Luminous Signals of Inelastic Dark Matter in Large Detectors

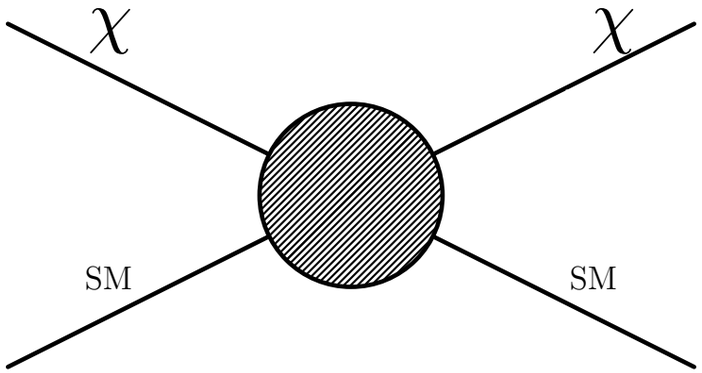
Patrick Fox

Fermilab

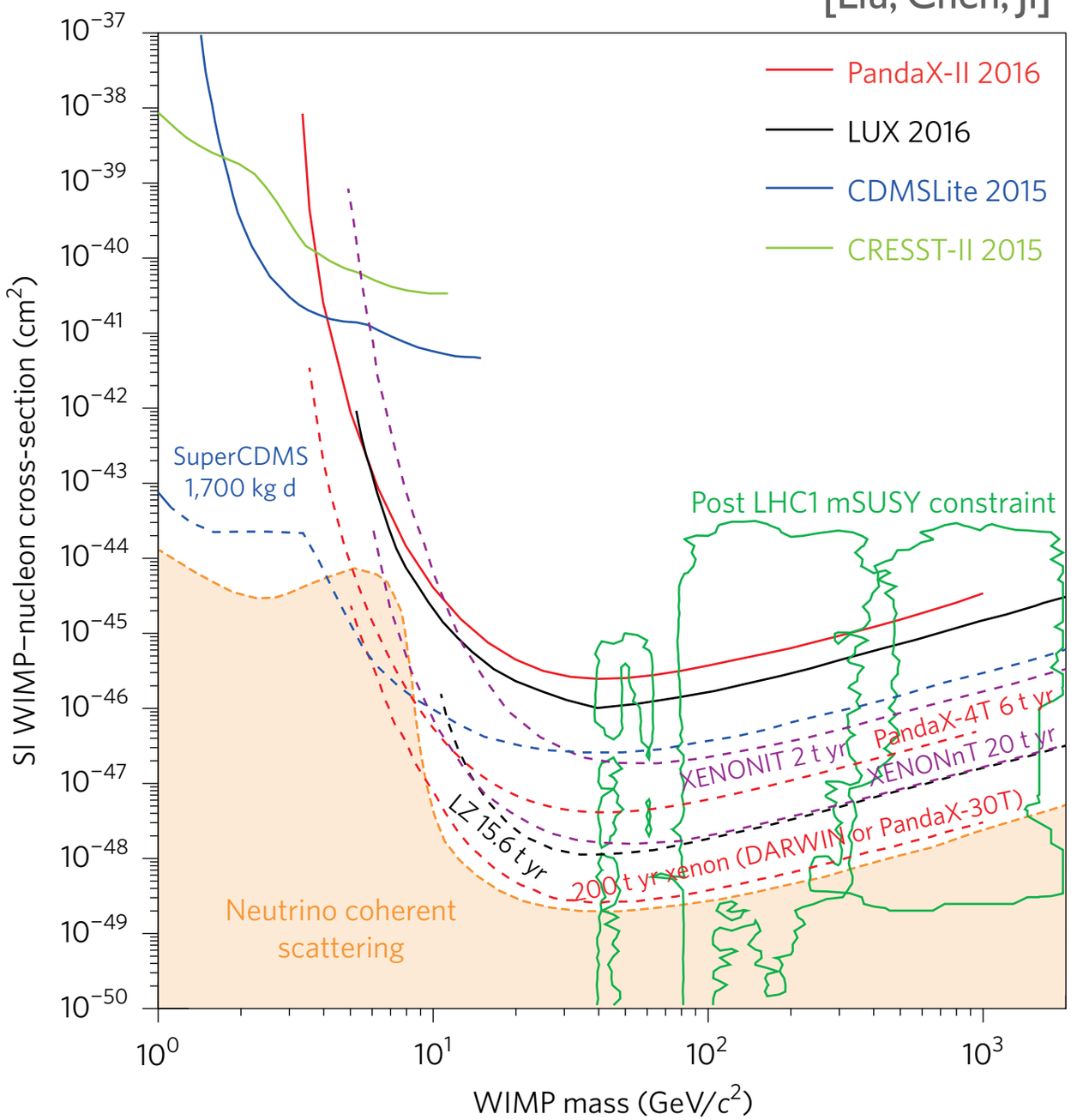
NEW PHYSICS KOREA INSTITUTE

Bramante, PF, Kribs, Martin (1608.02662)
Eby, PF, Harnik, Kribs (1904.09994)

Status of Direct Detection



[Liu, Chen, Ji]



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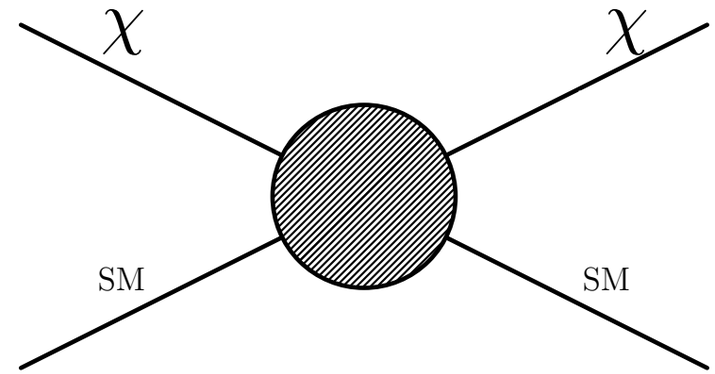

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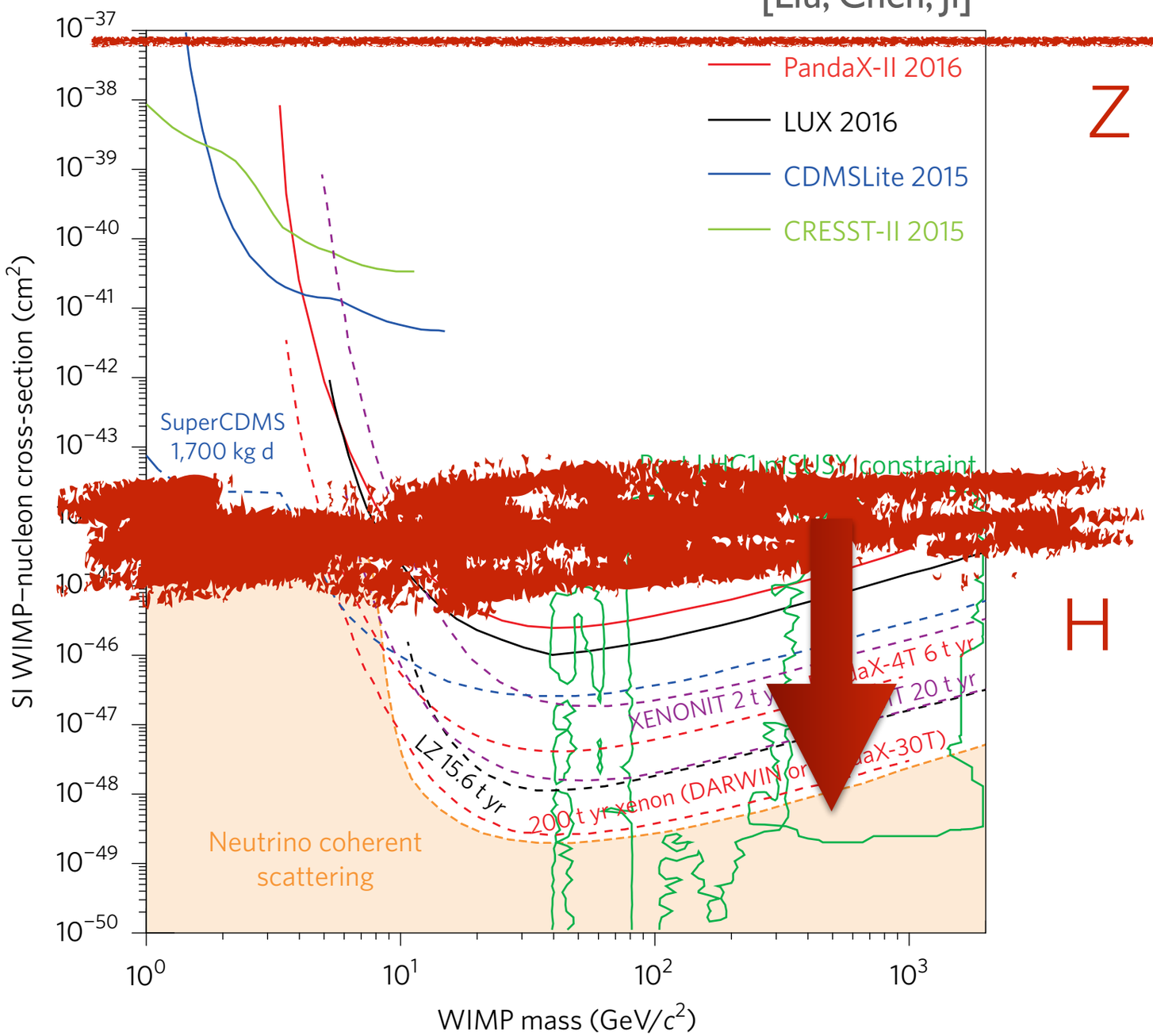
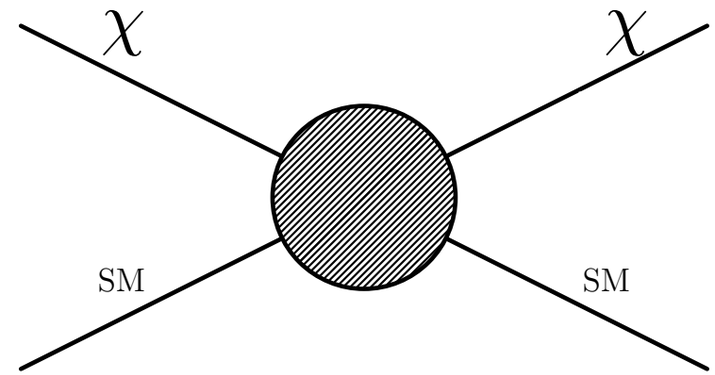
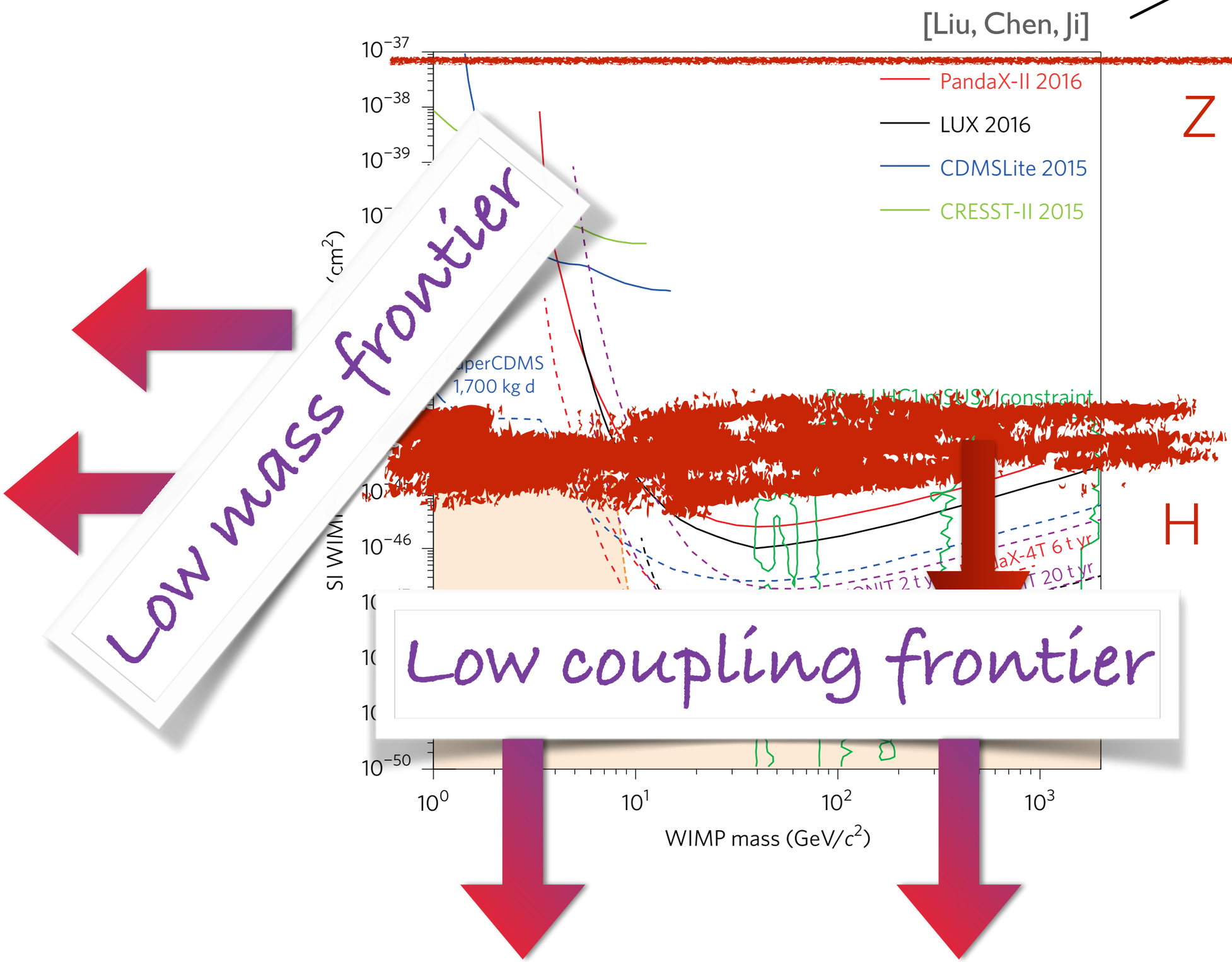


Z

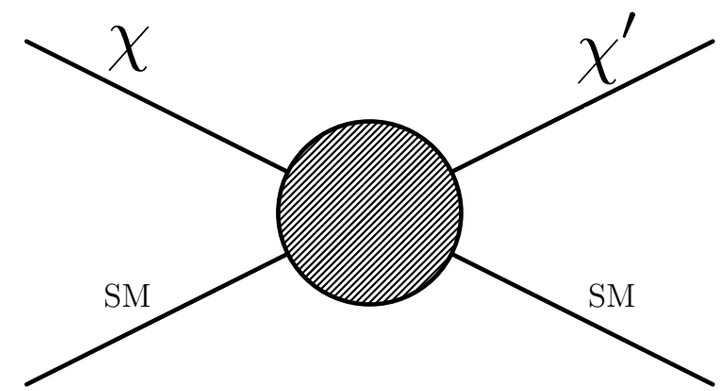
H

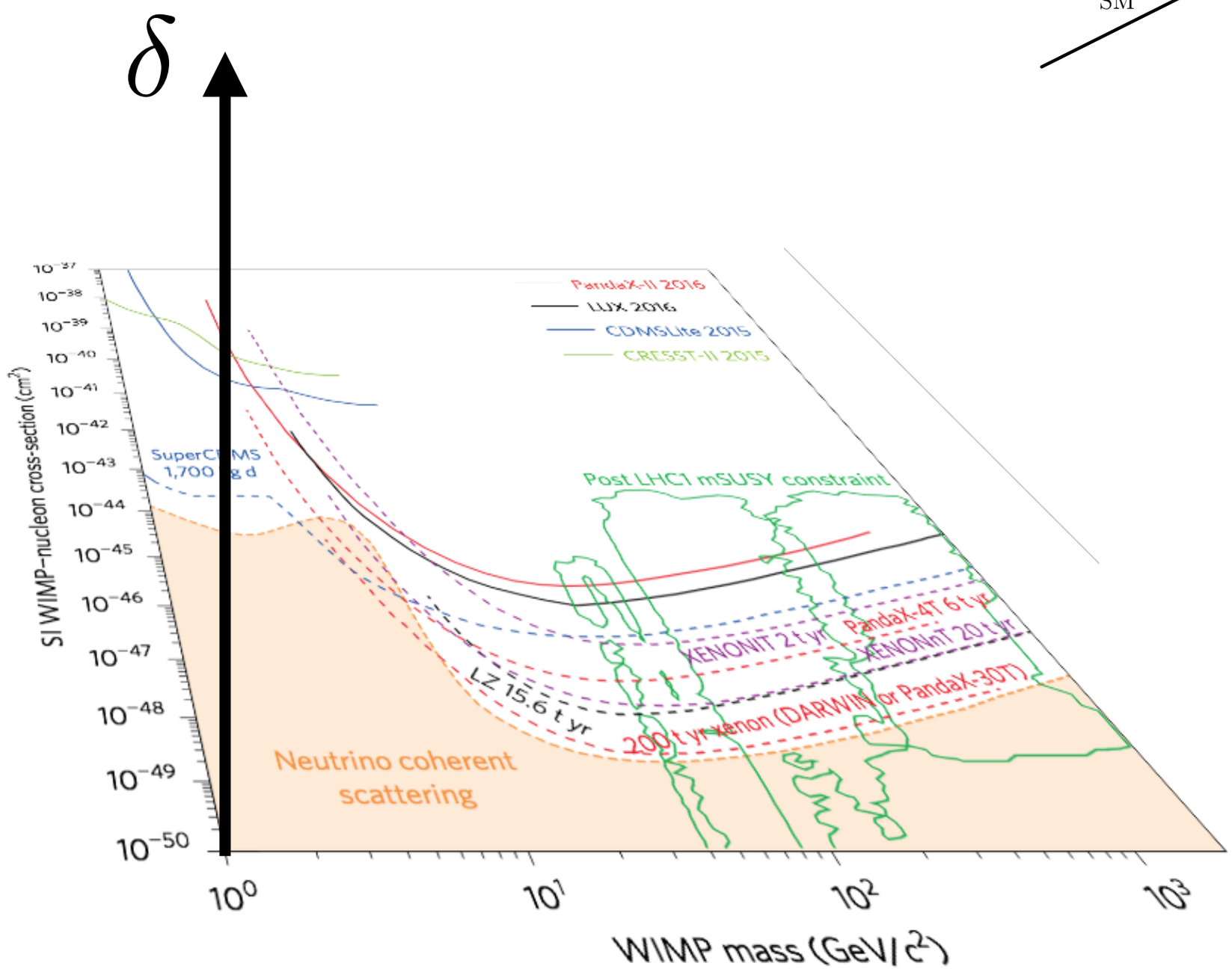
Status of Direct Detection





Inelastic scattering of DM





[Graham, Harnik, Rajendran, Saraswat]

$$\delta \equiv m_{\chi'} - m_{\chi}$$

Can be endothermic (iDM) or exothermic

[Tucker-Smith and Weiner]

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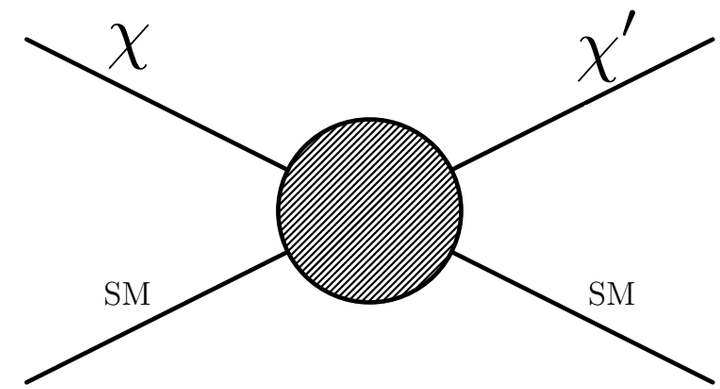
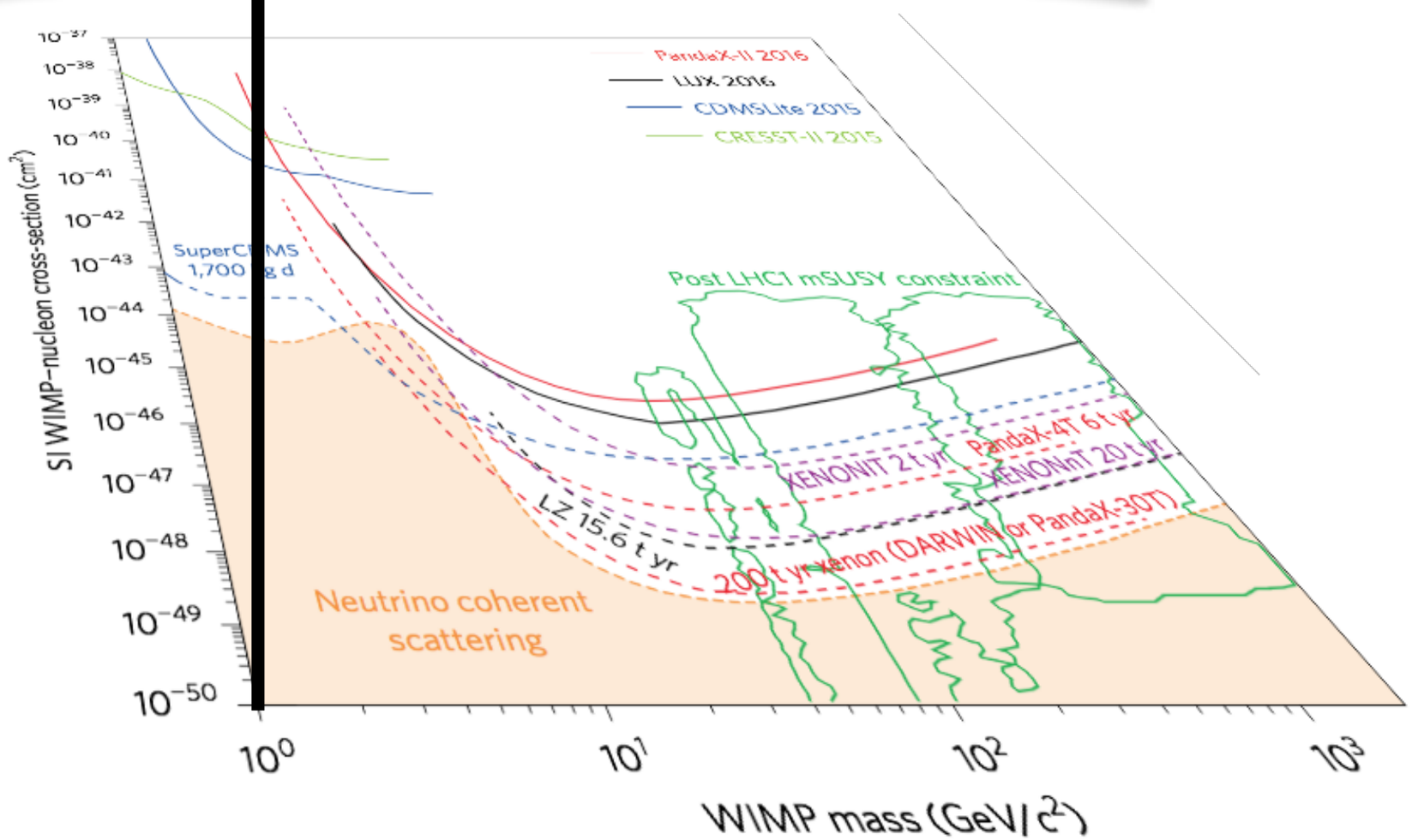


Mass splitting frontier

"Photon Phrontier"



[Graham, Harnik, Rajendran, Saraswat]

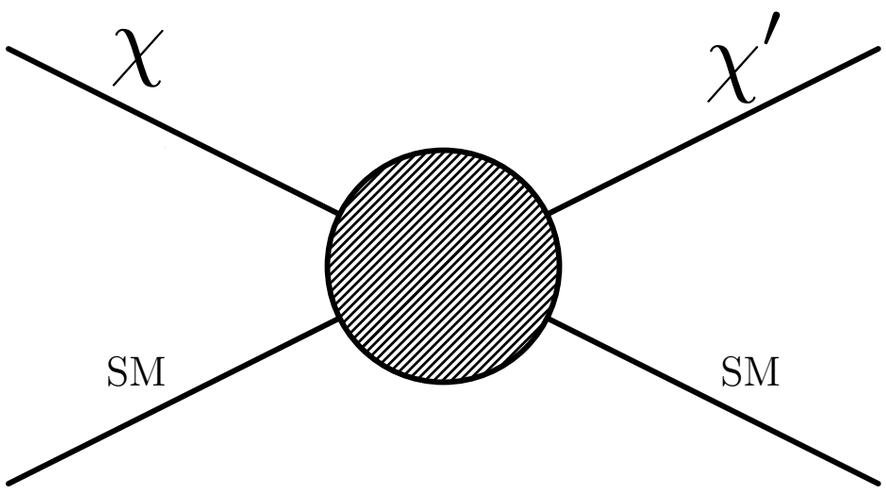
$\delta \equiv m_{\chi'} - m_{\chi}$ Can be endothermic (iDM) or exothermic

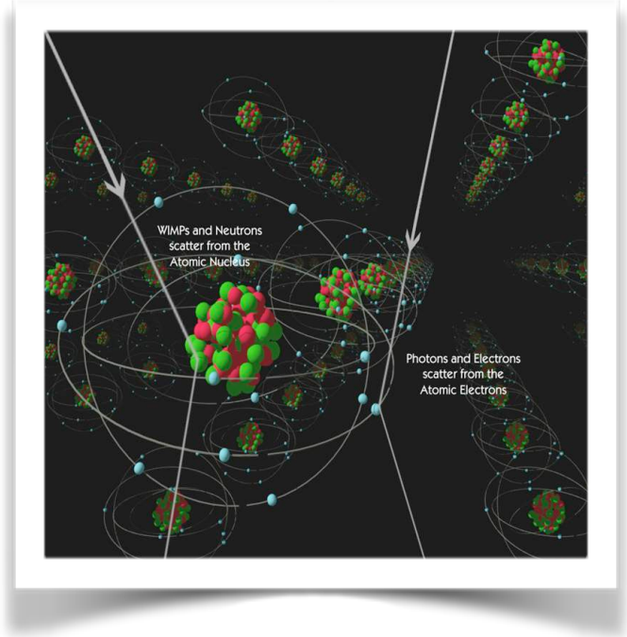
[Tucker-Smith and Weiner]

Inelastic Dark Matter (iDM)

[Tucker-Smith and Weiner]

(Suppress all thoughts of DAMA, impure or otherwise)





$$\frac{dR}{dE_R} = \frac{N_T m_N \rho_\chi}{2\mu_{N\chi}^2 m_\chi} \int_{v_{min}}^{v_{max}} d^3\vec{v} \frac{f(\vec{v}, \vec{v_E})}{v} \sigma_N F^2(E_R)$$

$$v_{min} = \sqrt{\frac{1}{2m_N E_R}} \left| \frac{m_N E_R}{\mu_{N\chi}} + \delta \right| + \mathcal{O}\left(\frac{E_R}{m_\chi}, \frac{\delta}{m_\chi}\right)$$

Inelastic kinematics

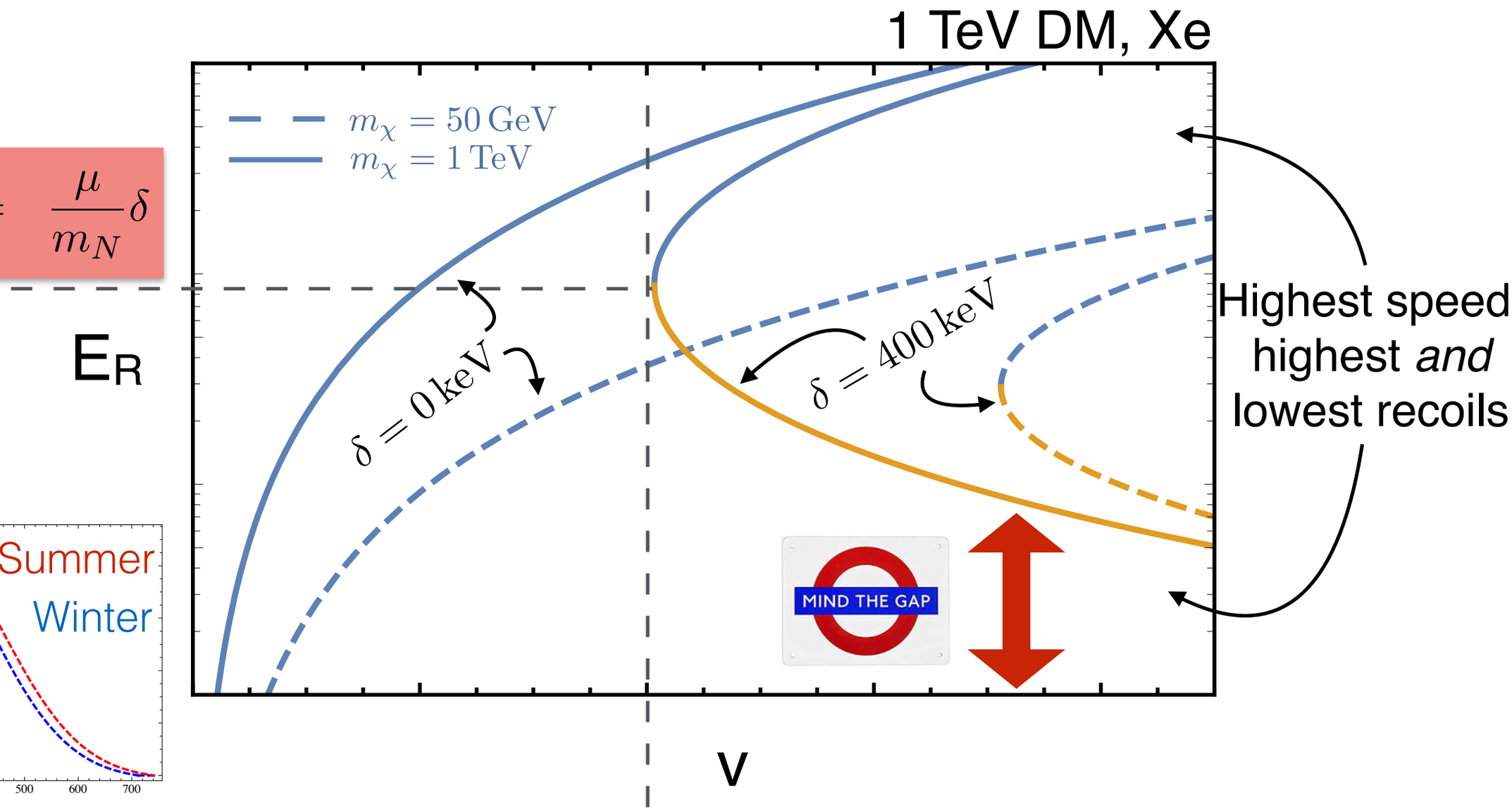
Nuclear recoil energy

Lab scattering angle

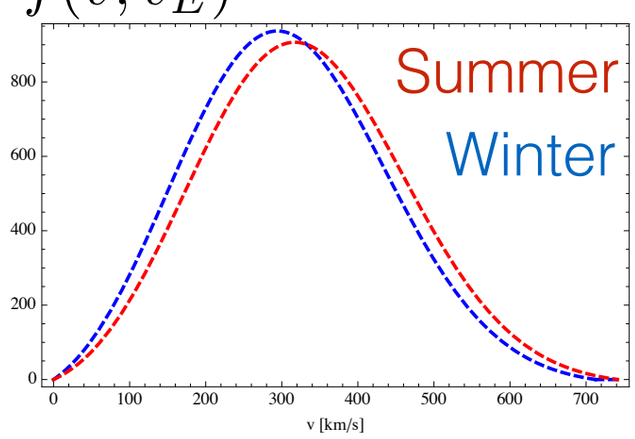
$$E_R = \frac{\mu}{m_N}\left[\left(\mu v^2 \cos^2\theta_{\rm lab} - \delta\right) \pm \left(\mu v^2 \cos^2\theta_{\rm lab}\right)^{1/2}\left(\mu v^2 \cos^2\theta_{\rm lab} - 2\delta\right)^{1/2}\right]$$

DM speed in lab frame

$$E_R(v_{\rm min}^{\rm apex}) = \frac{\mu}{m_N}\delta$$



$f(\vec{v}, \vec{v_E})$



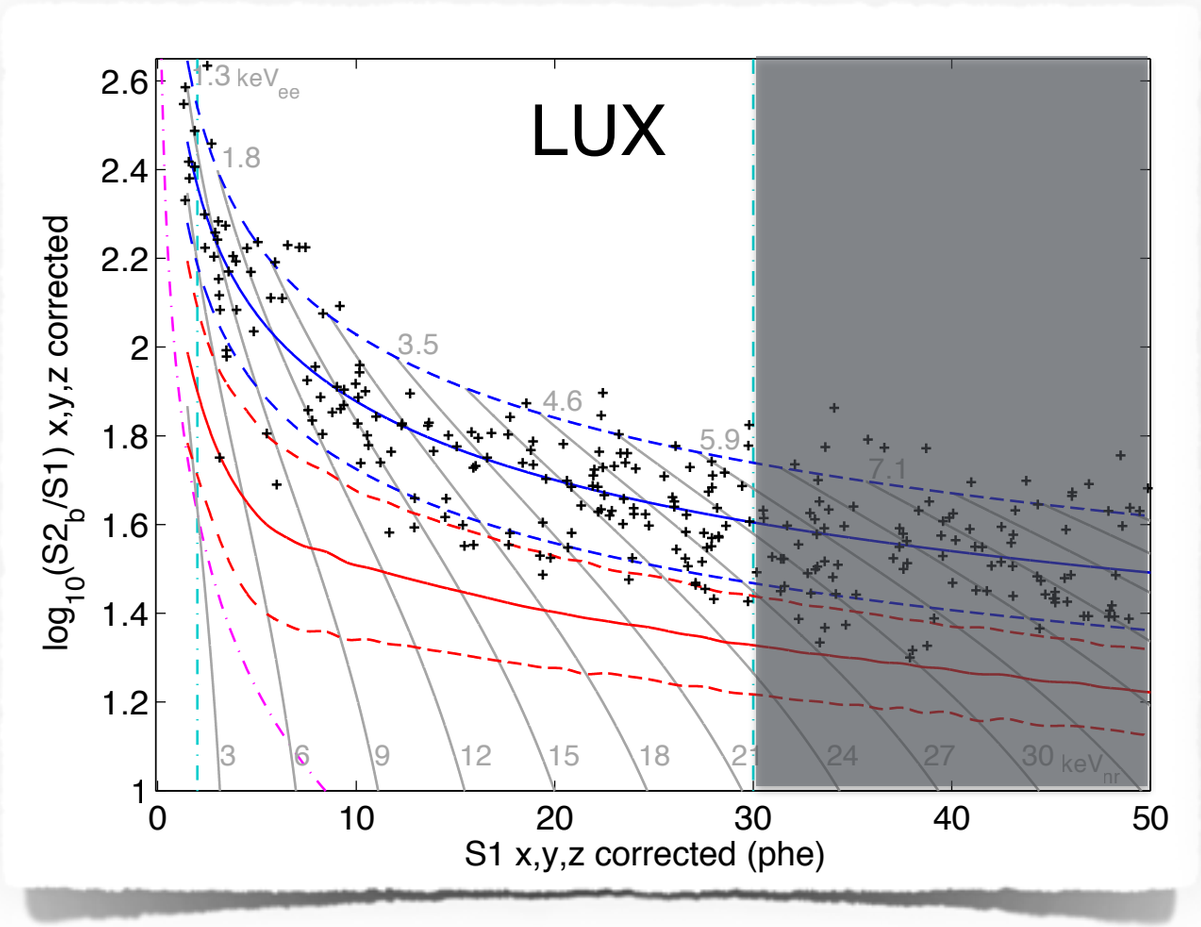
$$v_{\rm min}^{\rm apex} = \sqrt{\frac{2\delta}{\mu}}$$

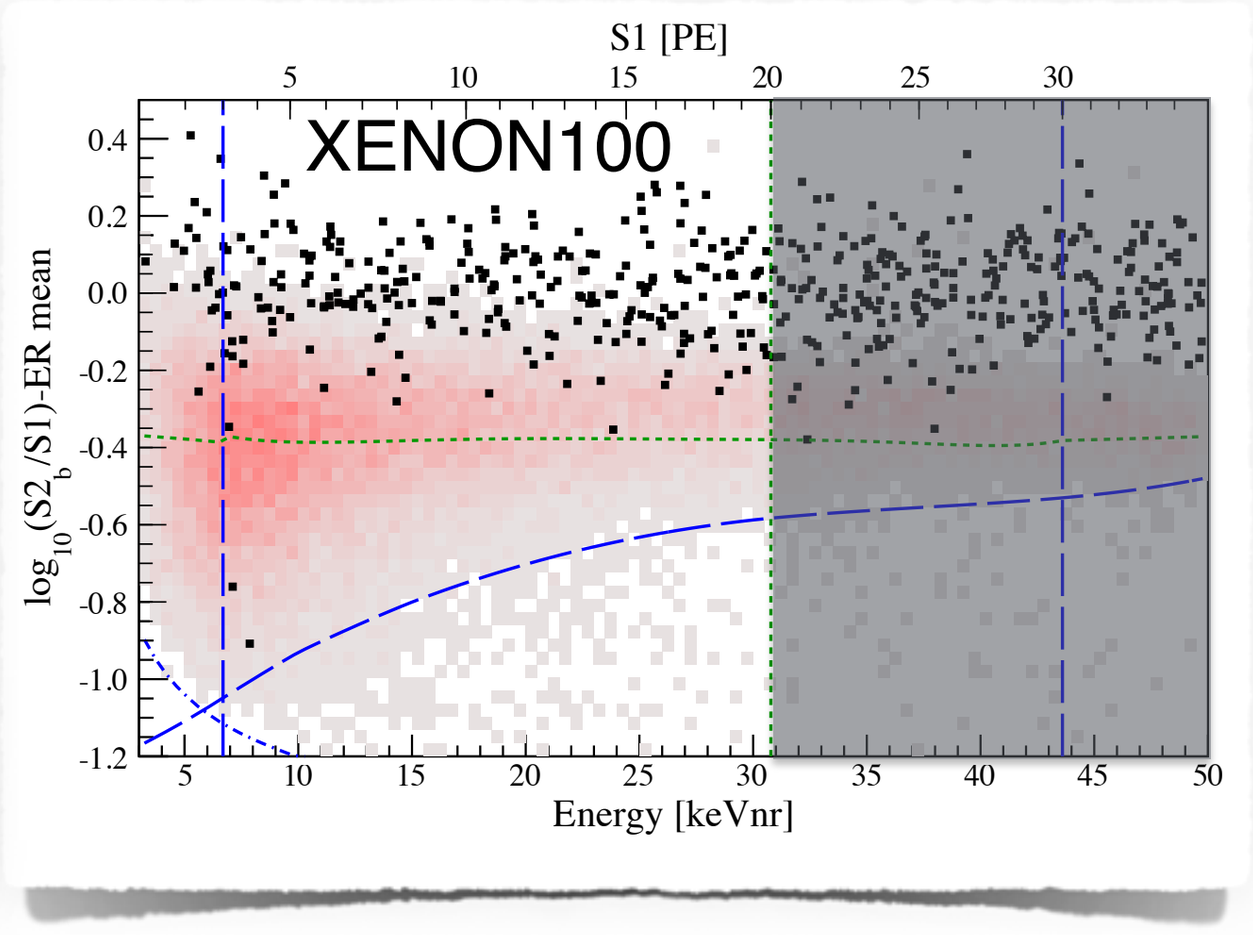
Inelastic Dark Matter (iDM)

- Requires "large" momentum exchange to upscatter
- Favours high velocity tail of phase space distribution
- Increased modulation
- Prefers heavy targets e.g. iodine, xenon, tungsten,..
- Recoil spectrum has a peak
- Sensitivity increased by going to *higher* recoil

Experimental situation

Experiment	Exposure [tonne-days]	Energy range [keV$_{nr}$]
PICO	1.3	7-20–$\mathcal{O}(1)$ MeV
LUX	14	1–30
PandaX	33	1–30
CRESST	0.052	30–120





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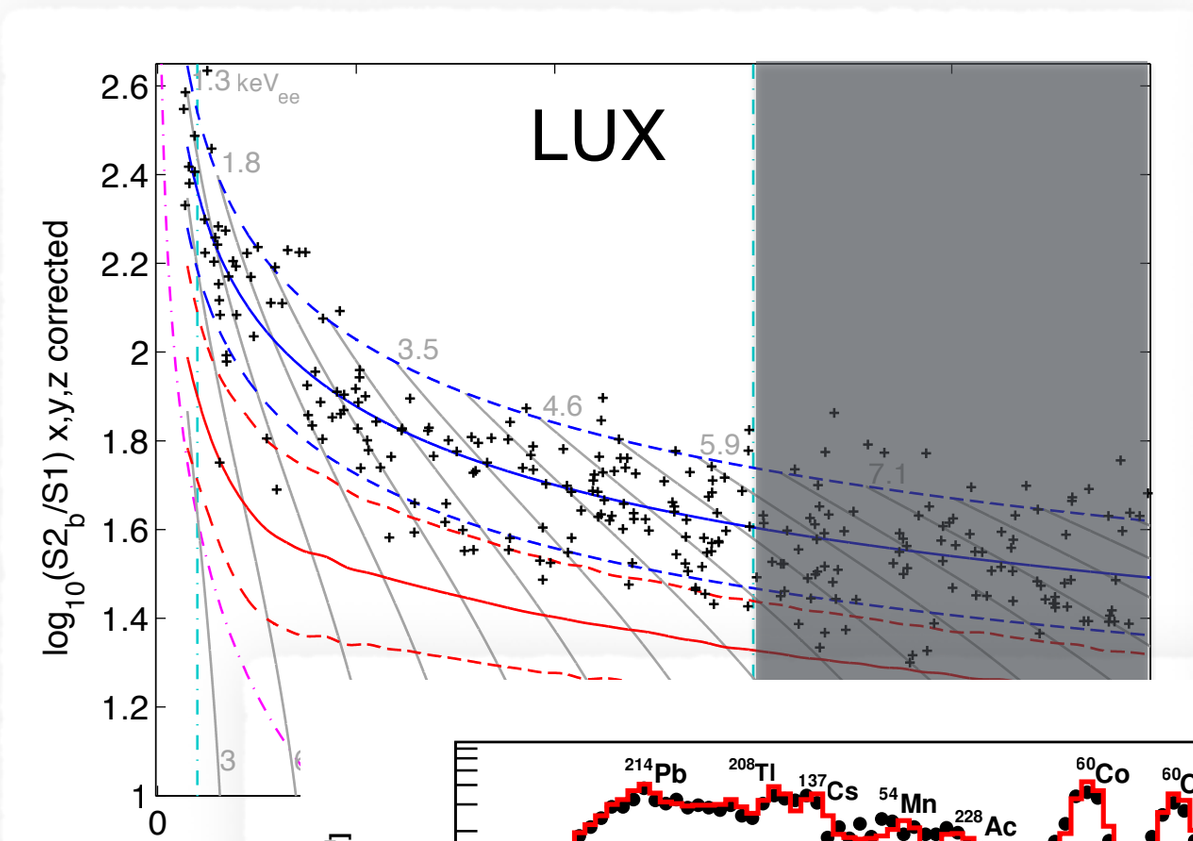
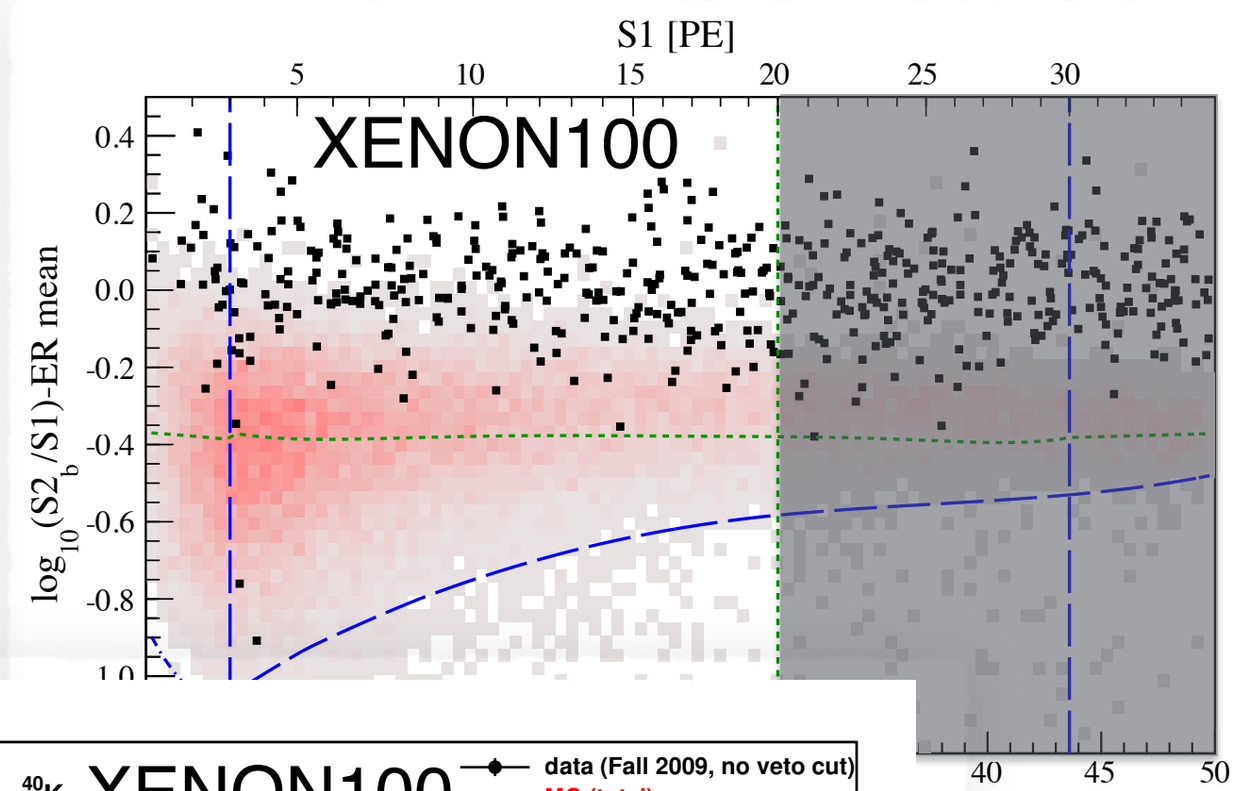
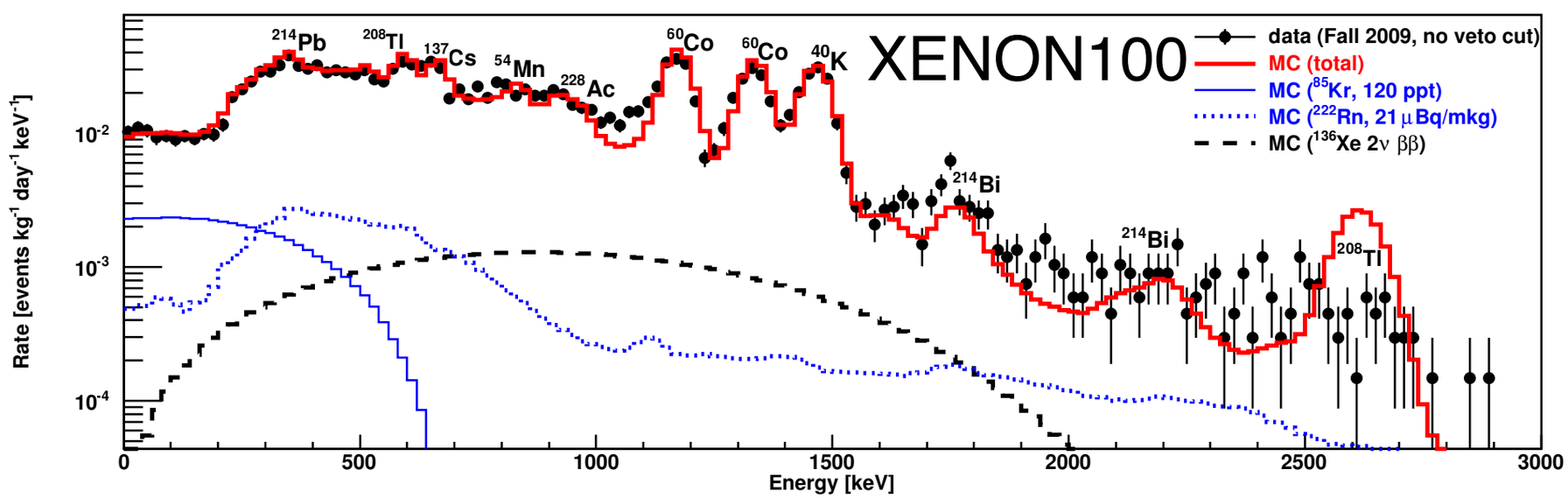


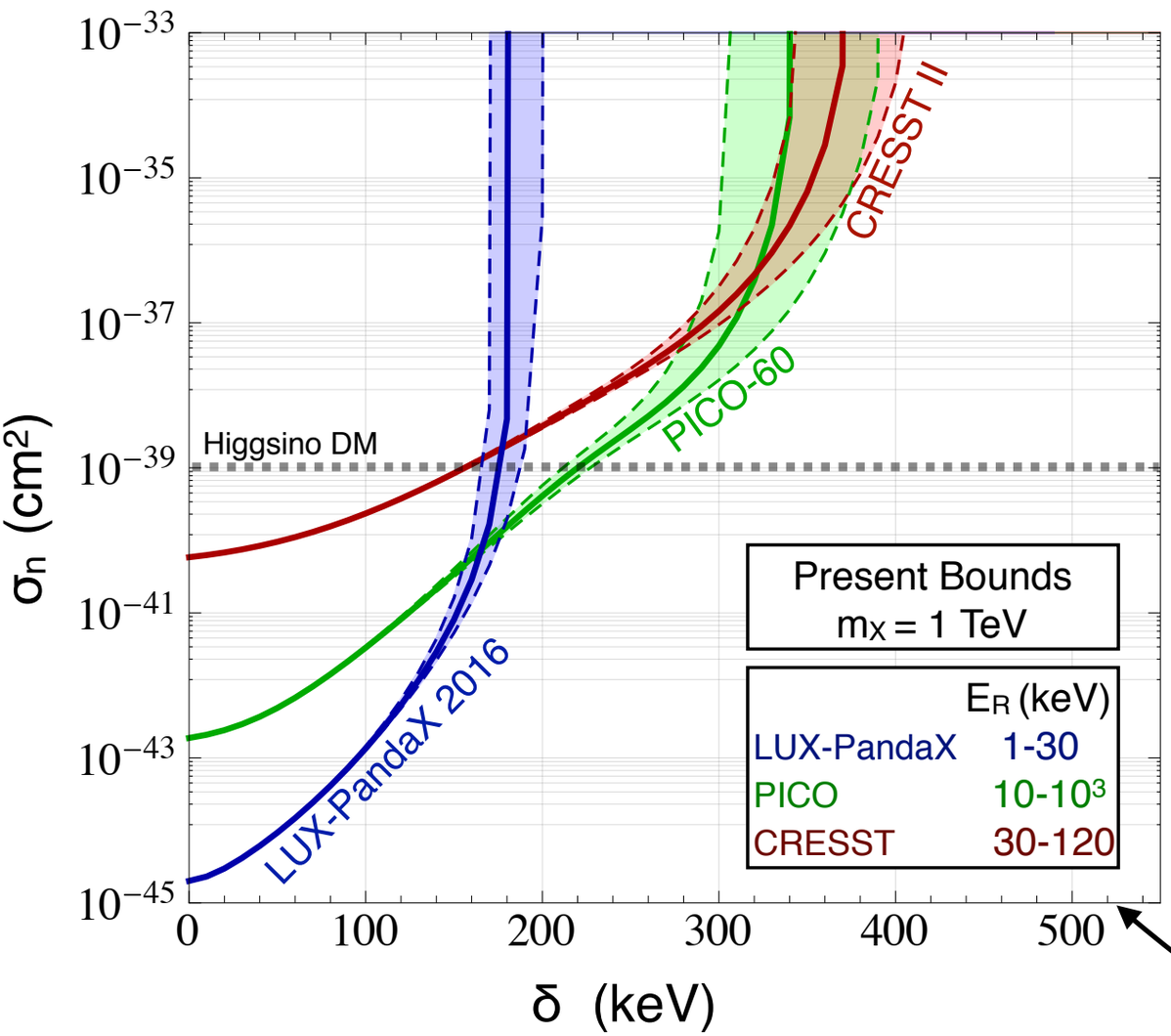


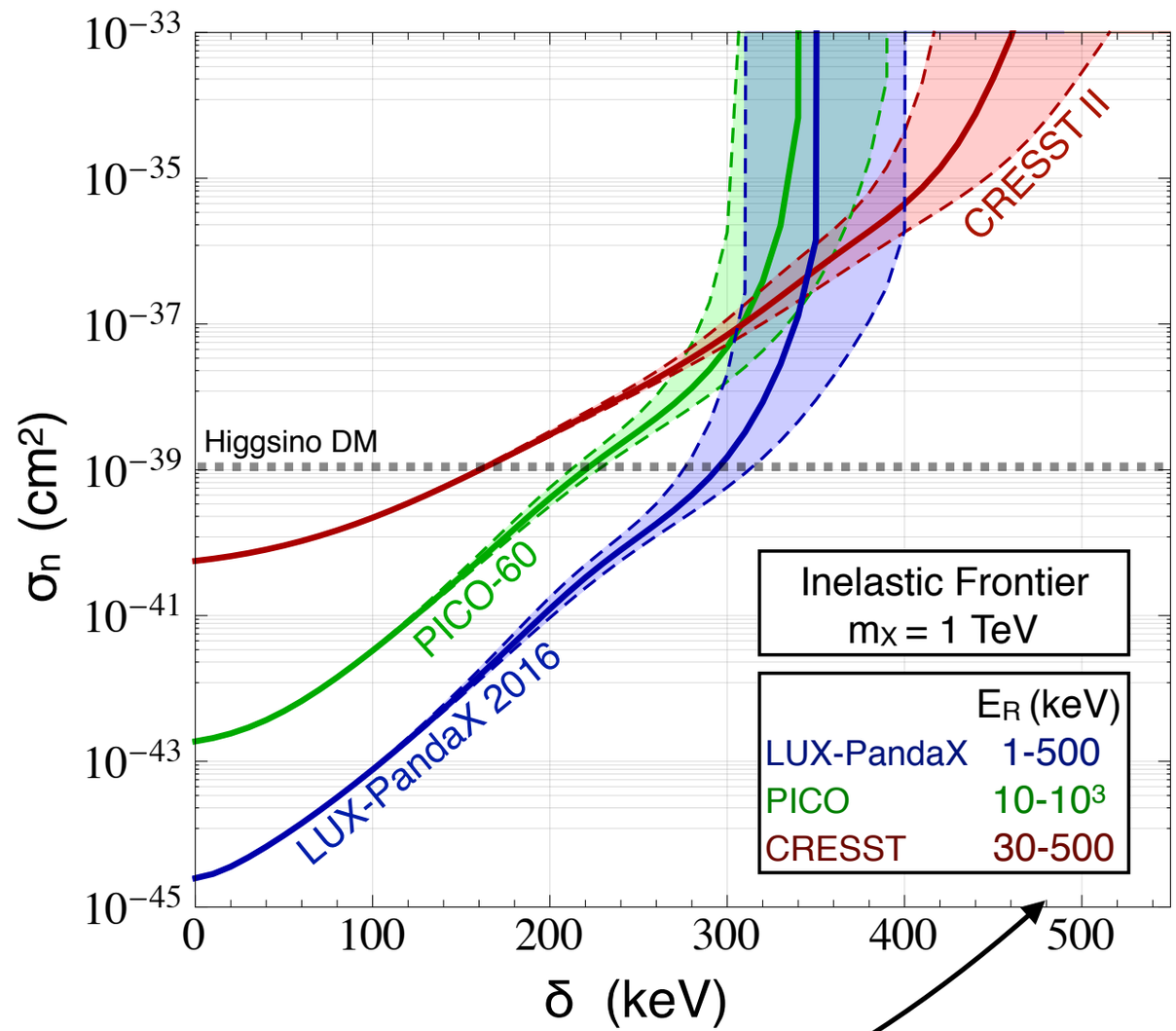


The Inelastic Frontier

Analyze existing data out to 500 keV recoil energies, assume no new events above background

[Bramante, PJF, Kribs, Martin]





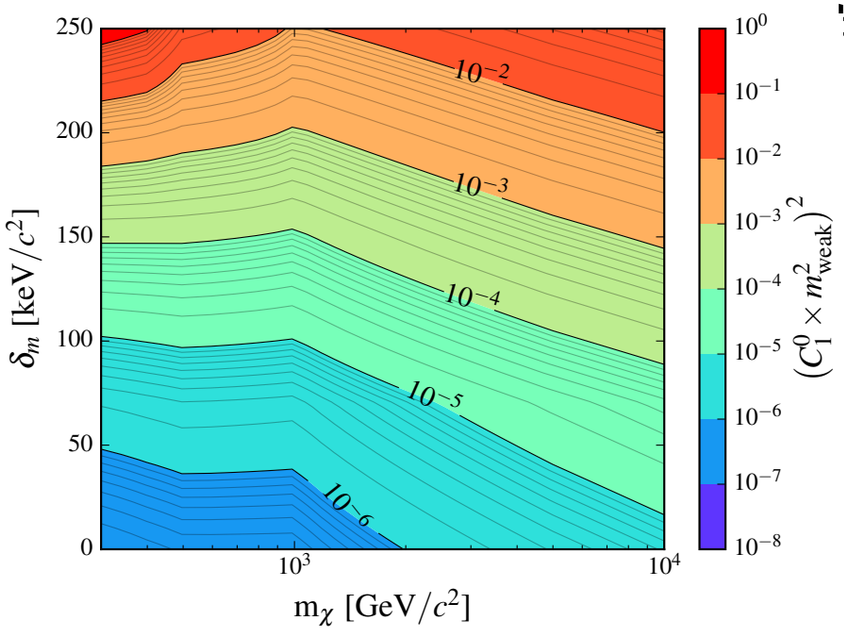
Crossing the Inelastic Frontier
Xenon100, PandaX

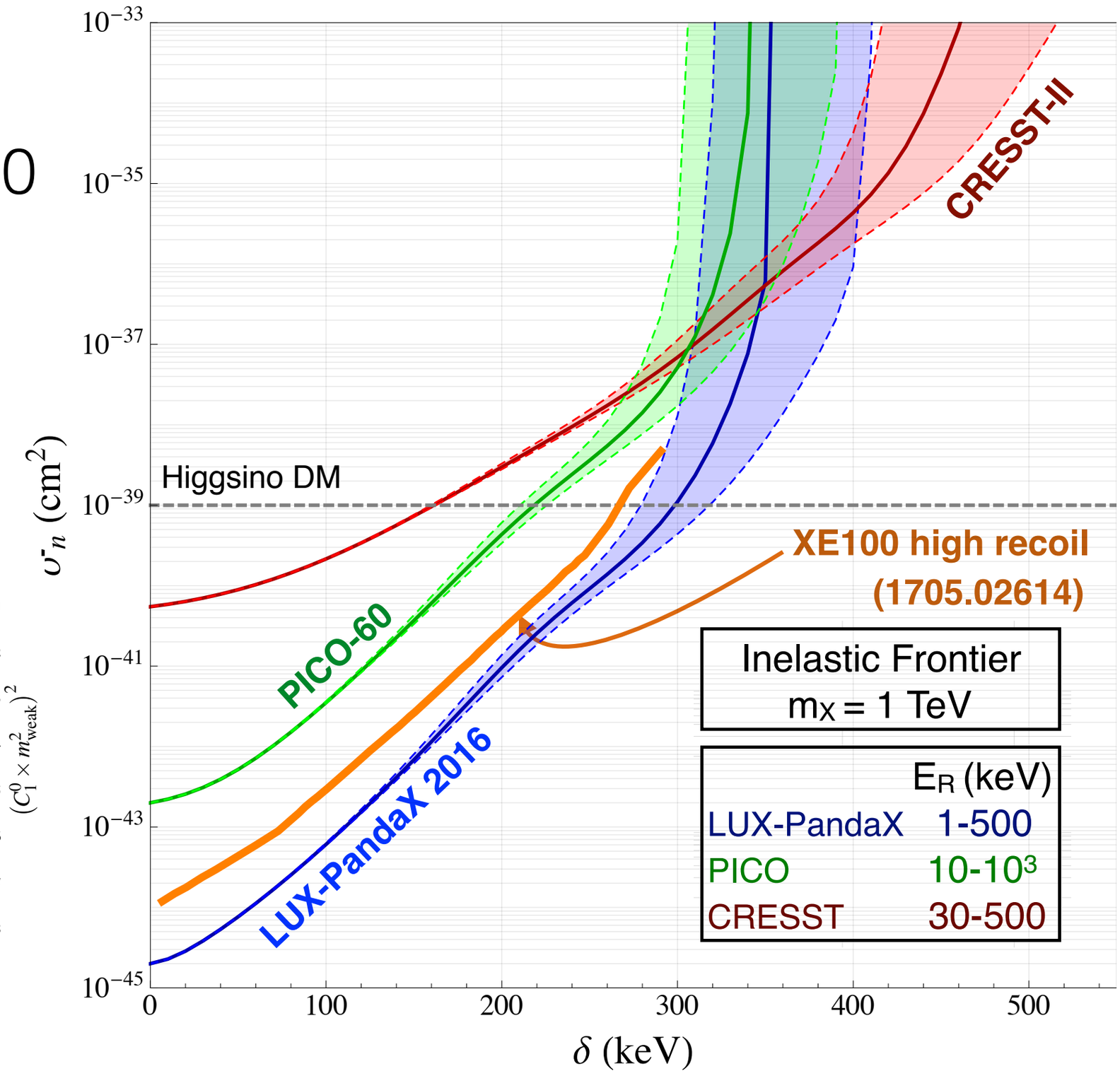
Reanalysis

7.6 ton-days, Xe100

6.6-240 keVnr

Inelastic analysis





Can we do better?

First a model….

iDM—Higgsino model

Dirac fermion coupled to vector, with small Majorana masses

$$V_\mu \left(\chi_1^\dagger \bar{\sigma}^\mu \chi_1 - \chi_2^\dagger \bar{\sigma}^\mu \chi_2\right) + m_D \left(\chi_1 \chi_2 + \text{h.c.}\right)$$

$$+\delta_1 \left(\chi_1 \chi_1 + \text{h.c.}\right) + \delta_2 \left(\chi_2 \chi_2 + \text{h.c.}\right)$$

Mass eigenstates only have off-diagonal couplings
e.g. (almost) pure Higgsinos

$$\delta_{\tilde{\text{H}}} \simeq m_Z^2 \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2}\right) + \mathcal{O}\left(\frac{1}{M_{1,2}^2}\right)$$

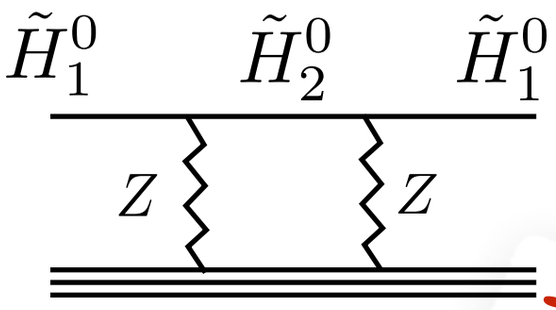
natural in Split-Dirac SUSY (PF, Kribs, Martin [1405.3692])

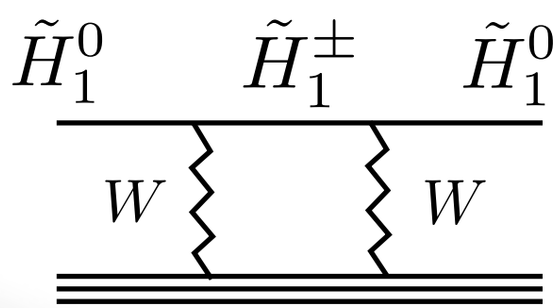
DM couples to the Z (a WIMP!)

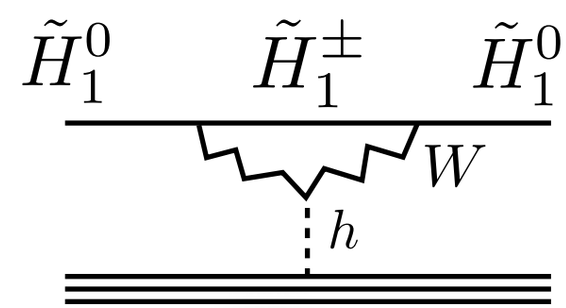
$$\sigma_{\text{n}}^{\tilde{H}} \sim \frac{\pi\, m_n^2\, \alpha_W^2}{8\, m_W^4} \times (\text{velocity factor}) \sim 10^{-39}\ \text{cm}^2 \times (\text{velocity factor})$$

iDM—loop level elastic rate

[Hisano et al.; Hill and Solon]





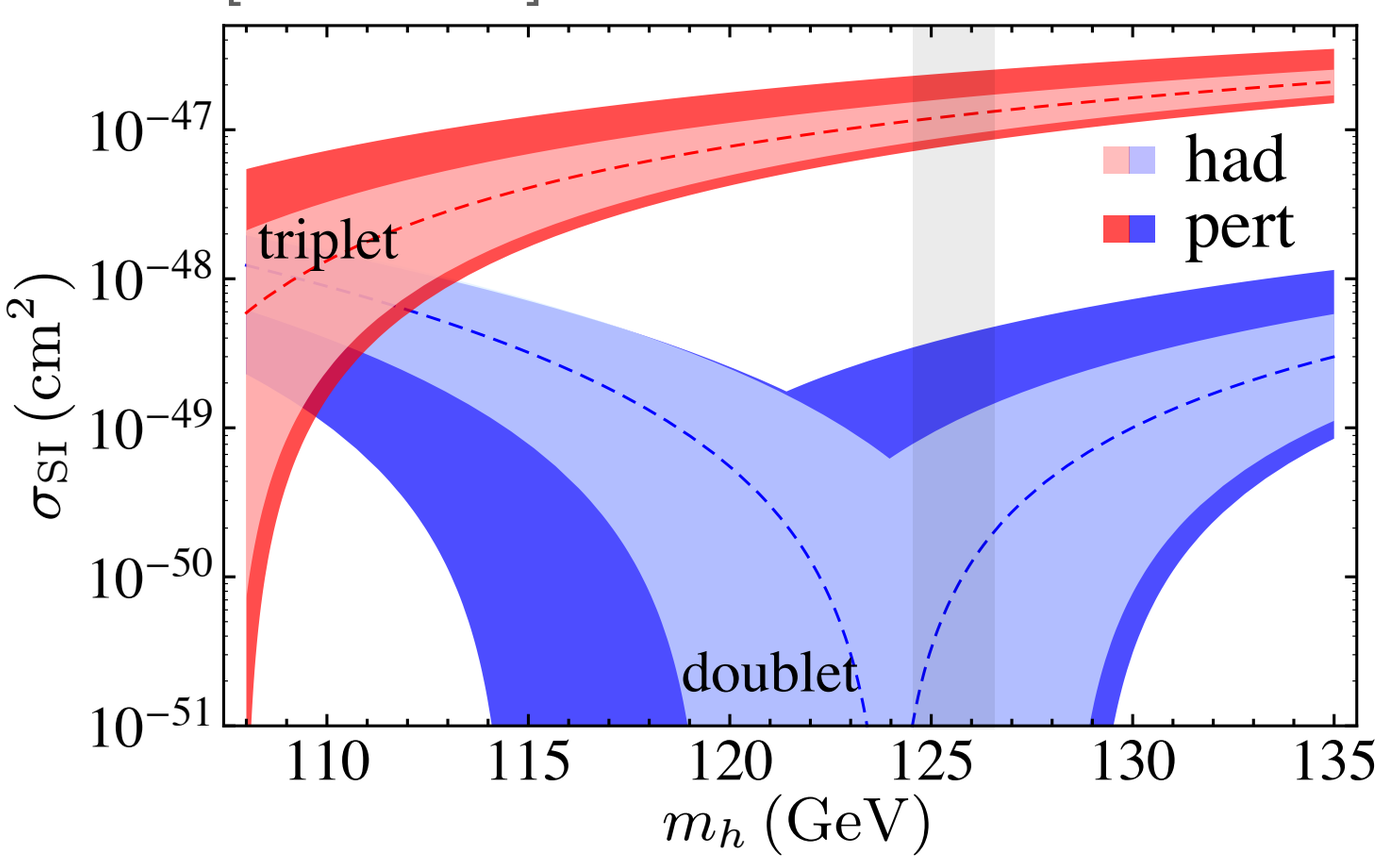


Twist-2

Twist-0

$$\sigma^{\tilde{H}}_{\rm n,loop} \sim \frac{m_n^4 \alpha_W^4}{\pi\, m_W^6} f_q^2 \sim 10^{-47}\ {\rm cm}^2$$

[Hill and Solon]

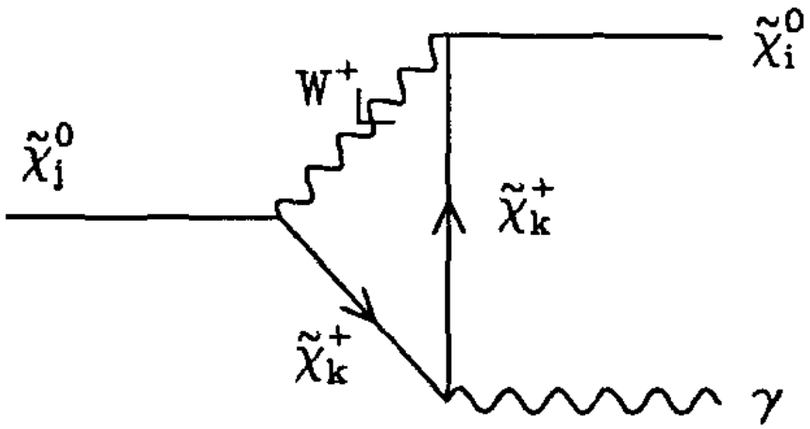


$$\sigma^{\tilde{H}}_{\rm n,loop} \lesssim 10^{-48}\ {\rm cm}^2$$

accidental cancellation

Higgsino decay

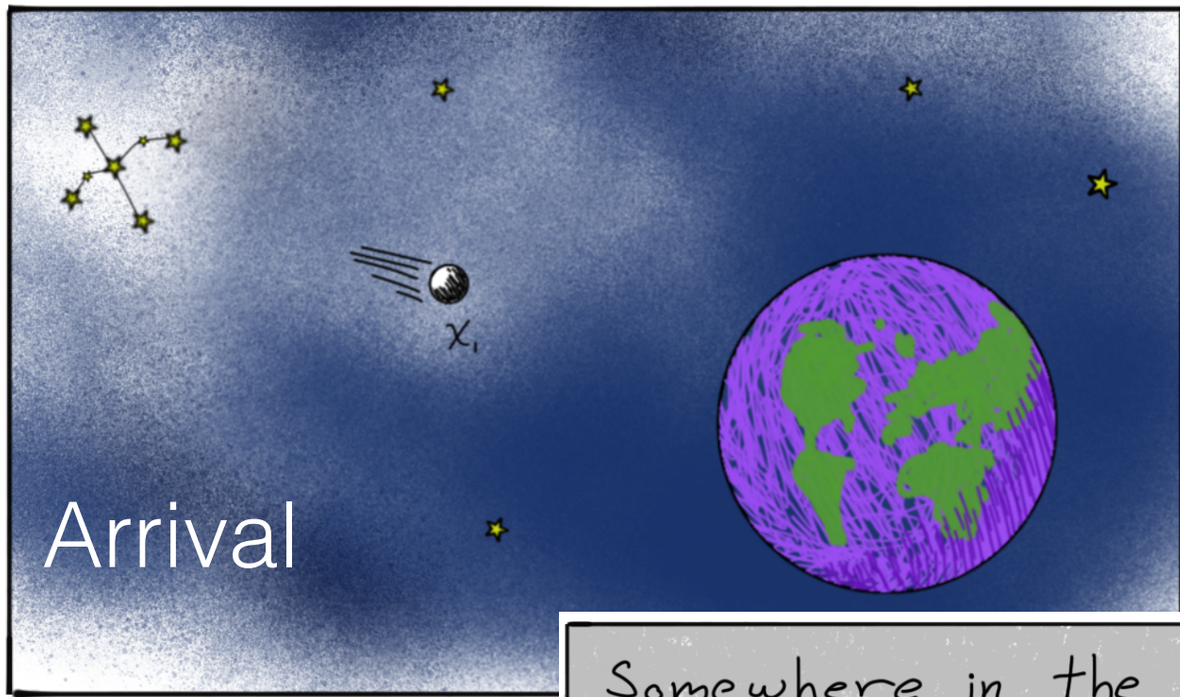
[Haber and Wyler]

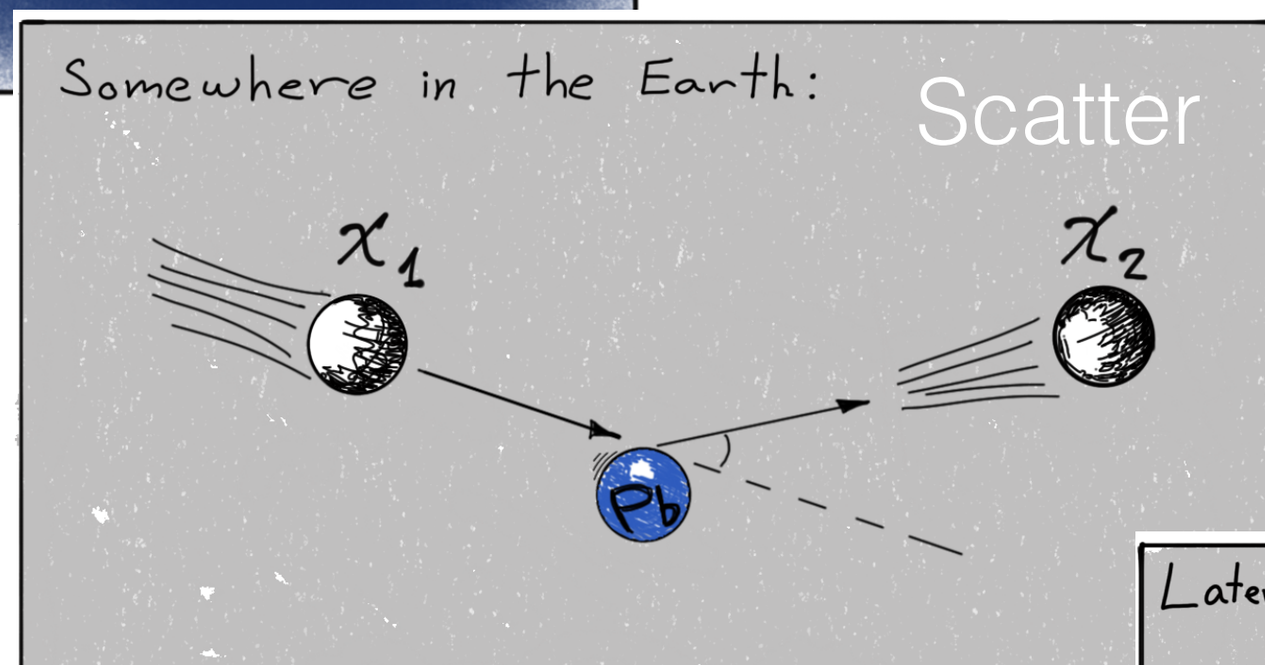


Excited Higgsino has a short-lived loop decay to a photon

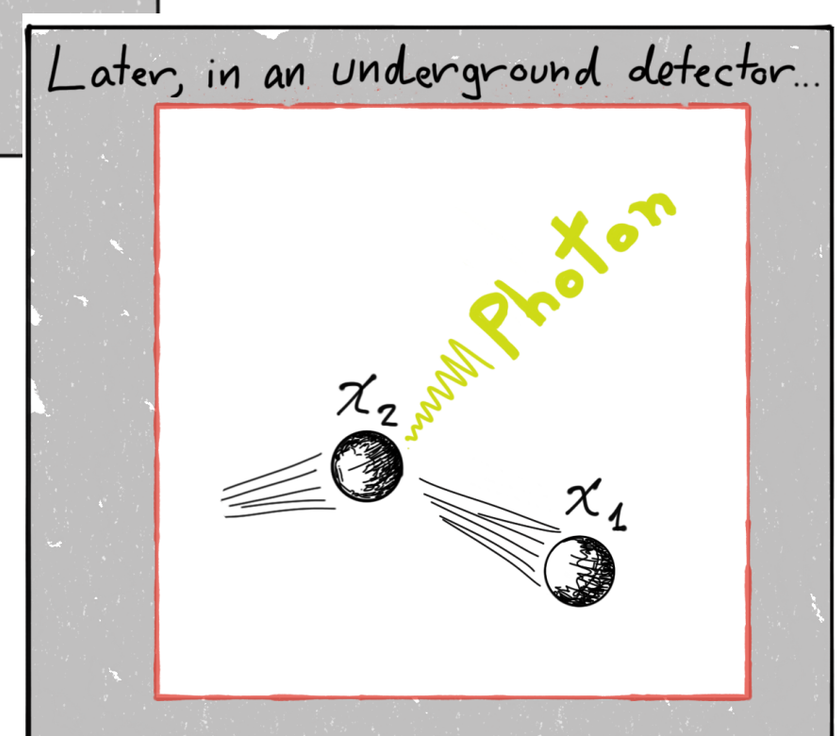
$$\Gamma_{\chi_2^0 \to \chi_1^0 + \gamma} \simeq \alpha_{\rm em}\, \alpha_W^2\, \frac{\delta^3}{4\pi^2 m^2_{\chi_1^0}}$$

$$\ell_{\chi_2^0} = \frac{cv}{\Gamma_{\chi_2^0 \to \chi_1^0 + \gamma}} = 20\ \text{km} \left(\frac{cv}{400\ \text{km/s}}\right) \left(\frac{400\ \text{keV}}{\delta}\right)^3 \left(\frac{m_{\chi_1^0}}{1\ \text{TeV}}\right)^2$$





Detection



A day in the life of luminous iDM

Illuminating the Inelastic Frontier

See also "Luminous DM" [Feldstein, Graham, Rajendran] and "DM in 2 Easy Steps" [Pospelov, Weiner, Yavin]

Large x-sec for $\chi_1 N \to \chi_2 N$
Decay time (not) long on detector (Earth) scales
Decays to mono energetic photon
Direct detection bounds satisfied [large/small (δ, σ)]

- Abundant heavy target
- Large volume, low threshold detector

Detector	Xenon 1T	Borexino	SNO	DUNE	IceCube
Mass (ton)	1	300	10^3	3×10^4	10^7
Threshold (MeV)	10^{-3}	0.15	1	$1 - 10$	10^4

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Decay time (not) long on det th) scales

Decays to mono en oton

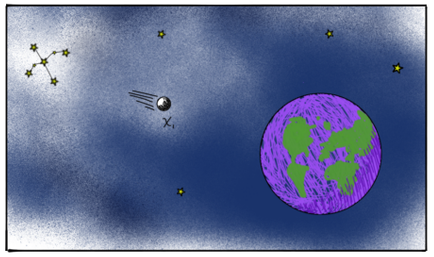
Direct detection nds satisfied [large/small (δ, σ)]

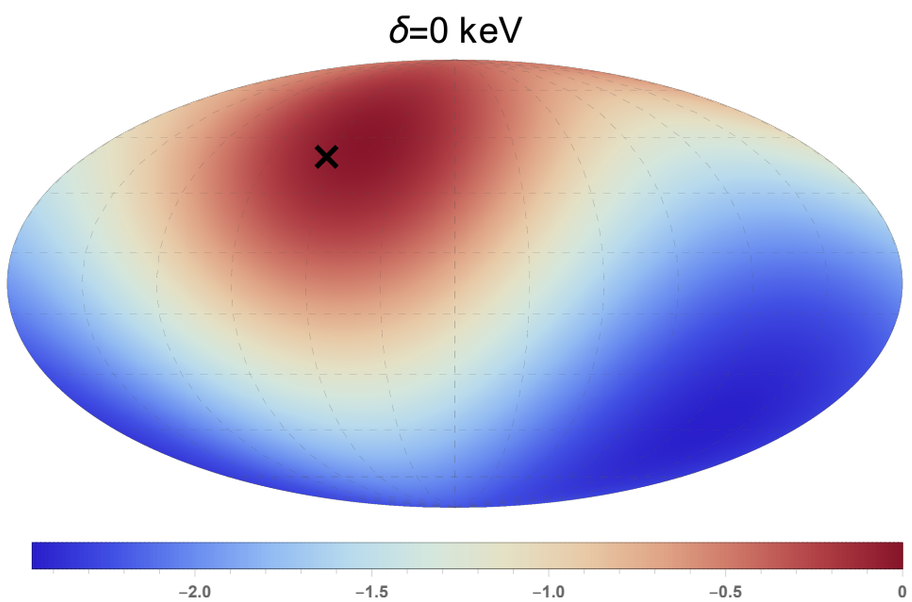
All natural for Higgsino

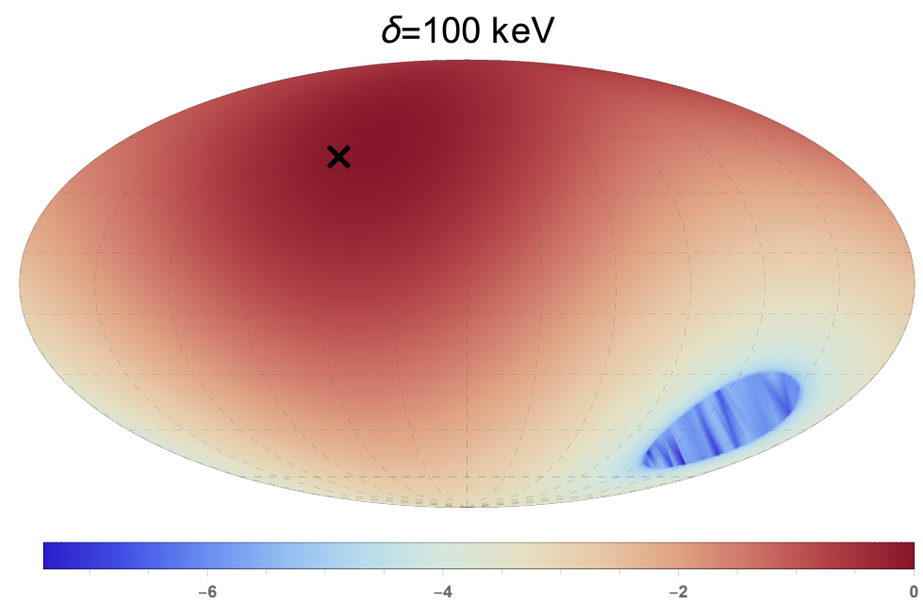
- Abundant heavy target —Pb
- Large volume, low threshold detector —Borexino

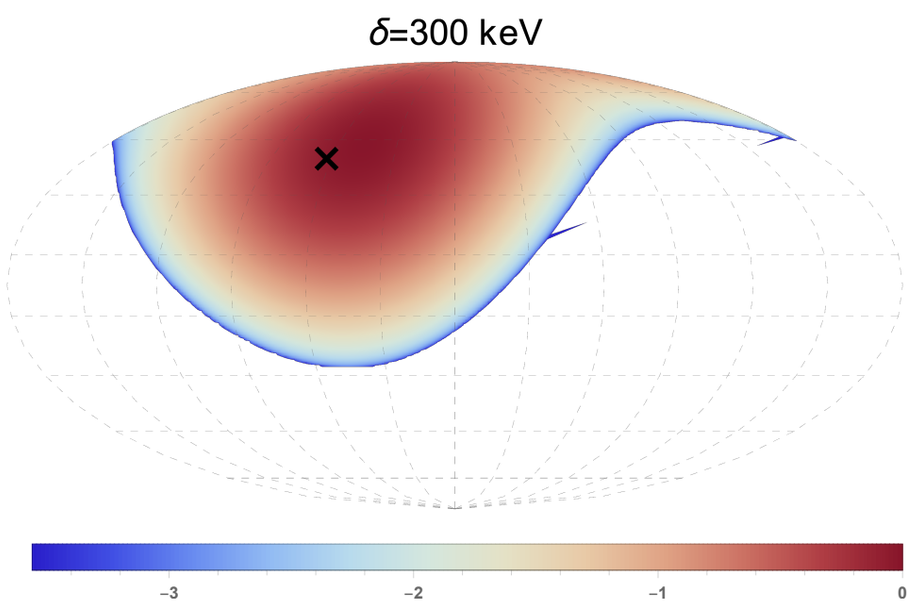
Detector	Xenon 1T	Borexino	SNO	DUNE	IceCube
Mass (ton)	1	300	10^3	3×10^4	10^7
Threshold (MeV)	10^{-3}	0.15	1	$1 - 10$	10^4

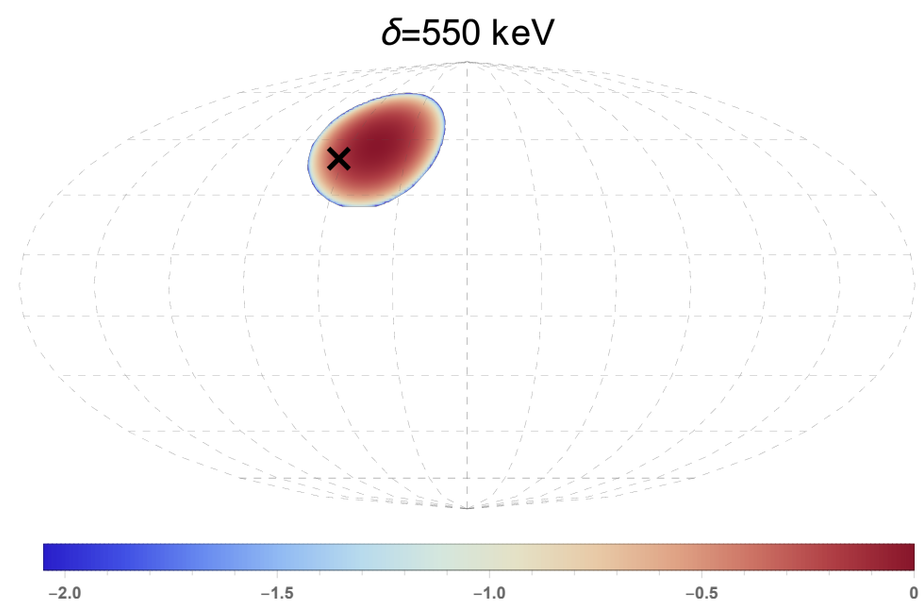
Arrival







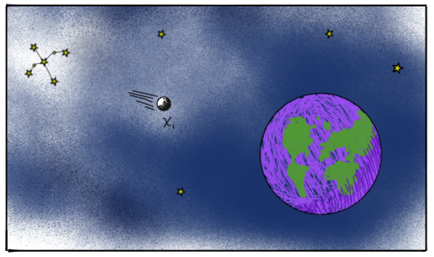


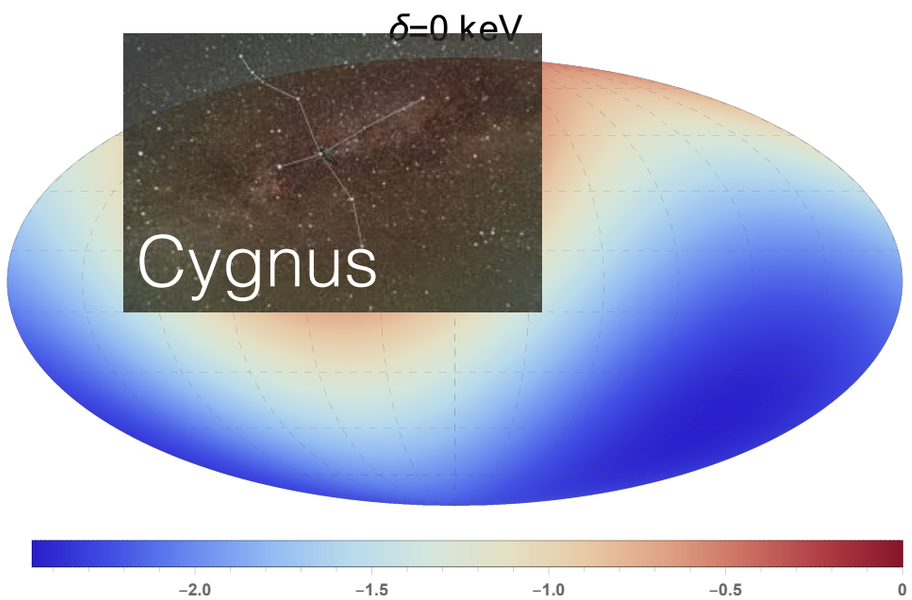


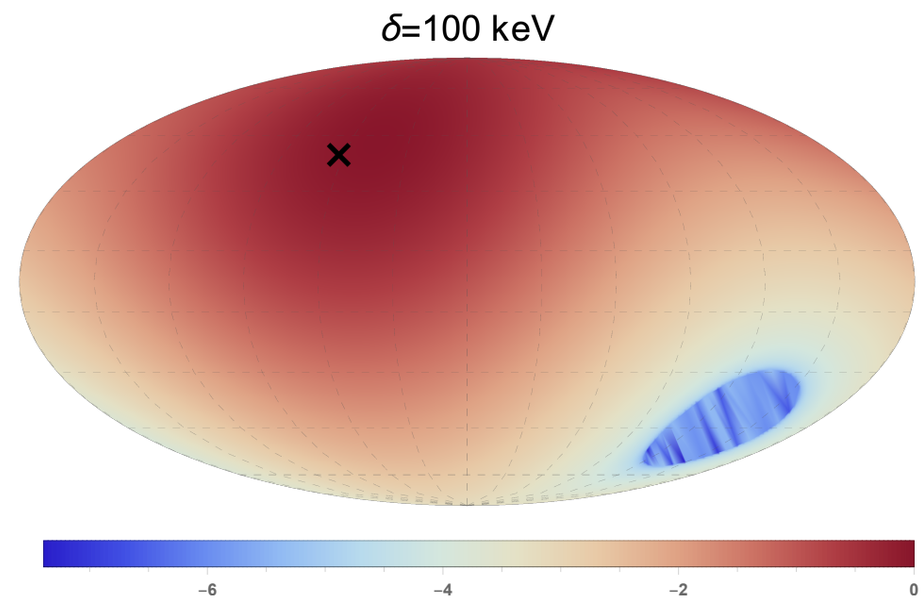
Position of <u>Cygnus</u> in sky (dec. ~45°N)

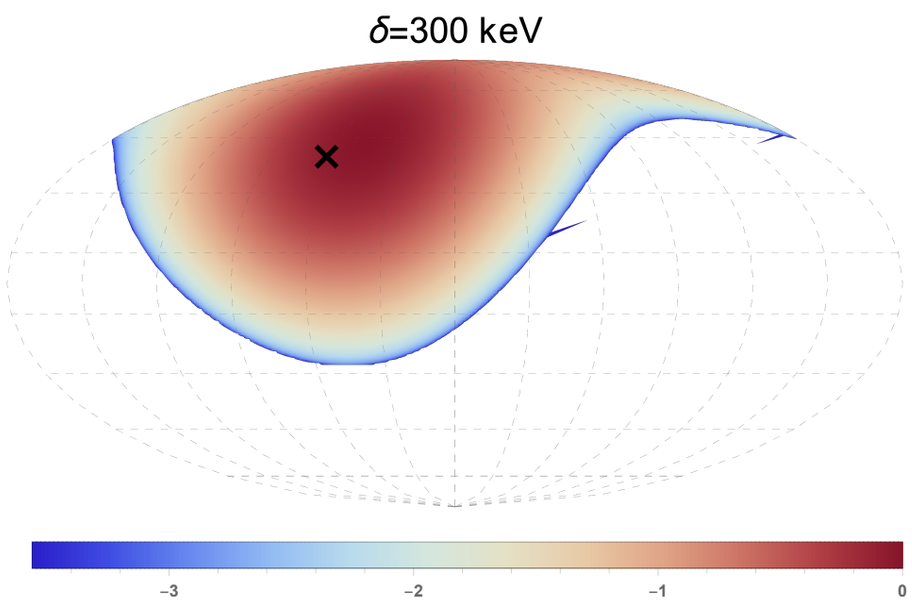
1 sidereal day = 23 hours 56 minutes 4 seconds

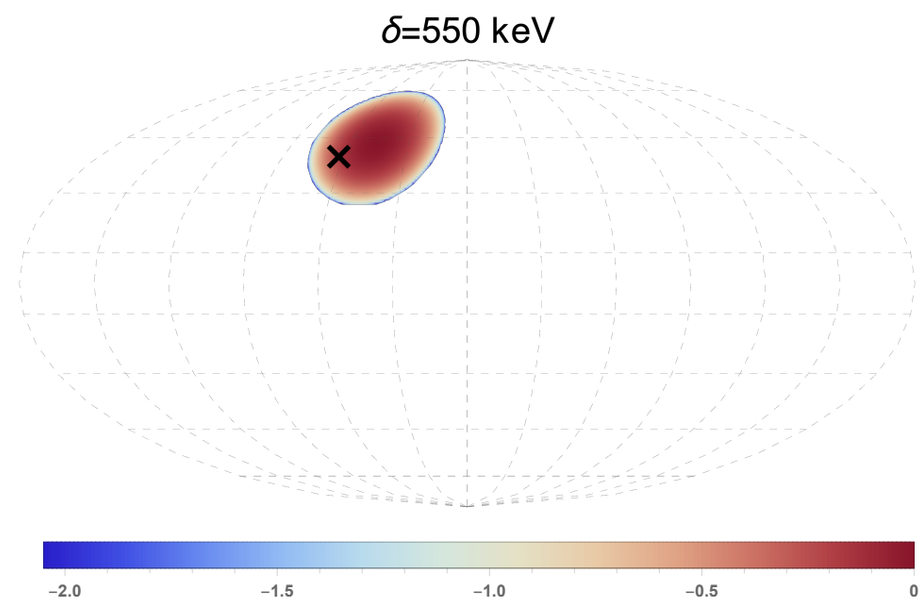
Arrival











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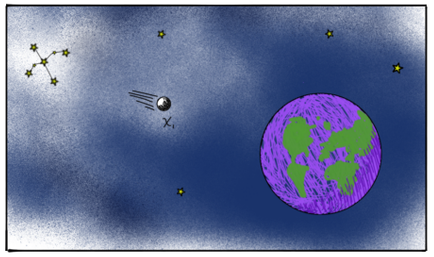

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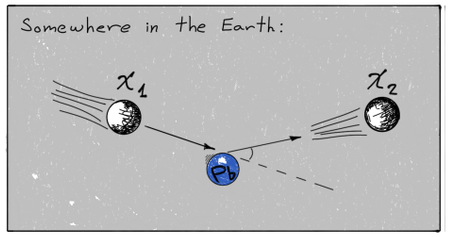
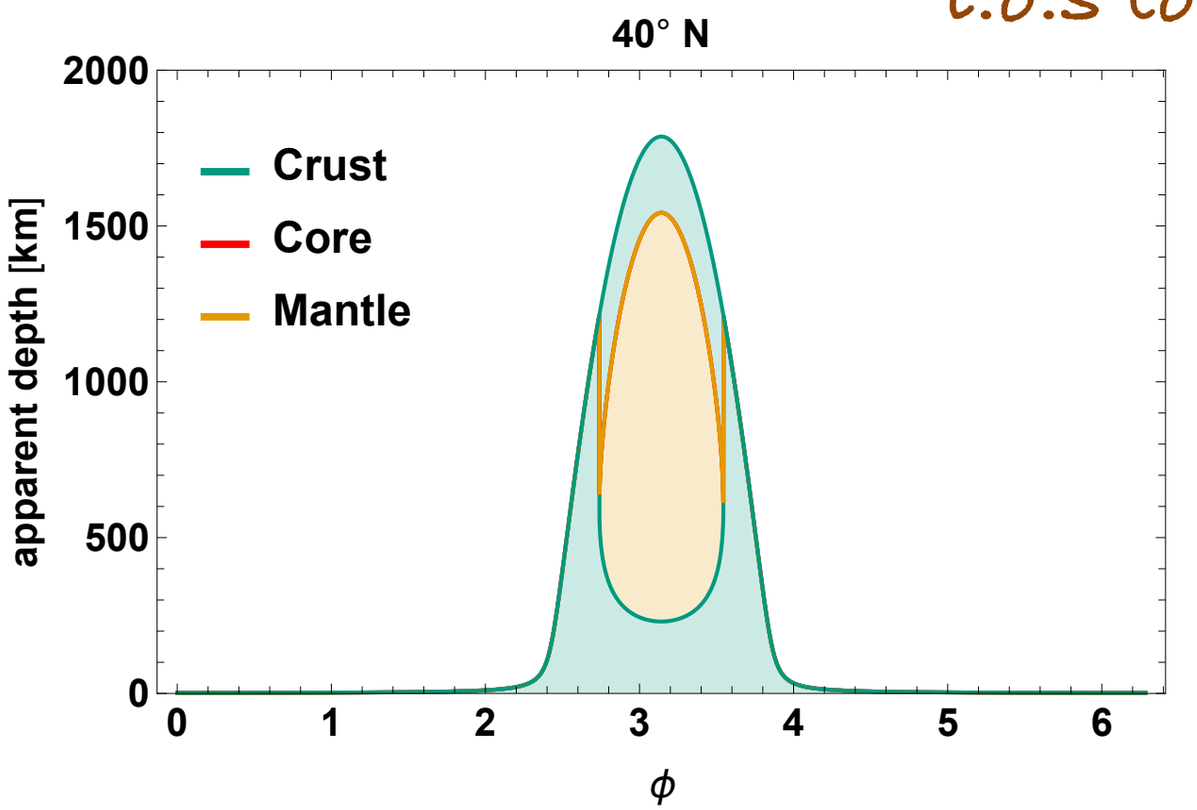
Scatter

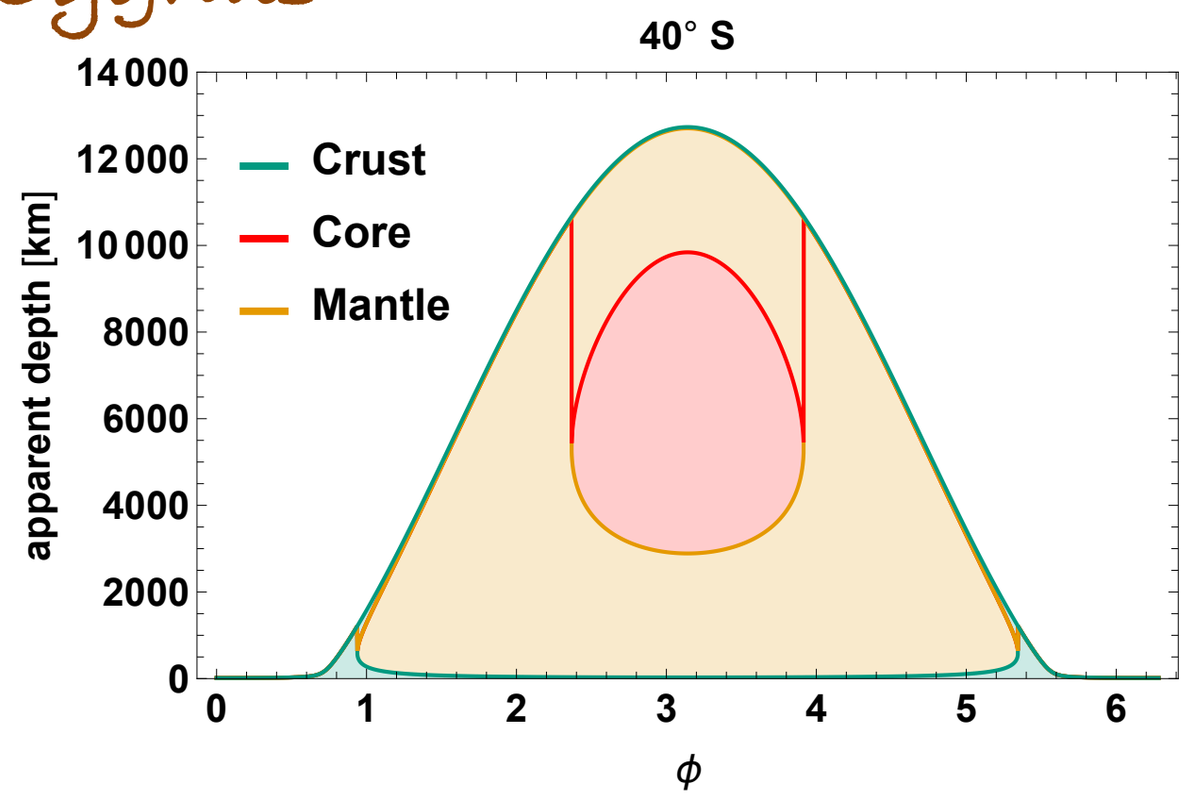


DM lifetime ~ radius of Earth

Depends upon overburden and geology

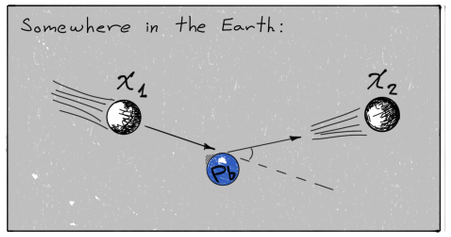
l.o.s to Cygnus





-	n_{Si} [km^{-3}]	n_{Fe} [km^{-3}]	n_{Pb} [km^{-3}]	Outer Radius [km]
Core	1.4×10^{37}	1.0×10^{38}	1.3×10^{31}	3483
Mantle	2.1×10^{37}	3.1×10^{36}	2.4×10^{30}	6341
Crust	1.7×10^{37}	2.0×10^{36}	8.4×10^{31}	6371

Scatter



For DM heavier than the target the scatter is forward

$$\cos^2\theta_{\rm max}^{\rm lab} = 1 - \left(\frac{m_T v_{\rm out}^{\rm cm}}{\mu_1 v_\chi}\right)^2 = \left(1 + \frac{m_T}{m_2}\right)\left(1 - \frac{m_T}{m_1} + \frac{2\, m_T\, \delta}{(m_1\, v_\chi)^2}\right)$$

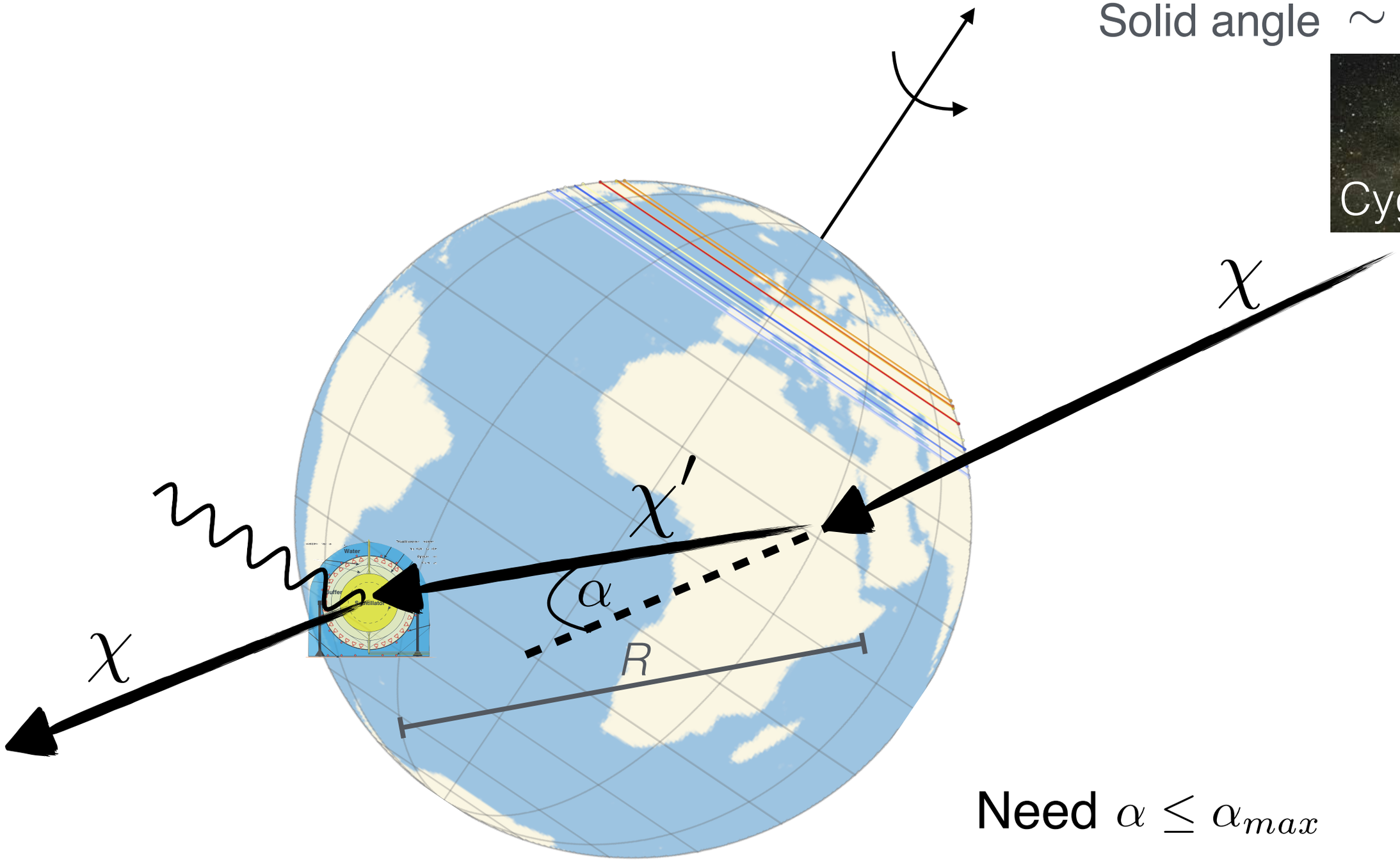
TeV DM scatters by less than 10°

Combination of these effects is a strong daily modulation in the signal, and sensitivity to lab latitude

Great for signal/background discrimination

Target vol. $\sim R^2$

Solid angle $\sim R^{-2}$



Need $\alpha \leq \alpha_{max}$

$$\cos^2 \alpha_{max} = \left(1 + \frac{m_T}{m_{\chi^*}}\right)\left(1 - \frac{m_T}{m_\chi} + \frac{2\, m_T\, \delta}{m_\chi^2\, (v_{in}^{lab})^2}\right)$$

Luminous Rate

$$\text{Rate} \sim n_T \, n_\chi \, \sigma \, v \, V$$

Complicated 6d integral, sensitive to lifetime, speed, position etc…

Solid angle Prob. to decay in det.

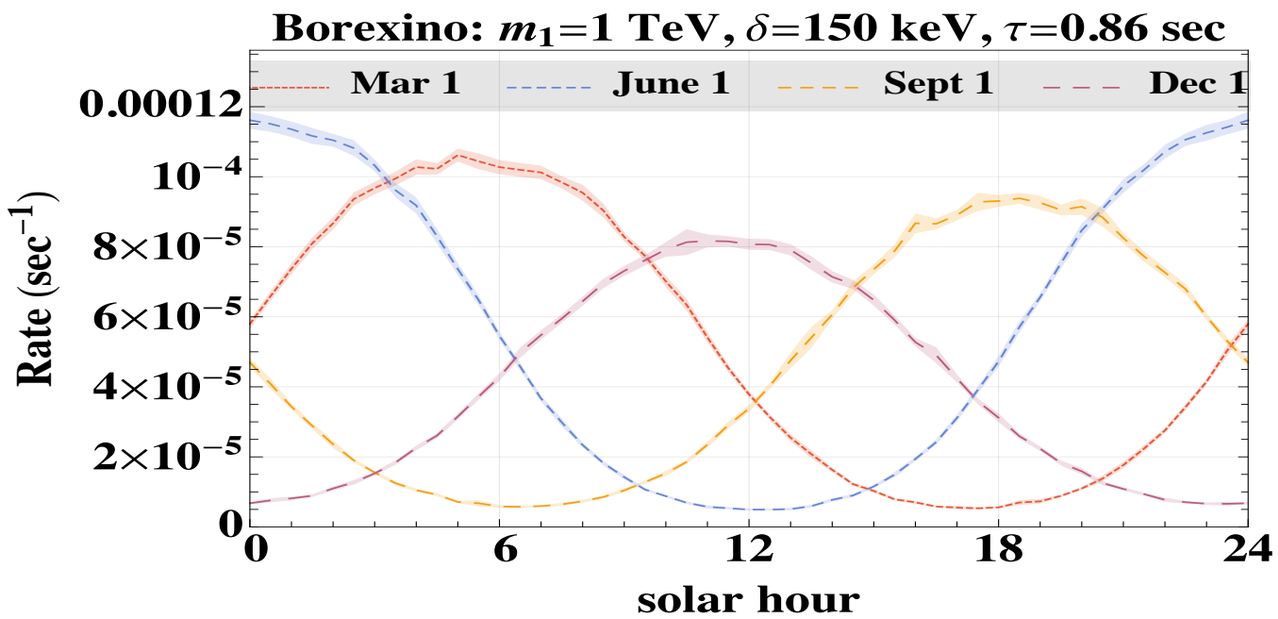
$$\Gamma = \sum_{\pm} \int d^3 r_s \, d^3 v_{\rm MB} \left\{ n_T(r_s) \, \frac{\rho_\chi}{m_1} \left[\frac{R_D}{|\vec{r}_s - \vec{r}_D| \; \theta^{\rm lab}_{\rm max}} \right]^2 P(v^{\rm lab}_{{\rm out},\pm}, L, \tau) \right.$$

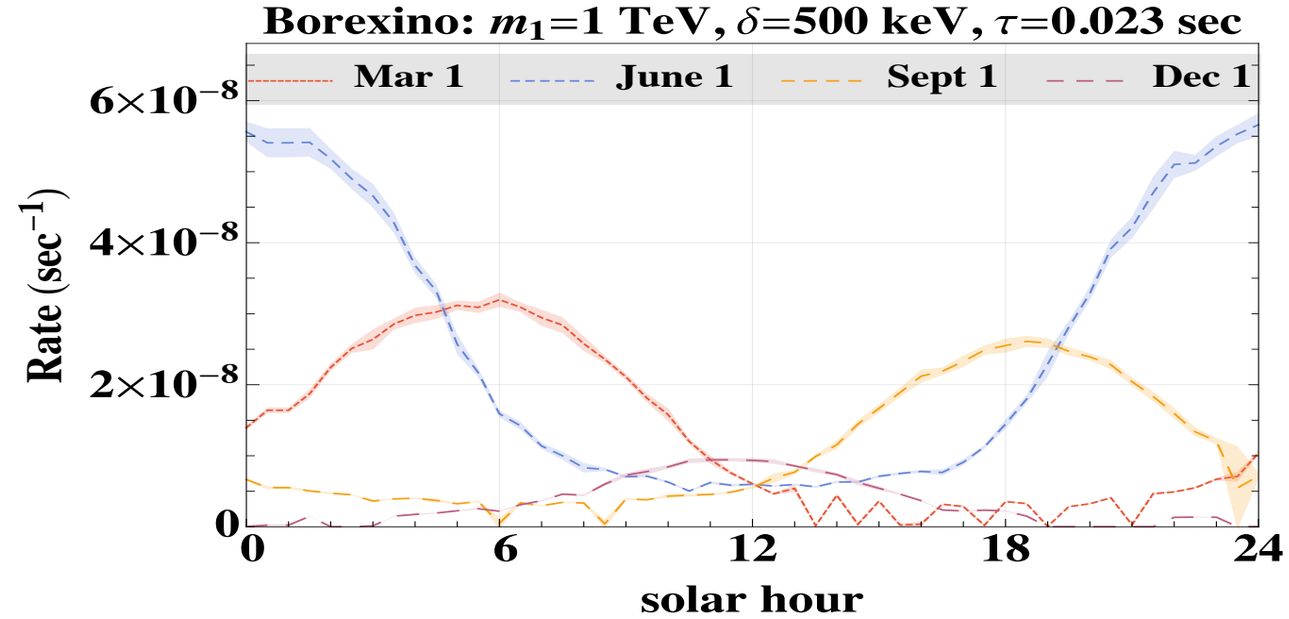
2 c.o.m. scattering angles

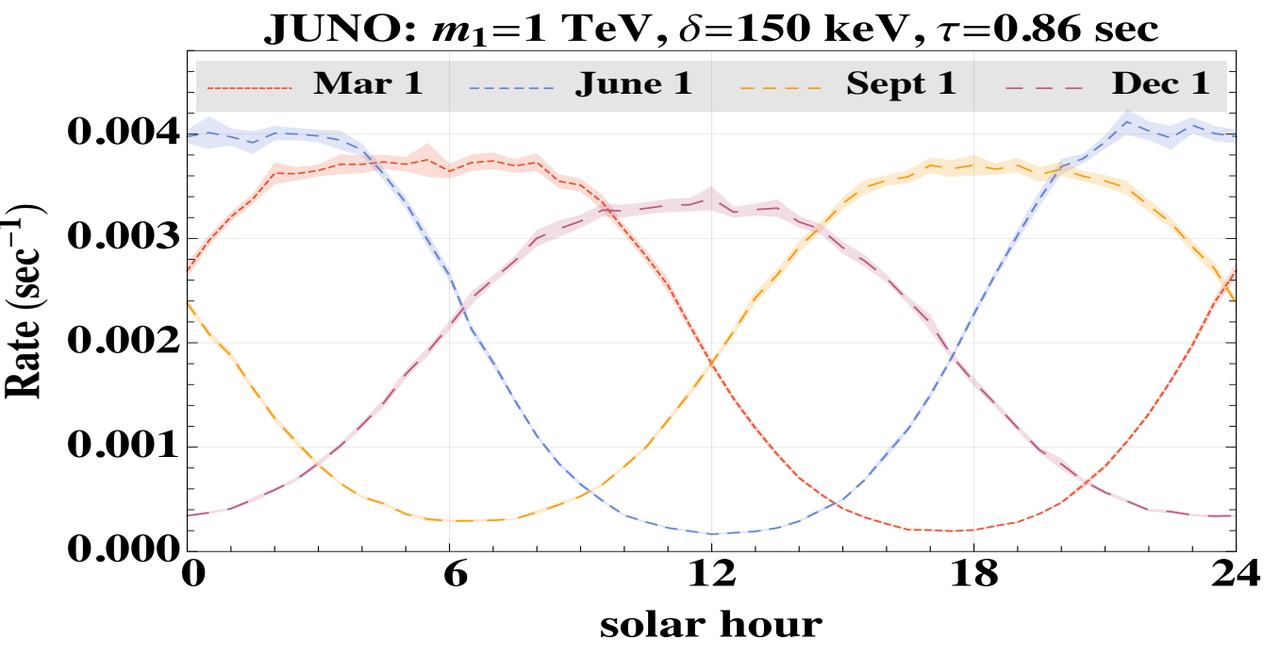
$$\left. \times \, f_{\rm gal}(v_{\rm MB}) \; |F(q_\pm)|^2 \; \frac{d\sigma \, v_\chi}{d\cos\theta^{\rm cm}} \, |J_\pm(v_\chi)|^2 \; \right\}$$

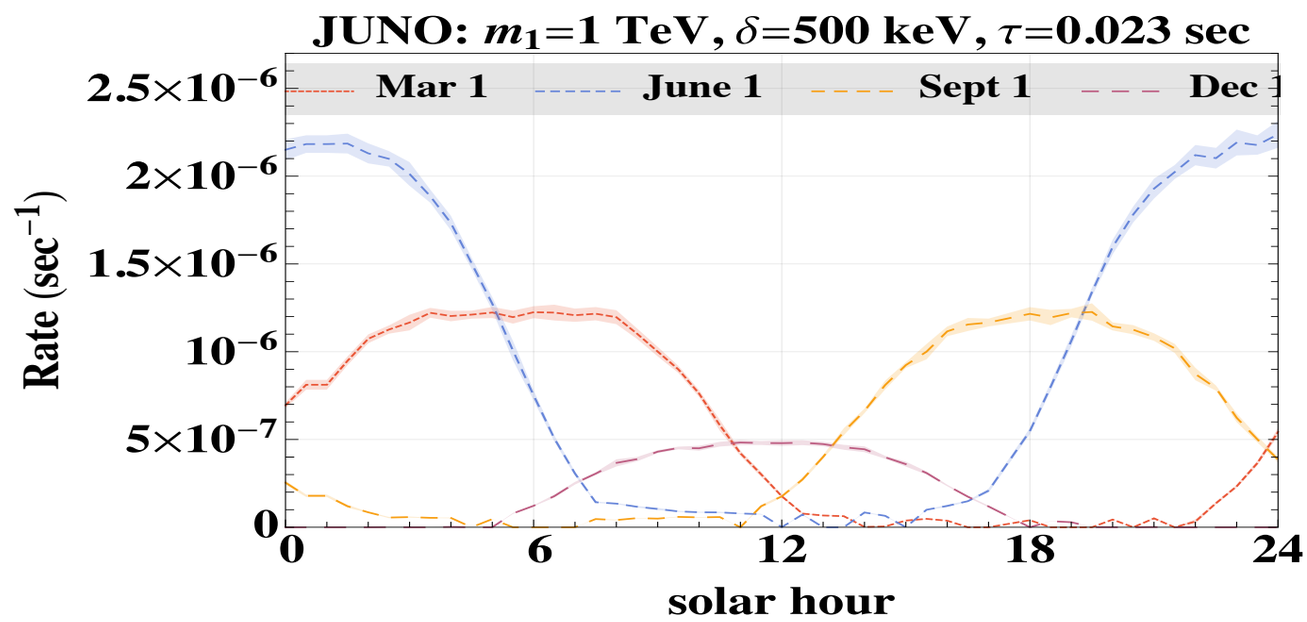
x-sec isotropic in c.o.m. frame

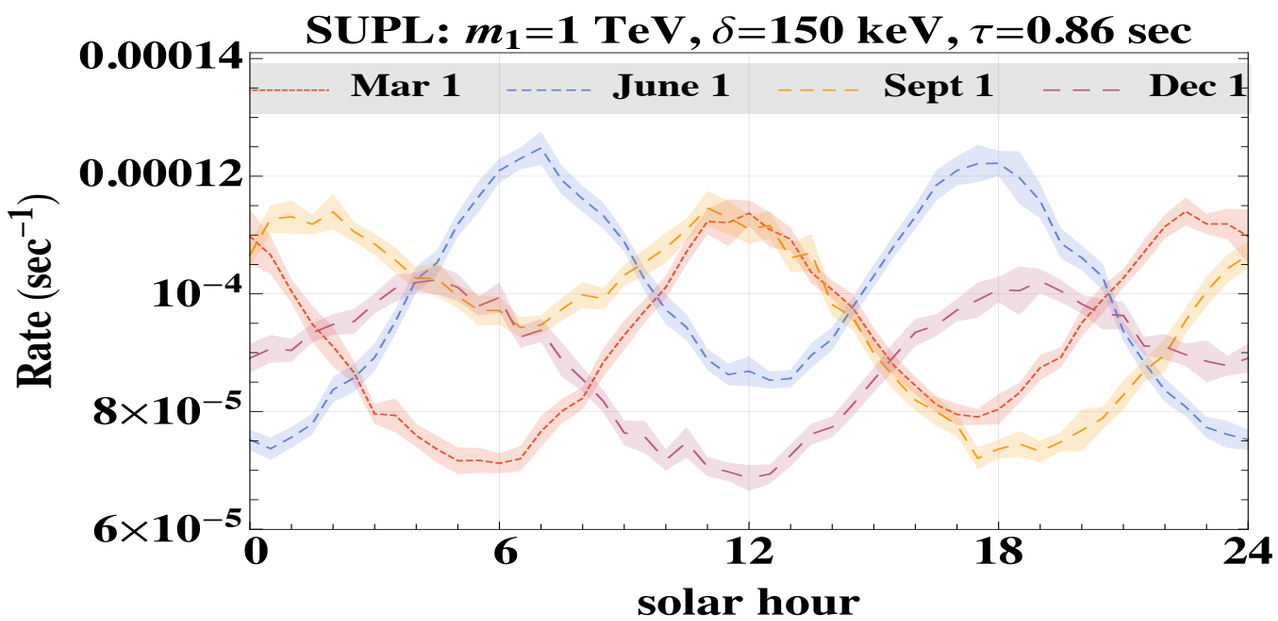
$$P_0(|\vec{r}_s - \vec{r}_D|, v_f) = 2 \, e^{-|\vec{r}_s - \vec{r}_D|/v_f \tau} \sinh \frac{L_D}{2 v_f \tau}$$

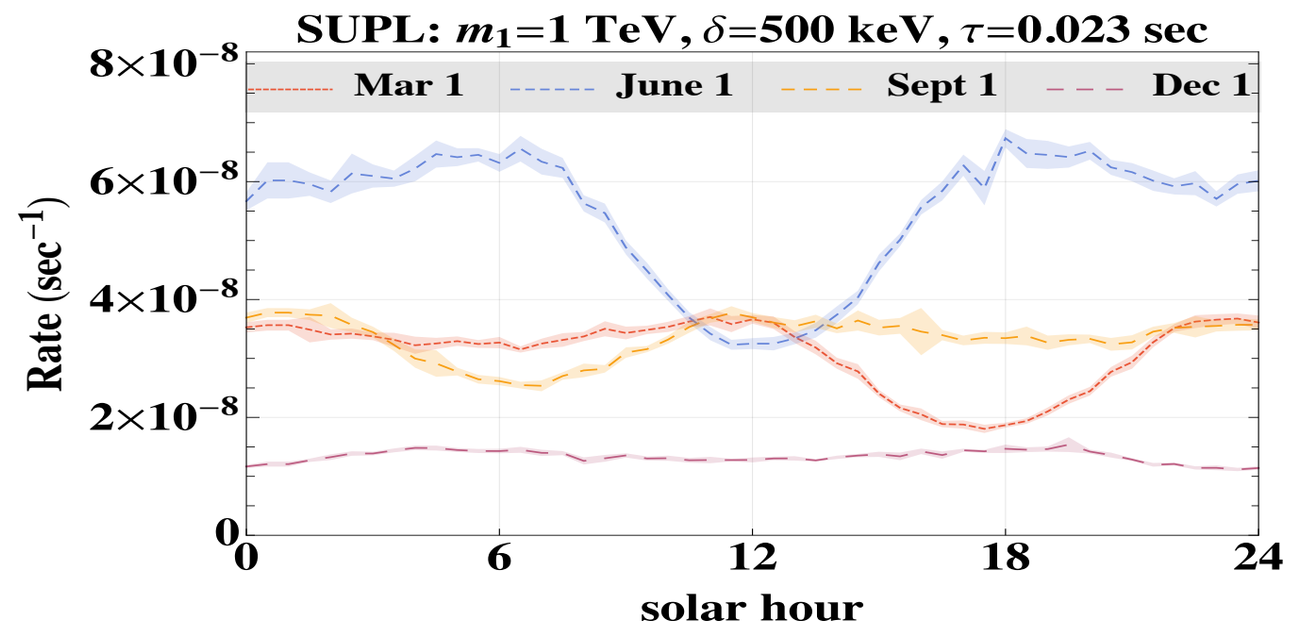

Borexino: m_1=1 TeV, δ=150 keV, τ=0.86 sec
Mar 1
June 1
Sept 1
Dec 1
Rate (sec^{-1})
solar hour


Borexino: m_1=1 TeV, δ=500 keV, τ=0.023 sec
Mar 1
June 1
Sept 1
Dec 1
Rate (sec^{-1})
solar hour


JUNO: m_1=1 TeV, δ=150 keV, τ=0.86 sec
Mar 1
June 1
Sept 1
Dec 1
Rate (sec^{-1})
solar hour

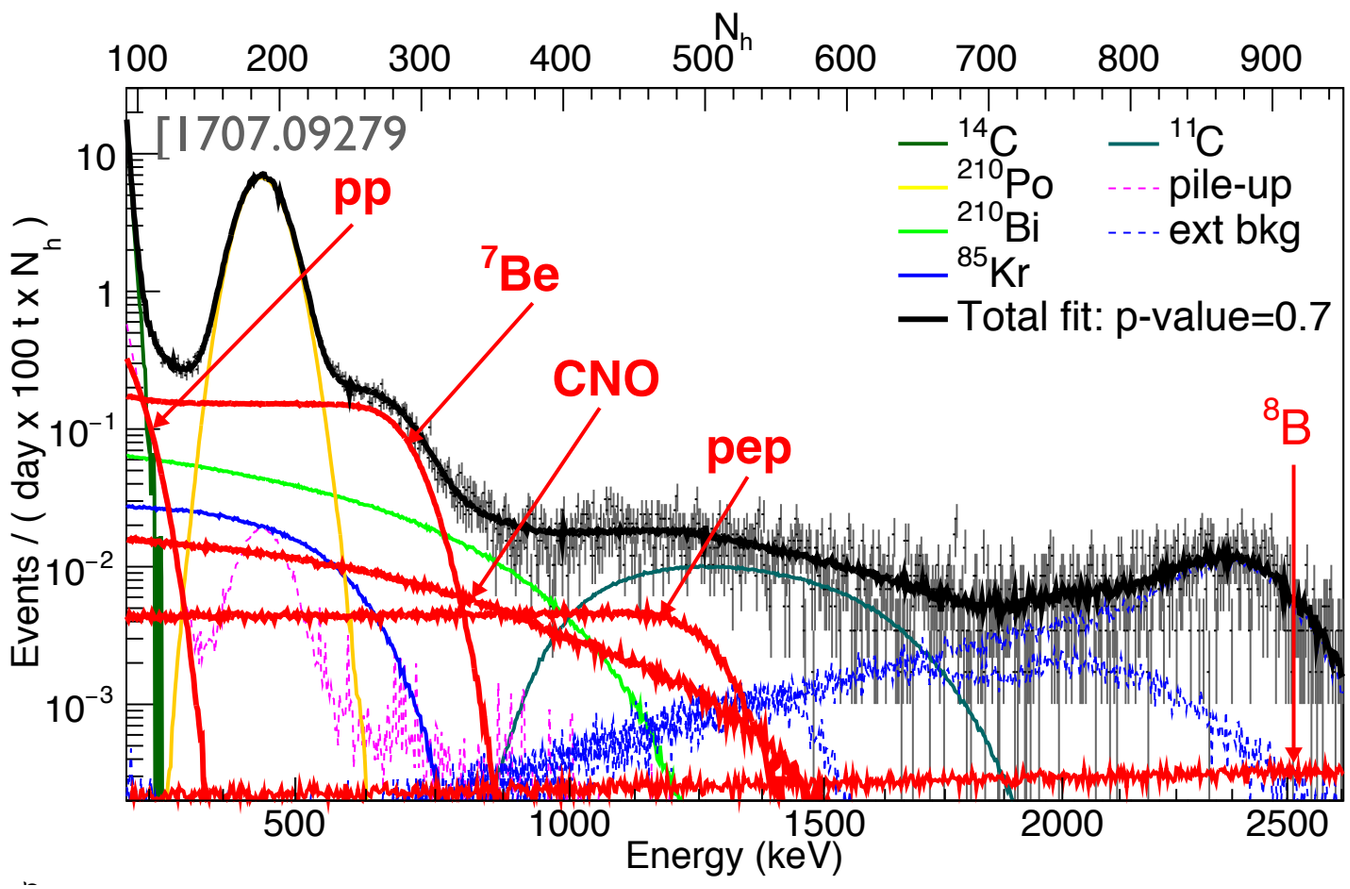

JUNO: m_1=1 TeV, δ=500 keV, τ=0.023 sec
Mar 1
June 1
Sept 1
Dec
Rate (sec^{-1})
solar hour

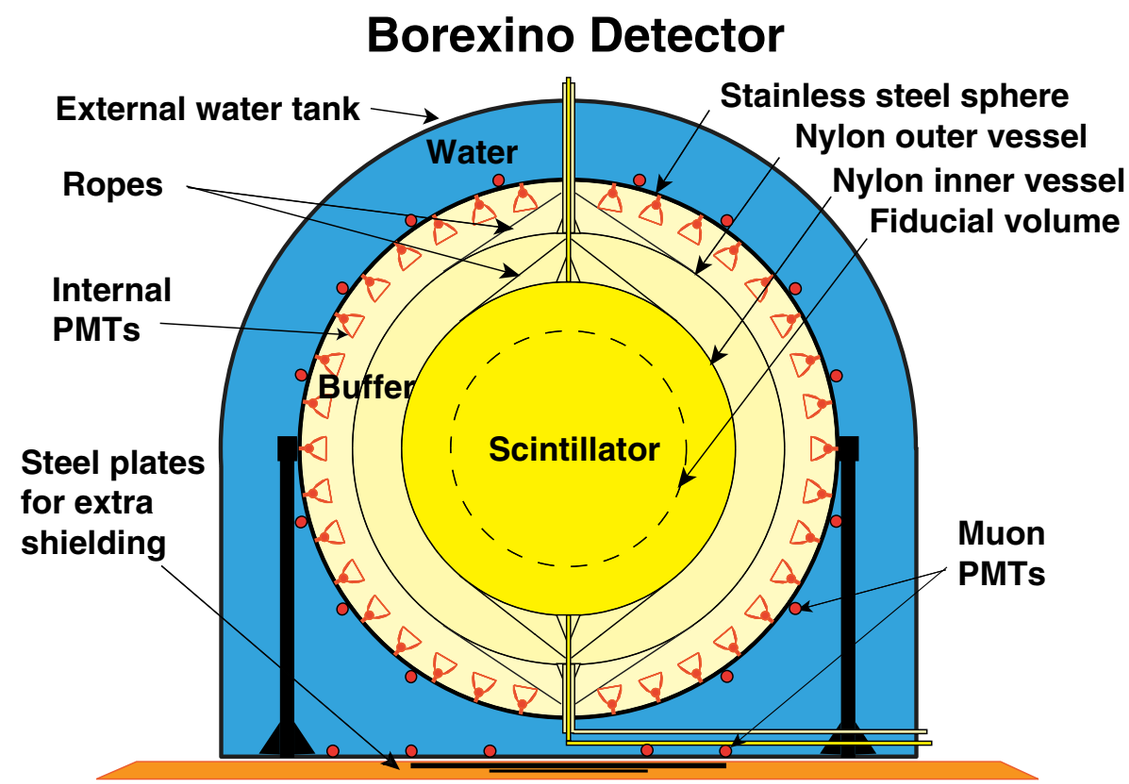

SUPL: m_1=1 TeV, δ=150 keV, τ=0.86 sec
Mar 1
June 1
Sept 1
Dec 1
Rate (sec^{-1})
solar hour


SUPL: m_1=1 TeV, δ=500 keV, τ=0.023 sec
Mar 1
June 1
Sept 1
Dec 1
Rate (sec^{-1})
solar hour

Borexino

- 278 tons of scintillator, ~5m radius
- ~1300 days of data
- ~150 keV threshold, maybe lower?
- Good energy resolution





PHYSICAL REVIEW D **89,** 112007 (2014)

"Yesterday's signal is tomorrow's background"

Borexino

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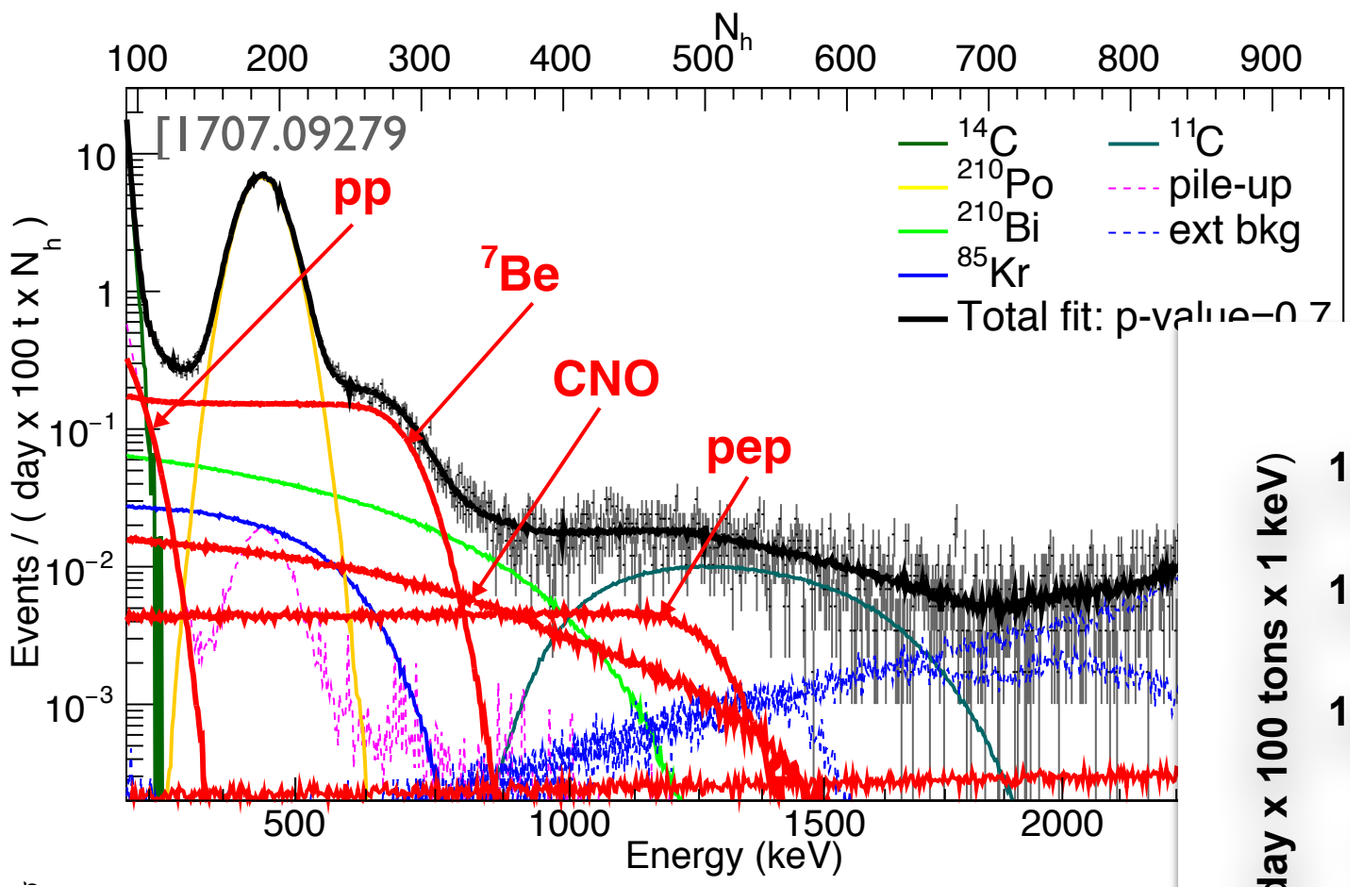
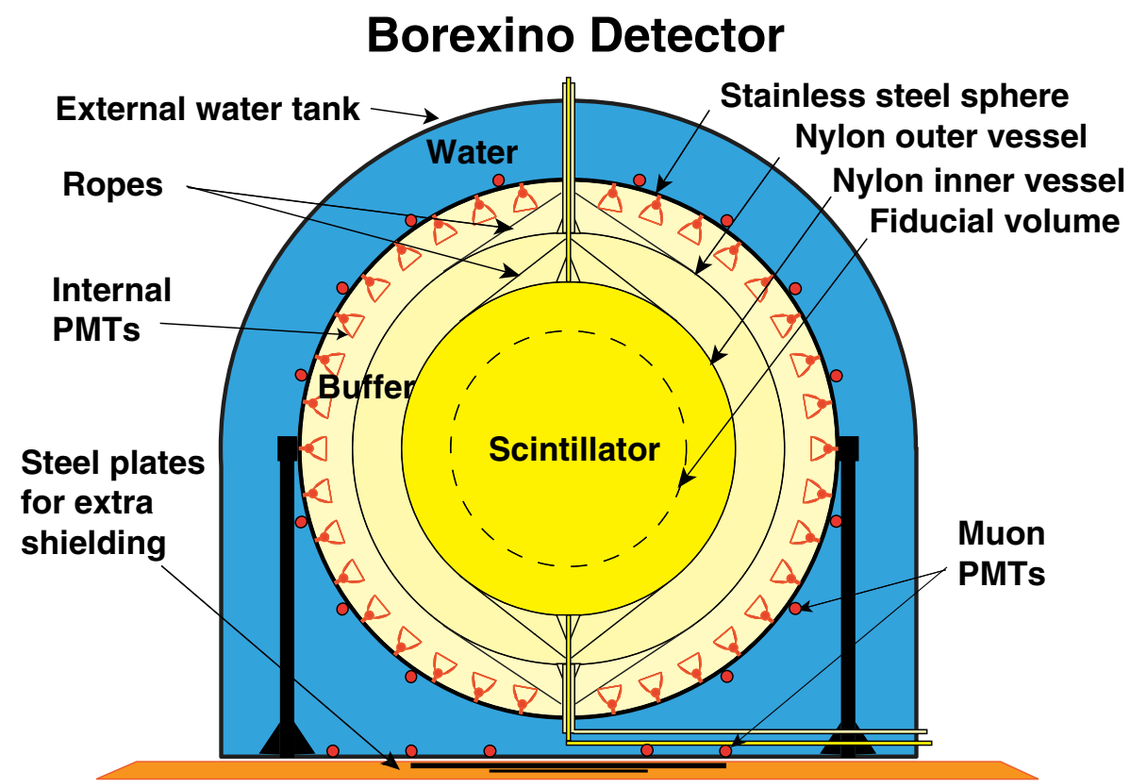
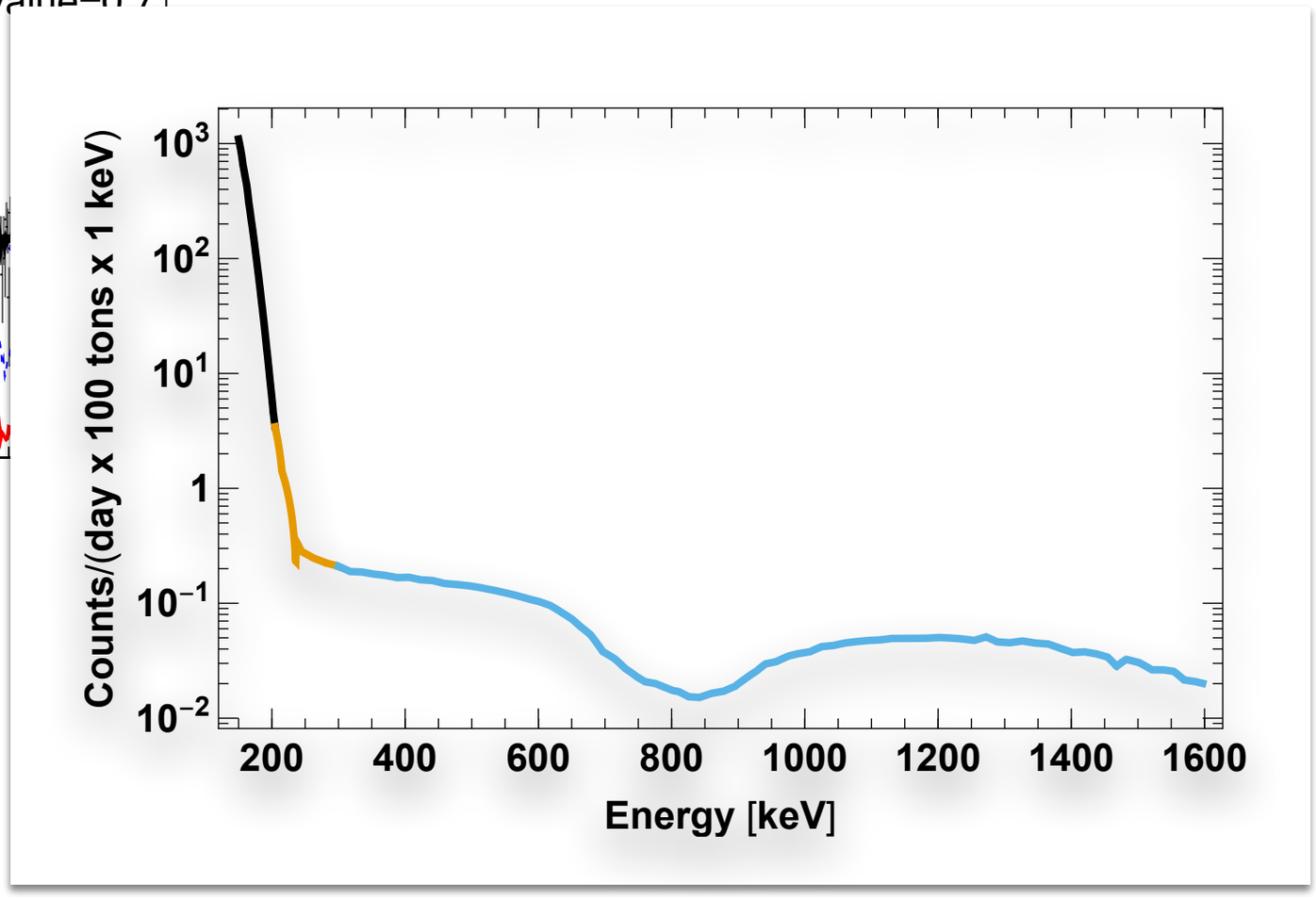




PHYSICAL REVIEW D **89,** 112007 (2014)



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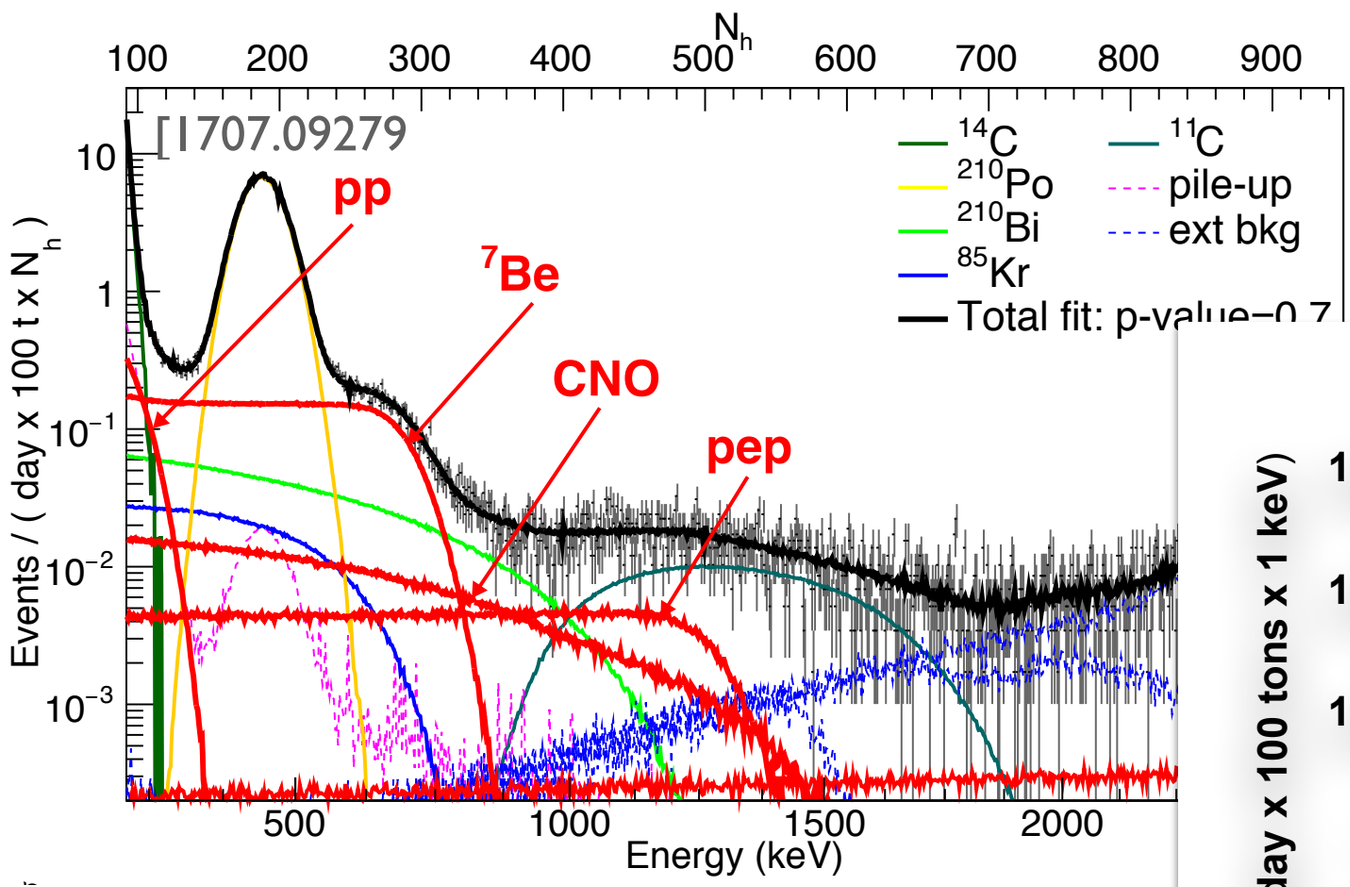
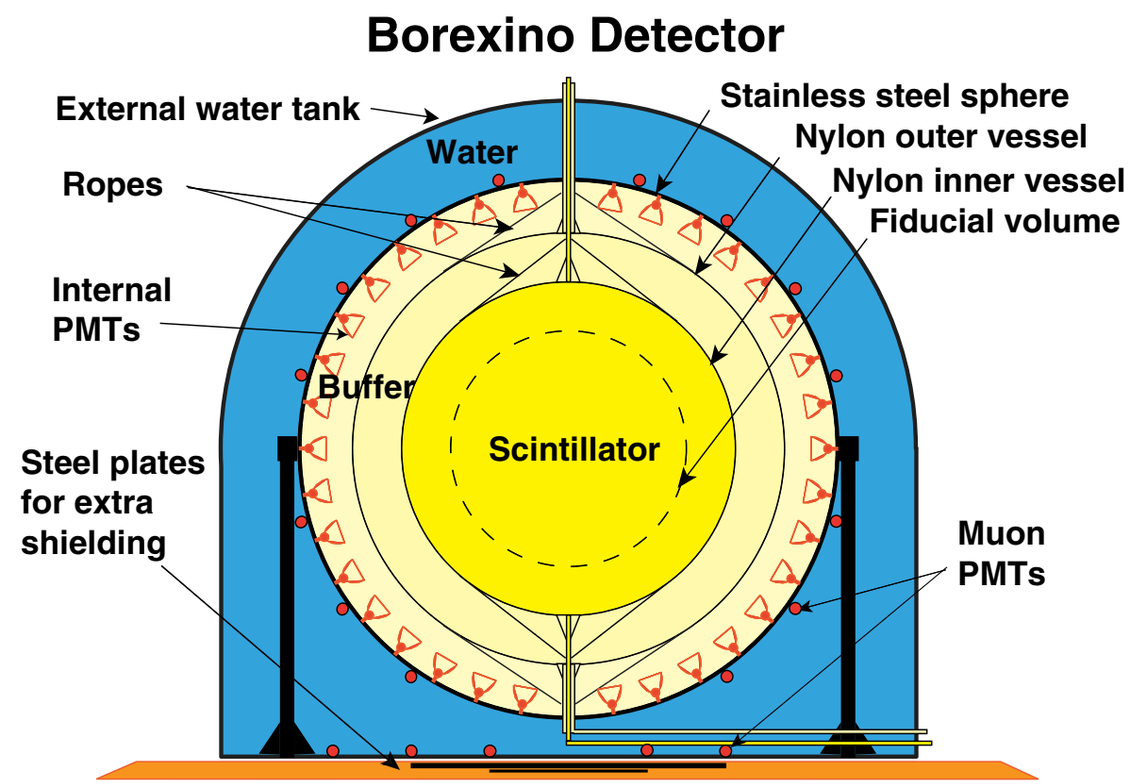
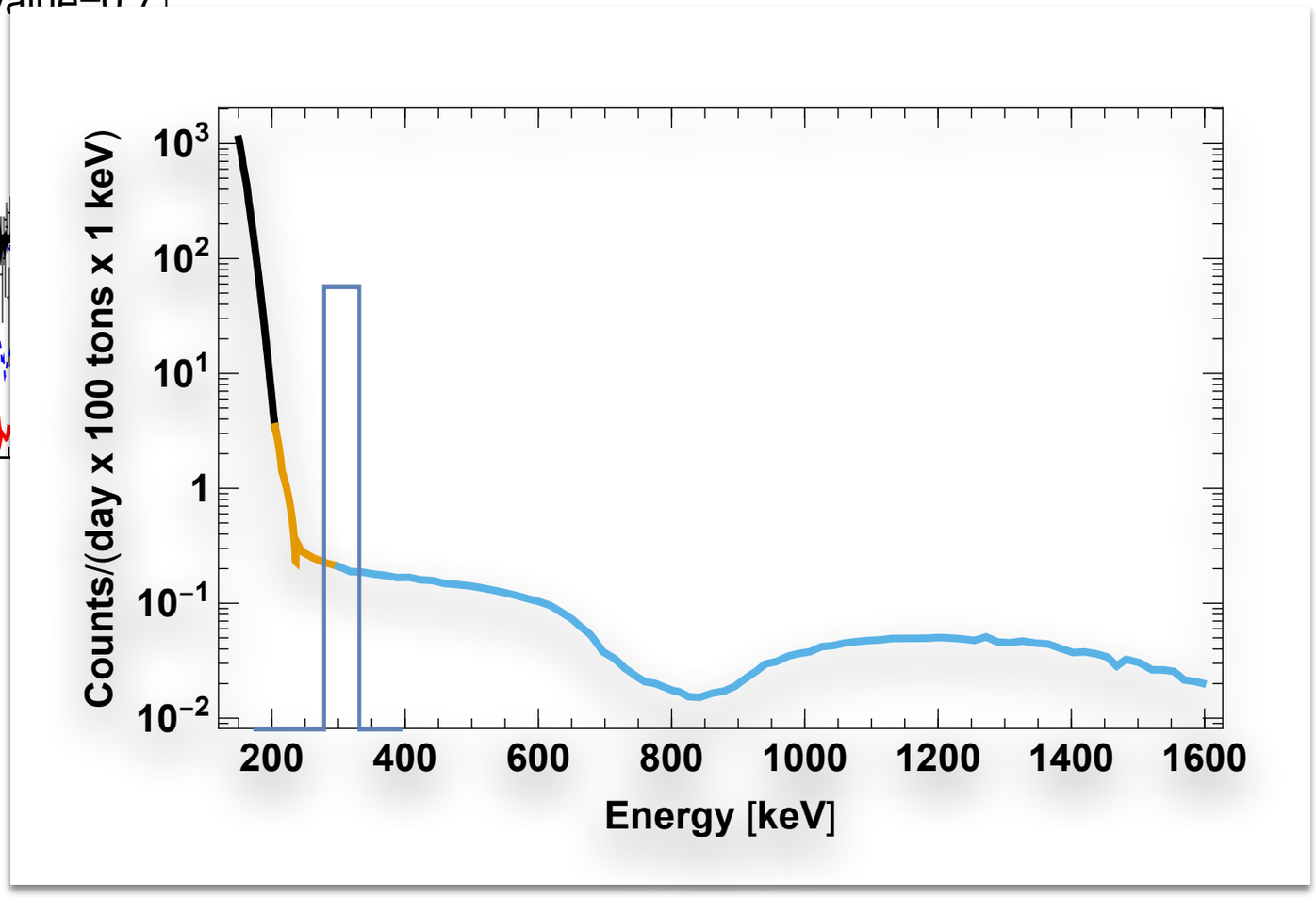




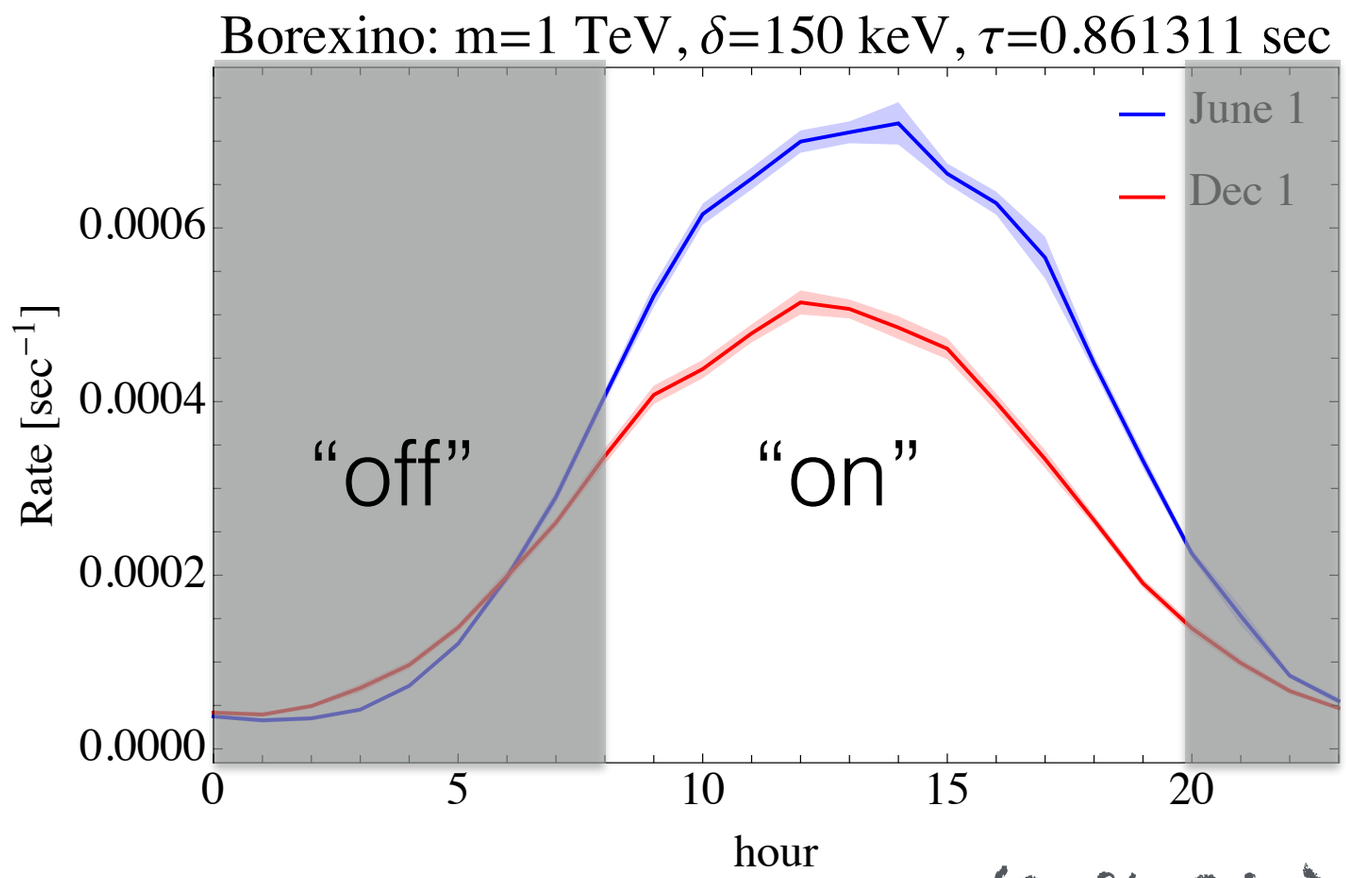
PHYSICAL REVIEW D **89,** 112007 (2014)



"Yesterday's signal is tomorrow's background"

A bound

- Expect ~5 events/day—weak bound, no benefit from large exposure
- Use modulation to our advantage to measure background

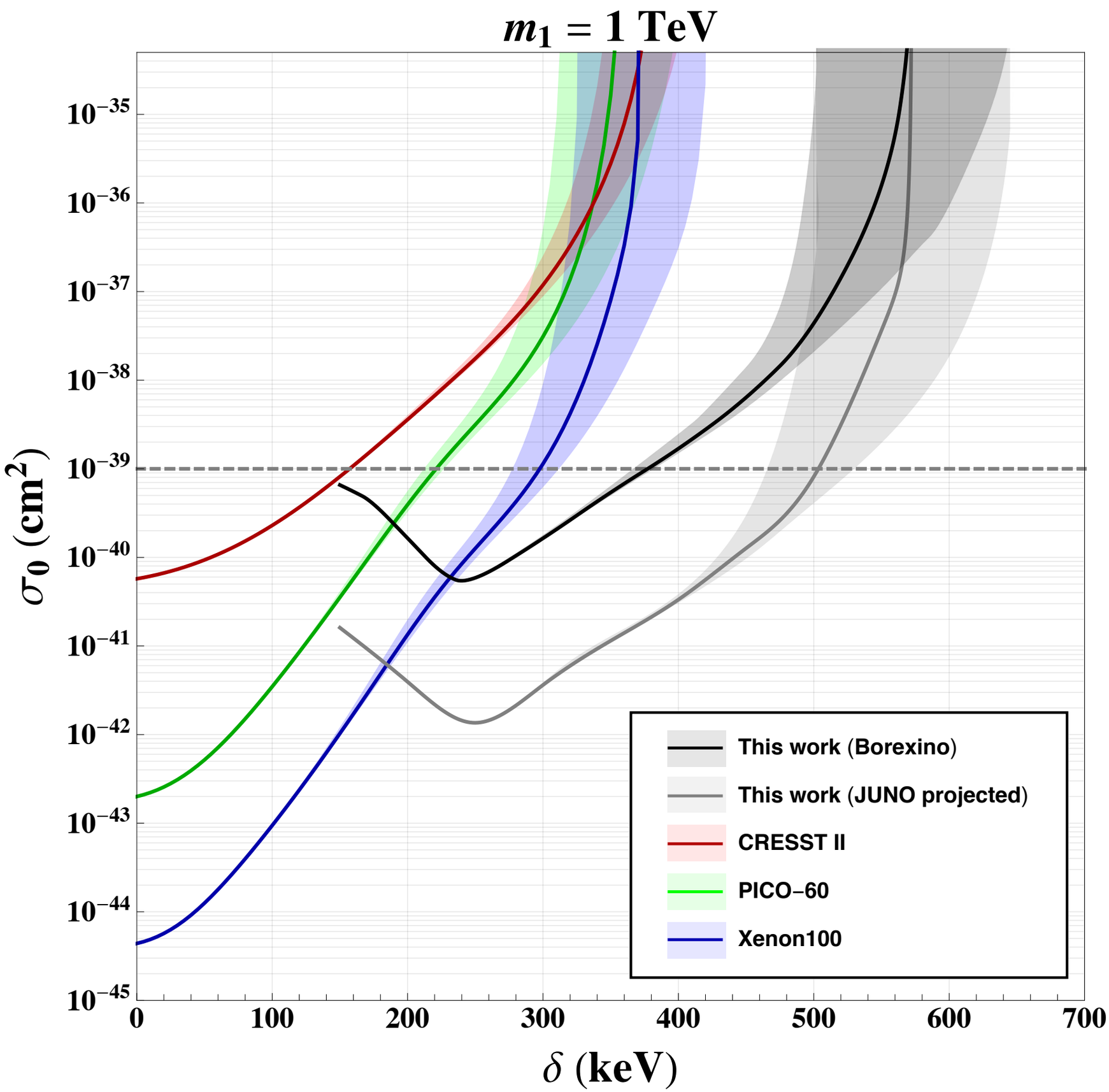


(90% C.L.)

$$\Gamma_{\rm signal} \lesssim \frac{2 \times 1.64}{\sqrt{N_{\rm off}}} \Gamma_{\rm off}$$

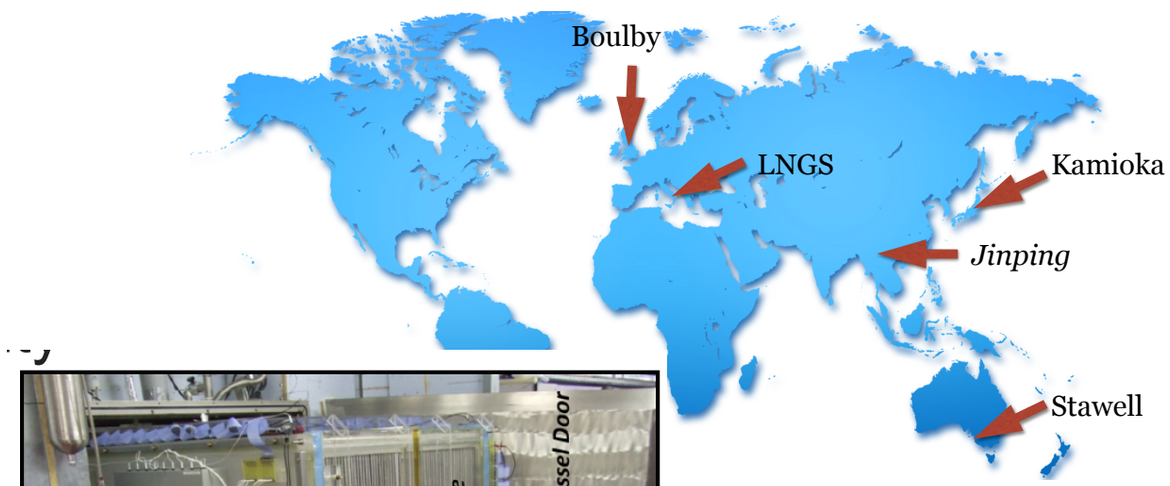
Collaboration could (should!) do a full modulation analysis (sidereal/Cygnus time)

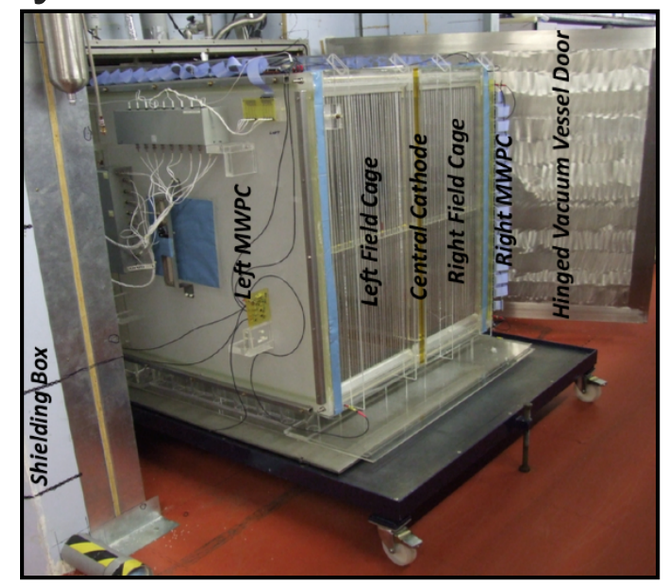
Sensitivity to the Inelastic Frontier

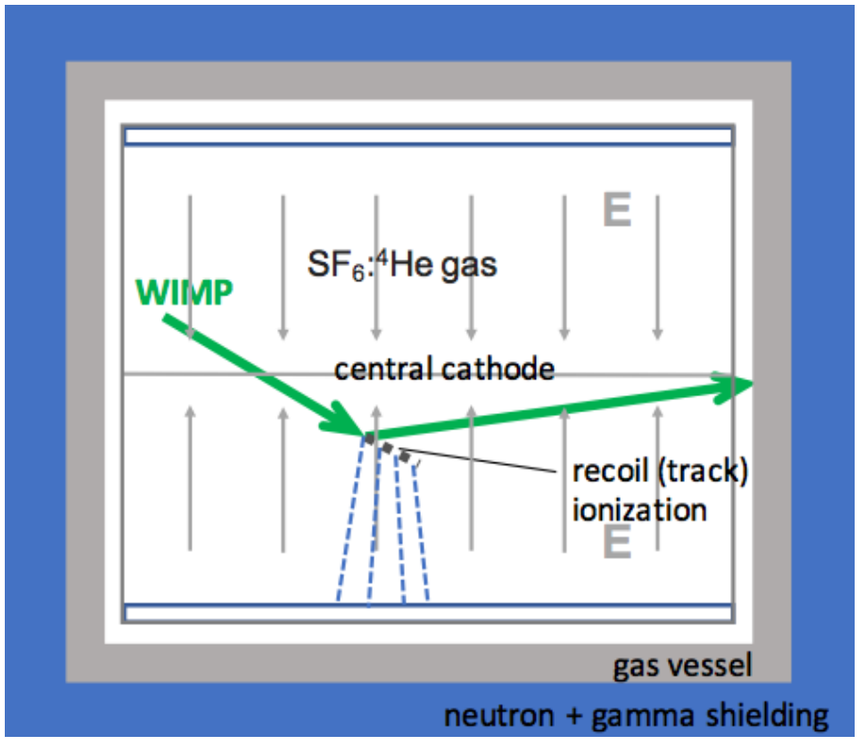


Limited by backgrounds at small splitting
Ideally would have a low threshold, large volume, low background (i.e. low <u>mass</u>) detector

Gas drift TPC's: DMTPC, DRIFT, <u>CYGNUS</u>

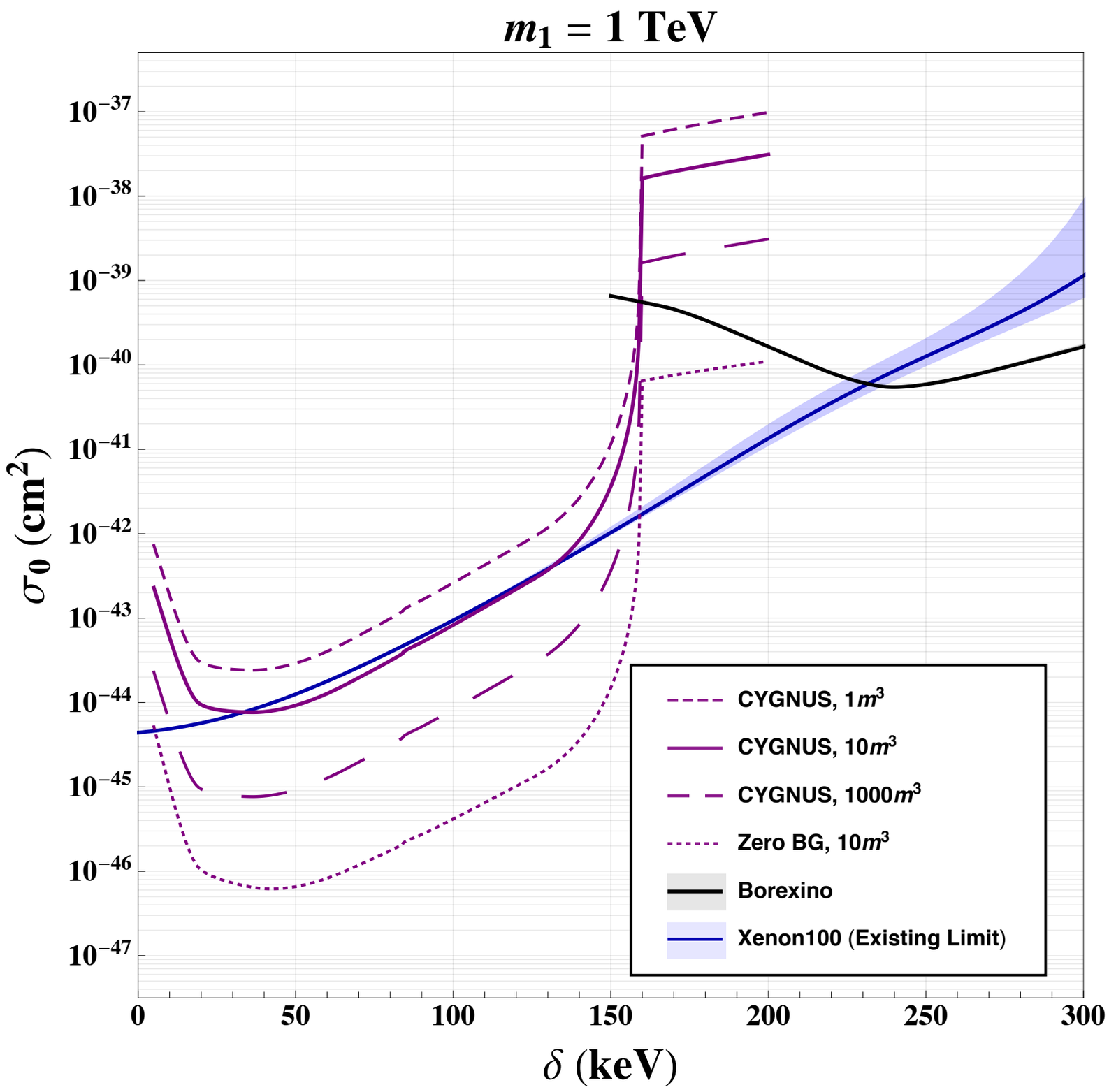




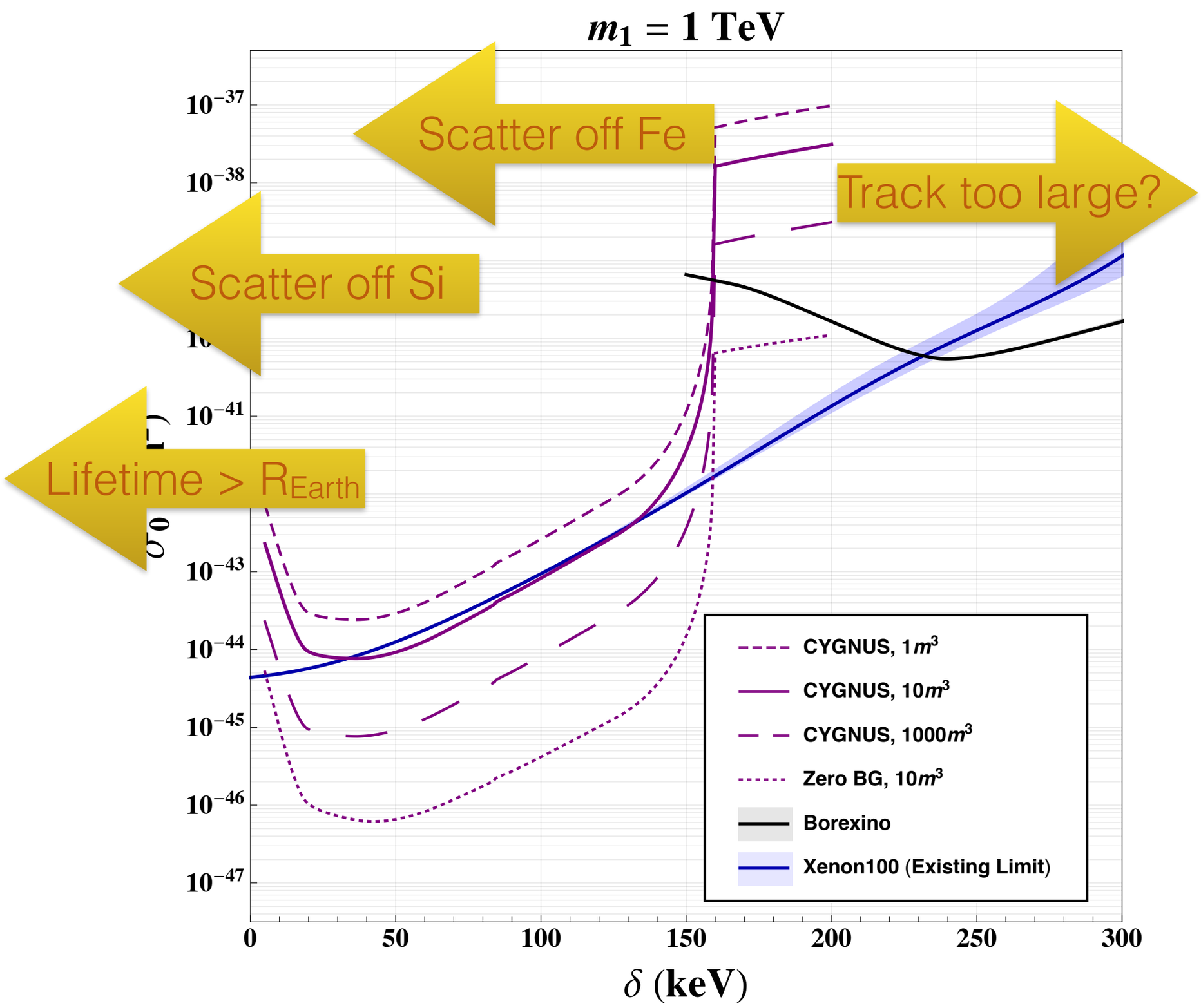


Energies ~10 keVee — ~ 200 keVee. 1m^3, 10m^3 ,1000m^3 volumes. Low mass (gass filled). No ^{14}C.

Projected Sensitivity at CYGNUS

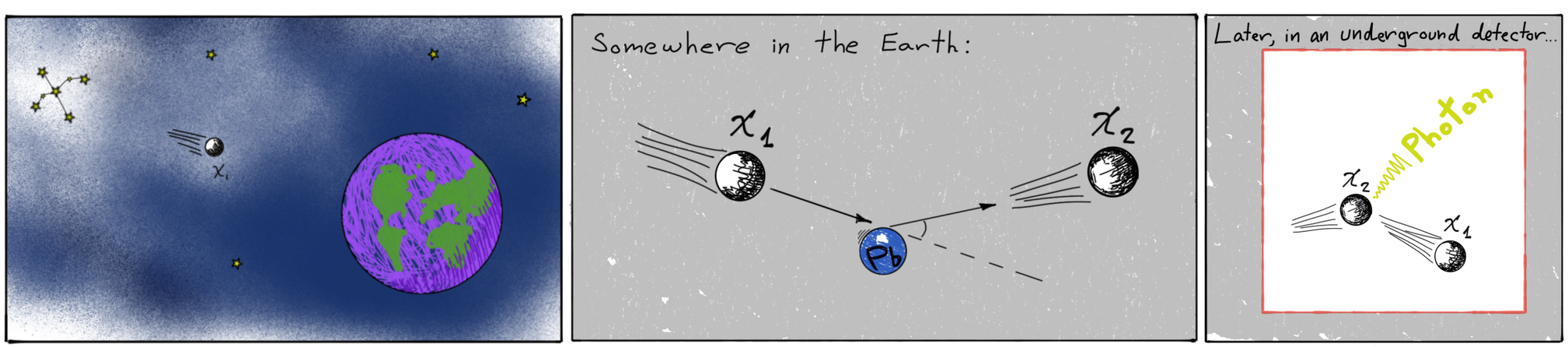


Projected Sensitivity at CYGNUS



The Photon Phrontier

- iDM challenges direct detection in unique ways—*raise* energy threshold
- Luminous process to probe inelastic DM
- Whole Earth is target, multiple elements
- Search for de-excitation photon in large volume (not mass!), low threshold detectors
  - Borexino, JUNO, CYGNUS
  - Can beat traditional direct detection experiments, at large and small delta
- Novel sidereal day modulation, latitude dependence



Extra slides

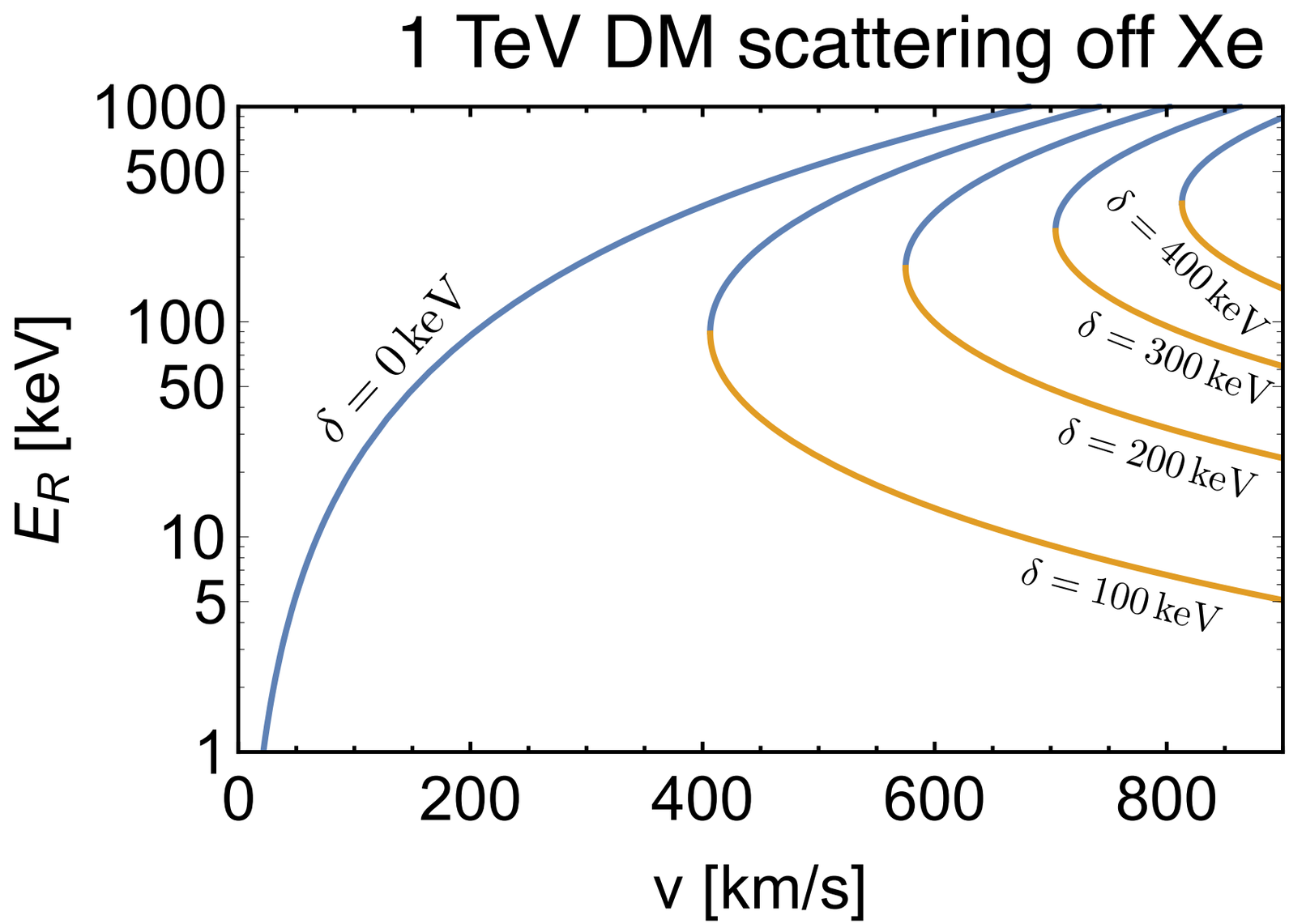
Inelastic kinematics

Nuclear recoil energy

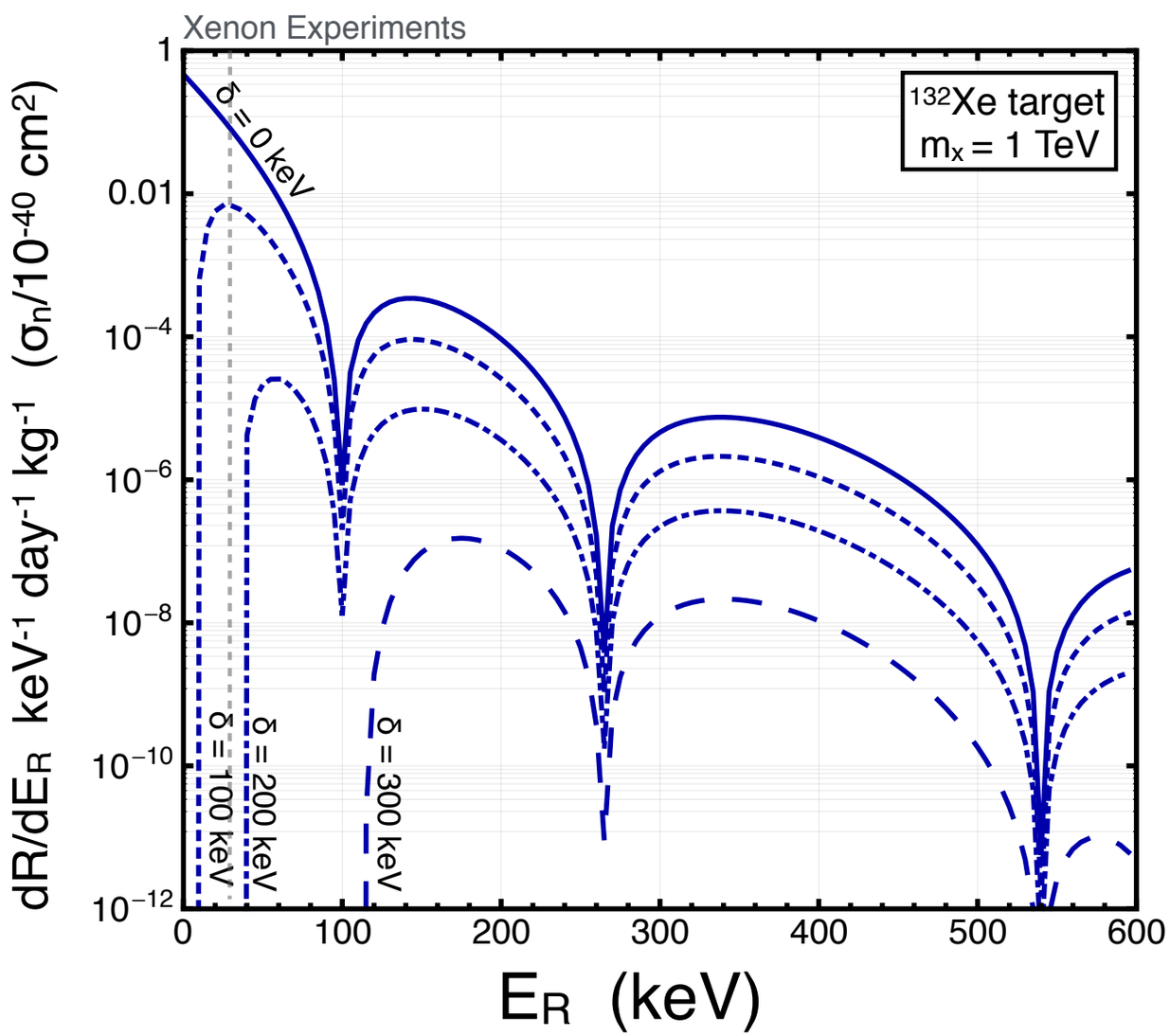
Lab scattering angle

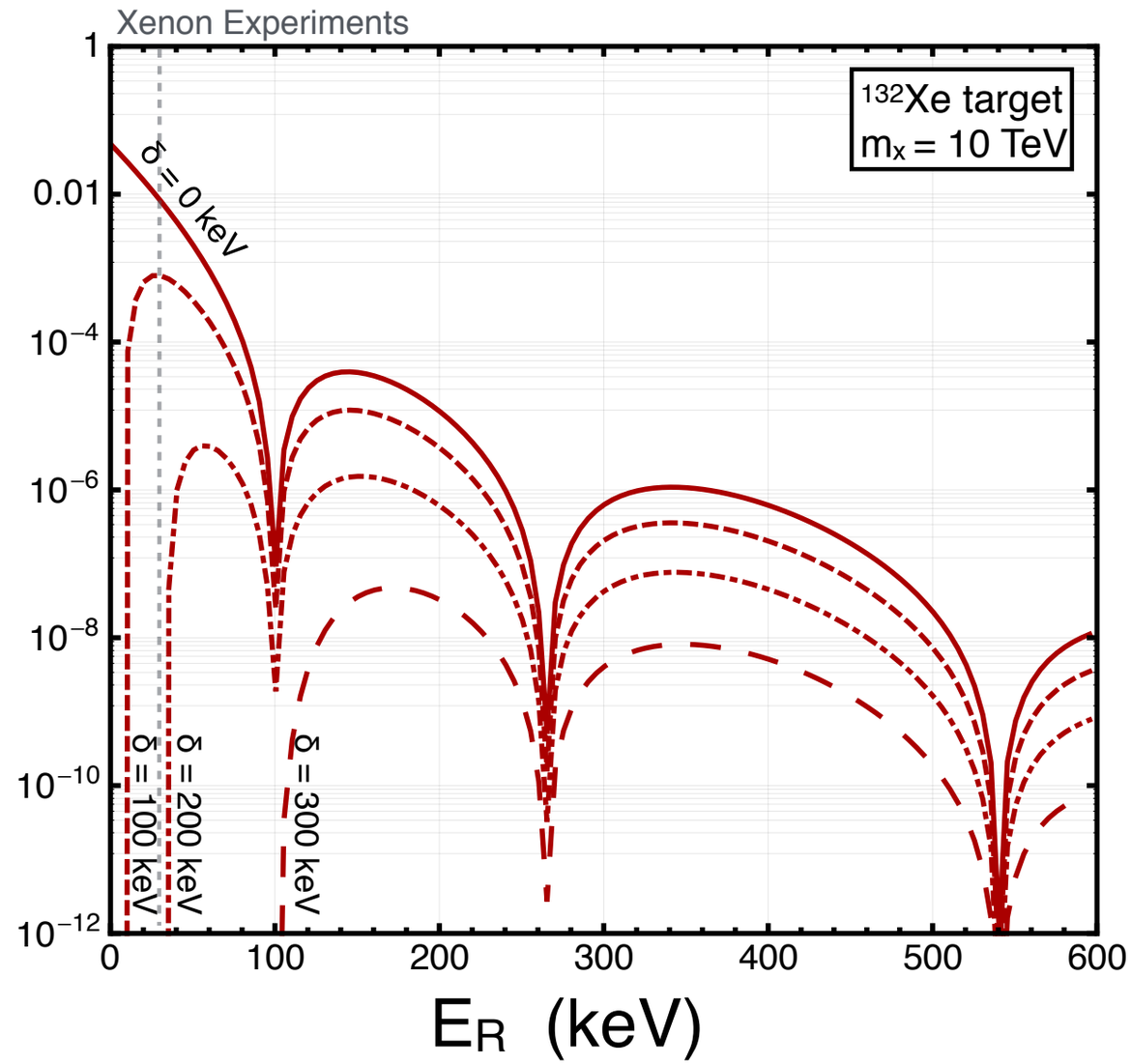
$$E_R = \frac{\mu}{m_N}\left[\left(\mu v^2 \cos^2\theta_{\rm lab} - \delta\right) \pm \left(\mu v^2 \cos^2\theta_{\rm lab}\right)^{1/2}\left(\mu v^2 \cos^2\theta_{\rm lab} - 2\delta\right)^{1/2}\right]$$

DM speed in lab frame



Form factors



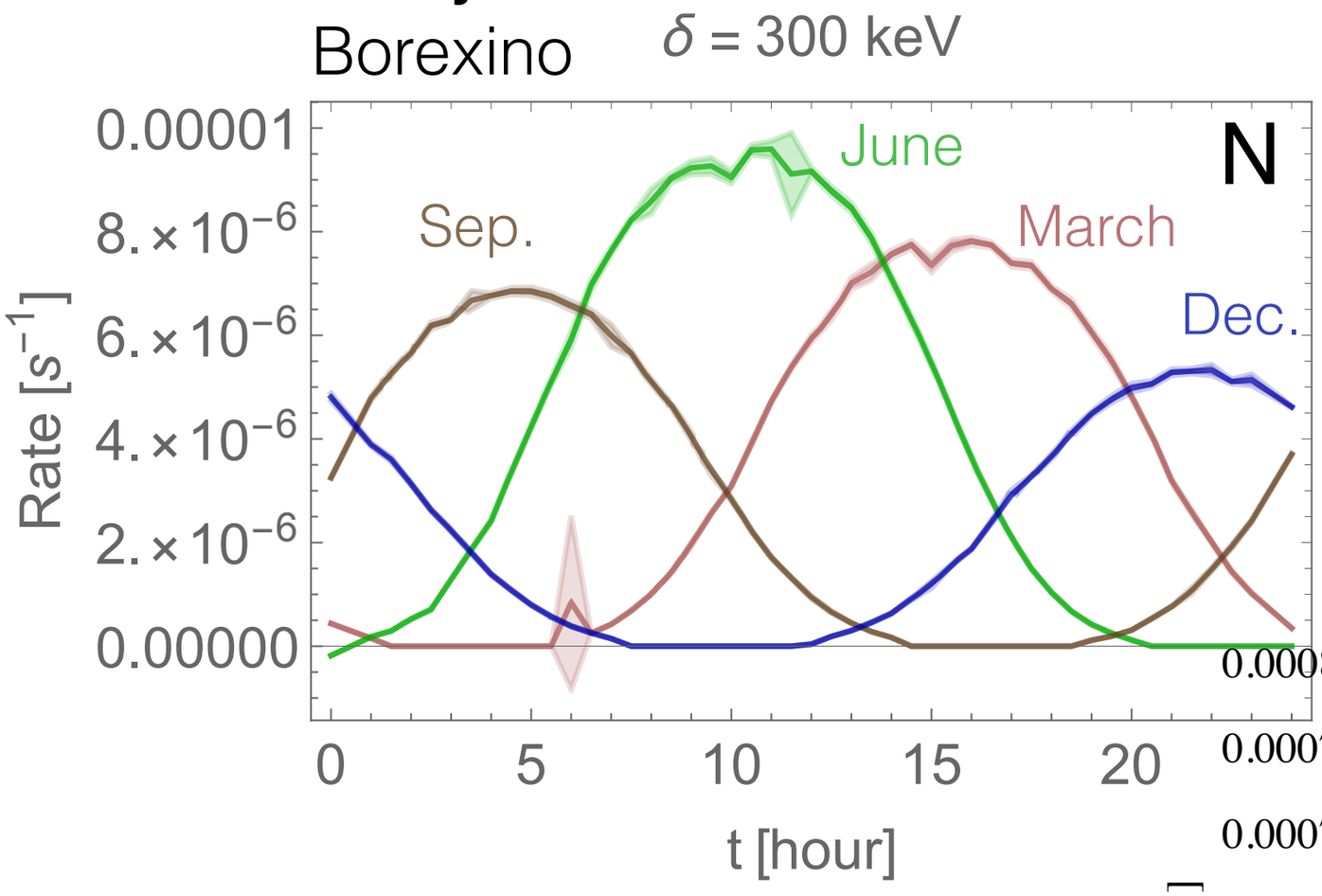


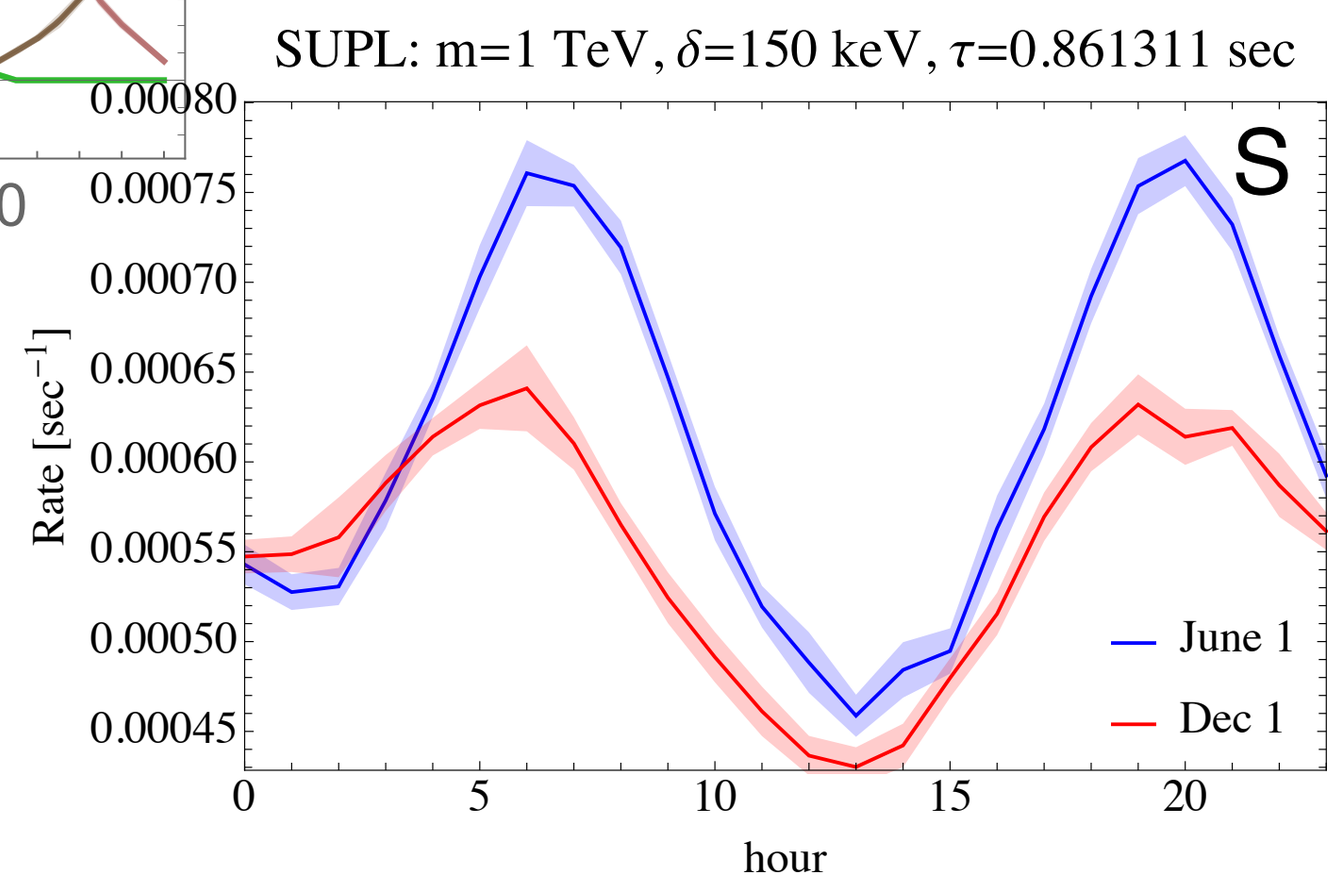
$$\frac{dR}{dE_{\rm R}} = n_X N_{\rm T} \int_{v_{\rm min}}^{v_{\rm max}} v \; f(\vec{v}, \vec{v}_{\rm e}) \; \frac{d\sigma}{dE_{\rm R}} \; d^3v$$

$$\frac{d\sigma}{dE_{\rm R}} = \frac{\sigma_{\rm n}}{v^2} \frac{m_{\rm N}}{2\mu_{\rm n}^2} \frac{[Z f_p + (A-Z) f_n]^2}{f_n^2} F^2(E_{\rm R})$$

Modulation

Lead overburden depends on position of Cygnus *not* the Sun.
1 sidereal day = 23 hours 56 minutes 4 seconds





Changing the lifetime