558457	0.135423	0.218871

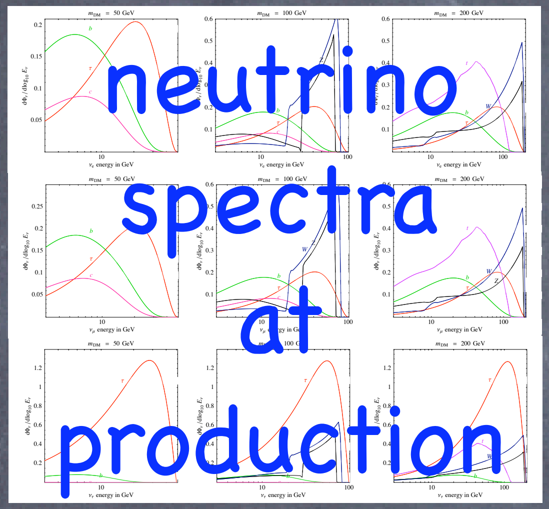
....

1000	0.01	2.79247	0.366511	1.3968	0.457048	5.61005	1.82716	0.919742
1000	0.02	2.15668	0.365559	0.991901	0.204231	3.82578	1.28553	0.712858
1000	0.03	1.79387	0.363911	0.8028	0.114483	2.93931	1.00812	0.605074
1000	0.04	1.53776	0.361895	0.684616	0.072157	2.4272	0.829507	0.53499
1000	0.05	1.33956	0.359693	0.599003	0.0489113	2.03234	0.70252	0.484414
1000	0.06	1.17884	0.357397	0.531702	0.0349214	1.75792	0.607543	0.44582
1000	0.07	1.04477	0.355012	0.475982	0.0258933	1.53263	0.534022	0.415265
1000	0.08	0.930248	0.352551	0.428124	0.0196568	1.3774	0.475356	0.390323
1000	0.09	0.831432	0.350011	0.386264	0.0152195	1.24919	0.42789	0.369668
1000	0.1	0.745226	0.347383	0.349104	0.011944	1.13285	0.38883	0.352289
1000	0.11	0.669511	0.344657	0.315824	0.00946636	1.04641	0.356319	0.337515
1000	0.12	0.602507	0.341833	0.285792	0.00755059	1.0035	0.328926	0.324818
1000	0.13	0.543024	0.338898	0.25861	0.00605045	0.930891	0.305688	0.313837
1000	0.14	0.490023	0.335856	0.233942	0.00486824	0.869851	0.285842	0.304284
1000	0.15	0.442533	0.332695	0.211482	0.00391743	0.807676	0.268692	0.295895
1000	0.16	0.400033	0.329426	0.191078	0.00315756	0.790941	0.253876	0.288535
1000	0.17	0.36183	0.326042	0.172485	0.00254717	0.750797	0.240991	0.282023
1000	0.18	0.327358	0.322539	0.155526	0.00205104	0.711319	0.229683	0.276229
1000	0.19	0.296333	0.318929	0.14011	0.00165182	0.670335	0.219782	0.271073
1000	0.2	0.26834	0.315198	0.126087	0.00132906	0.633146	0.211067	0.266473
1000	0.21	0.243019	0.311357	0.113333	0.00106751	0.599613	0.203352	0.262345
1000	0.22	0.220099	0.307412	0.10174	0.000855653	0.567975	0.19651	0.258626
1000	0.23	0.19935	0.303359	0.0912182	0.00068483	0.536348	0.190429	0.255276
1000	0.24	0.18052	0.299203	0.081661	0.000546588	0.510498	0.185002	0.252245
1000	0.25	0.163438	0.29495	0.0730024	0.000435292	0.486773	0.180152	0.249489
1000	0.26	0.148007	0.290594	0.0651978	0.000346617	0.464841	0.175832	0.246999
1000	0.27	0.133941	0.286149	0.0581121	0.000274763	0.445278	0.17194	0.244725
1000	0.28	0.121202	0.281612	0.0517329	0.000217414	0.424888	0.168453	0.242649
1000	0.29	0.109634	0.276991	0.0459836	0.00017143	0.404331	0.165314	0.240749
1000	0.3	0.0990979	0.272294	0.0407912	0.00013467	0.384466	0.162474	0.239005
1000	0.31	0.0895467	0.26752	0.0361336	0.000105558	0.367805	0.159916	0.237409
1000	0.32	0.0808812	0.262672	0.0319576	0	0.354232	0.15761	0.235943
1000	0.33	0.0729865	0.257752	0.028202	0	0.340394	0.155516	0.234588
1000	0.34	0.0658381	0.252773	0.0248526	0	0.32613	0.153627	0.233339
1000	0.35	0.0593534	0.24774	0.0218644	0	0.312305	0.151917	0.232187
1000	0.36	0.0534345	0.242648	0.0191816	0	0.300595	0.15035	0.23112
1000	0.37	0.0480904	0.237508	0.0168079	0	0.290465	0.148936	0.23013
1000	0.38	0.043242	0.232323	0.0146969	0	0.279485	0.14765	0.229213
1000	0.39	0.0388436	0.227099	0.0128232	0	0.267057	0.14648	0.228365
1000	0.4	0.0348627	0.221838	0.0111693	0	0.254385	0.145416	0.227578
1000	0.41	0.0312476	0.216542	0.00970278	0	0.245628	0.144445	0.226843
1000	0.42	0.0279685	0.211219	0.00840448	0	0.236505	0.143556	0.226158
1000	0.43	0.025004	0.205876	0.00726341	0	0.227047	0.142747	0.225522
1000	0.44	0.022328	0.200516	0.00626447	0	0.217614	0.142008	0.22493
1000	0.45	0.0199072	0.195143	0.00538629	0	0.209036	0.141332	0.224375
1000	0.46	0.0177311	0.18976	0.00462535	0	0.200618	0.140716	0.223858
1000	0.47	0.0157624	0.184373	0.00395738	0	0.192007	0.140151	0.223377
1000	0.48	0.0139824	0.178988	0.00337234	0	0.18399	0.139633	0.222928
1000	0.49	0.0123819	0.173606	0.00286701	0	0.176558	0.139159	0.22251
1000	0.5	0.010941	0.168237	0.00242644	0	0.169532	0.138724	0.222119
1000	0.51	0.00965083	0.162883	0.00204701	0	0.162891	0.138325	0.221754
1000	0.52	0.00850324	0.157544	0.00172533	0	0.156615	0.13796	0.221413
1000	0.53	0.00748234	0.152221	0.00145363	0	0.150381	0.13763	0.221097
1000	0.54	0.00656094	0.146929	0.00121609	0	0.143788	0.137328	0.220802
1000	0.55	0.00573535	0.141673	0.00101126	0	0.136946	0.137048	0.220526
1000	0.56	0.00500765	0.136446	0.000841468	0	0.129317	0.136791	0.220267
1000	0.57	0.00435469	0.131266	0.000694397	0	0.122395	0.136553	0.220025
1000	0.58	0.00377281	0.126133	0.000568917	0	0.116143	0.136336	0.2198

....

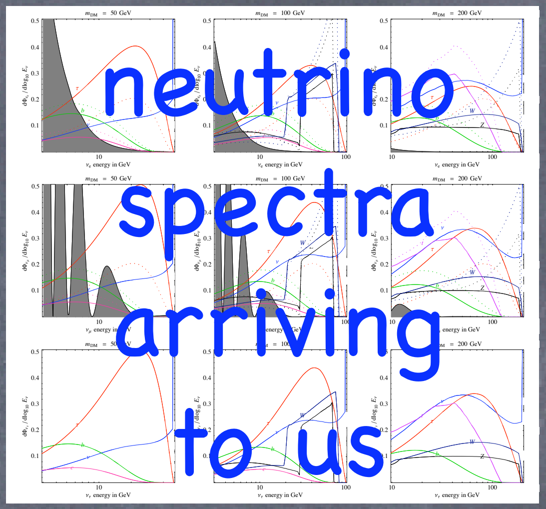
http://pantheon.yale.edu/~mc654/DMnu.html

1. Production



neutrino spectra at production

2. Propagation



neutrino spectra arriving to us

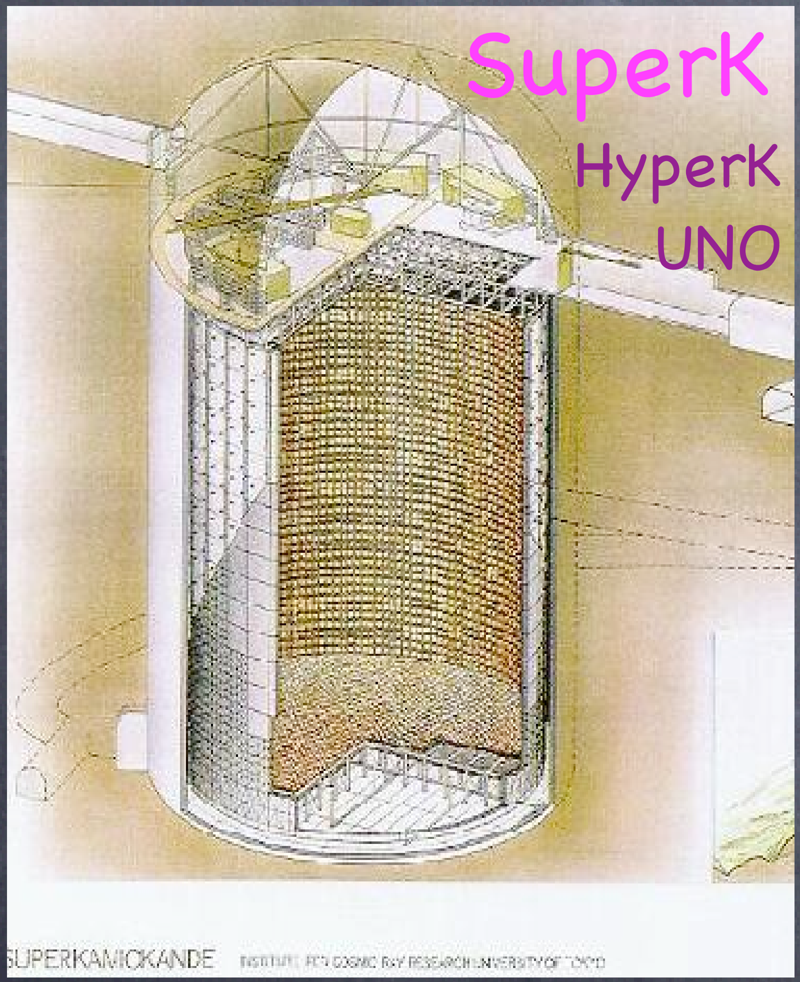
3. Detection

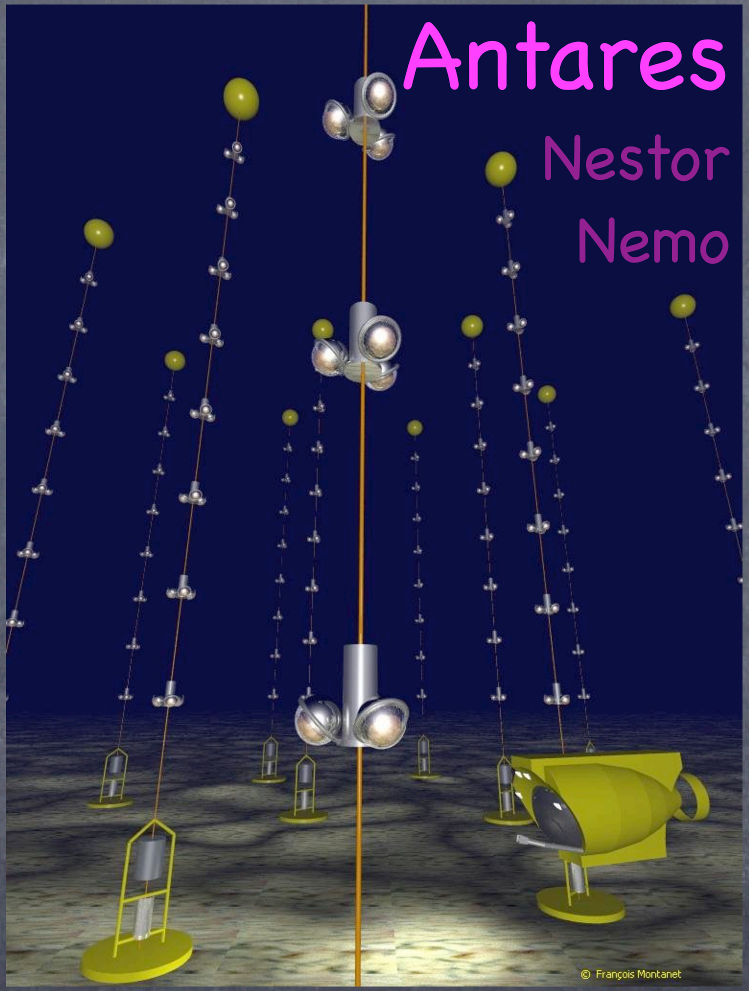
spectra of events in a detector

3. Detection: where

"Neutrino Telescopes"

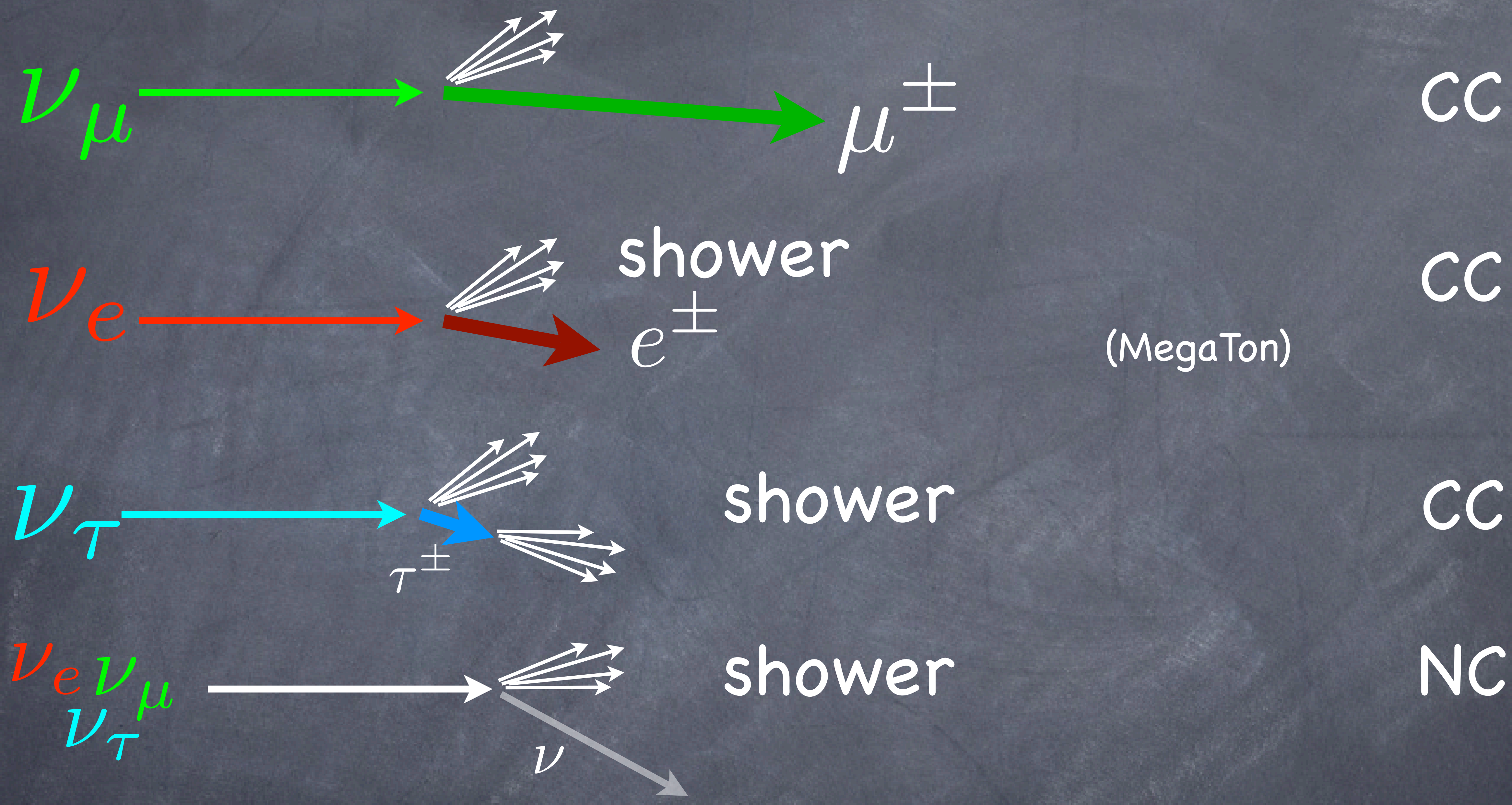
UnderGround | UnderWater | UnderIce





	UnderGround	UnderWater	UnderIce
Size:	"small"	large	large/huge
Energy thres:	GeV	tens GeV	100 GeV
Energy resol:	GeV	10 GeV	tens GeV
Angle resol:	degree	few degrees	tens degrees

3. Detection: what

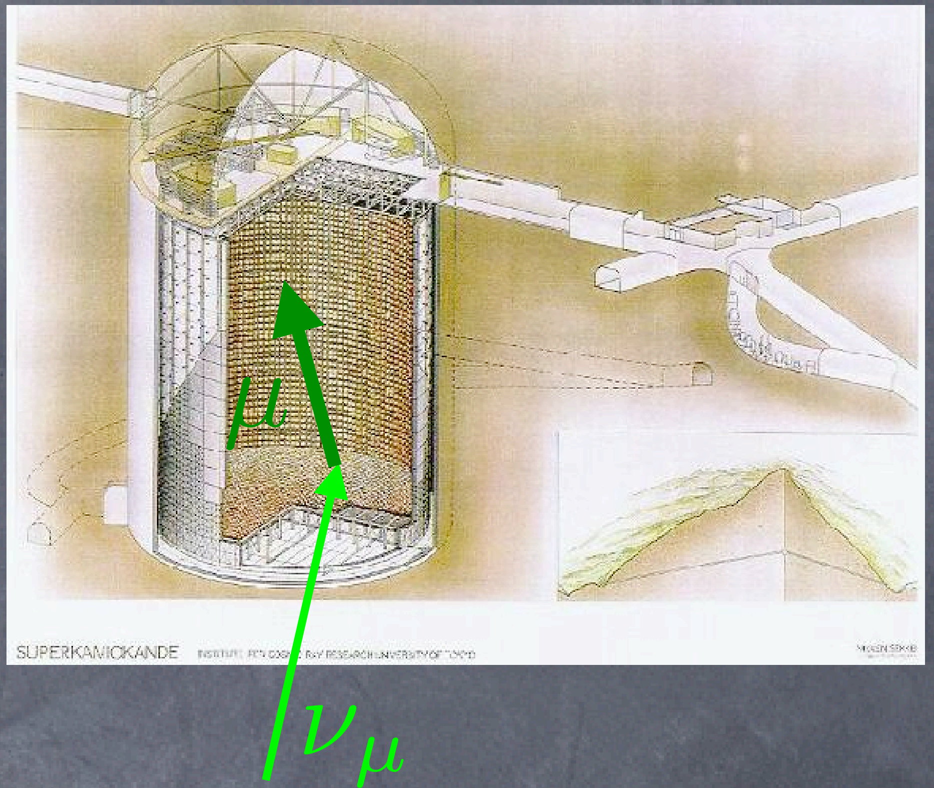


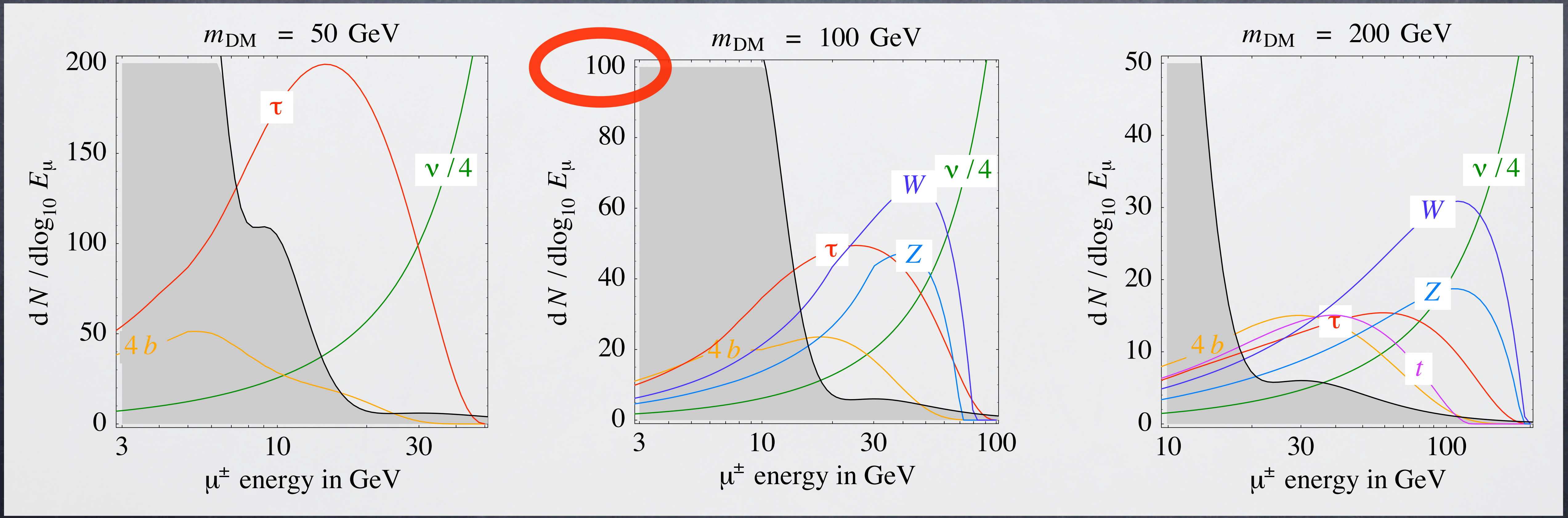
Typologies: muons, (electrons) or showers

Pros/Cons: energy reconstruction, angle reconstruction

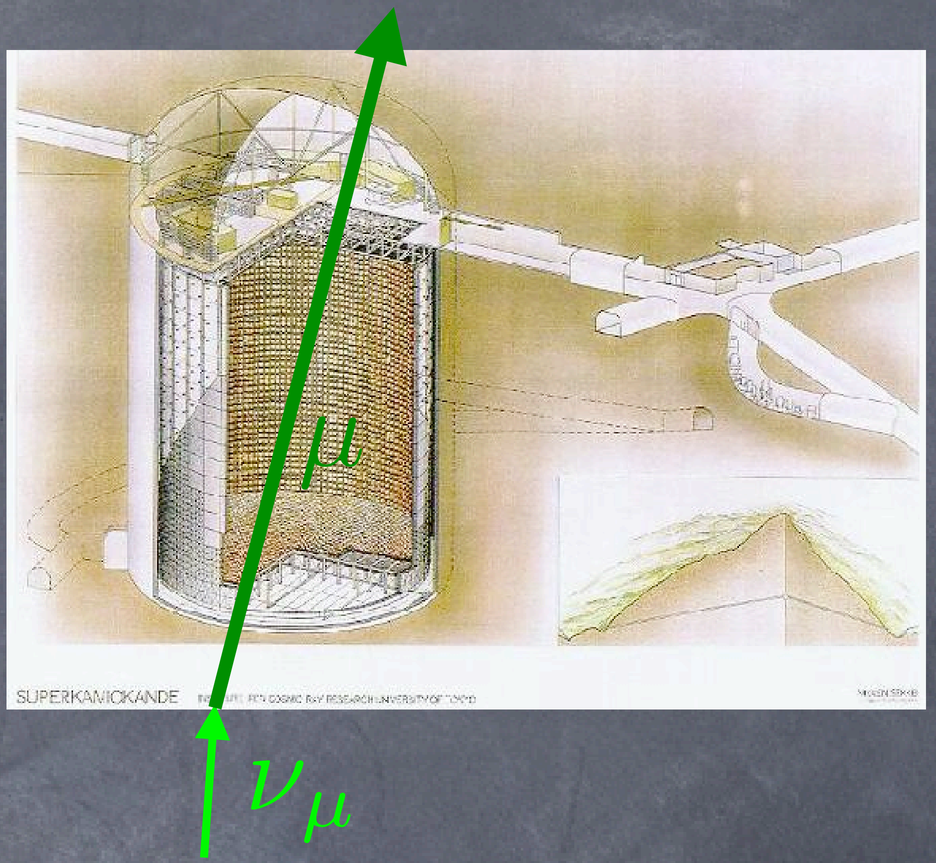
3. Detection: what

events from contained muons
(from Earth) in a MegaTon /yr

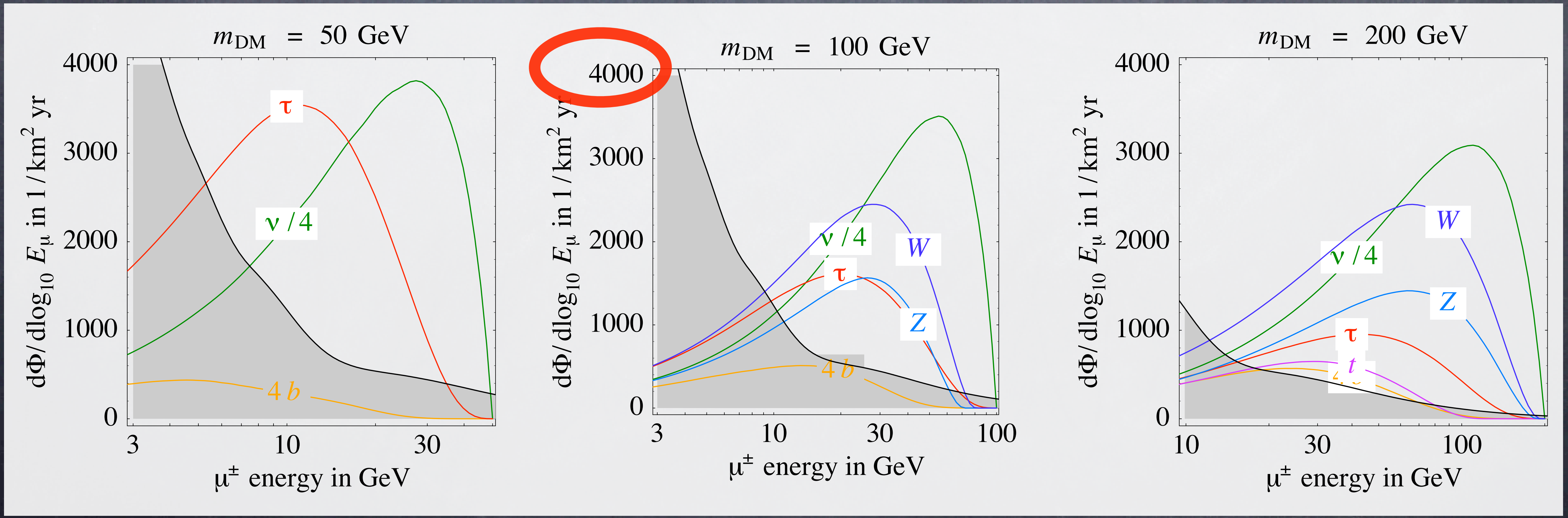




3. Detection: what

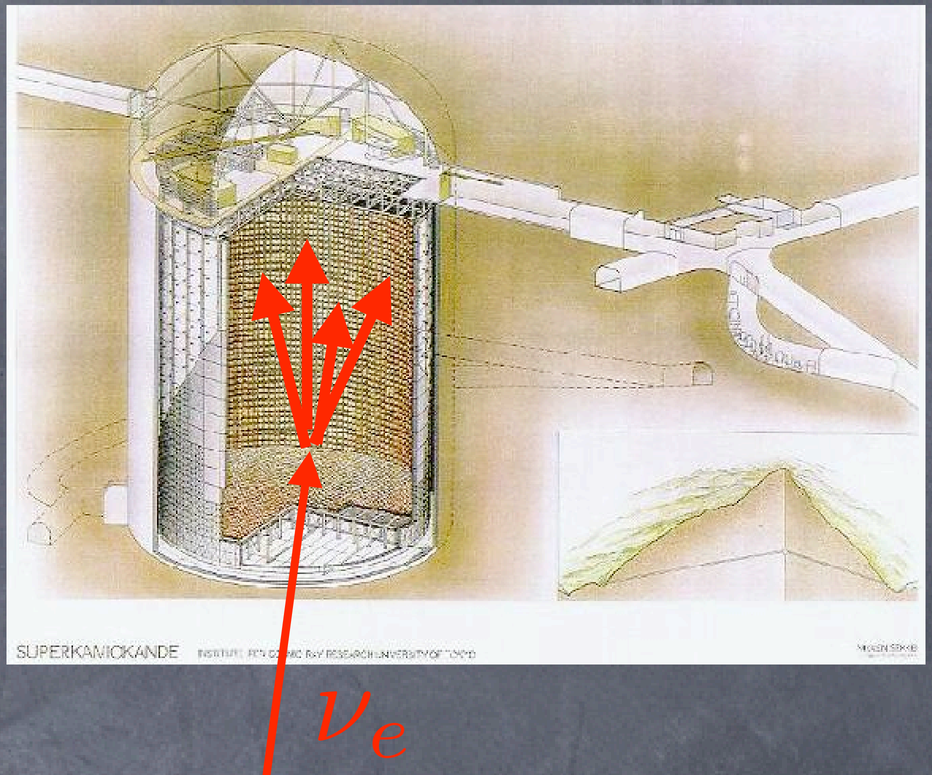


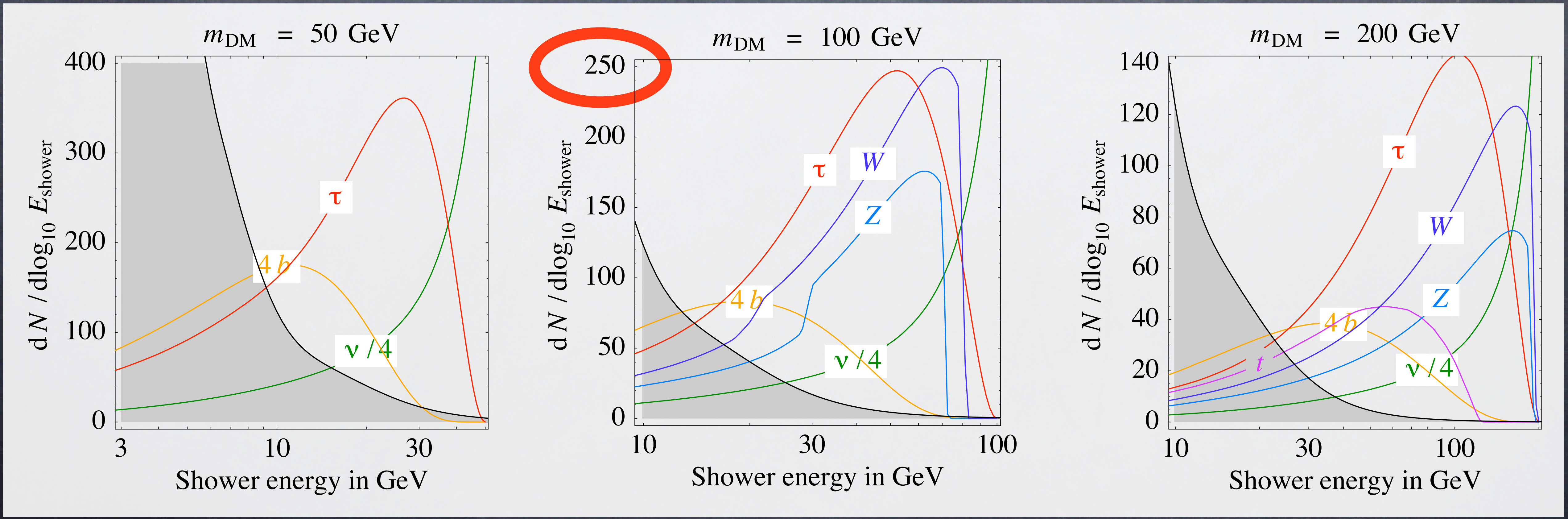
events from thru-going muons (from Earth) in a km^2/yr



3. Detection: what

showers from ν_e, ν_τ
(from Earth) in a MegaTon /yr





Picturing Dark Matter

An example: a DM particle of 100 GeV

annihilating into $\tau\bar{\tau}$ at 80% and $\nu\bar{\nu}$ at 20%;

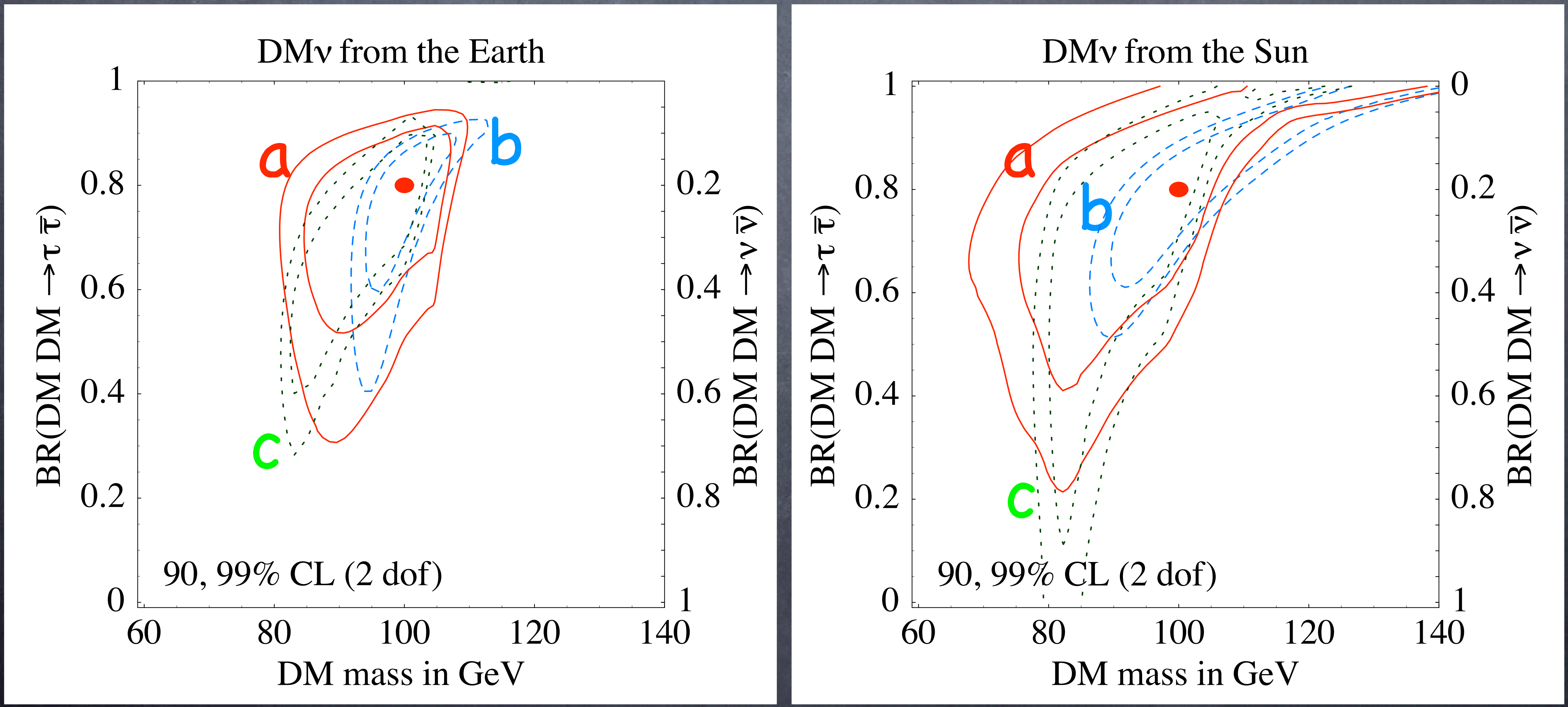
detector with threshold 15 GeV and energy resolution 30 GeV

including limitations due to background;

a) 100 contained muons or

b) 1000 thru-going muons or

c) 300 shower events



Take-home message

For everybody: ν from DM carry precious insight on the properties of DM.

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For the theorist: the formalism to compute spectra, including everything.

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THE END

Back-up slides

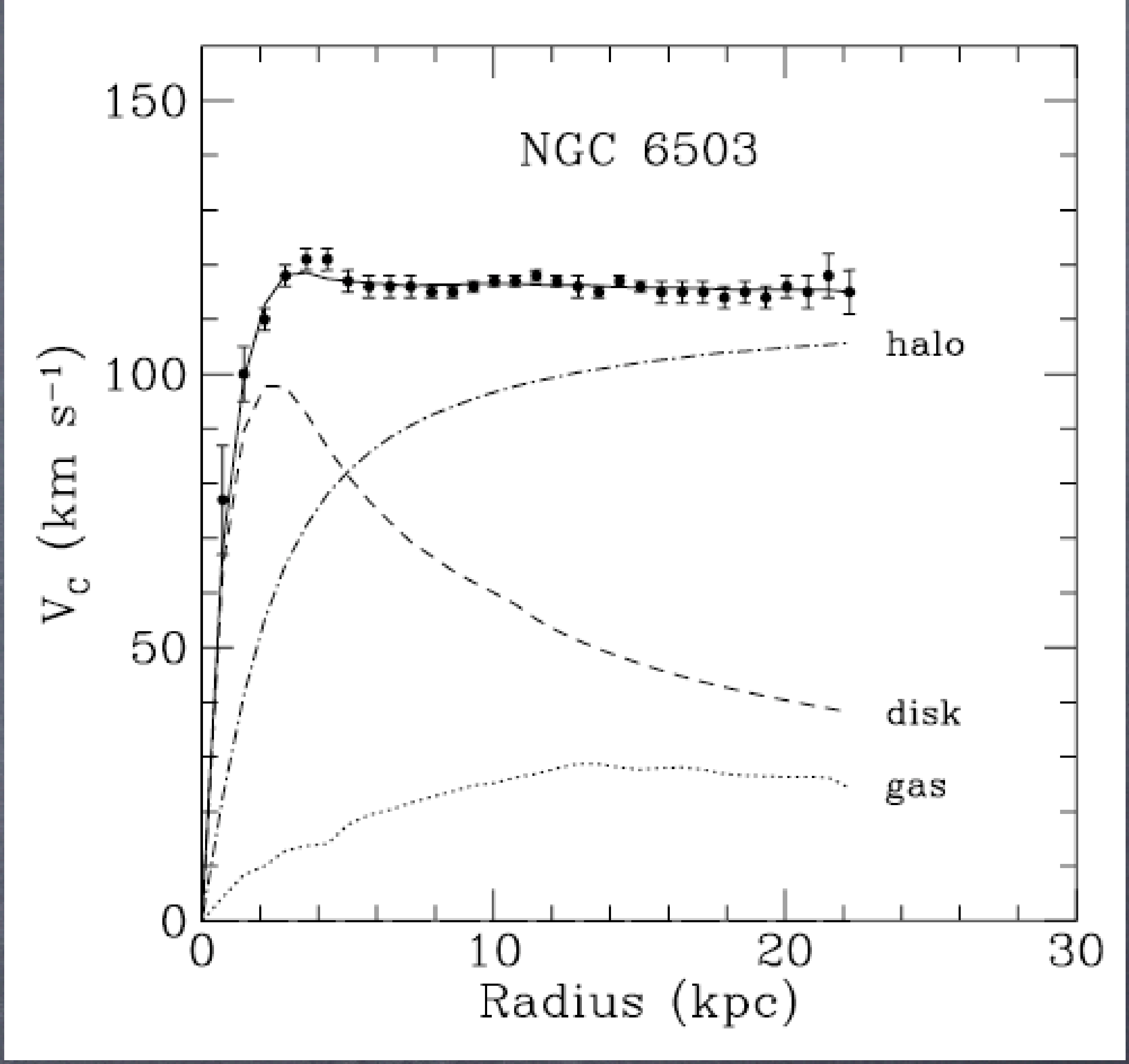
The Evidence for DM

1) galaxy rotation curves

$$v_c(r) = \sqrt{\frac{2G_N M(r)}{r}}$$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

$$\Omega_{\rm M} \gtrsim 0.1$$

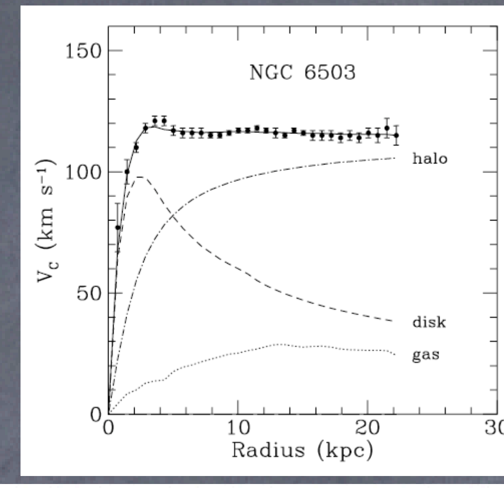


Begeman et al., MNRAS 249 (1991)

back

The Evidence for DM

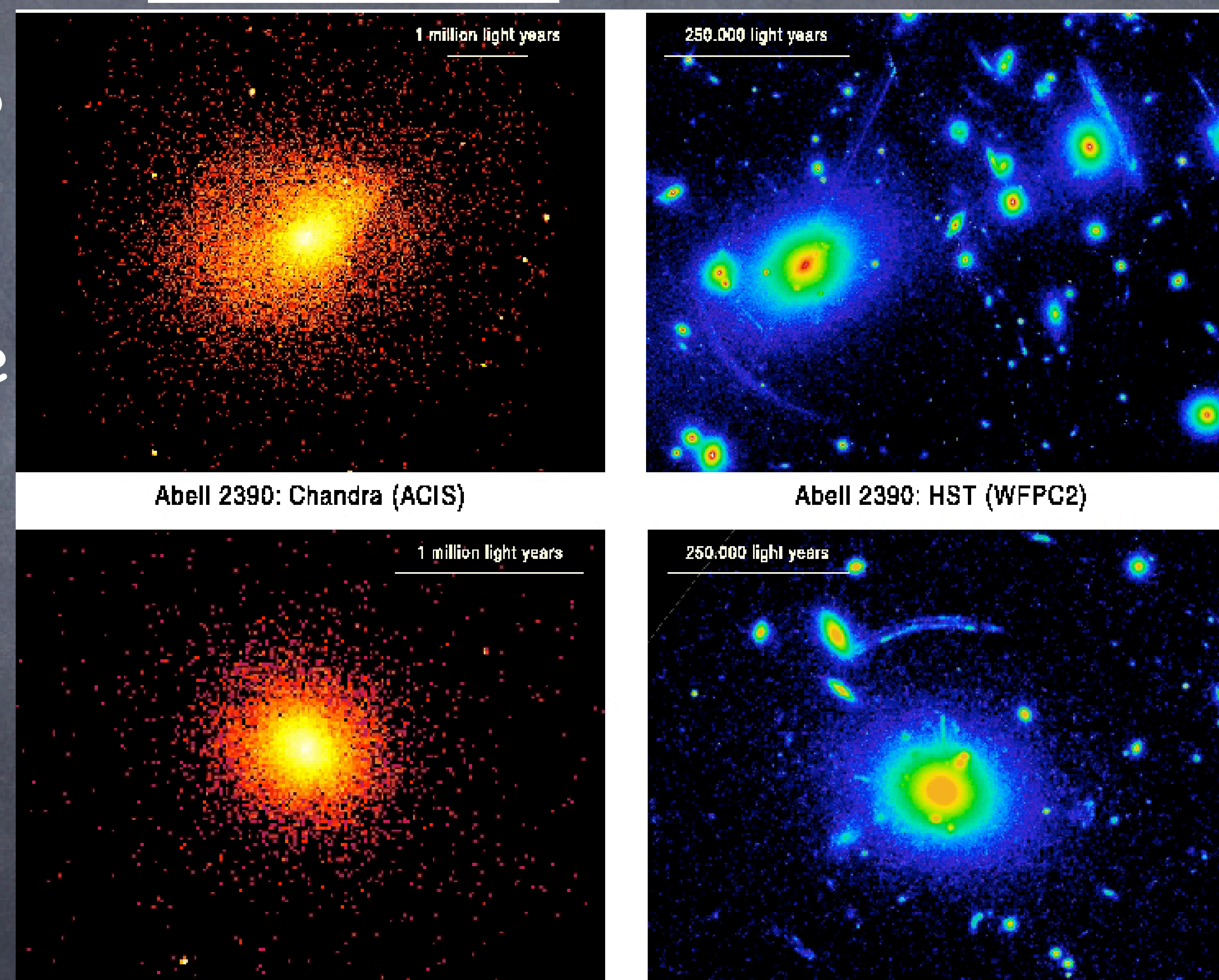
1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

2) clusters of galaxies
- "rotation curves"
- gravitation lensing
- X-ray gas Temperature

$\Omega_M \sim 0.2 \div 0.4$



Abell 2390: Chandra (ACIS)

Abell 2390: HST (WFPC2)

MS2137.3-2353: Chandra (ACIS)

MS2137.3-2353: HST (WFPC2)

astro-ph/0304020

back

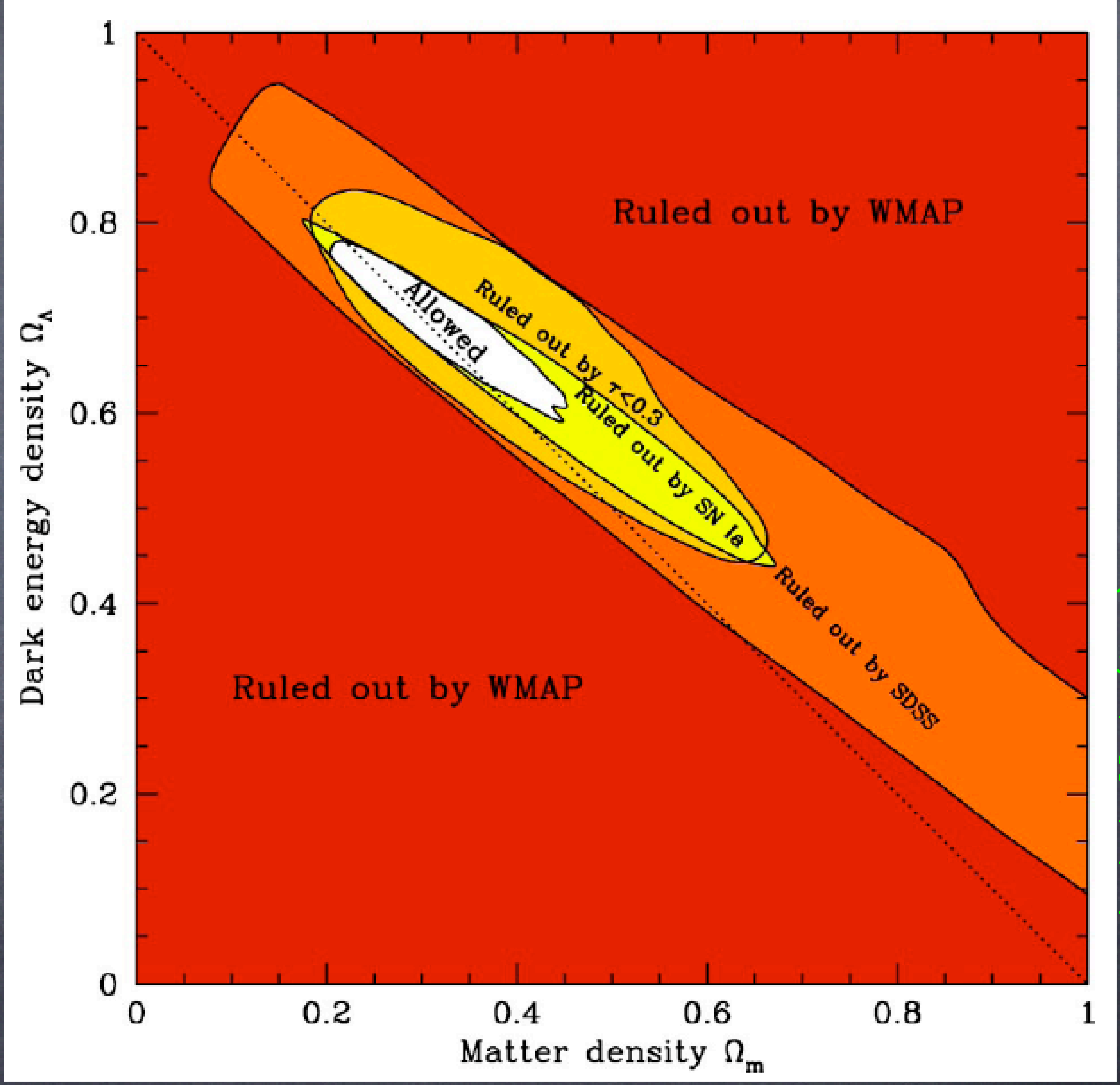
The Evidence for DM

1) galaxy rotation curves

2) clusters of galaxies

3) CMB+LSS+SNIa:

$$\Omega_{\rm M} \approx 0.30 \pm 0.04$$



M.Tegmark et al., PRD69 (2004)

back

Relic abundance calculation

The result for the relic abundance is

$$\Omega_\chi h^2 = Y_\infty s_0 m_\chi/(\rho_{\rm crit}/h^2) \approx 2.82 \times 10^8 \, Y_\infty (m_\chi/\mathrm{GeV})$$

where

$$Y_\infty^{-1} = 0.264 g_*^{1/2} m_{\rm Pl} m_\chi \left\{a/x_{\rm f} + 3(b - \tfrac{1}{4}a)/x_{\rm f}^2\right\} .$$

The freezeout epoch $x_{\rm f} = m_\chi/T_{\rm f}$ is determined by

$$x_{\rm f} = \ln\left[0.0764 m_{\rm Pl}(a + 6b/x_{\rm f})c(2 + c)m_\chi/(g_* x_{\rm f})^{1/2}\right]$$

which can be solved iteratively to the required precision. H

[back to “The case for WIMP”]

Neutralino "properties"

neutralino mass matrix in MSSM $(\tilde{B} - \tilde{W}^3 - \tilde{H}_1^0 - \tilde{H}_2^0$ basis)

$$M_\chi = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

superpotential

$$\mathcal{W} = -\mu \mathcal{H}_1 \mathcal{H}_2 + \mathcal{H}_1 h_e^{ij} \mathcal{L}_{Li} \mathcal{E}_{Rj} + \mathcal{H}_1 h_d^{ij} \mathcal{Q}_{Li} \mathcal{D}_{Rj} - \mathcal{H}_2 h_u^{ij} \mathcal{Q}_{Li} \mathcal{U}_{Rj}$$

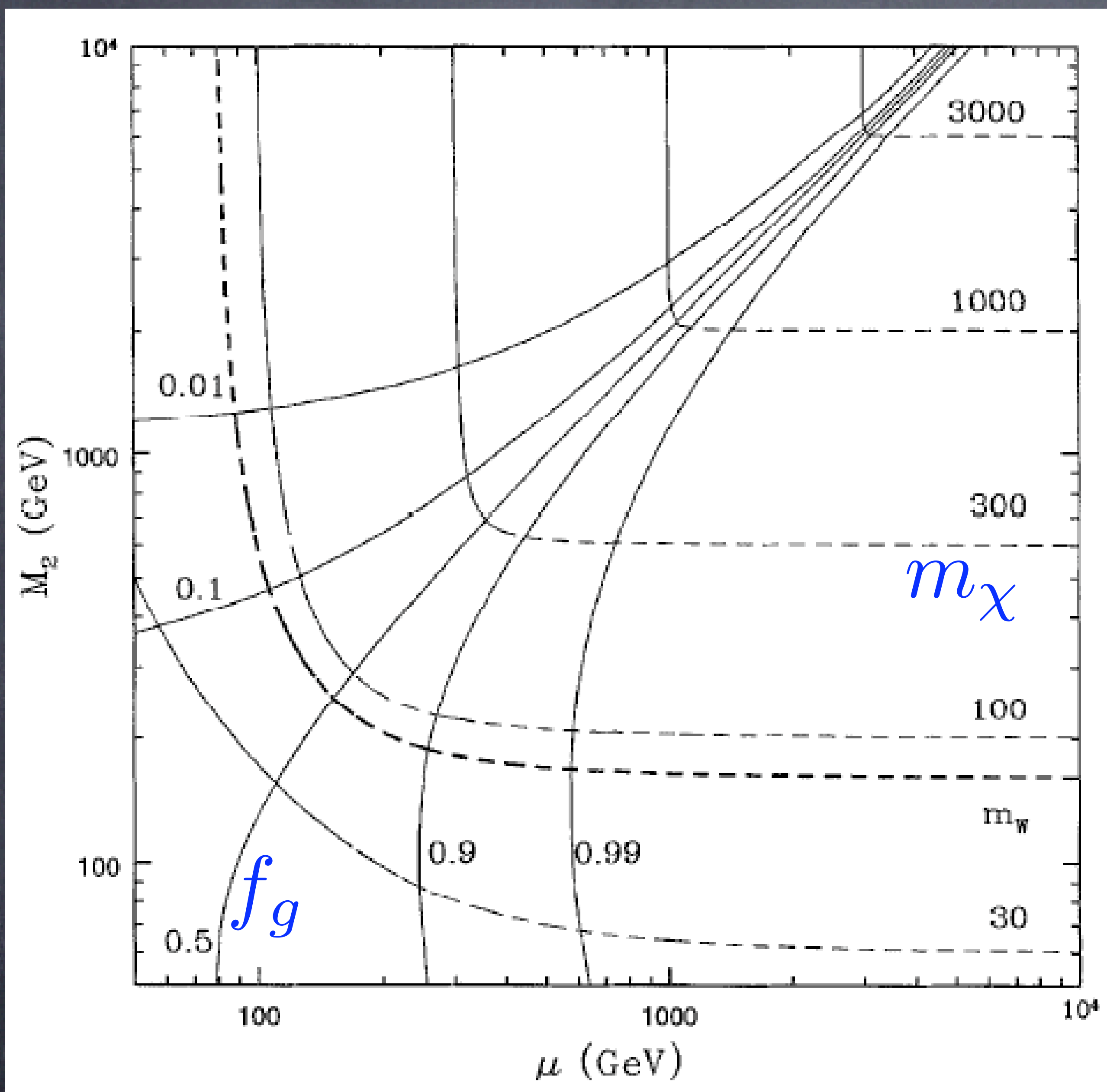
soft SUSYB terms

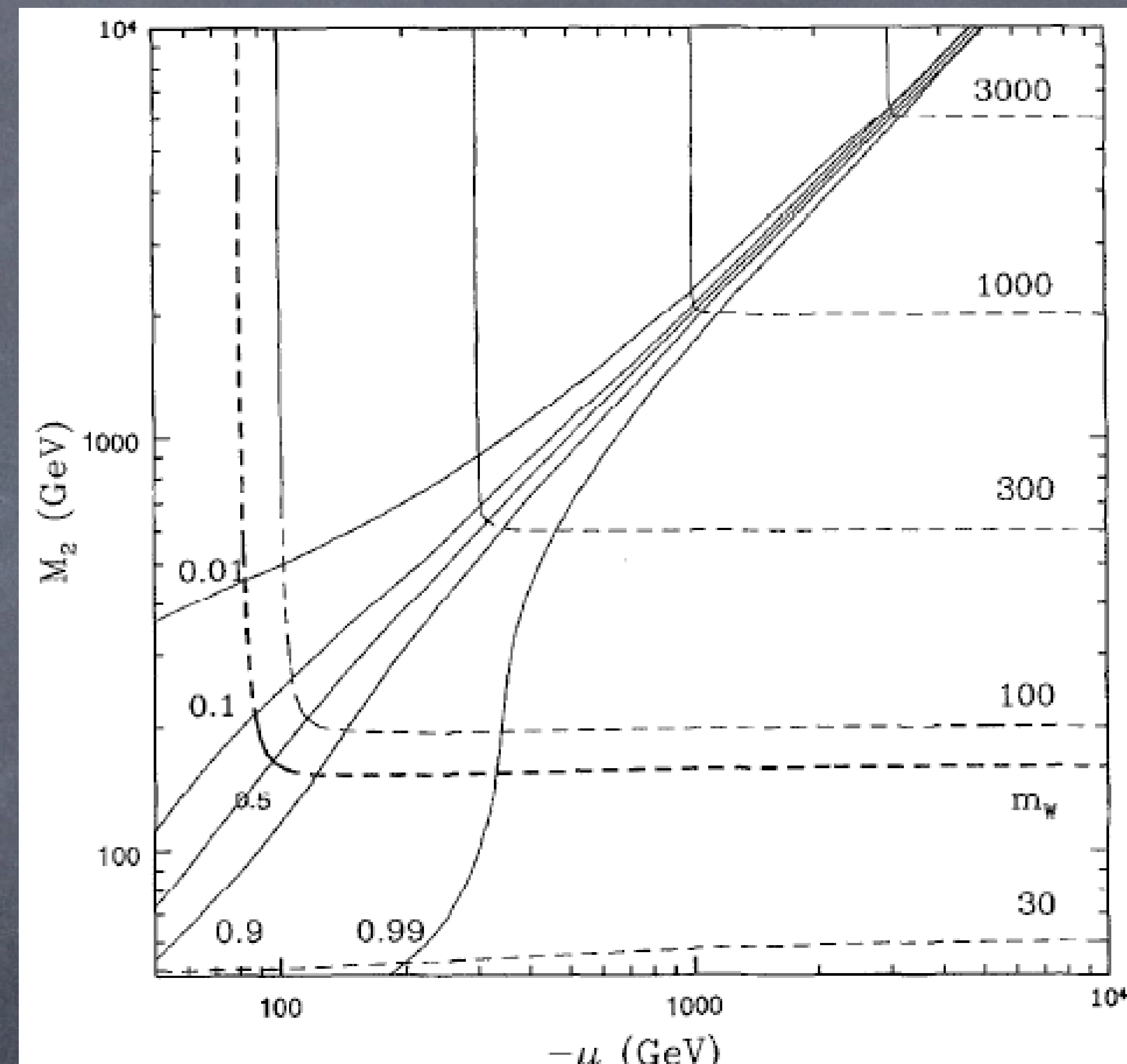
$$\mathcal{L}_{\rm soft} = -\frac{1}{2}\left(M_1 \bar{\tilde{B}} \tilde{B} + M_2 \bar{\tilde{W}}^a \tilde{W}^a + M_3 \bar{\tilde{G}}^a \tilde{G}^a \right) + \ldots$$

$$\tan\beta = \frac{\langle v_1 \rangle}{\langle v_2 \rangle}$$

[back to "The case for Neutralinos"]

Neutralino "properties"





[back to "The case for Neutralinos"]

Capture and annihilation rates

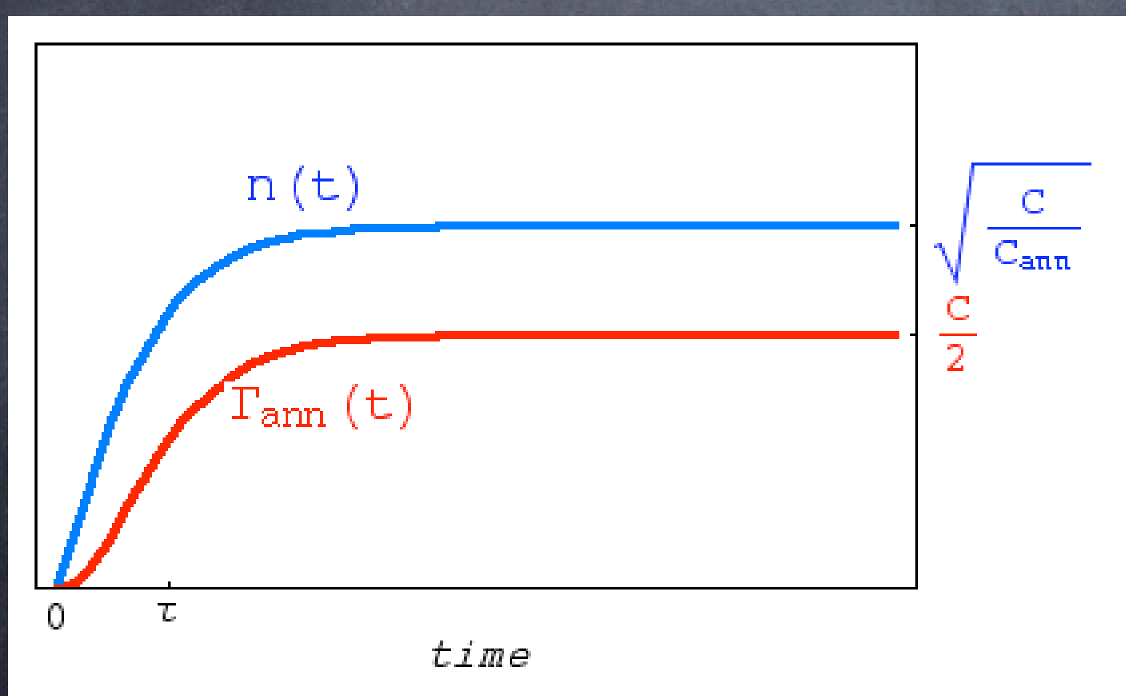
basics: DM particle scatters with nuclei and looses energy

if $v_f < v_{\rm esc}$ particle is gravitationally trapped

it spirals to center of body, accumulates and annihilates

$$v_{\rm halo} \simeq 270 \text{ km/s}$$
$$v_{{\rm esc},\odot} \simeq 620 \text{ km/s}$$
$$v_{{\rm esc},\oplus} \simeq 12 \text{ km/s}$$

equilibrium attained:



$$\dot{n} = \underbrace{C_{\rm capt}}_{\sigma_{\rm capt},\, V_{\rm eff}} - C_{\rm ann}\, n^2$$

$$n(t) = \sqrt{\frac{C_{\rm capt}}{C_{\rm ann}}}\tanh\left(\frac{t}{\tau}\right) \qquad \left(\tau = \frac{1}{\sqrt{C_{\rm capt}C_{\rm ann}}}\right)$$

$$\Gamma_{\rm ann}(t) = \frac{C_{\rm capt}}{2}\tanh^2\left(\frac{t}{\tau}\right)$$

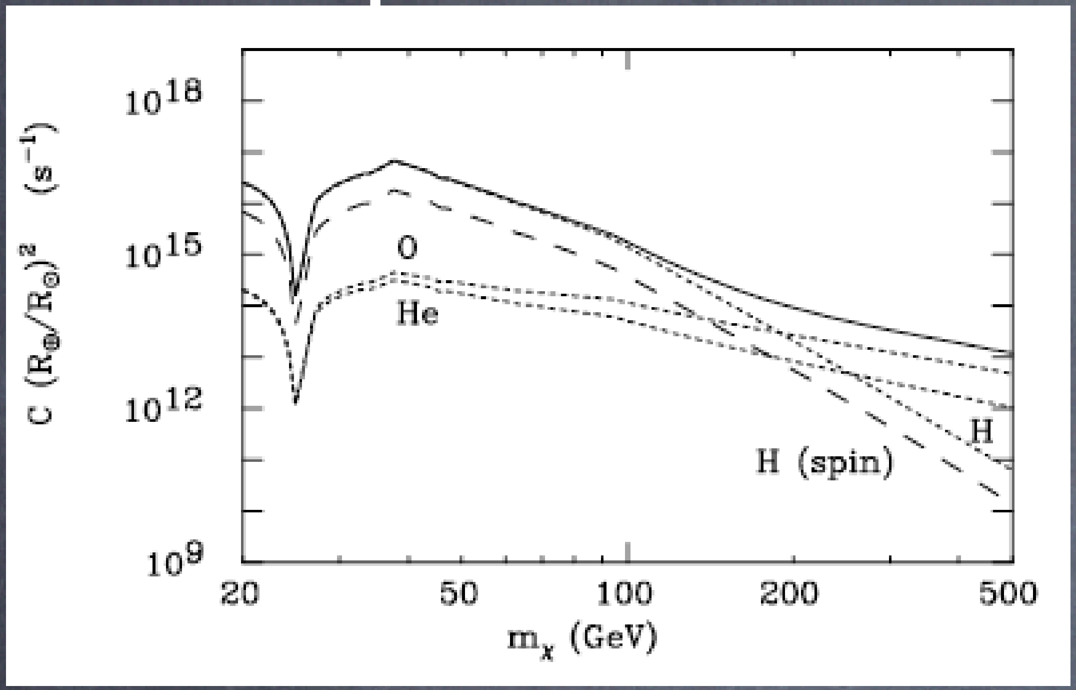
Sun: equilibrium attained

Earth: maybe

[back to nu from DM]

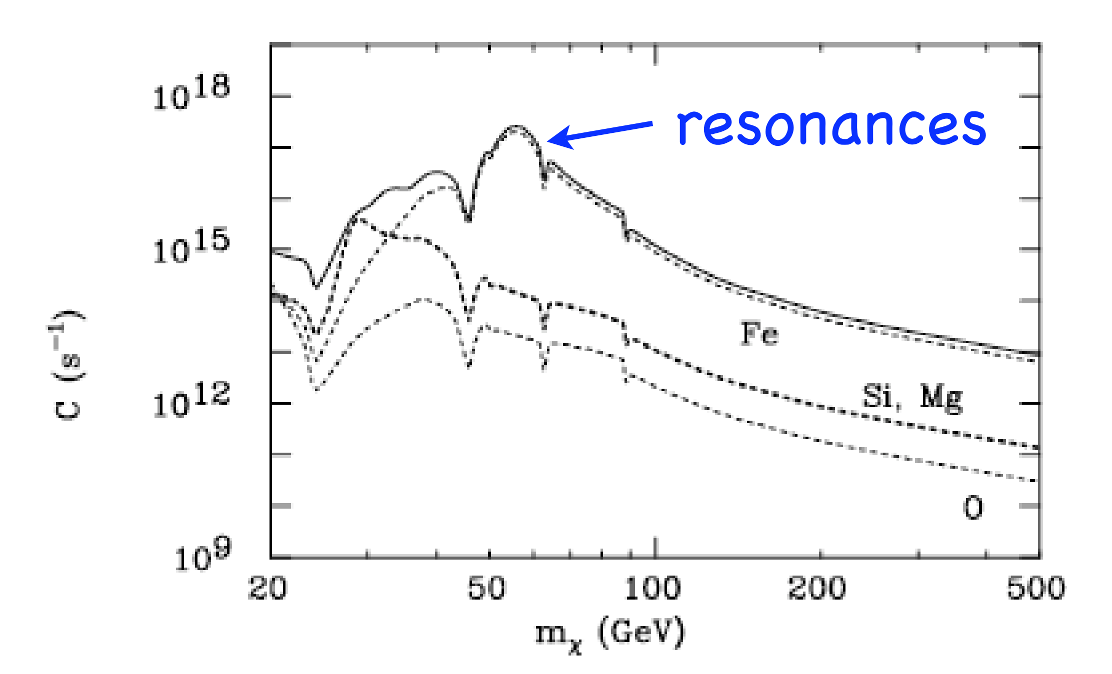
Rates from Sun and Earth

Sun capture:



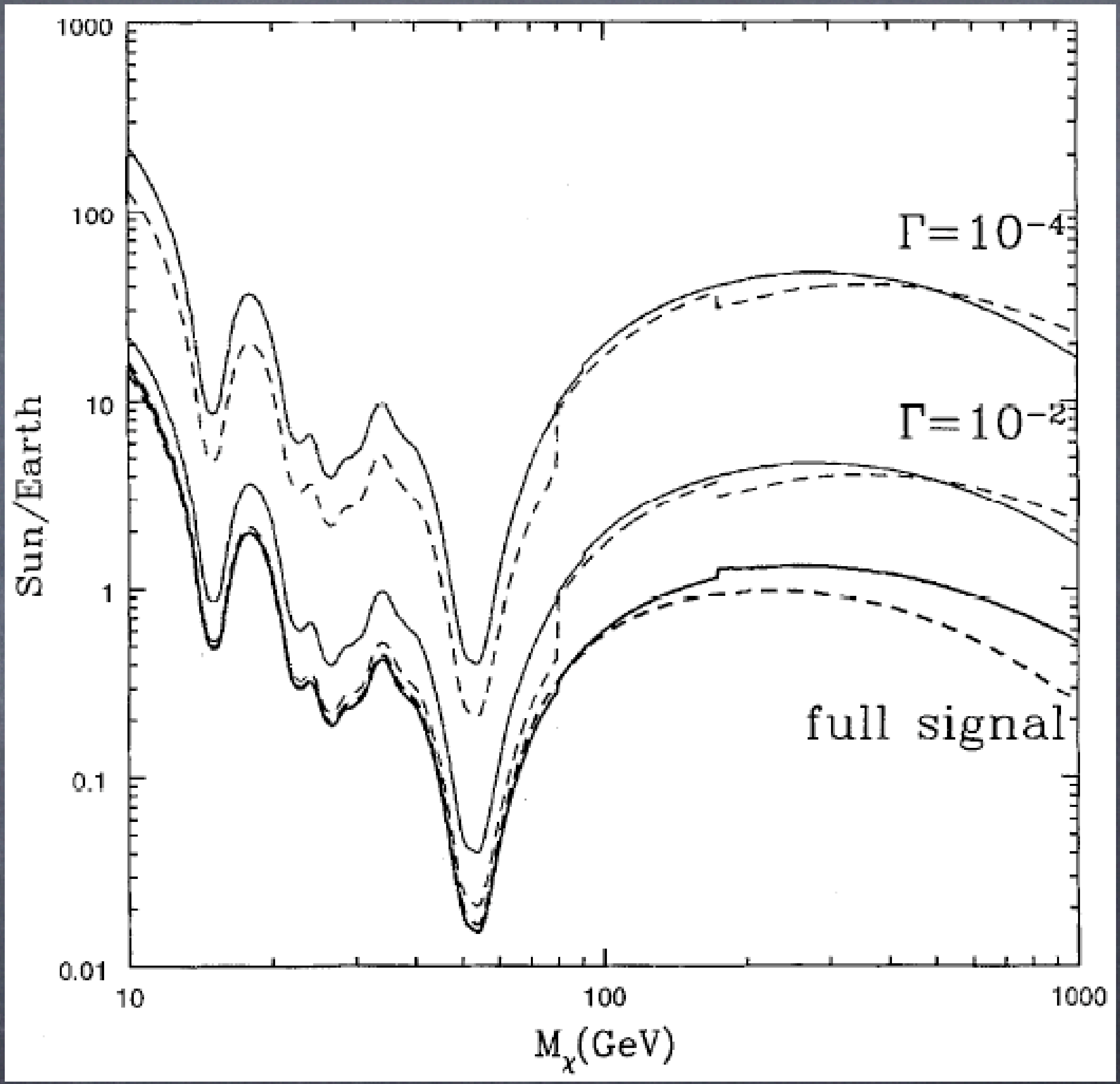
N.Fornengo, Ph.D. Thesis

Earth capture:



N.Fornengo, Ph.D. Thesis

ratio of neutrino rates:



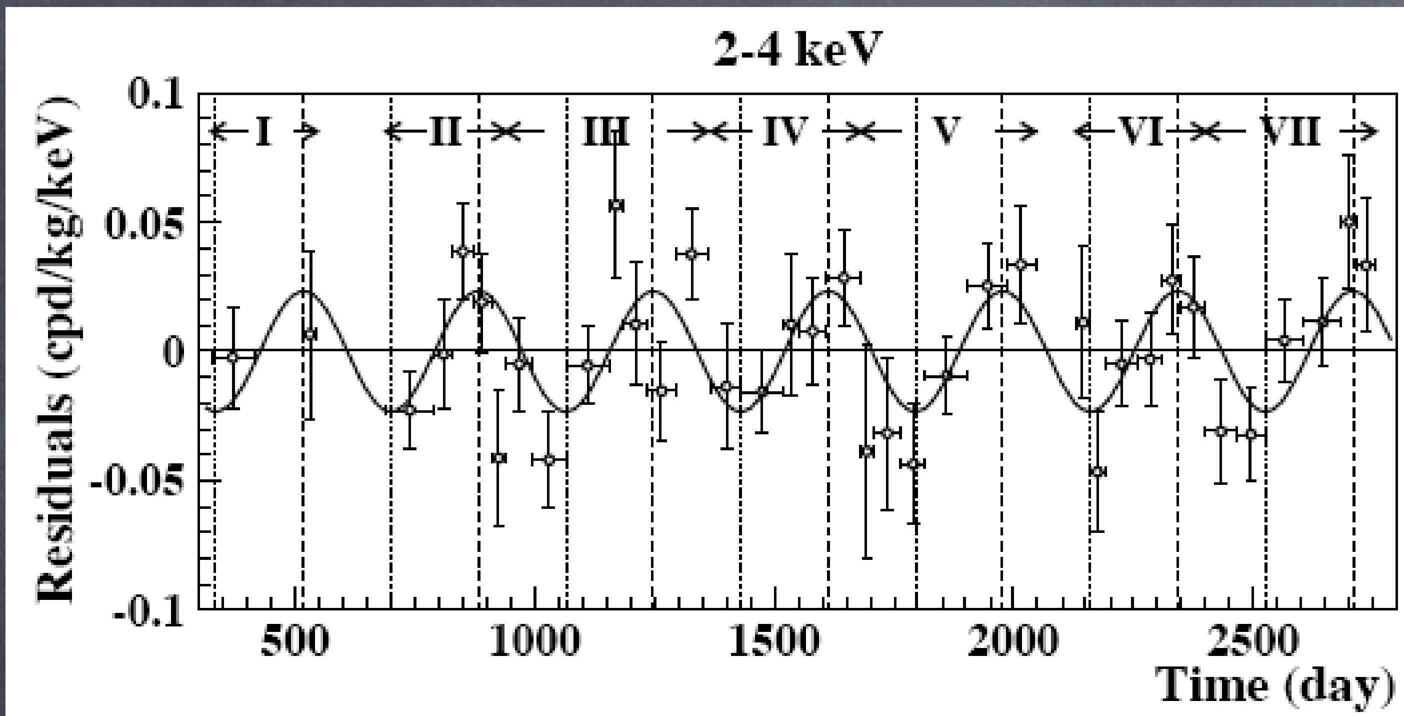
Jungman, Kamionkowski, Griest, Phys.Rept.267 (1996)

Earth/Sun: - capture rate (volume, cross section)
- escape velocity
+ closer

[back to nu from DM]

Direct detected *already*?

DAMA annual modulation:



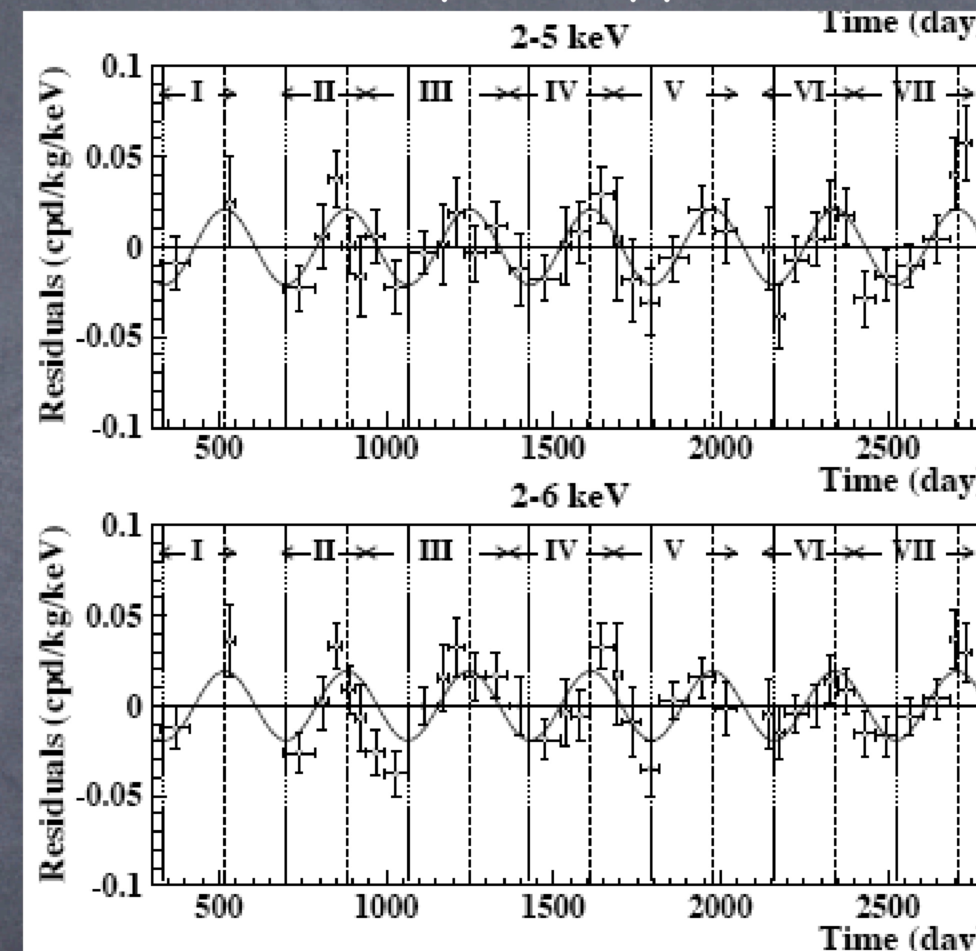
DAMA Coll.

however:

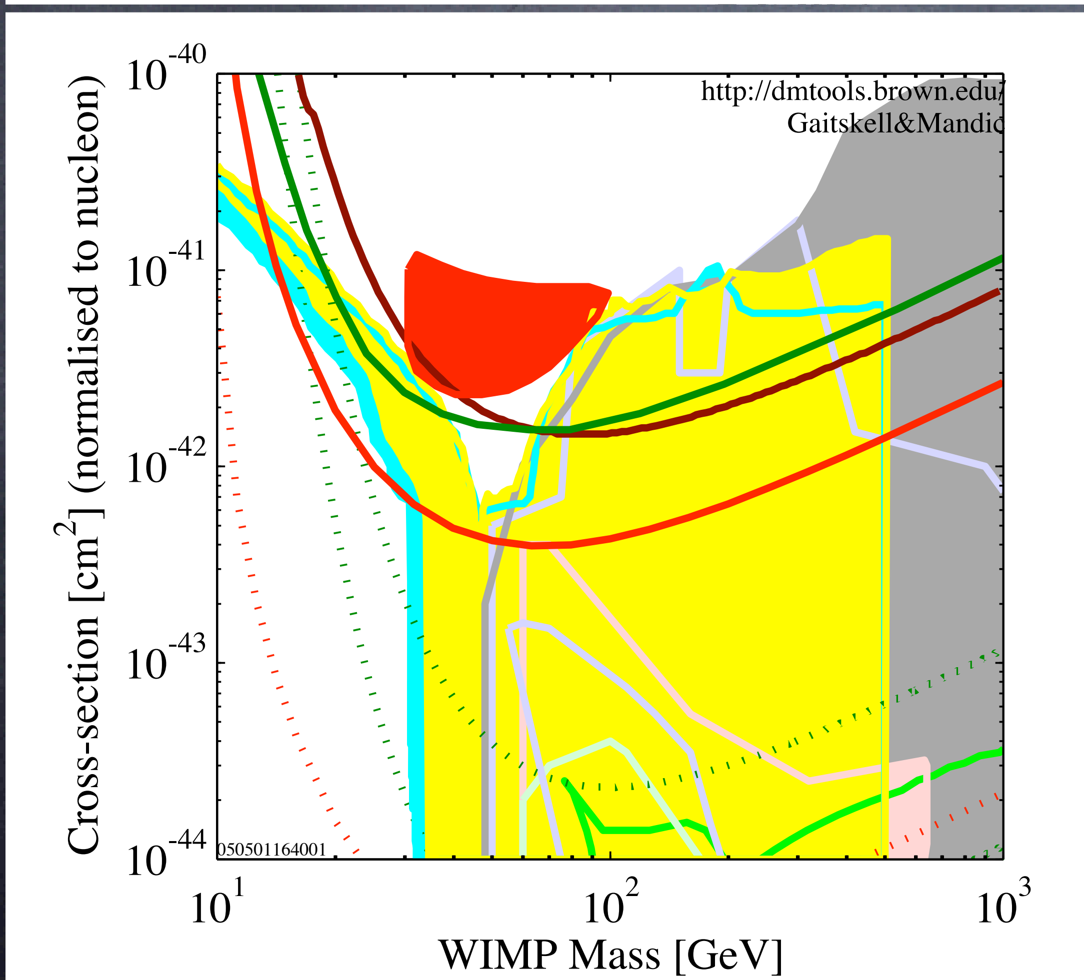
-raw data??

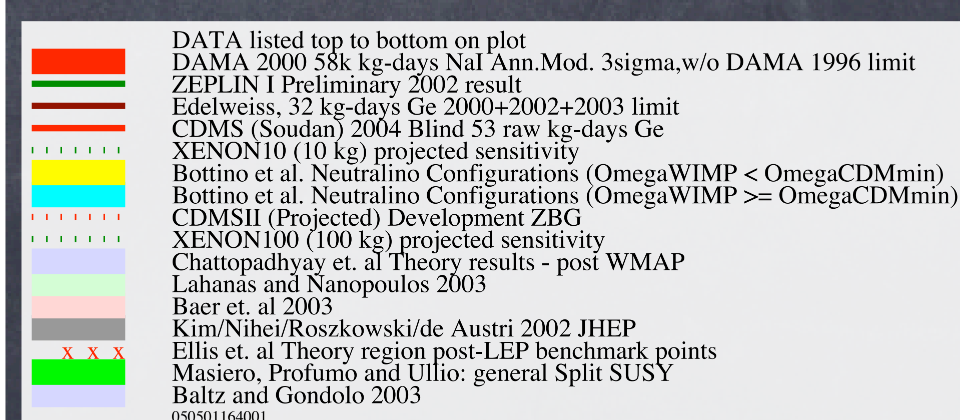
-bkgd (Rn emission)

-higher bins not expon suppressed



DAMA Coll.

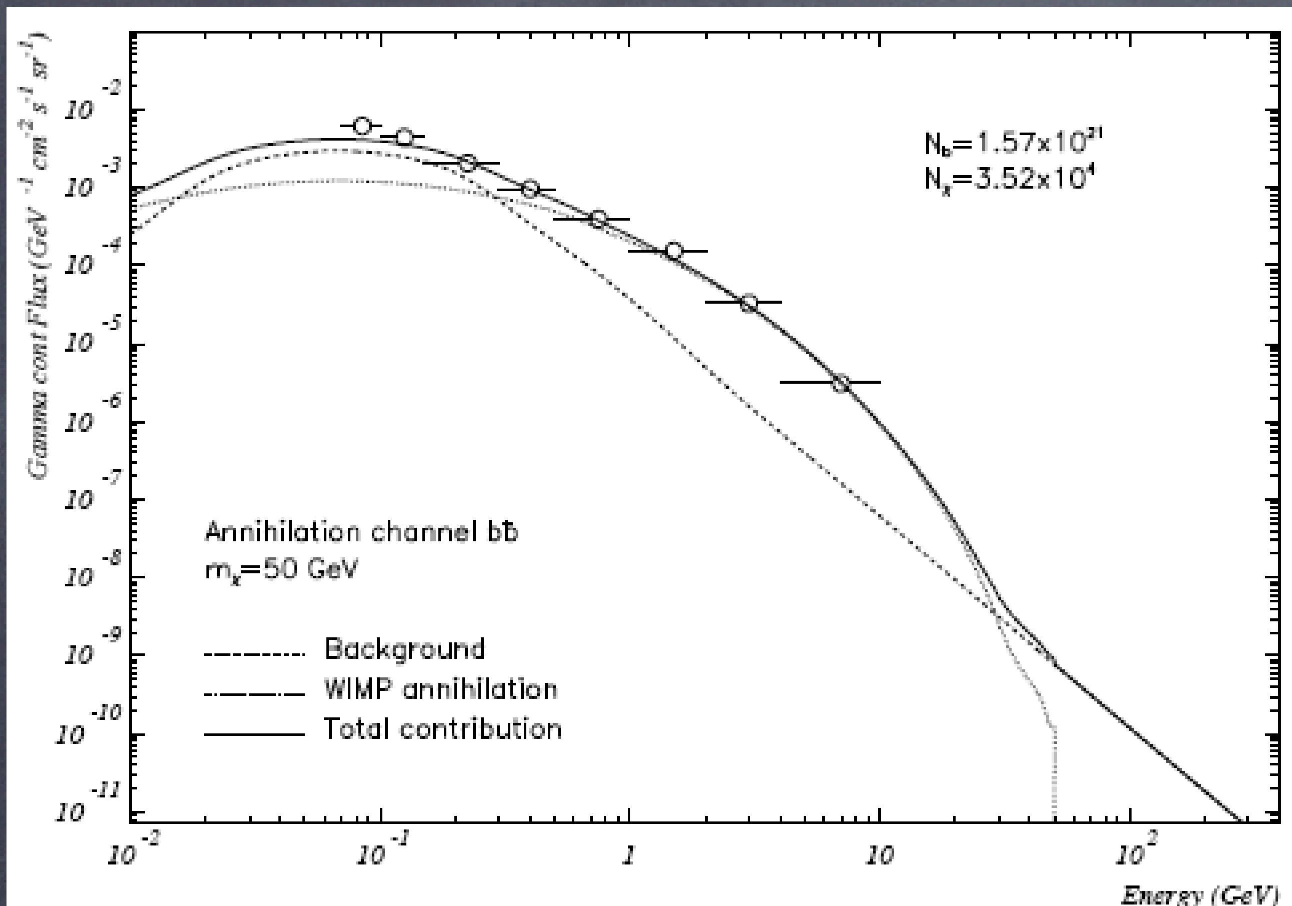




[back to DM detection]

Hints from photons?

EGRET excess

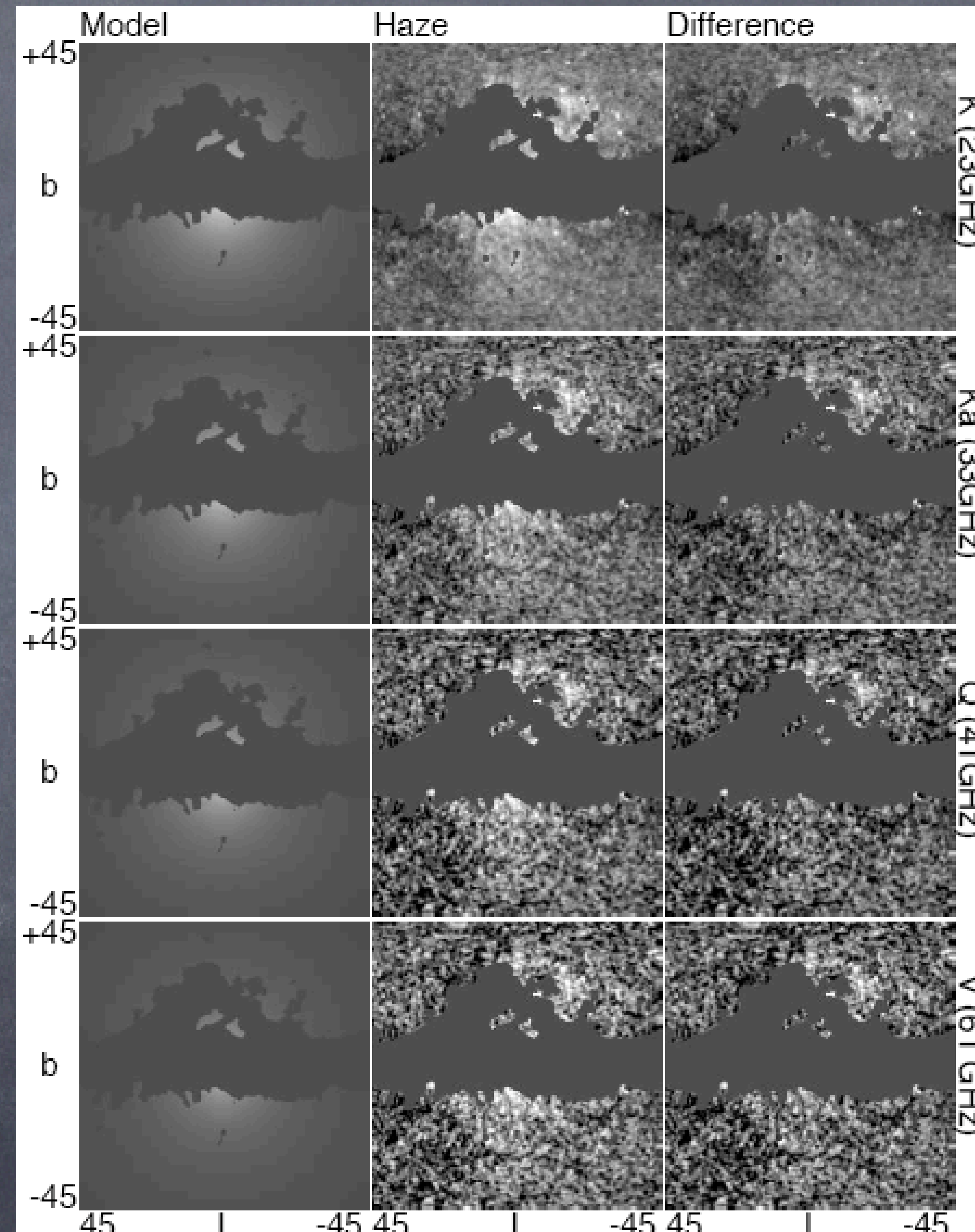


Ullio et al., ApP 21 (2004), astro-ph/0305075

however:
- source not centered
- variability...

+ CANGAROO (2004)
+ HESS (2004)

WMAP "haze"



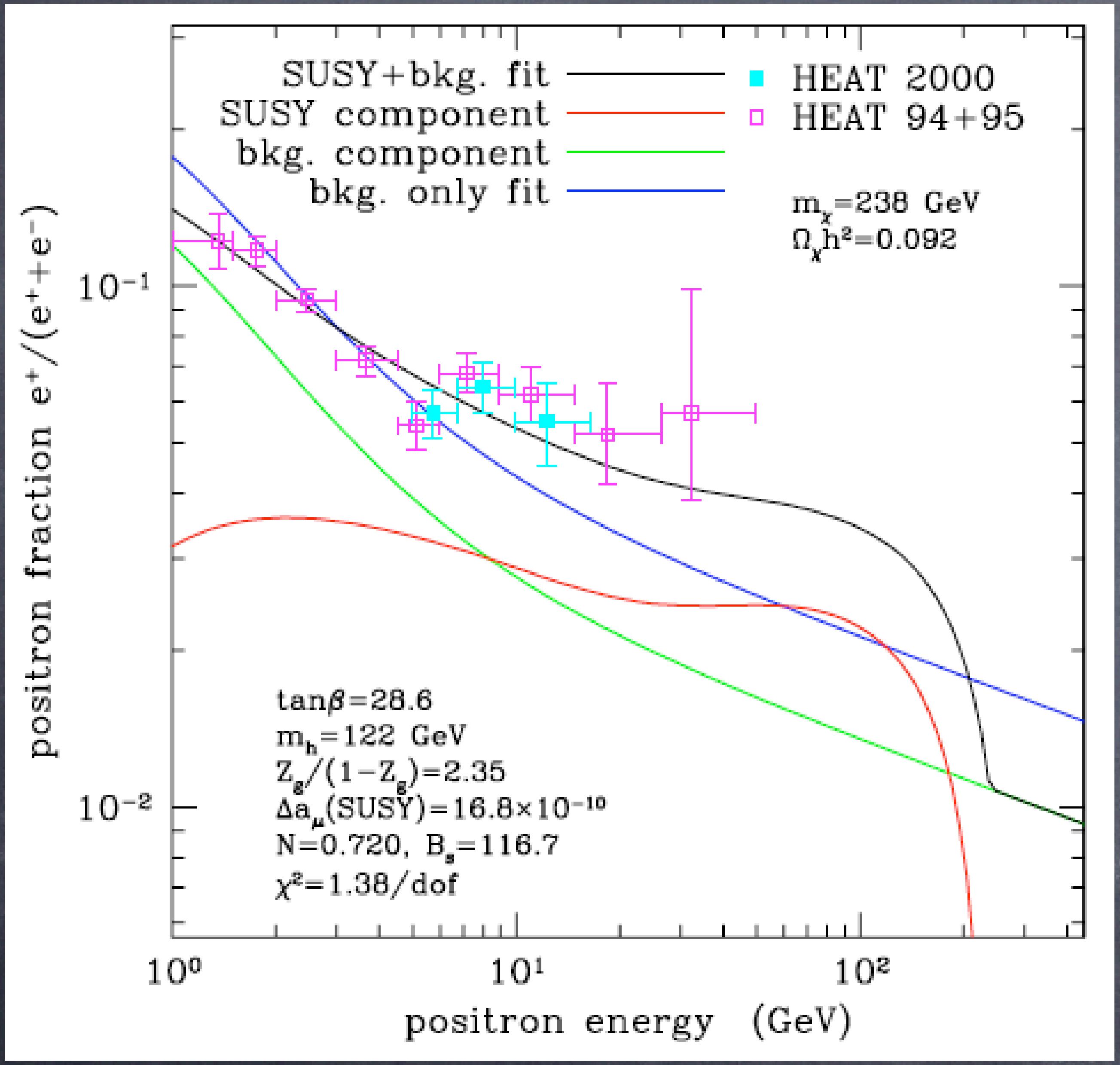
Finkbeiner, ApJ 614 (2004)

The Galactic emission found by Finkbeiner (2004) in the *WMAP* data in excess of the expected foreground Galactic ISM signal may be a signature of such dark matter annihilation.

[back to DM detection]

Hints from positrons?

HEAT excess (1994+95 & 2000)



Baltz, Edsjo, Gondolo, Freese PRD65 (2002)

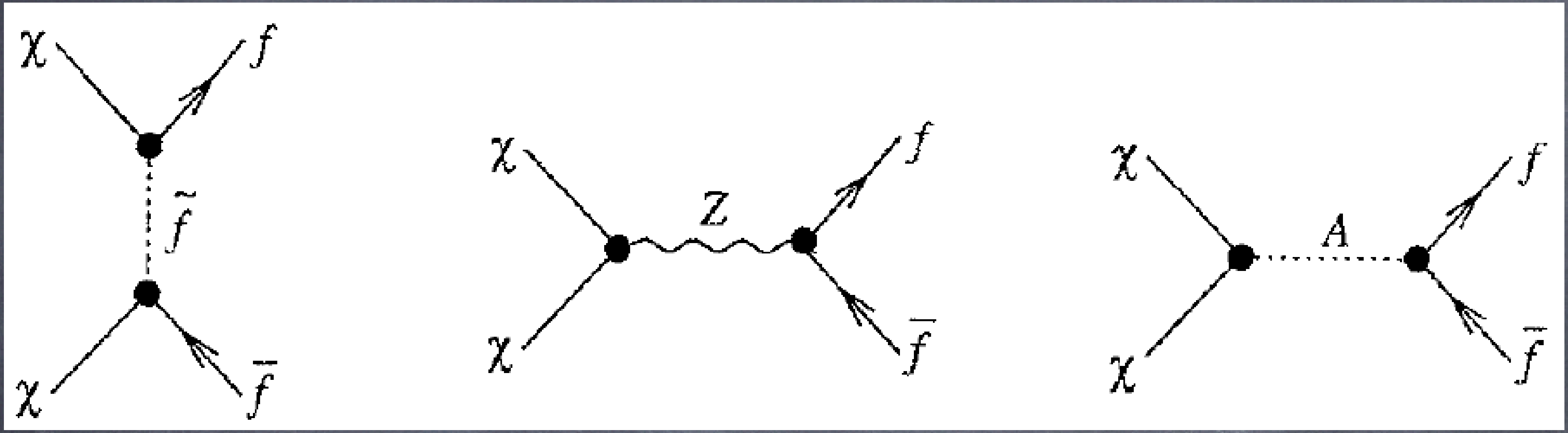
however:

-random trajectories in magnetic field

-flux requires too much DM...

[back to DM detection]

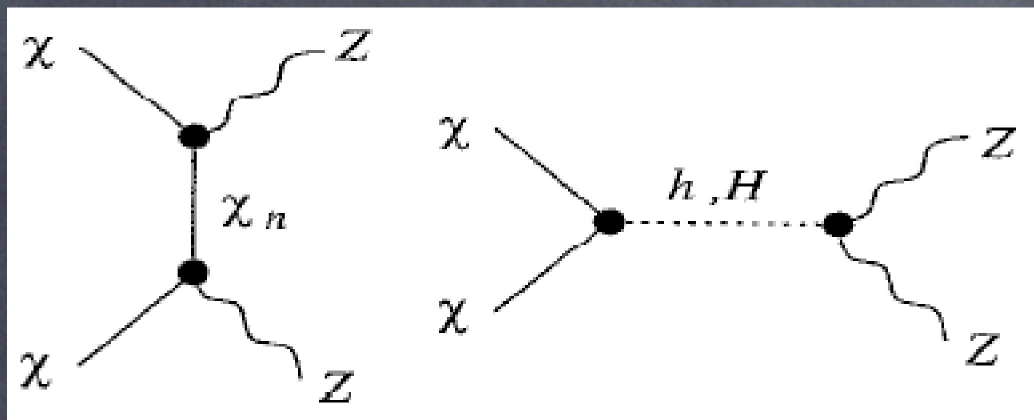
Annihilation into $f\,\bar{f}$

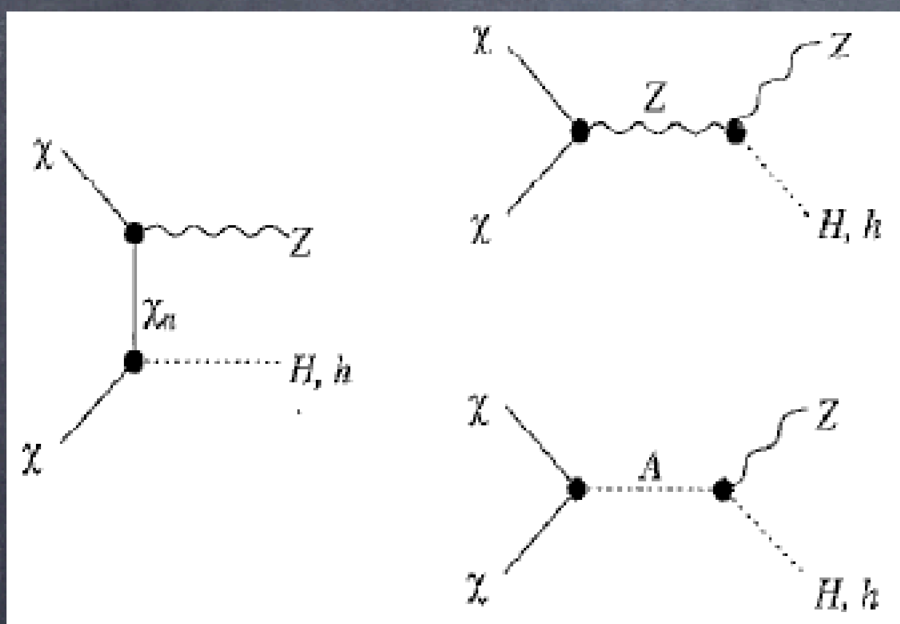


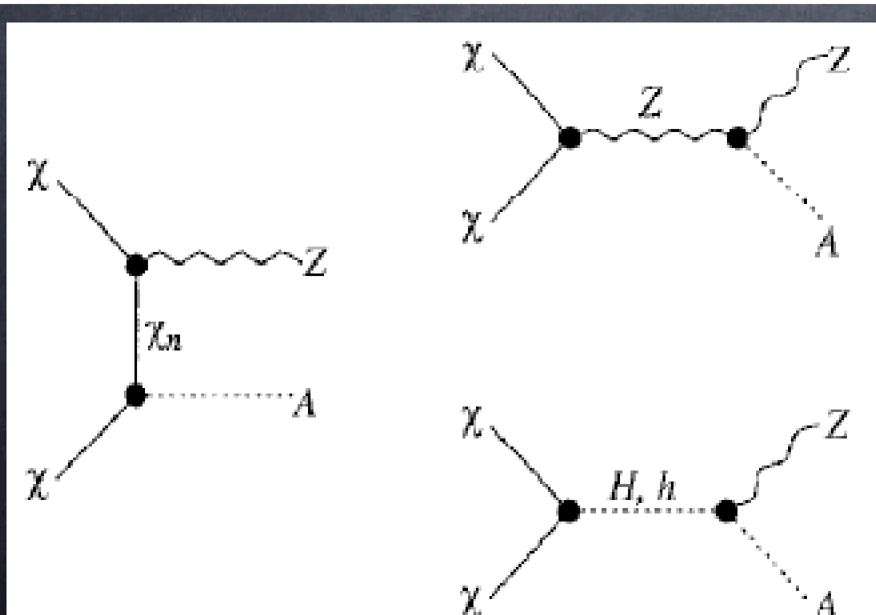
Jungman, Kamionkowski, Griest, Phys.Rept.267 (1996)

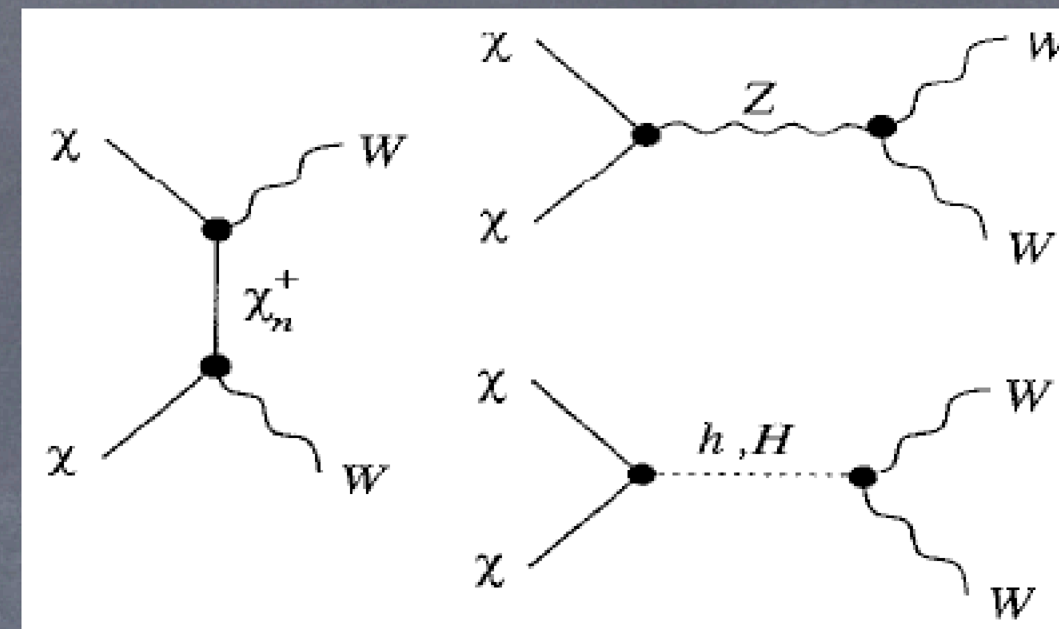
[back to Production]

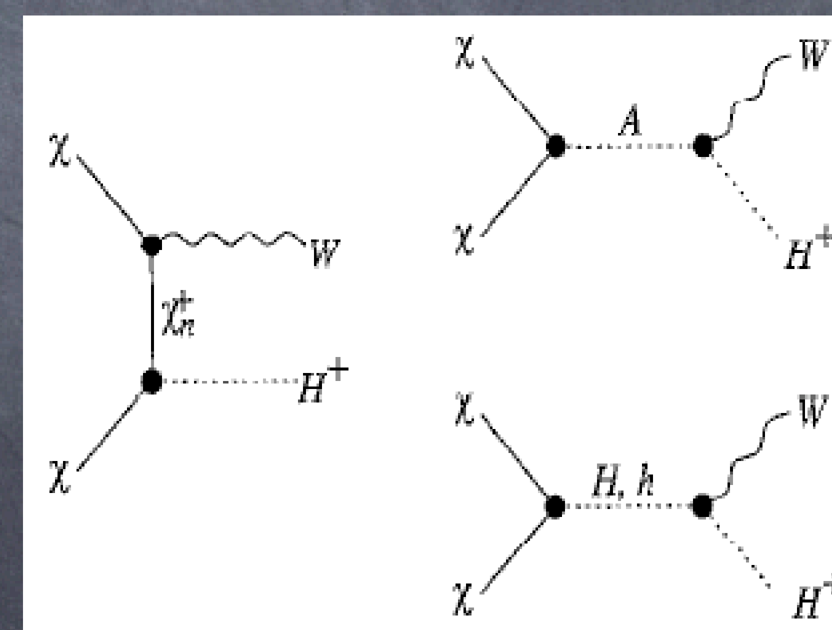
Annihilation into $Z\bar{Z}, W^+W^-$







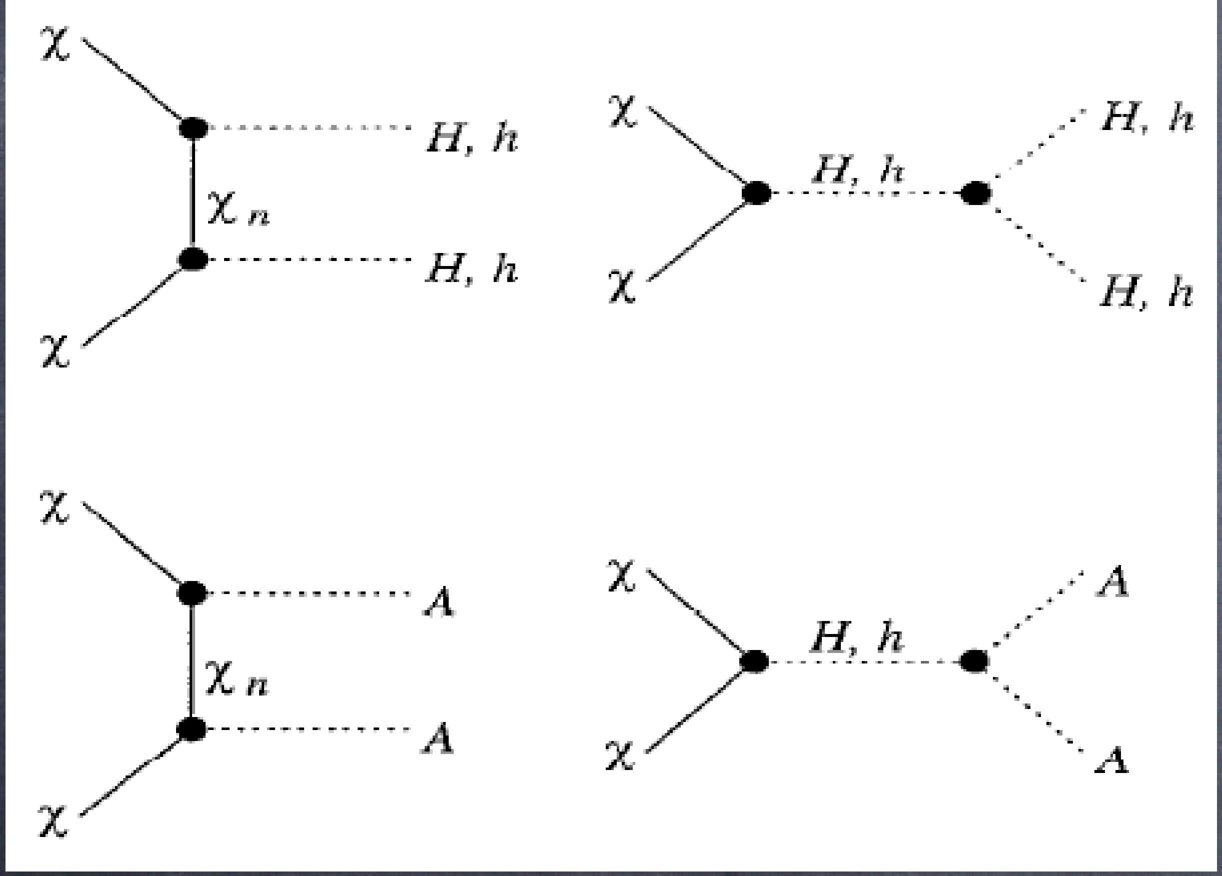


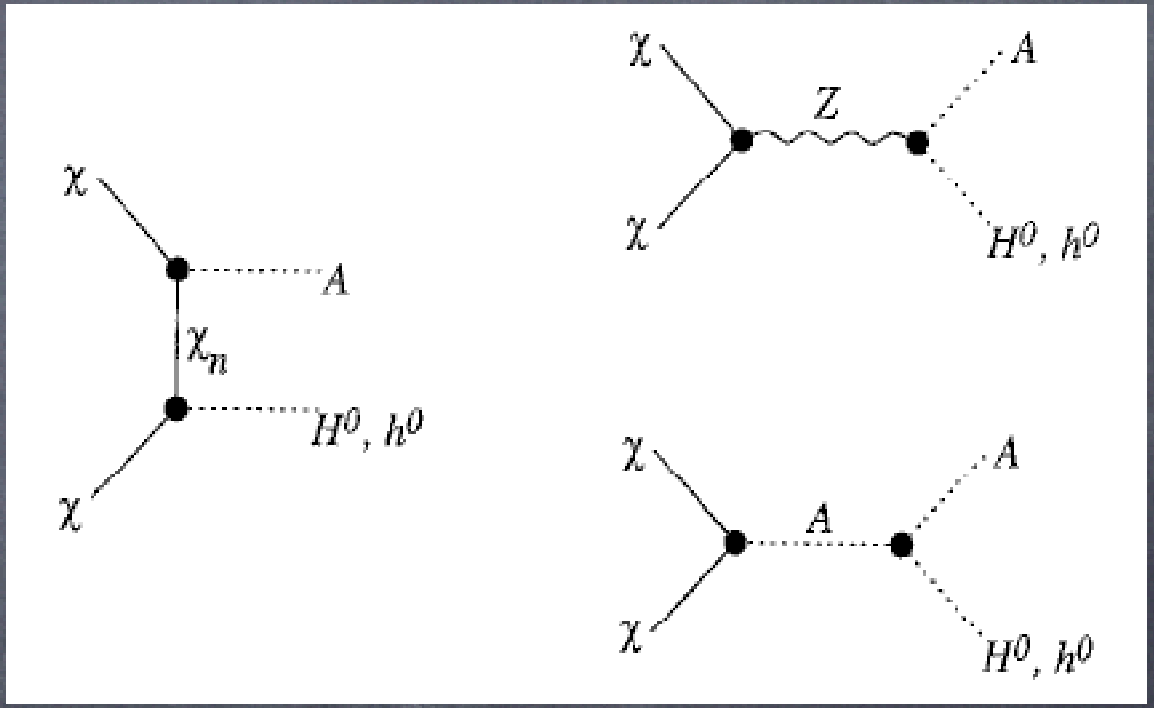


Jungman, Kamionkowski, Griest, Phys.Rept.267 (1996)

[back to Production]

Other annihilations into the MSSM Higgs sector

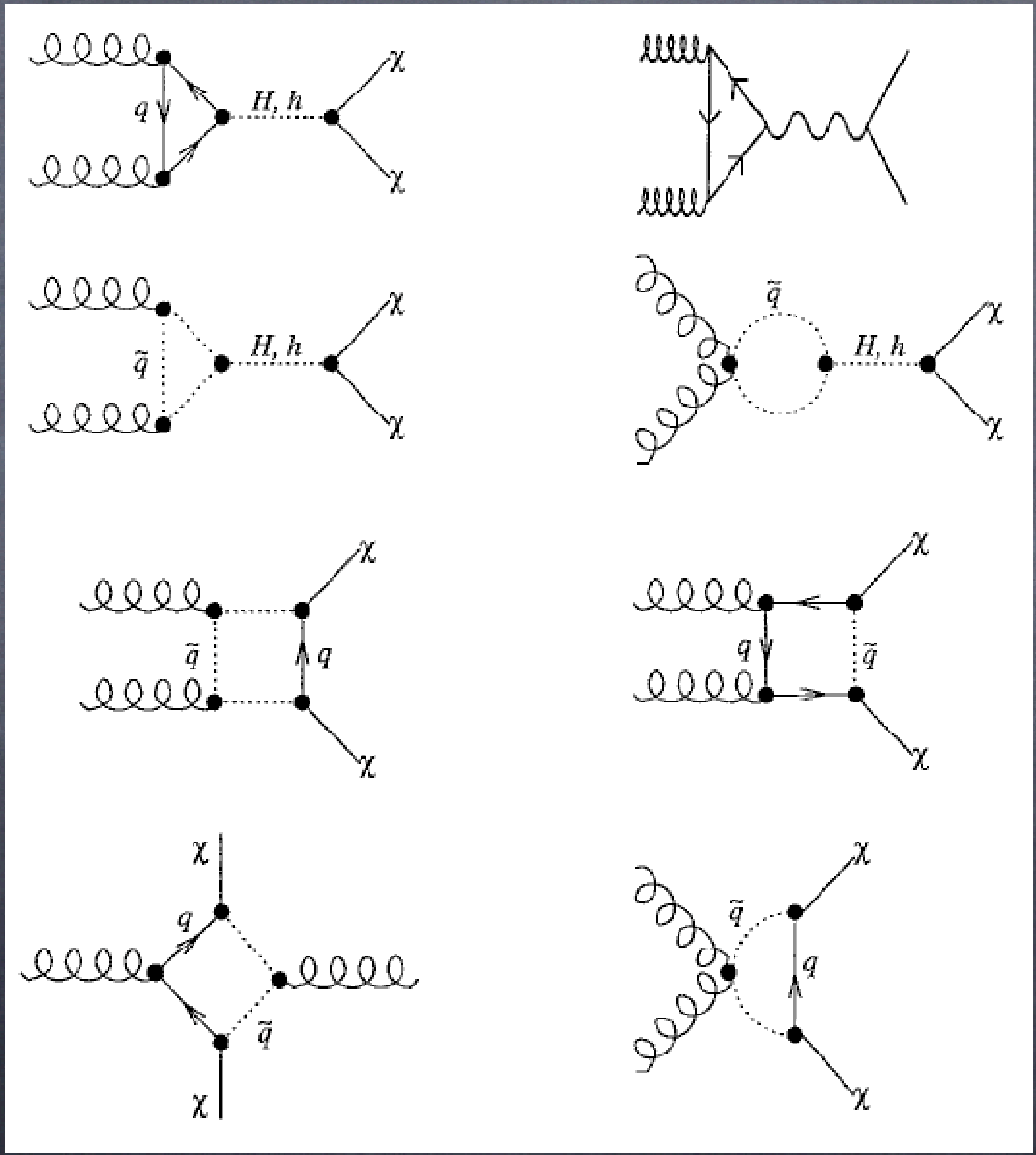




Jungman, Kamionkowski, Griest, Phys.Rept.267 (1996)

[back to Production]

Annihilations into gg



Jungman, Kamionkowski, Griest, Phys.Rept.267 (1996)

[back to Production]

LAST slide