The Maximum Patch Method for Directional Dark Matter Detection

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DMTPC

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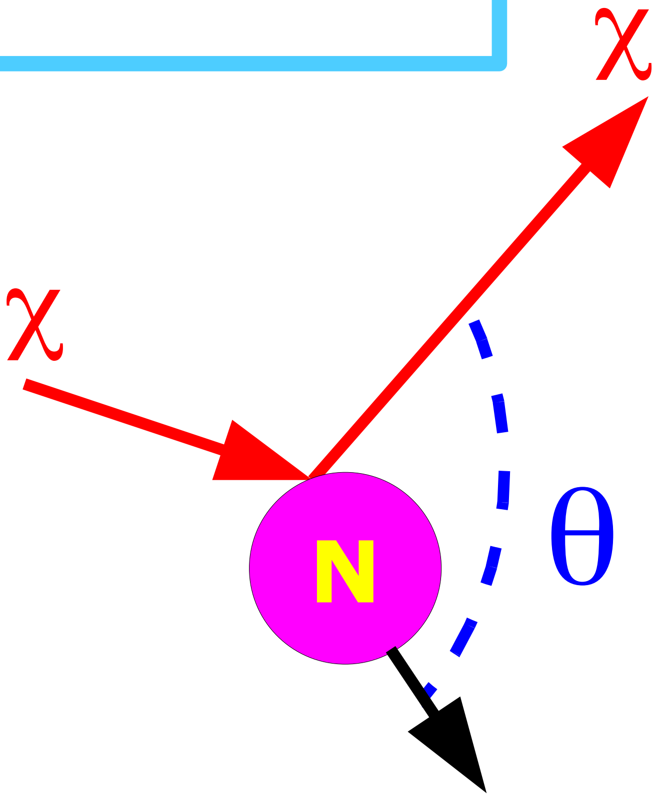
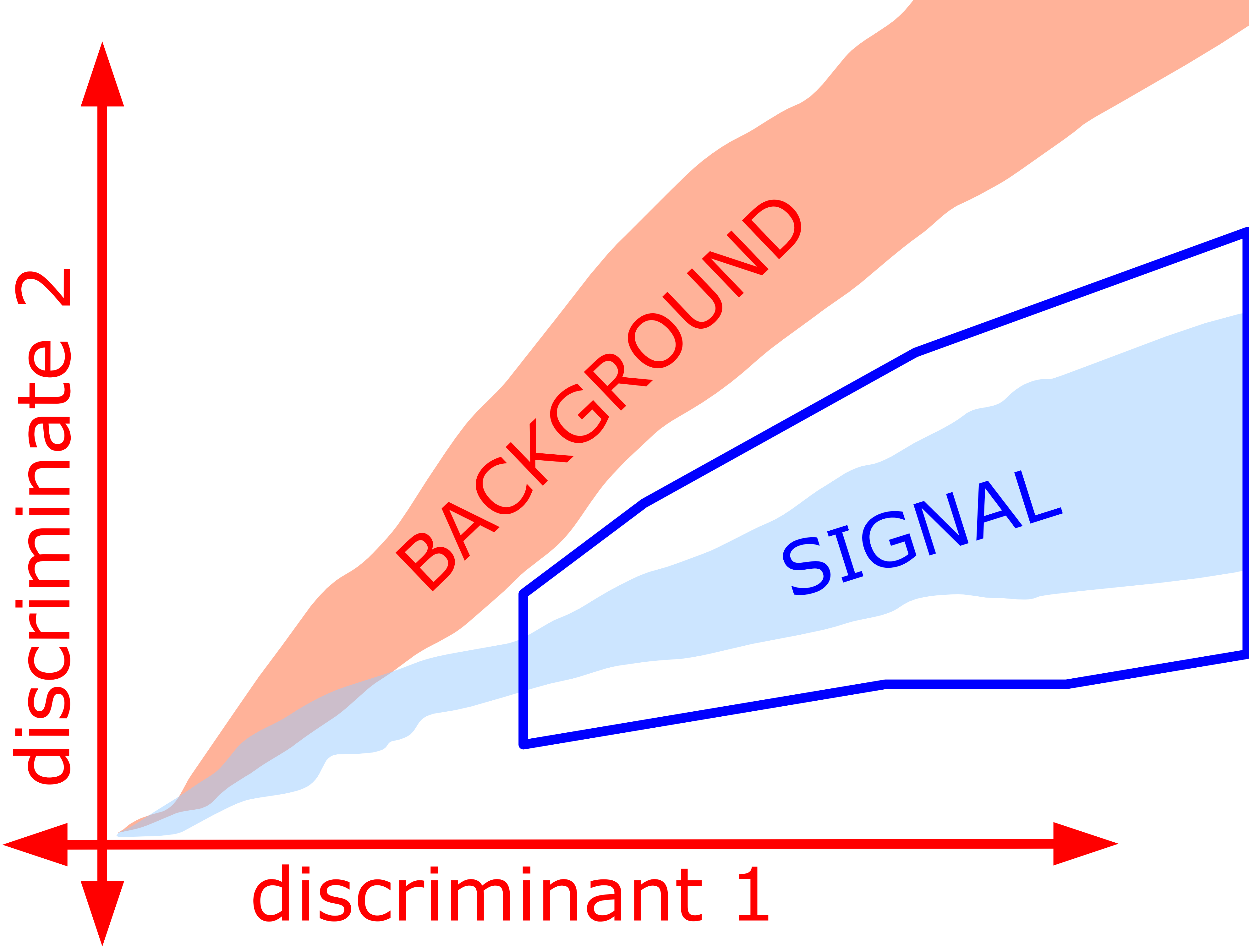
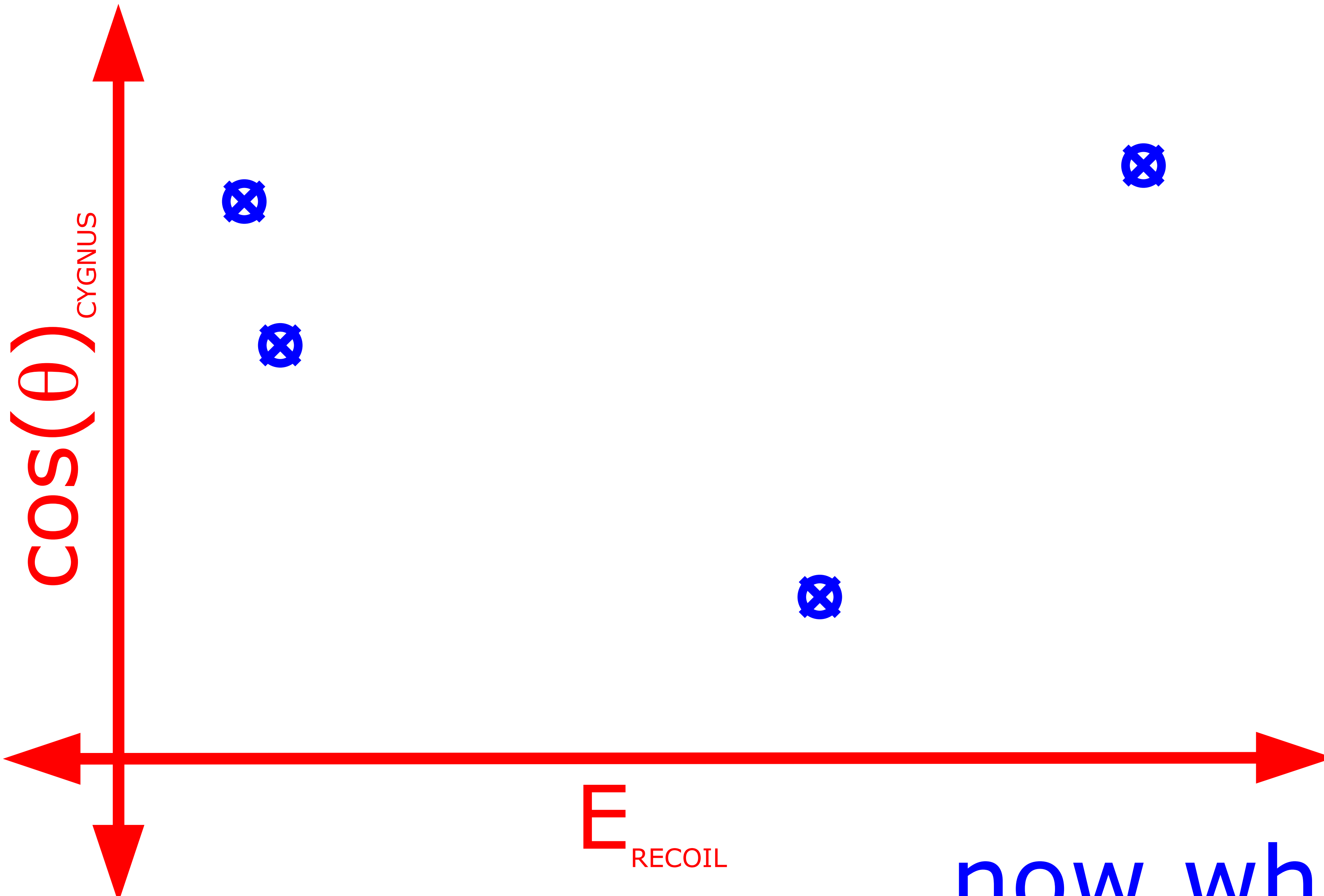


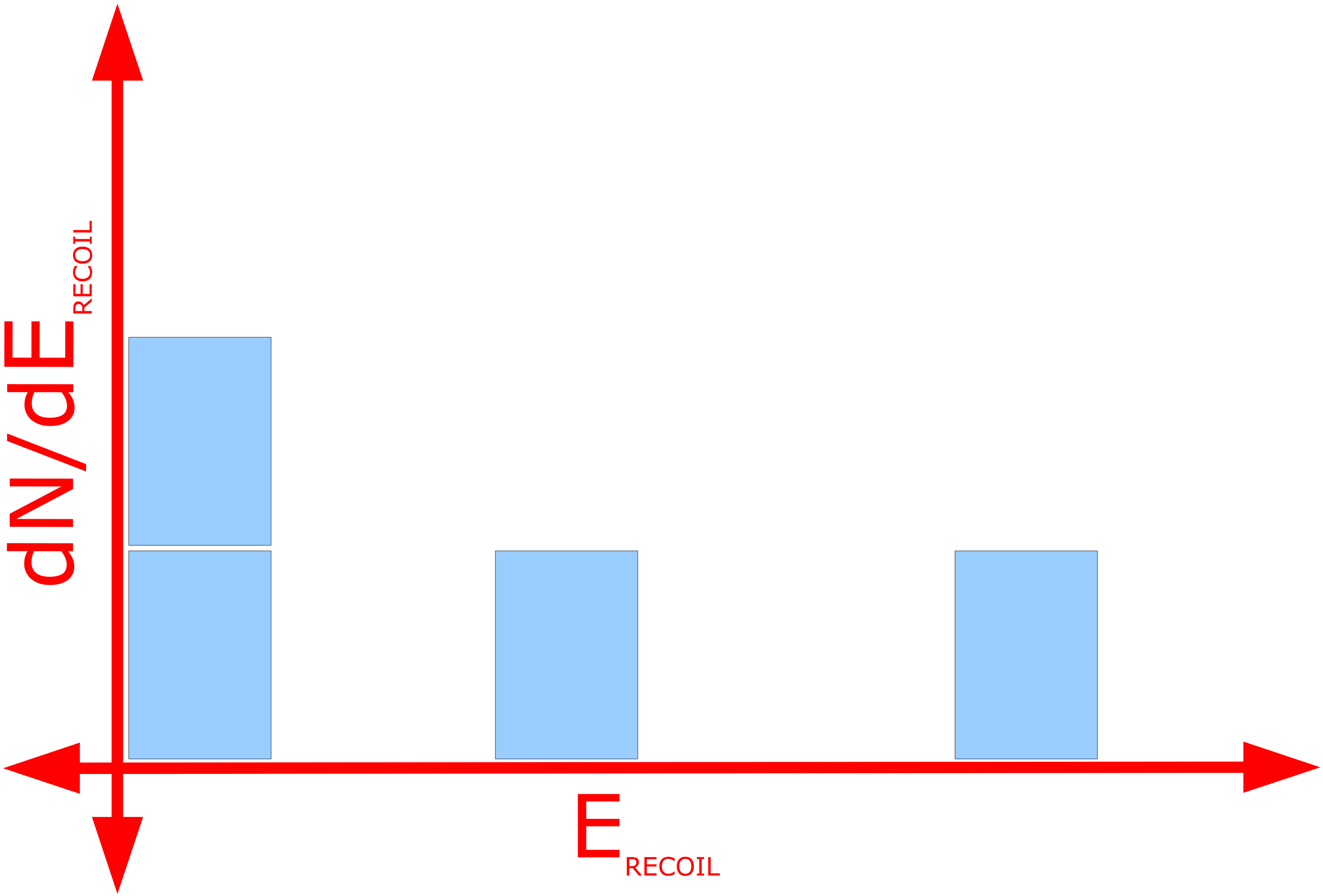

BACKGROUND
SIGNAL
discriminate 2
discriminant 1

in your signal region, you measured



now what?

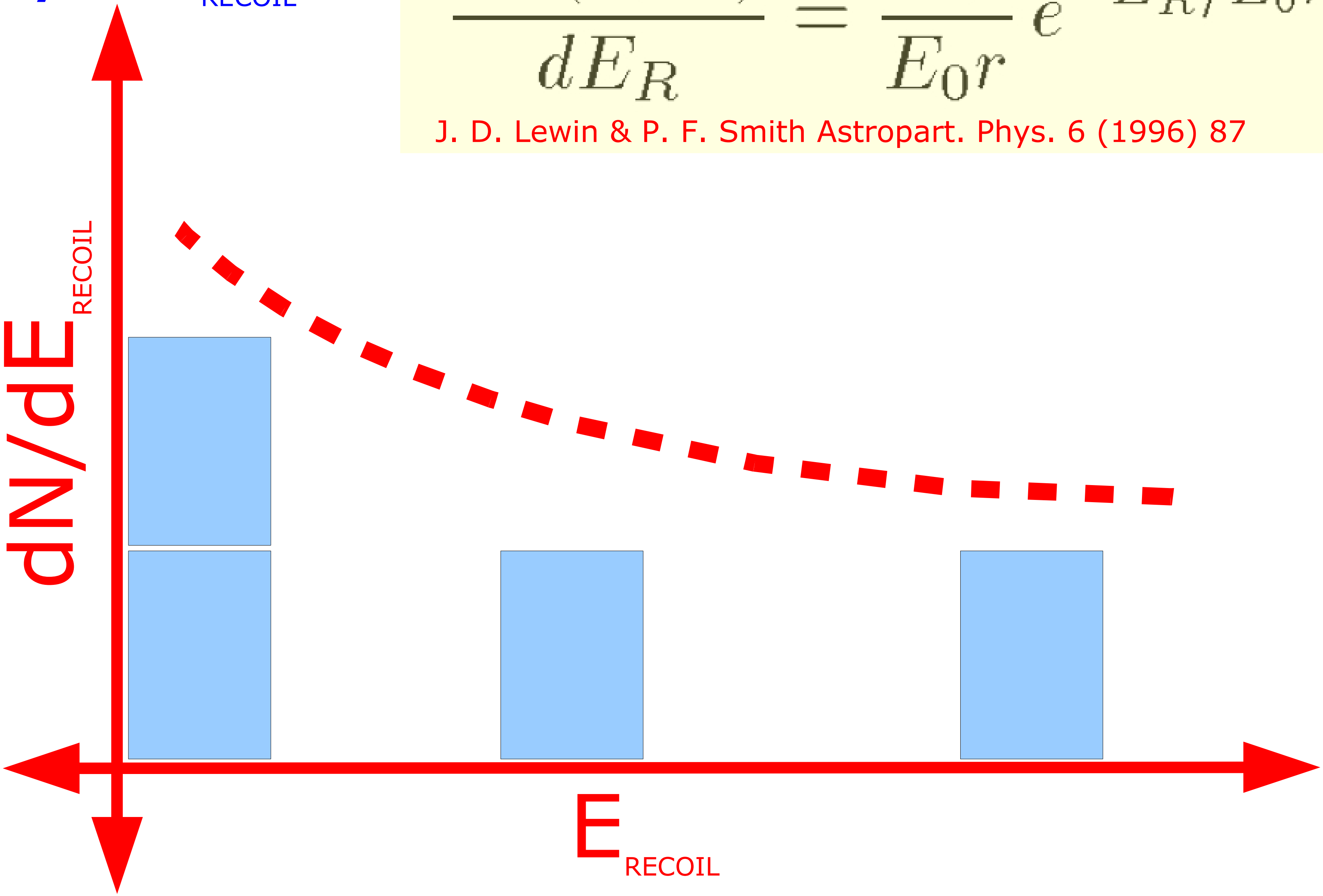
if you're Xe XENON Dark Matter Project or CDMS



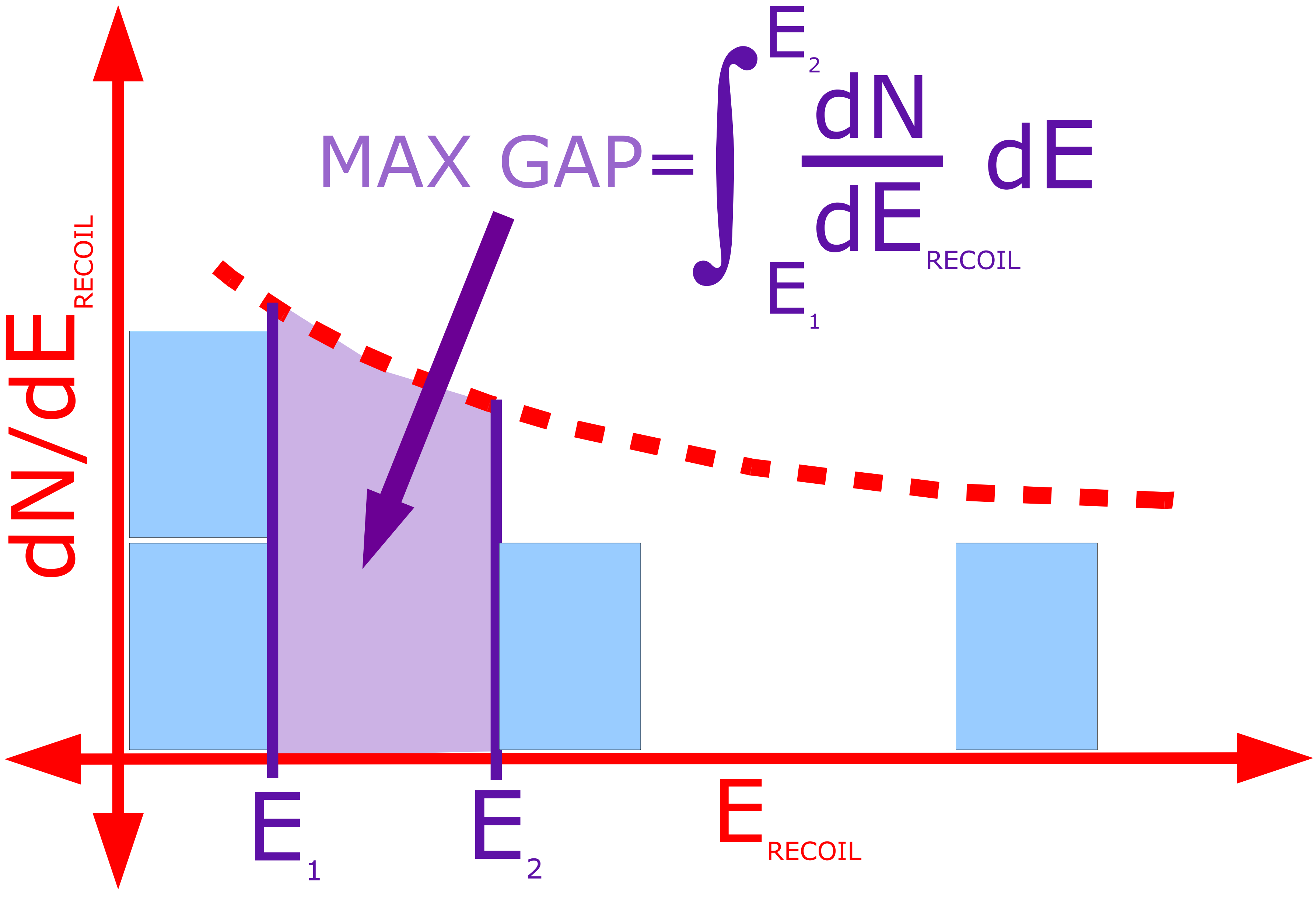
you have a prediction for dN/dE_{RECOIL}

$$\frac{dR(0,\infty)}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r}$$

J. D. Lewin & P. F. Smith Astropart. Phys. 6 (1996) 87



set an upper limit using this and the maximum gap method*

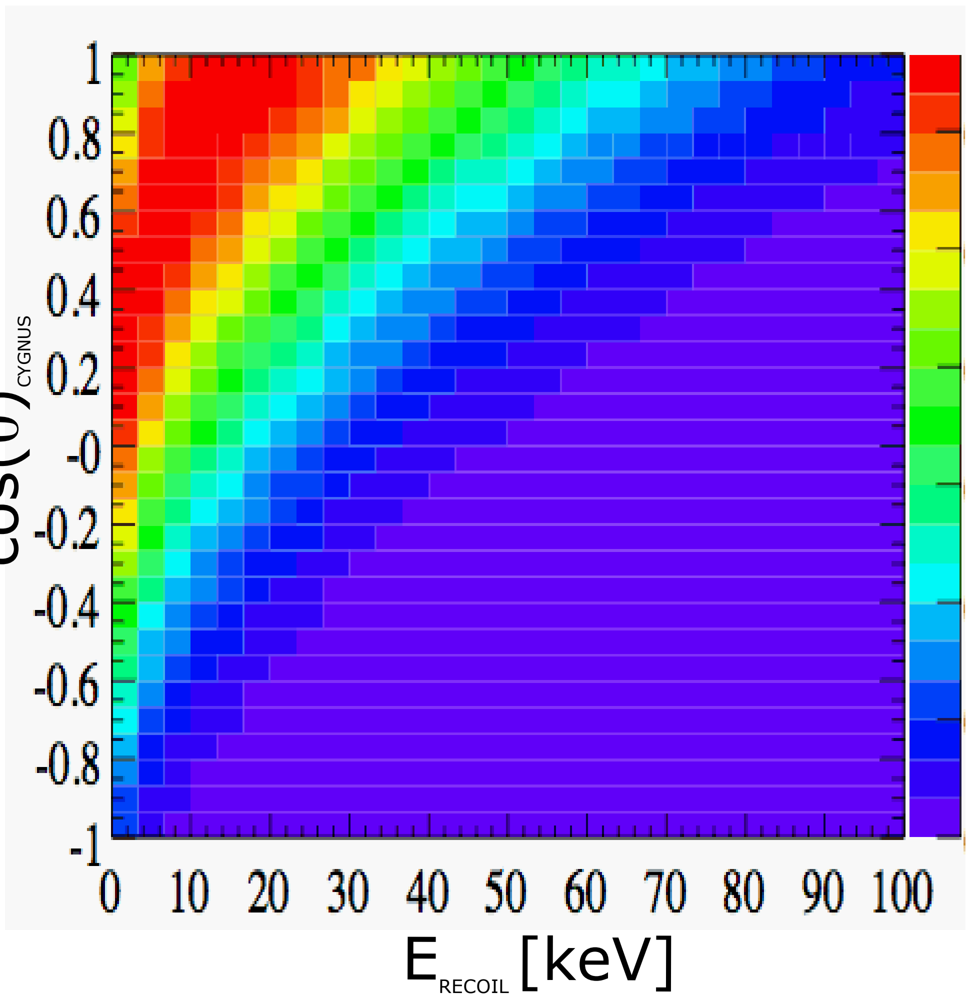


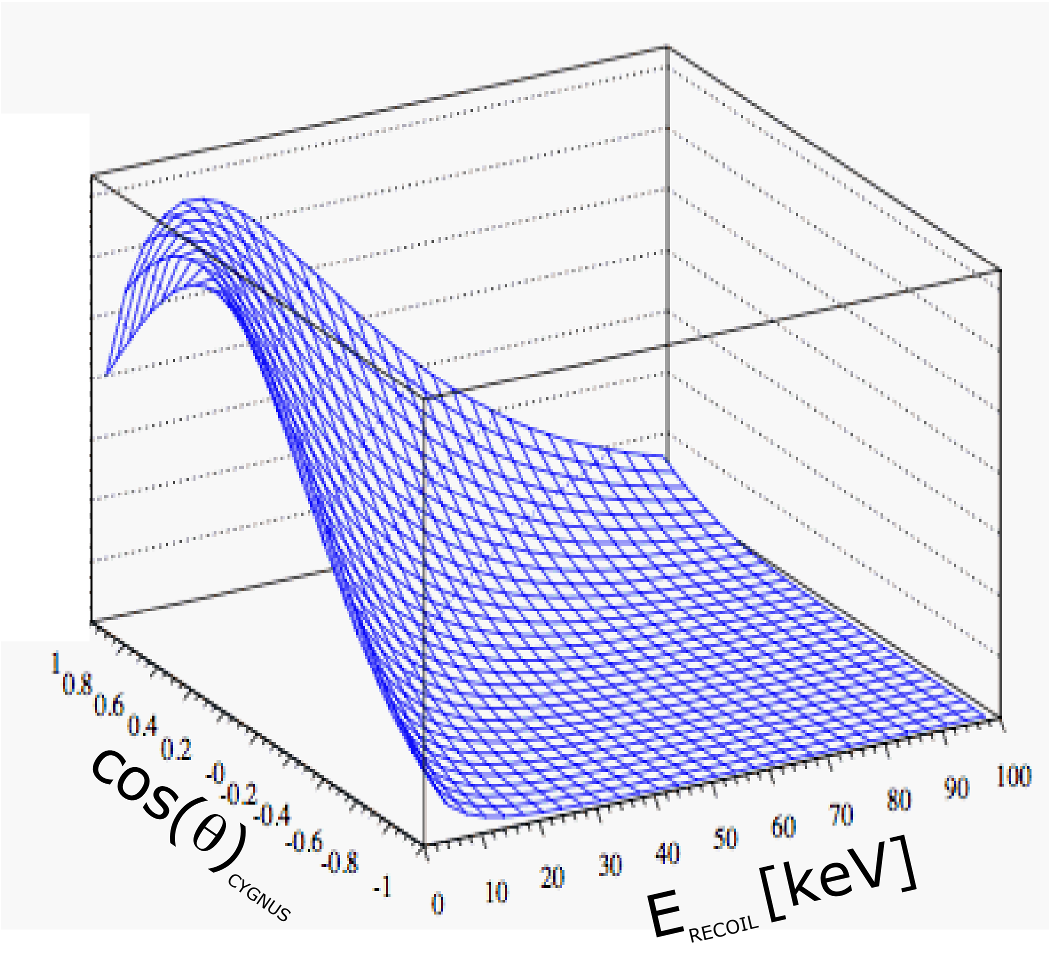
S. Yellin, Phys. Rev. D66, 032005 (2002)

directional detectors have a prediction too!

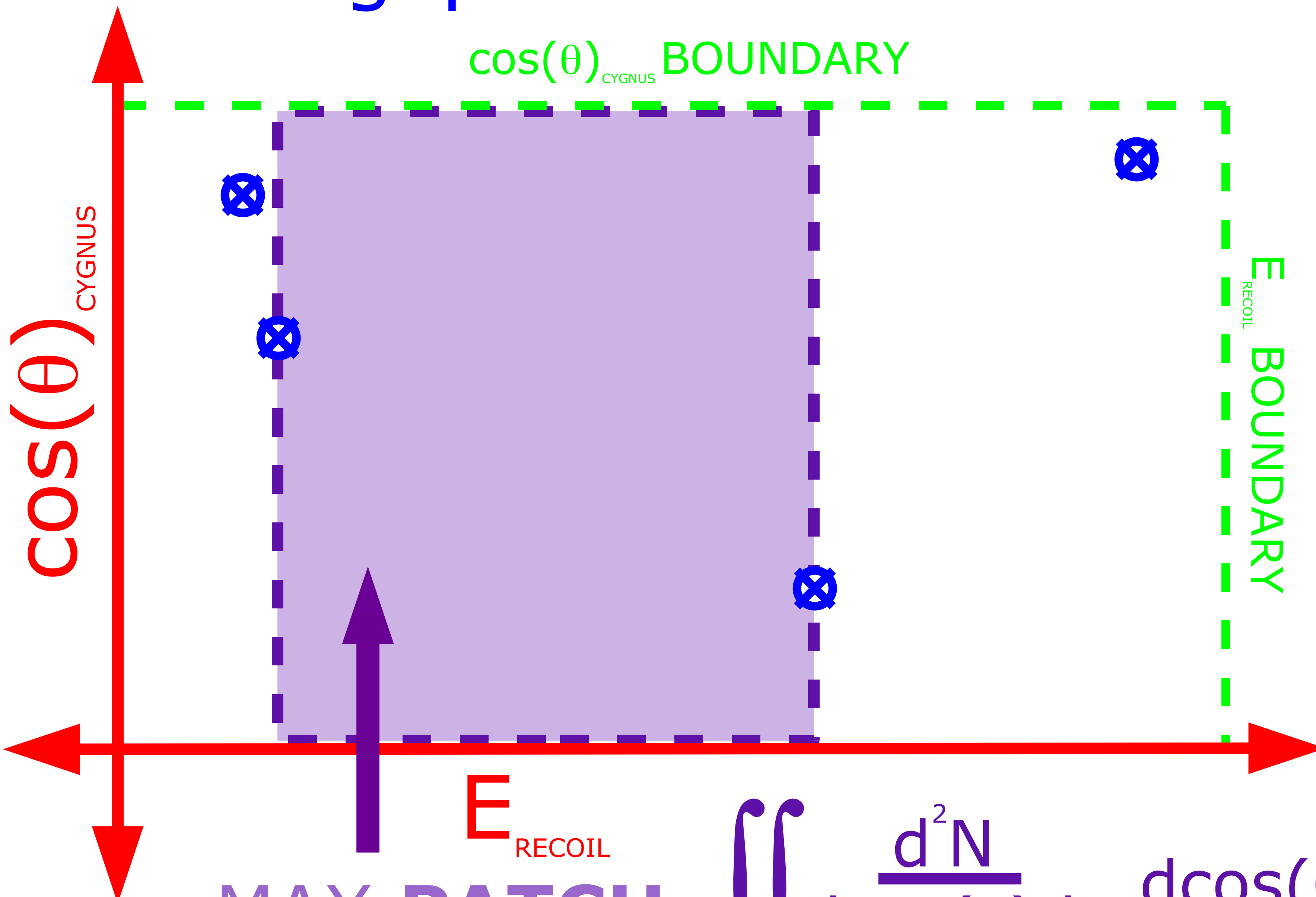
$$\frac{d^2R(v_E,\infty)}{dE_R\,d(\cos\psi)} = \frac{1}{2}\frac{R_0}{E_0 r}\,e^{-(v_E\cos\psi - v_{min})^2/v_0^2}$$

D. N. Spergel, Phys. Rev. D37 (1988) 1353





can we make a 2D analogue to the maximum gap?



$$\text{MAX } \textbf{PATCH} = \iint \frac{d^2N}{d\cos(\theta)dE} \, d\cos(\theta)dE$$

S. Henderson et al., Phys. Rev. D78, 015020 (2008)

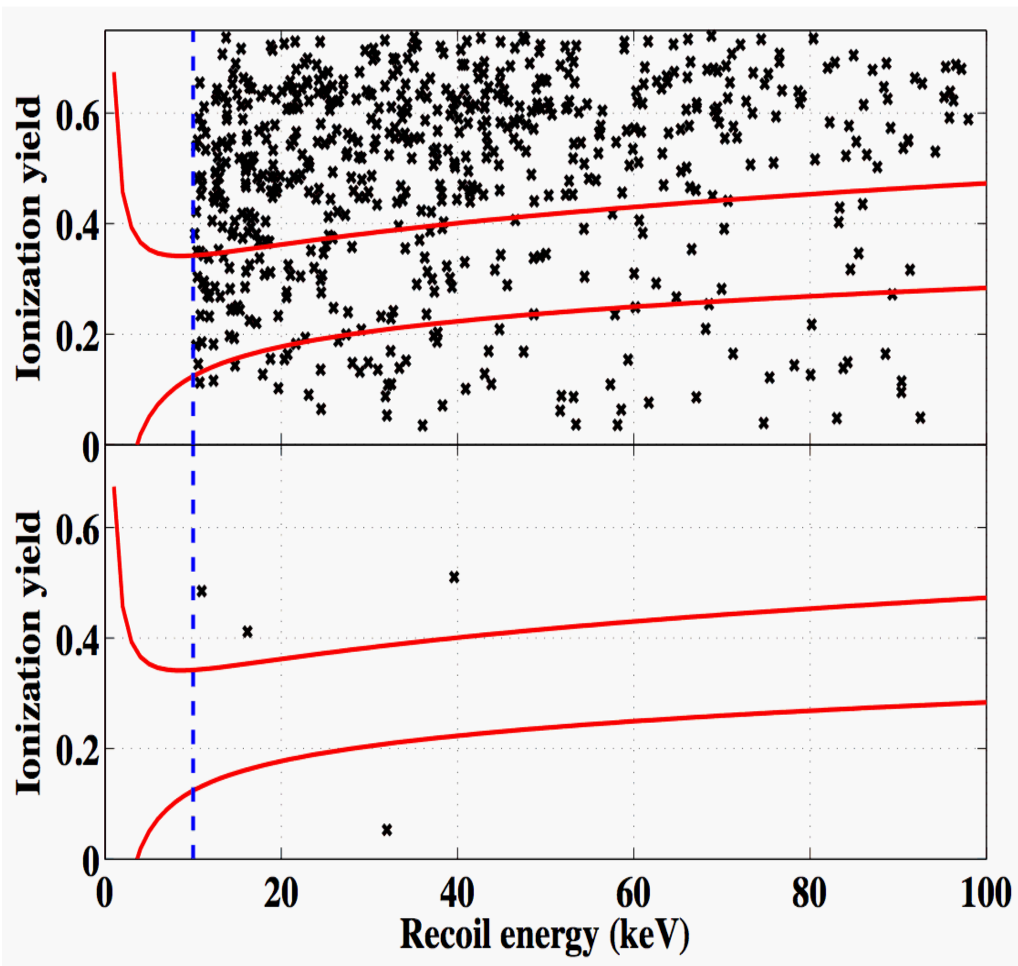
why is this worth thinking about?
two cases:

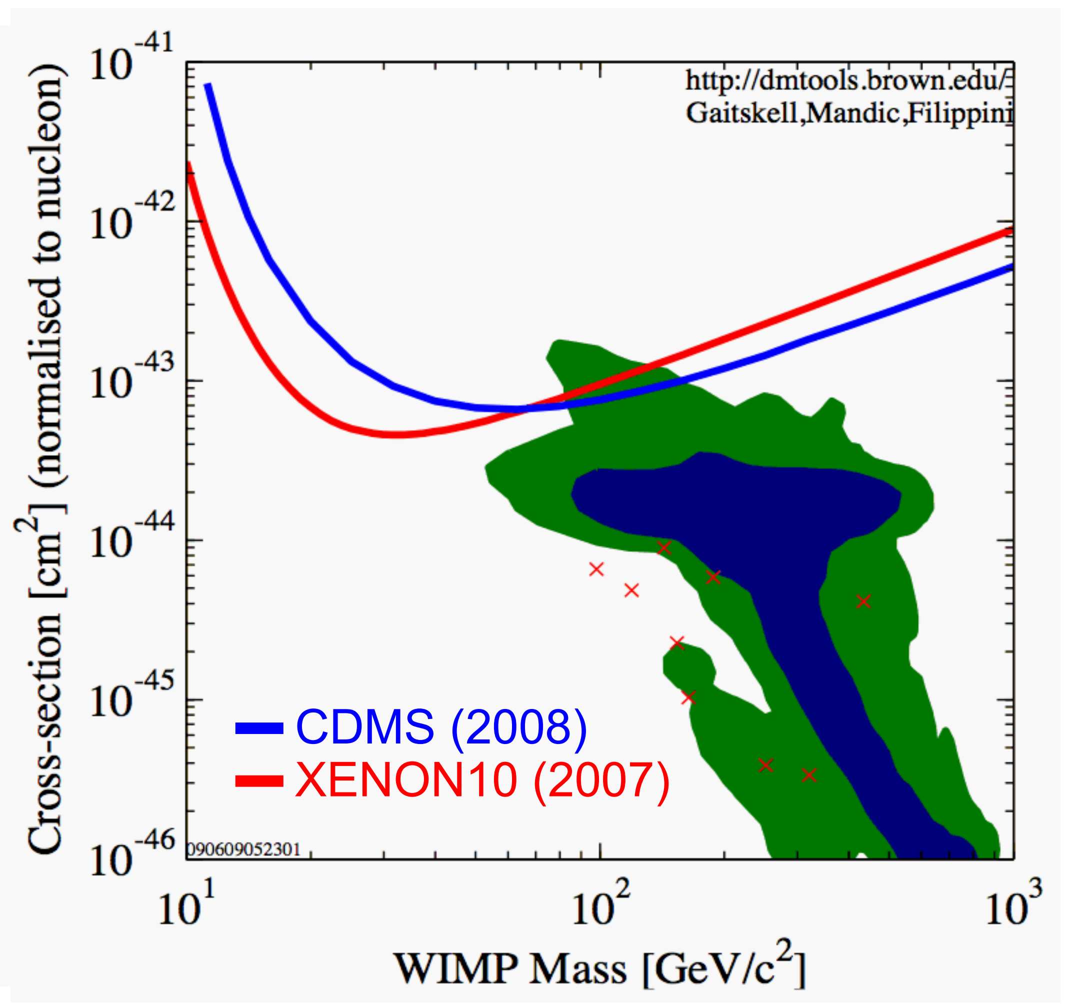
CDMS

Z. Ahmed et al., PRL 102, 011301 (2009)

observes zero events

exposure=121 kg*days

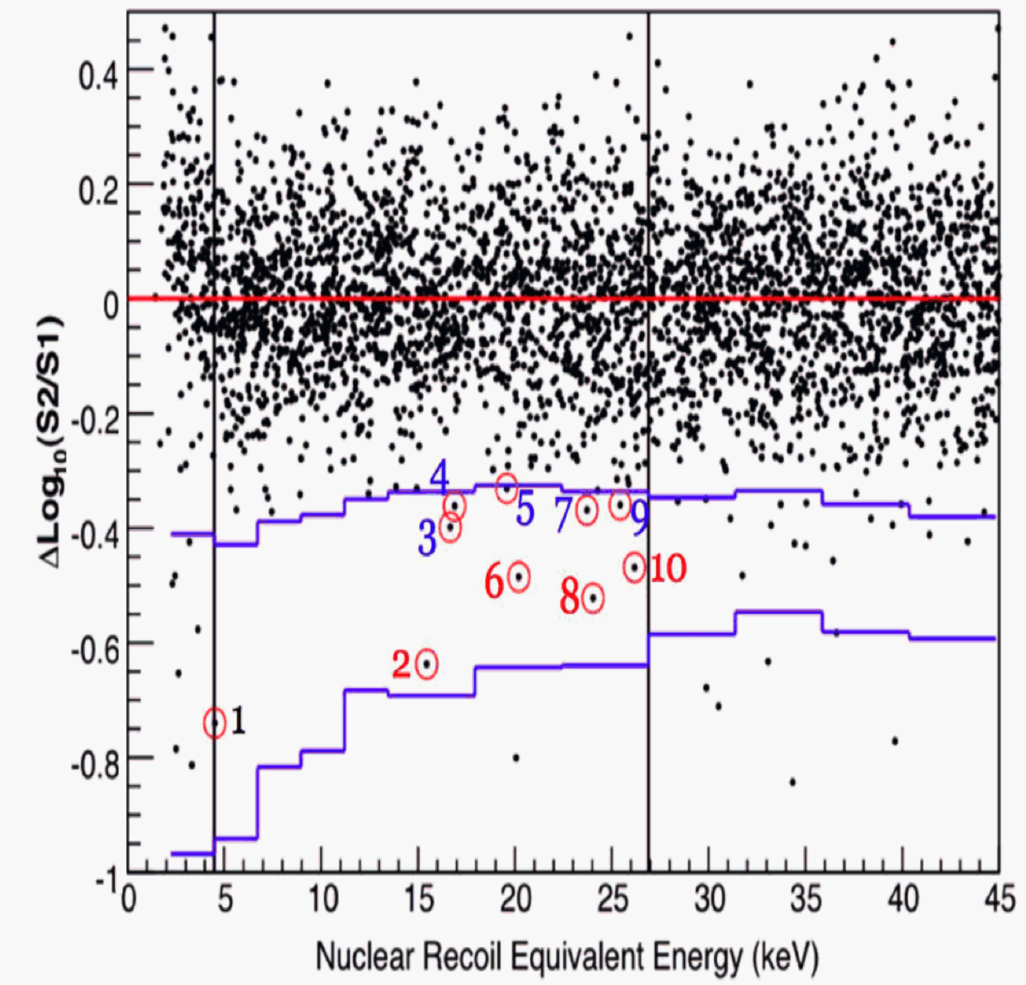


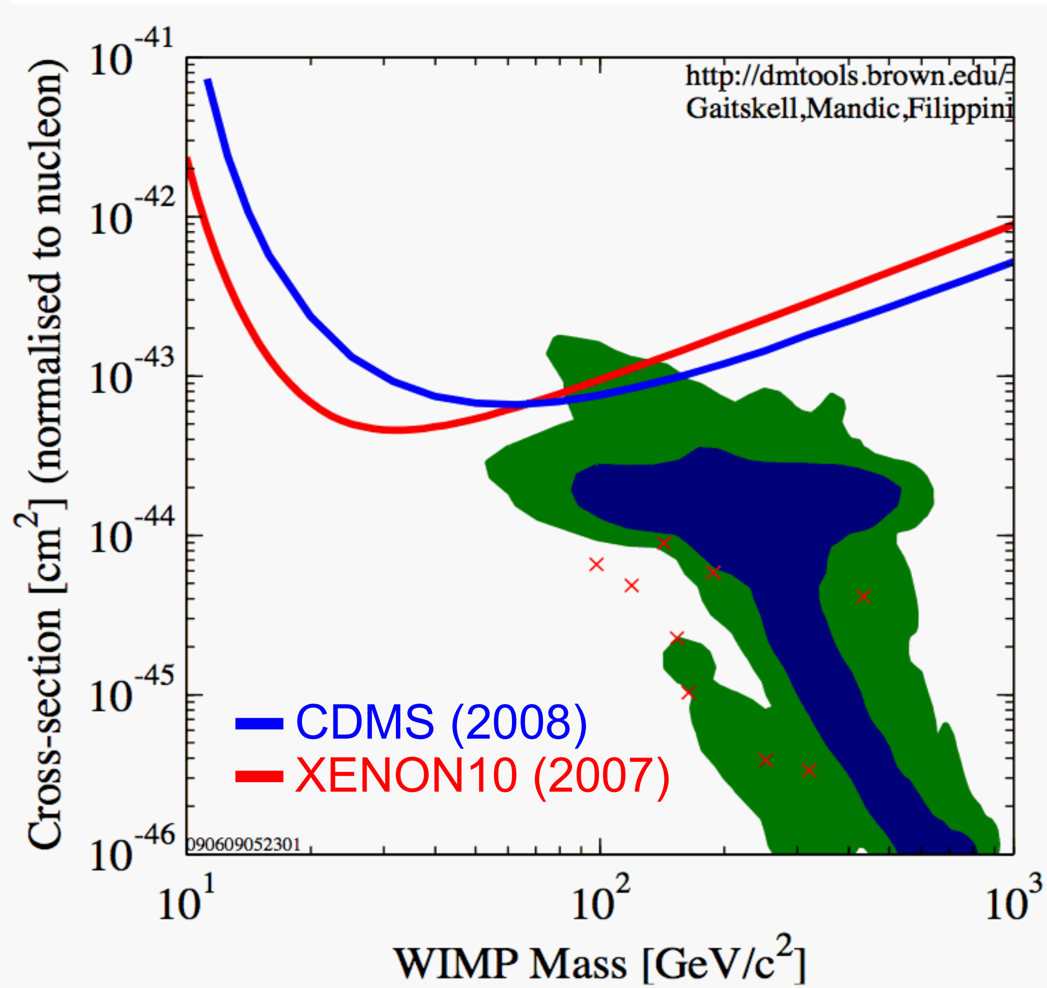


J. Angle et al., PRL 100, 021303 (2008)

observes ten events

exposure=136 kg*days

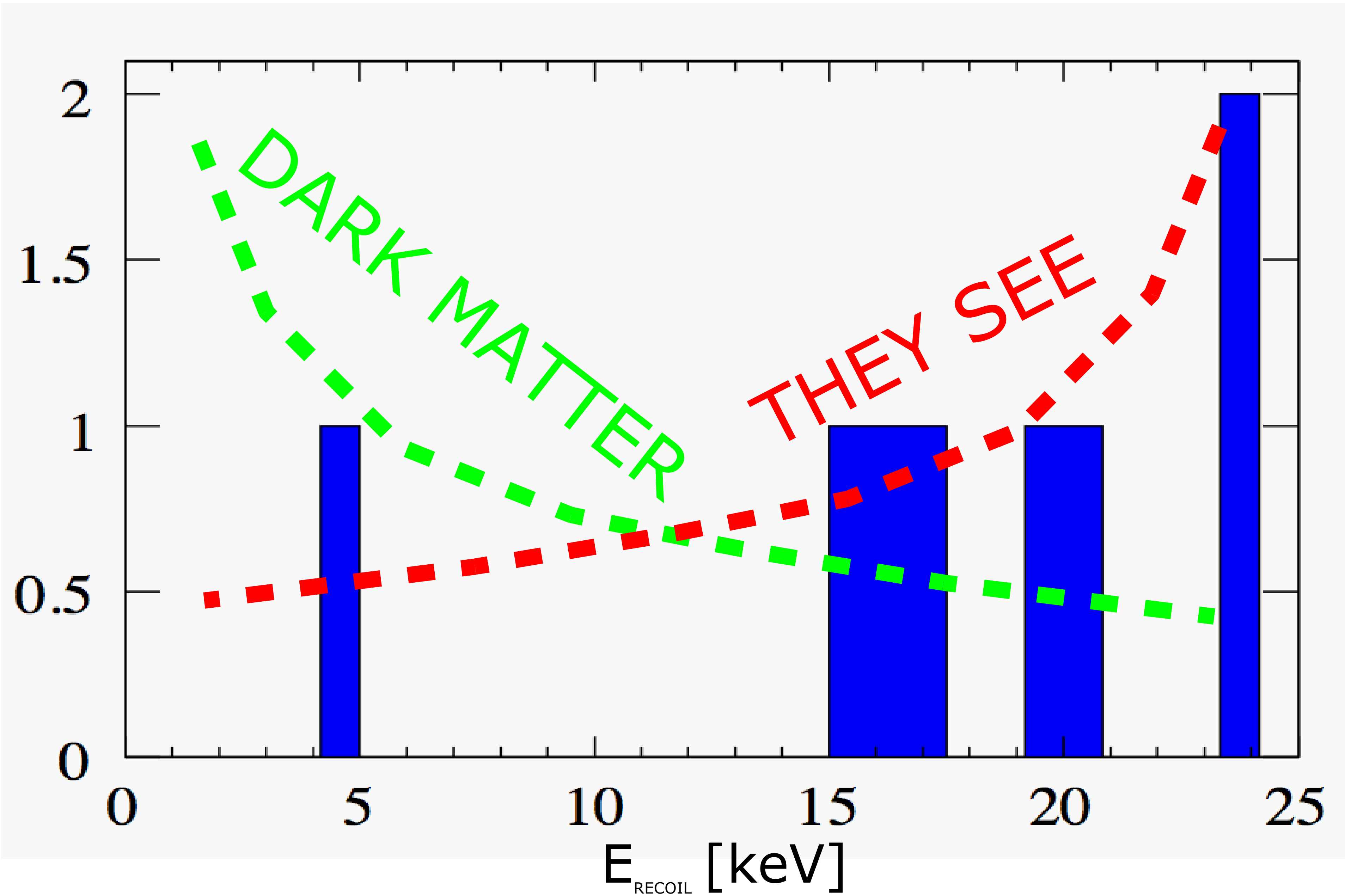


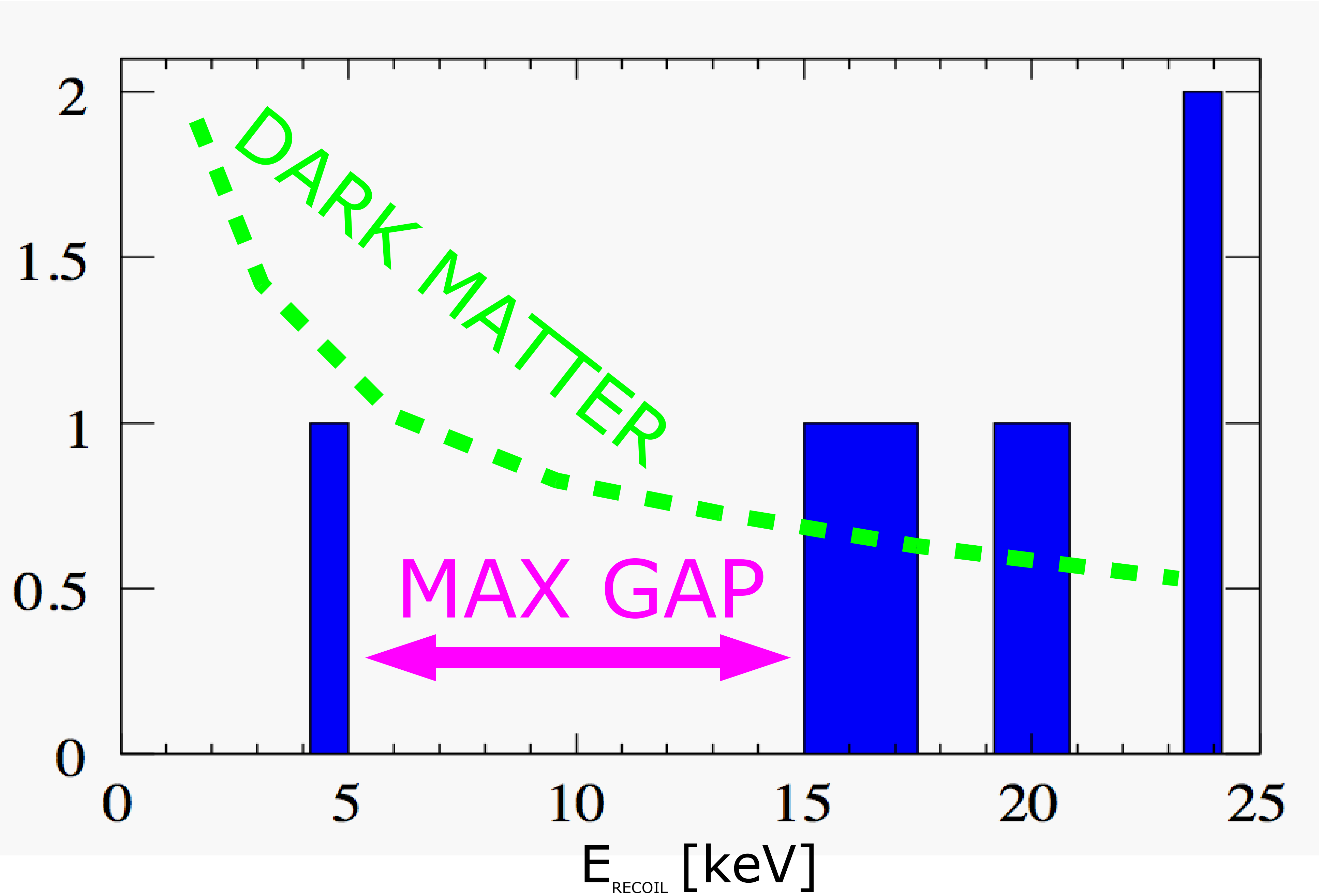


10 events and similar exposures!?

why are they competitive?

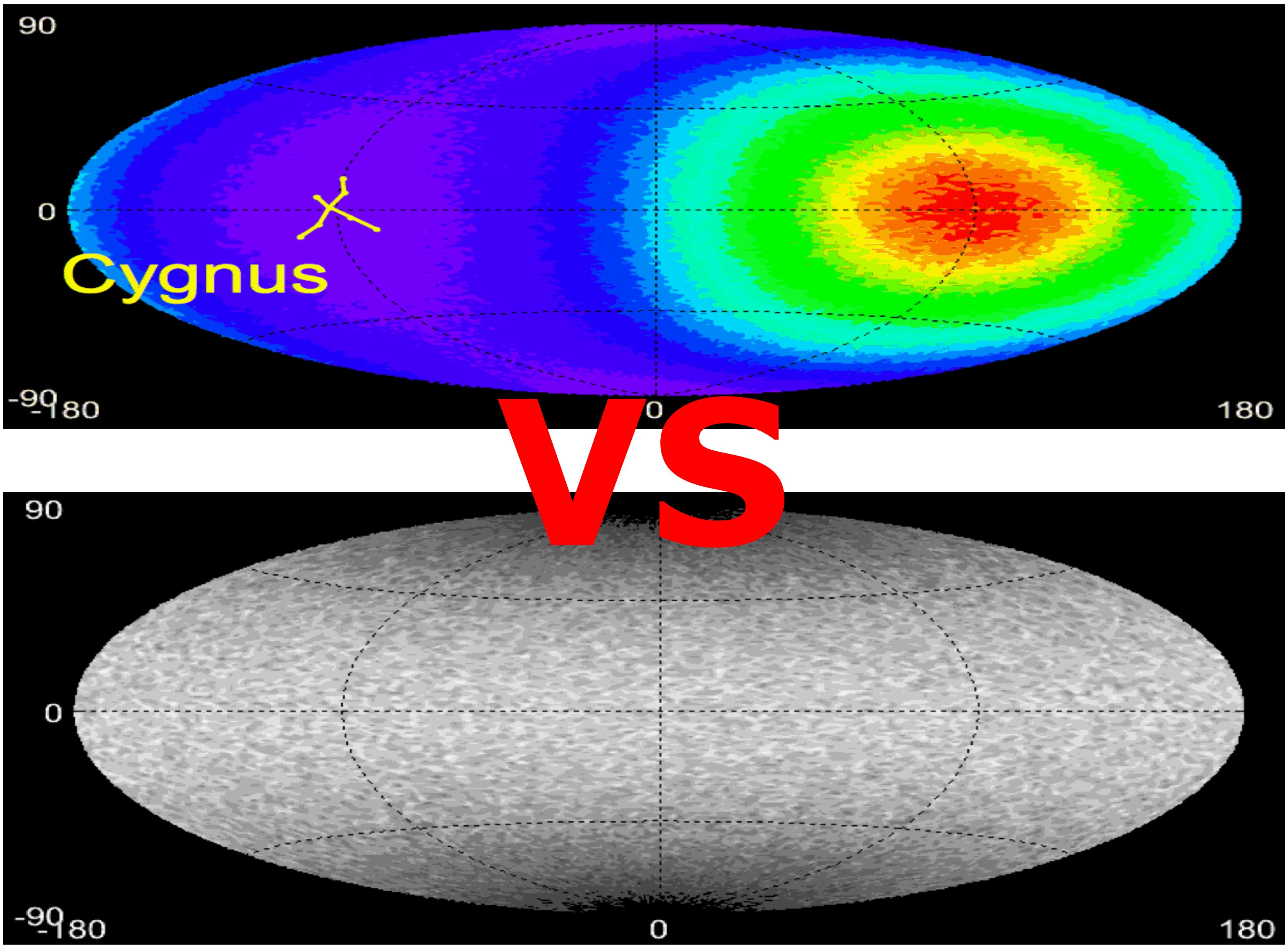
project Xe XENON Dark Matter Project onto E_{RECOIL}:





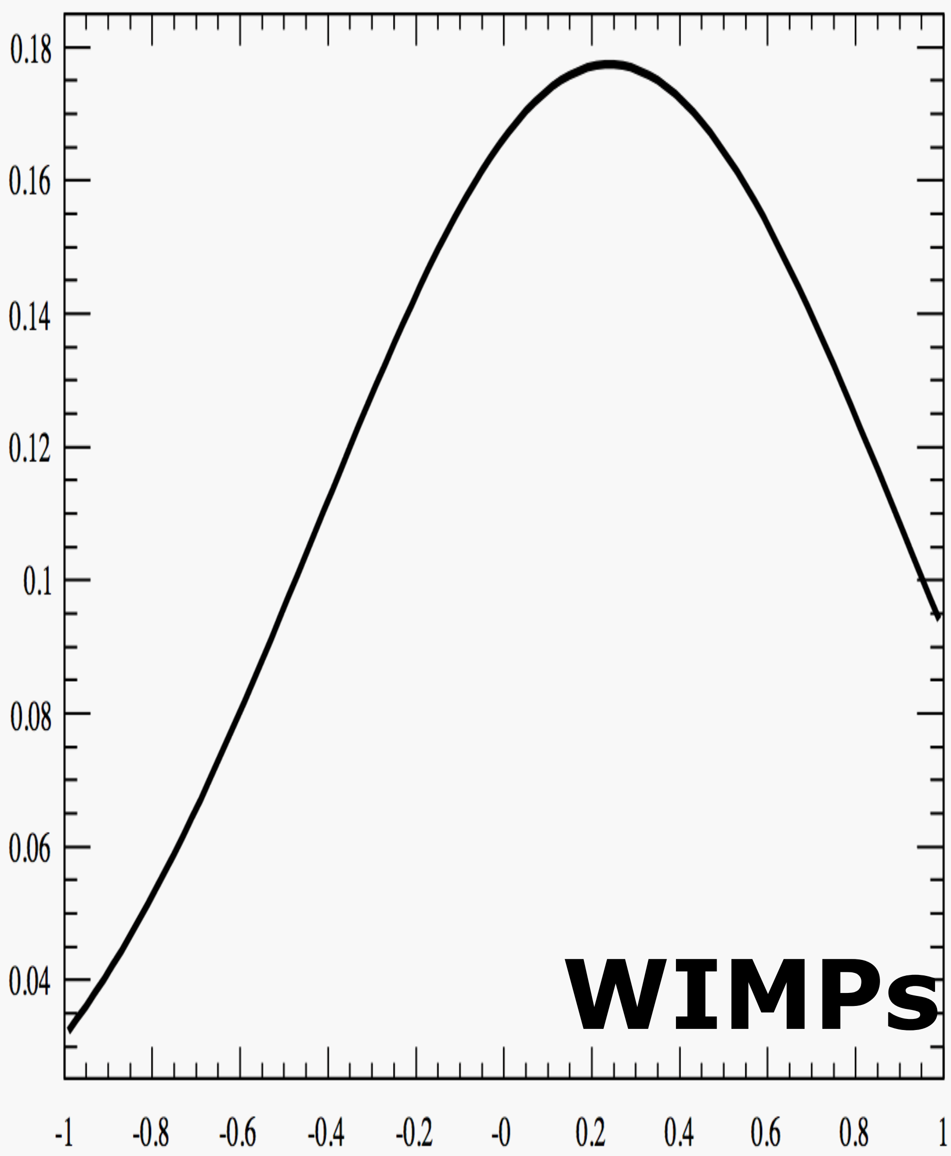
max gap sets a much tighter limit than poisson because it knows what signal looks like

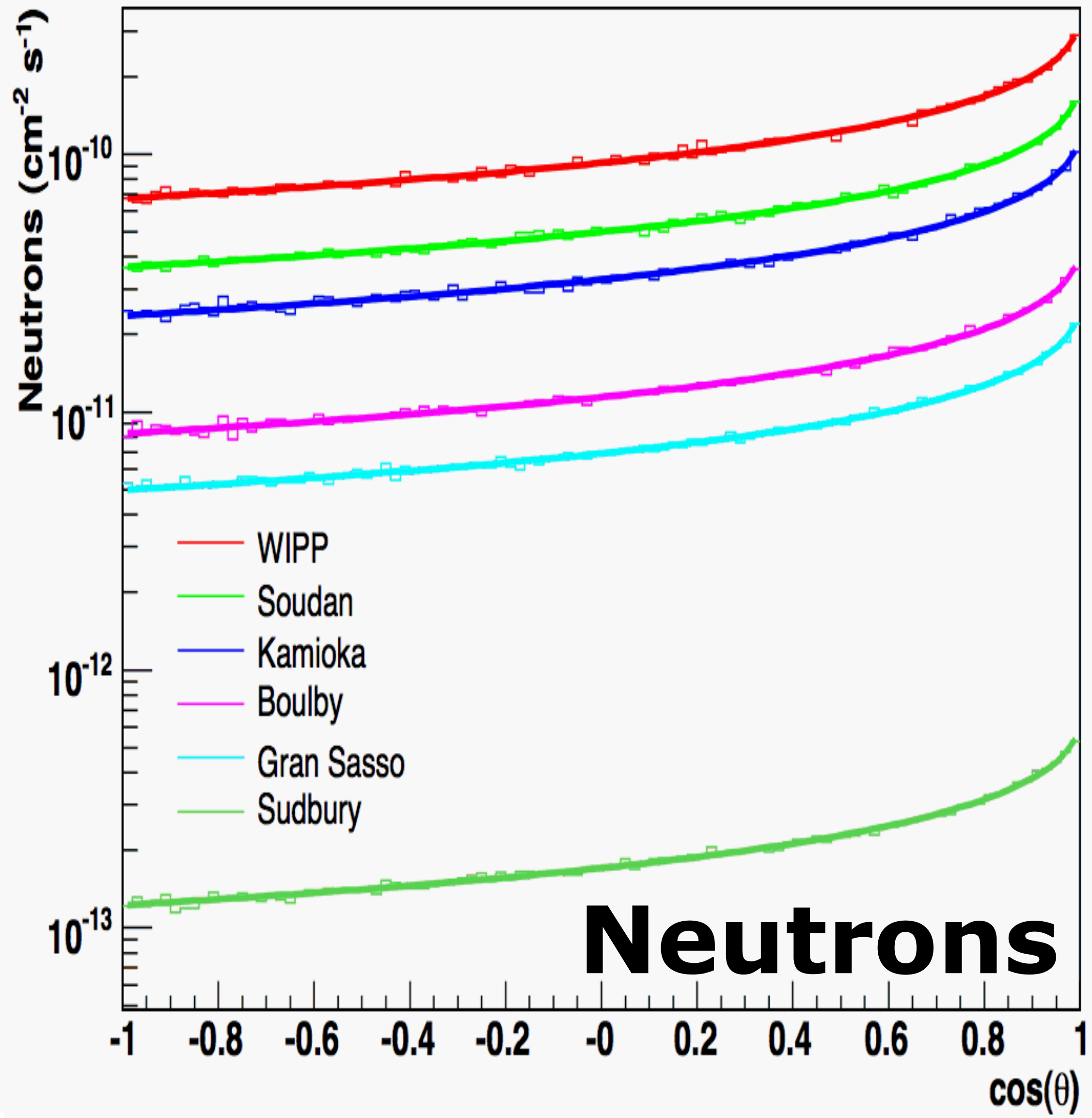
we have a strong angular anisotropy to exploit



D. N. Spergel, Phys. Rev. D37 (1988) 1353

D. M. Mei and A. Hime, Phys. Rev. D73, 053004 (2006)



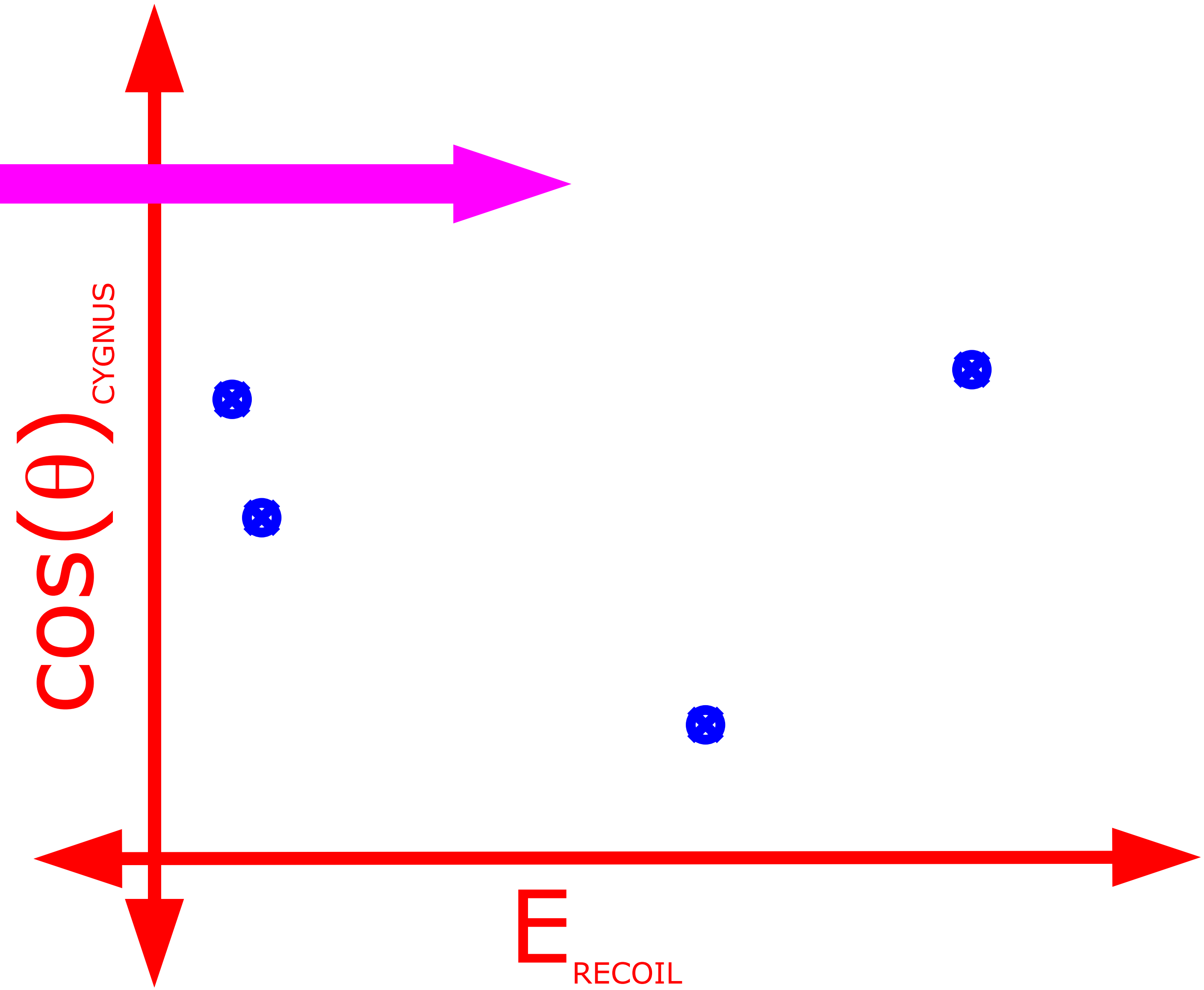


cos(θ)$_{CYGNUS}$

so what's the recipe?

1) take some data (hard part):

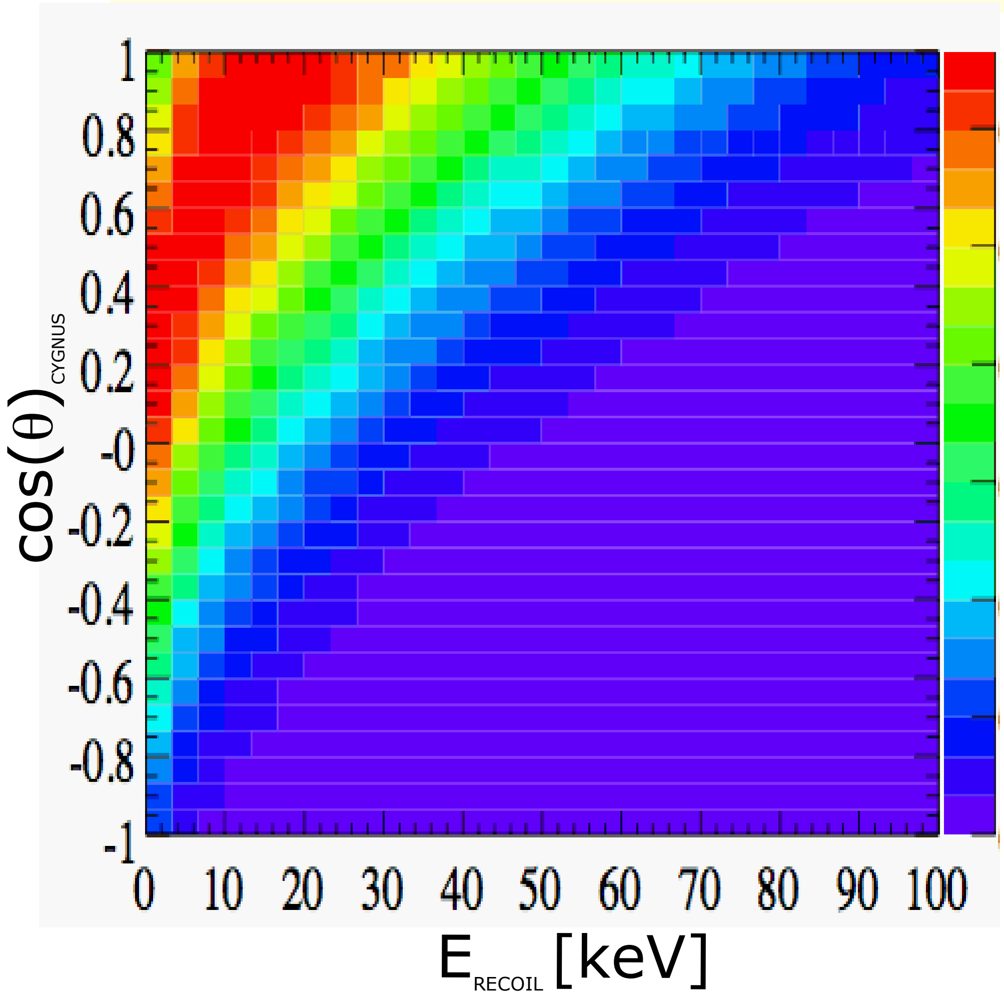
shameless
DMTPC
plug

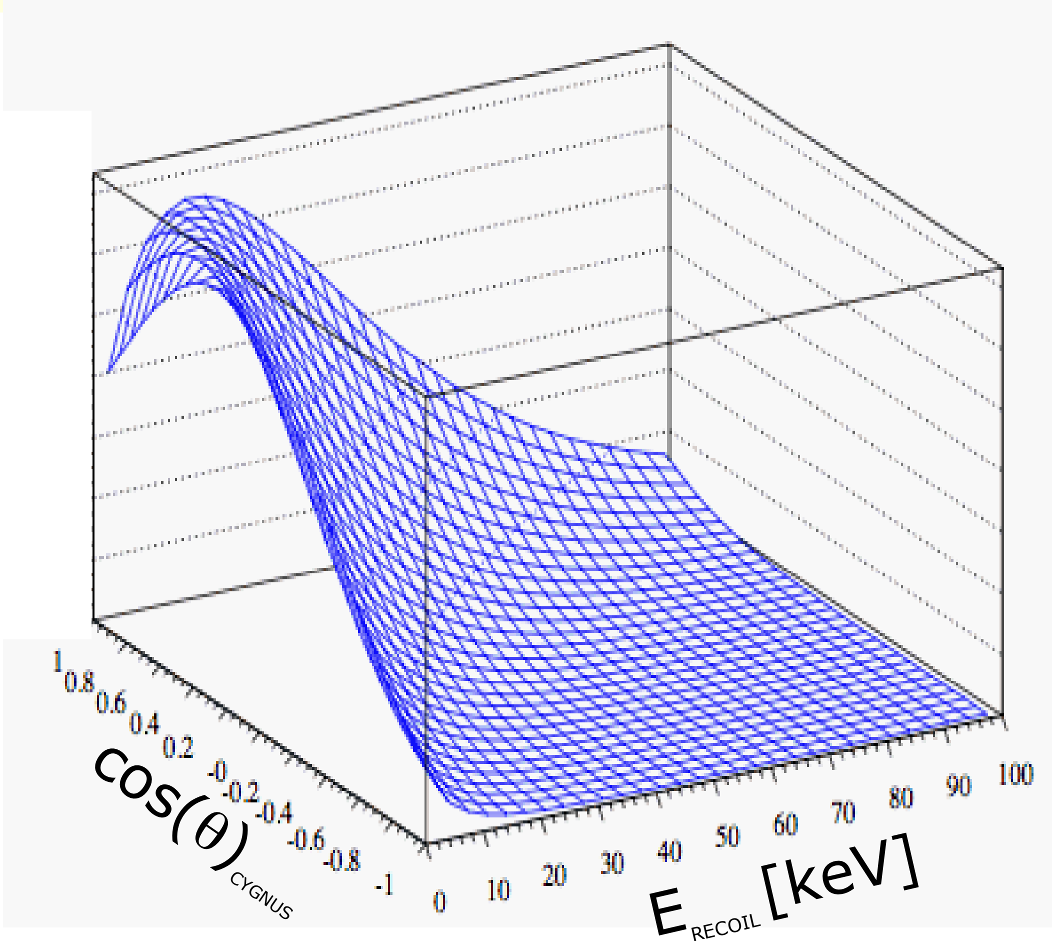


2) pick a model for the 2D WIMP detection rate

$$\frac{d^2R(v_E,\infty)}{dE_R\,d(\cos\psi)} = \frac{1}{2}\frac{R_0}{E_0 r}\,e^{-(v_E\cos\psi - v_{min})^2/v_0^2}$$

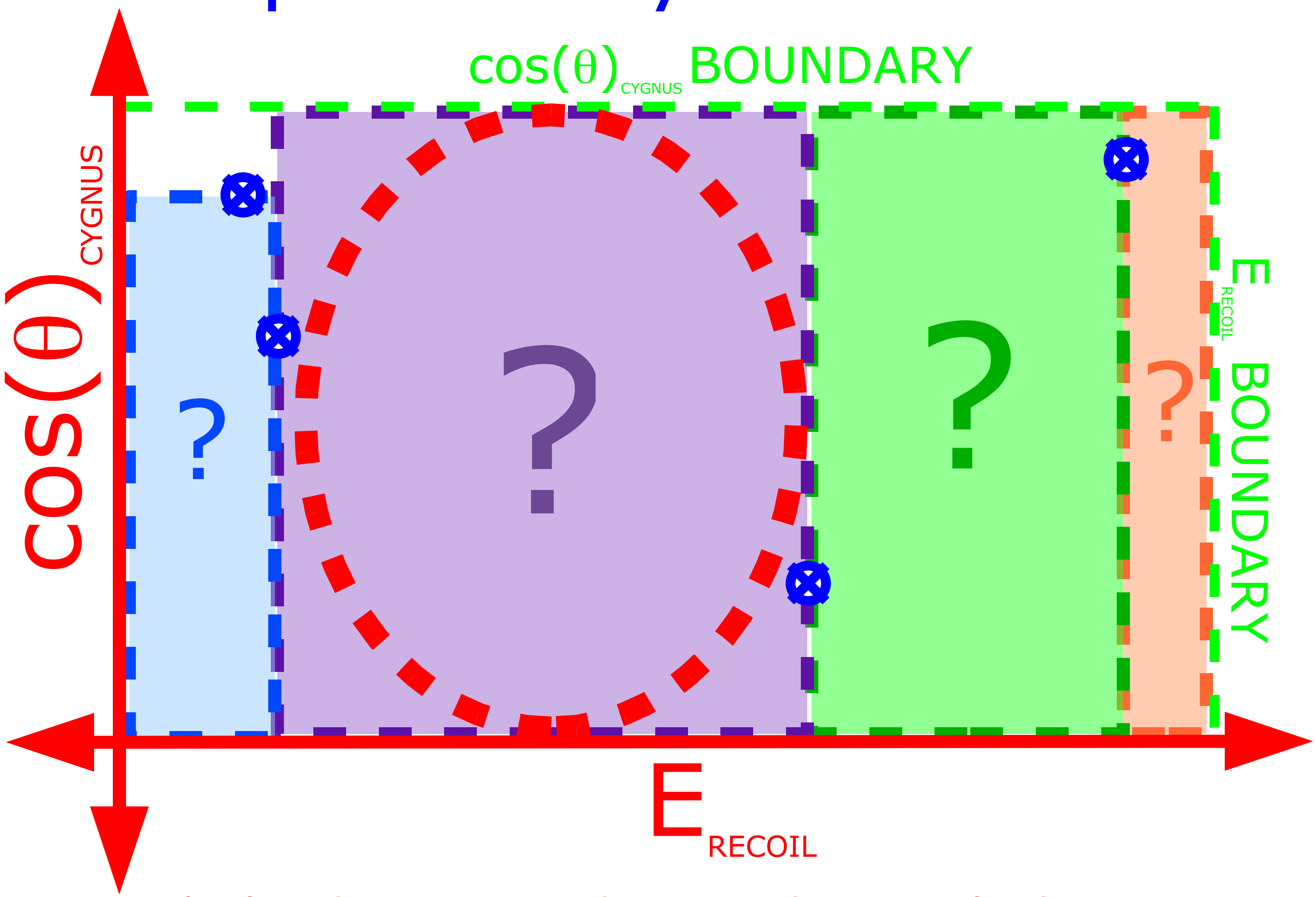
D. N. Spergel, Phys. Rev. D37 (1988) 1353





3a) you see zero events – set a poisson limit

3b) you see events – calculate the maximum patch of your data



an example algorithm is presented in S. Henderson et al., Phys. Rev. D78, 015020 (2008)

4) use our calculated maximum patch CDFs to get probability of that patch

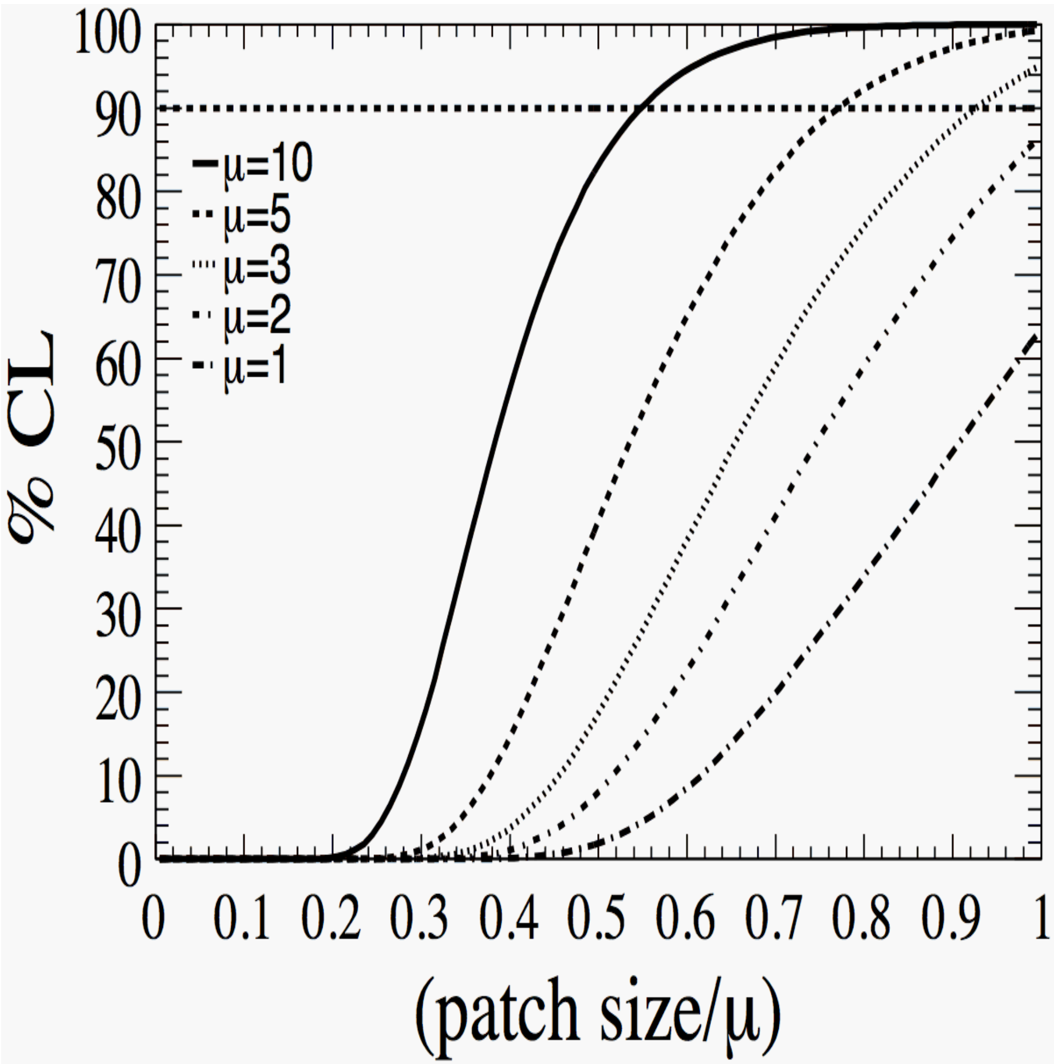


TABLE I: Table of maximum patch CDF's (the $\hat{h}_{c,k}(x_{SI})$'s of section IV A) given an observation of $n = 1, ..., 54$ events. These values of the CDFs are given as a function of the observed maximum patch divided by the total expected number of events. Upper limits can be set on two-dimensional data with these tabulated CDFs following the recipe laid out in section IV C.

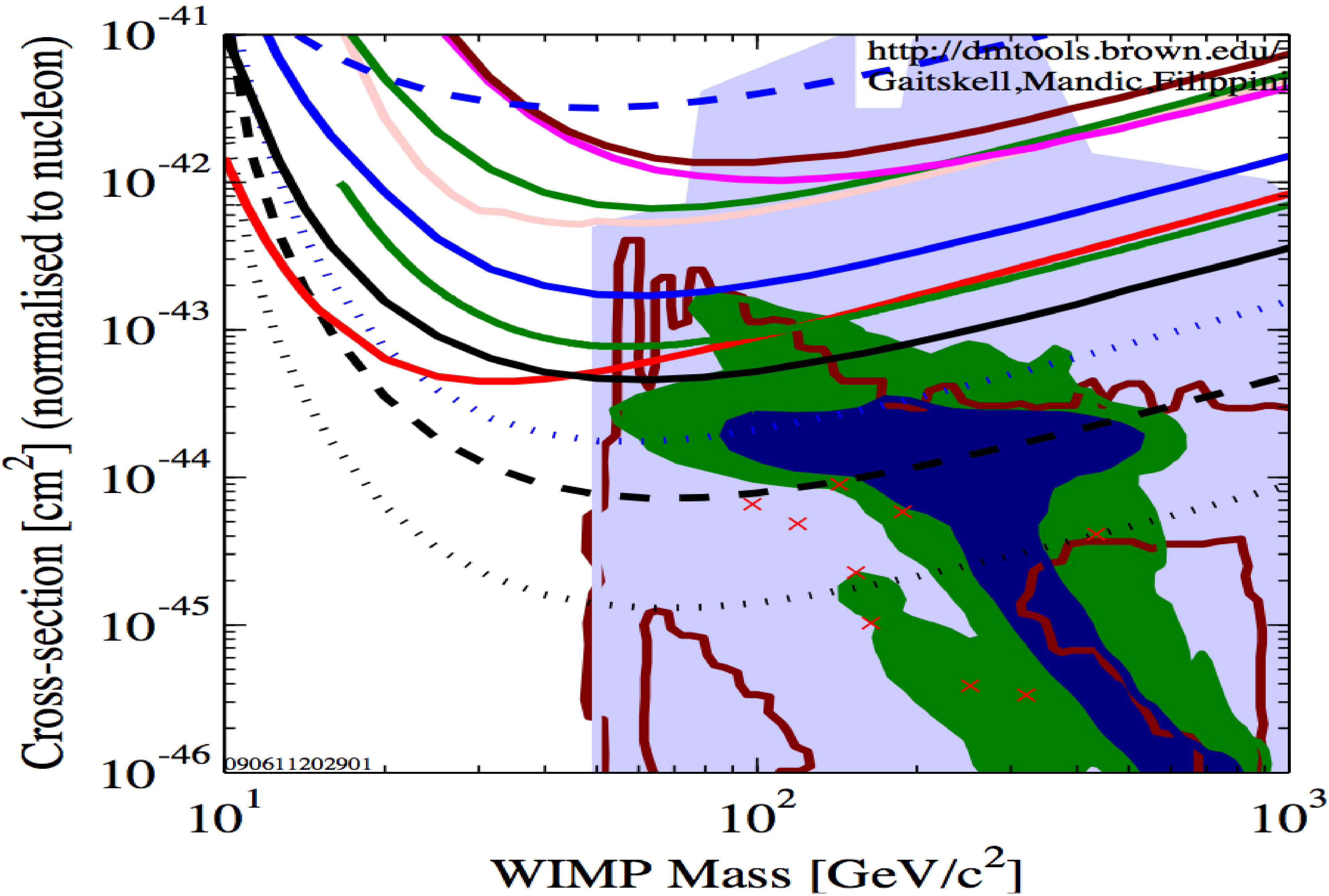
(y/μ)	n=1	n=2	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10	n=11	n=12	n=13	n=14	n=15	n=16	n=17	n=18
$\leq$ 0.17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.004	0.006	0.013	0.022	0.038
0.24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.008	0.017	0.030	0.056	0.093	0.141	0.192	0.251
0.28	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.011	0.024	0.047	0.081	0.131	0.188	0.263	0.339	0.420	0.483	0.556
0.32	0.000	0.000	0.000	0.000	0.002	0.012	0.034	0.071	0.119	0.189	0.271	0.359	0.447	0.534	0.606	0.679	0.735	0.786
0.36	0.000	0.000	0.000	0.005	0.024	0.063	0.121	0.199	0.292	0.409	0.509	0.596	0.676	0.748	0.796	0.836	0.878	0.907
0.40	0.000	0.000	0.007	0.034	0.091	0.170	0.283	0.395	0.505	0.627	0.706	0.768	0.828	0.869	0.902	0.930	0.956	0.969
0.44	0.000	0.003	0.030	0.102	0.204	0.318	0.464	0.583	0.679	0.775	0.842	0.884	0.920	0.948	0.965	0.976	0.986	0.992
0.48	0.000	0.015	0.083	0.204	0.345	0.481	0.619	0.730	0.814	0.875	0.924	0.950	0.969	0.980	0.987	0.993	0.997	0.997
0.52	0.003	0.056	0.171	0.324	0.491	0.631	0.749	0.841	0.895	0.936	0.965	0.979	0.986	0.991	0.996	0.997	0.998	0.999
0.56	0.017	0.115	0.276	0.448	0.628	0.755	0.843	0.911	0.943	0.969	0.983	0.990	0.993	0.997	0.998	0.999	1.000	1.000
0.60	0.042	0.190	0.400	0.578	0.732	0.838	0.911	0.951	0.973	0.987	0.994	0.996	0.997	0.999	0.999	1.000	1.000	1.000
0.64	0.080	0.286	0.518	0.691	0.817	0.902	0.954	0.975	0.987	0.993	0.997	0.998	0.999	1.000	1.000	1.000	1.000	1.000
0.68	0.134	0.376	0.625	0.788	0.891	0.946	0.975	0.986	0.993	0.997	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000
0.72	0.194	0.491	0.726	0.865	0.944	0.975	0.990	0.994	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.76	0.276	0.608	0.820	0.916	0.975	0.991	0.997	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.80	0.368	0.705	0.877	0.953	0.989	0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.84	0.471	0.801	0.935	0.980	0.996	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.88	0.581	0.883	0.969	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.92	0.717	0.946	0.991	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.96	0.859	0.985	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

(y/μ)	n=19	n=20	n=21	n=22	n=23	n=24	n=25	n=26	n=27	n=28	n=29	n=30	n=31	n=32	n=33	n=34	n=35	n=36
$\leq$0.10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.003	0.003	0.007
0.14	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.002	0.003	0.006	0.009	0.014	0.021	0.033	0.046	0.059	0.074	0.093
0.16	0.001	0.002	0.003	0.005	0.009	0.015	0.025	0.036	0.052	0.069	0.093	0.117	0.143	0.168	0.199	0.232	0.273	0.315
0.18	0.010	0.014	0.025	0.036	0.055	0.084	0.119	0.155	0.193	0.227	0.271	0.313	0.352	0.396	0.437	0.482	0.521	0.560
0.20	0.057	0.081	0.117	0.154	0.200	0.249	0.293	0.344	0.385	0.433	0.492	0.533	0.571	0.611	0.645	0.682	0.717	0.751
0.22	0.164	0.209	0.269	0.321	0.370	0.423	0.476	0.528	0.576	0.625	0.676	0.715	0.744	0.777	0.800	0.824	0.854	0.874
0.24	0.313	0.368	0.432	0.493	0.547	0.596	0.651	0.696	0.731	0.767	0.804	0.835	0.855	0.879	0.893	0.908	0.928	0.939
0.26	0.486	0.548	0.609	0.655	0.703	0.748	0.786	0.820	0.841	0.870	0.895	0.913	0.929	0.940	0.950	0.958	0.966	0.972
0.28	0.627	0.686	0.736	0.781	0.814	0.847	0.874	0.893	0.912	0.930	0.946	0.954	0.962	0.968	0.975	0.980	0.985	0.987
0.30	0.745	0.789	0.826	0.858	0.881	0.904	0.926	0.941	0.956	0.966	0.975	0.980	0.985	0.987	0.991	0.993	0.995	0.996
0.32	0.826	0.866	0.895	0.917	0.932	0.946	0.958	0.966	0.975	0.982	0.989	0.992	0.994	0.995	0.996	0.997	0.998	0.999
0.34	0.887	0.915	0.931	0.947	0.956	0.965	0.975	0.980	0.987	0.990	0.994	0.996	0.997	0.998	0.999	0.999	1.000	1.000
0.36	0.931	0.950	0.963	0.972	0.977	0.981	0.988	0.990	0.993	0.995	0.996	0.998	0.999	1.000	1.000	1.000	1.000	1.000
0.38	0.960	0.975	0.982	0.987	0.990	0.991	0.995	0.996	0.998	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.40	0.979	0.986	0.991	0.994	0.995	0.997	0.999	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
$\geq$0.42	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

(y/μ)	n=37	n=38	n=39	n=40	n=41	n=42	n=43	n=44	n=45	n=46	n=47	n=48	n=49	n=50	n=51	n=52	n=53	n=54
$\leq$0.08	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.10	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.002	0.002	0.004	0.005	0.008	0.011	0.013	0.017	0.022	0.034
0.12	0.010	0.013	0.021	0.025	0.034	0.045	0.057	0.067	0.084	0.098	0.118	0.142	0.167	0.190	0.214	0.240	0.267	0.301
0.14	0.114	0.144	0.172	0.198	0.228	0.261	0.297	0.329	0.358	0.390	0.422	0.458	0.497	0.527	0.557	0.586	0.614	0.640
0.16	0.353	0.396	0.434	0.469	0.504	0.540	0.582	0.617	0.648	0.674	0.700	0.724	0.751	0.775	0.795	0.813	0.831	0.847
0.18	0.603	0.641	0.673	0.706	0.731	0.763	0.786	0.806	0.828	0.847	0.864	0.876	0.893	0.901	0.914	0.925	0.934	0.943
0.20	0.783	0.812	0.834	0.857	0.876	0.893	0.909	0.920	0.932	0.940	0.948	0.955	0.960	0.965	0.970	0.973	0.977	0.982
0.22	0.897	0.913	0.924	0.937	0.947	0.956	0.964	0.969	0.975	0.979	0.982	0.984	0.986	0.988	0.990	0.991	0.993	0.993
0.24	0.951	0.959	0.965	0.973	0.979	0.982	0.984	0.986	0.989	0.991	0.993	0.994	0.996	0.997	0.997	0.999	0.999	0.999
0.26	0.978	0.982	0.987	0.990	0.991	0.993	0.994	0.994	0.995	0.997	0.998	0.998	0.998	0.999	0.999	0.999	1.000	1.000
0.28	0.990	0.992	0.995	0.995	0.996	0.996	0.997	0.997	0.998	0.999	0.999	0.999	0.999	0.999	0.999	0.999	1.000	1.000
$\geq$0.30	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

the CDF tables and a play-by-play description of how to use them is presented in S. Henderson et al., Phys. Rev. D78, 015020 (2008)

5) set an upper limit!



CONCLUSIONS

1) god forbid, but if you see backgrounds, we've developed a 2D version of the maximum gap method

2) doesn't require a background model or subtraction

3) not just for dark matter! works for any limit setting in 2D*

4) we plan to deploy this method on DMTPC data from our upcoming WIPP run