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Picturing Dark Matter from its Neutrinos

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

The Quest for DM

DM is there

- galaxy rotation curves
- clusters
- CMB+LSS+SNIa

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

[details]

What is DM?

A **Weakly Interacting, Massive** Particle has the correct relic abundance today.

$$\Omega_X \approx \frac{6 \cdot 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle}$$
$$\langle \sigma_{\text{ann}} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{100 \text{ GeV}^2}$$

$$M \approx \mathcal{O}(100 \text{ GeV})$$

(SuSy neutralino,
KaluzaKlein DM,
superheavy DM,
technibaryon...)

DM detection

production at colliders

direct detection DAMA

indirect

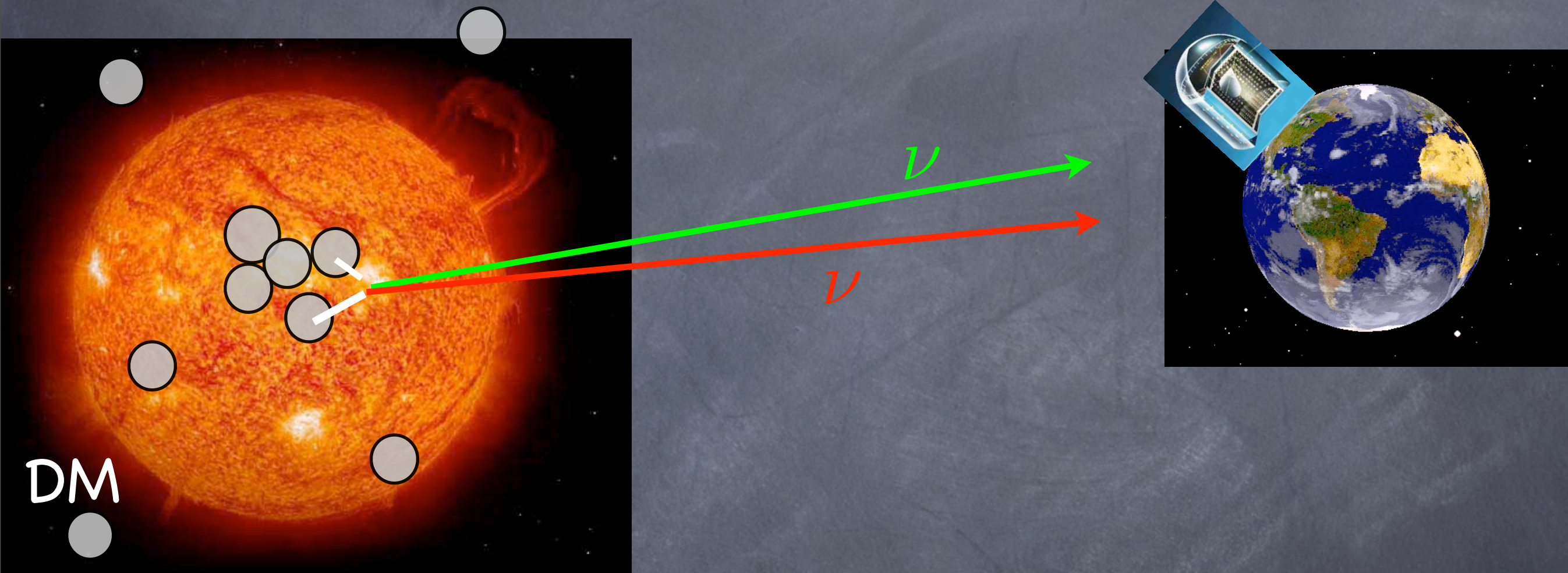
- γ from annihil in galactic halo or center
(line + continuum) EGRET, WMAP
- e^+ from annihil in galactic halo or center HEAT
- $\bar{p}$ from annihil in galactic halo or center
- $\bar{D}$ from annihil in galactic halo or center
- $\nu, \bar{\nu}$ from annihil in massive bodies

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

Sun

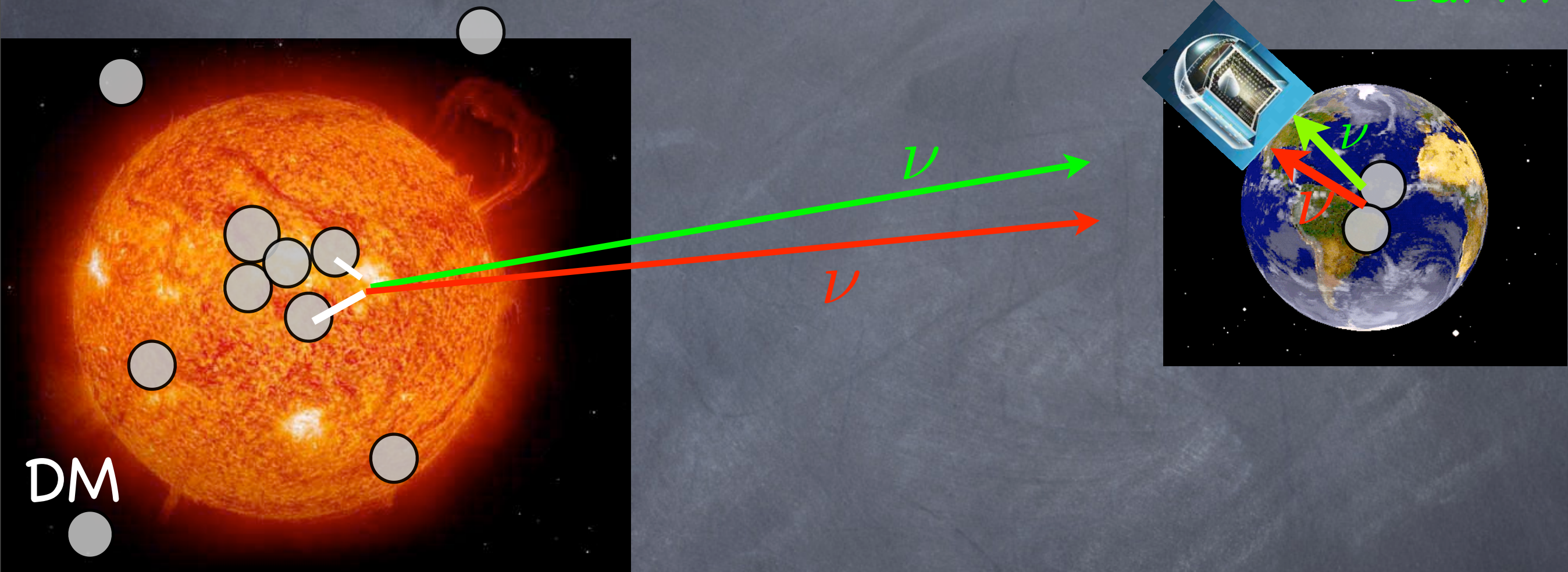


Capture rates

Neutrinos from DM

Sun

Earth

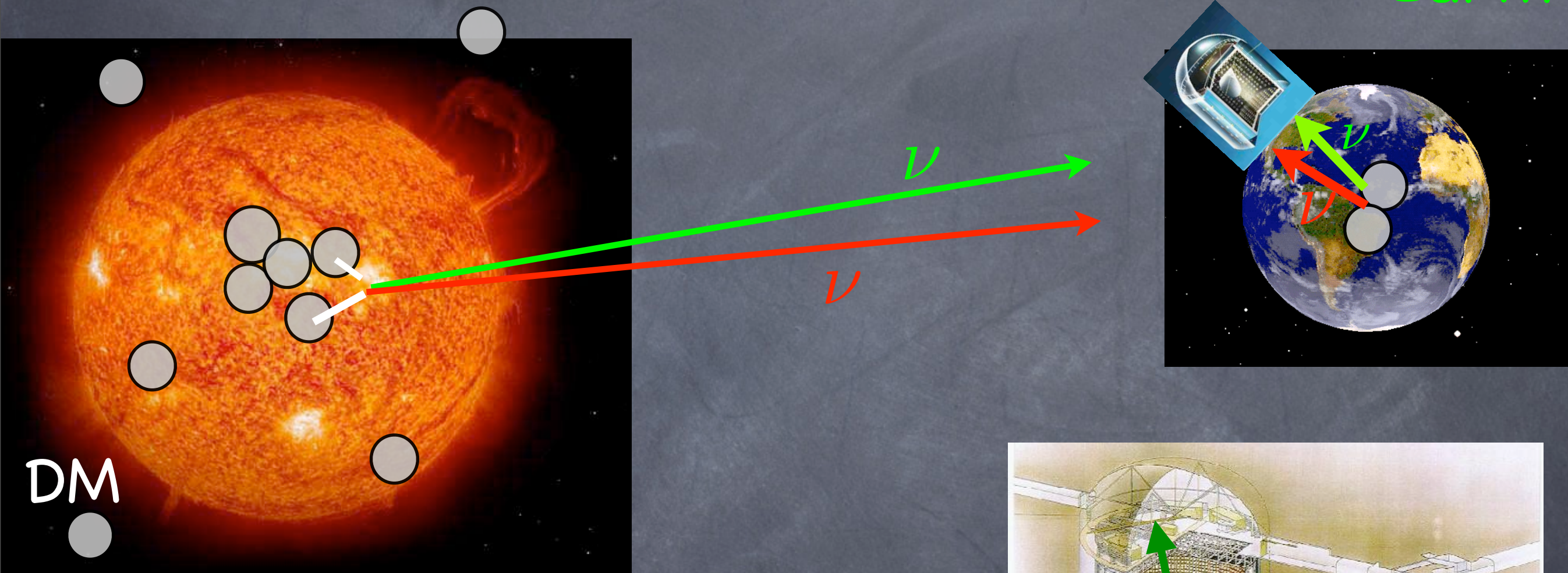


Capture rates

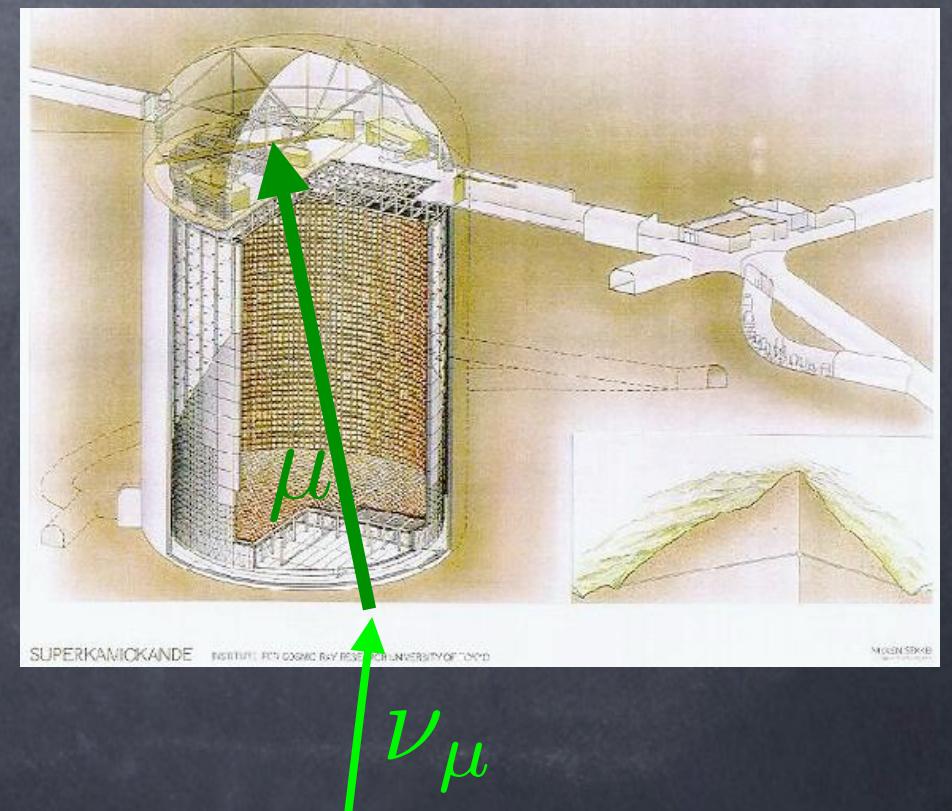
Neutrinos from DM

Sun

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
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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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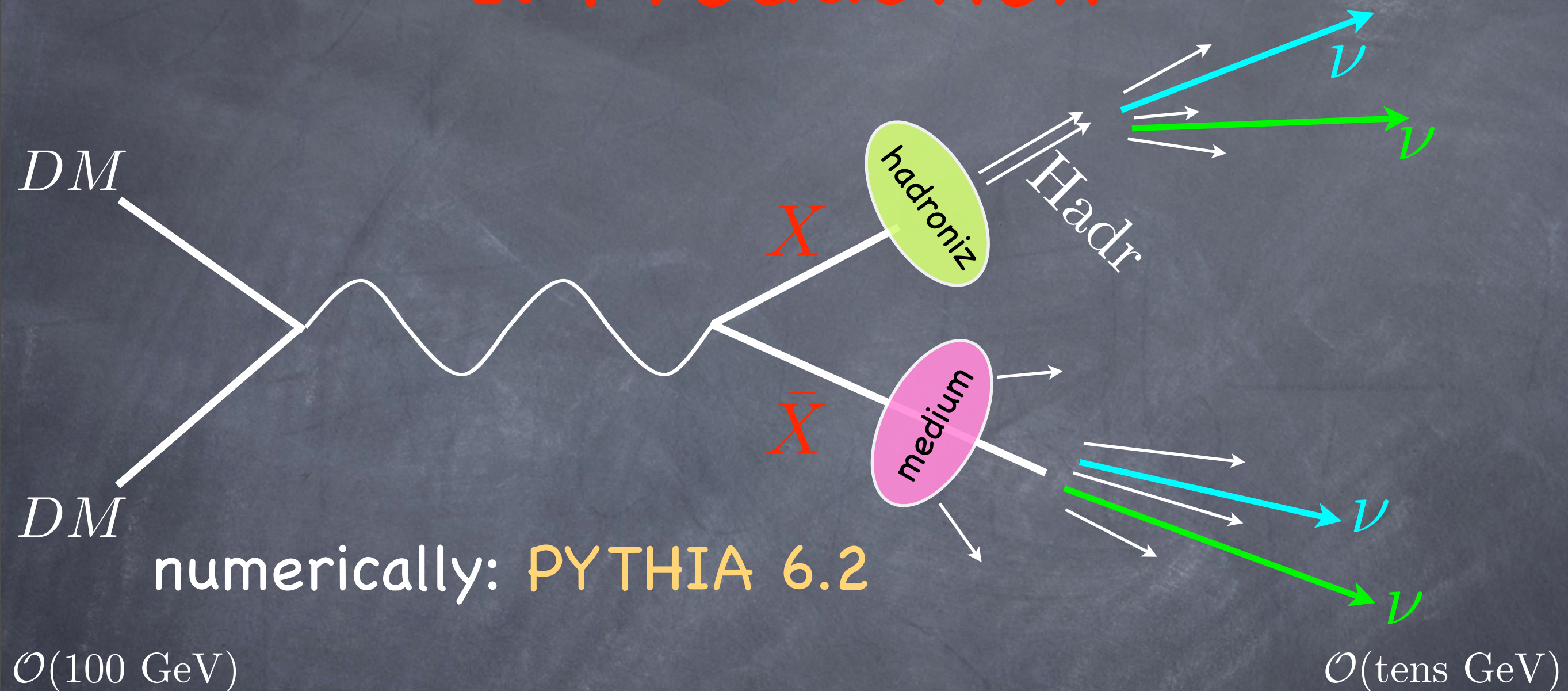
(B) neutrino **spectra**, not only rates

(C) ν_e, ν_μ and ν_τ not only ν_μ

astrophysical
uncertainties!



1. Production



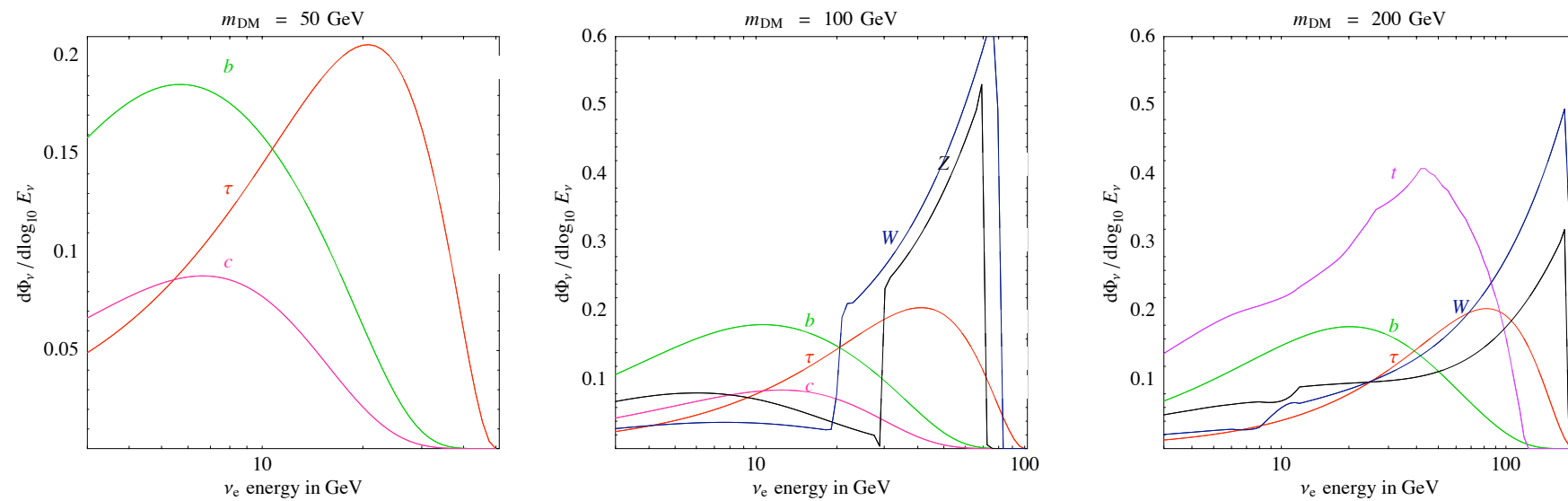
Main variables of the game:

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

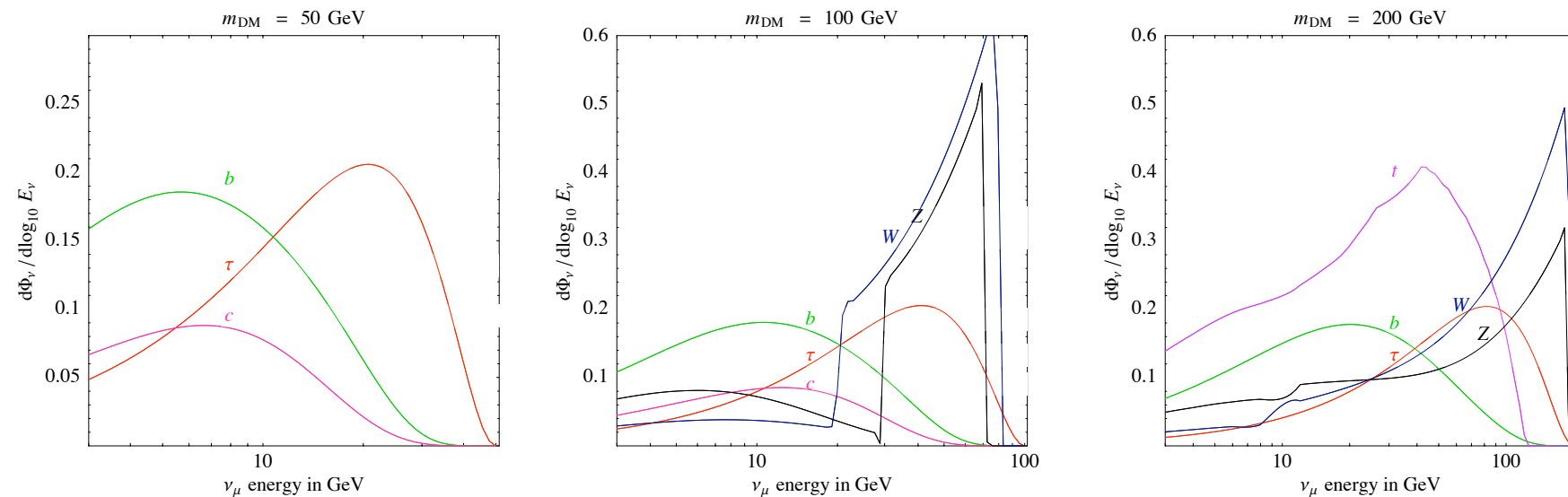
1. Production

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

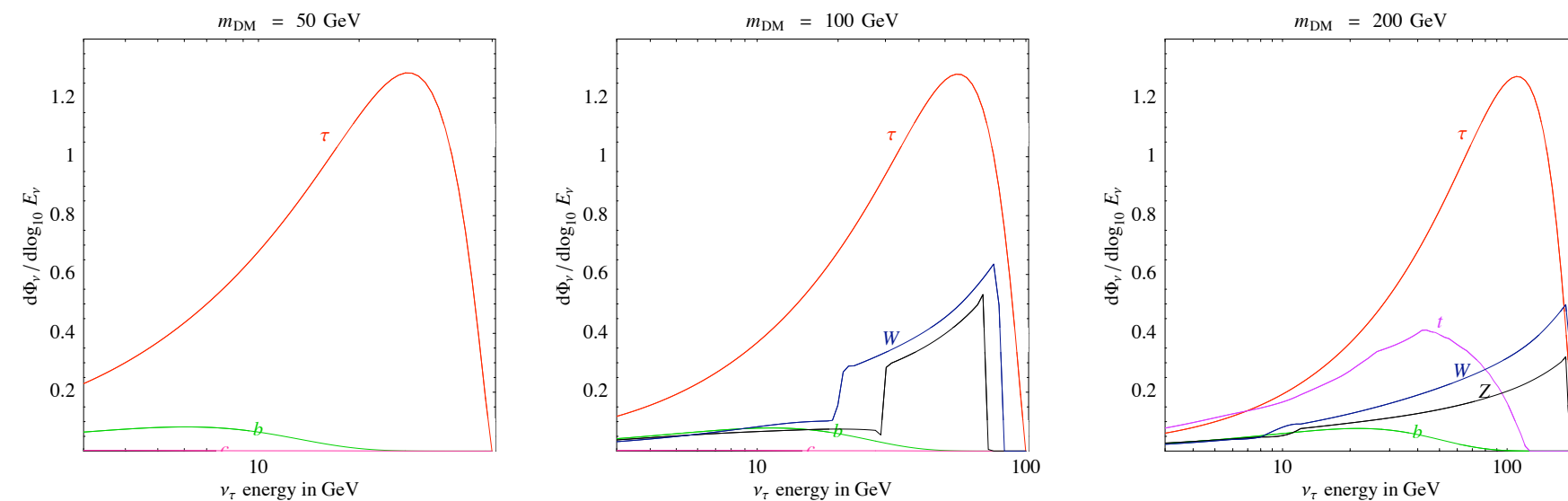
ν_e



ν_μ



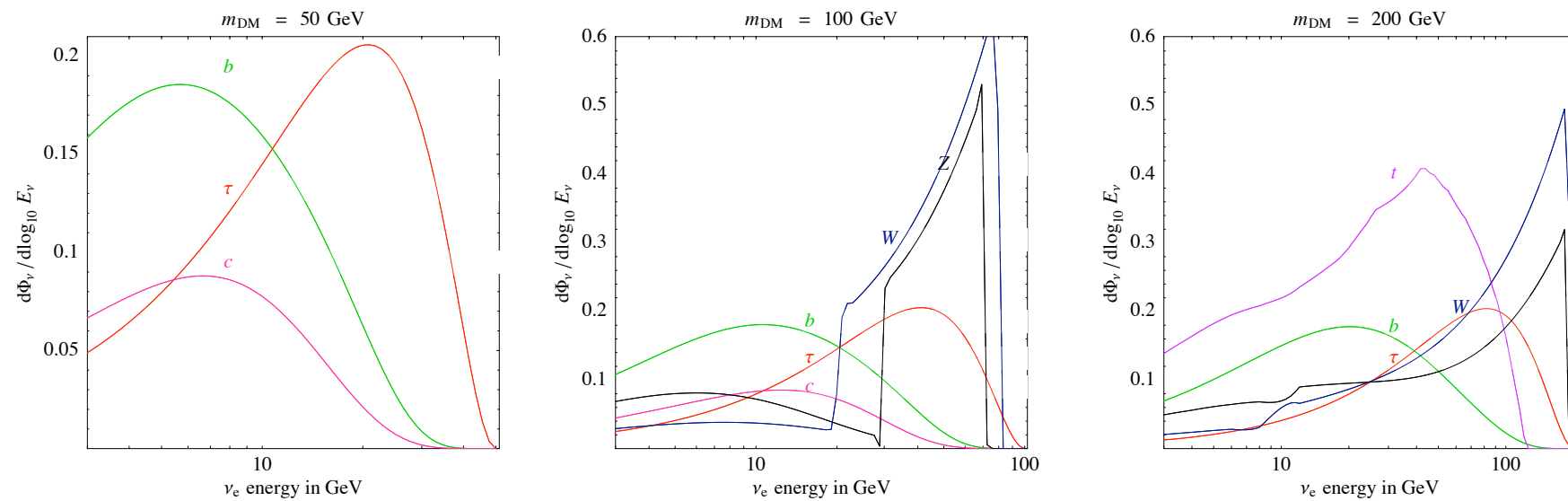
ν_τ



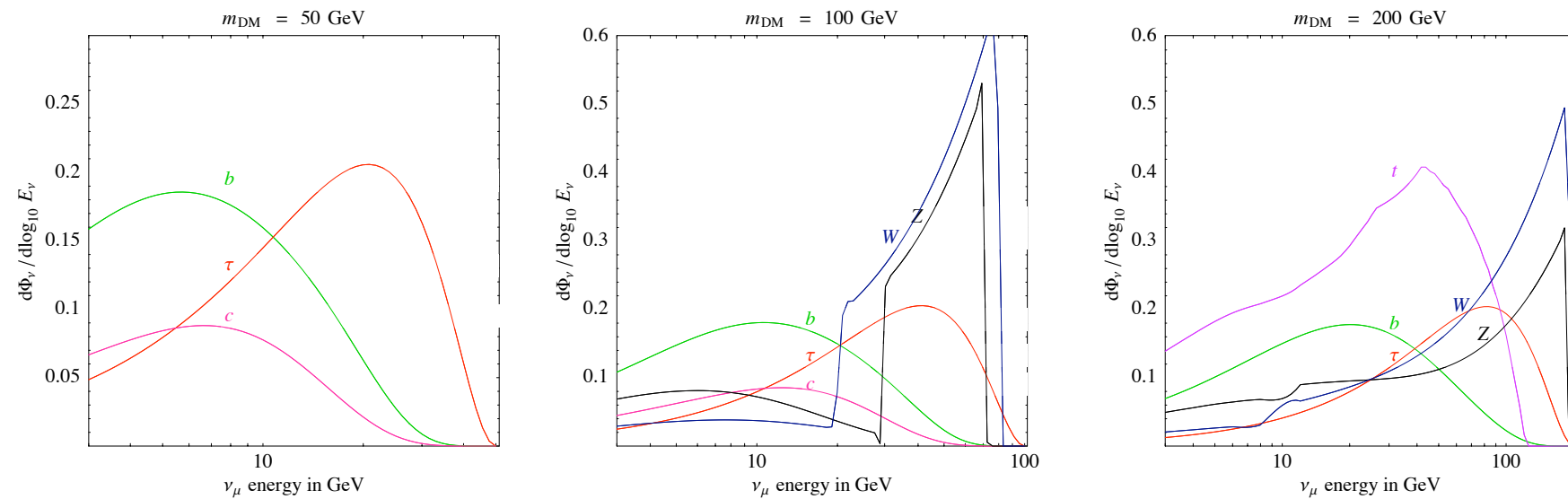
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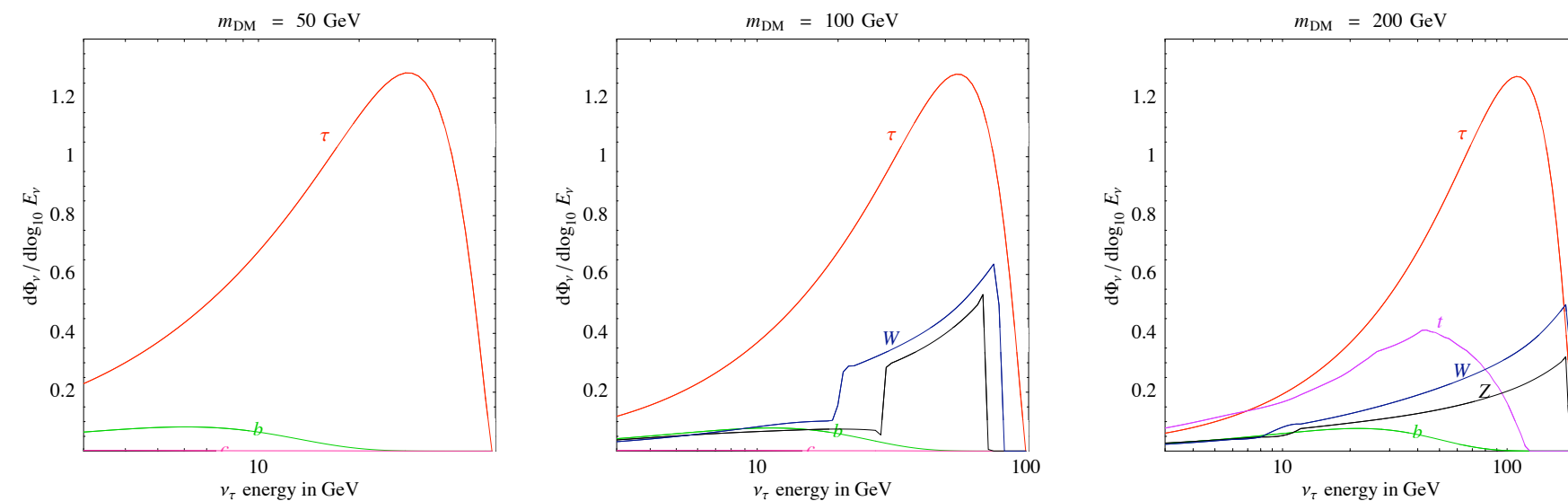
ν_e



ν_μ



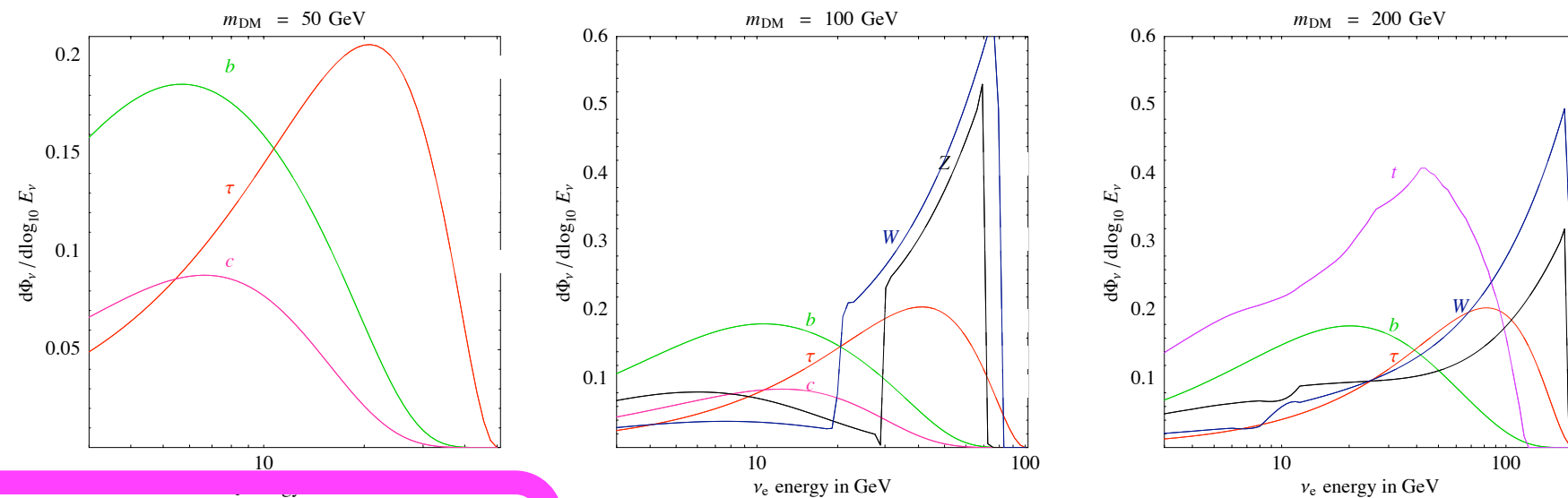
ν_τ



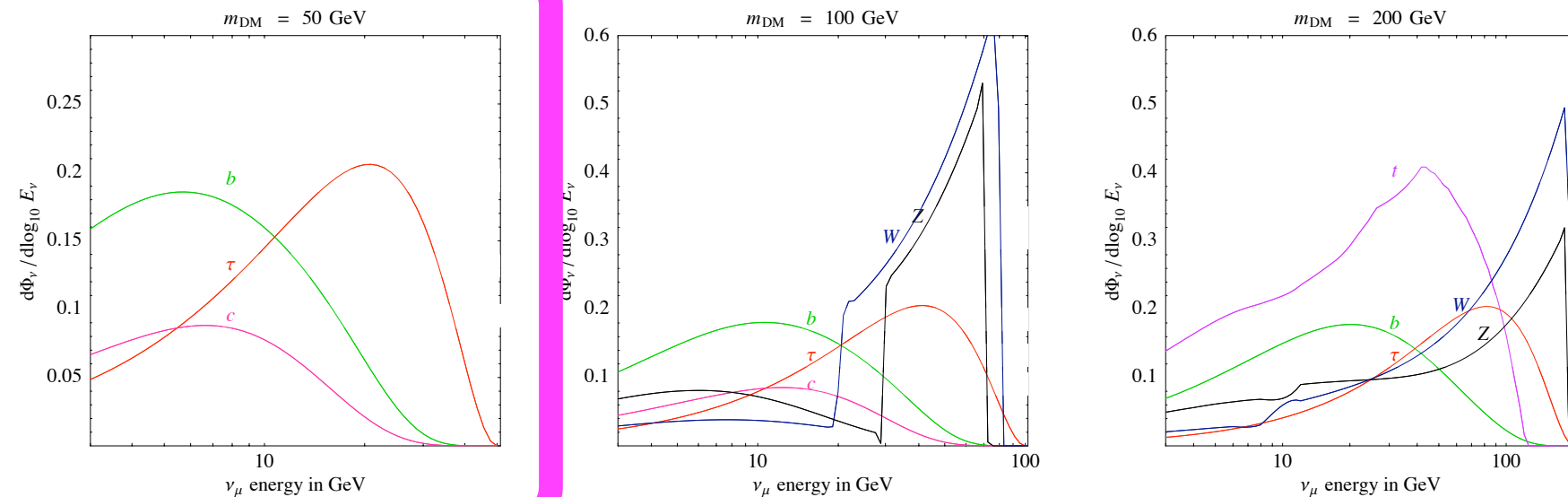
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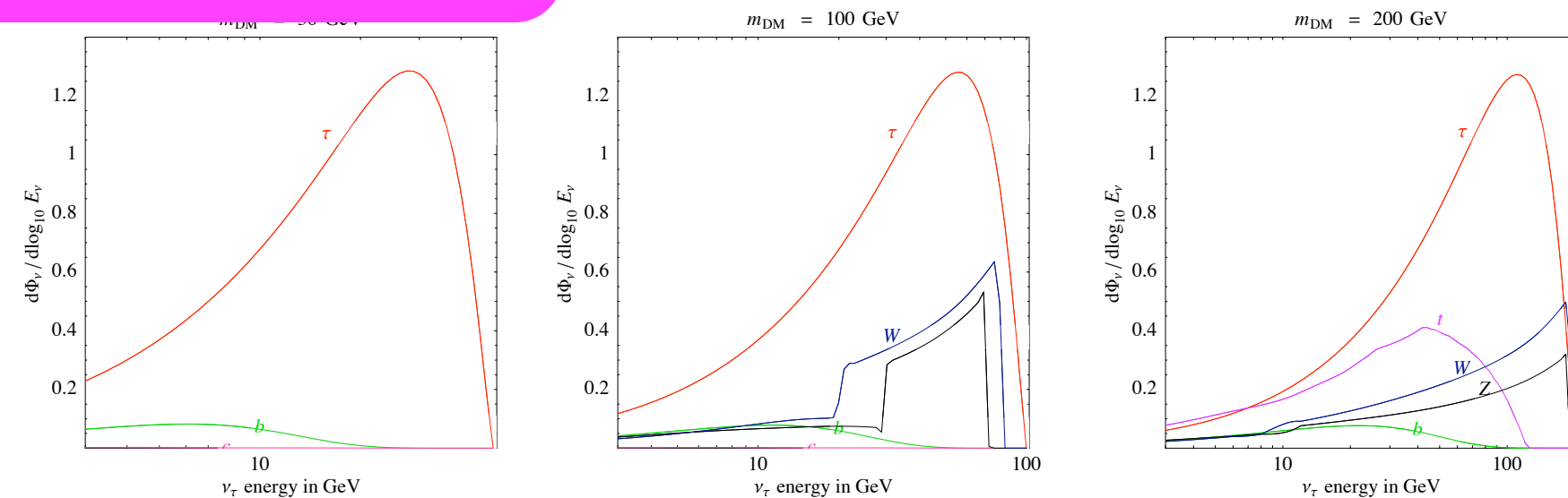
ν_e



ν_μ

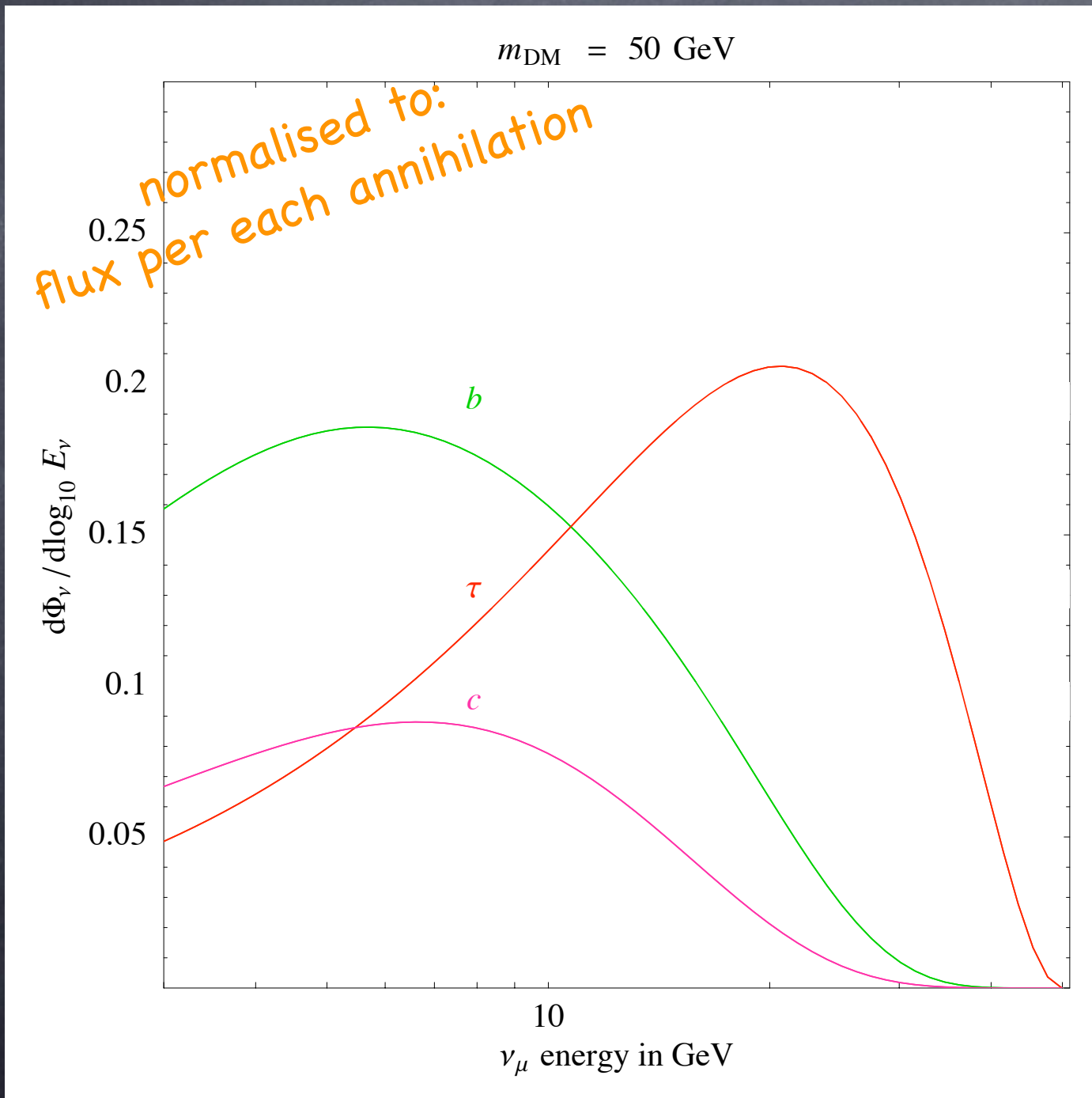


ν_τ



1. Production

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



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

footnote:

for h-mediated channels

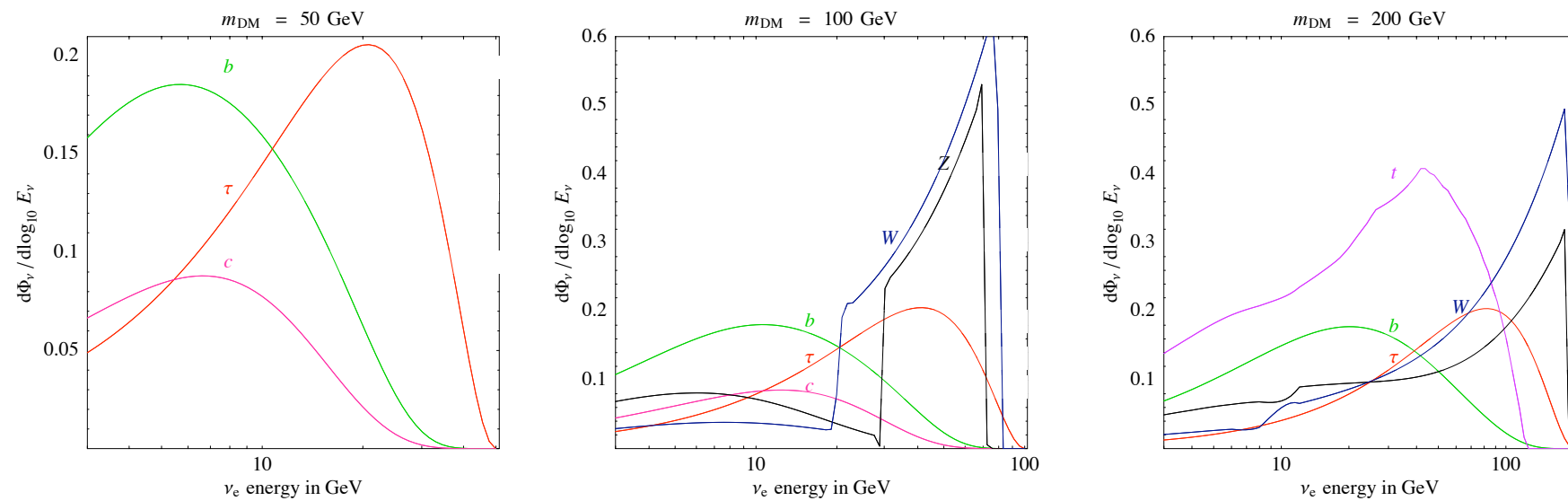
$$BR(b\bar{b})/BR(\tau\bar{\tau}) = 3m_b^2/m_\tau^2 \approx 20$$

but in general independent

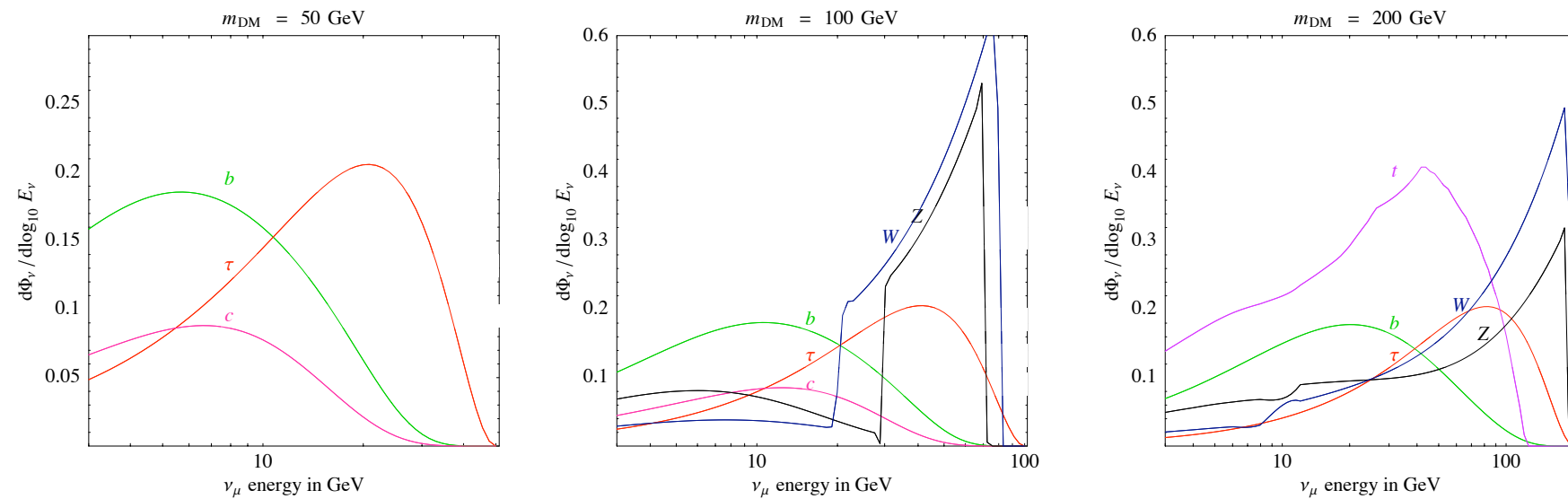
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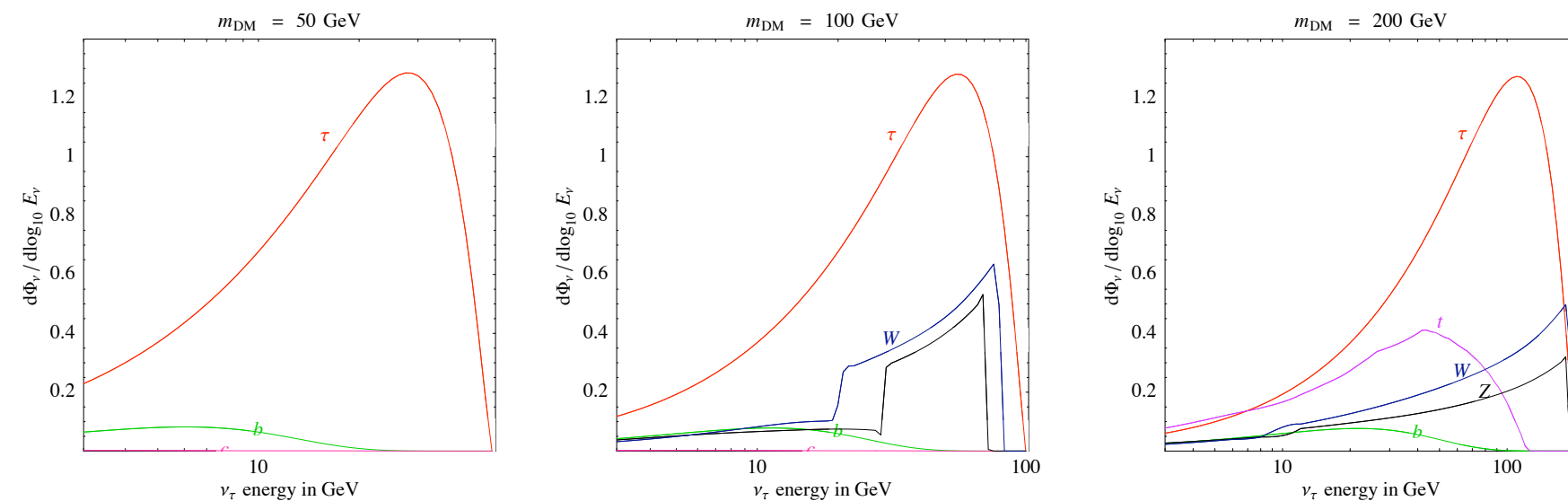
ν_e



ν_μ



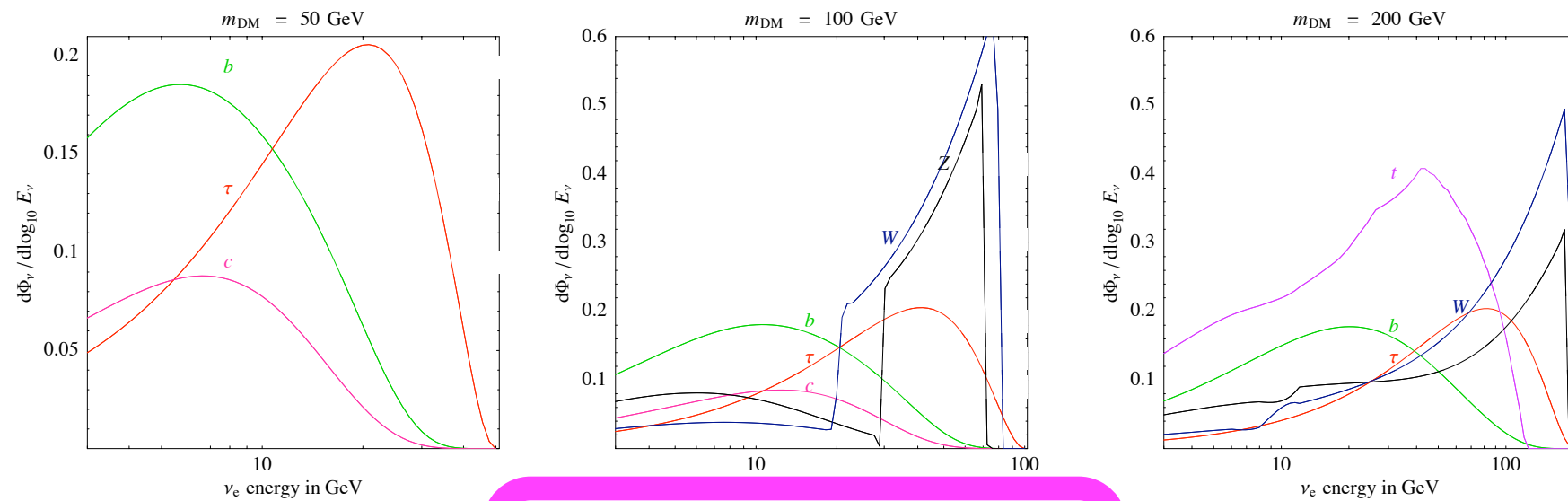
ν_τ



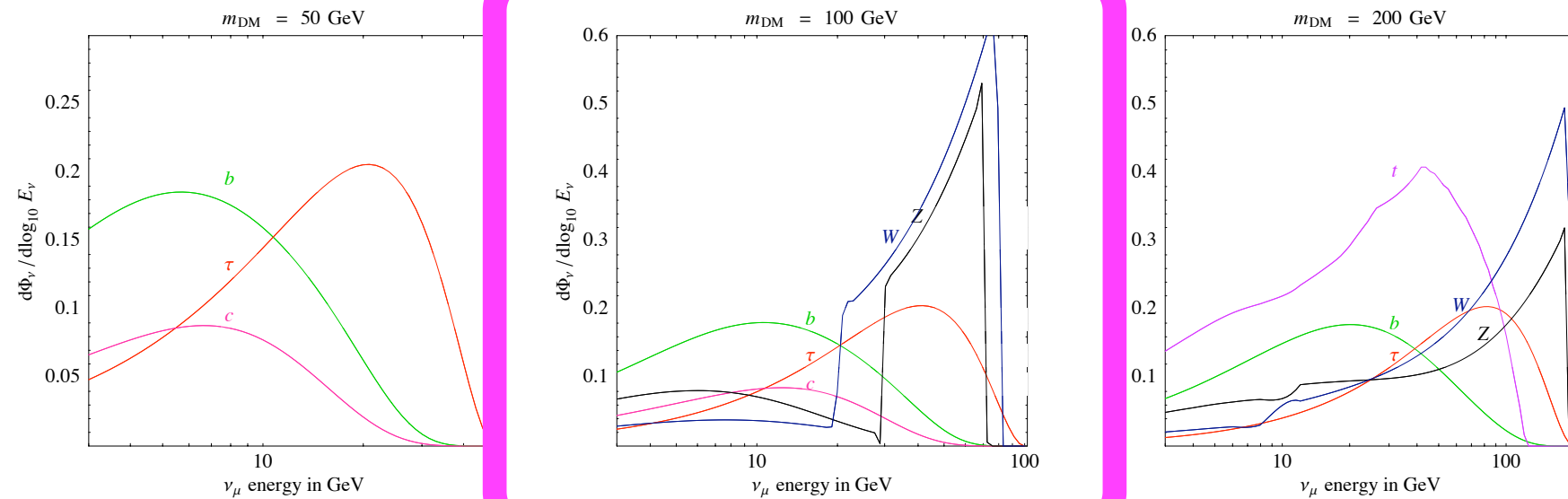
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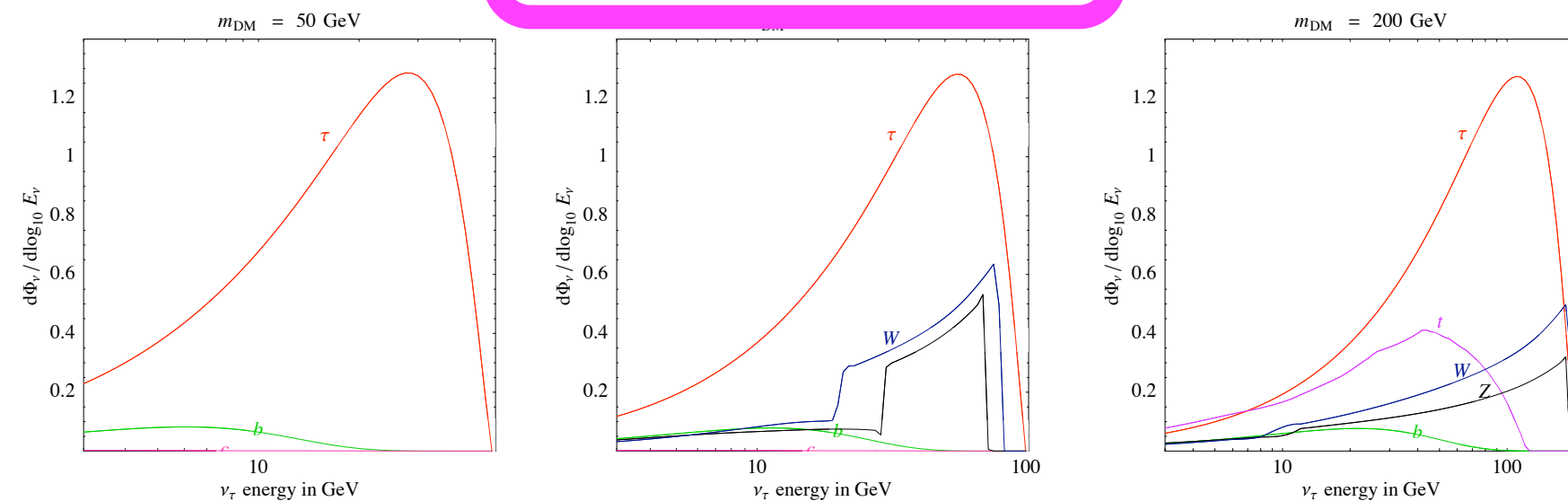
ν_e



ν_μ

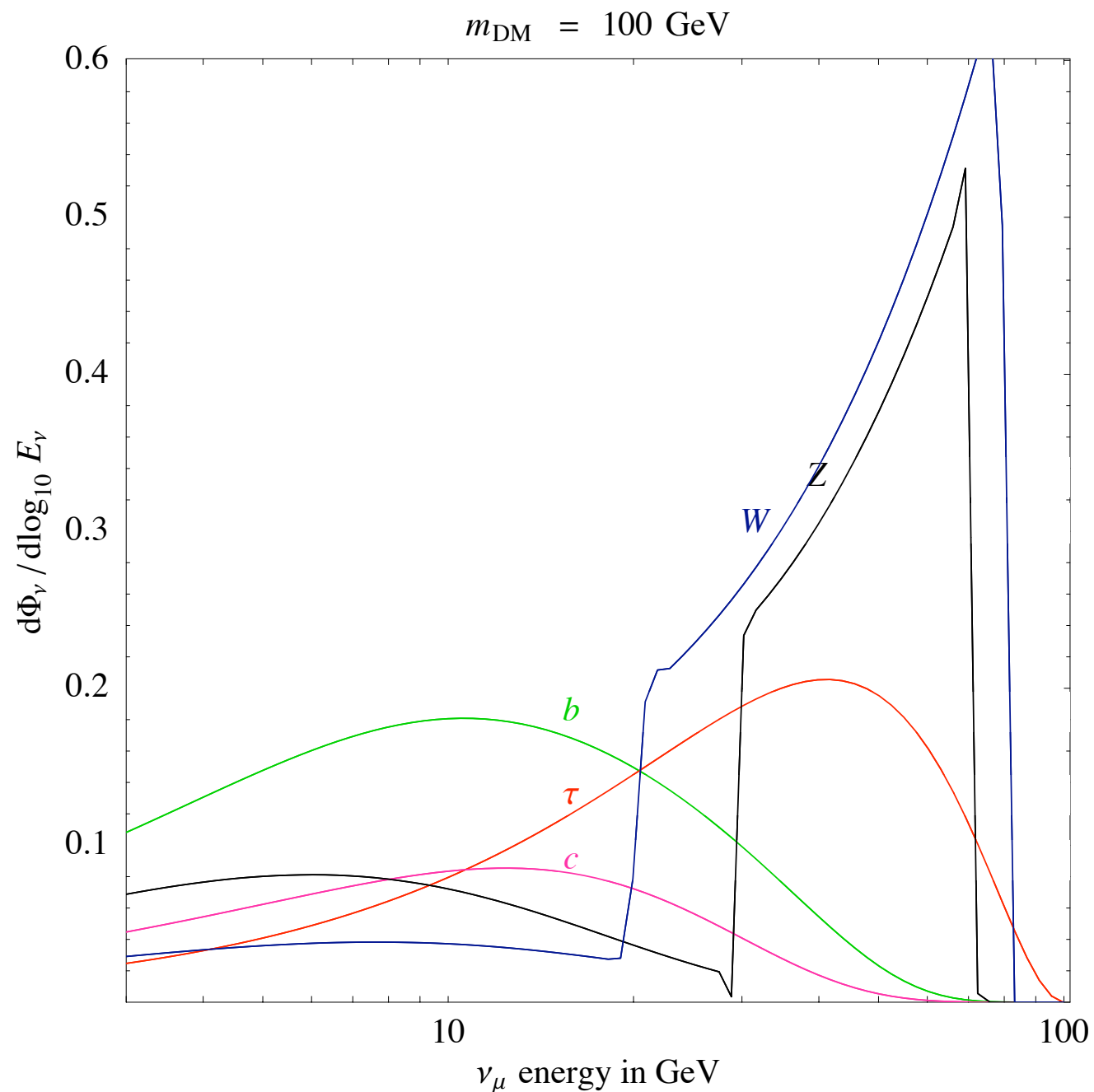


ν_τ



1. Production

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



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

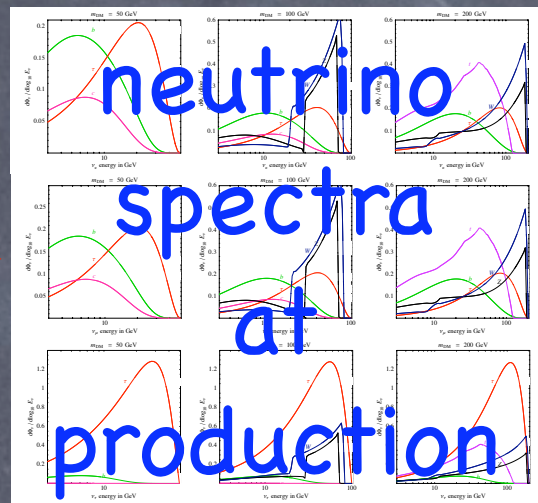
[diagrams]

- “prompt” ν +
“secondary” ν

mDM	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>



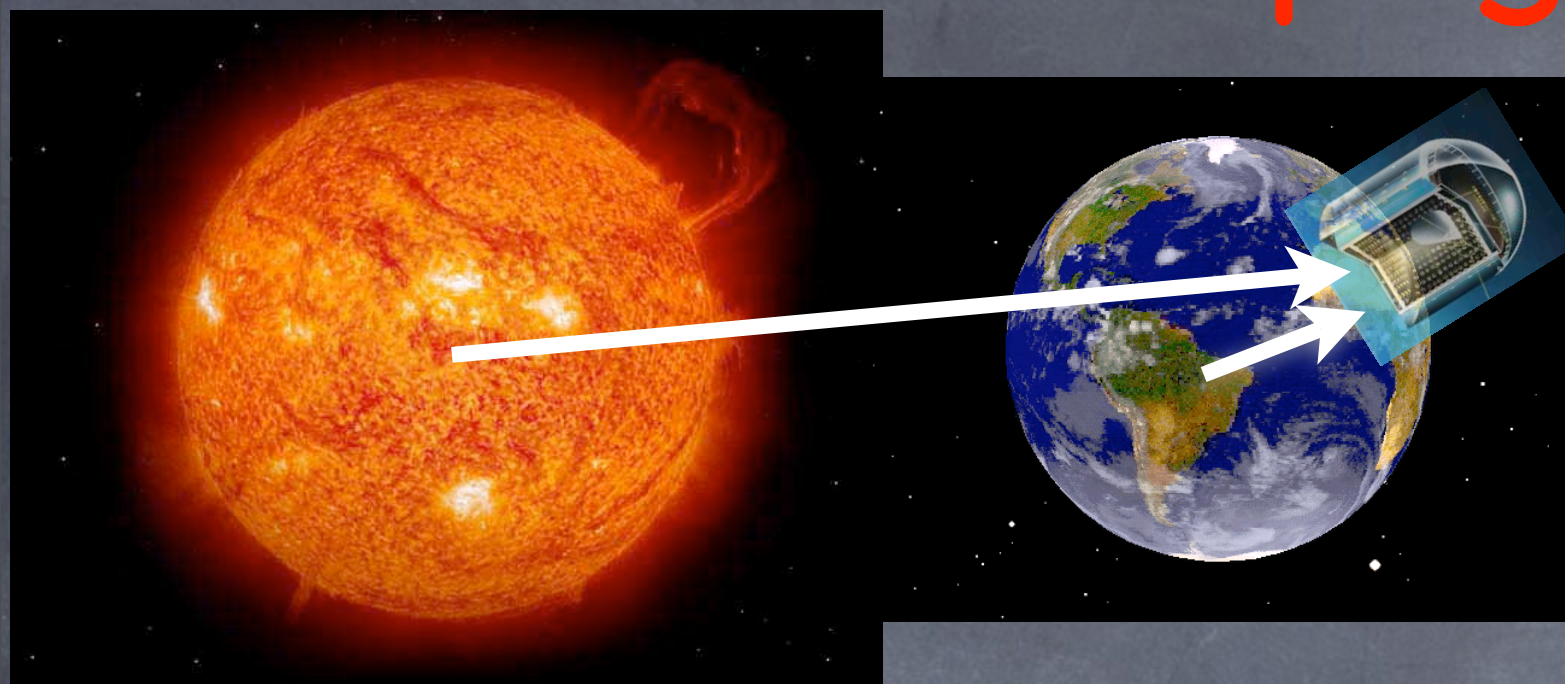
neutrino
spectra
at
production

neutrino
spectra
arriving
to us

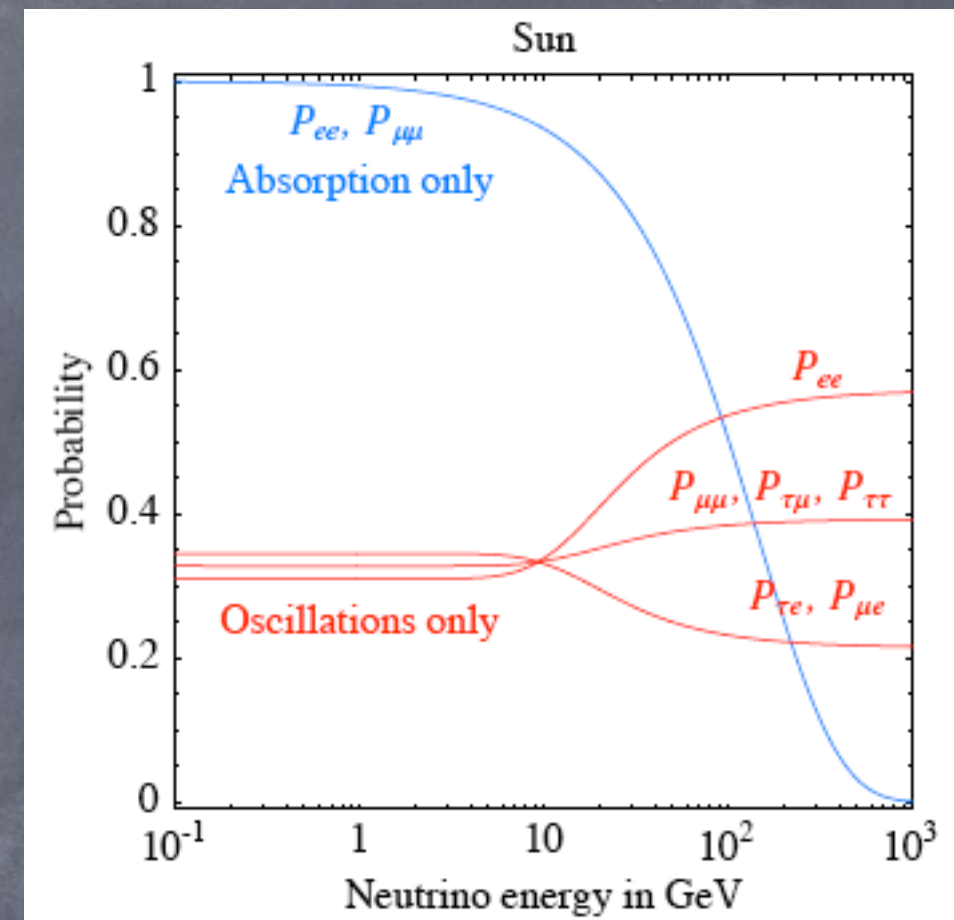
1. production

2. propagation

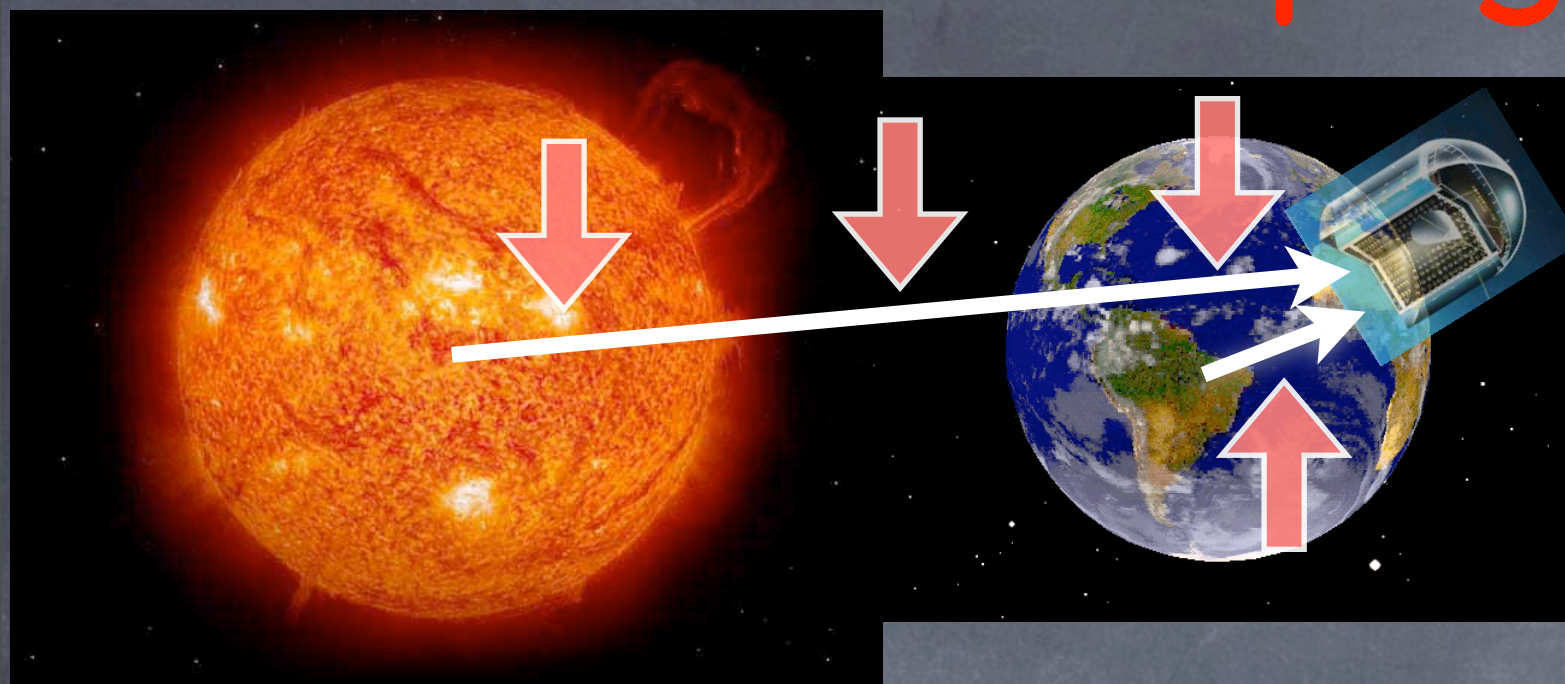
2. Propagation



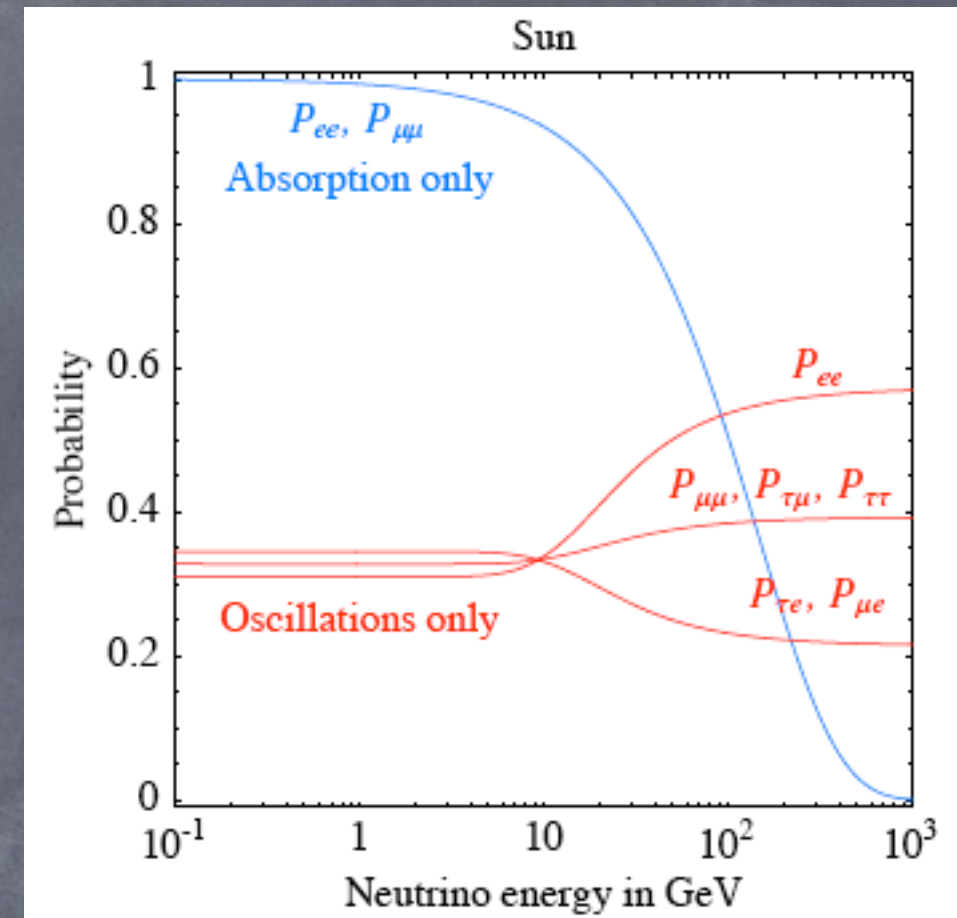
oscillations + interactions



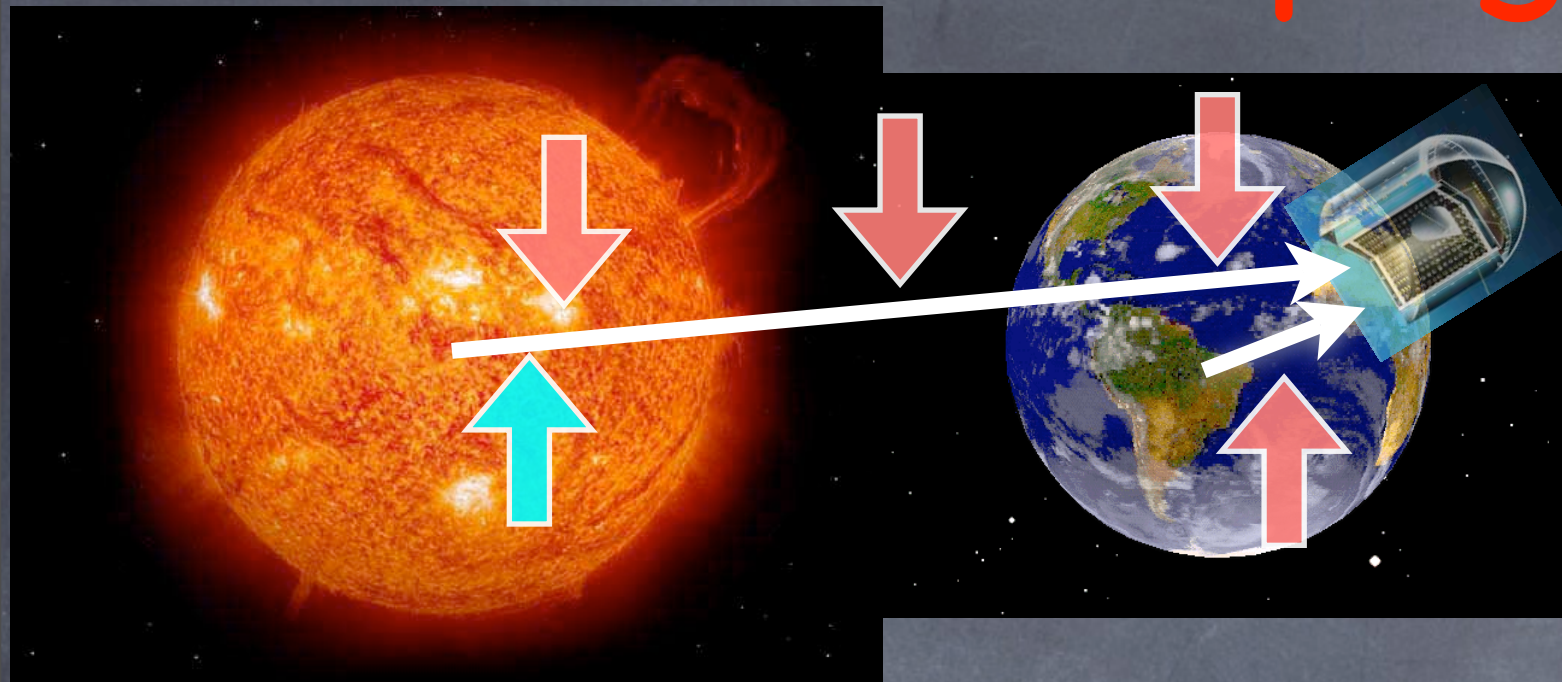
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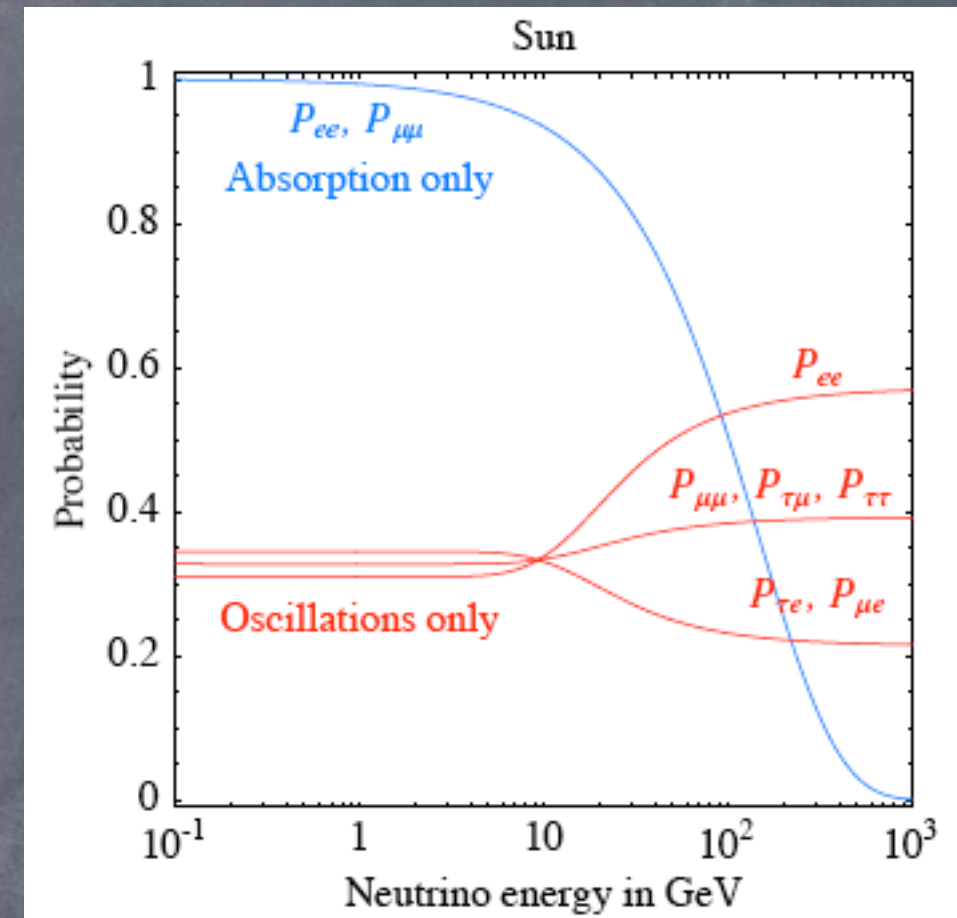
oscillations + interactions



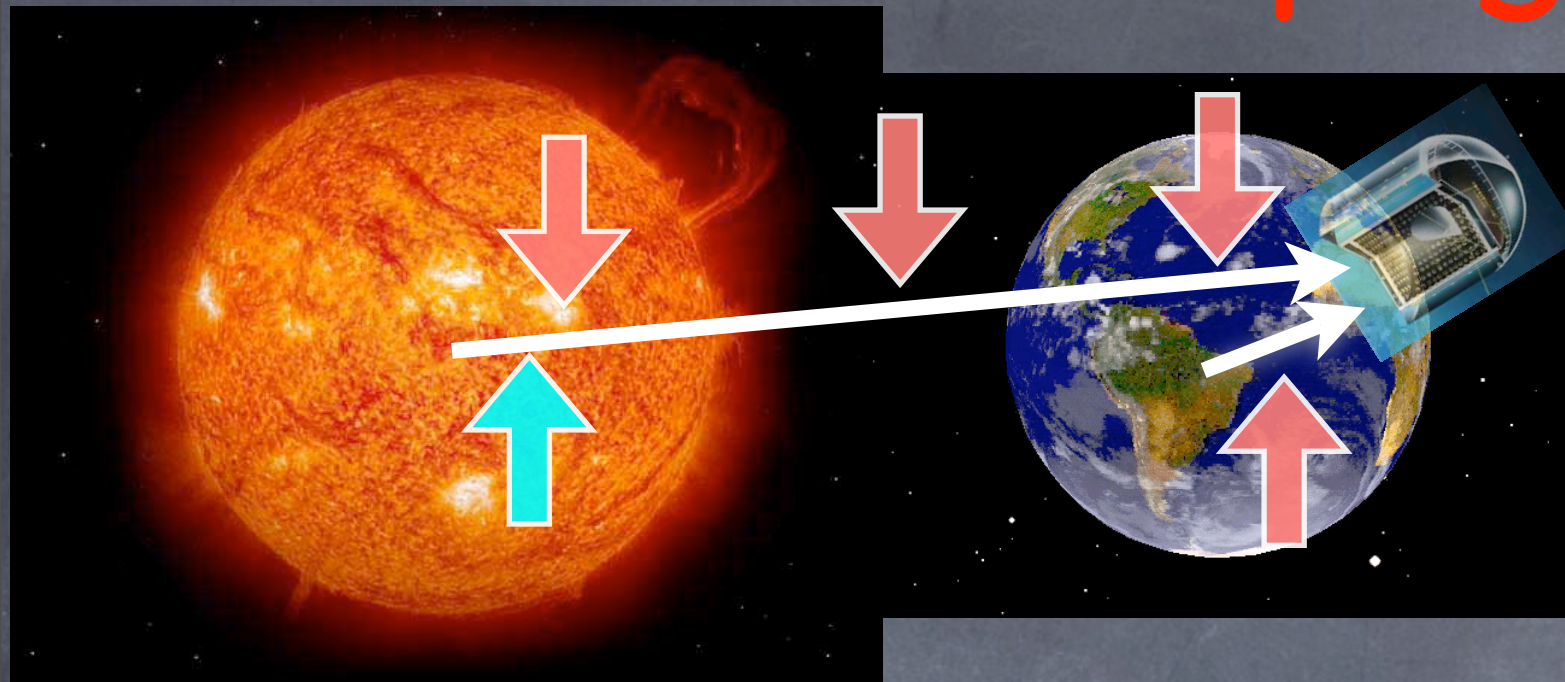
2. Propagation



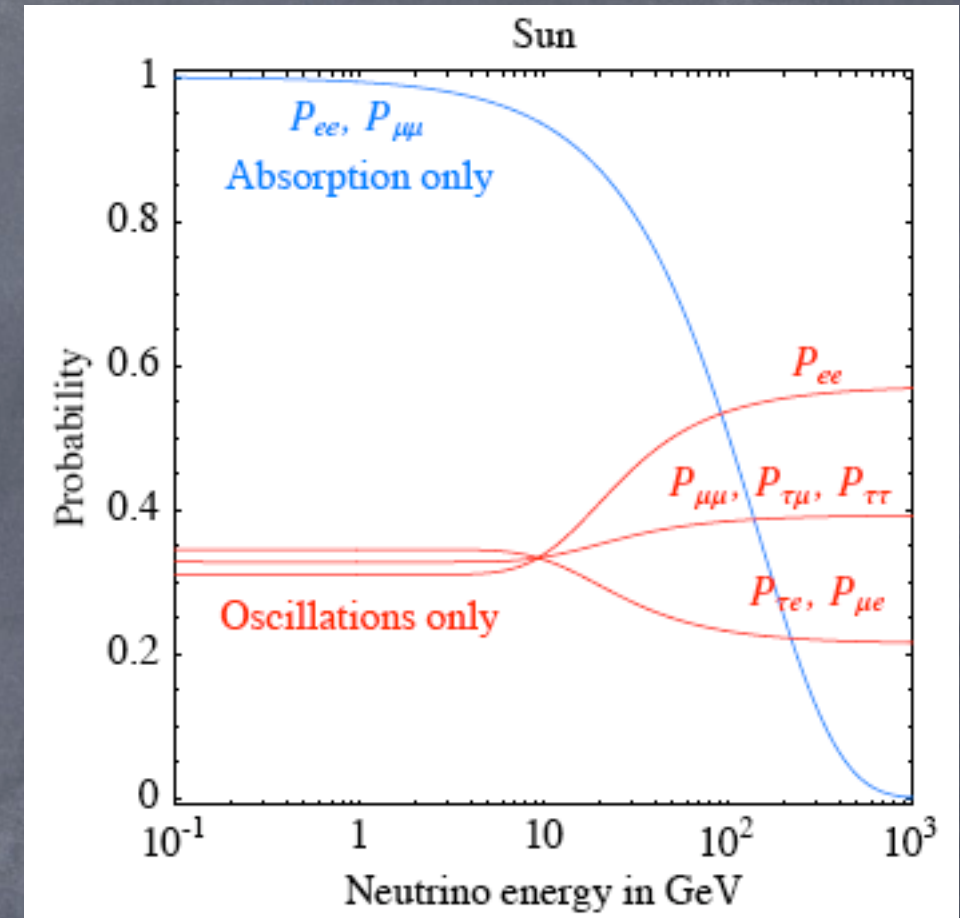
oscillations + interactions



2. Propagation

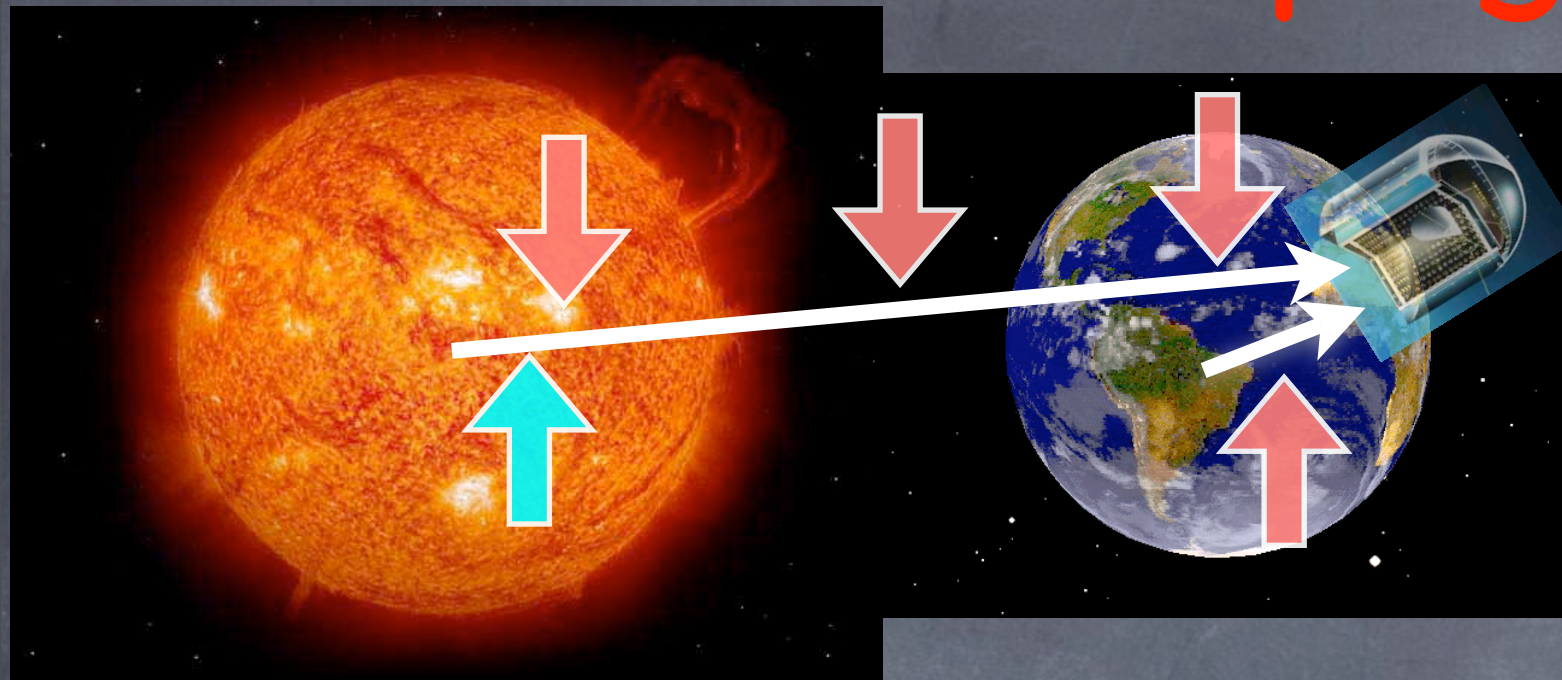


oscillations + interactions

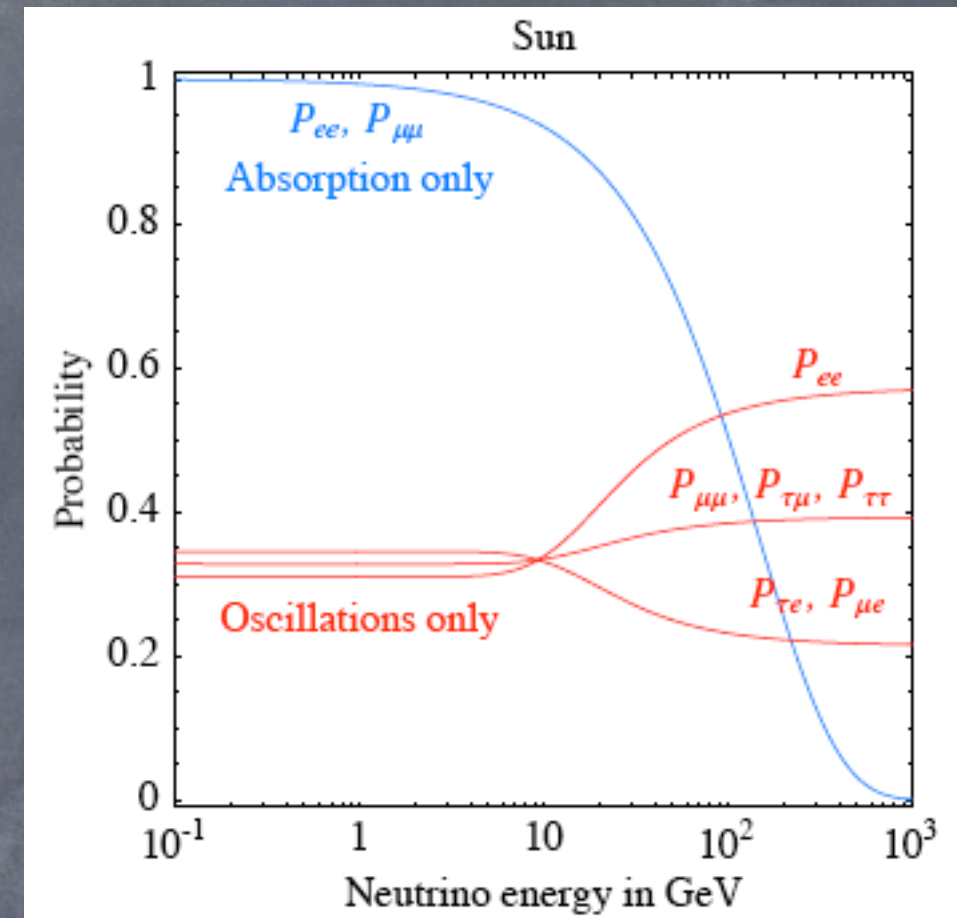


production $\longrightarrow \begin{pmatrix} \Phi_{\nu_e} \\ \Phi_{\nu_\mu} \\ \Phi_{\nu_\tau} \end{pmatrix} \longrightarrow$ detection

2. Propagation



oscillations + interactions



density matrix

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

full evolution equation:

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

2. Propagation: oscillations

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

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

2. Propagation: oscillations

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

vacuum mixing:

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

$$\theta_{\text{sun}} = 32^\circ$$

$$\theta_{\text{atm}} = 45^\circ$$

$$\theta_{13} = 0$$

$$\Delta m_{\text{sun}}^2 = 8.0 \cdot 10^{-5} \text{eV}^2$$

$$|\Delta m_{\text{atm}}^2| = 2.5 \cdot 10^{-3} \text{eV}^2$$

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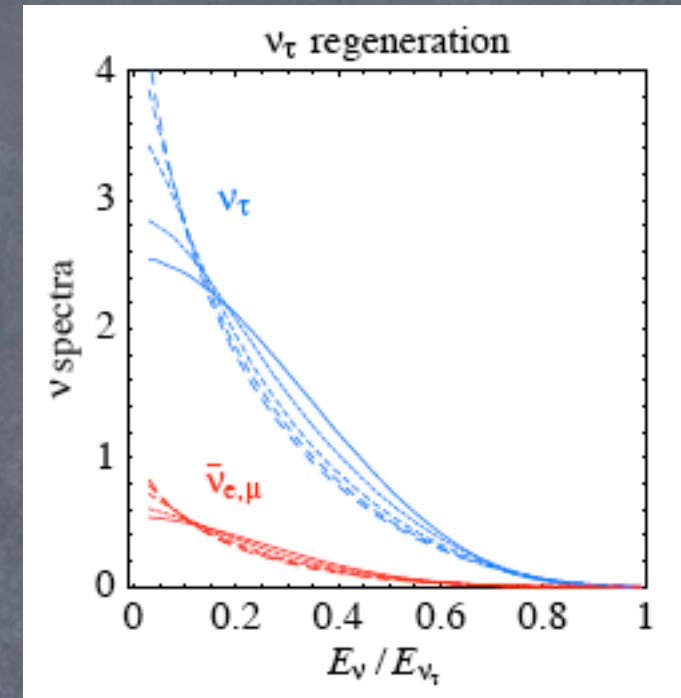
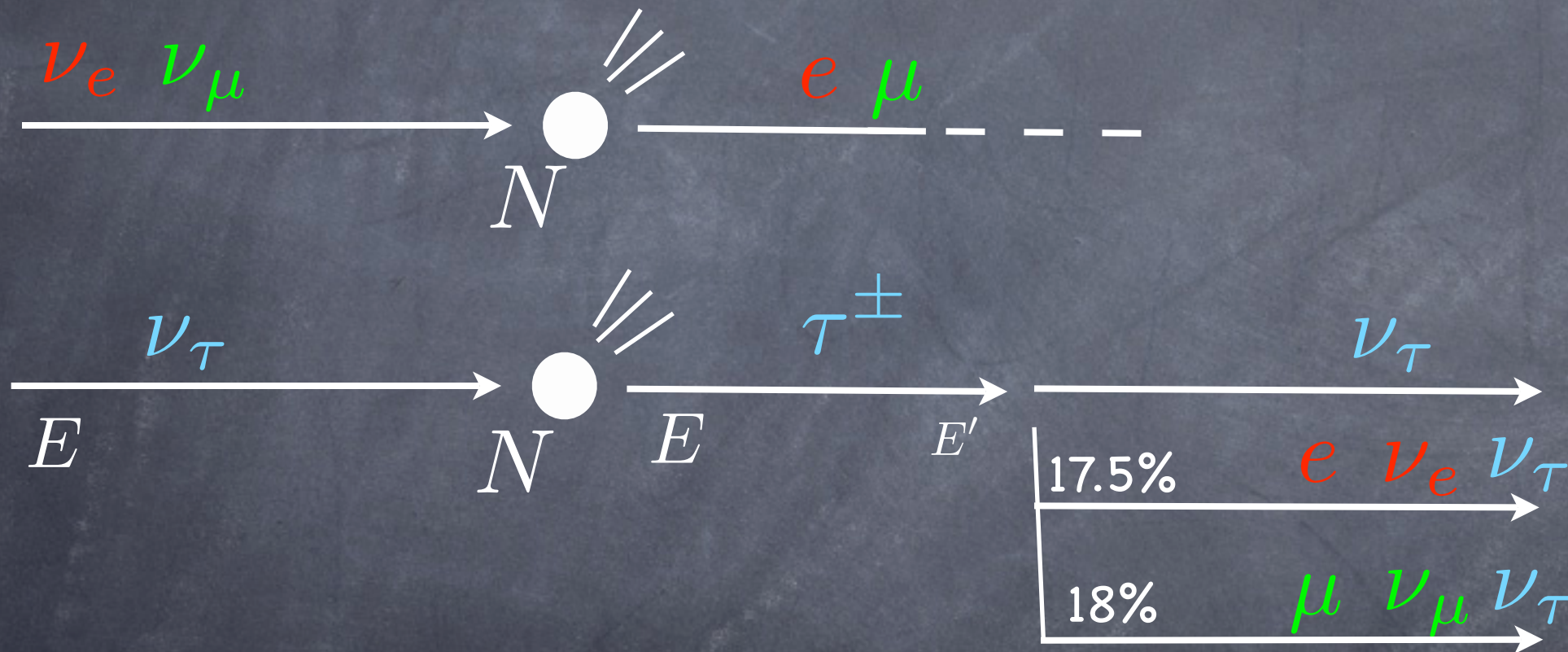
$$|\Delta m_{\text{atm}}^2| = 2.5 \cdot 10^{-3} \text{eV}^2$$

matter effect (MSW):

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

2. Propagation: CC absorption and tau regeneration

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

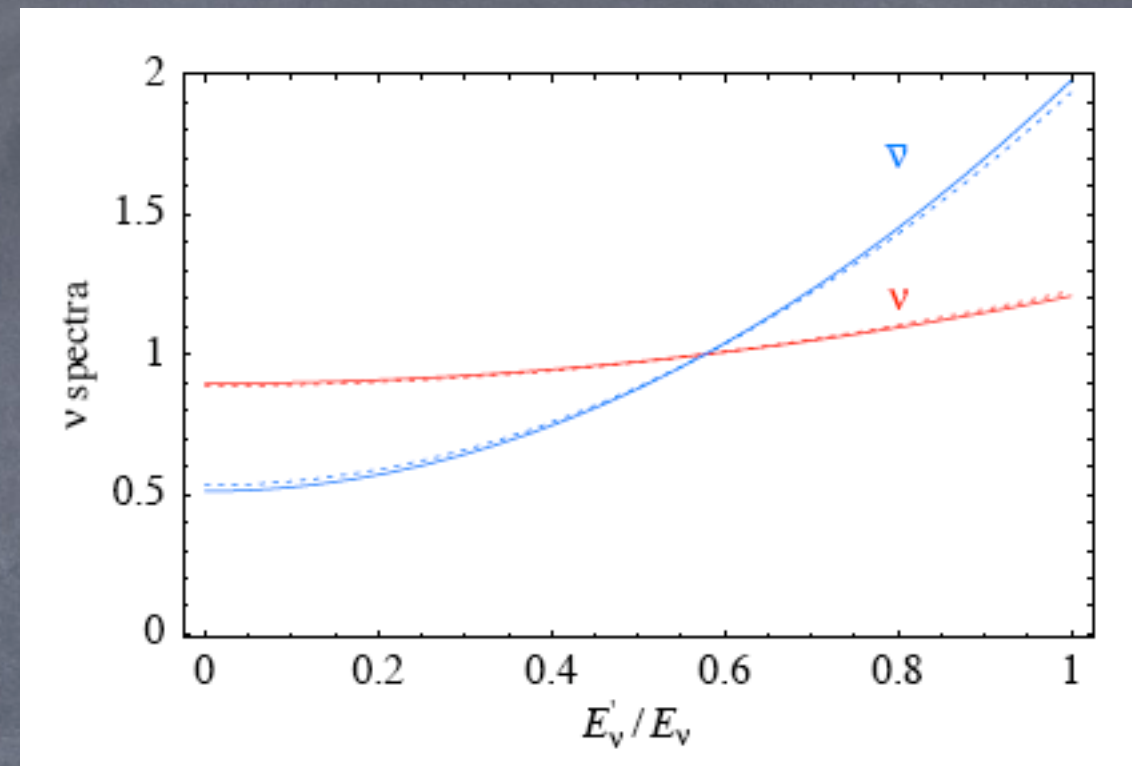
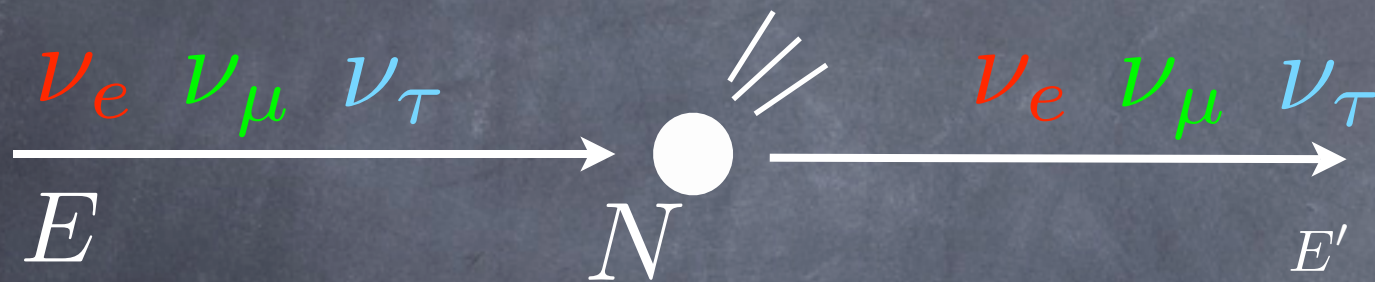


(re)generation!

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

2. Propagation: NC scatterings

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



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

2. Propagation: summary

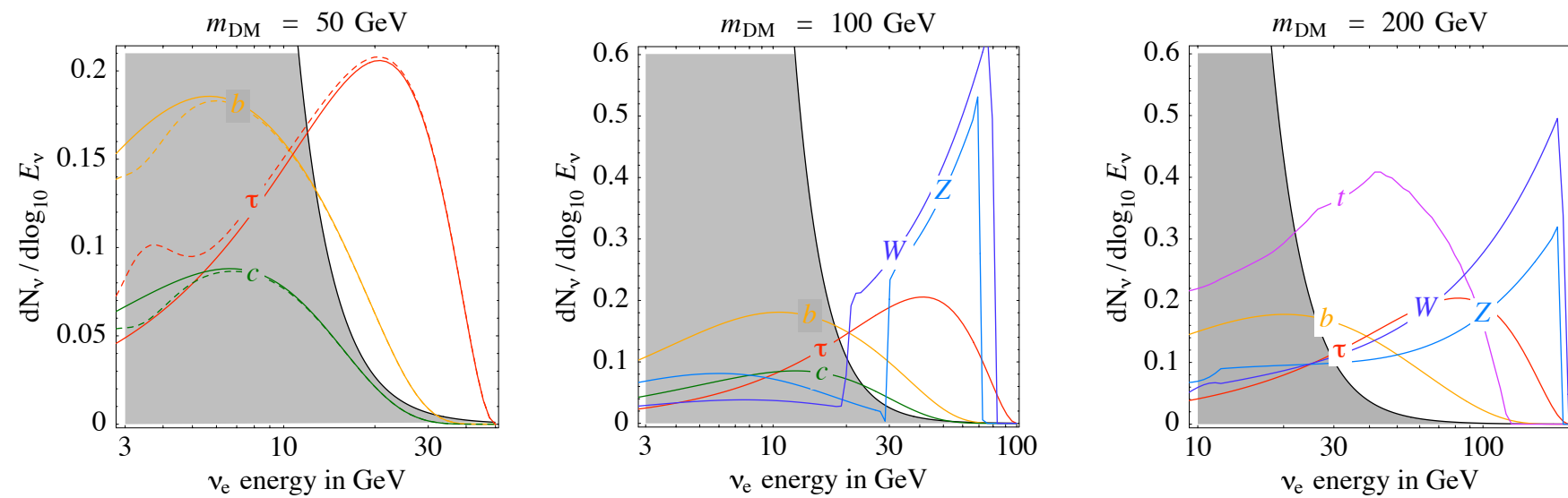
Effects of oscillations and interactions:

- reshuffle of the 3 flavors
(oscillations and regeneration)
- attenuation of the fluxes
- degradation of energy
(distortion of spectra)

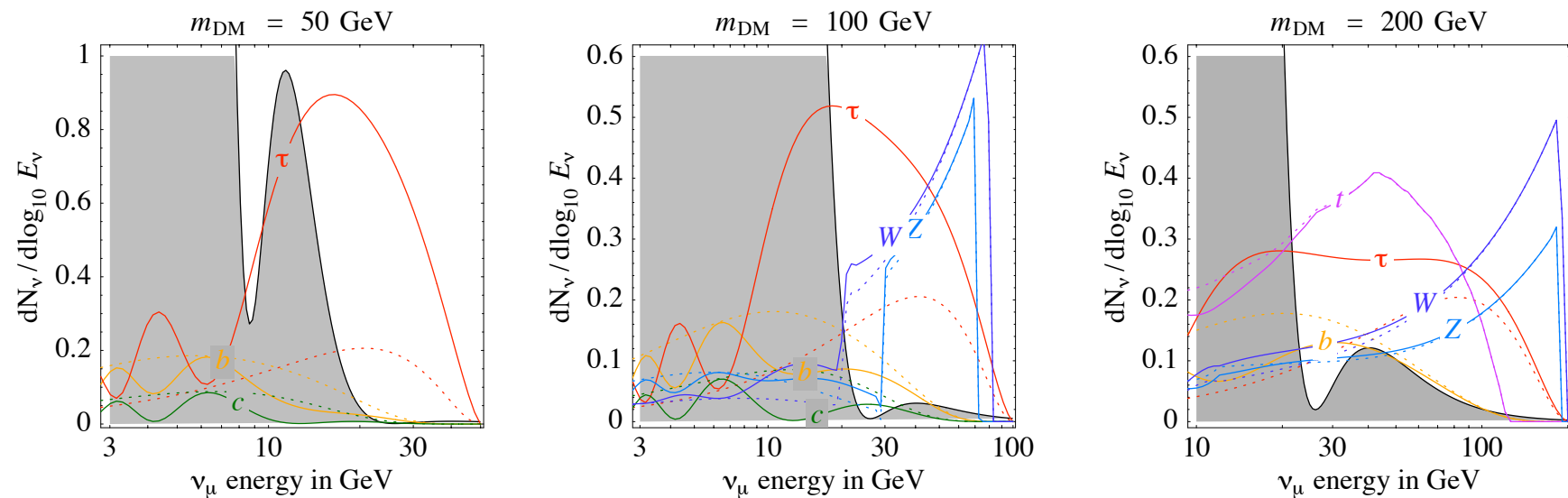
2. Final ν fluxes from Earth

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

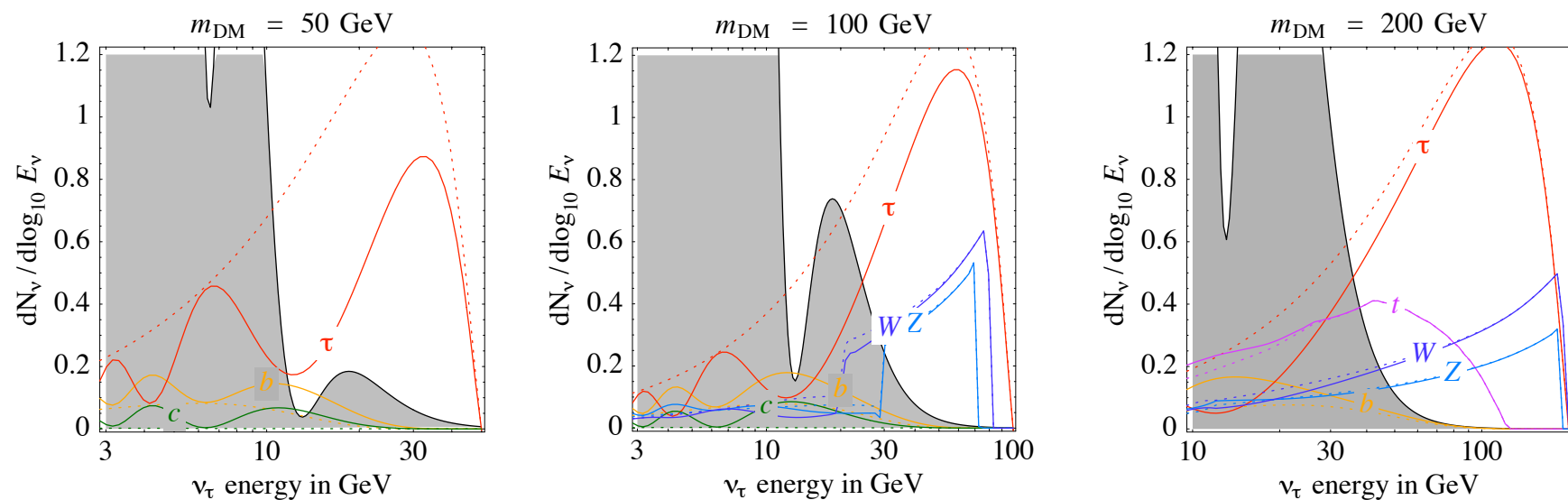
ν_e



ν_μ



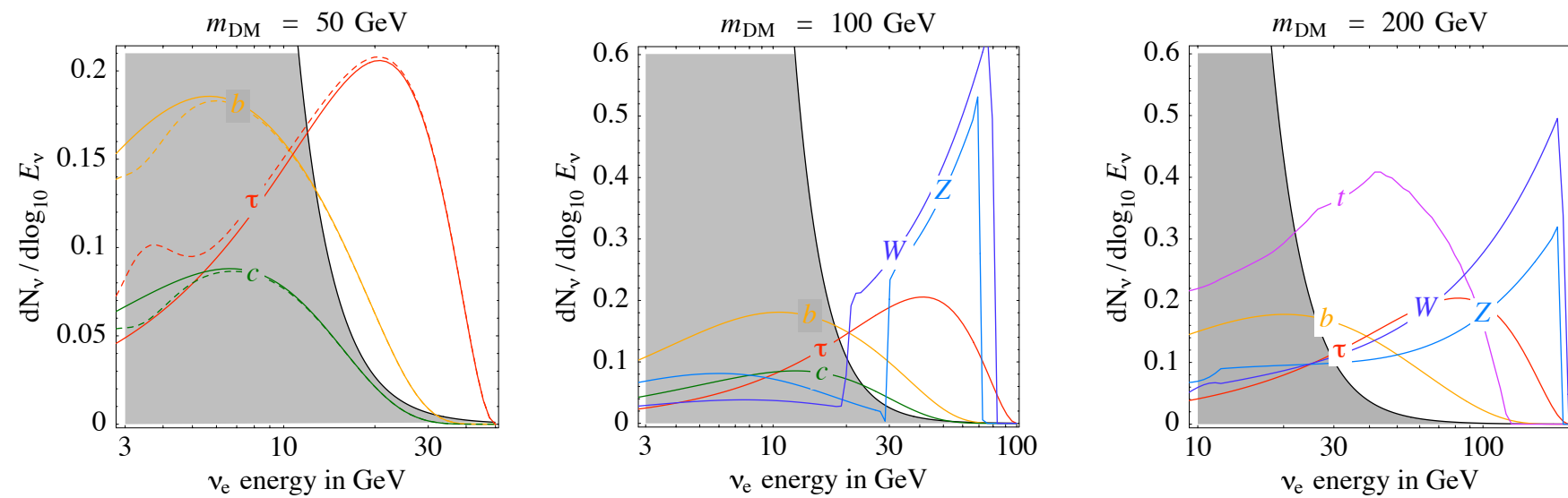
ν_τ



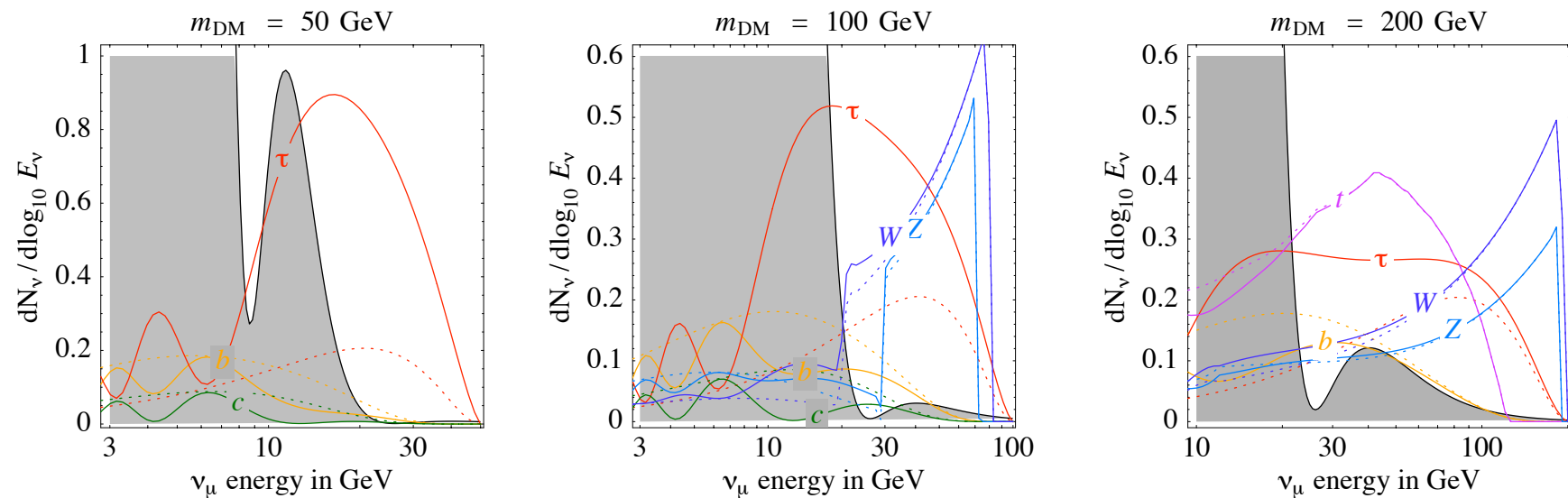
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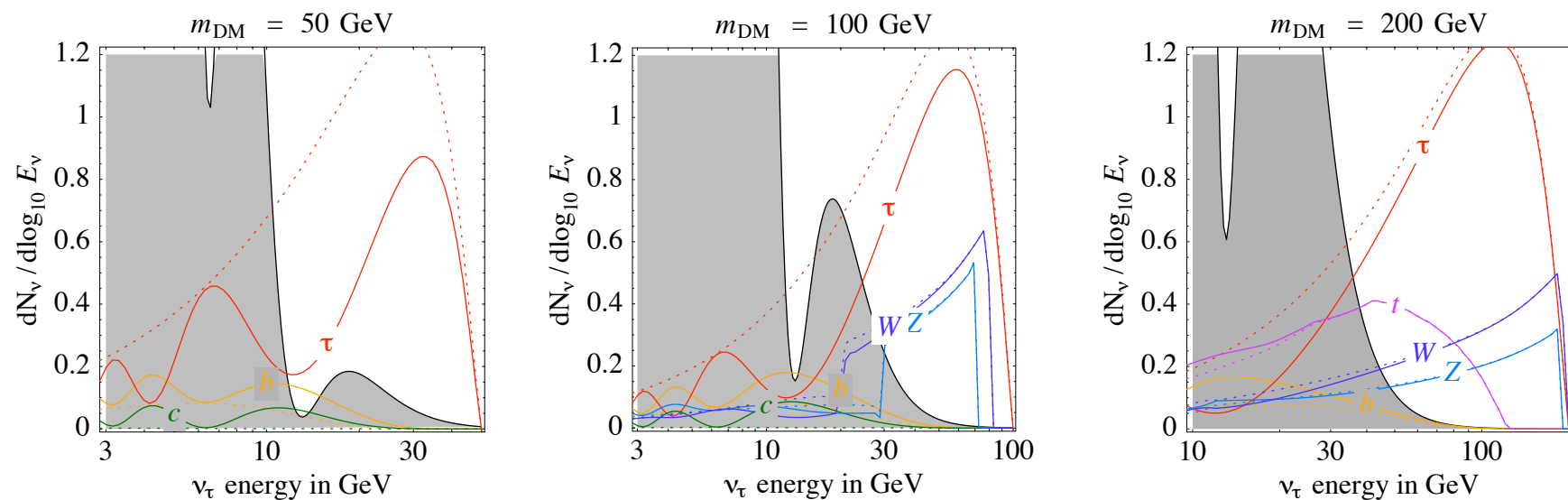
ν_e



ν_μ



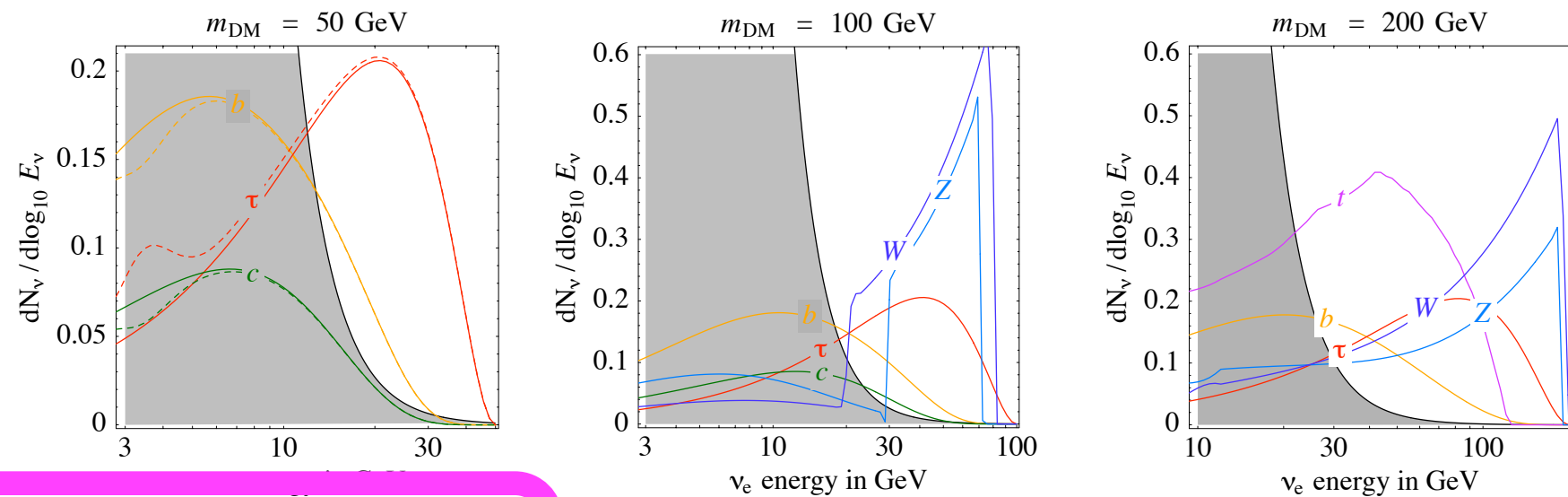
ν_τ



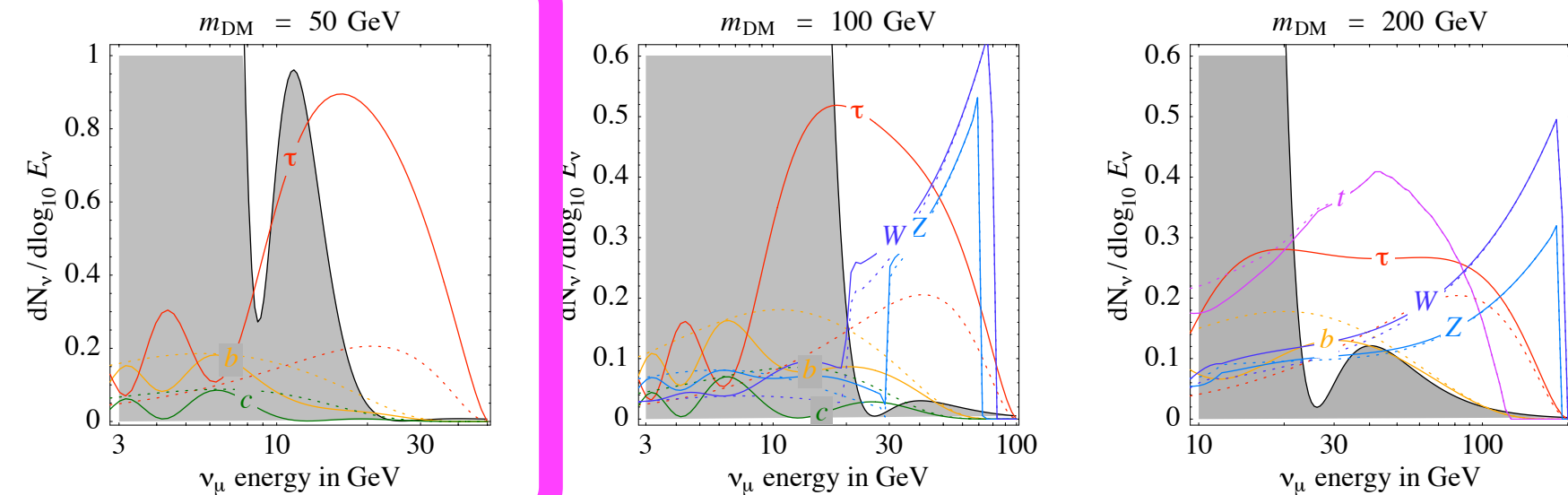
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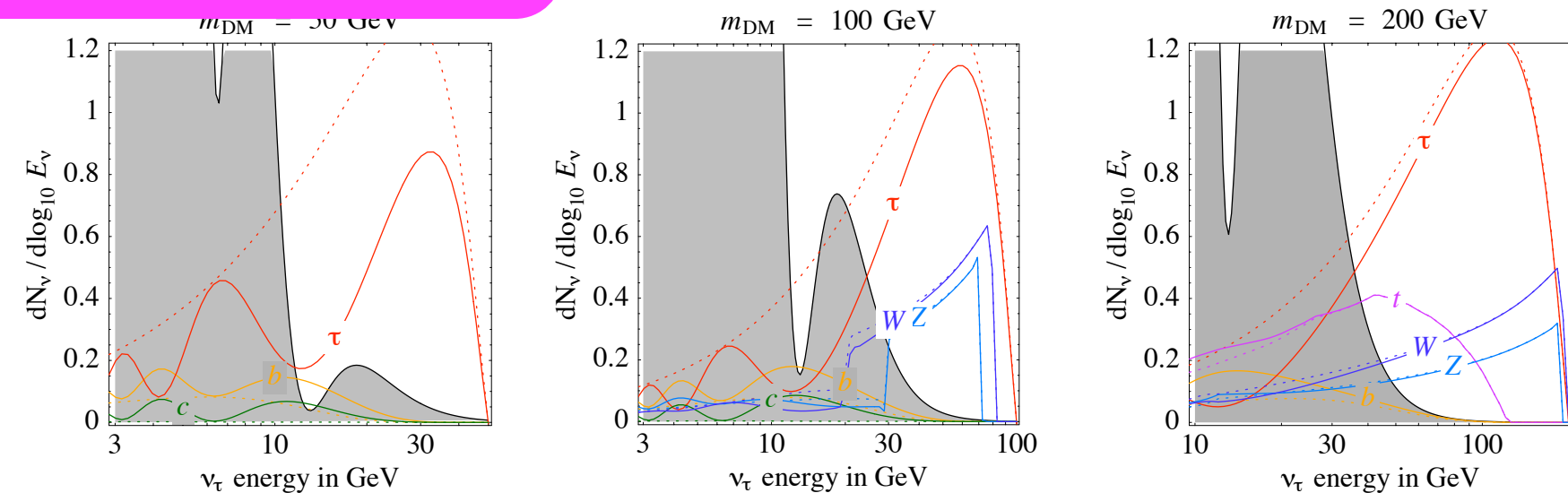
ν_e



ν_μ

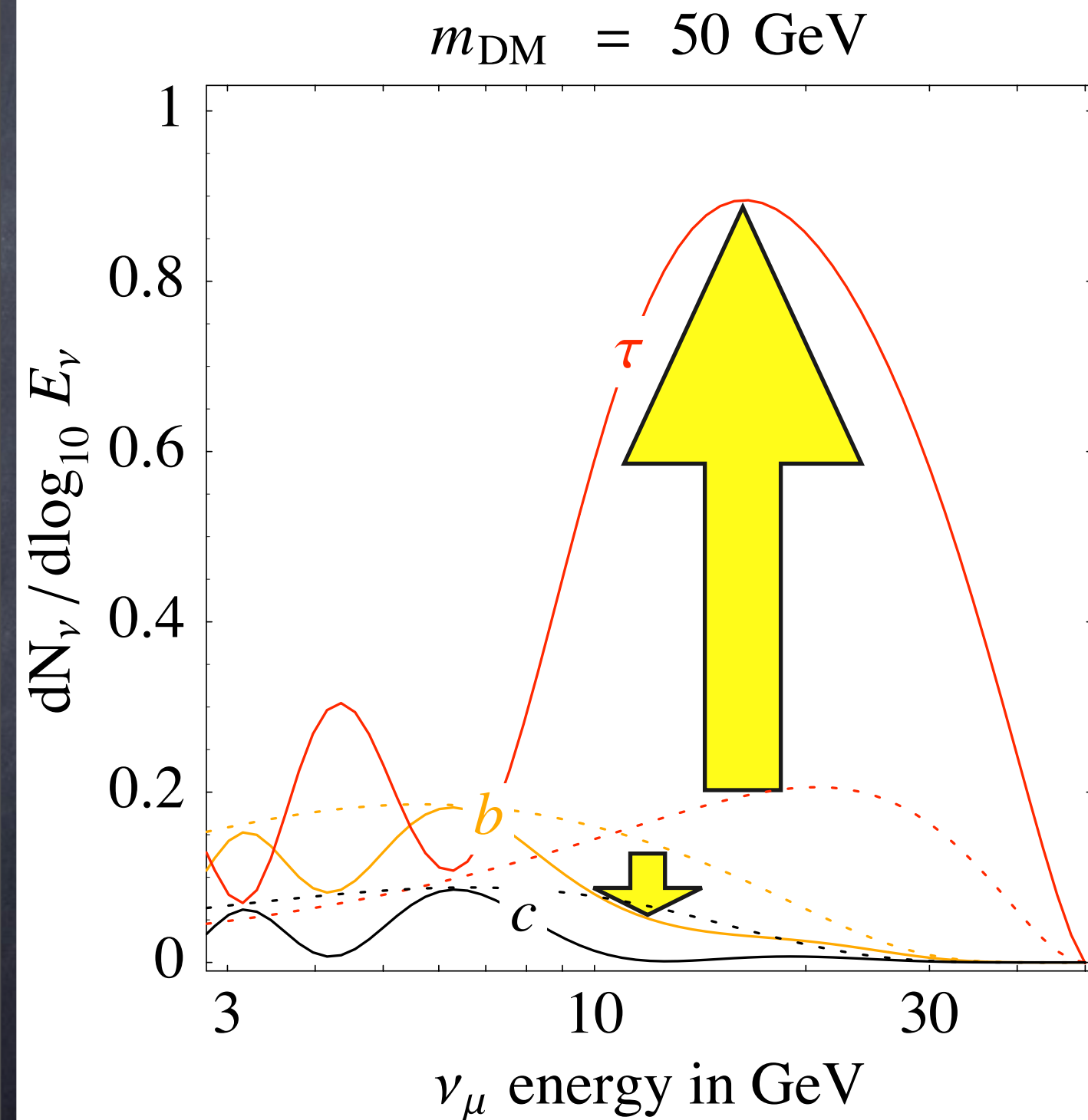


ν_τ



2. Final fluxes

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

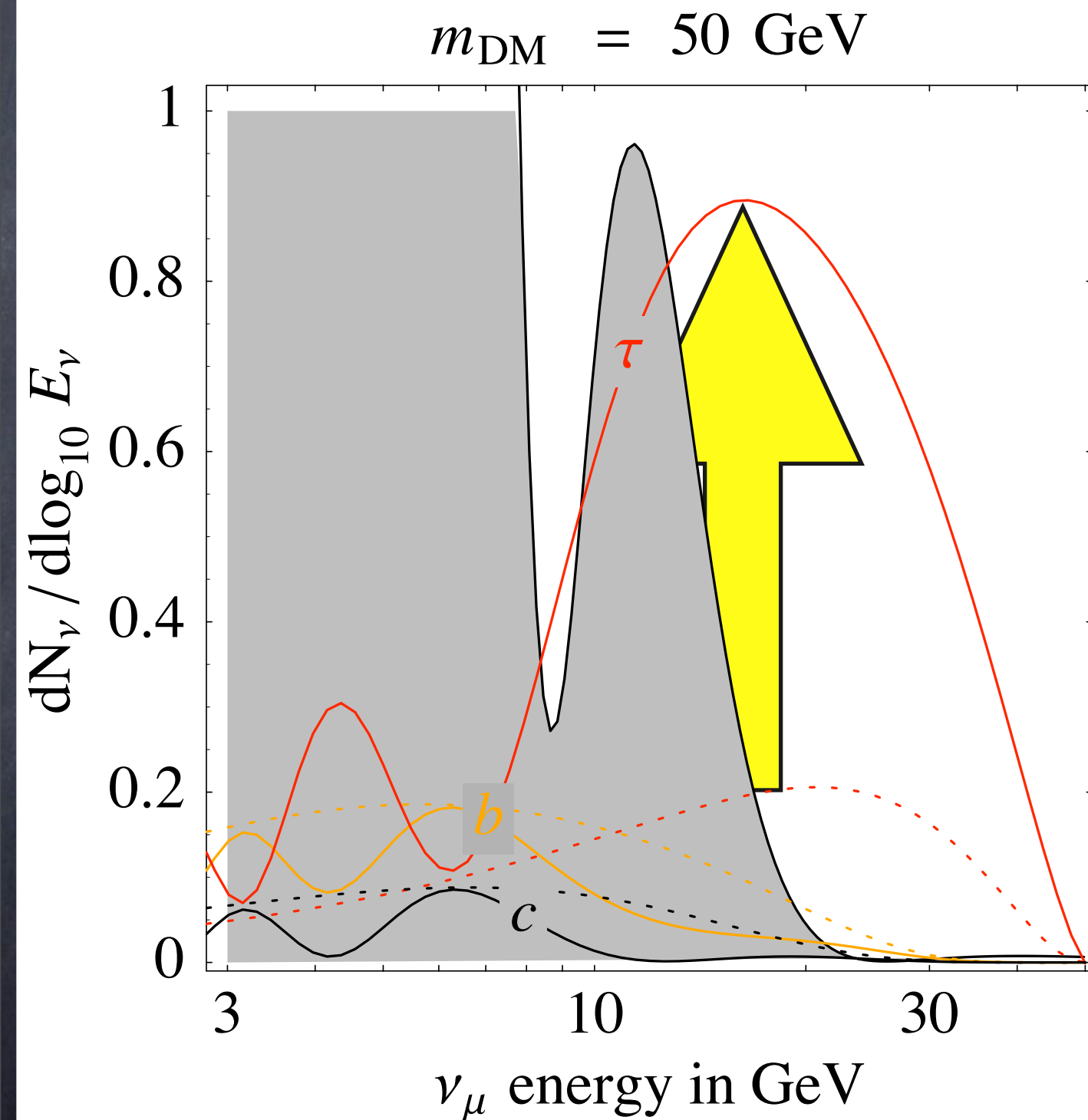


– OSCILLATIONS! [quantitatively...]
atmospheric oscillations with

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

2. Final fluxes

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



– OSCILLATIONS!

atmospheric oscillations with

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

– BACKGROUND: from atmospheric neutrinos!

– smaller at large E

– known angular extrapolation

– relative normalisation assuming

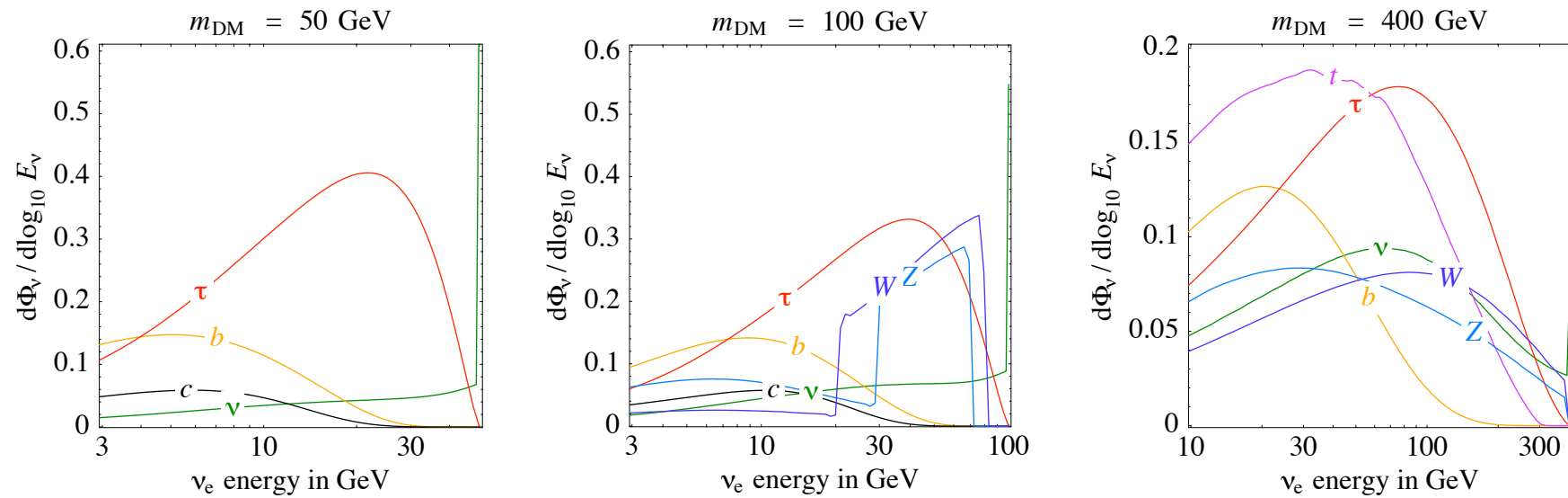
$$10^{14} \left(\frac{100 \text{ GeV}}{m_{\text{DM}}} \right)^2 \text{ annihil/sec}$$

(FLUKA)

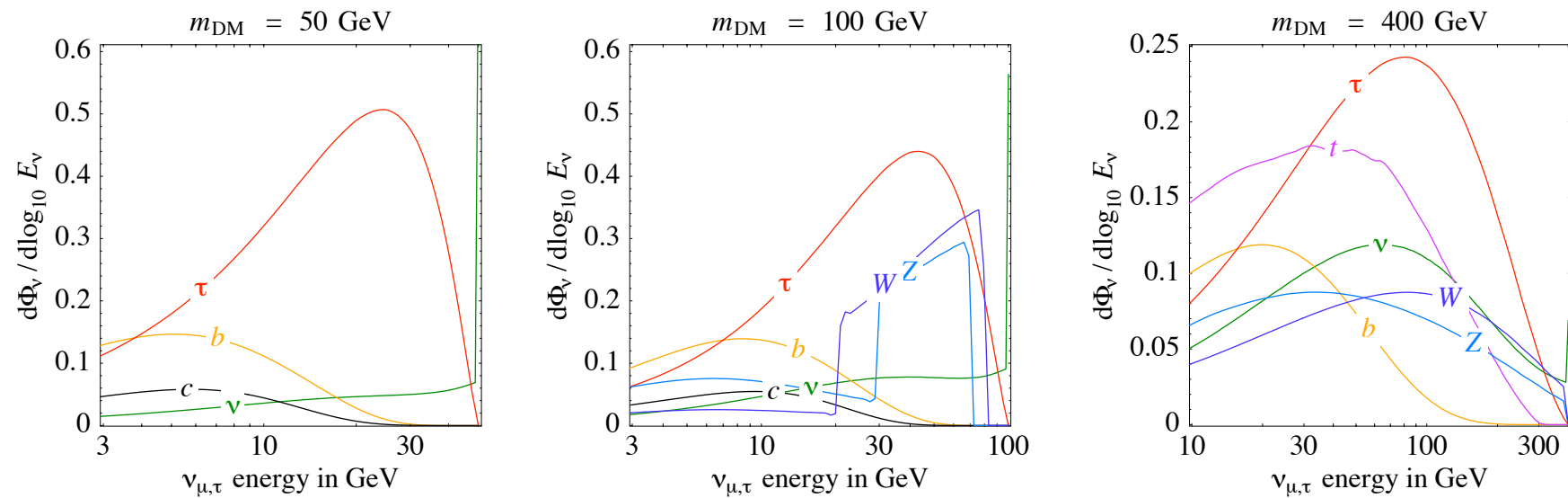
2. Final ν fluxes from Sun

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

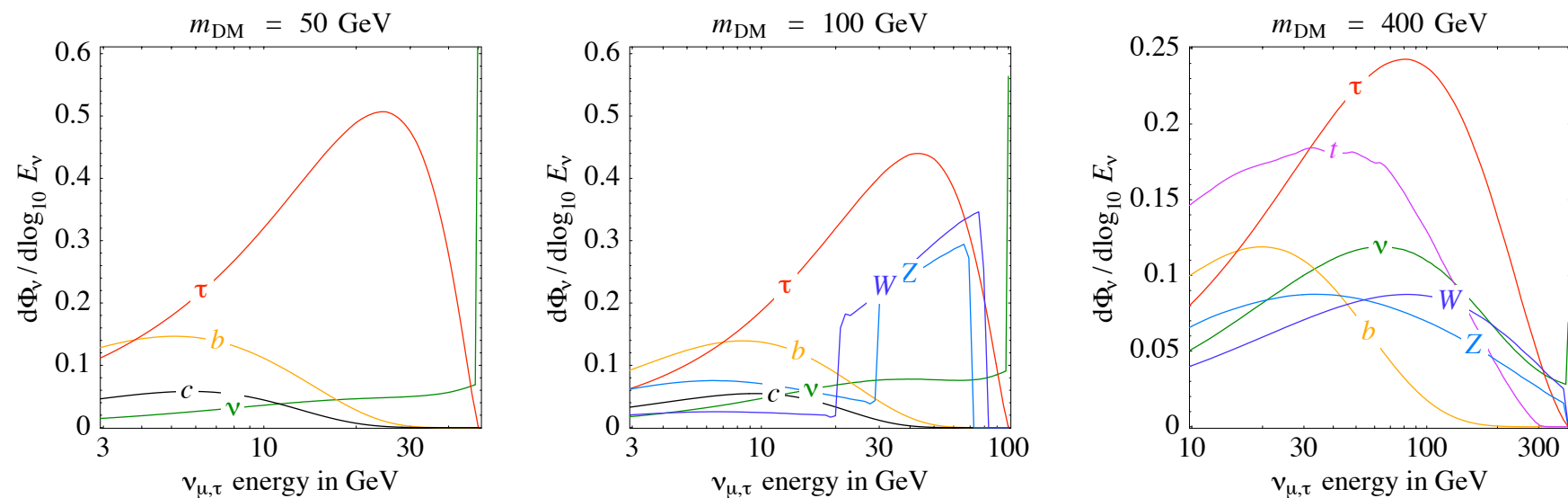
ν_e



ν_μ



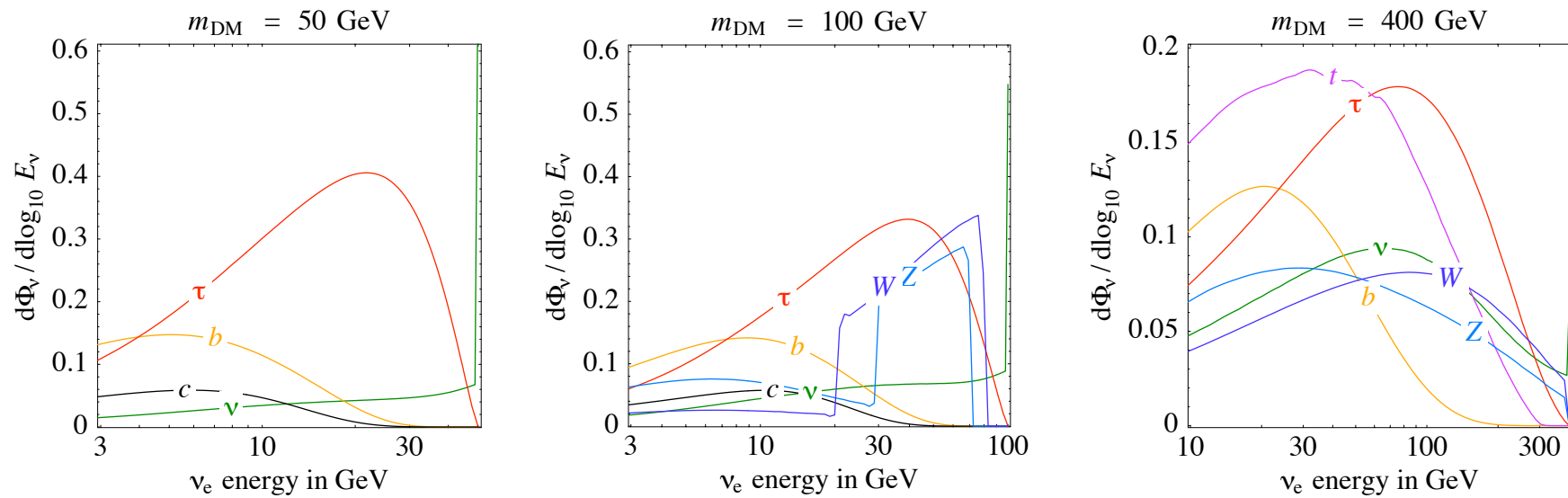
ν_τ



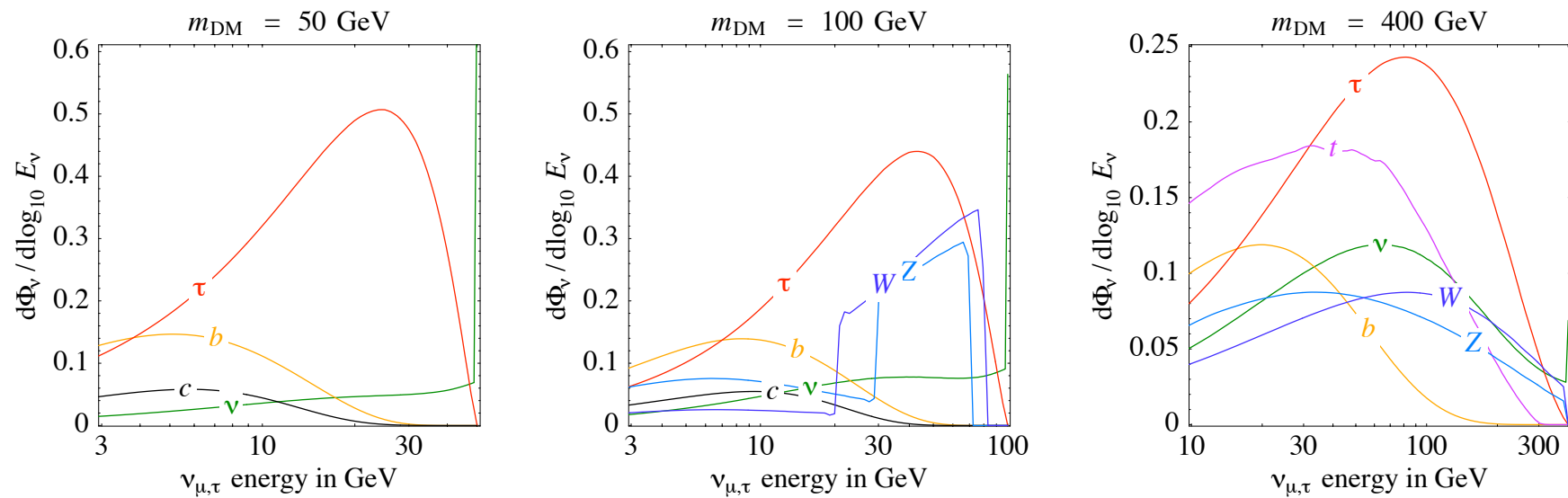
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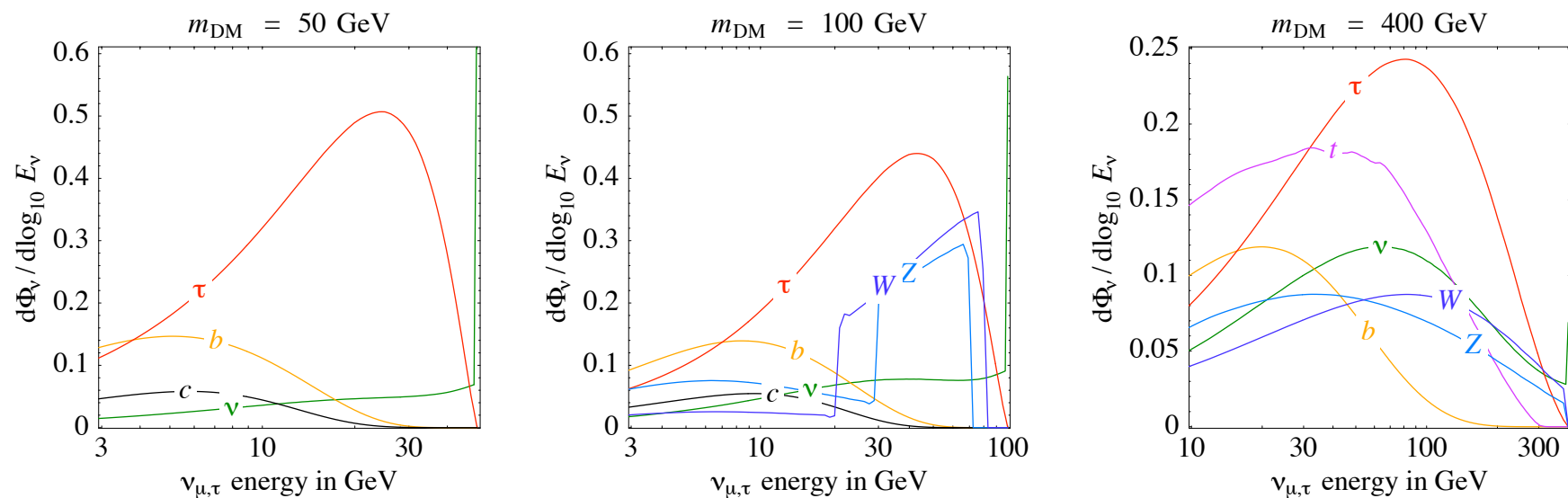
ν_e



ν_μ



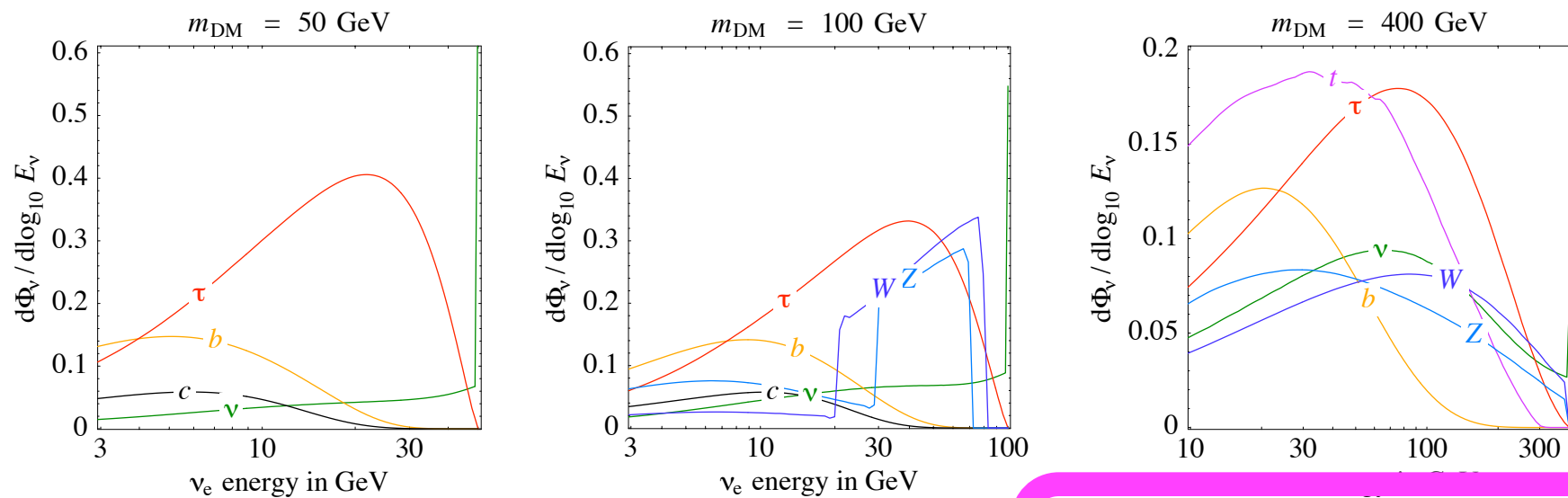
ν_τ



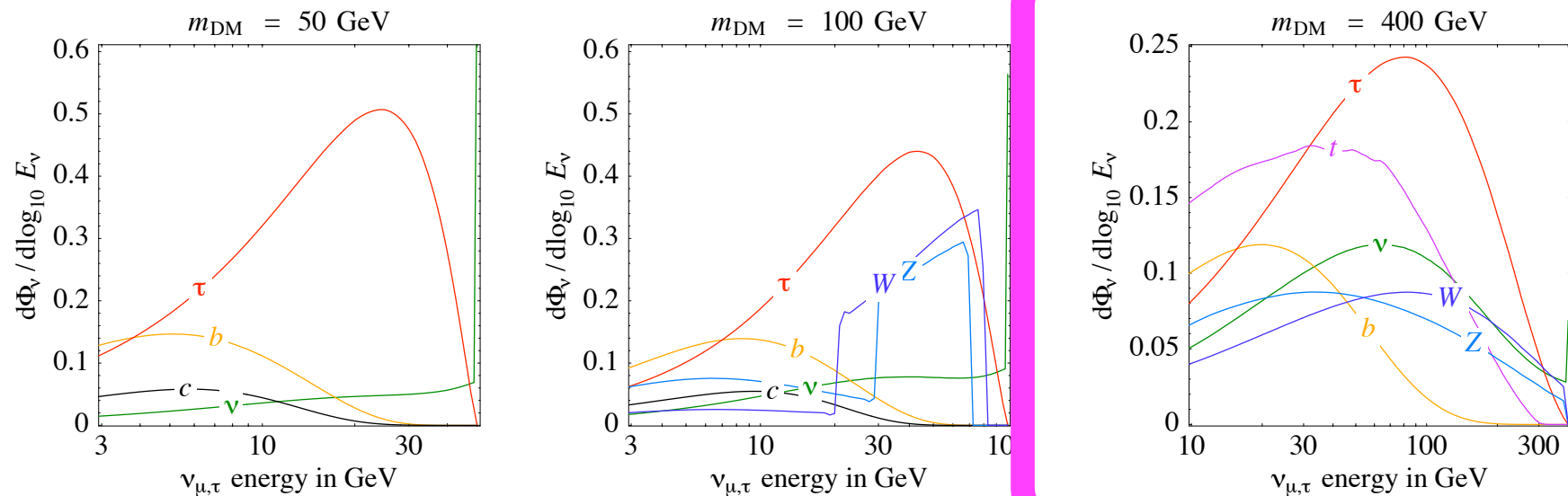
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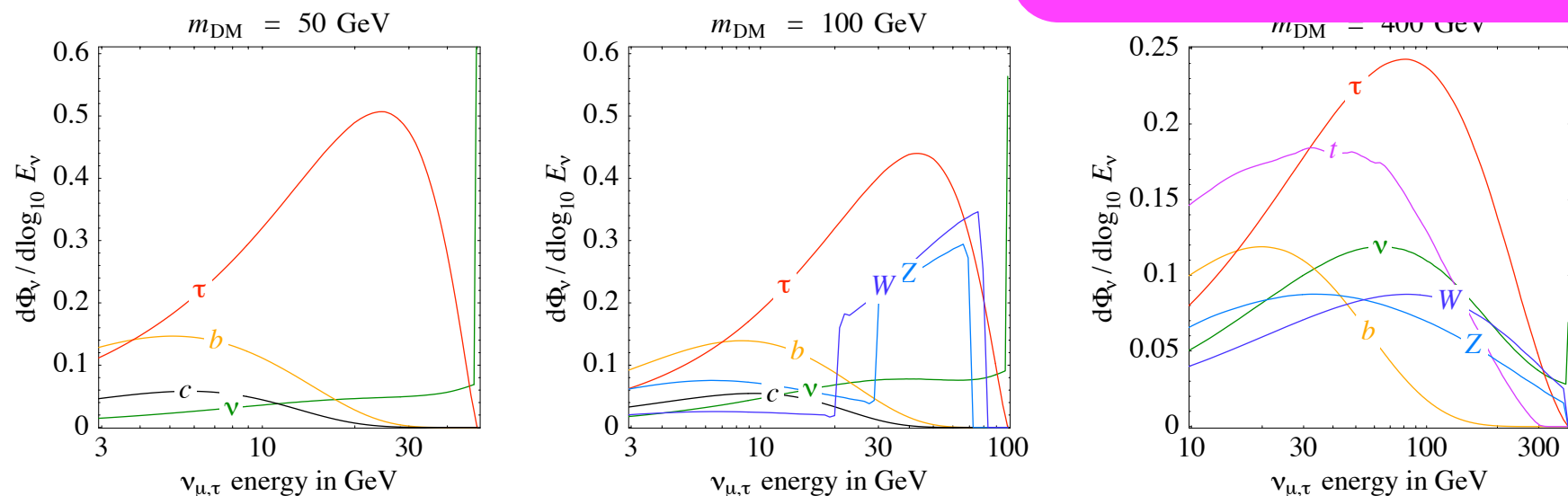
ν_e



ν_μ

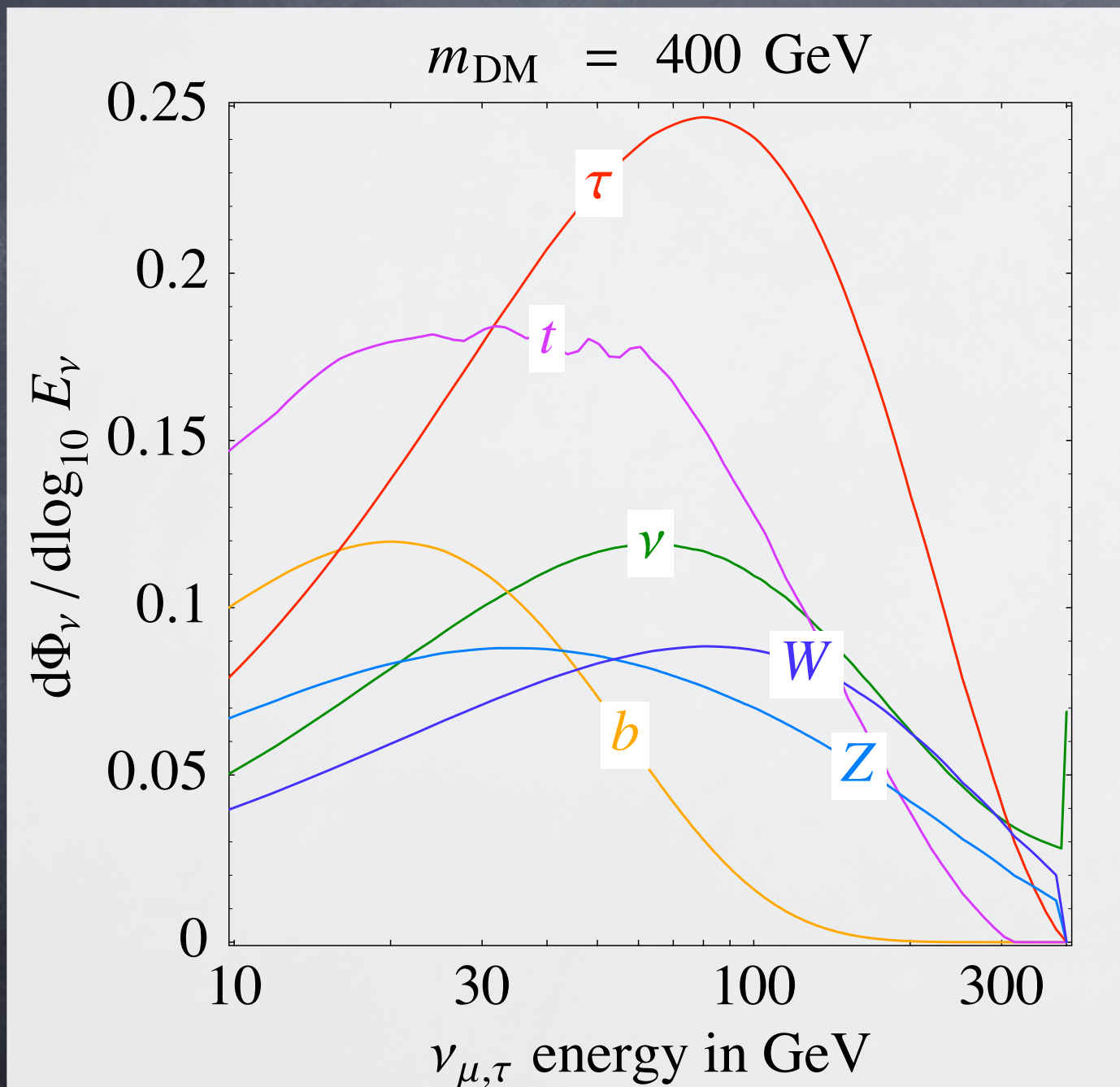


ν_τ

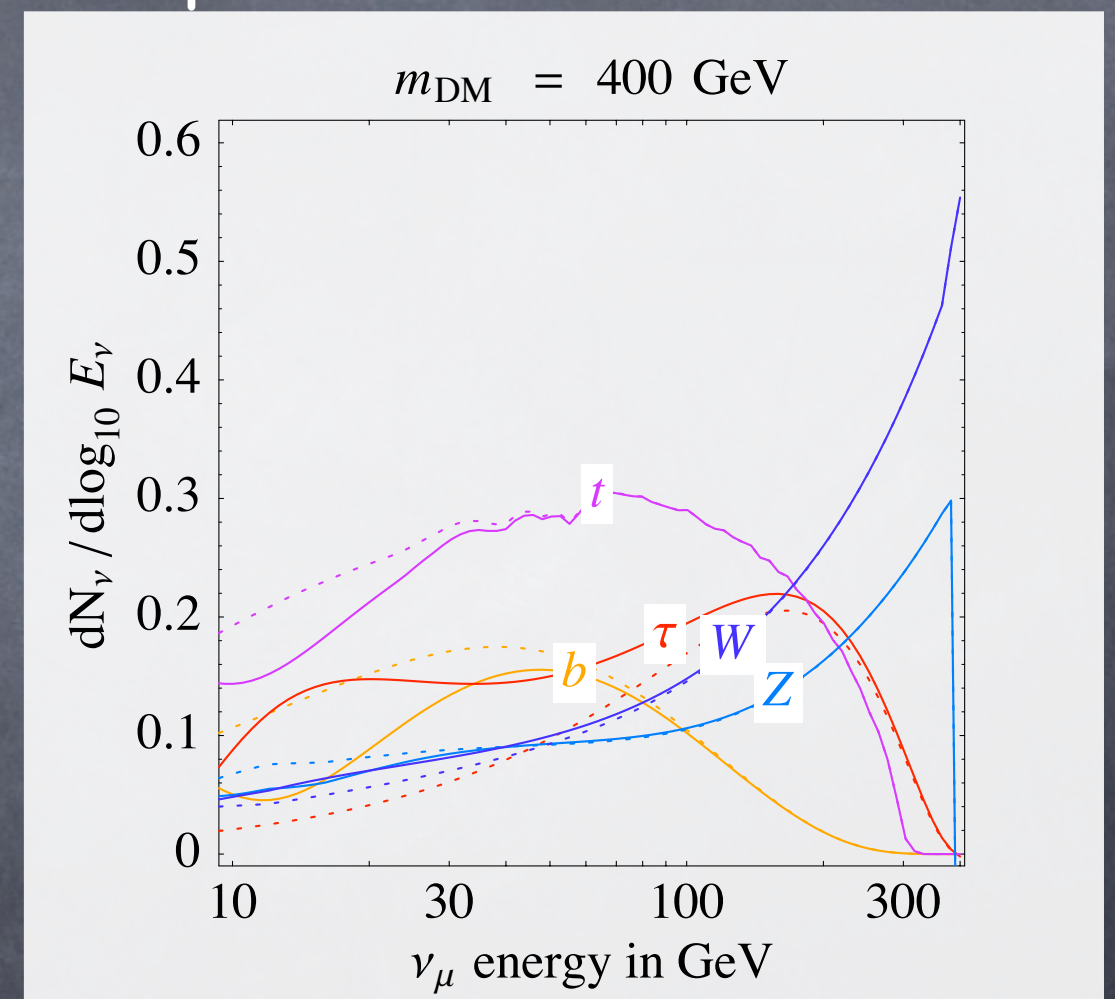


2. Final fluxes

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

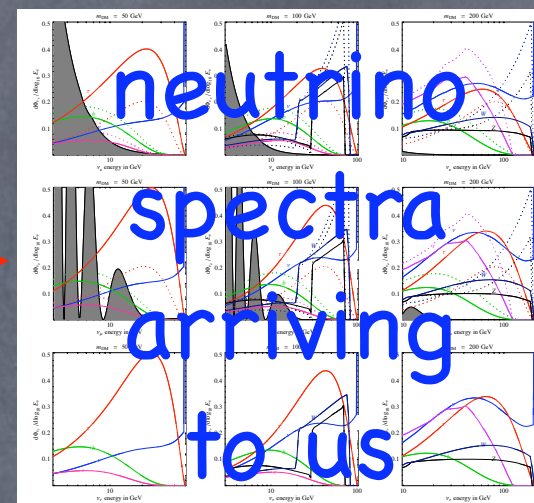
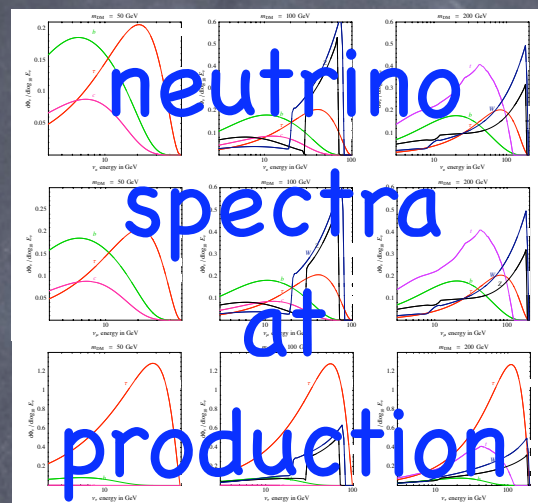


compare with Earth's case:



- interactions degrade and smoothen spectrum, approach “limit spectrum”

700	0.12	0.608978	0.341566	0.288158	0.00732825	1.01016	0.329712	0.325684	1000	0.01	2.79247	0.366511	1.3968	0.457048	5.61005	1.82716	0.919742
700	0.13	0.549979	0.338742	0.261576	0.00587295	0.938862	0.306415	0.314678	1000	0.02	2.15668	0.365559	0.991901	0.204231	3.82578	1.28553	0.712858
700	0.14	0.497406	0.335783	0.237414	0.00472903	0.879793	0.28655	0.305119	1000	0.03	1.79387	0.363911	0.8028	0.114483	2.93931	1.00812	0.605074
700	0.15	0.45023	0.332688	0.215358	0.00380882	0.814194	0.269374	0.296714	1000	0.04	1.53776	0.361895	0.684616	0.072157	2.4272	0.829507	0.53499
700	0.16	0.407863	0.329461	0.195214	0.00307157	0.79659	0.254494	0.289315	1000	0.05	1.33956	0.359693	0.599003	0.0489113	2.03234	0.70252	0.484414
700	0.17	0.369843	0.326101	0.176844	0.00248237	0.753636	0.24159	0.282798	1000	0.06	1.17884	0.357397	0.531702	0.0349214	1.75792	0.607543	0.44582
700	0.18	0.335522	0.322618	0.160047	0.00200452	0.716648	0.230284	0.277002	1000	0.07	1.04477	0.355012	0.475982	0.0258933	1.53263	0.534022	0.415265
700	0.19	0.304578	0.31901	0.14472	0.00162001	0.675494	0.220381	0.271845	1000	0.08	0.930248	0.352551	0.428124	0.0196568	1.3774	0.475356	0.390323
700	0.2	0.276564	0.315279	0.130711	0.00130737	0.637912	0.211633	0.26723	1000	0.09	0.831432	0.350011	0.386264	0.0152195	1.24919	0.42789	0.369668
700	0.21	0.251174	0.311436	0.117905	0.00105404	0.604016	0.203894	0.263081	1000	0.1	0.745226	0.347383	0.349104	0.011944	1.13285	0.38883	0.352289
700	0.22	0.228188	0.307472	0.10625	0.000849125	0.572074	0.19704	0.259361	1000	0.11	0.669511	0.344657	0.315824	0.00946636	1.04641	0.356319	0.337515
700	0.23	0.207361	0.30339	0.0956315	0.000683914	0.540172	0.190963	0.25601	1000	0.12	0.602507	0.341833	0.285792	0.00755059	1.0035	0.328926	0.324818
700	0.24	0.188471	0.299207	0.0859745	0.00055027	0.514165	0.185543	0.25298	1000	0.13	0.543024	0.338898	0.25861	0.00605045	0.930891	0.305688	0.313837
700	0.25	0.171298	0.29493	0.0771891	0.000442236	0.490279	0.180708	0.250232	1000	0.14	0.490023	0.335856	0.233942	0.00486824	0.869851	0.285842	0.304284
700	0.26	0.155638	0.290551	0.0691846	0.00035443	0.46804	0.176369	0.247734	1000	0.15	0.442533	0.332695	0.211482	0.00391743	0.807676	0.268692	0.295895
700	0.27	0.141436	0.28608	0.0619432	0.000283948	0.449289	0.172486	0.245459	1000	0.16	0.400033	0.329426	0.191078	0.00315756	0.790941	0.253876	0.288535
700	0.28	0.12846	0.281519	0.0553506	0.000226624	0.425593	0.168987	0.243375	1000	0.17	0.36183	0.326042	0.172485	0.00254717	0.750797	0.240991	0.282023
700	0.29	0.116646	0.276873	0.0493849	0.00018028	0.402885	0.165838	0.241472	1000	0.18	0.327358	0.322539	0.155526	0.00205104	0.711319	0.229683	0.276229
700	0.3	0.105937	0.272149	0.044022	0.000143647	0.385856	0.163012	0.239737	1000	0.19	0.296333	0.318929	0.14011	0.00165182	0.670335	0.219782	0.271073
700	0.31	0.0961617	0.267351	0.0391701	0.00011413	0.370693	0.160458	0.238141	1000	0.2	0.26834	0.315198	0.126087	0.00132906	0.633146	0.211067	0.266473
700	0.32	0.0872398	0.262489	0.0347864	0	0.356329	0.158152	0.236669	1000	0.21	0.243019	0.311357	0.113333	0.00106751	0.599613	0.203352	0.262345
700	0.33	0.0791152	0.257559	0.0308456	0	0.342135	0.156067	0.235315	1000	0.22	0.220099	0.307412	0.10174	0.000855653	0.567975	0.19651	0.258626
700	0.34	0.0716946	0.252566	0.0272953	0	0.327646	0.154173	0.234065	1000	0.23	0.19935	0.303359	0.0912182	0.00068483	0.536348	0.190429	0.255276
700	0.35	0.0649382	0.247521	0.0241132	0	0.313854	0.15246	0.232911	1000	0.24	0.18052	0.299203	0.081661	0.000546588	0.510498	0.185002	0.252245
700	0.36	0.0587938	0.242423	0.0212697	0	0.302327	0.150908	0.231843	1000	0.25	0.163438	0.29495	0.0730024	0.000435292	0.486773	0.180152	0.249489
700	0.37	0.053184	0.237281	0.0187219	0	0.292082	0.149494	0.230853	1000	0.26	0.148007	0.290594	0.0651978	0.000346617	0.464841	0.175832	0.246999
700	0.38	0.0480605	0.232096	0.0164396	0	0.280878	0.148205	0.229935	1000	0.27	0.133941	0.286149	0.0581121	0.000274763	0.445278	0.17194	0.244725
700	0.39	0.0433863	0.226871	0.0144014	0	0.26817	0.14703	0.229083	1000	0.28	0.121202	0.281612	0.0517329	0.000217414	0.424888	0.168453	0.242649
700	0.4	0.0391341	0.221616	0.0125922	0	0.255281	0.145962	0.228293	1000	0.29	0.109634	0.276991	0.0459836	0.00017143	0.404331	0.165314	0.240749
700	0.41	0.0352722	0.216337	0.0109905	0	0.246658	0.144988	0.227559	1000	0.3	0.0990979	0.272294	0.0407912	0.00013467	0.384466	0.162474	0.239005
700	0.42	0.0317531	0.211032	0.00956675	0	0.237501	0.1441	0.226875	1000	0.31	0.0895467	0.26752	0.0361336	0.000105558	0.367805	0.159916	0.237409
700	0.43	0.0285549	0.205707	0.00830948	0	0.227852	0.143291	0.22624	1000	0.32	0.0808812	0.262672	0.0319576	0	0.354232	0.15761	0.235943
700	0.44	0.0256505	0.200367	0.00720247	0	0.218472	0.142555	0.225648	1000	0.33	0.0729865	0.257752	0.028202	0	0.340394	0.155516	0.234588
700	0.45	0.0230042	0.195016	0.00622261	0	0.211149	0.14188	0.225094	1000	0.34	0.0658381	0.252773	0.0248526	0	0.32613	0.153627	0.233339
700	0.46	0.0206088	0.189659	0.00536784	0	0.203462	0.141266	0.224579	1000	0.35	0.0593534	0.24774	0.0218644	0	0.312305	0.151917	0.232187
700	0.47	0.0184371	0.184305	0.00461755	0	0.193263	0.140705	0.224098	1000	0.36	0.0534345	0.242648	0.0191816	0	0.300595	0.15035	0.23112
700	0.48	0.0164685	0.178953	0.00395984	0	0.184528	0.140192	0.223651	1000	0.37	0.0480904	0.237508	0.0168079	0	0.290465	0.148936	0.23013
700	0.49	0.0146954	0.173603	0.00339197	0	0.17742	0.139723	0.223235	1000	0.38	0.043242	0.232323	0.0146969	0	0.279485	0.14765	0.229213
700	0.5	0.0130821	0.168269	0.00289159	0	0.1702	0.139291	0.222845	1000	0.39	0.0388436	0.227099	0.0128232	0	0.267057	0.14648	0.228365
700	0.51	0.0116199	0.162952	0.00245495	0	0.162878	0.138894	0.222479	1000	0.4	0.0348627	0.221838	0.0111693	0	0.254385	0.145416	0.227578
700	0.52	0.0103006	0.157653	0.00207853	0	0.155461	0.138529	0.222137	1000	0.41	0.0312476	0.216542	0.00970278	0	0.245628	0.144445	0.226843
700	0.53	0.0091172	0.152373	0.00175797	0	0.14865	0.138198	0.221818	1000	0.42	0.0279685	0.211219	0.00840448	0	0.236505	0.143556	0.226158
700	0.54	0.00804896	0.147125	0.00147903	0	0.142326	0.137896	0.221523	1000	0.43	0.025004	0.205876	0.00726341	0	0.227047	0.142747	0.225522
700	0.55	0.00708584	0.141913	0.00123738	0	0.135811	0.137616	0.221247	1000	0.44	0.022328	0.200516	0.00626447	0	0.217614	0.142008	0.22493
700	0.56	0.00622815	0.136728	0.00103514	0	0.128866	0.13736	0.22099	1000	0.45	0.0199072	0.195143	0.00538629	0	0.209036	0.141332	0.224375
700	0.57	0.00545587	0.131592	0.000859692	0	0.122174	0.137124	0.22075	1000	0.46	0.0177311	0.18976	0.00462535	0	0.200618	0.140716	0.223858
700	0.58	0.00476481	0.126503	0.000709713	0	0.115727	0.136909	0.220526	1000	0.47	0.0157624	0.184373	0.00395738	0	0.192007	0.140151	0.223377
700	0.59	0.00415106	0.121462	0.000583949	0	0.109512	0.136713	0.220318	1000	0.48	0.0139824	0.178988	0.00337234	0	0.18399	0.139633	0.222928
700	0.6	0.00361091	0.116466	0.000481224	0	0.103521	0.136535	0.220125	1000	0.49	0.0123819	0.173606	0.00286701	0	0.176558	0.139159	0.22251
700	0.61	0.00313234	0.111516	0.000395915	0	0.0987924	0.136371	0.219943	1000	0.5	0.010941	0.168237	0.00242644	0	0.169532	0.138724	0.222119
700	0.62	0.00270273	0.106636	0.000321888	0	0.0940419	0.136217	0.219773	1000	0.51	0.00965083	0.162883	0.00204701	0	0.162891	0.138325	0.221754
700	0.63	0.00232052	0.101826	0.000258944	0	0.0888425	0.136075	0.219615	1000	0.52	0.00850324	0.157544	0.00172533	0	0.156615	0.13796	0.221413
700	0.64	0.0019903	0.0970669	0.000209454	0	0.0824631	0.135944	0.219471	1000	0.53	0.00748234	0.152221	0.00145363	0	0.150381	0.13763	0.221097
700	0.65	0.0016971	0.09239	0.000167397	0	0.0763778	0.135822	0.219336	1000	0.54	0.00656094	0.146929	0.00121609	0	0.143788	0.137328	0.220802
700	0.66	0.00143827	0.0877947	0.00013201	0	0.0706895	0.13571	0.219209	1000	0.55	0.00573535	0.141673	0.00101126	0	0.136946	0.137048	0.220526
700	0.67	0.00121235	0.0832786	0.000103	0	0.0653816	0.135606	0.219089	1000	0.56	0.00500765	0.136446	0.000841468	0	0.129317	0.136791	0.220267
700	0.68	0.00101793	0.0788391	0	0	0.0604386	0.13551	0.218977	1000	0.57	0.00435469	0.1312					



spectra of events in a detector

1. Production

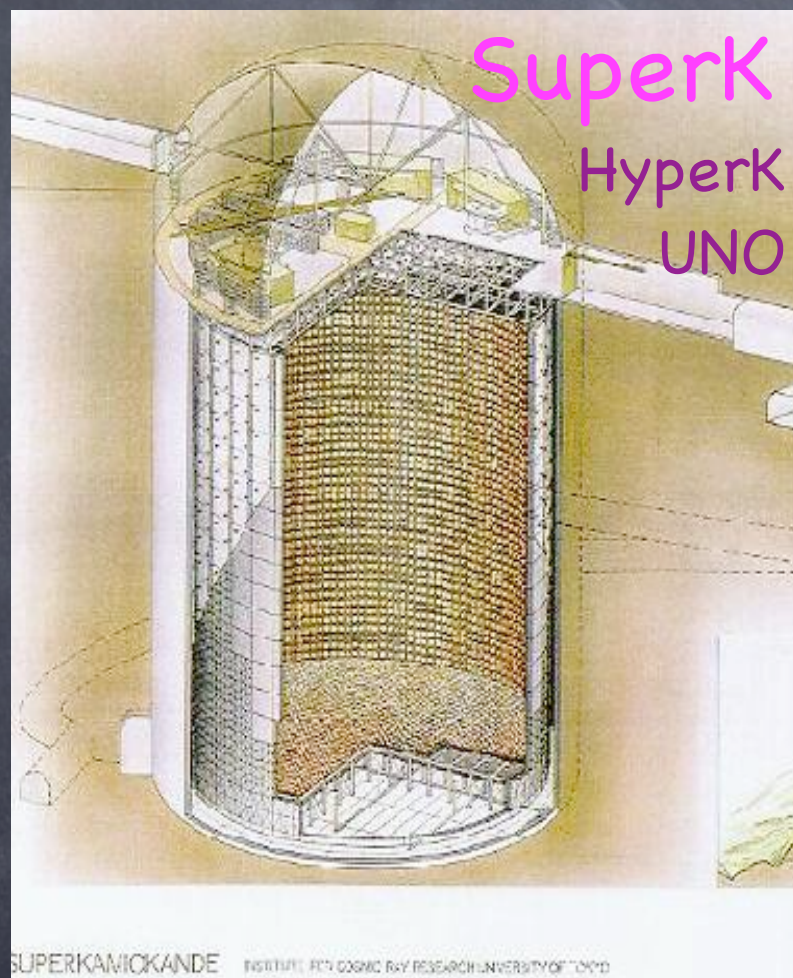
2. Propagation

3. Detection

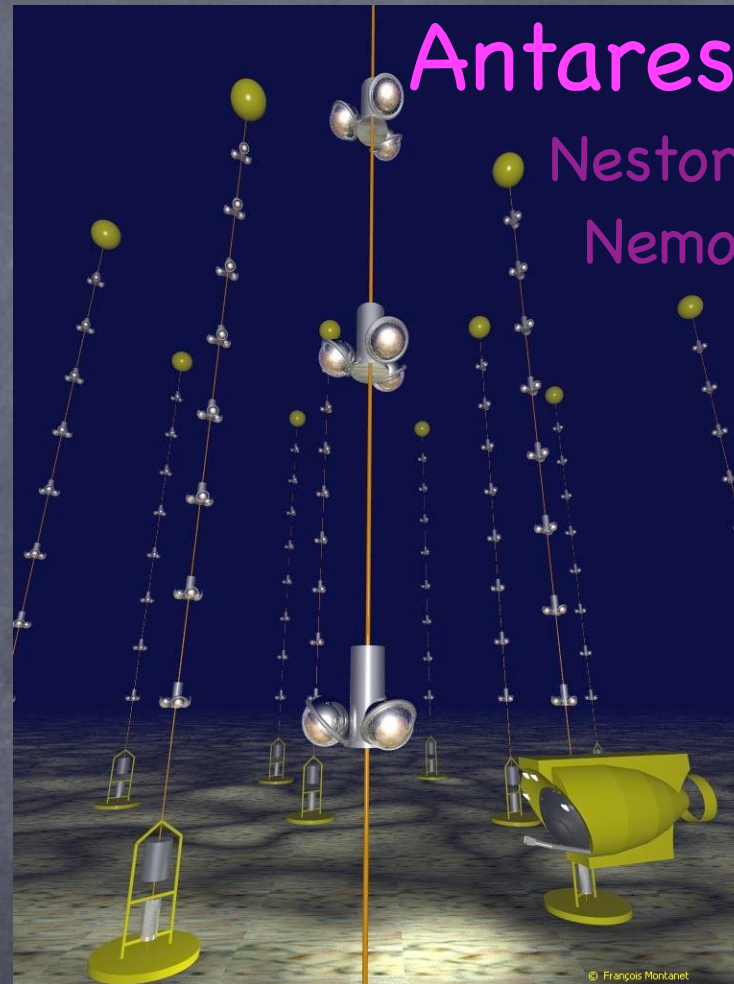
3. Detection: where

“Neutrino Telescopes”

UnderGround



UnderWater



UnderIce



Size:

“small”

Energy thres:

GeV

Energy resol:

GeV

Angle resol:

degree

large

tens GeV

10 GeV

few degrees

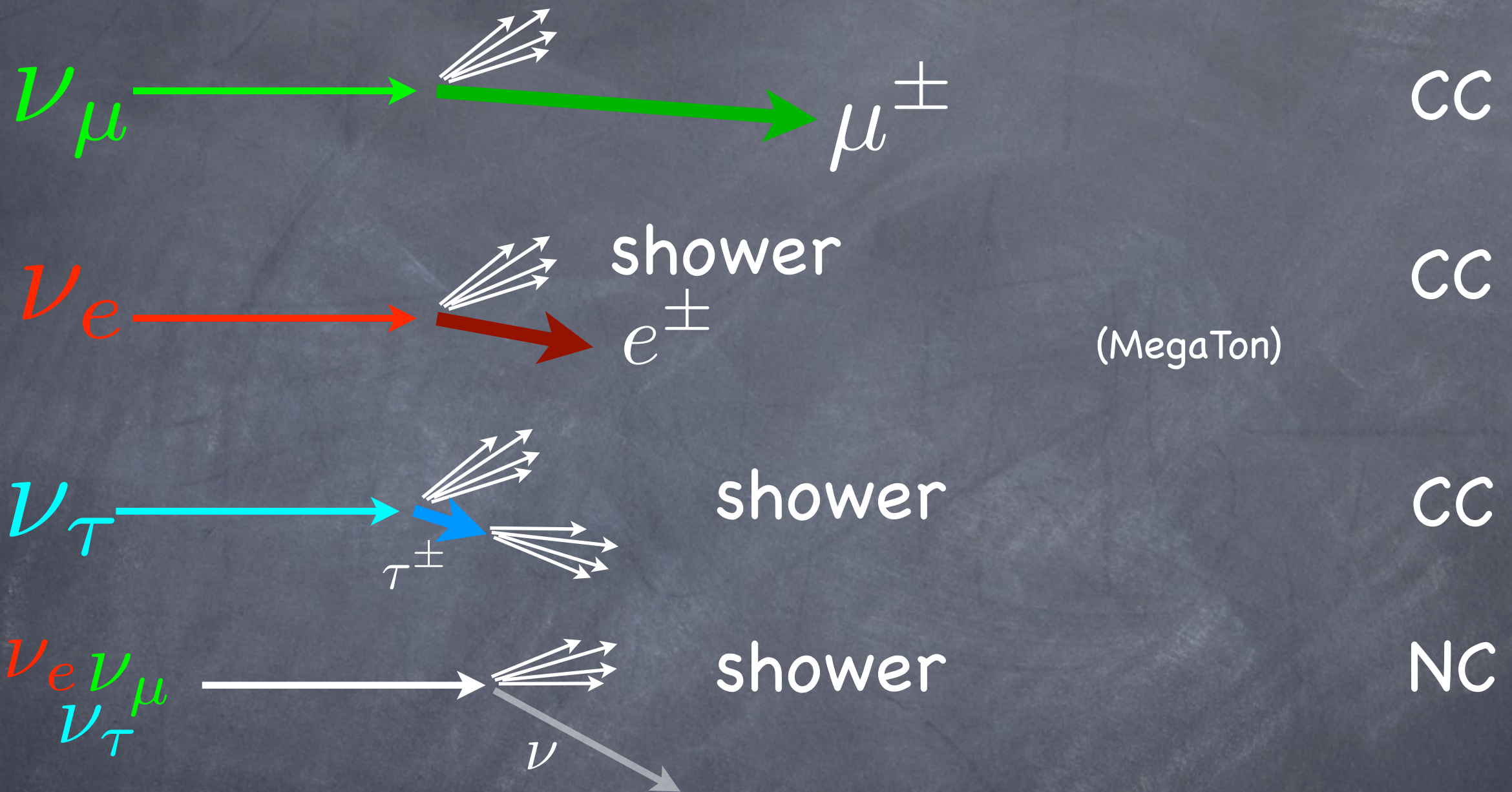
large/huge

100 GeV

tens GeV

tens degrees

3. Detection: what

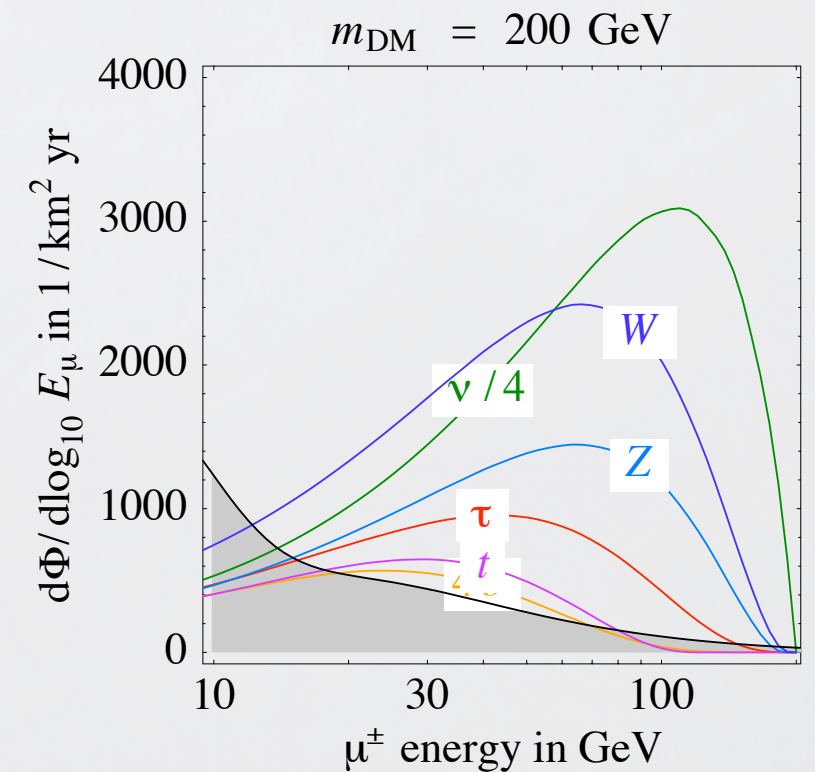
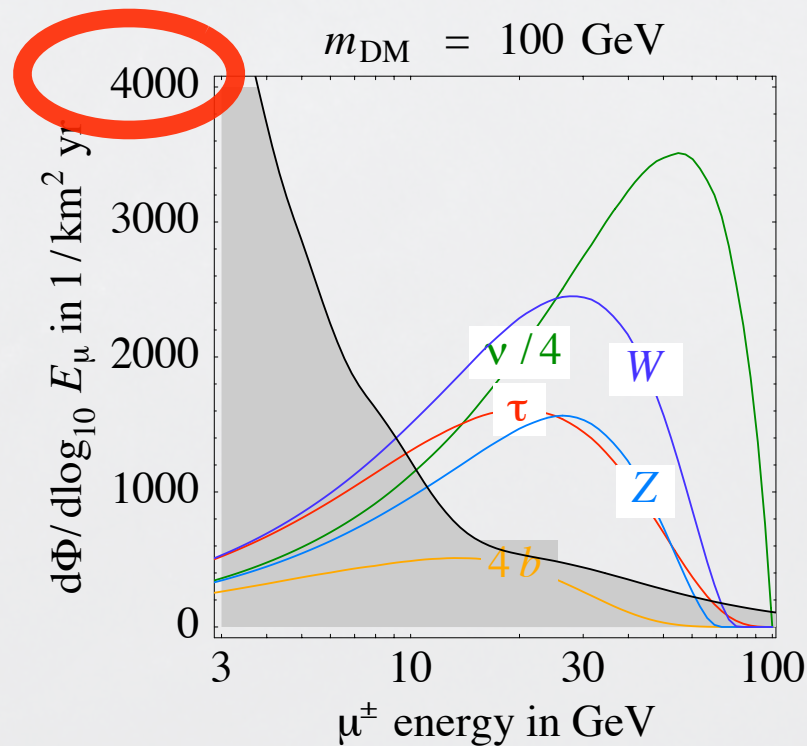
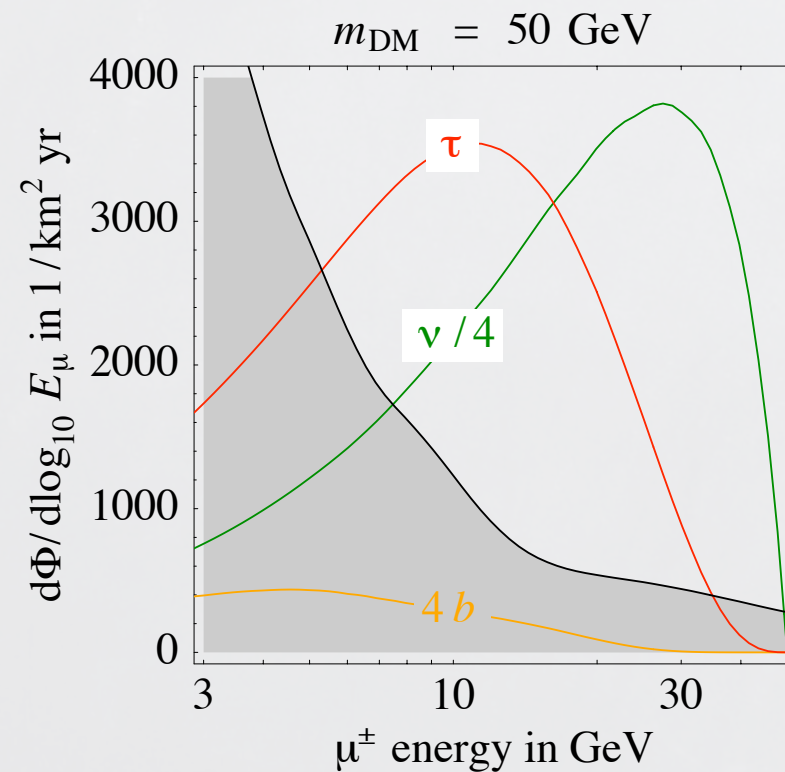
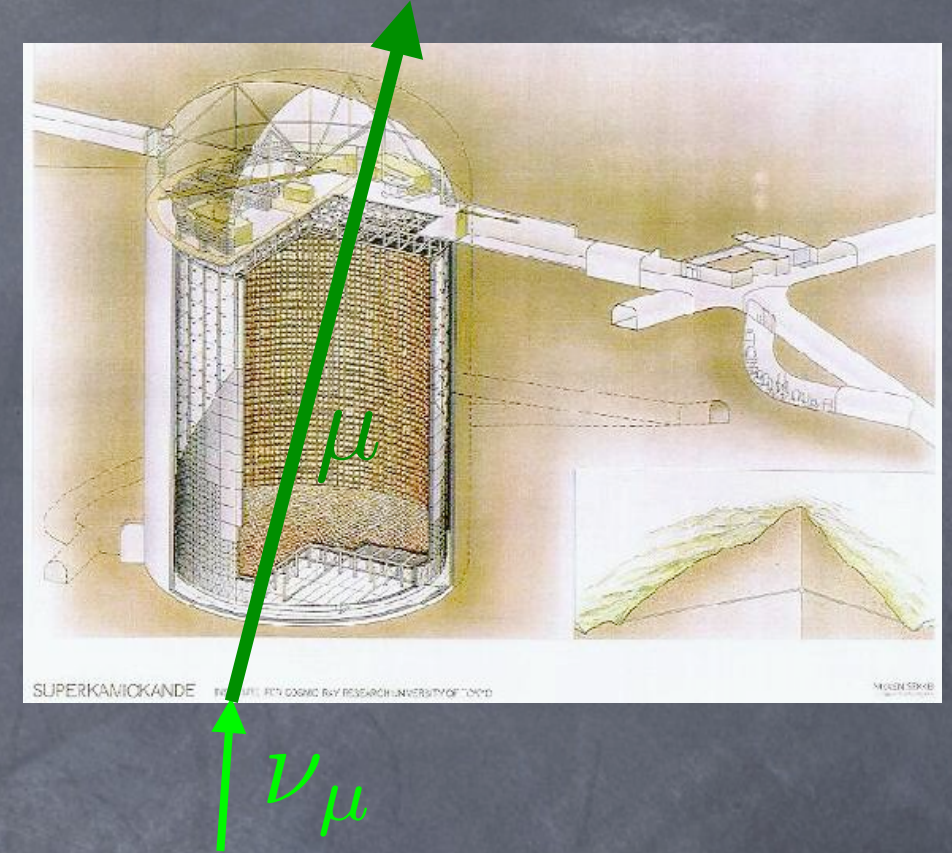


Typologies: **muons**, (**electrons**) or showers

Pros/Cons: energy reconstruction, angle reconstruction

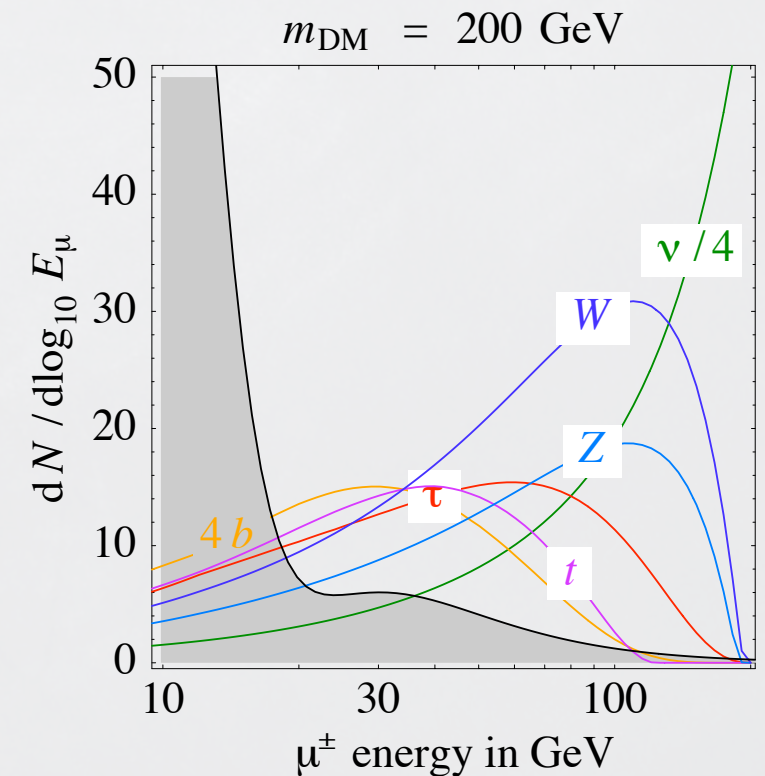
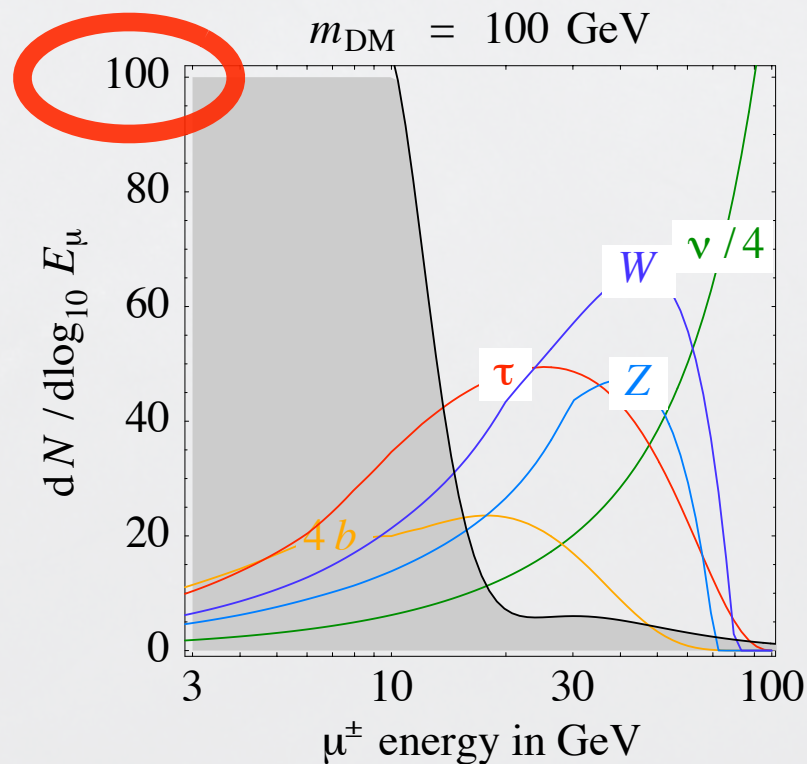
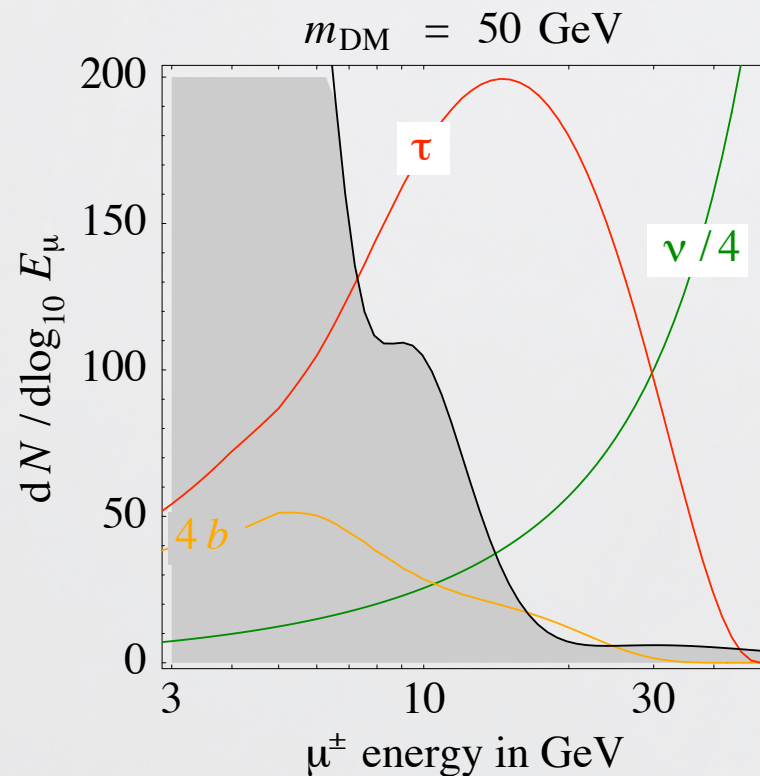
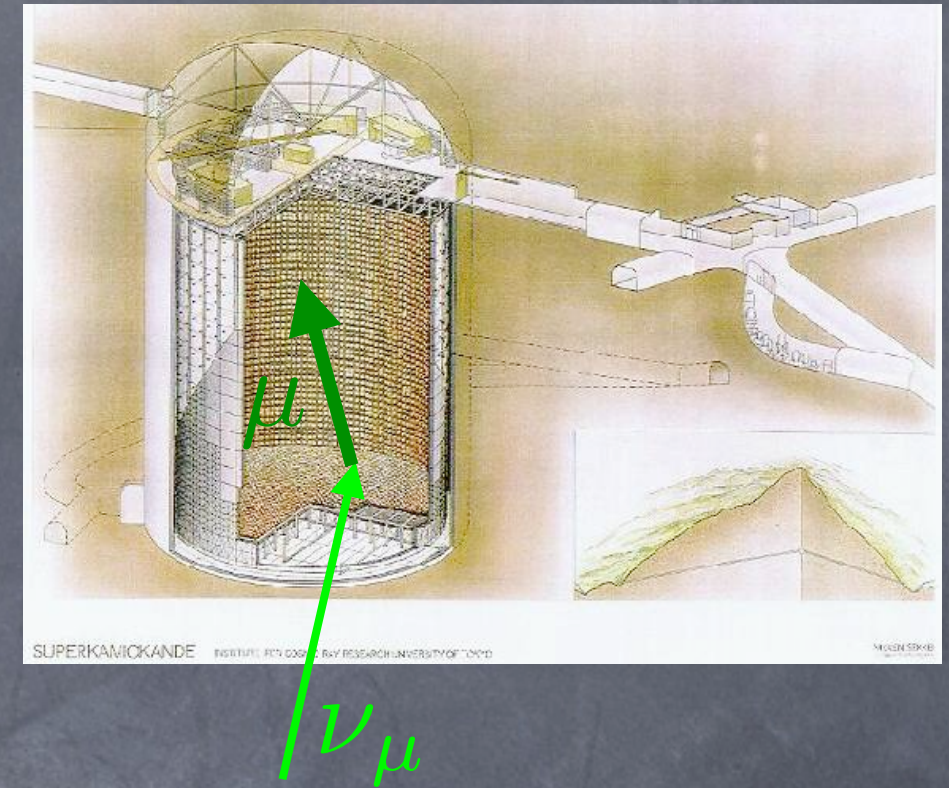
3. Detection: what

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



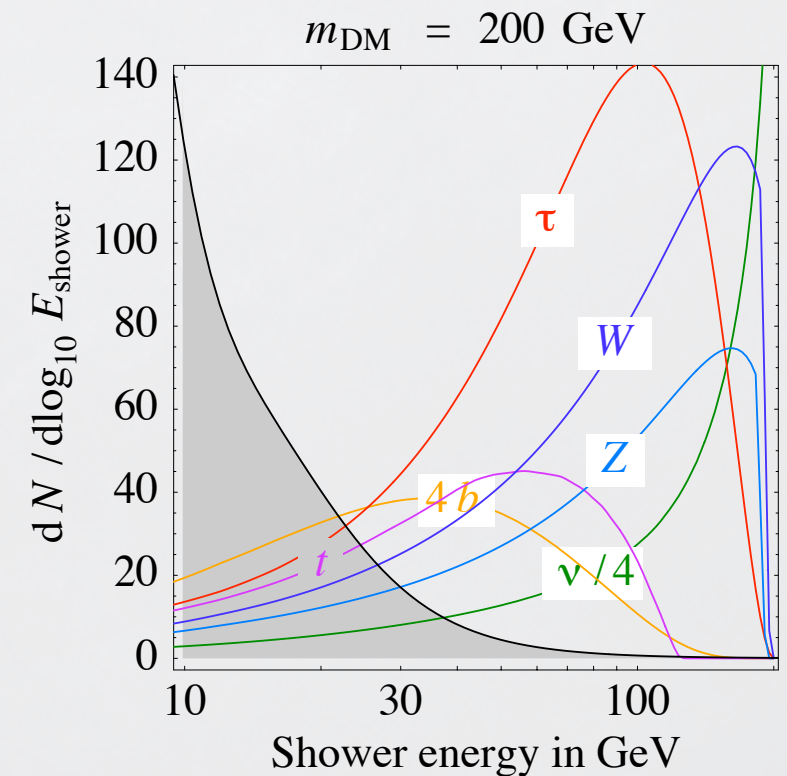
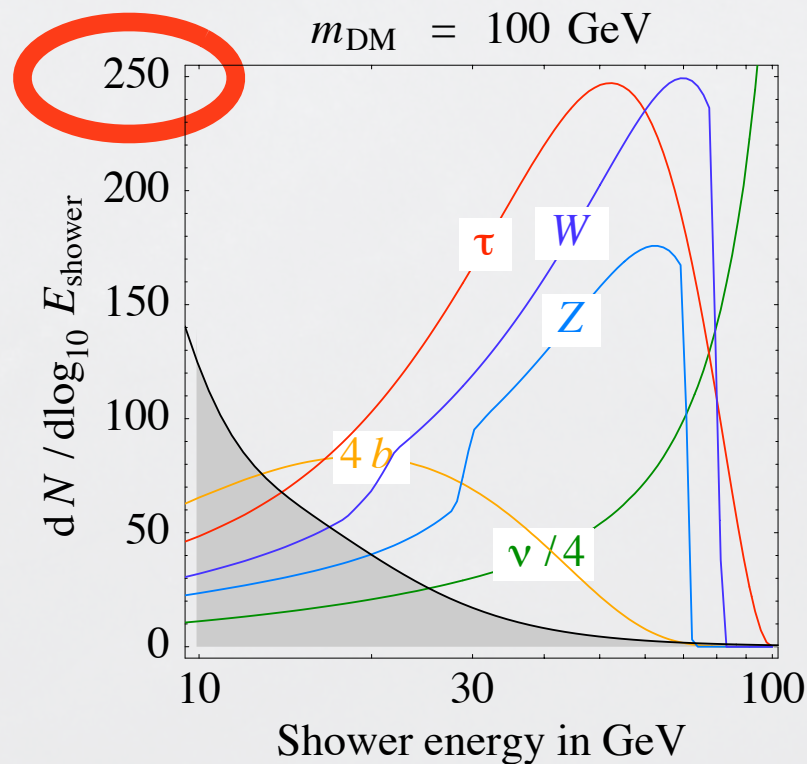
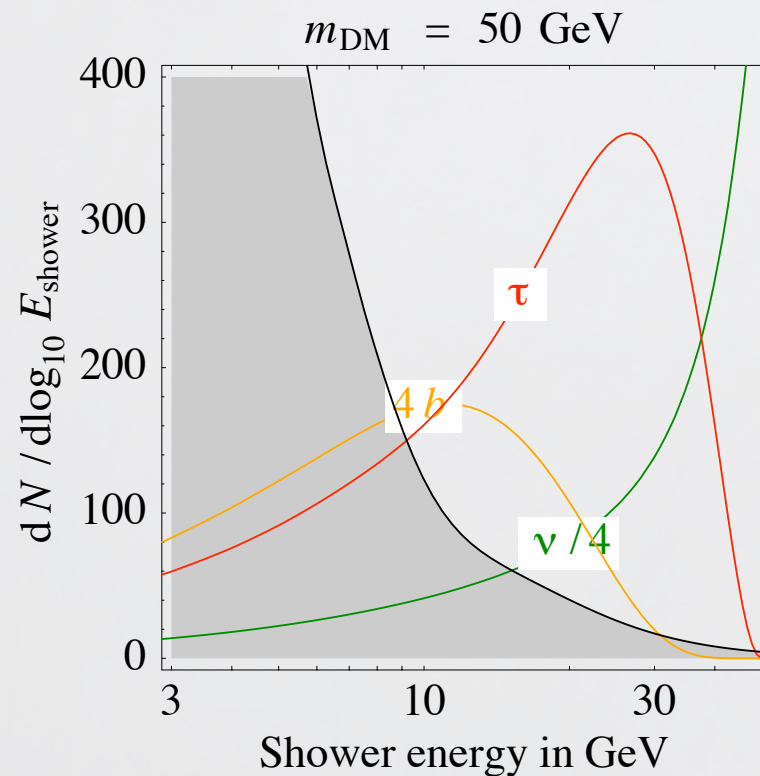
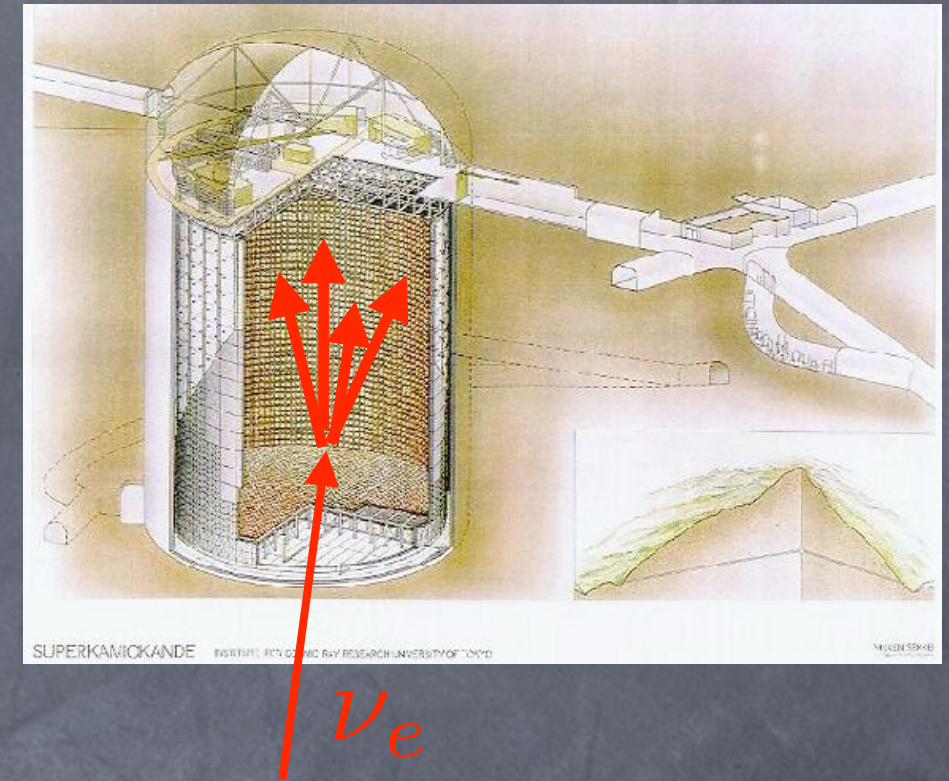
3. Detection: what

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



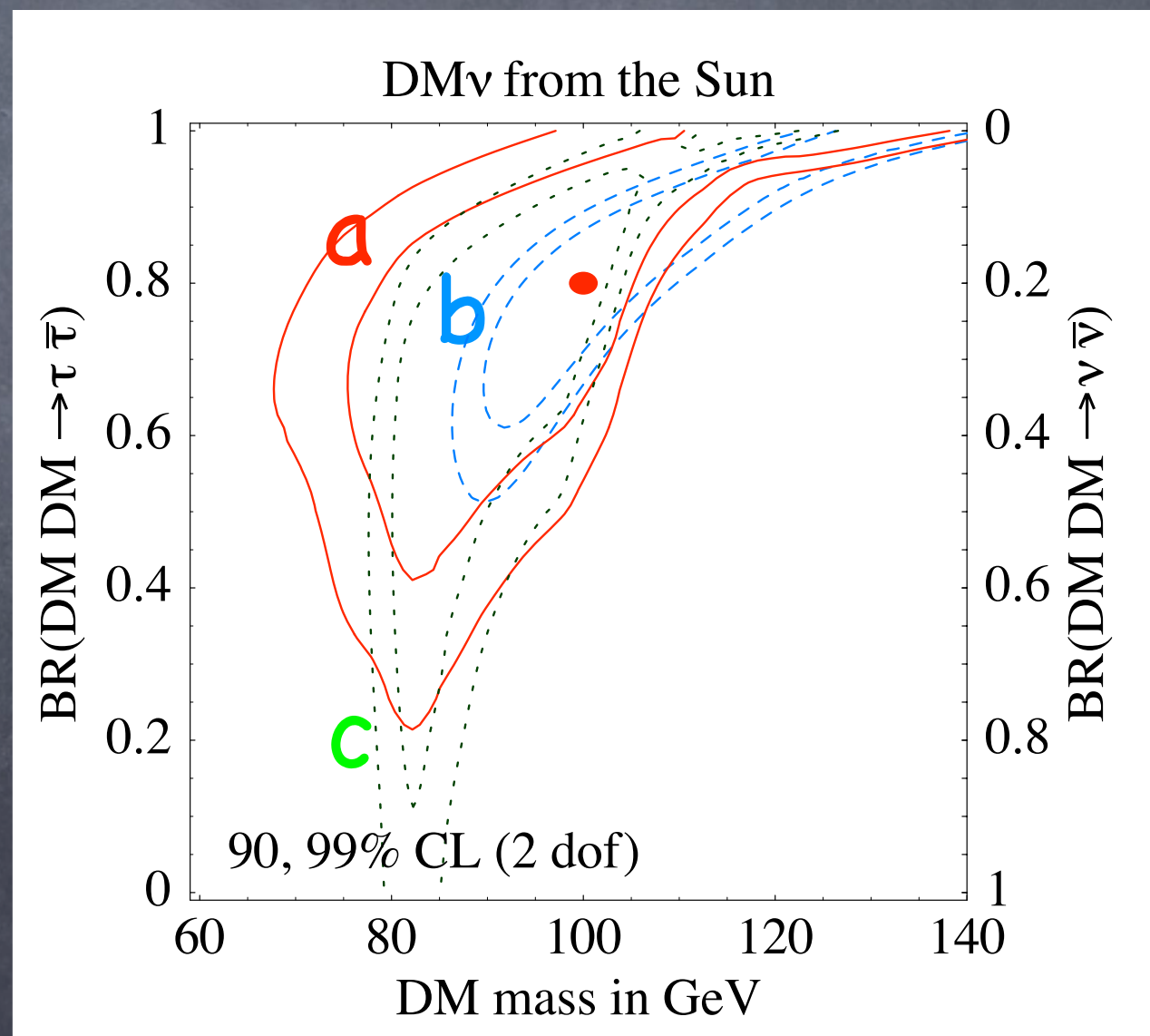
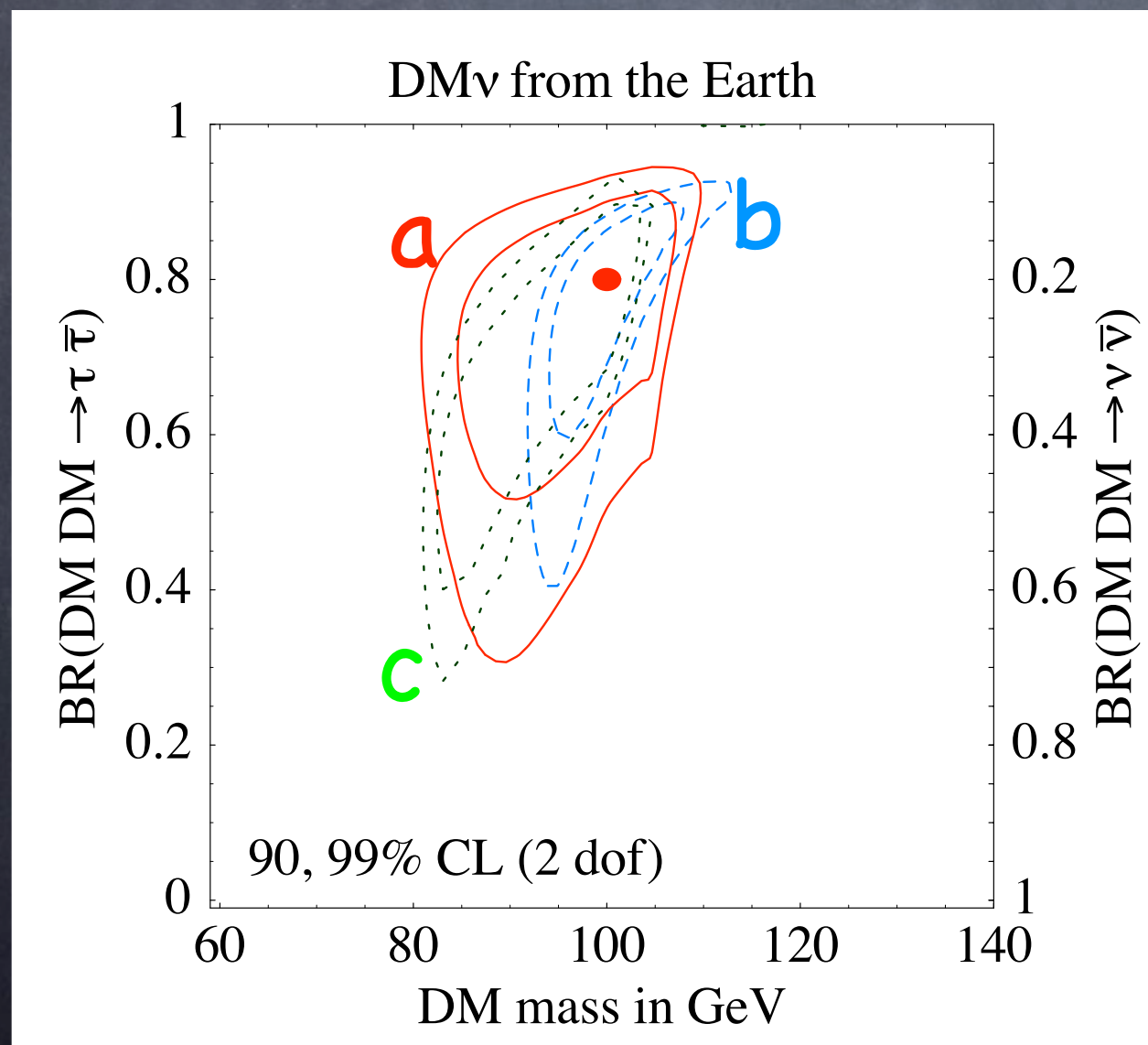
3. Detection: what

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

ν from DM carry precious insight
on the properties of DM.

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on the properties of DM.

We have the formalism to compute spectra,
including everything.

Take-home message

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We have the formalism to compute spectra,
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Now: – go out and discover DM

Take-home message

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Now:

- go out and discover DM
- consider topologies besides thru- μ
(i.e. showers, contained muons)

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ν from DM carry precious insight
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We have the formalism to compute spectra,
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- then, focus on reconstruction via
neutrino spectra.

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Now:

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Take-home message

ν from DM carry precious insight
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We have the formalism to compute spectra,
including everything.

Now:

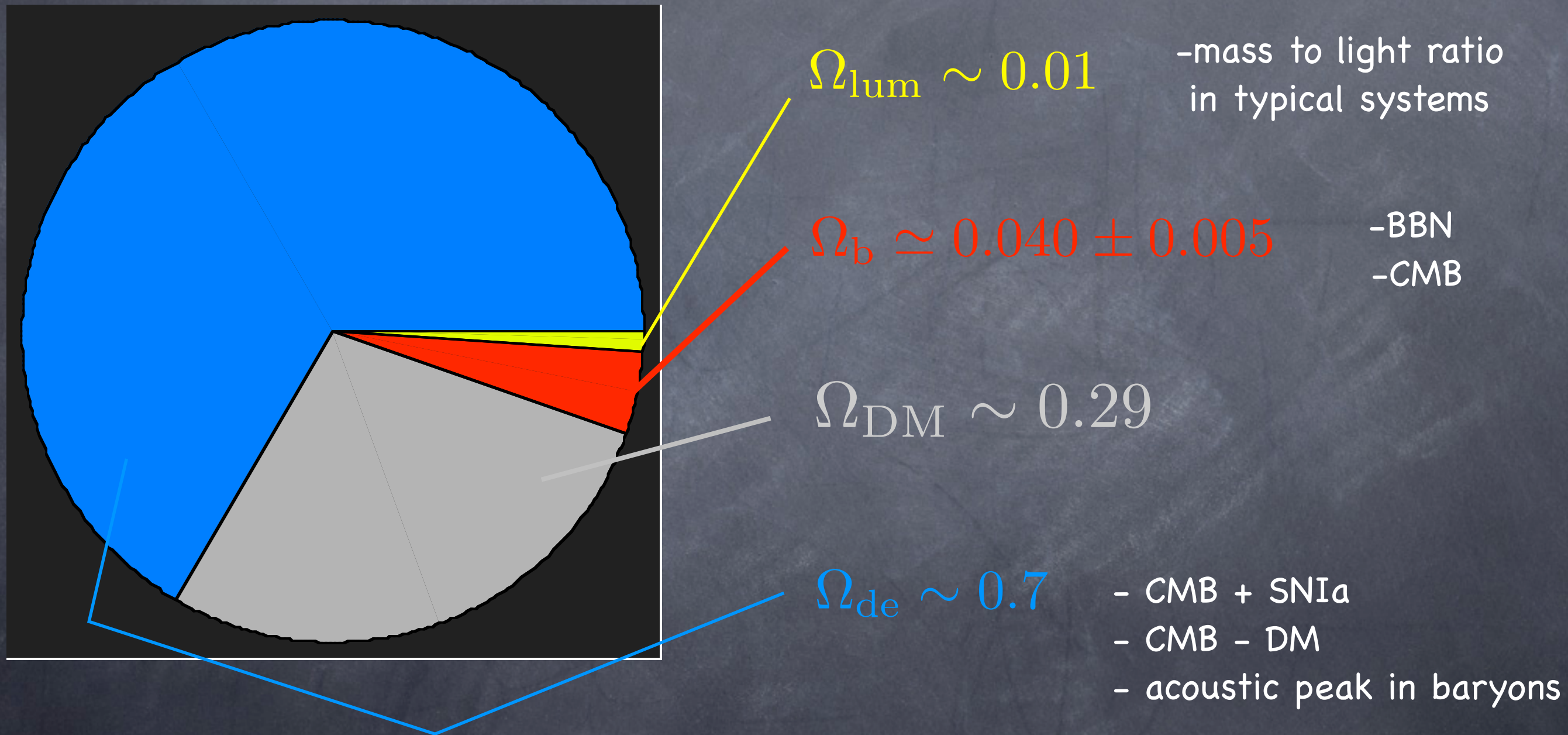
- go out and discover DM
- consider topologies besides thru- μ
(i.e. showers, contained muons)
- then, focus on reconstruction via
neutrino spectra.

THE END

Back-up slides

The cosmic inventory

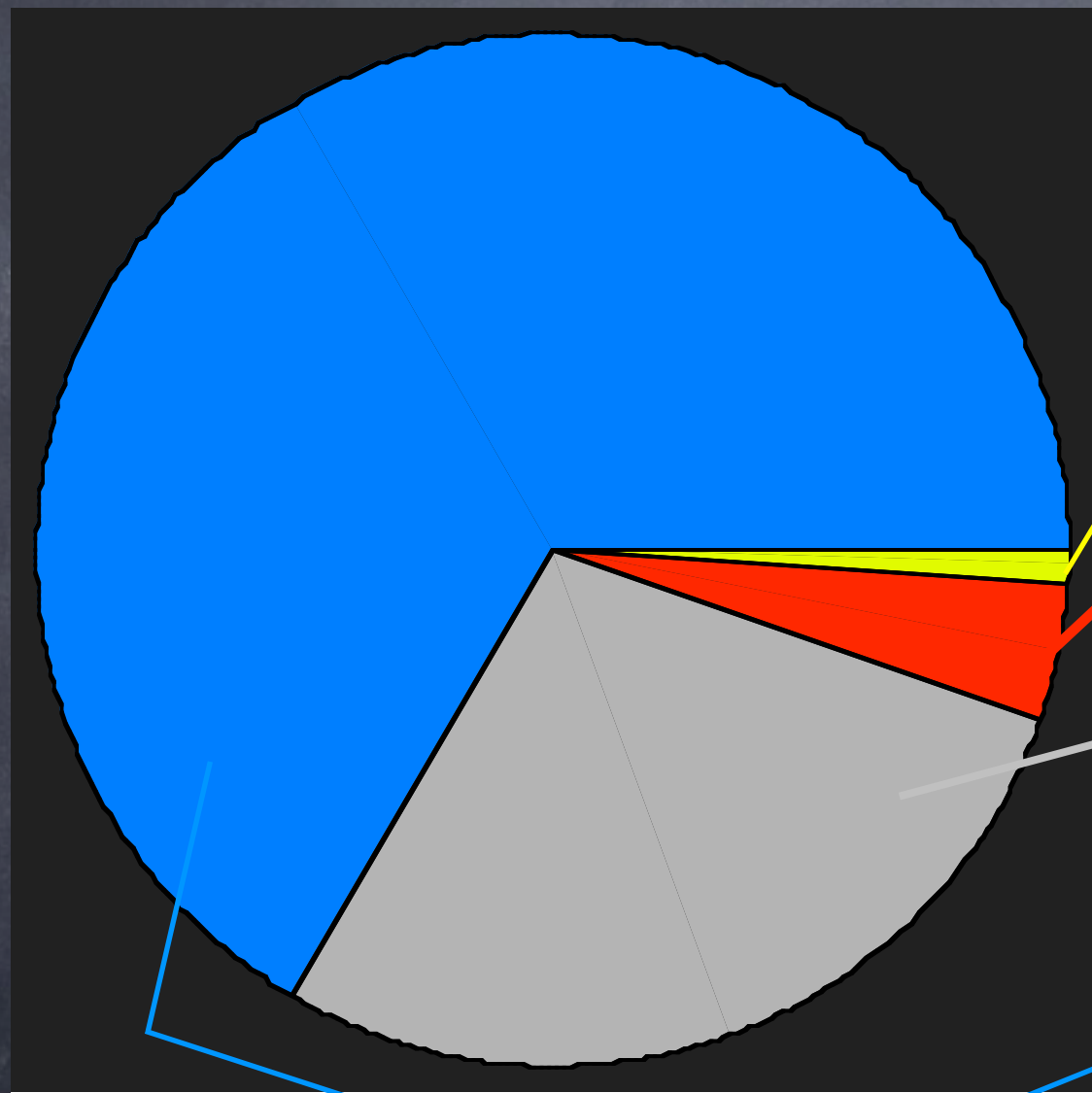
most of the Universe is Dark



$\left(\Omega_x = \frac{\rho_x}{\rho_c}; \text{CMB first peak} \Rightarrow \Omega_{tot} = 1 \text{ (flat)}; \right.$
 $\left. \text{HST } h = 0.71 \pm 0.07 \right)$

The cosmic inventory

most of the Universe is Dark



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

-mass to light ratio
in typical systems

$$\Omega_b \simeq 0.040 \pm 0.005$$

-BBN
-CMB

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

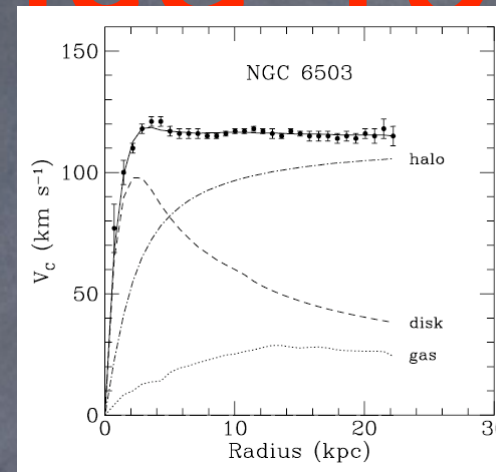
$$\Omega_{de} \sim 0.7$$

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

$\left(\Omega_x = \frac{\rho_x}{\rho_c}; \text{CMB first peak} \Rightarrow \Omega_{tot} = 1 \text{ (flat)}; \right.$
 $\left. \text{HST } h = 0.71 \pm 0.07 \right)$

The Evidence for DM

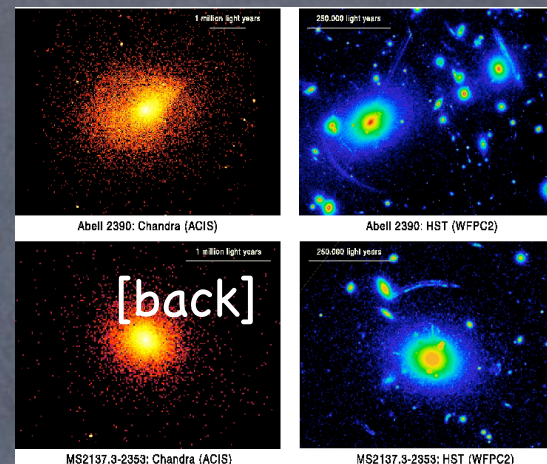
1) galaxy rotation curves



$$\Omega_M \gtrsim 0.1$$

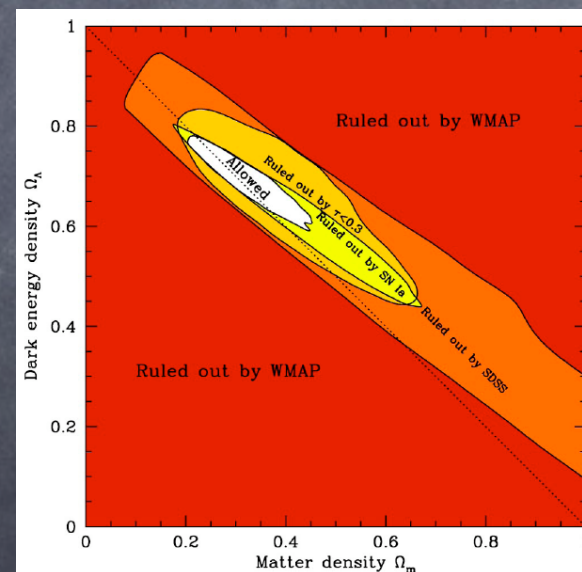
details

2) clusters of galaxies



details

3) CMB+LSS+SNIa



details

$$\Omega_M \approx 0.30 \pm 0.04$$



DM is there.
What is DM?

[back]

The case for a WIMP

A **Weakly Interacting, Massive Particle**
has

the correct relic abundance today!

Boltzmann equ. in the Early Universe

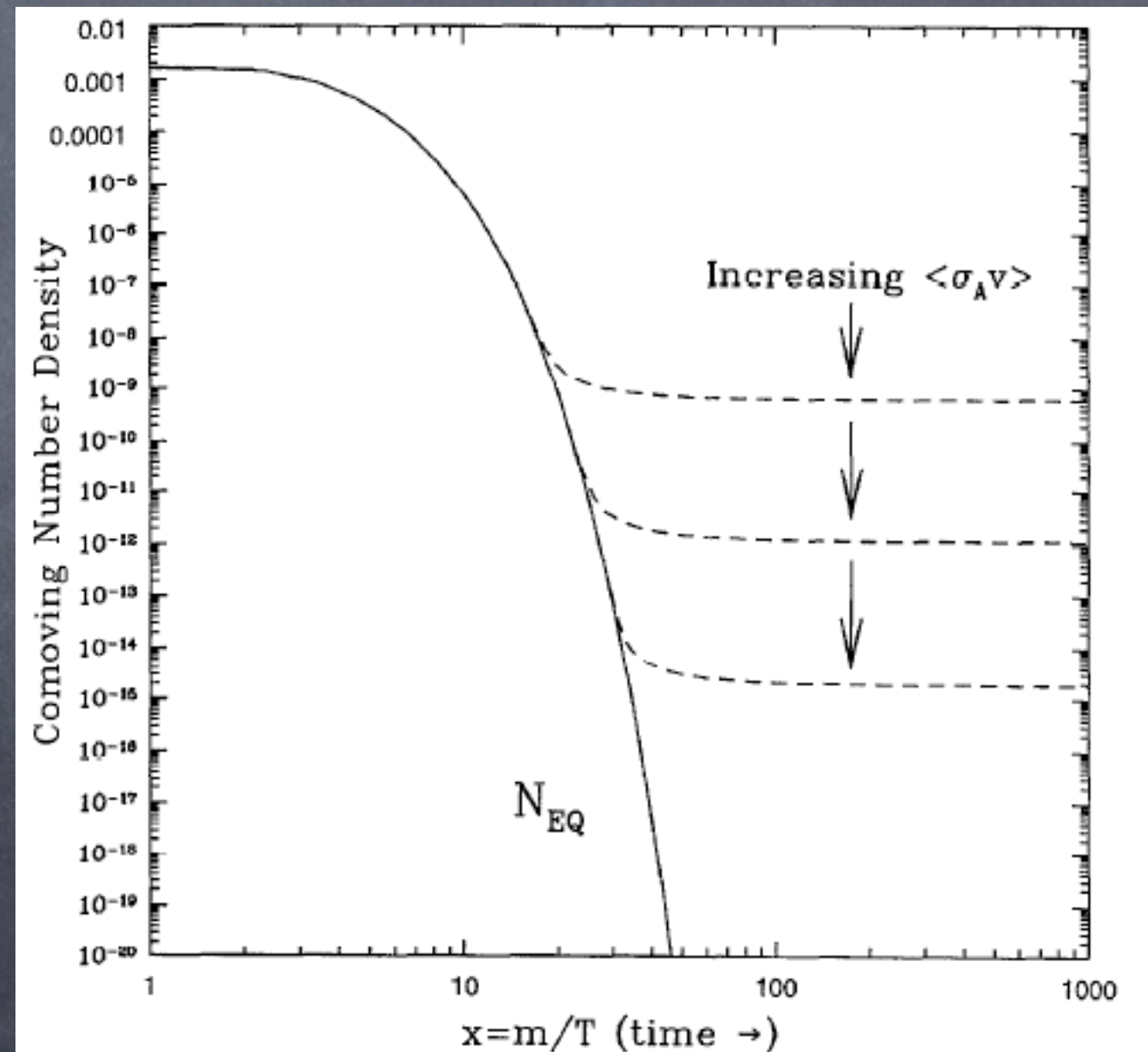
$$\Omega_X \approx \frac{6 \cdot 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle}$$

Weak cross section:

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



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



The case for SUSY neutralino

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

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

[details]

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....)

The Evidence for DM

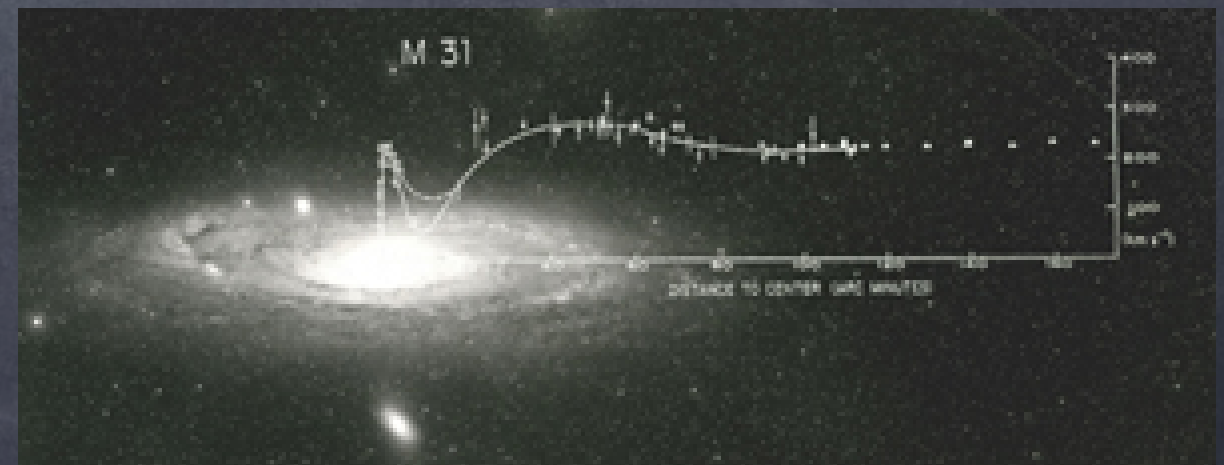
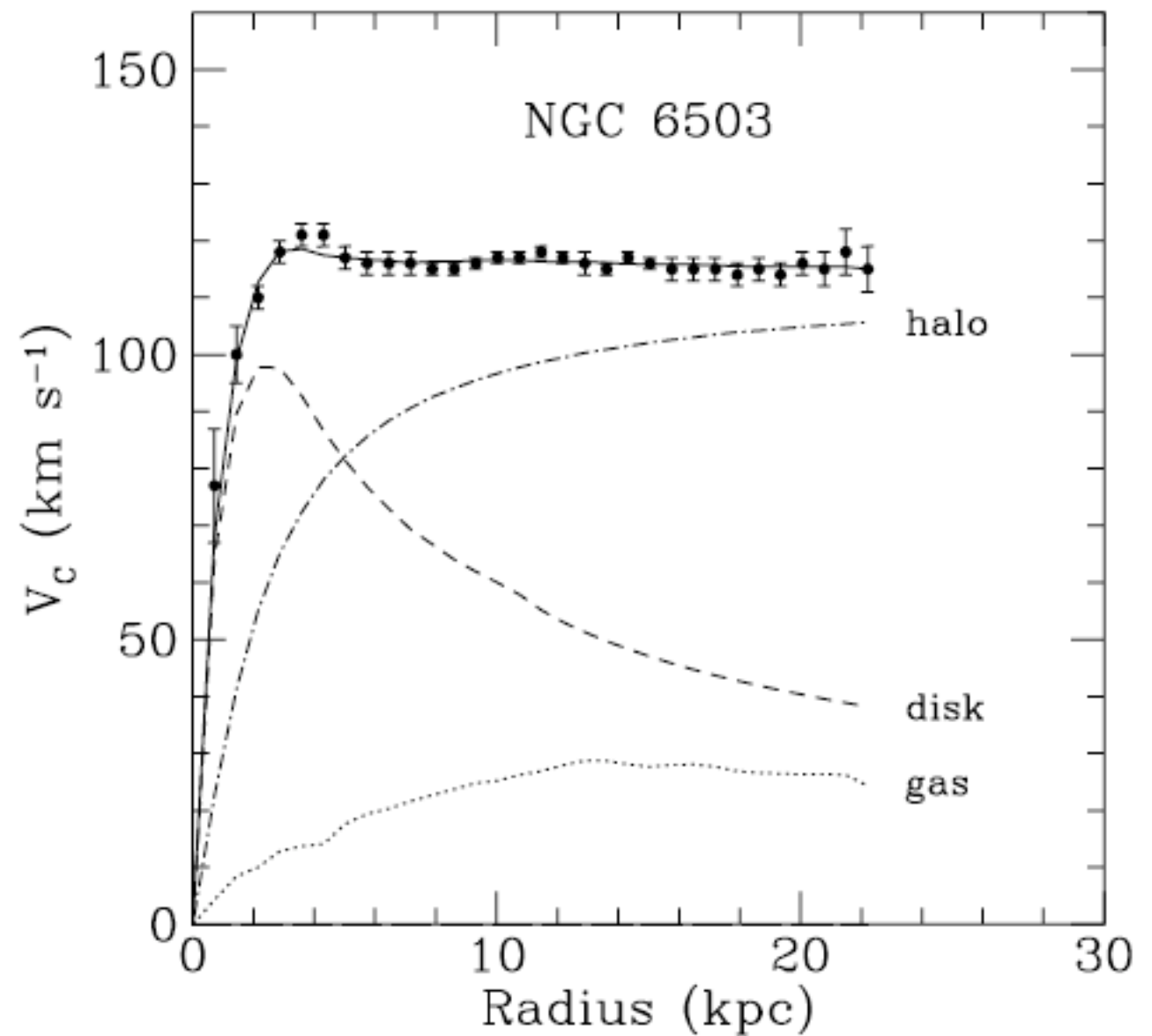
1) galaxy rotation curves

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

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

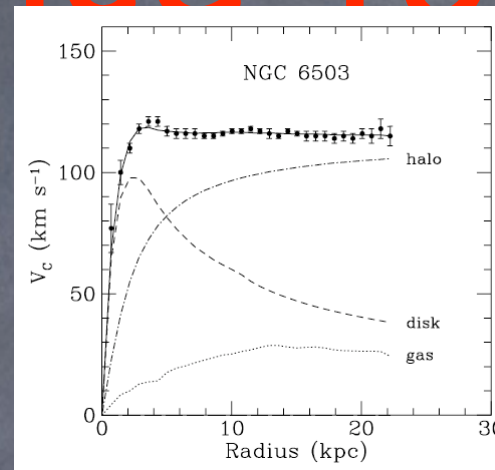


$$\Omega_M \gtrsim 0.1$$



The Evidence for DM

1) galaxy rotation curves



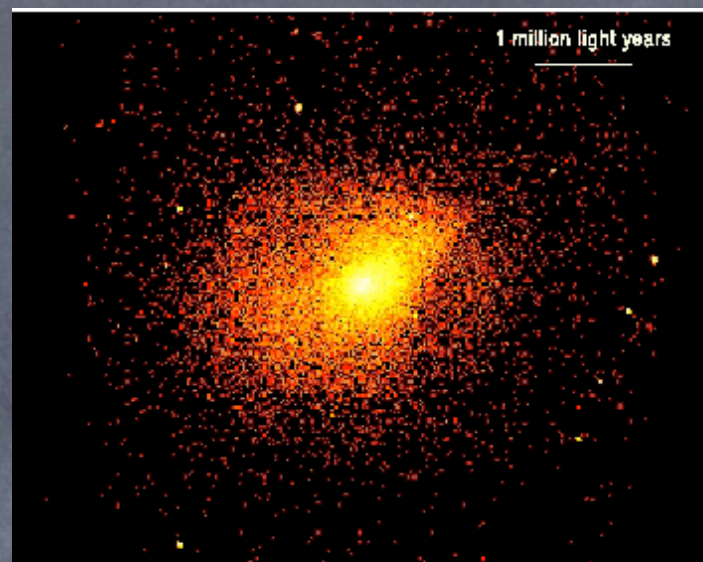
$$\Omega_M \gtrsim 0.1$$

2) clusters of galaxies

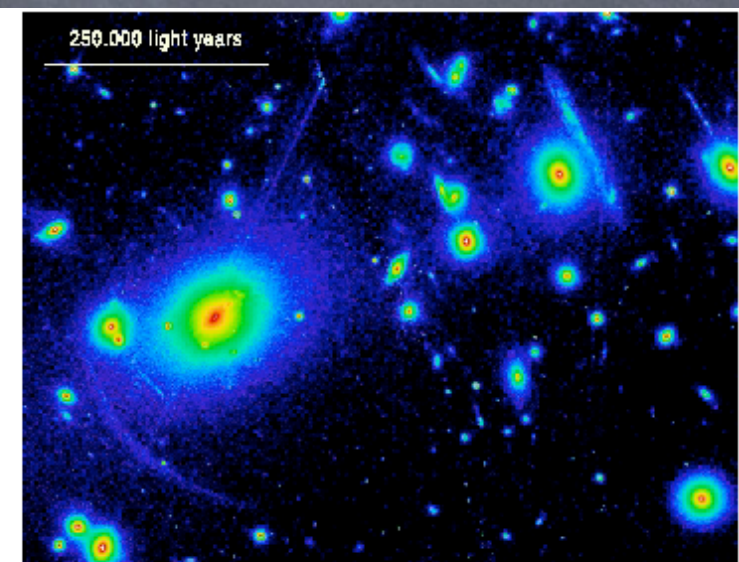
- "rotation curves"
- gravitation lensing
- X-ray gas Temperature



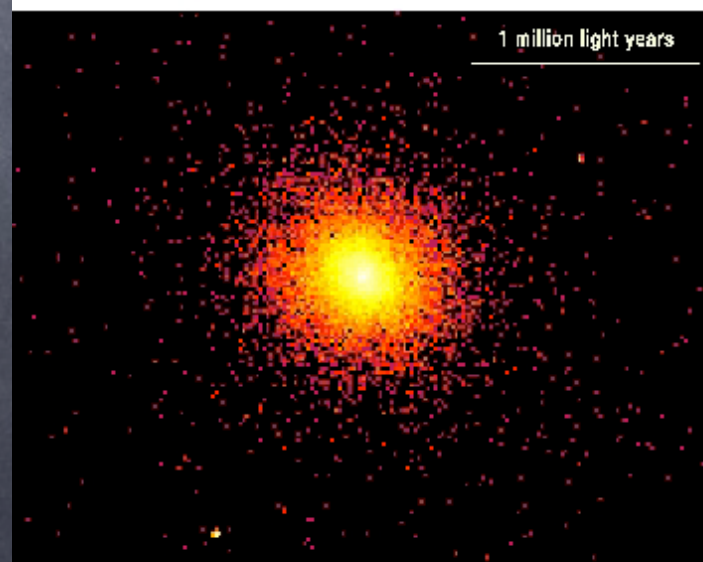
$$\Omega_M \sim 0.2 \div 0.4$$



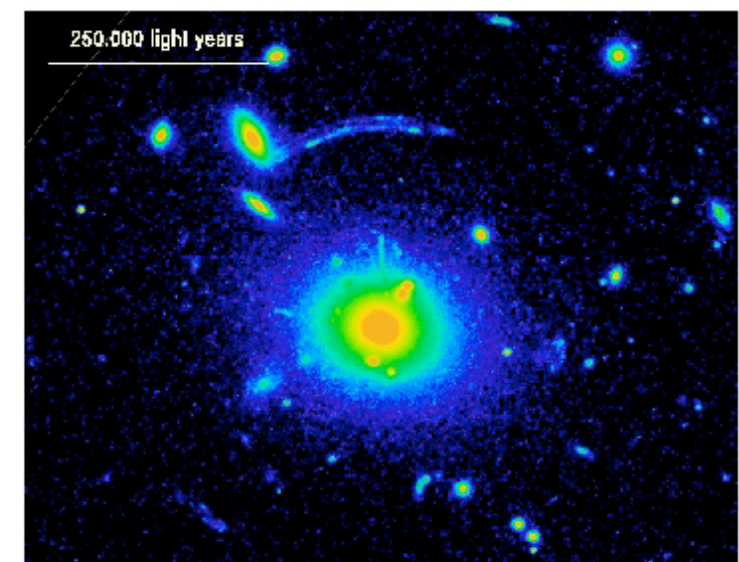
Abell 2390: Chandra (ACIS)



Abell 2390: HST (WFPC2)



MS2137.3-2353: Chandra (ACIS)



MS2137.3-2353: HST (WFPC2)

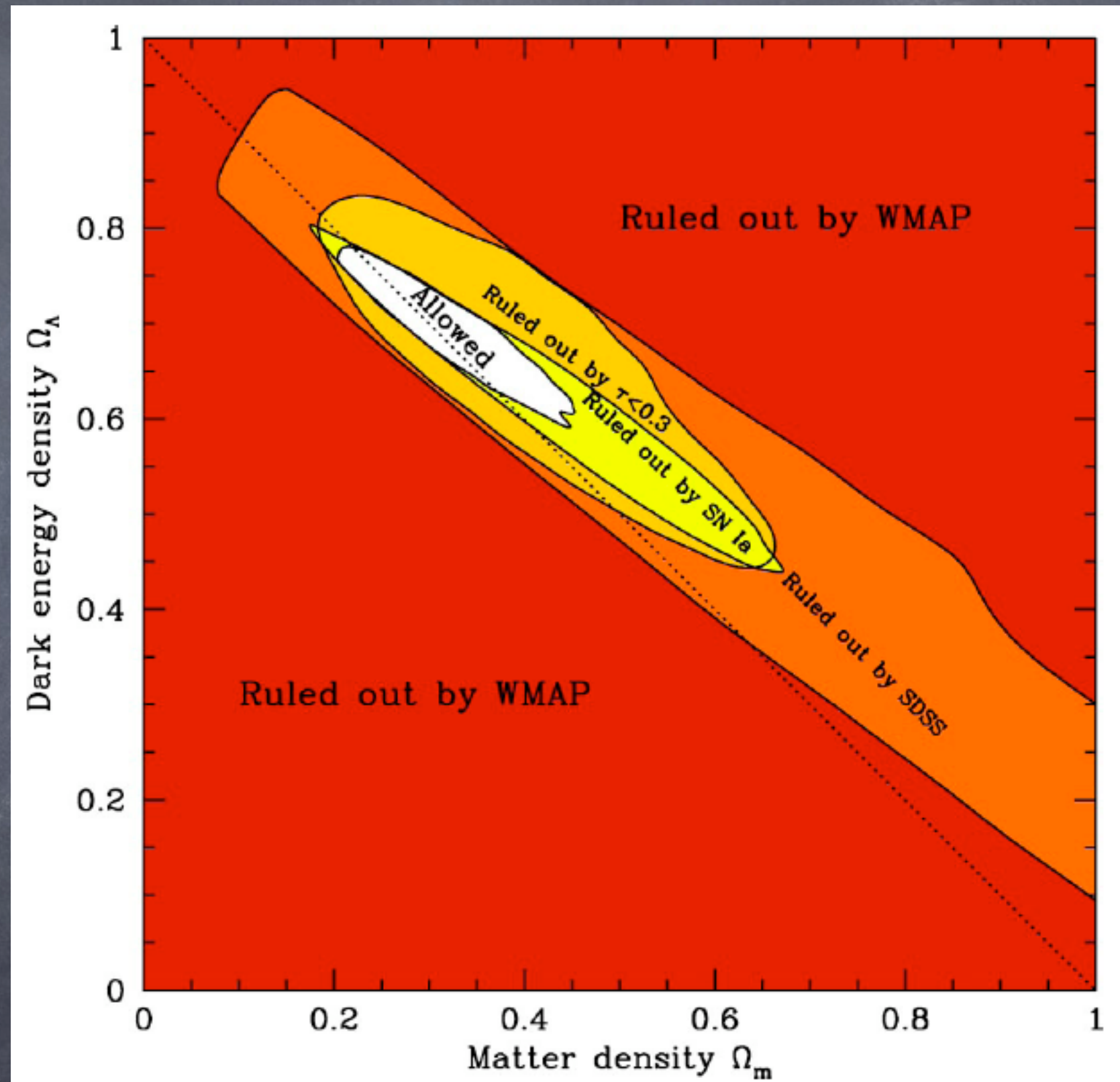
The Evidence for DM

1) galaxy rotation curves

2) clusters of galaxies

3) CMB+LSS+SN Ia:

$\Omega_M \approx 0.30 \pm 0.04$



M. Tegmark et al., PRD69 (2004)

Relic abundance calculation

The result for the relic abundance is

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

where

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

The freezeout epoch $x_f = m_\chi/T_f$ is determined by

$$x_f = \ln [0.0764 m_{\text{Pl}} (a + 6b/x_f) c(2 + c) m_\chi / (g_* x_f)^{1/2}]$$

which can be solved iteratively to the required precision. H

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

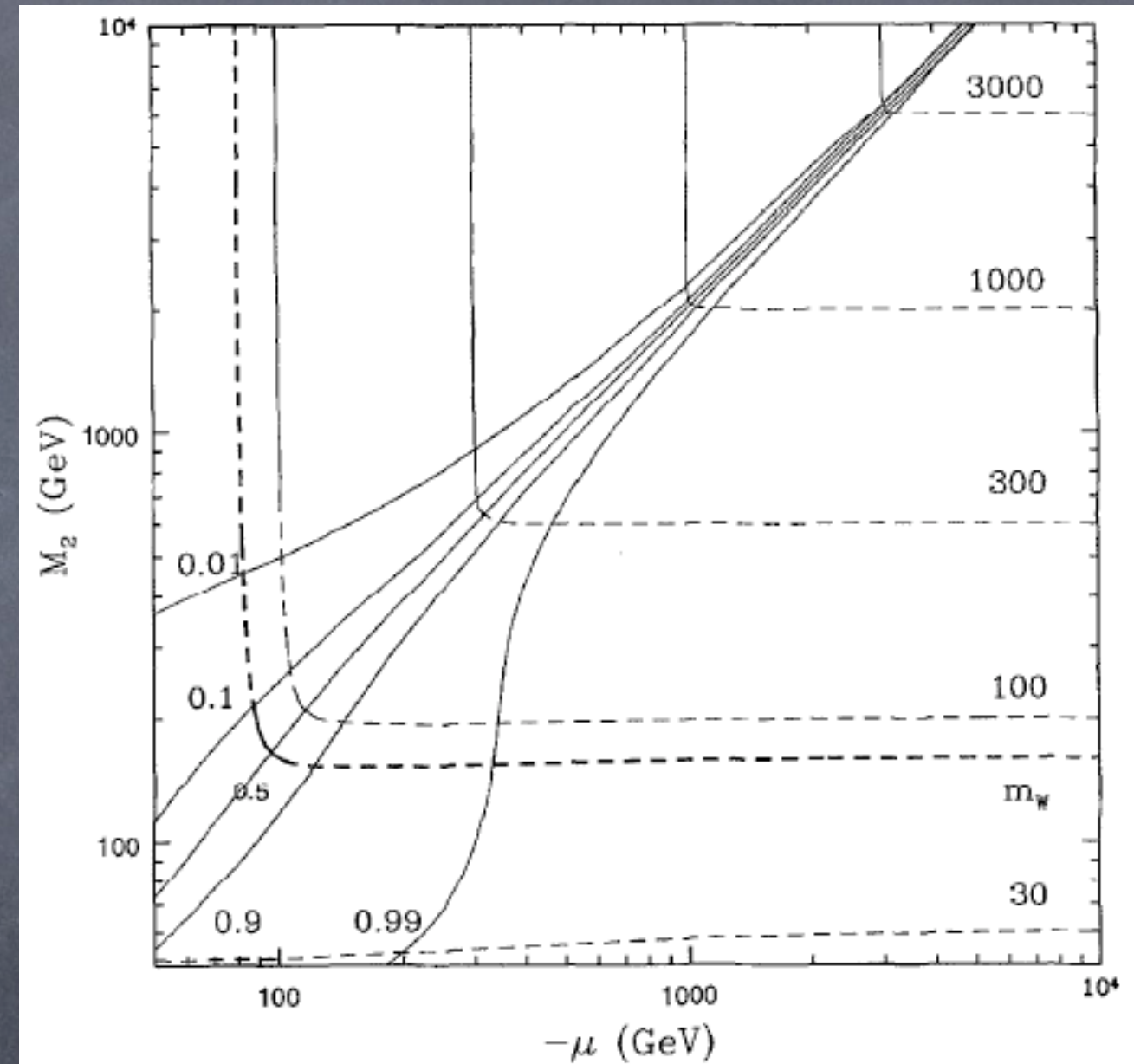
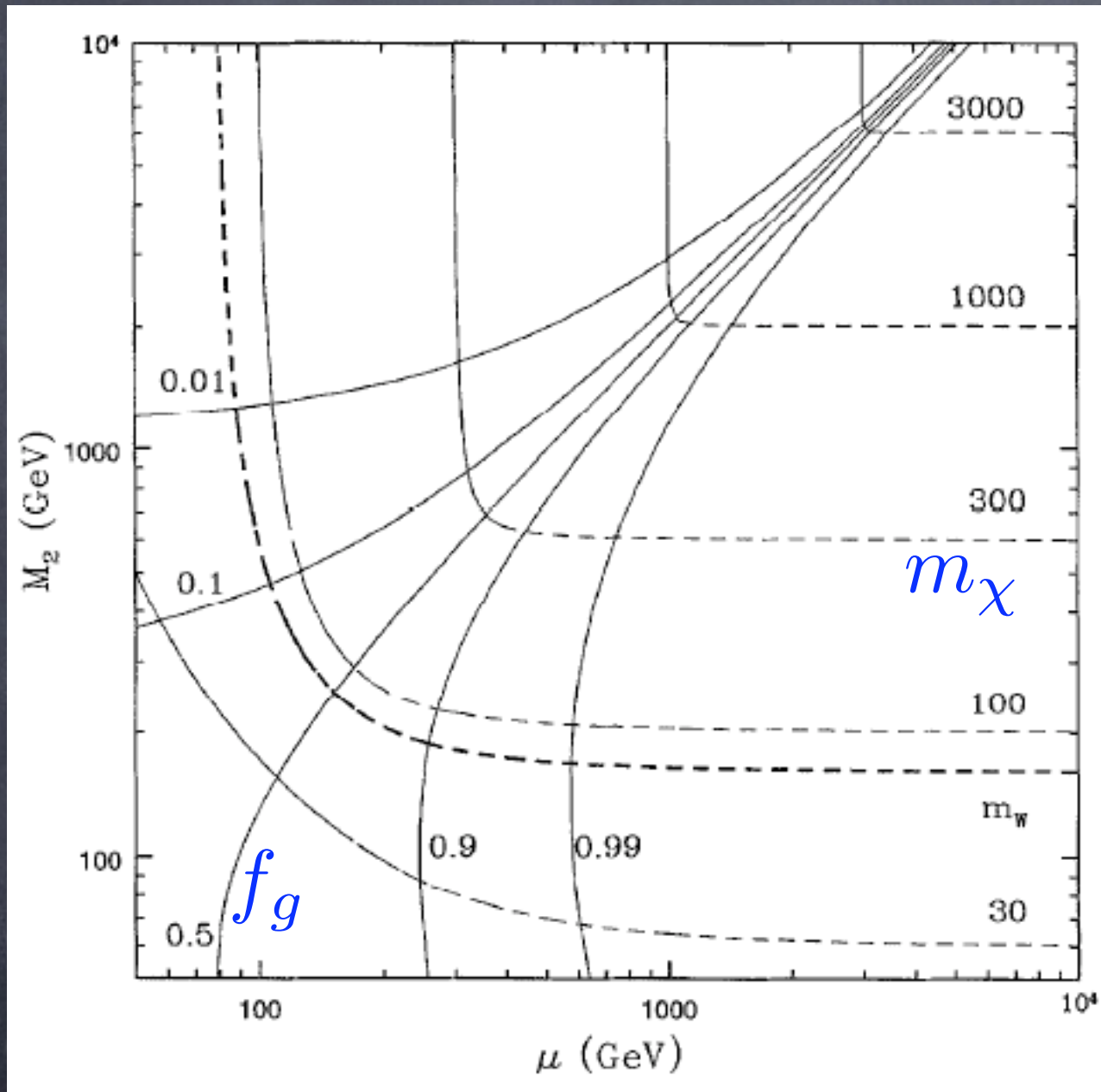
$$\mathcal{W} = -\mu \mathcal{H}_1 \mathcal{H}_2 + \mathcal{H}_1 h_e^{ij} \mathcal{L}_{Li} \mathcal{E}_{Rj} + \mathcal{H}_1 h_d^{ij} \mathcal{Q}_{Li} \mathcal{D}_{Rj} - \mathcal{H}_2 h_u^{ij} \mathcal{Q}_{Li} \mathcal{U}_{Rj}$$

soft SUSYB terms

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

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

Neutralino "properties"



Capture and annihilation rates

basics: DM particle scatters with nuclei and loses energy

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

it spirals to center of body, accumulates and annihilates

$$v_{\text{halo}} \simeq 270 \text{ km/s}$$

$$v_{\text{esc}, \odot} \simeq 620 \text{ km/s}$$

$$v_{\text{esc}, \oplus} \simeq 12 \text{ km/s}$$

equilibrium attained:

$$\dot{n} = C_{\text{capt}} - C_{\text{ann}} n^2$$

$\nwarrow \sigma_{\text{capt}}, V_{\text{eff}}$

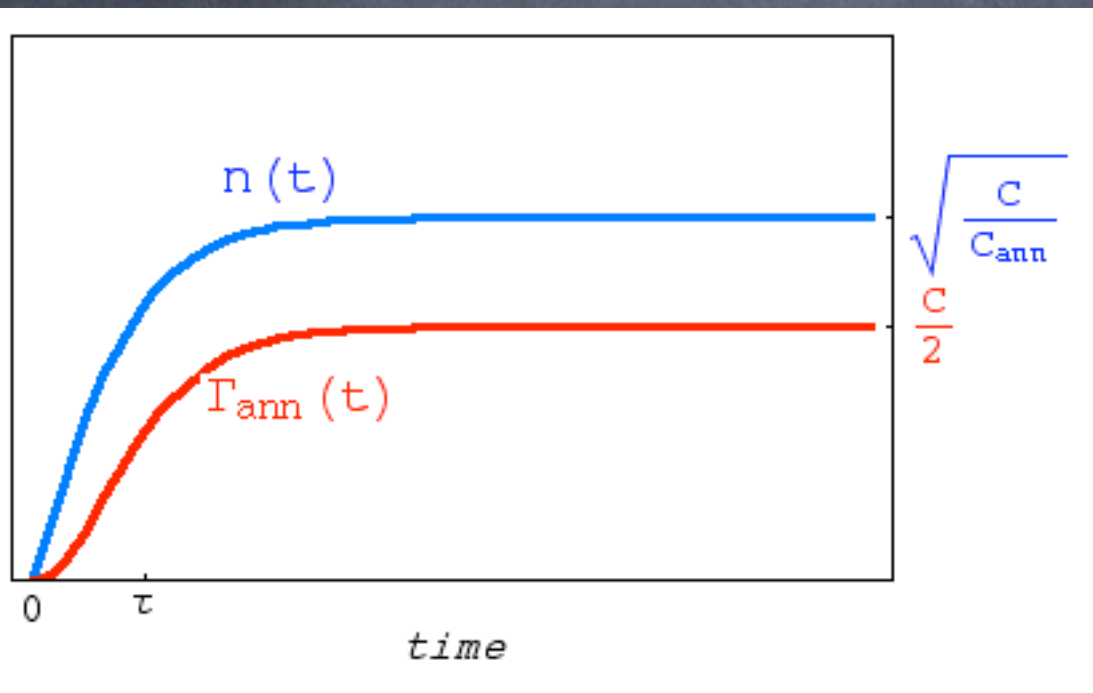
$$n(t) = \sqrt{\frac{C_{\text{capt}}}{C_{\text{ann}}}} \tanh\left(\frac{t}{\tau}\right) \quad \left(\tau = \frac{1}{\sqrt{C_{\text{capt}} C_{\text{ann}}}}\right)$$

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

Sun: equilibrium attained

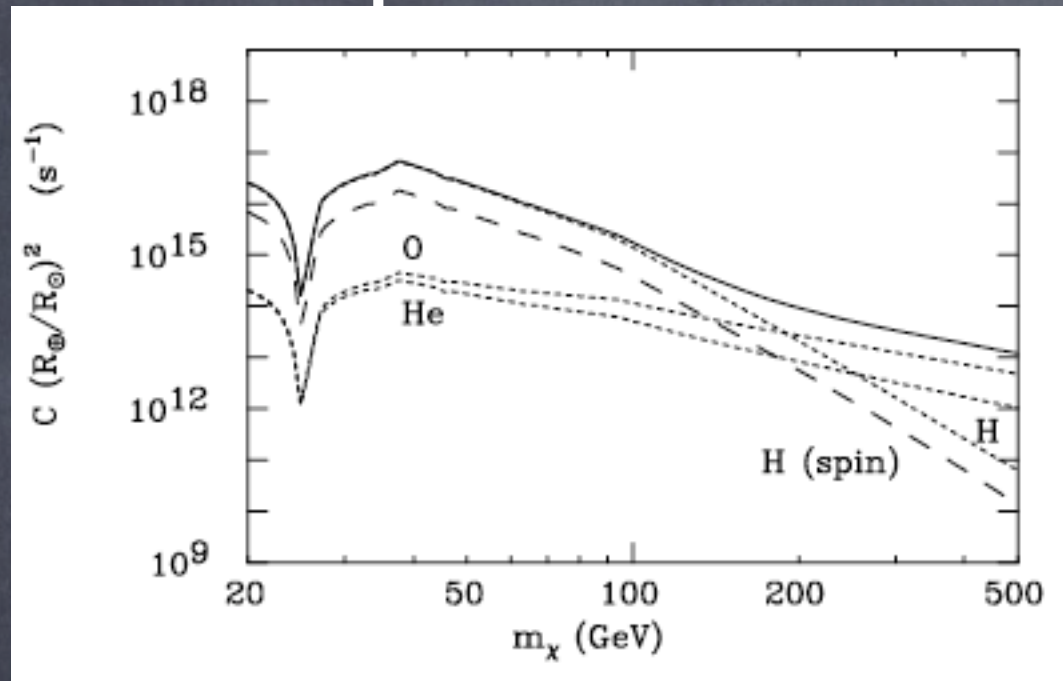
Earth: maybe

[back to nu from DM]



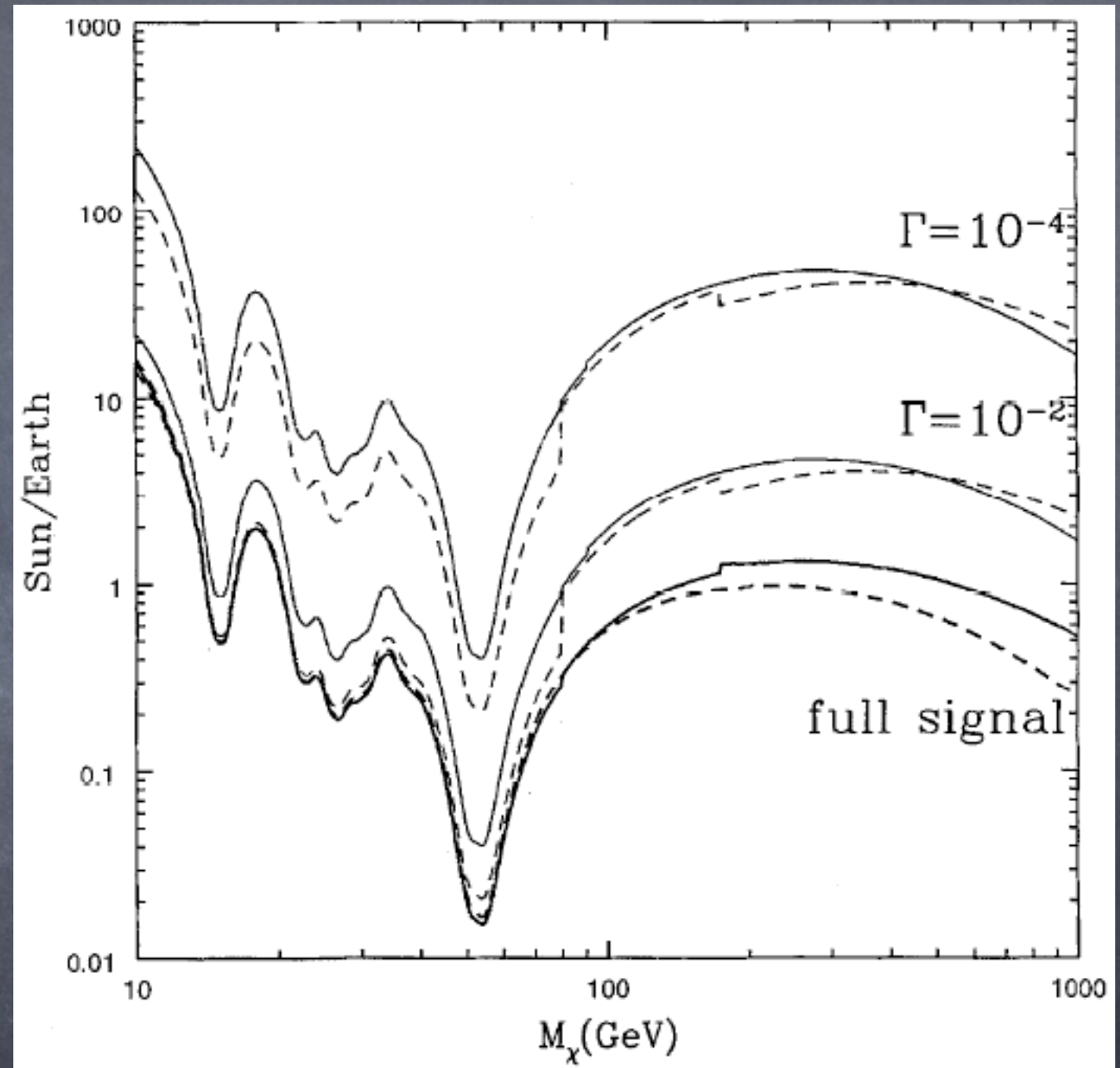
Rates from Sun and Earth

Sun capture:



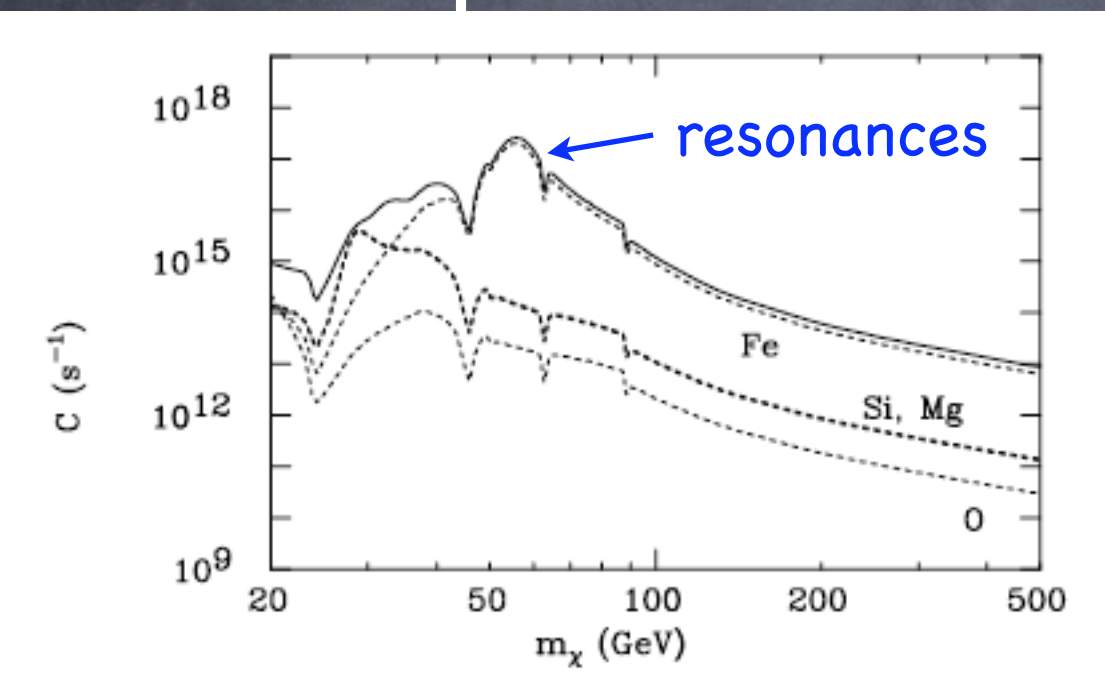
N.Fornengo, Ph.D. Thesis

ratio of neutrino rates:



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

Earth capture:



N.Fornengo, Ph.D. Thesis

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

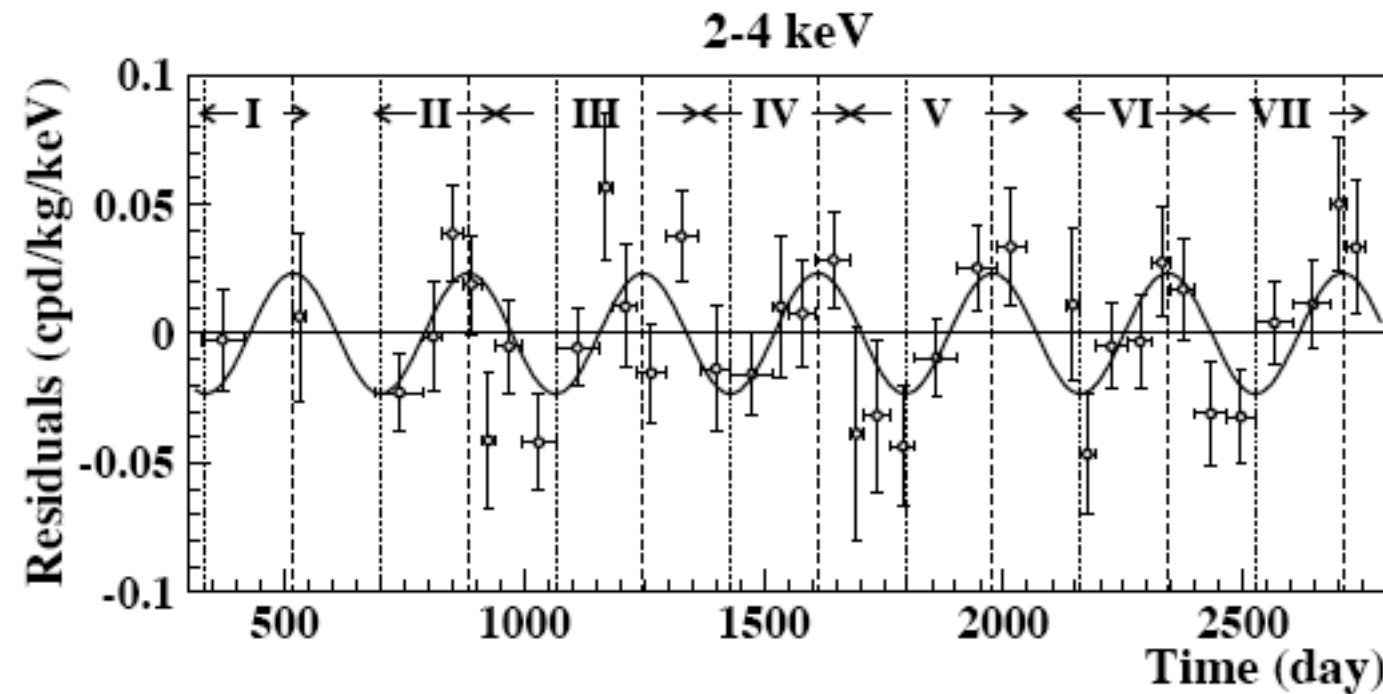
[back to nu from DM]

Direct detected *already*?

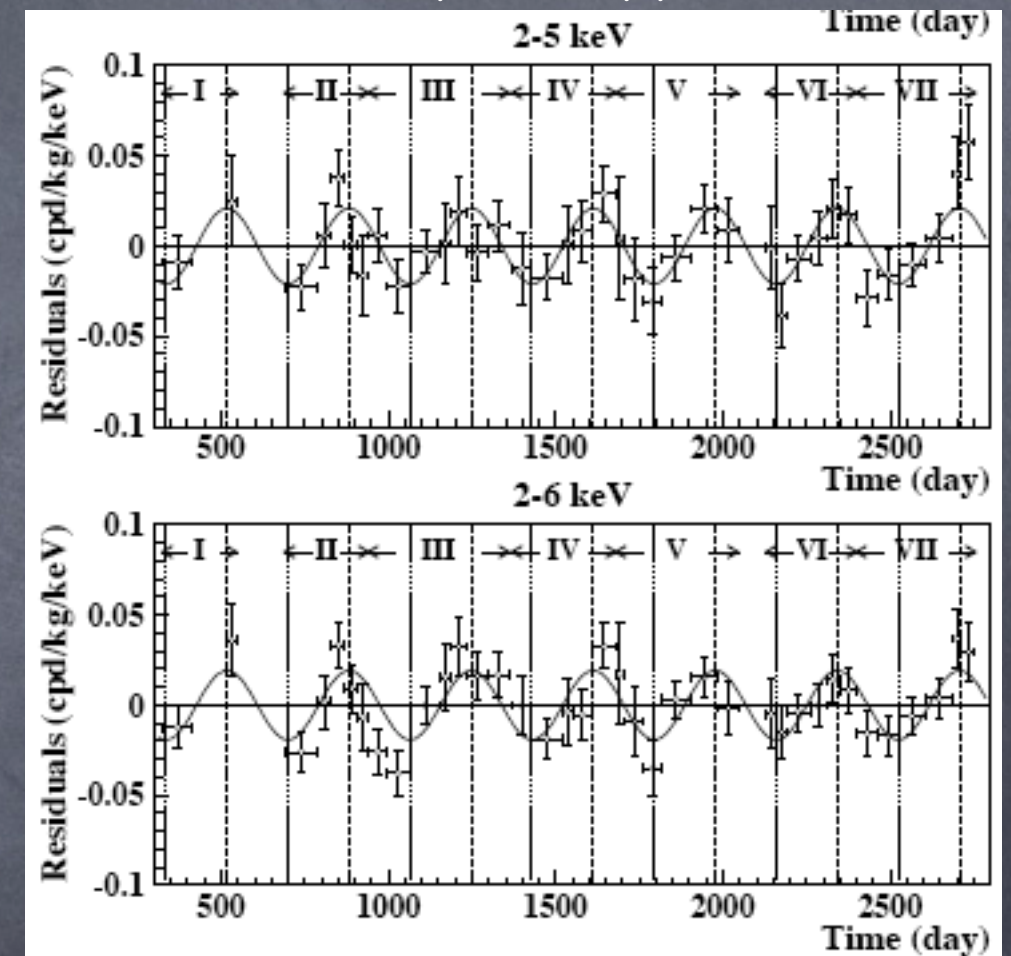
DAMA annual modulation:

however:

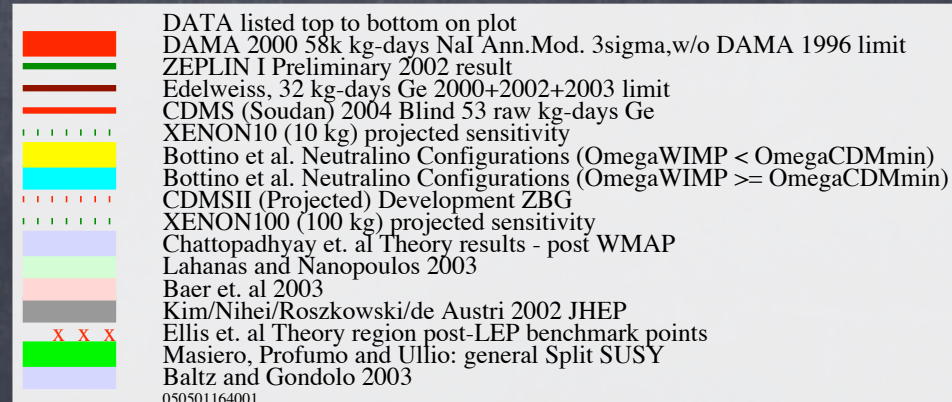
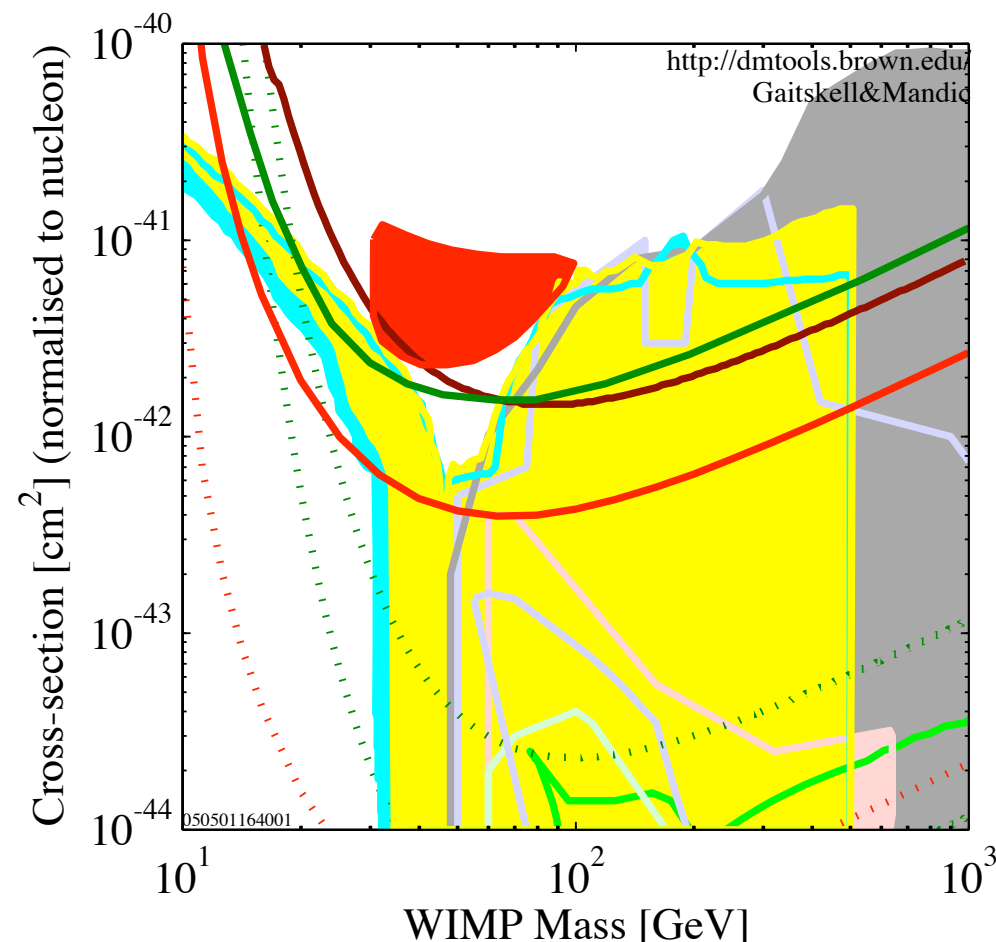
- raw data??
- bkgd (Rn emission)
- higher bins not expon suppressed



DAMA Coll.



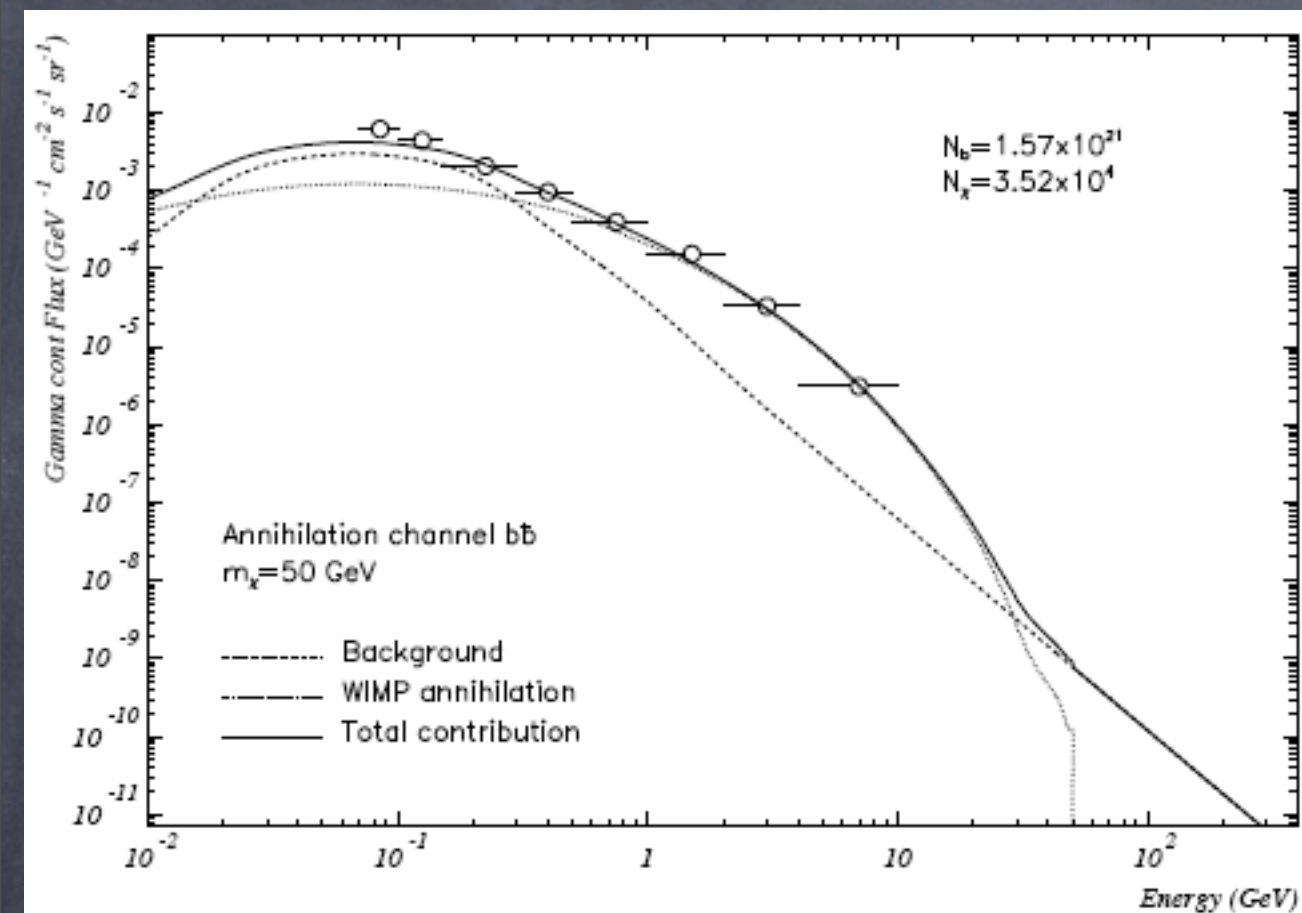
DAMA Coll.



[back to DM detection]

Hints from photons?

EGRET excess



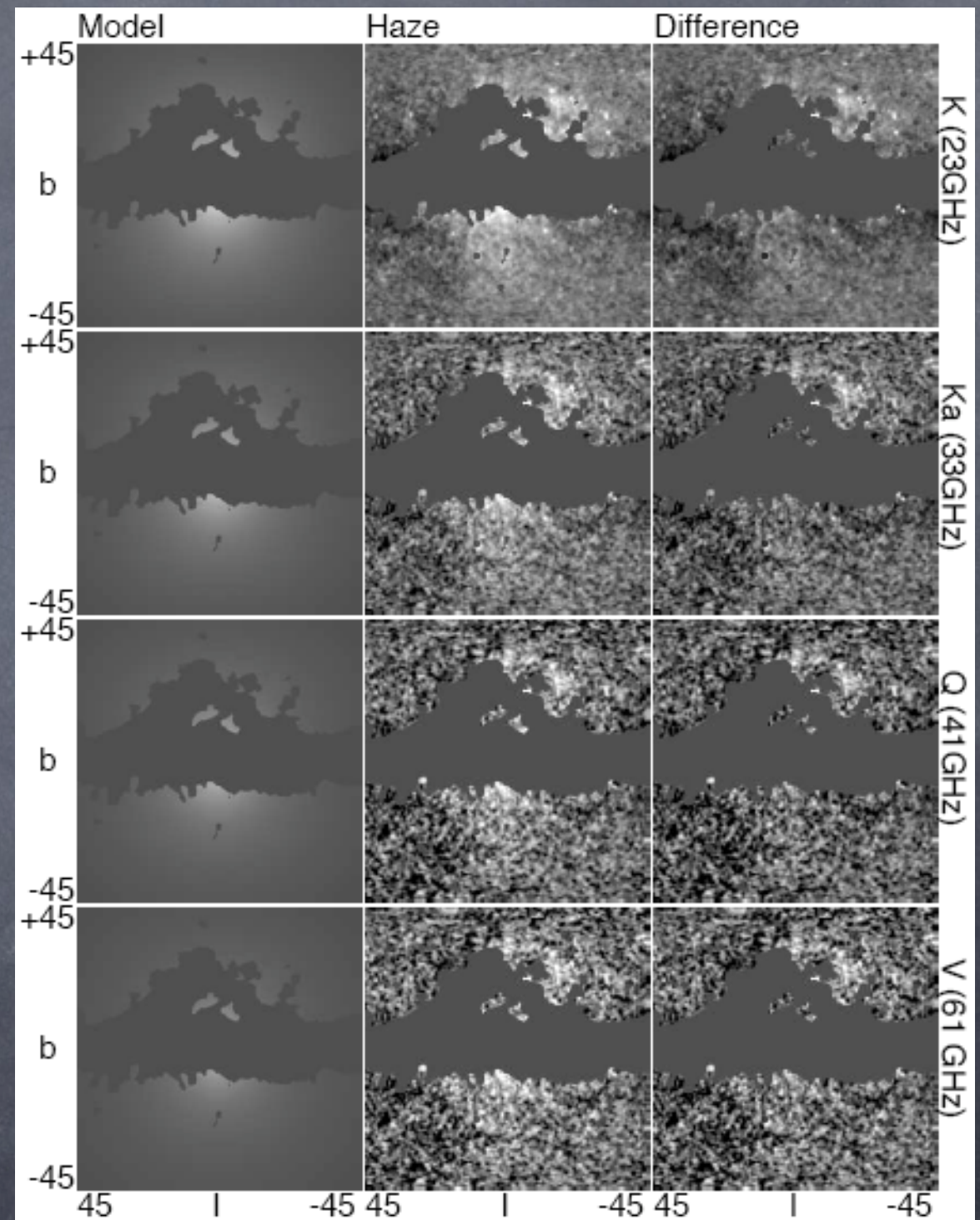
however:

- source not centered
- variability...

+ **CANGAROO** (2004)

+ **HESS** (2004)

WMAP "haze"



(Synchrotron rad from e^+e^- from DM annihilations)

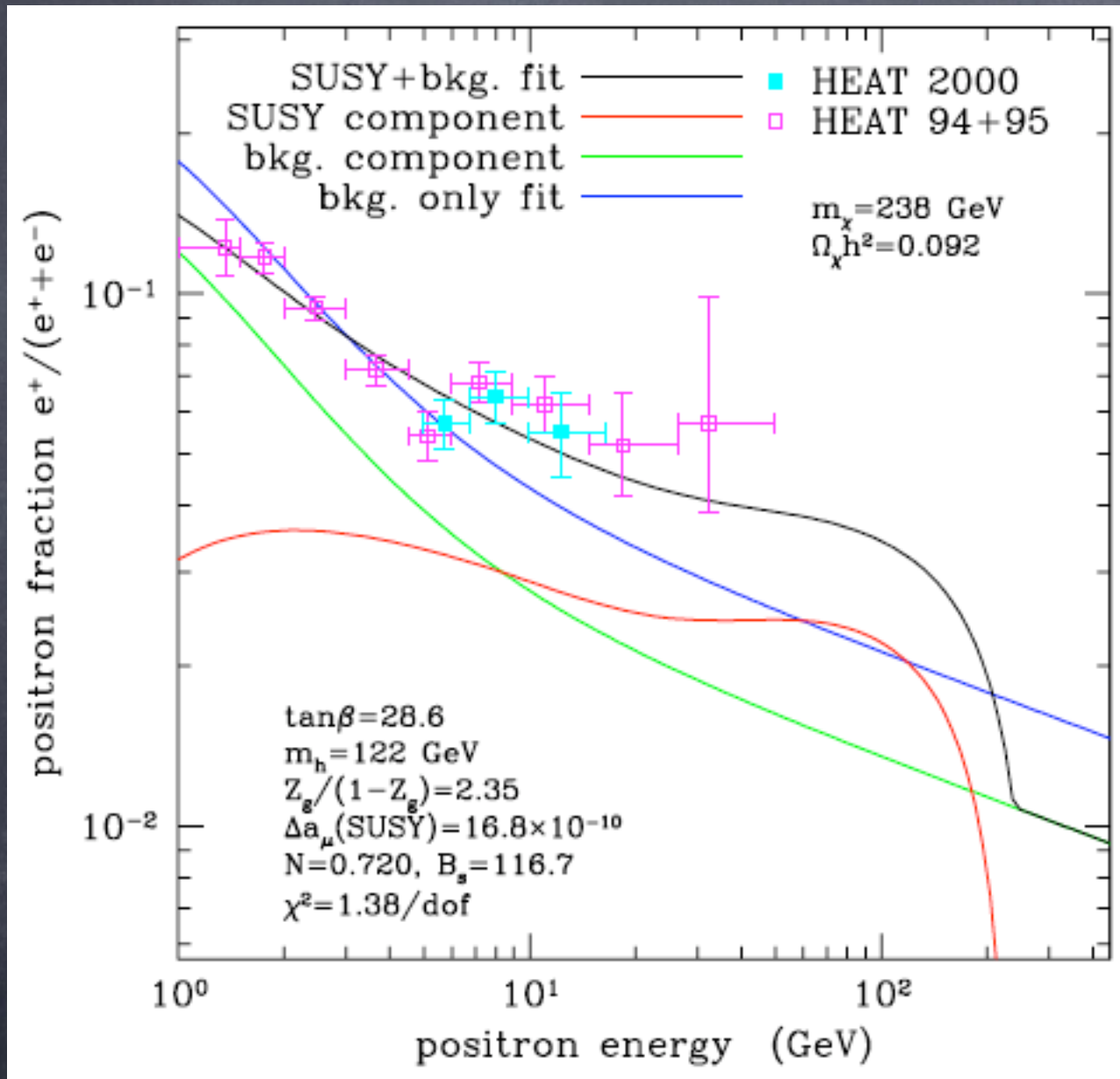
The Galactic emission found by Finkbeiner (2004) in the *WMAP* data in excess of the expected foreground Galactic ISM signal may be a signature of such dark matter annihilation.

Finkbeiner, ApJ 614 (2004)

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

Hints from positrons?

HEAT excess (1994+95 & 2000)

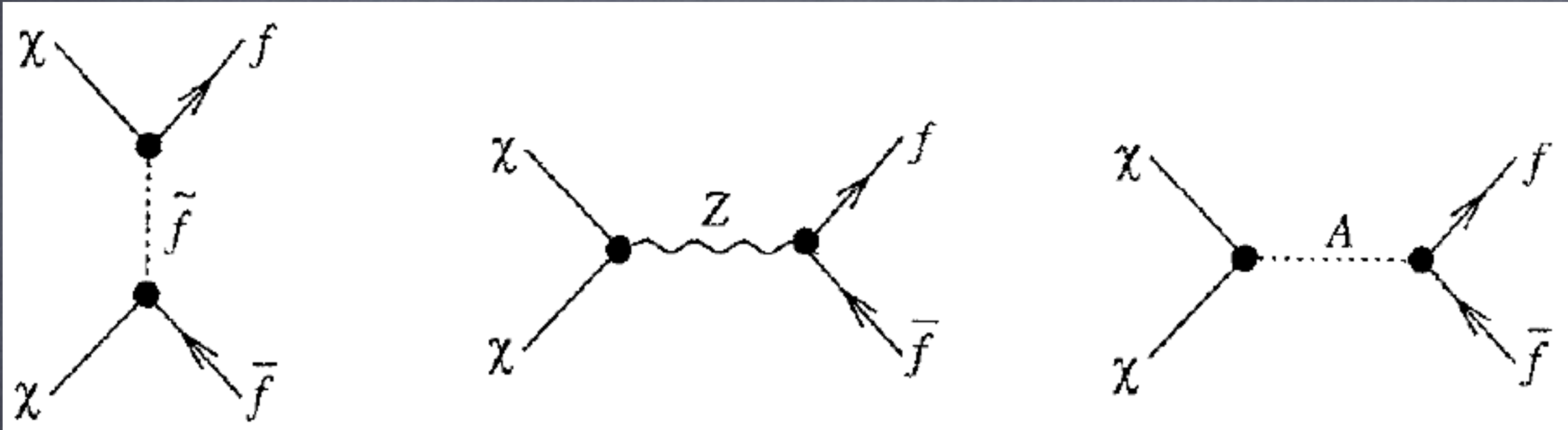


Baltz, Edsjo, Gondolo, Freese PRD65 (2002)

however:

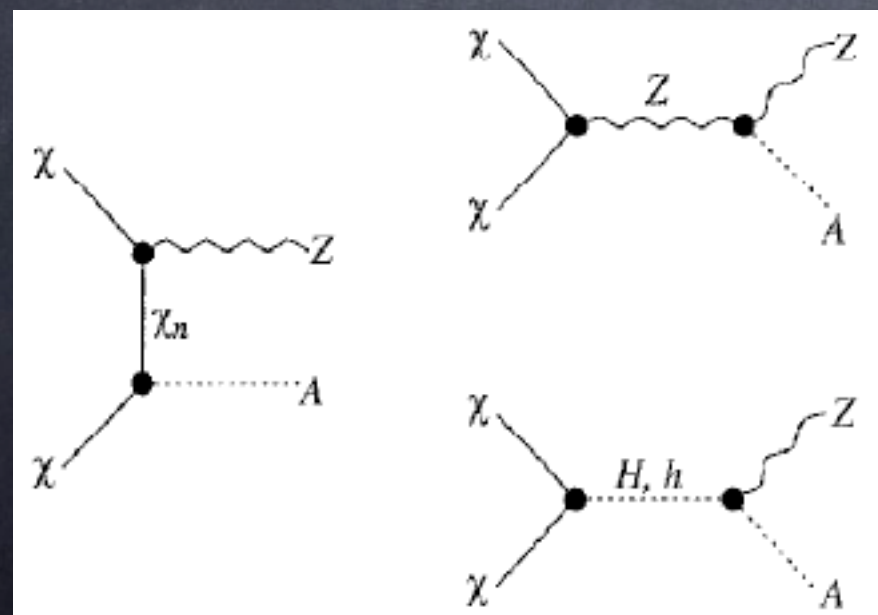
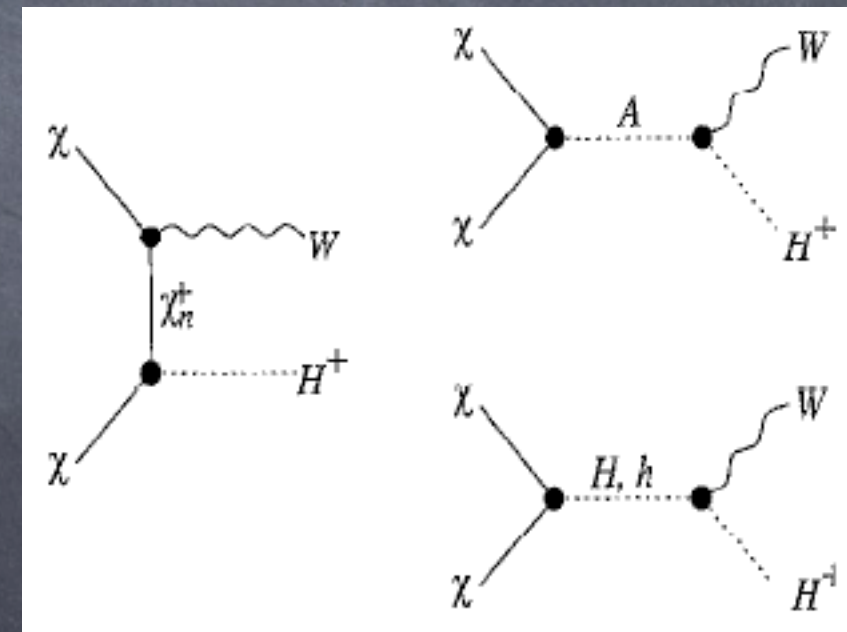
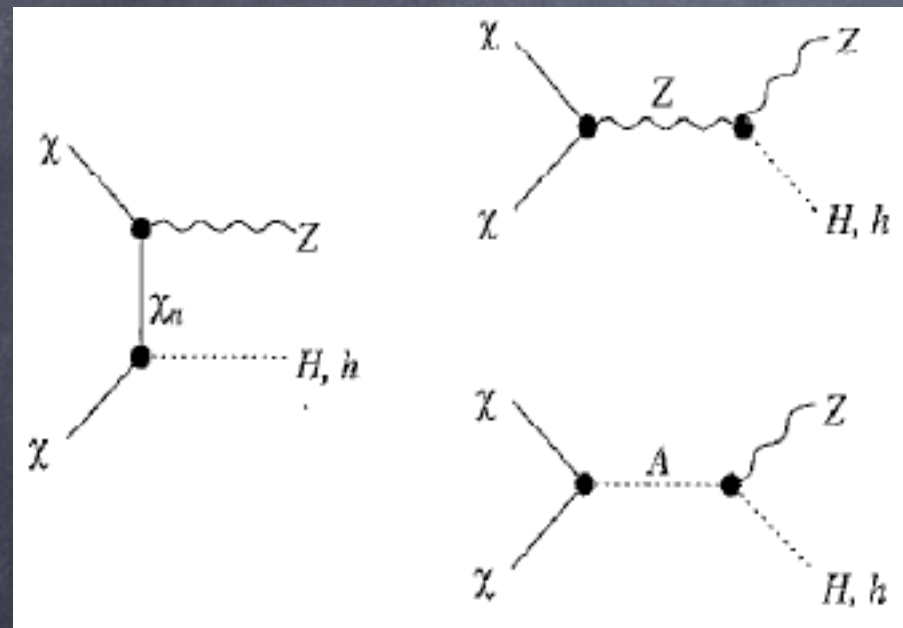
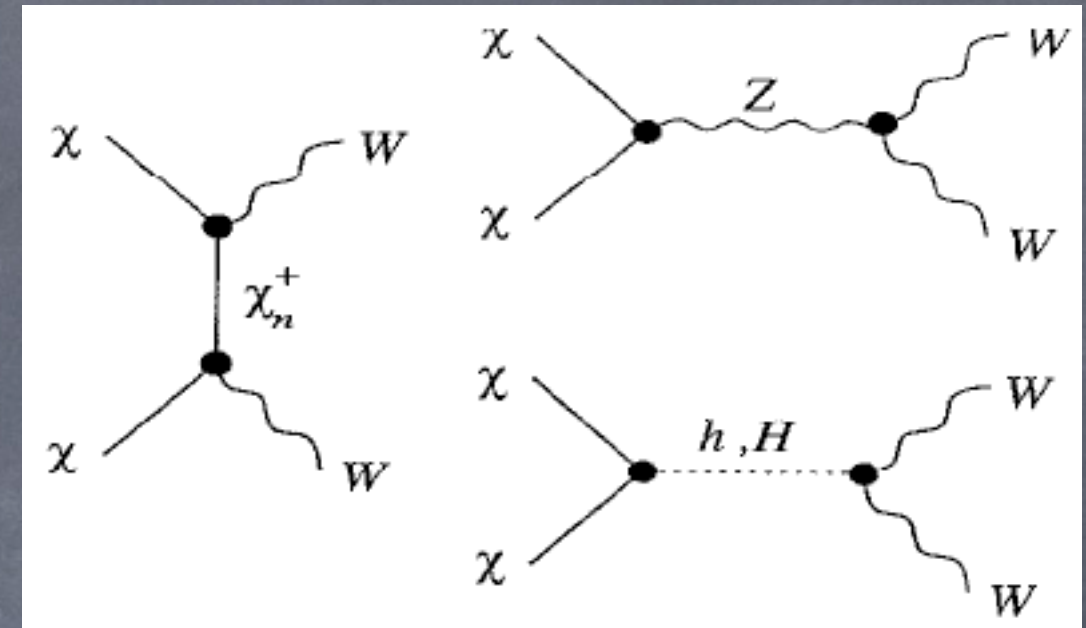
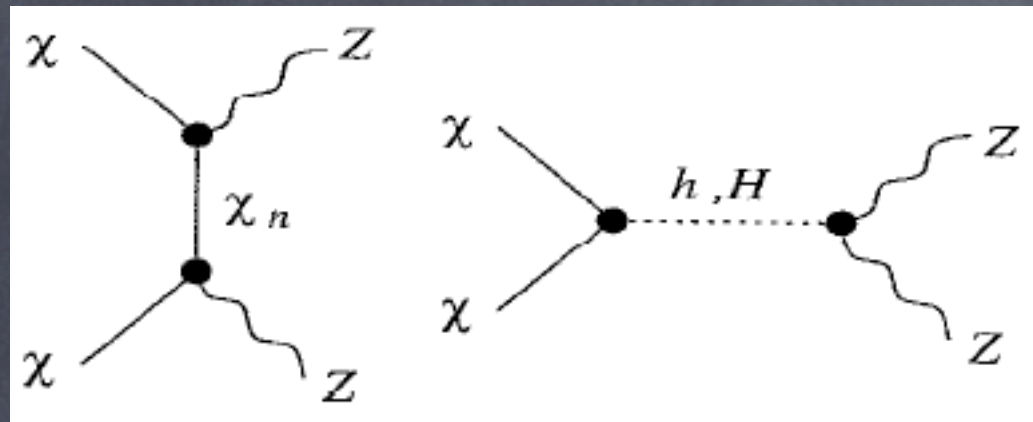
- random trajectories in magnetic field
- flux requires too much DM...

Annihilation into $f\bar{f}$

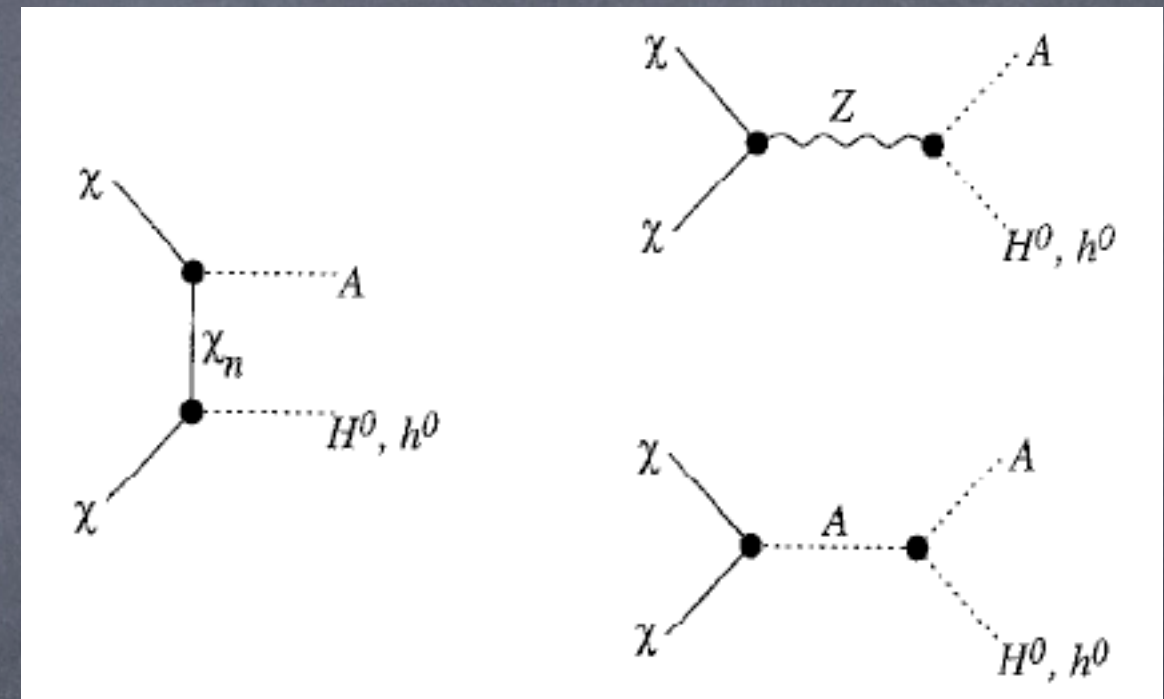
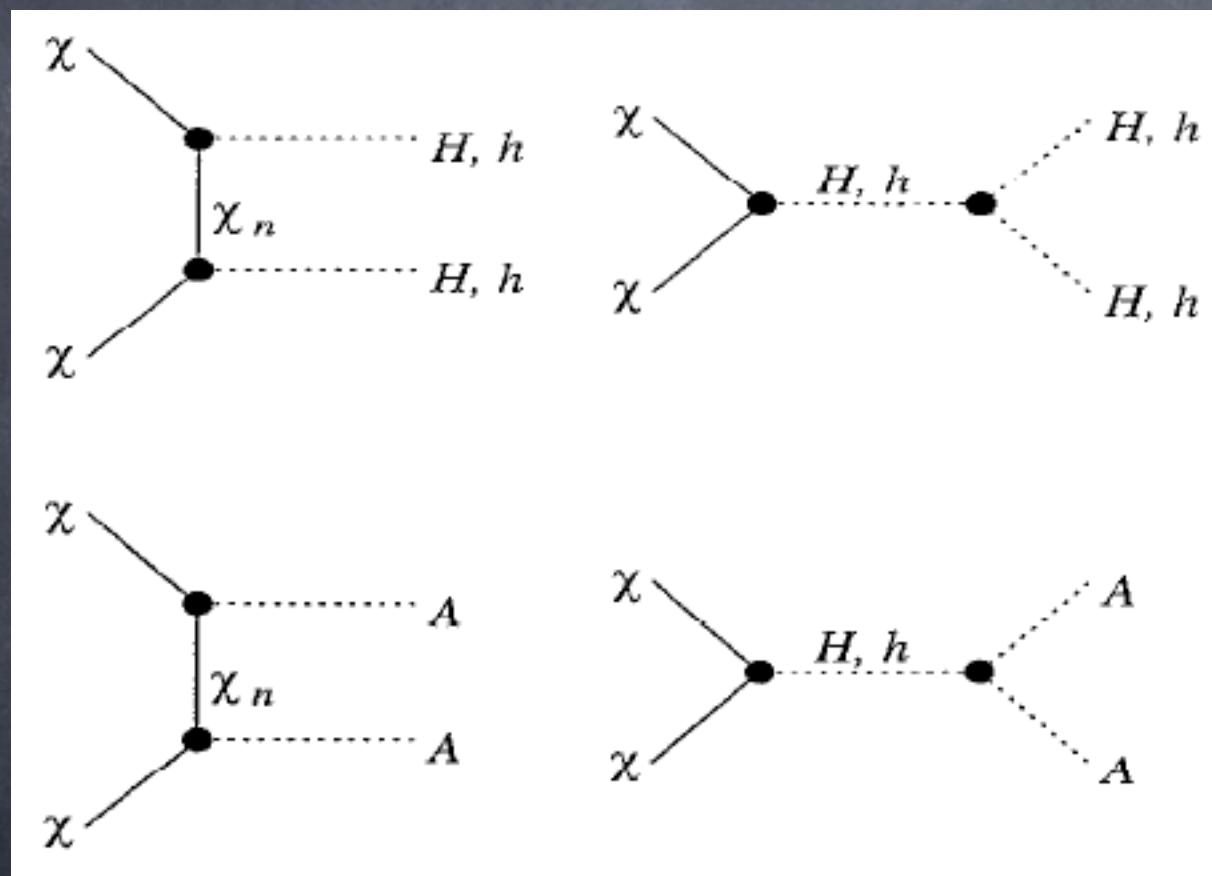


Jungman, Kamionkowski, Griest,
Phys.Rept.267 (1996)

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

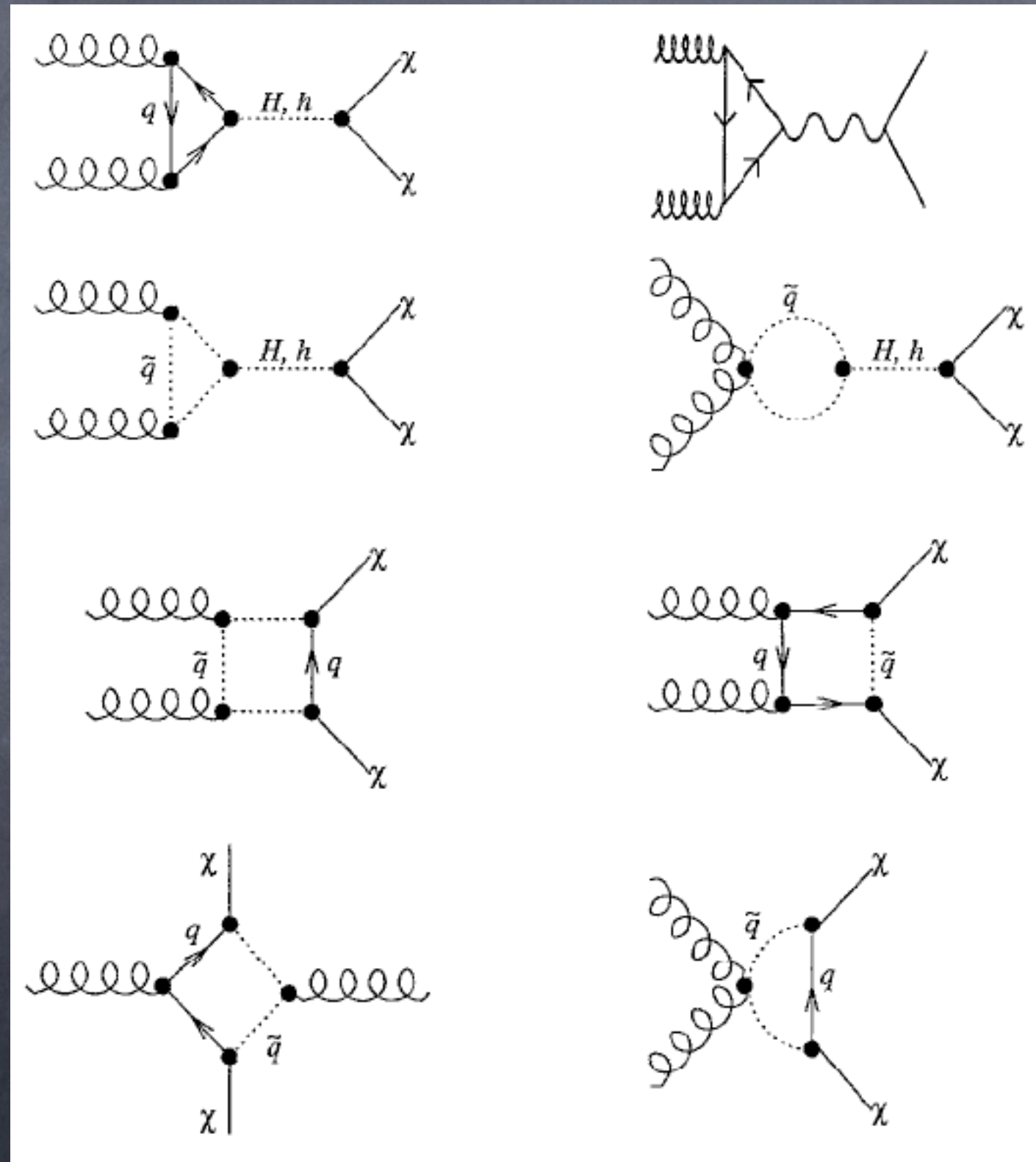


Other annihilations into the MSSM Higgs sector



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

Annihilations into gg



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

Effects of propagation (oscillations + interactions)

DM mass m_{DM}	DM annihilation channels in the Earth/Sun							
	$\nu\bar{\nu}$	$b\bar{b}$	$\tau\bar{\tau}$	$c\bar{c}$	$q\bar{q}$	$t\bar{t}$	ZZ	W^+W^-
50 GeV	1/0.71	0.51/0.68	3.9/3.0	0.33/0.61	0.50/0.68	—/—	—/—	—/—
100 GeV	1/0.50	0.69/0.63	2.1/2.5	0.49/0.56	0.46/0.65	—/—	1.0/0.71	1.0/0.66
200 GeV	1/0.25	0.86/0.54	1.3/1.7	0.75/0.49	0.54/0.58	1.00/0.60	1.0/0.39	1.0/0.37
400 GeV	1/0.07	0.95/0.44	1.1/0.81	0.90/0.41	0.72/0.50	1.00/0.31	1.0/0.17	1.0/0.15
1000 GeV	1/0.01	0.99/0.29	1.0/0.20	0.98/0.32	0.92/0.41	1.00/0.09	1.0/0.04	1.0/0.03

Table 3: Ratios of through-going muon rates ‘with’ over ‘without’ the effects of the neutrino propagation, for DM annihilations around the center of the Earth/Sun. E.g. the bottom-right

DM mass m_{DM}	DM annihilation channels in the Earth/Sun							
	$\nu\bar{\nu}$	$b\bar{b}$	$\tau\bar{\tau}$	$c\bar{c}$	$q\bar{q}$	$t\bar{t}$	ZZ	W^+W^-
50 GeV	100/89	11/10	32/32	11/10	4.9/3.8	—/—	—/—	—/—
100 GeV	100/77	9.9/8.5	25/30	11/8.2	2.5/3.2	—/—	33/28	40/41
200 GeV	100/56	13/7.0	22/25	15/6.5	2.6/2.4	15/13	33/21	40/31
400 GeV	100/28	12/5.2	22/18	13/4.7	2.5/2.0	15/9.3	31/13	41/20
1000 GeV	100/7.7	10/1.3	26/8.4	10/2.7	2.2/1.1	15/5.0	32/5.6	41/7.8

Table 4: Average percentage energies in units of m_{DM} of $(\bar{\nu}_\mu)$ produced by DM annihilations around the center of the Earth/Sun, computed for various annihilation channels and for various DM

LAST slide