ν DM Searches

(a case study, or three?)

Patrick Fox

Fermilab

Based on
Bramante, PF, Kribs, Martin (1608.02662)
Eby, PF, Harnik, Kribs (1904.09994)
and
de Gouvea, PF, Harnik, Kelly, Zhang
(1809.06388)

Some Detectors

Detector	Mass	Energy
LUX/XENON1T	~1 ton	~1-30* keV
CDMS	~few kg	“
DAMA	~250 kg	“
Borexino	~300 ton	>~150 keV
SNO	~1000 ton	>~ 1 MeV
Icecube	~10^7 ton	>~10 GeV
DUNE (near/far)	~75 ton/40,000 ton	>~ 5 MeV

* this upper limit is typical upper limit of “search window”

Some Comments

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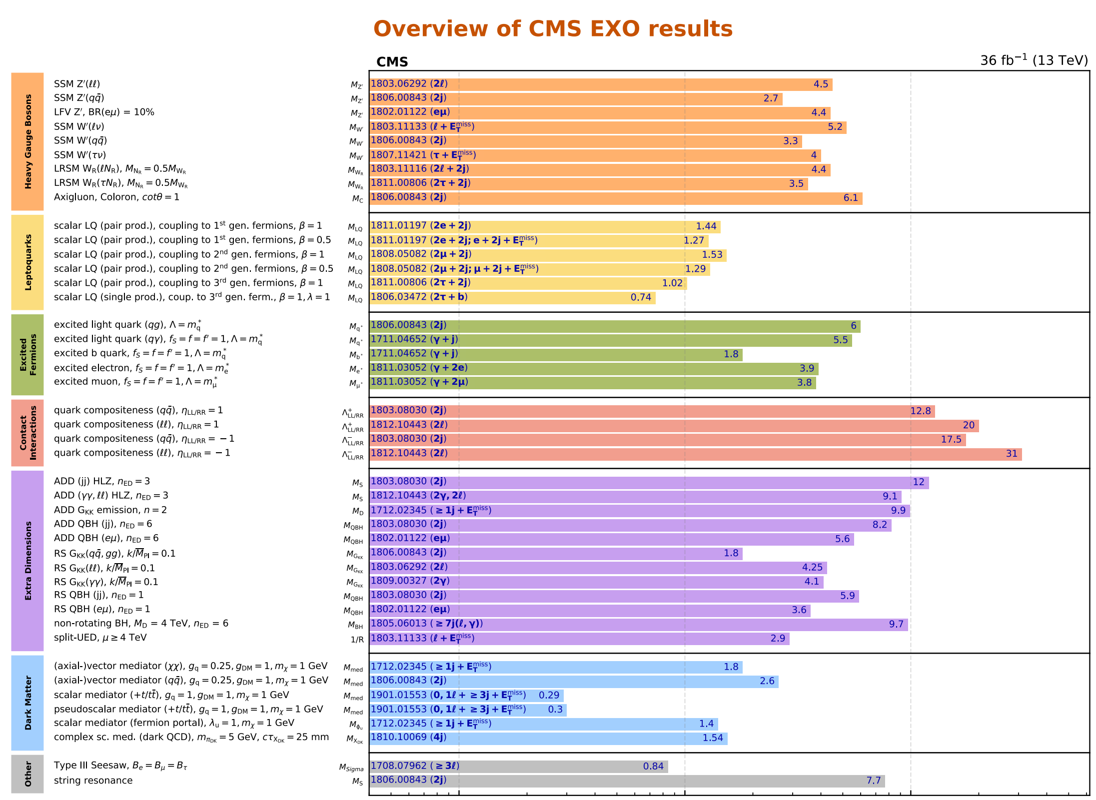
- Both DM and neutrino detectors are looking for low rate signal
  - Low backgrounds
- Often similar technologies e.g. LAr vs LXe
  - Excellent tracking, energy resolution, PID, etc
- Larger volumes and higher thresholds
  - Non-standard DM models can pass thresholds

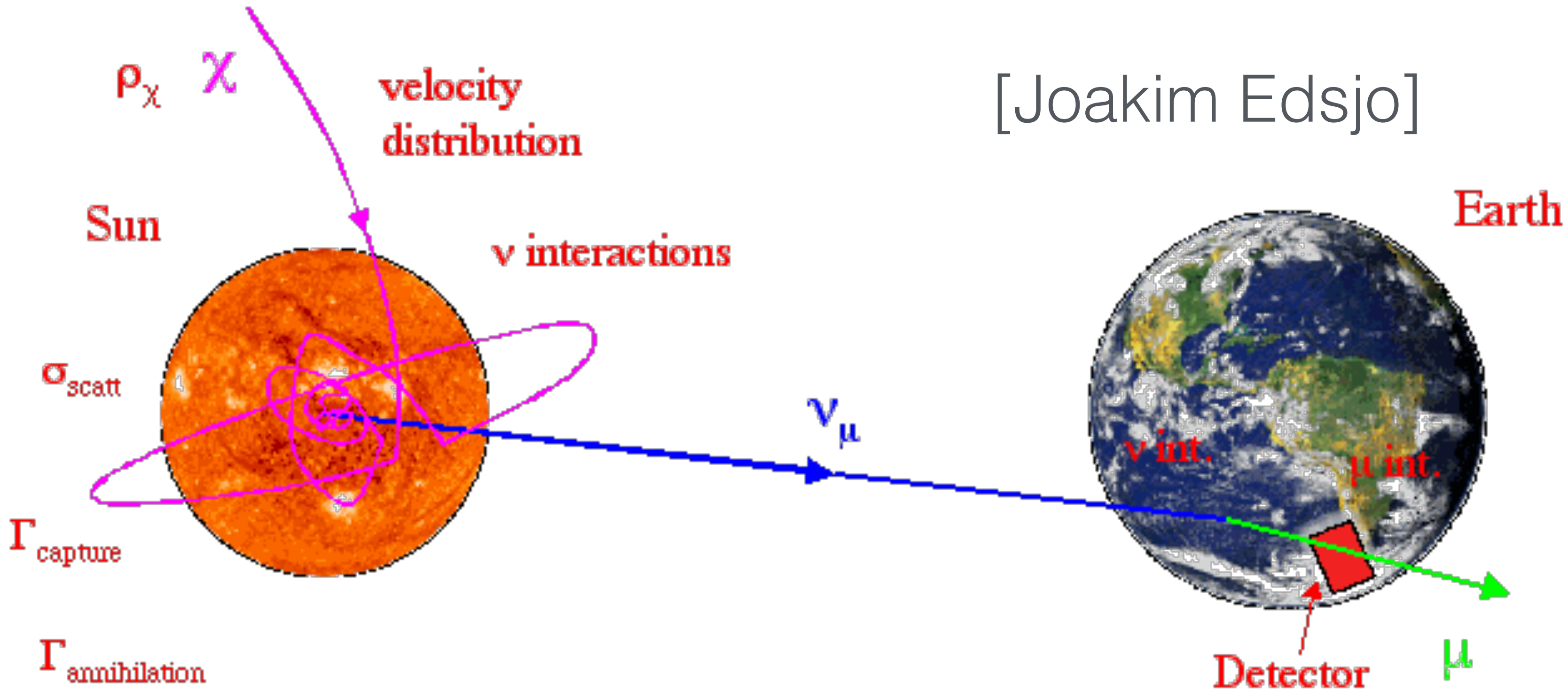
Use neutrino detectors for DM (and vice versa)

Broaden and strengthen the search program



DM @ neutrino detectors

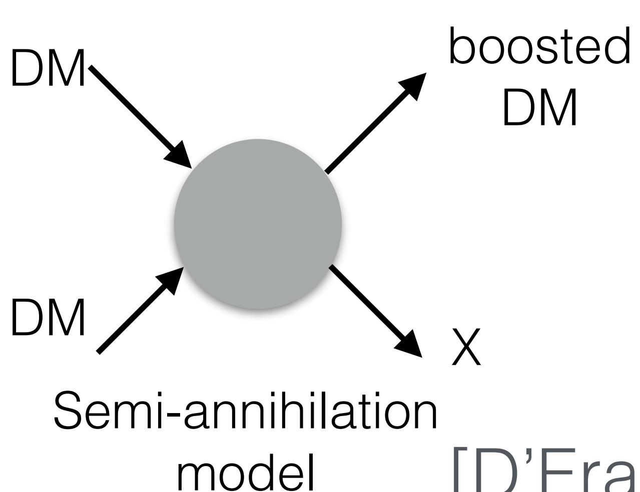
- Indirect effects e.g. solar capture of DM followed by annihilation into neutrinos



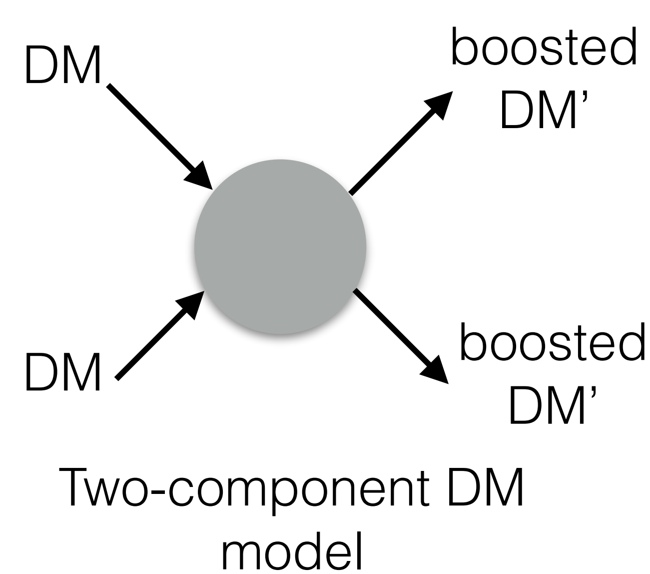
[Joakim Edsjo]

- Boosted DM variant (also from GC)

[Cui + collaborators]



[D'Eramo and Thaler]

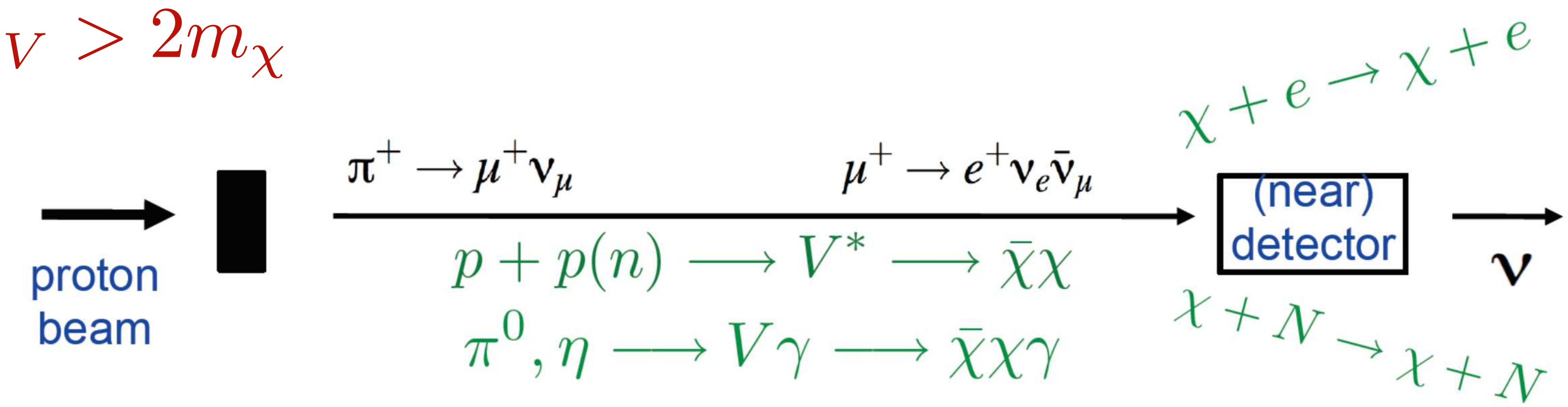


DM @ neutrino detectors

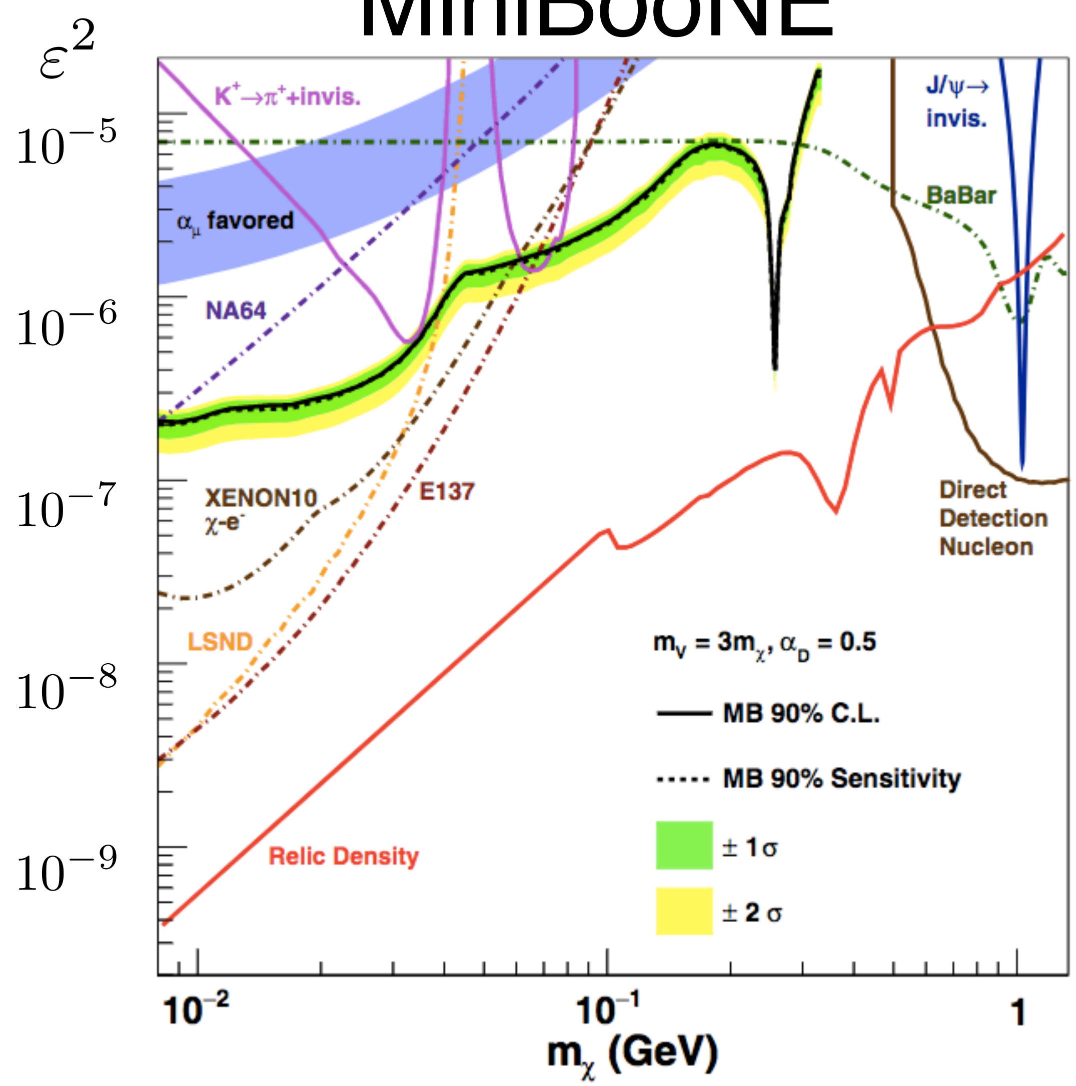
- Beam produced DM/dark sector states in near detectors

$m_V > 2m_\chi$

[e.g. Batell, Pospelov, Ritz]



MiniBooNE



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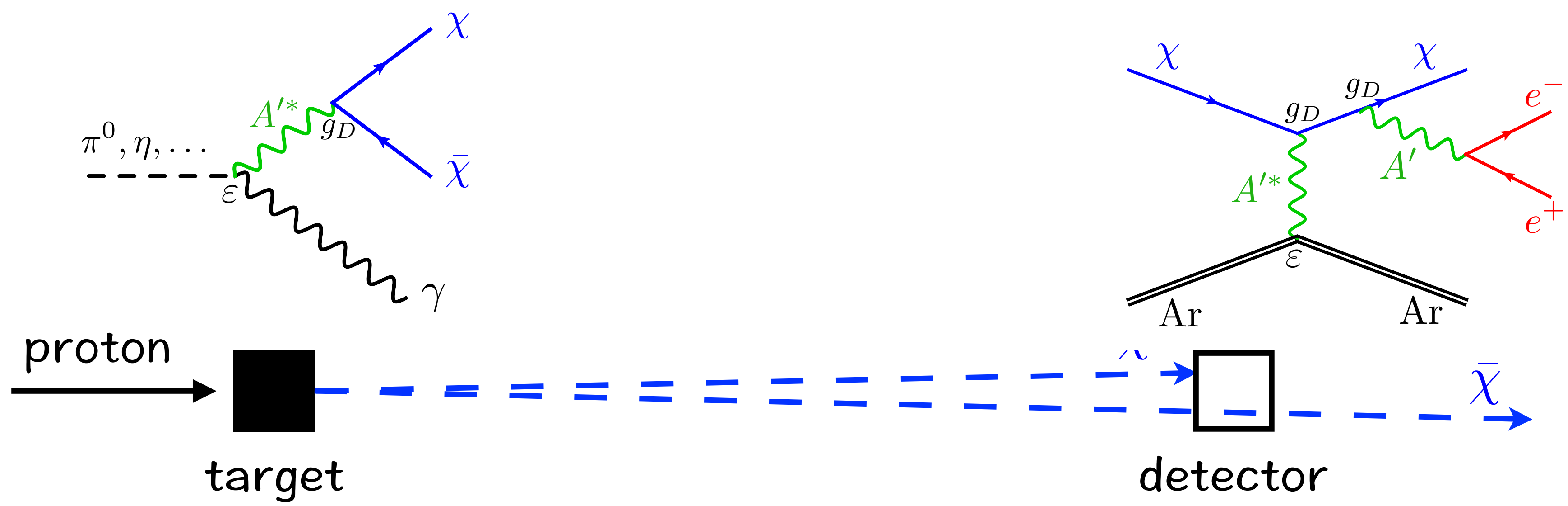
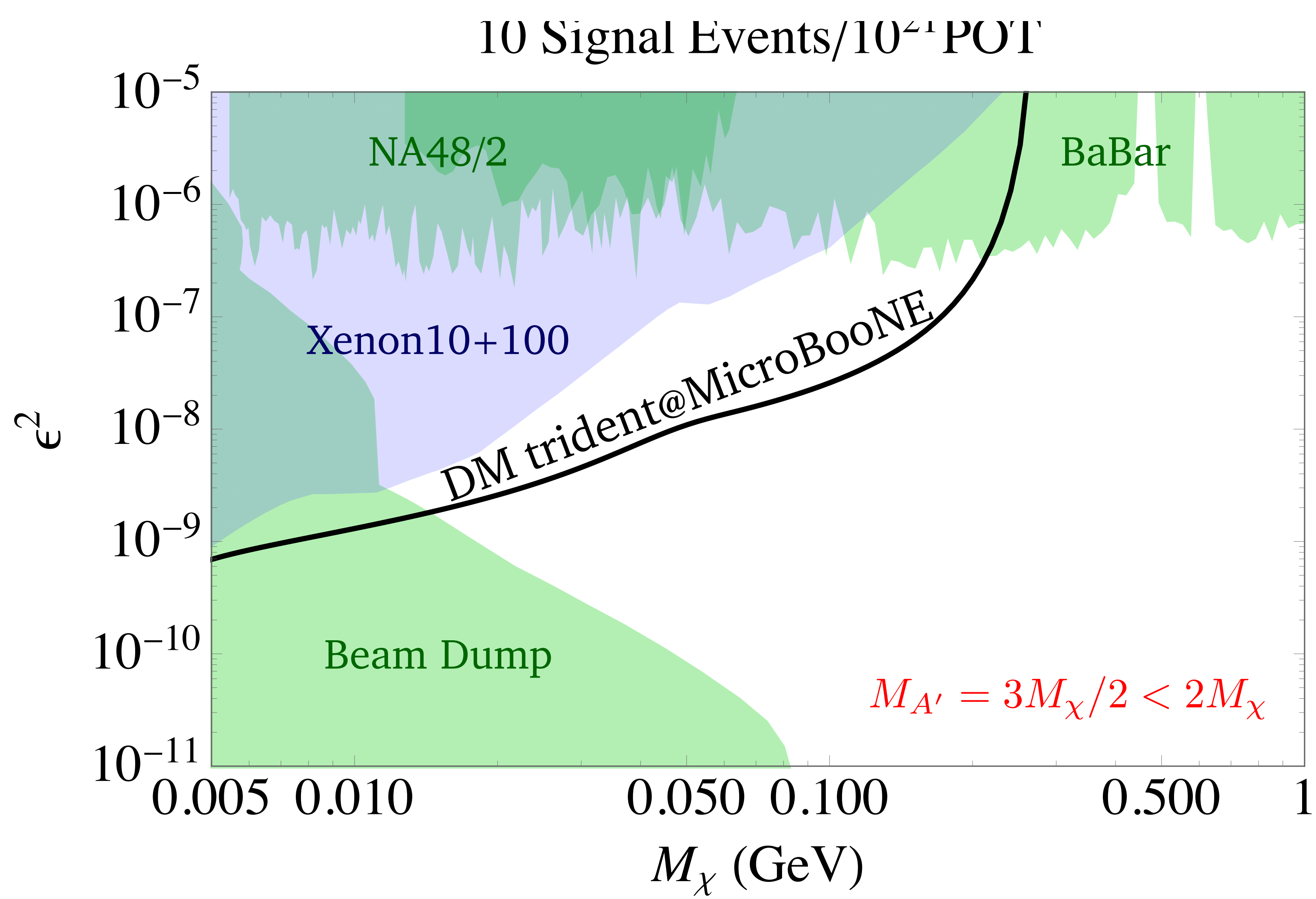
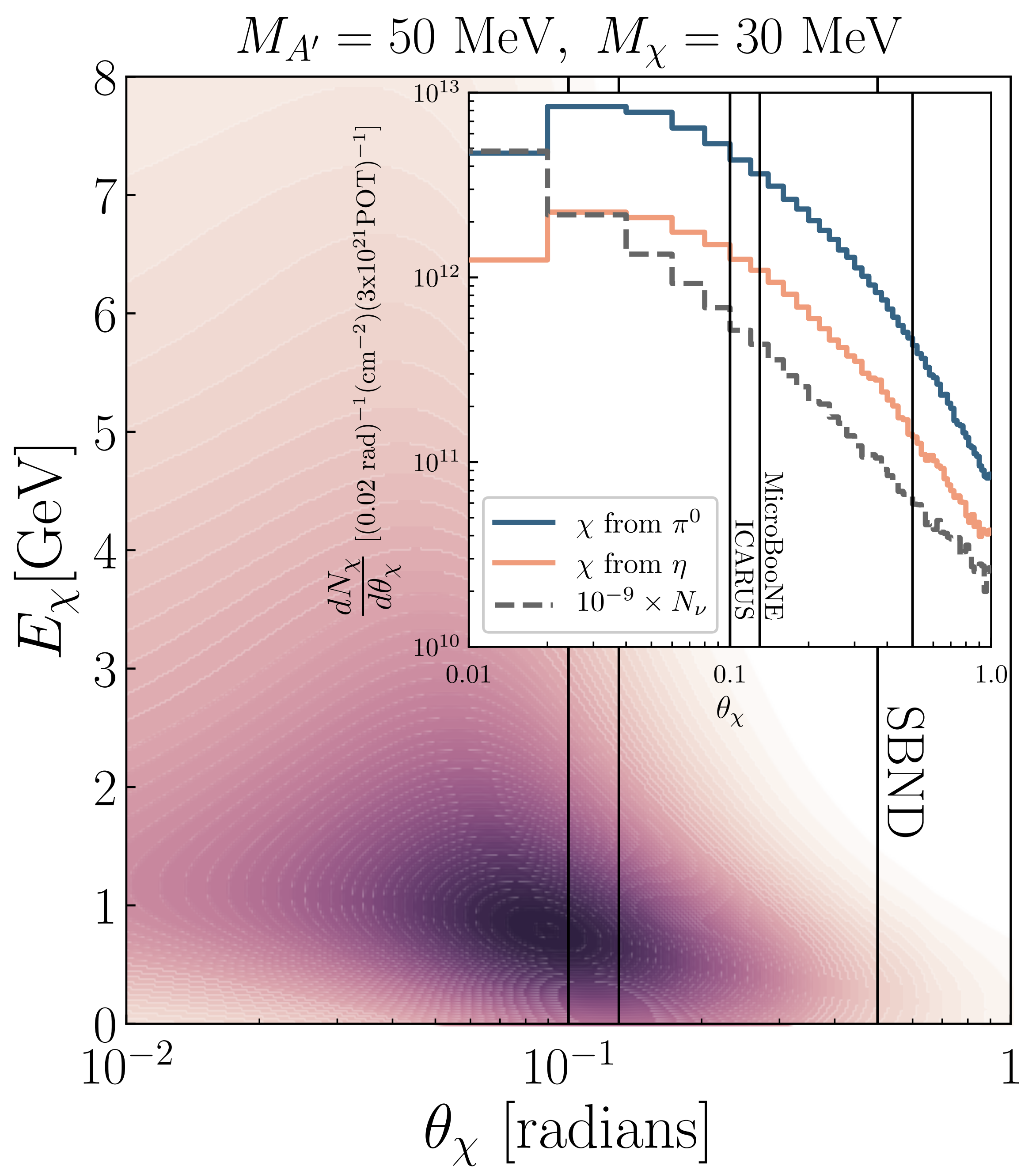
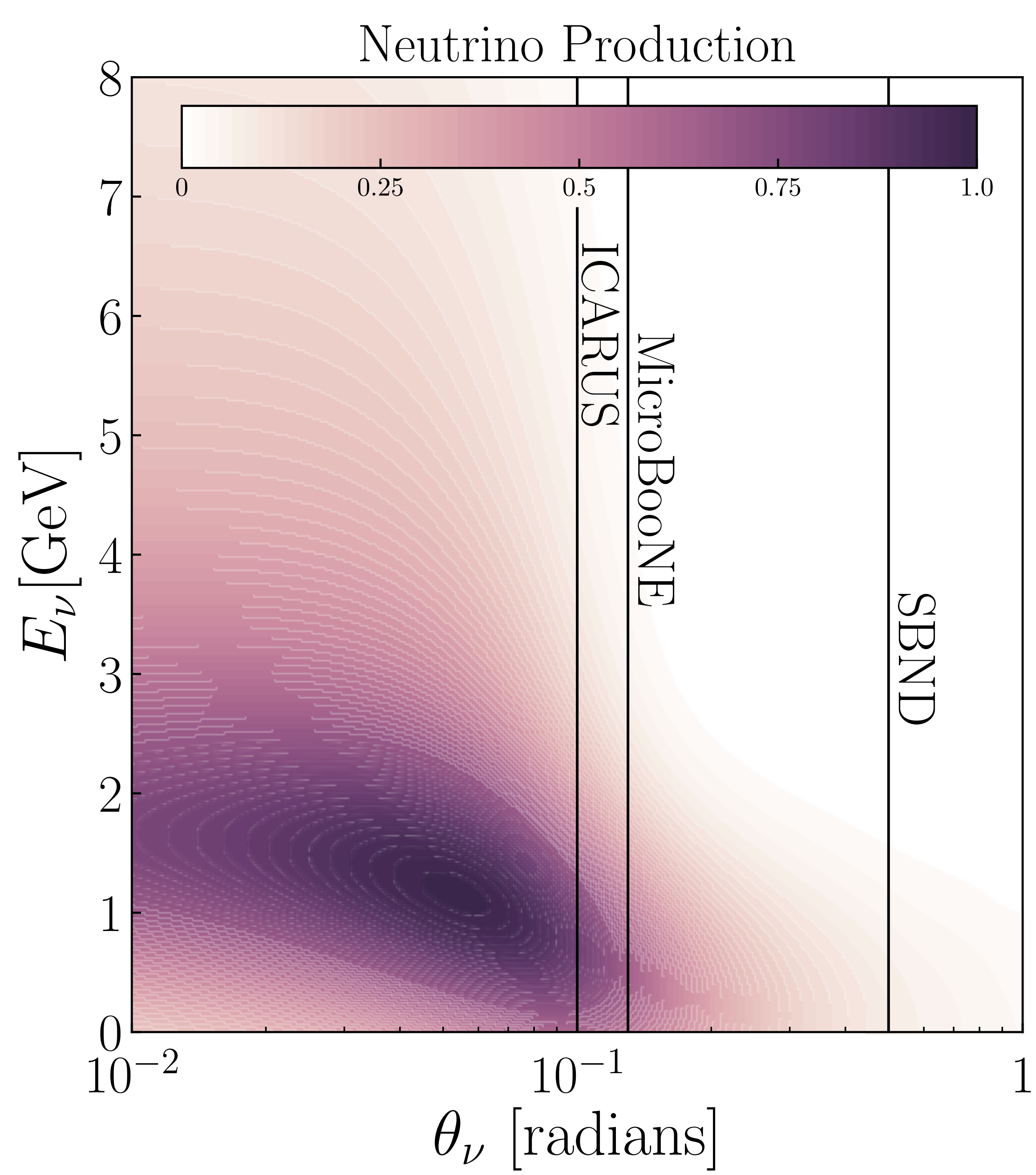


[e.g. de Gouvea, PF, Harnik, Kelly, Yang]



Useful to look off axis





Other places with detectors near (but not on) beam lines?
e.g. protoDUNE/LHC

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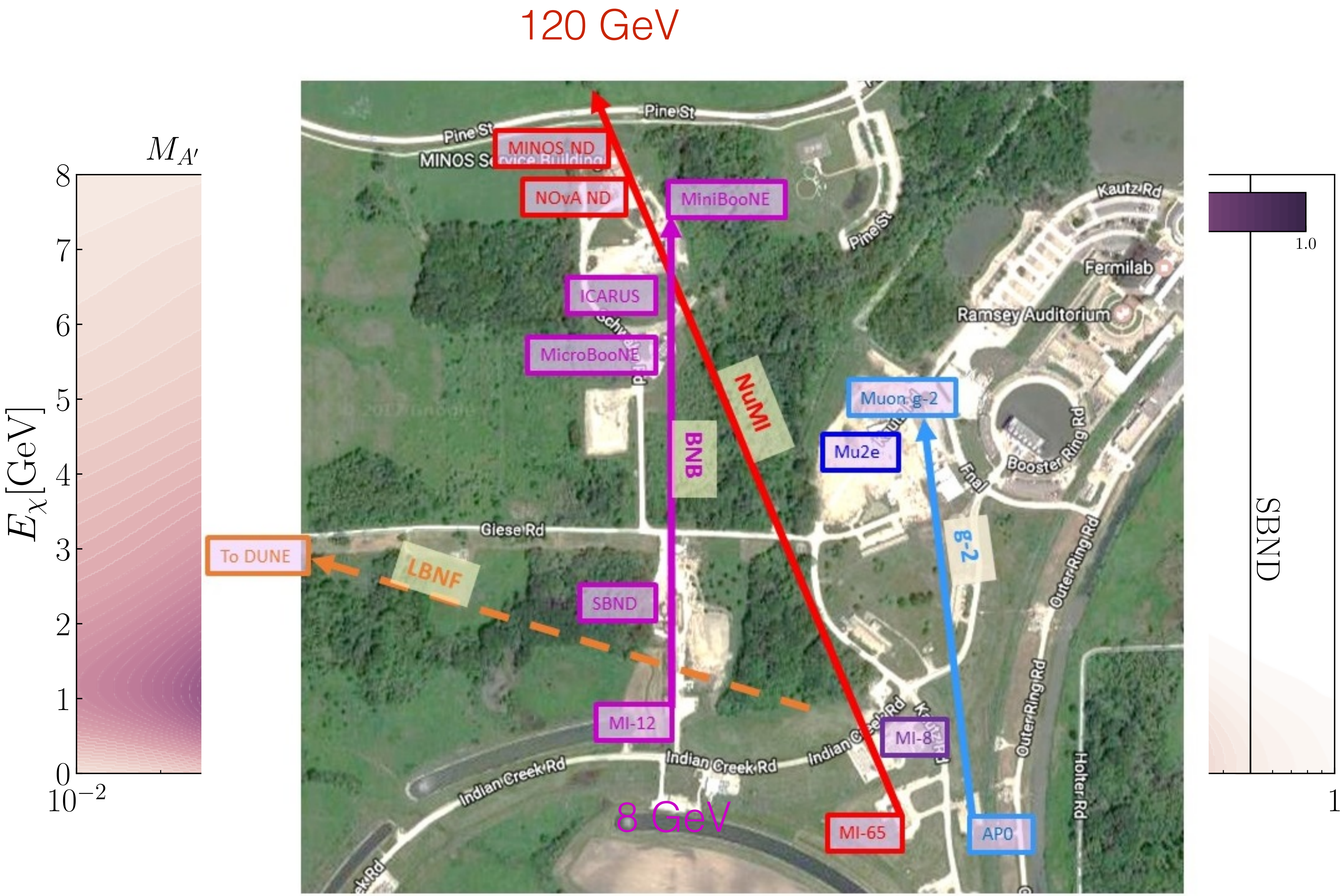

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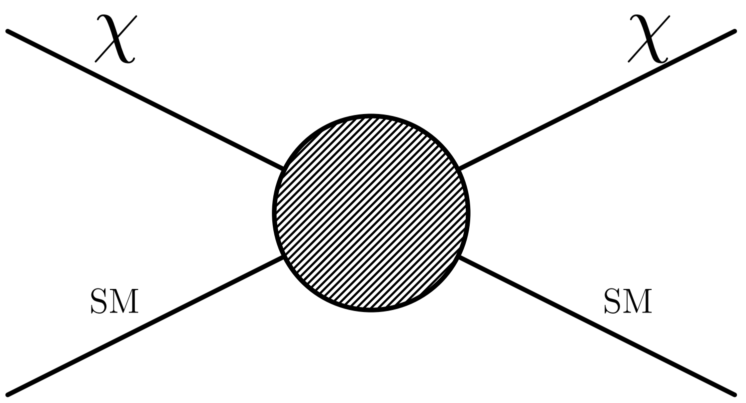
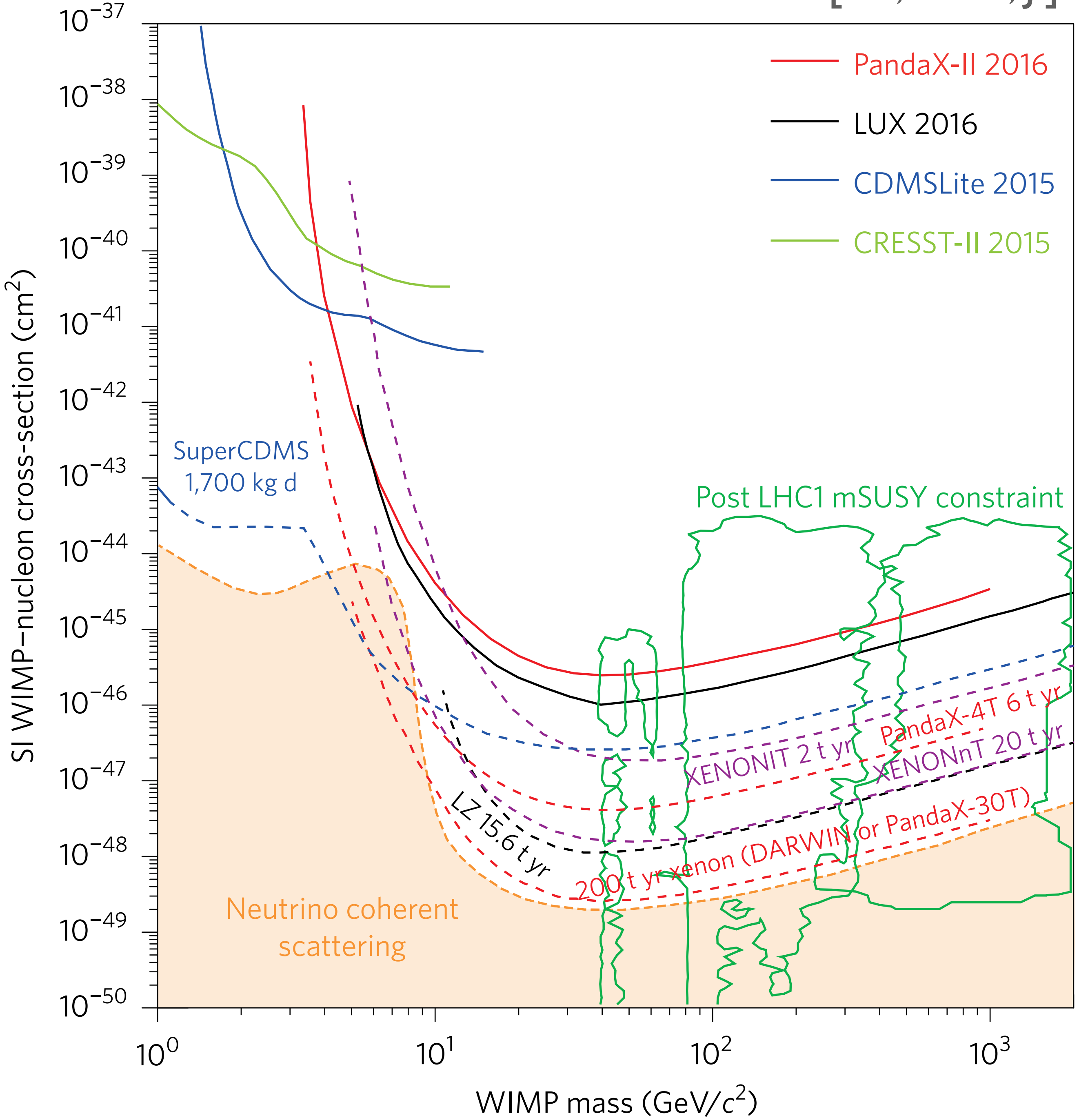
Status of Direct Detection



[Liu, Chen, Ji]



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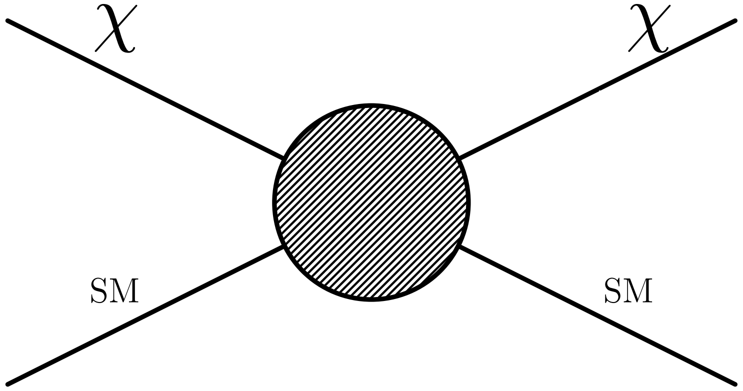

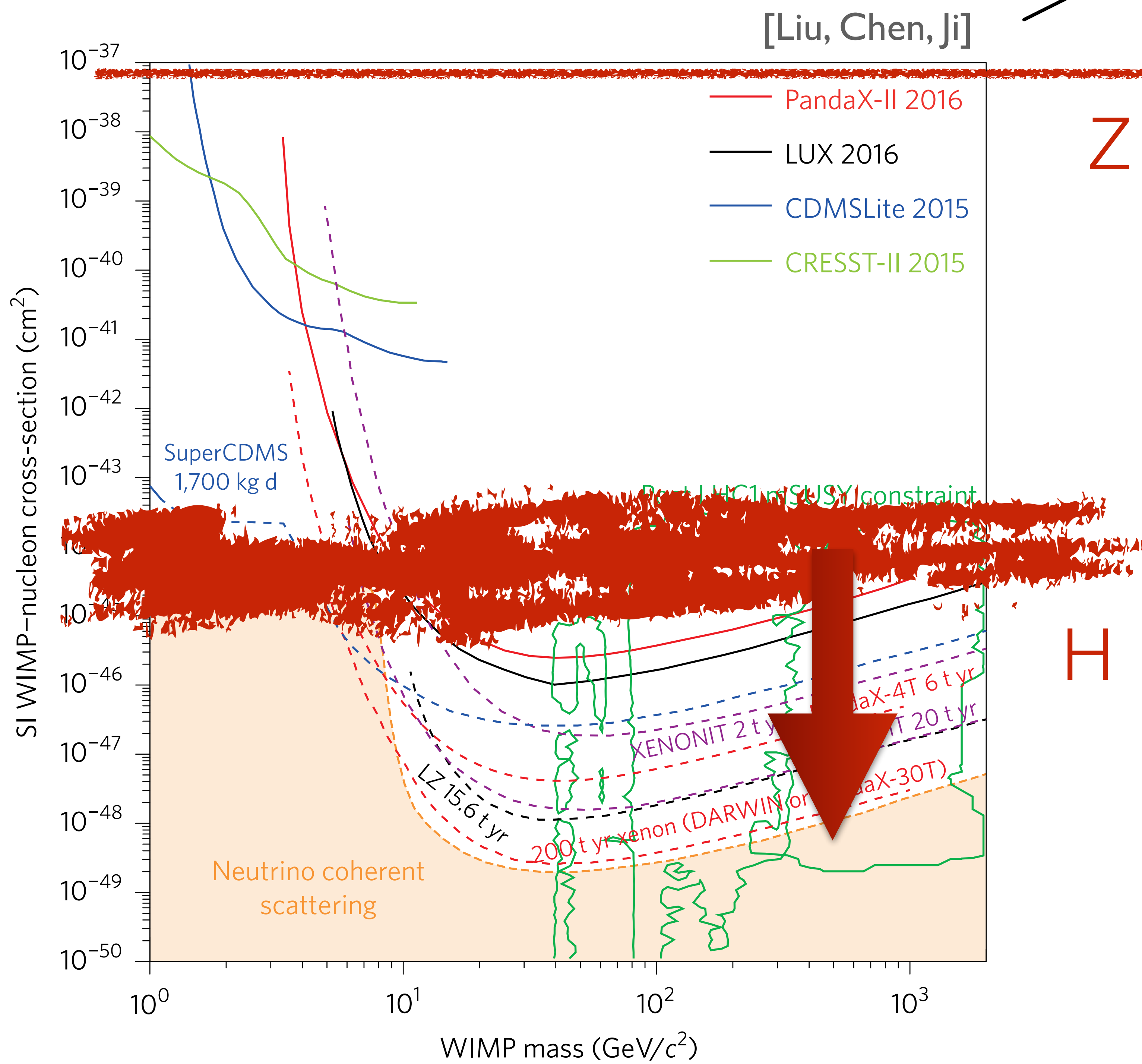

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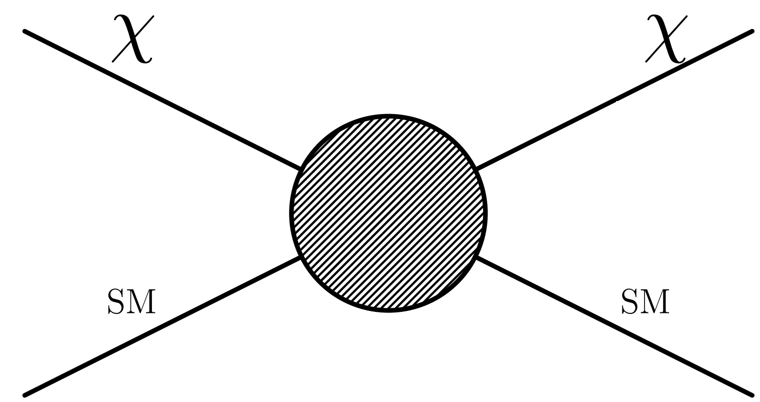
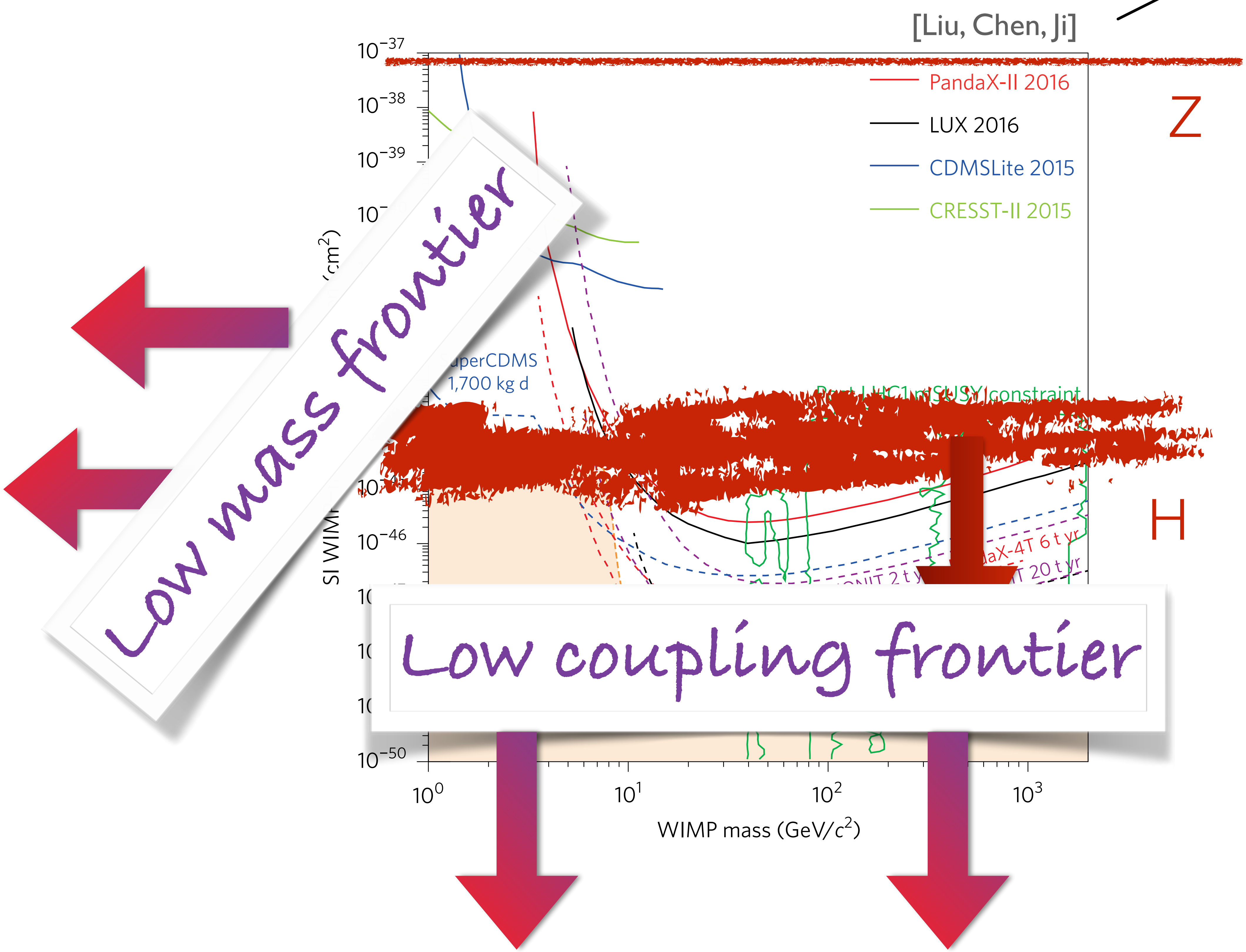
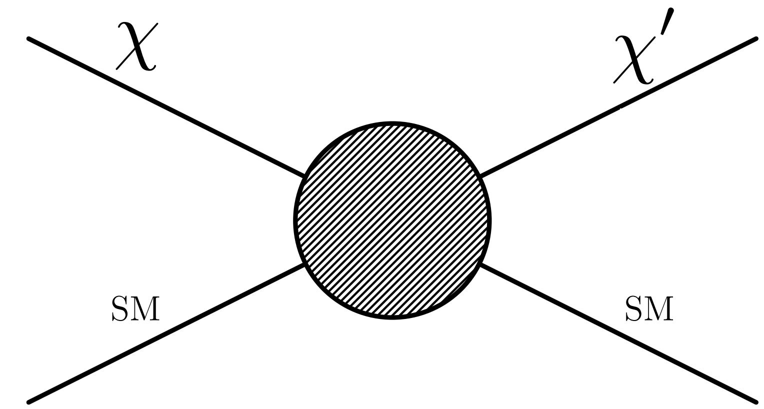
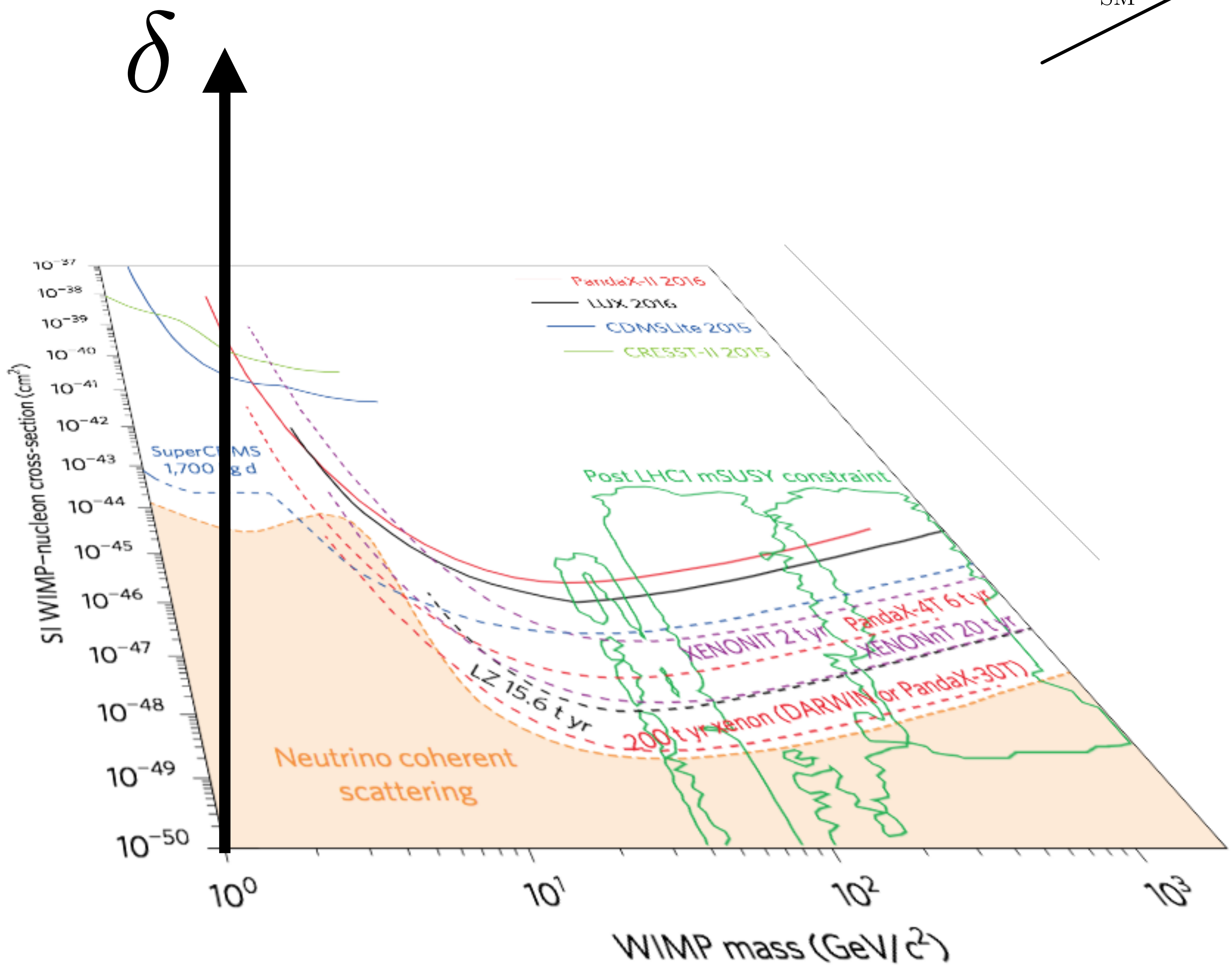




Inelastic scattering of DM





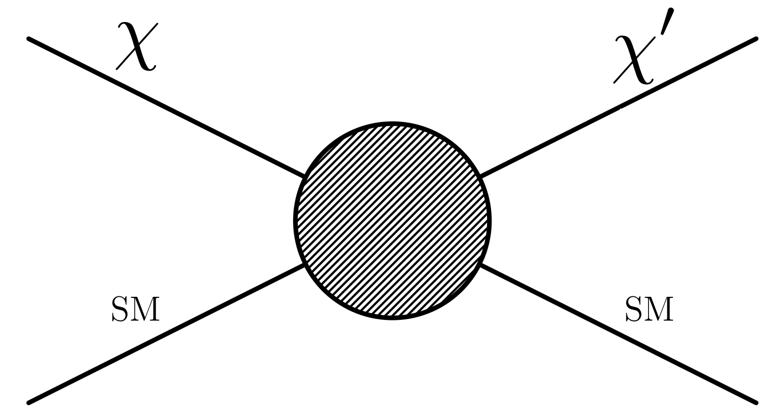
[Graham, Harnik, Rajendran, Saraswat]

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

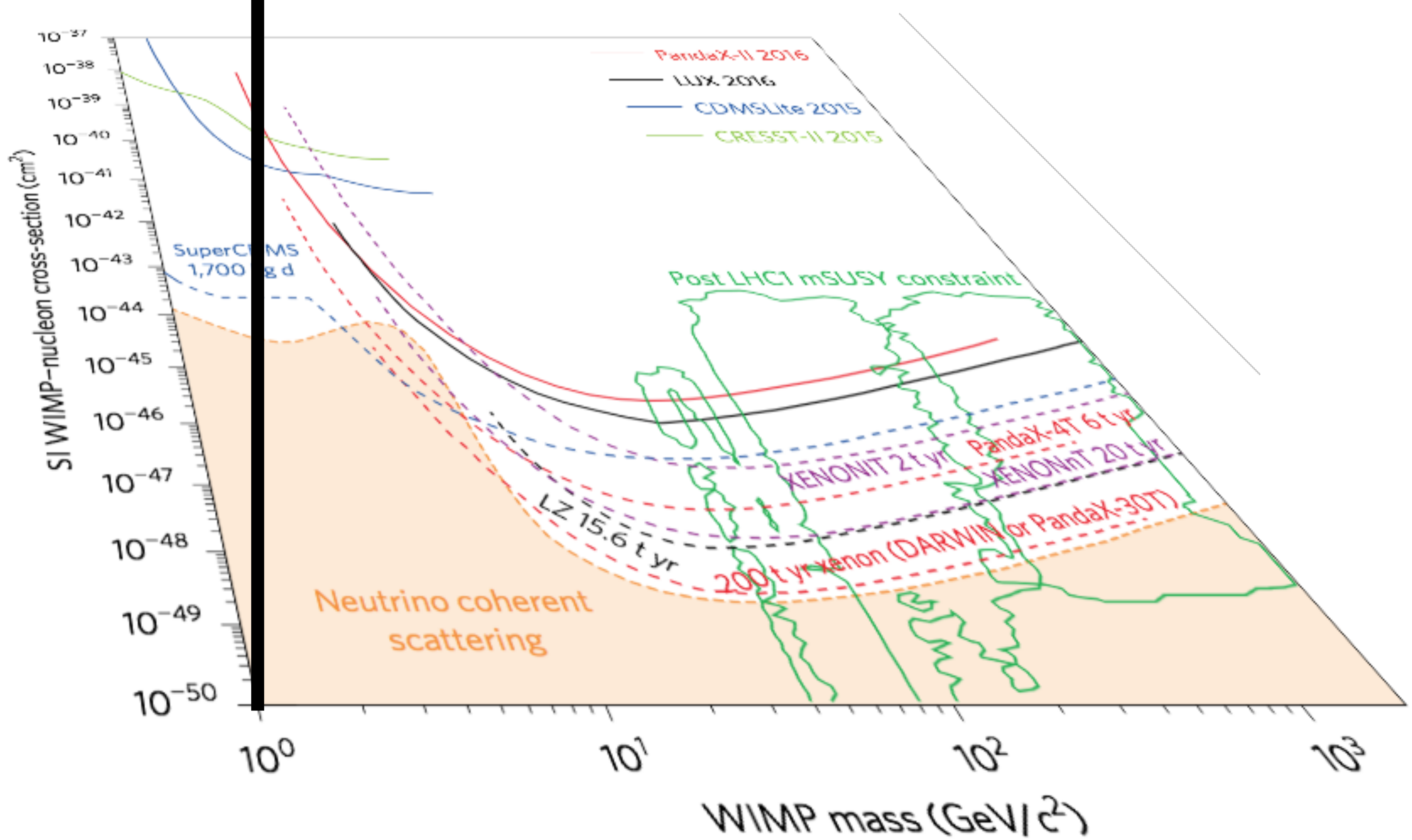
Can be endothermic (iDM) or exothermic

[Tucker-Smith and Weiner]

Inelastic scattering of DM



Mass splitting frontier



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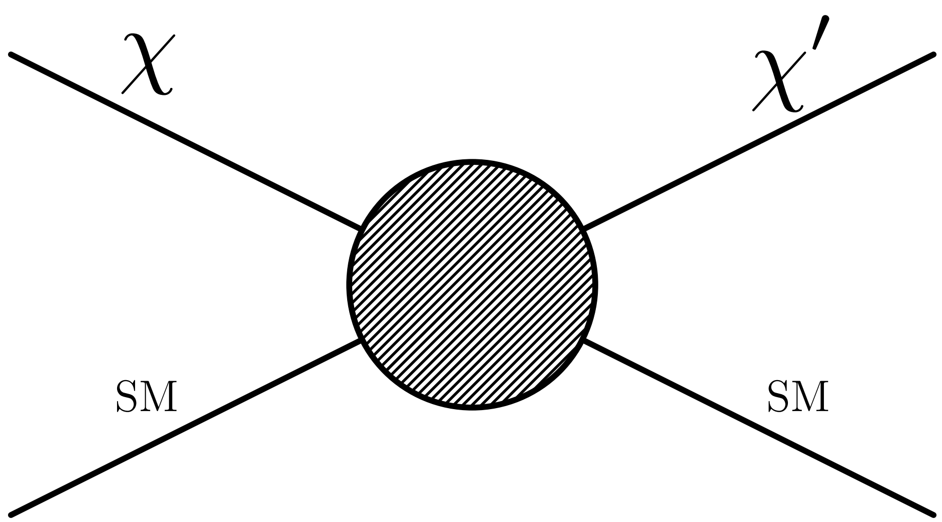
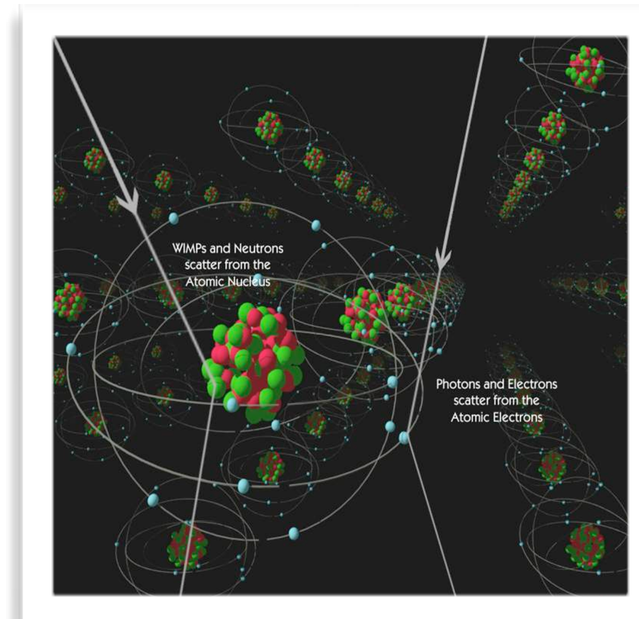
Inelastic Dark Matter (iDM)

[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

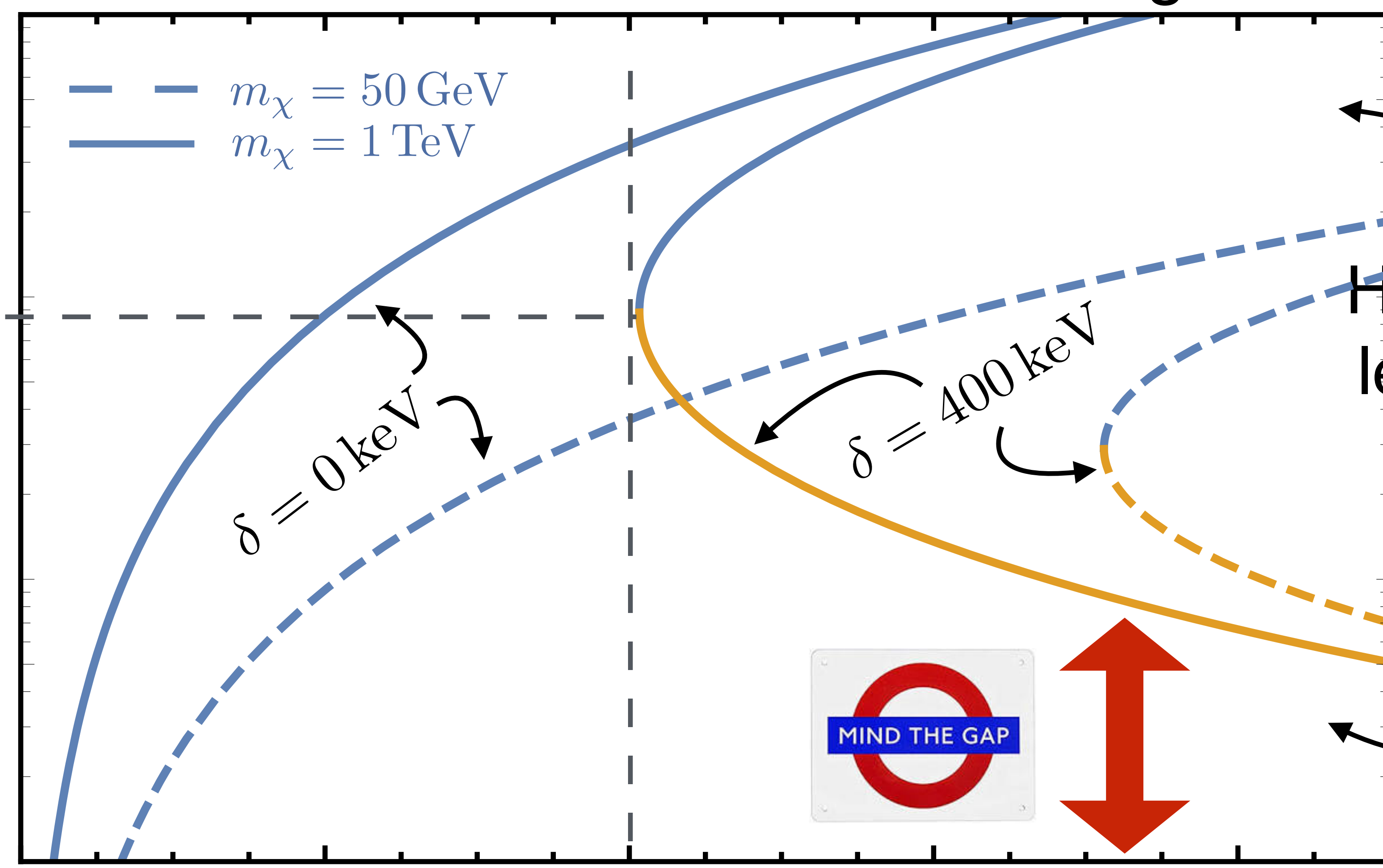
Lab scattering angle

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

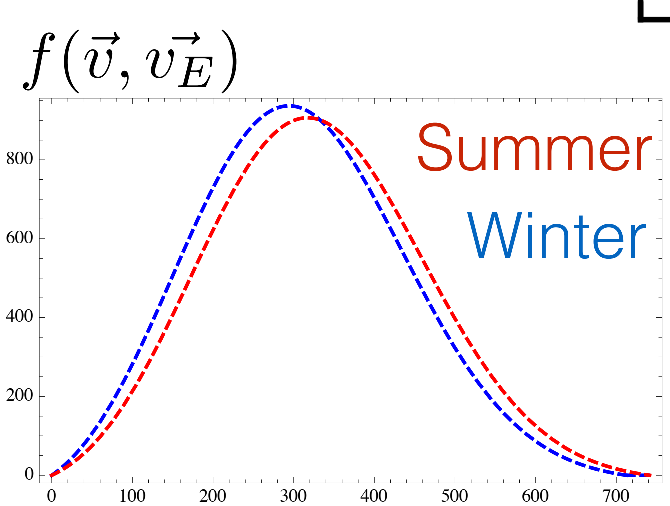
DM speed in lab frame

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

DM scattering off Xe



Highest speeds lead to highest *and* lowest recoils



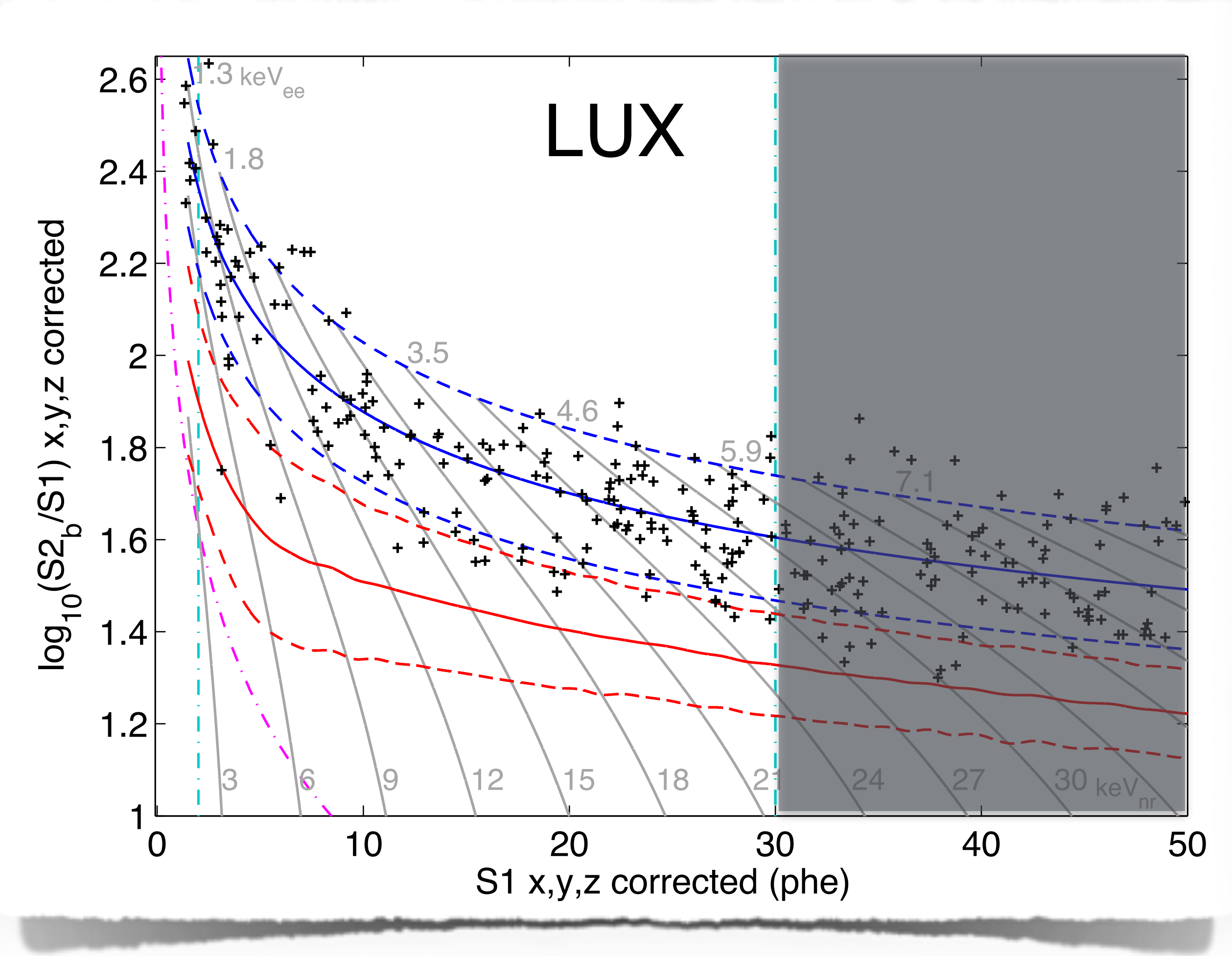
$$v_{\rm min}^{\rm apex} = \sqrt{\frac{2\delta}{\mu}}$$

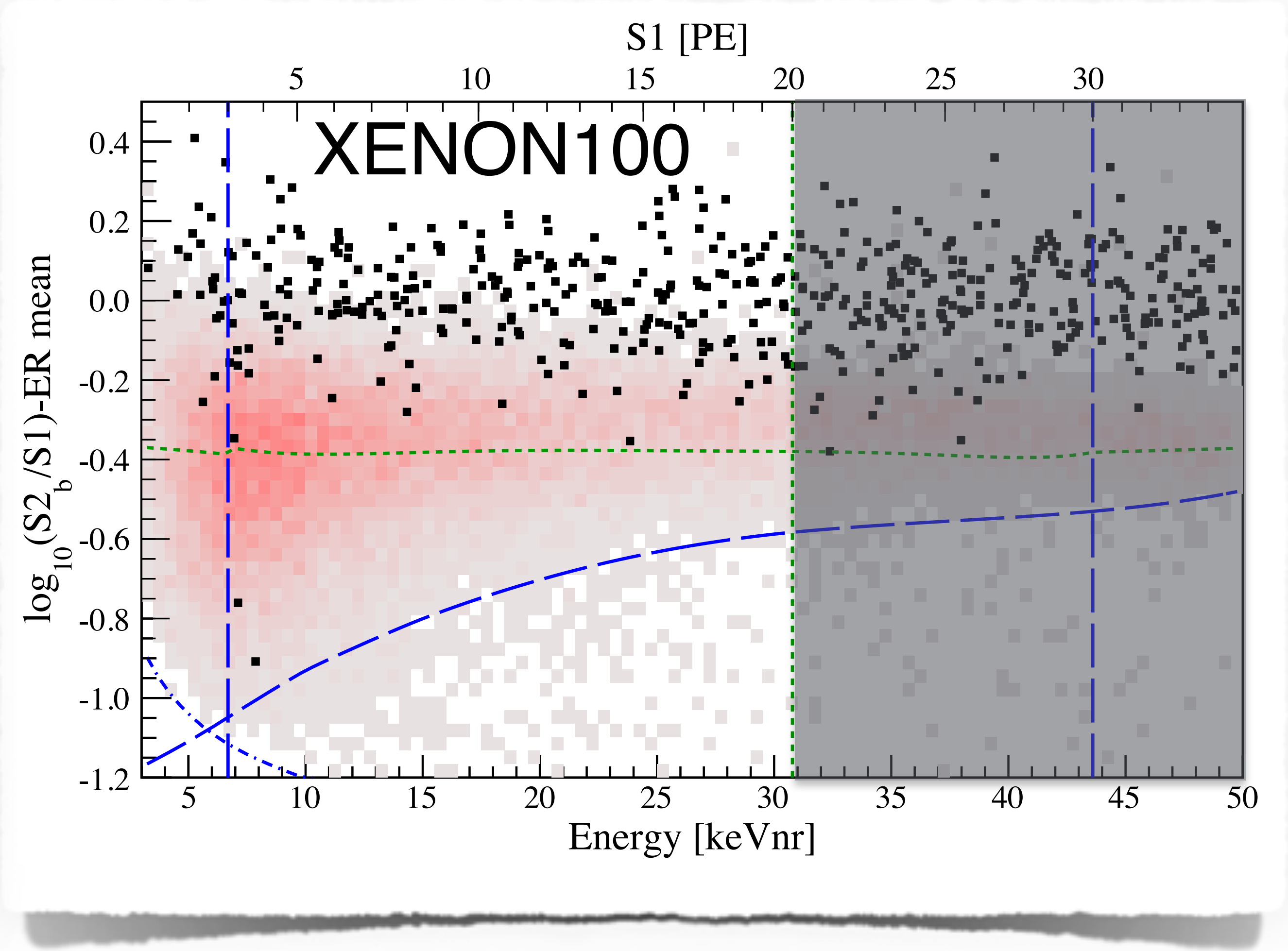
Inelastic Dark Matter (iDM)

- 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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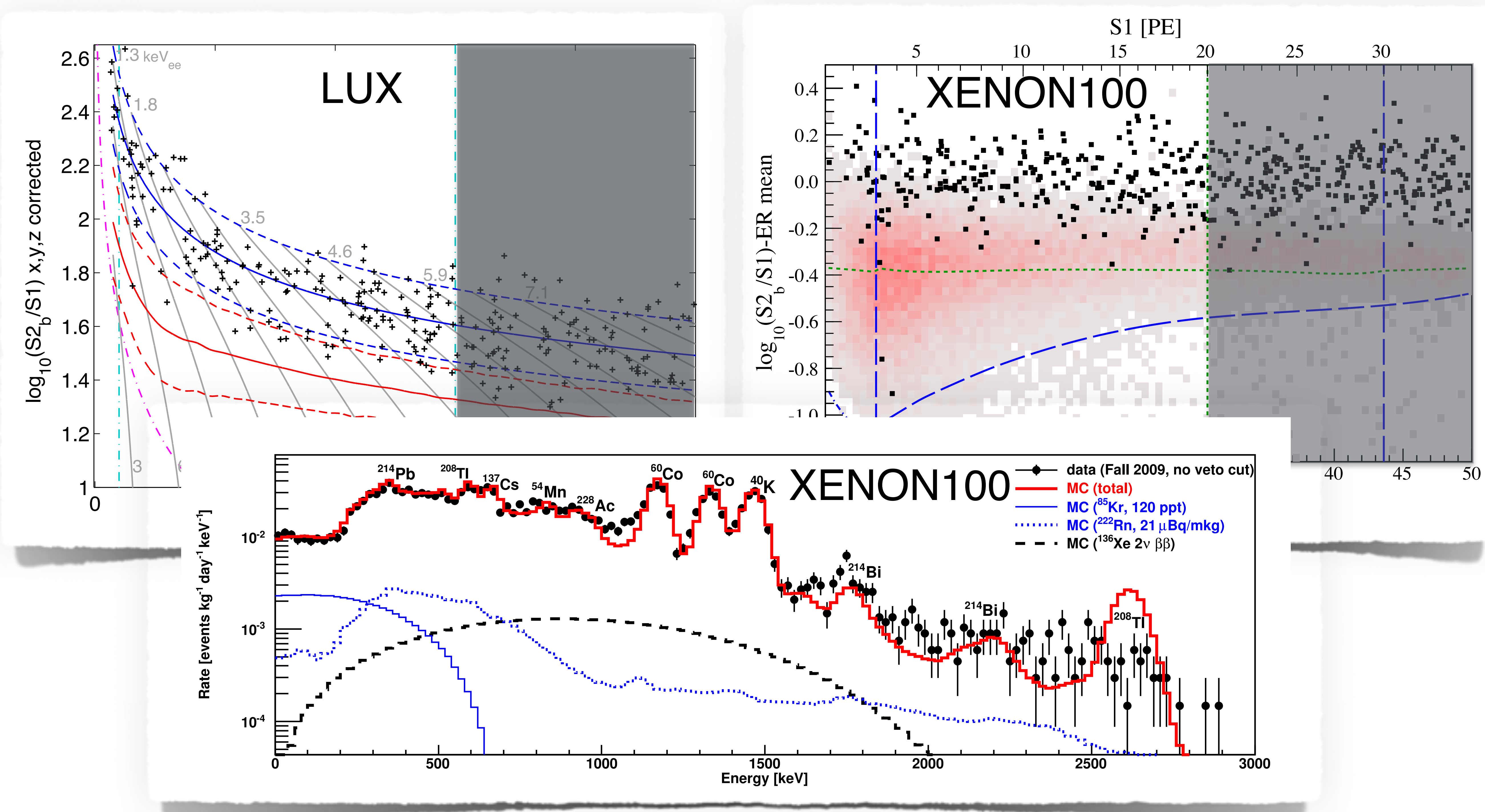
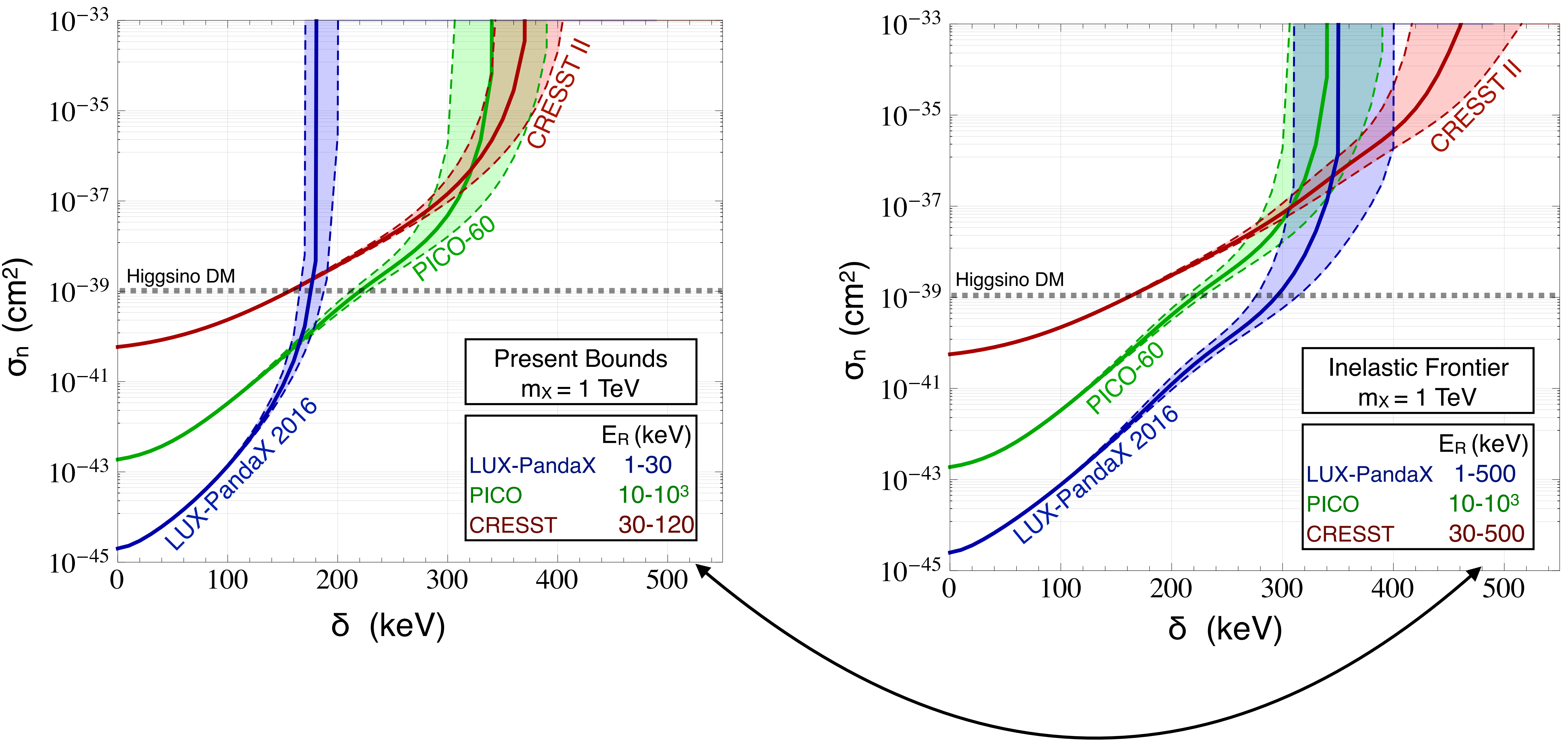


The Inelastic Frontier

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

[Bramante, PJF, Kribs, Martin]

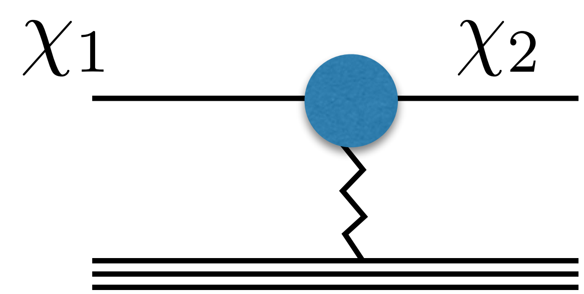


Can we do better?

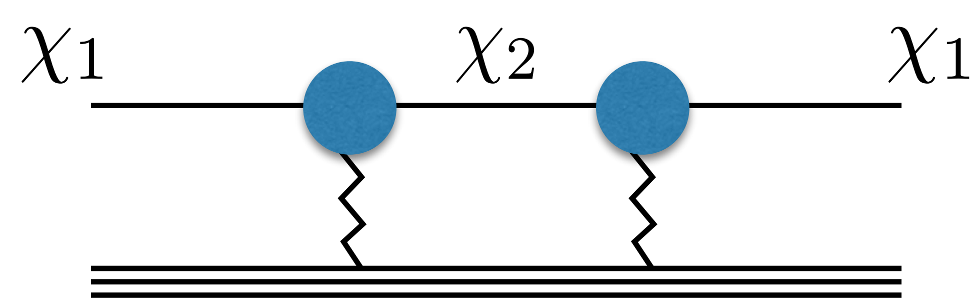
First a model....

Inelastic DM

- Two mass eigenstates: **only** off-diagonal coupling to mediator



- Loop induced elastic scattering rate?



- Abundance of excited state: “primordial” and “regenerated”?

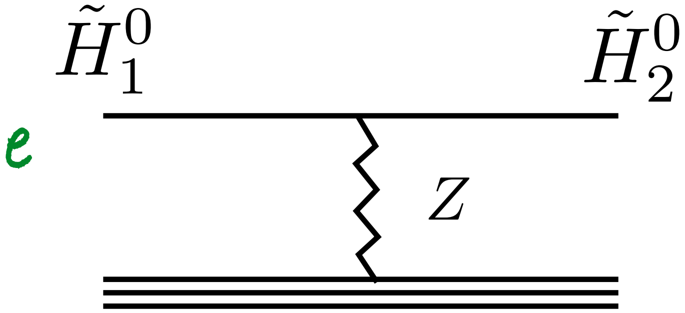
$$\tau(\chi_2 \to \chi_1 + \ldots)$$

$$\frac{n_{X_2}}{n_{X_1}} \approx 4 \times 10^{-12} \left(\frac{1\,\mathrm{TeV}}{M_{X_1}}\right) \left(\frac{\tau_{X_2}}{\tau_U}\right) \left(\frac{\langle \sigma_{X_1 X_1 \to X_2 X_2}\, v\rangle}{3 \times 10^{-26}\mathrm{cm}^3\,\mathrm{s}^{-1}}\right)$$

- Relic abundance?

iDM—Higgsino model

DM couples to the Z (a WIMP!)



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 of SUSY

$$\delta_{\tilde{\mathrm{H}}} \simeq m_Z^2 \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2}\right) + \mathcal{O}\left(\frac{1}{M_{1,2}^2}\right) = \begin{cases} 192\,\mathrm{keV}\left(\frac{10^7\,\mathrm{GeV}}{M_1}\right) & M_2 \gg M_1 \gg \mu \\ 640\,\mathrm{keV}\left(\frac{10^7\,\mathrm{GeV}}{M_2}\right) & M_1 \gg M_2 \gg \mu \end{cases}$$

iDM—Higgsino model

Couples to Z, makes definitive predictions

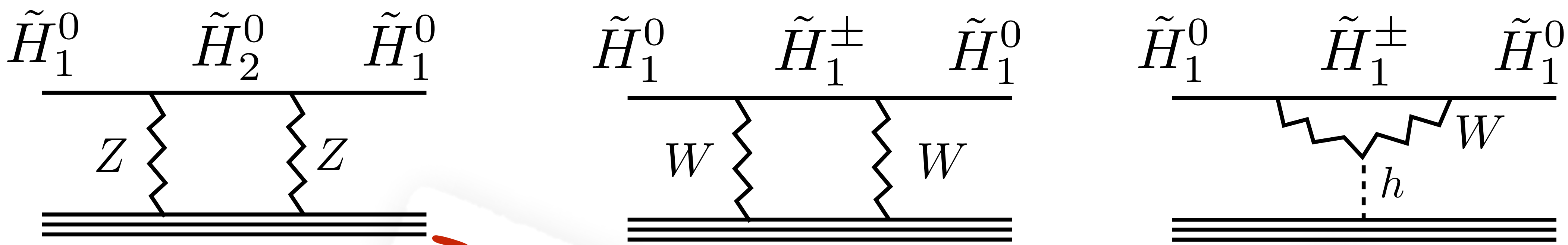
Relic abundance: $\Omega h^2 = 0.10 \left(\frac{\mu}{1\,\mathrm{TeV}} \right)^2$ (all χ_1)

Direct detection:

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

iDM—loop level elastic rate

[Hisano et al.; Hill and Solon]

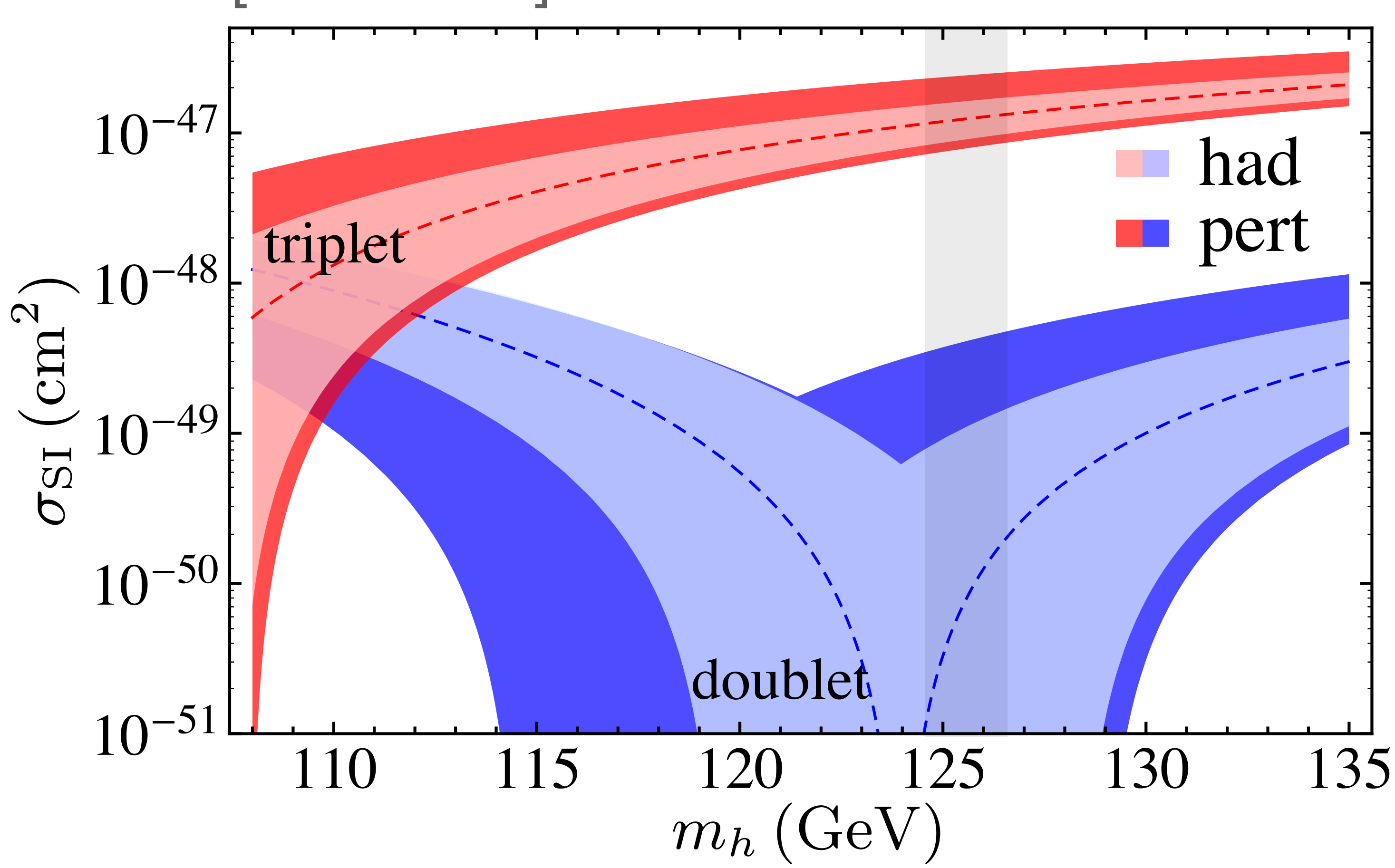


Twist-2

Twist-0

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

[Hill and Solon]

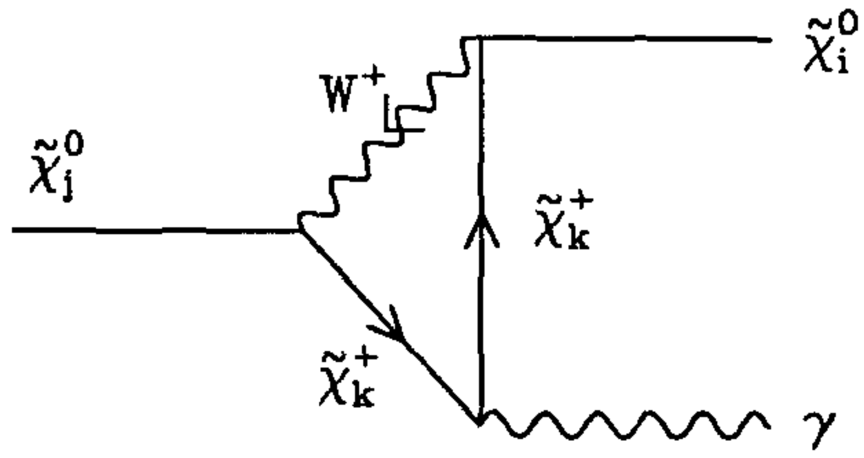


$$\sigma^{\tilde{H}}_{\text{n,loop}} \lesssim 10^{-48}\ \text{cm}^2$$

accidental cancellation

Higgsino decay

[Haber and Wyler]

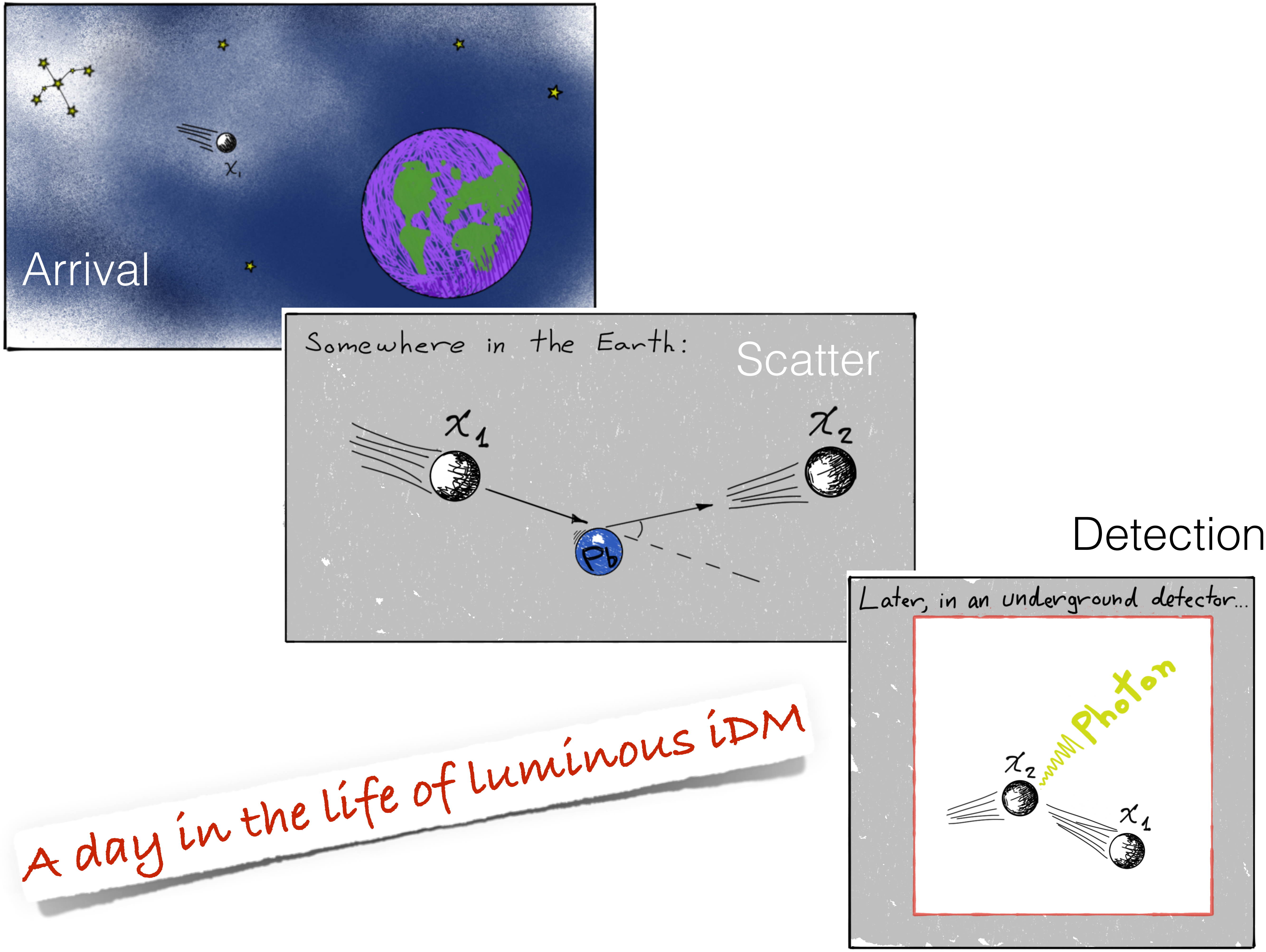


Excited Higgsino has a short-lived loop decay to a photon

Fast

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

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


Arrival
χ_1
Somewhere in the Earth:
Scatter
χ_1
χ_2
Pb
Detection
Later, in an underground detector...
Photon
χ_2
χ_1
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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All natural for Higgsino

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All natural for Higgsino

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

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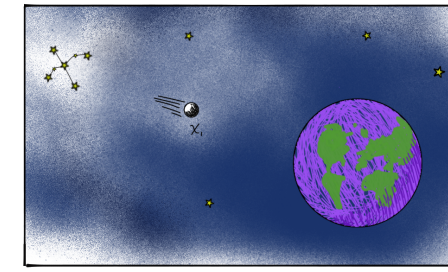
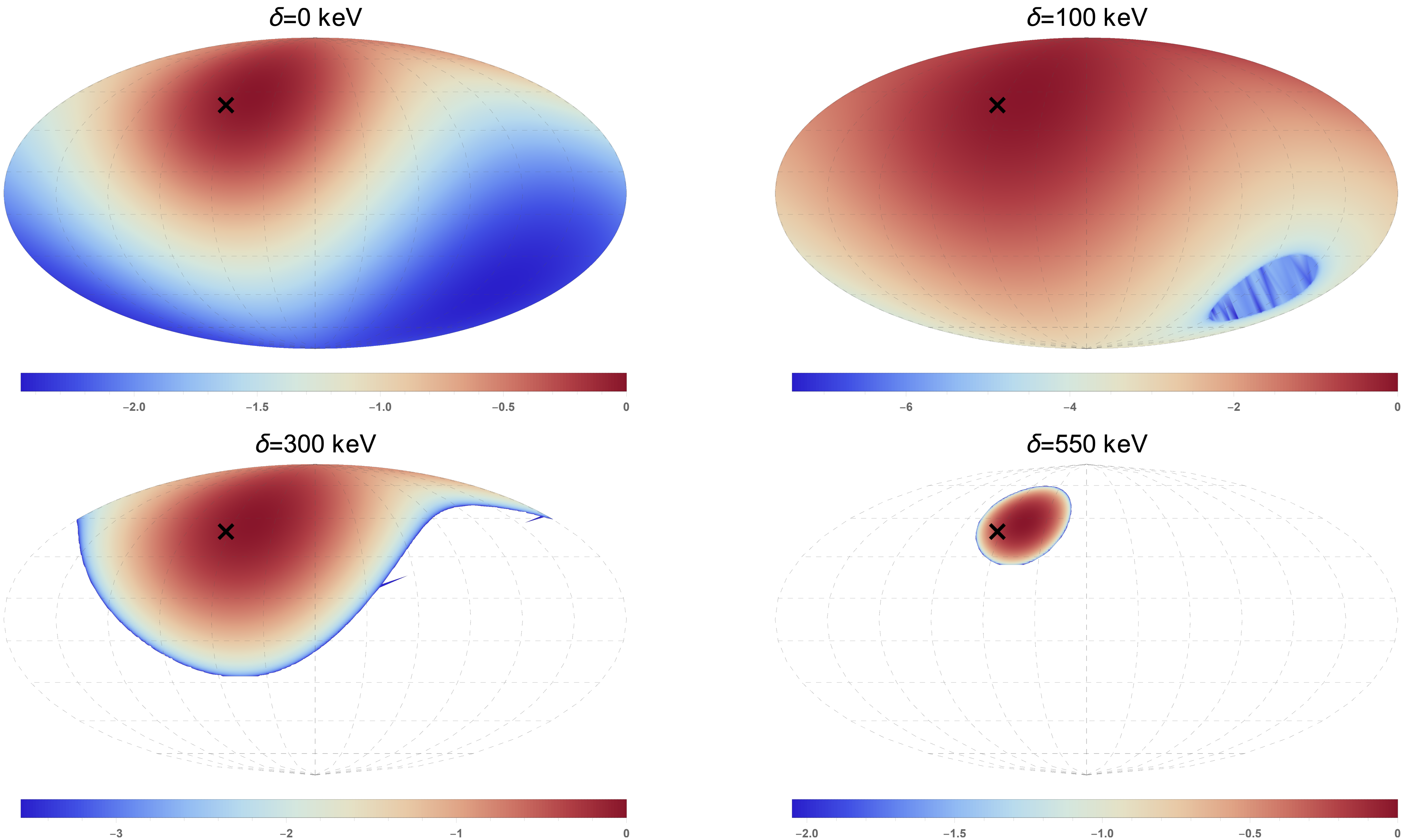
Threshold (MeV)	10^{-3}	0.15	1	$1 - 10$	10^4

Arrival

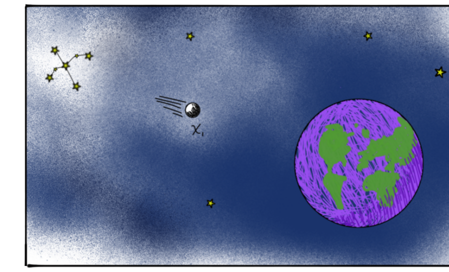


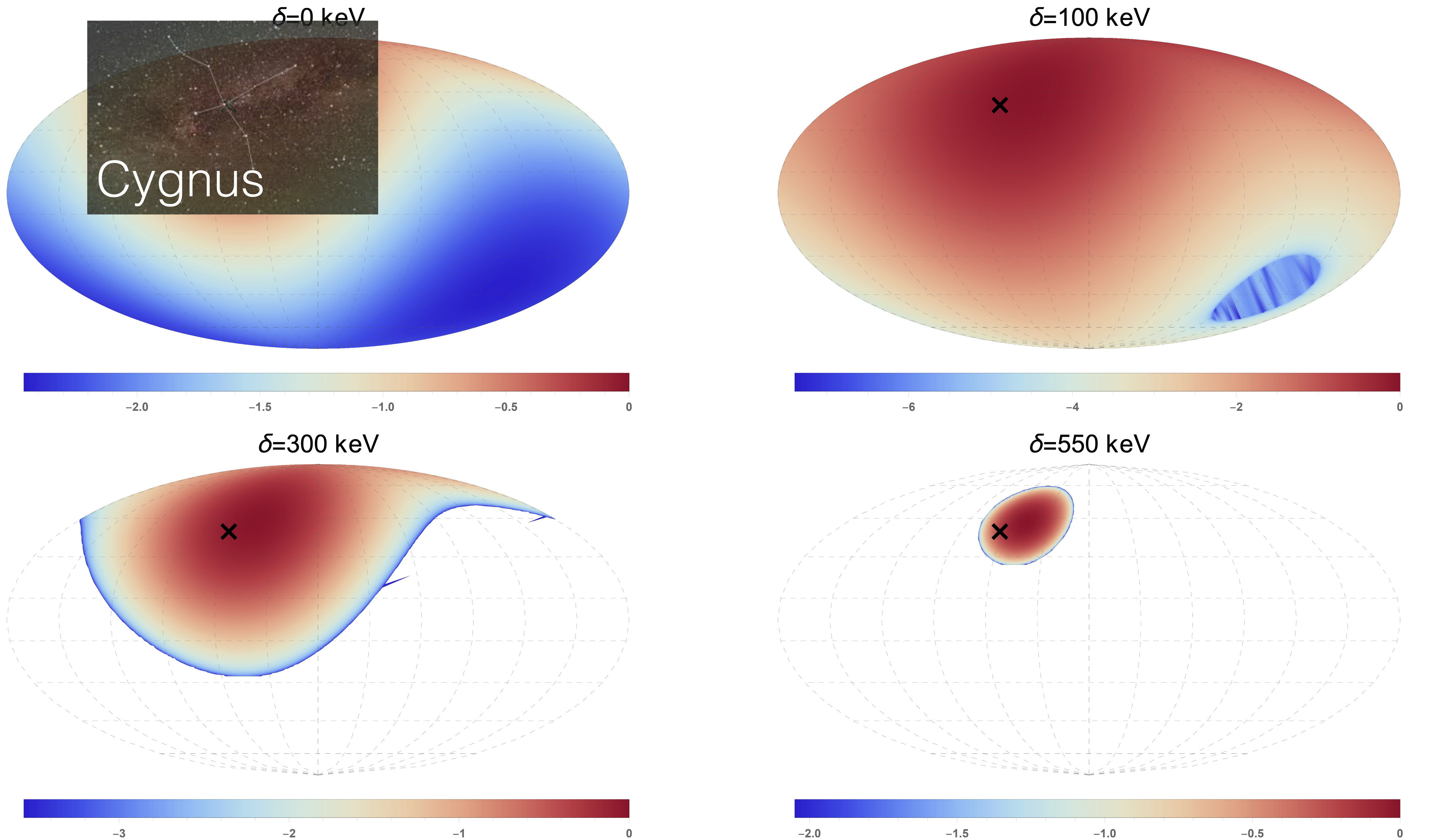


Position of Cygnus in sky (dec. ~45°N)

1 sidereal day = 23 hours 56 minutes 4 seconds

Arrival





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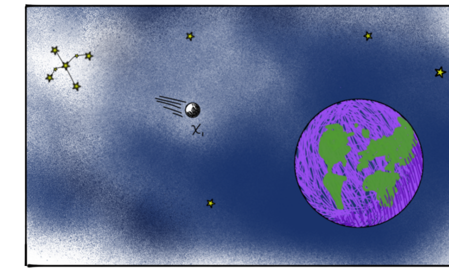

Position of <u>Cygnus</u> in sky (dec. ~45°N)

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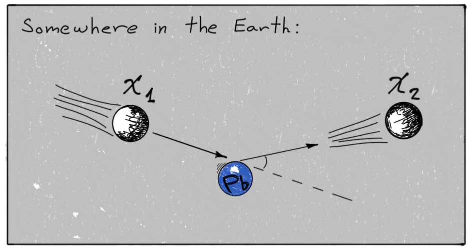
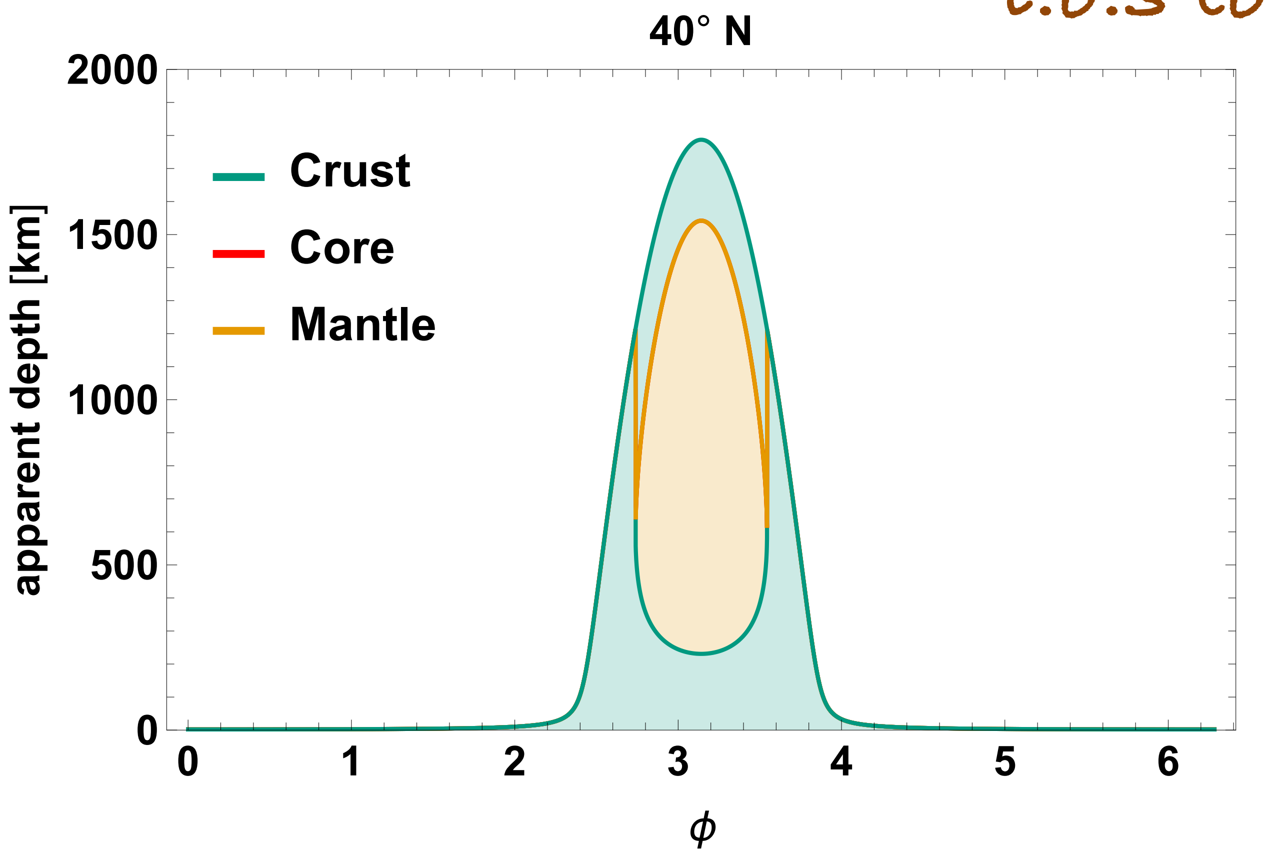
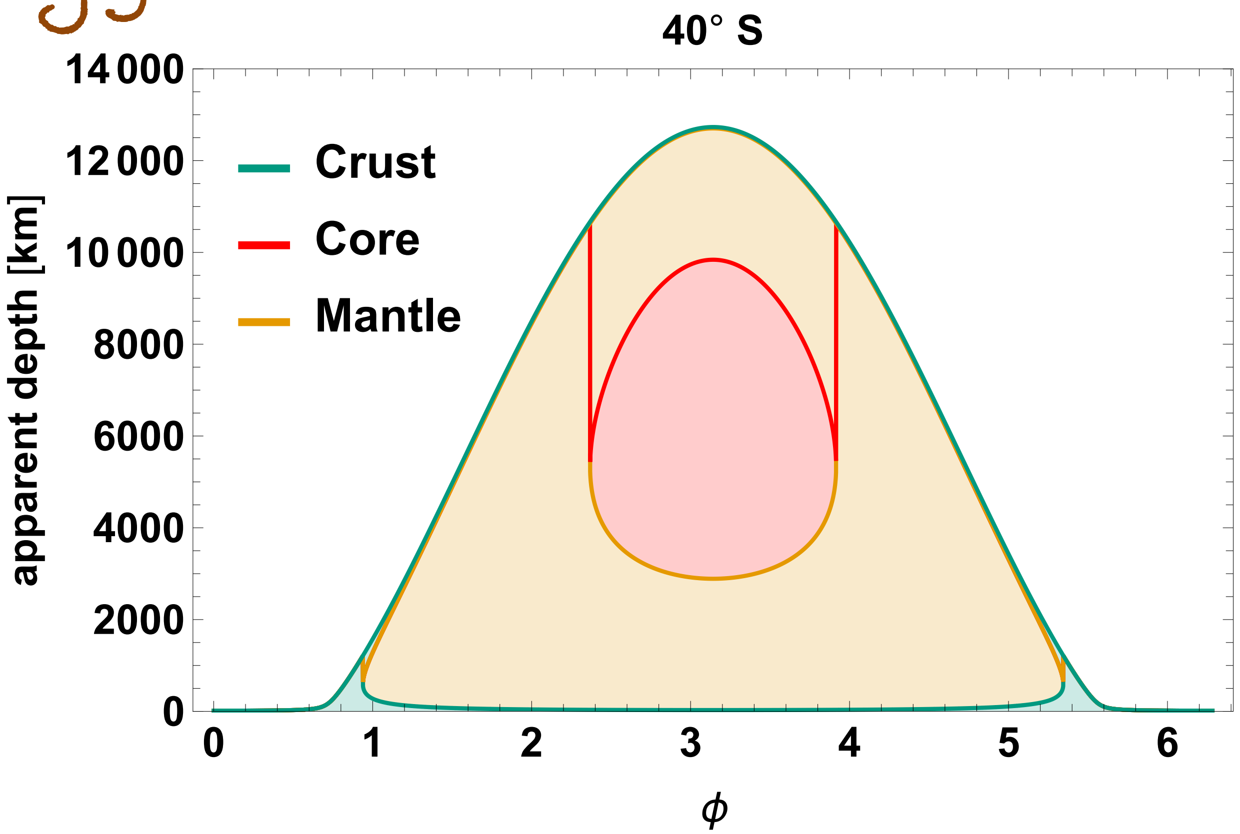
Scatter



DM lifetime ~ radius of Earth
Depends upon overburden and geology

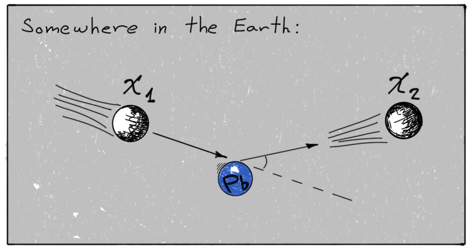
l.o.s to Cygnus





-	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

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.

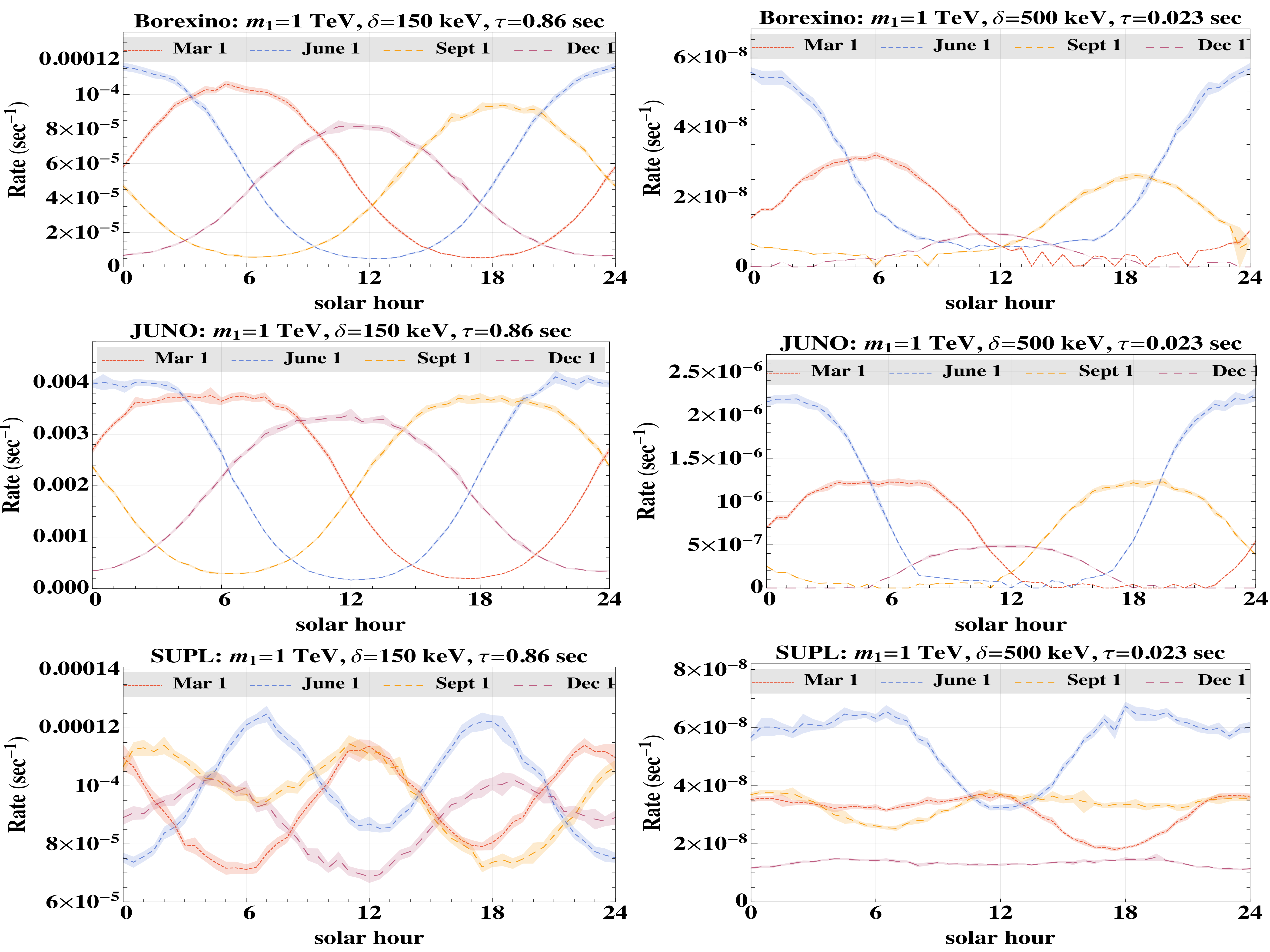
$$\Gamma = \sum_{\pm} \int d^3 r_s \, d^3 v_{\text{MB}} \left\{ n_T(r_s) \, \frac{\rho_\chi}{m_1} \left[\frac{R_D}{|\vec{r}_s - \vec{r}_D| \; \theta^{\text{lab}}_{\text{max}}} \right]^2 P(v^{\text{lab}}_{\text{out},\pm}, L, \tau) \right.$$

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

2 c.o.m.
scattering angles

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 1
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
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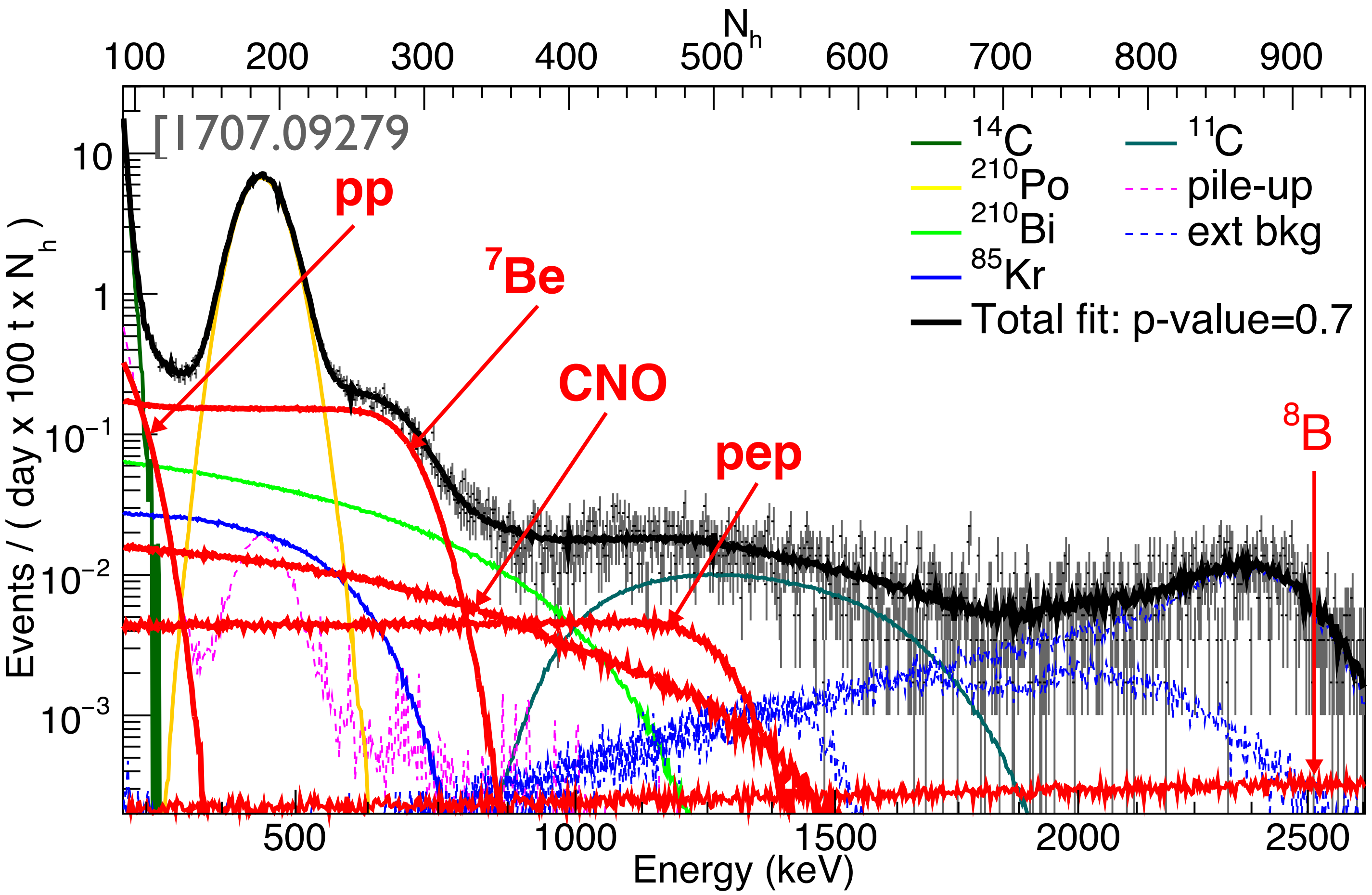
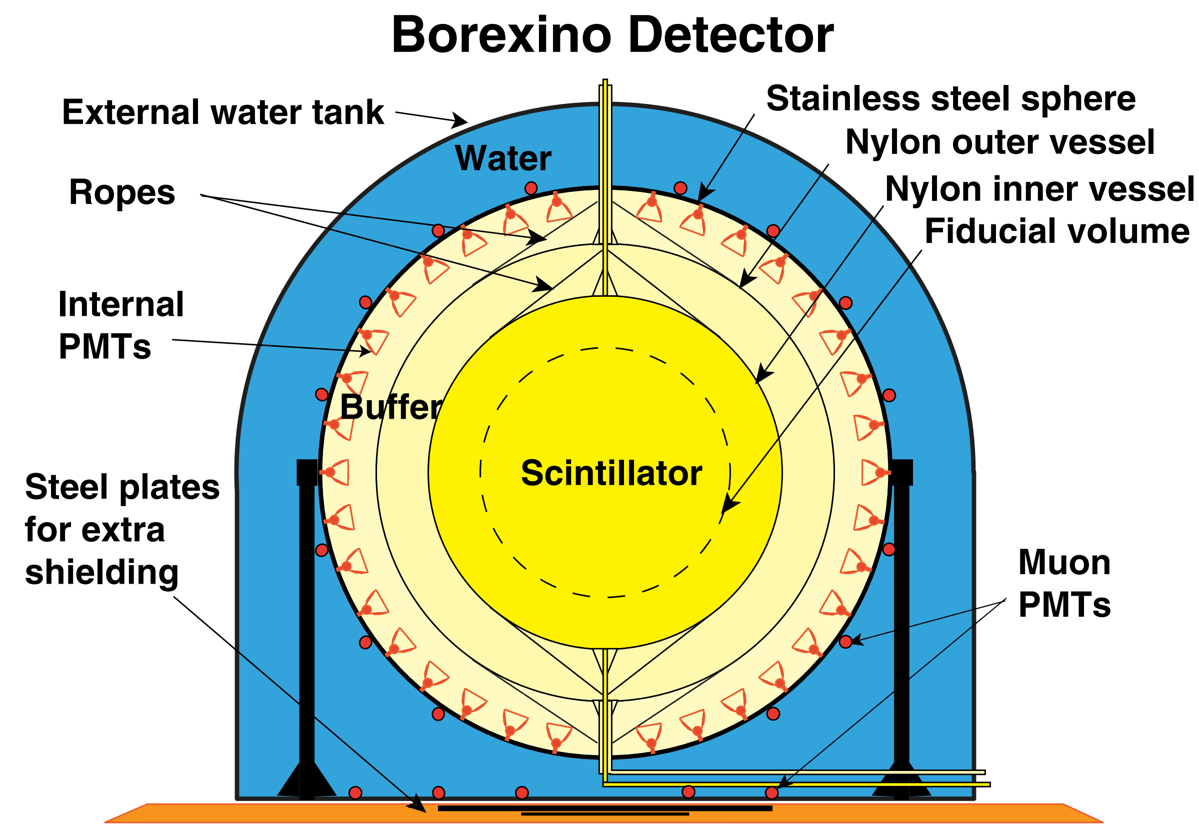
Rate (sec^{-1})
solar hour

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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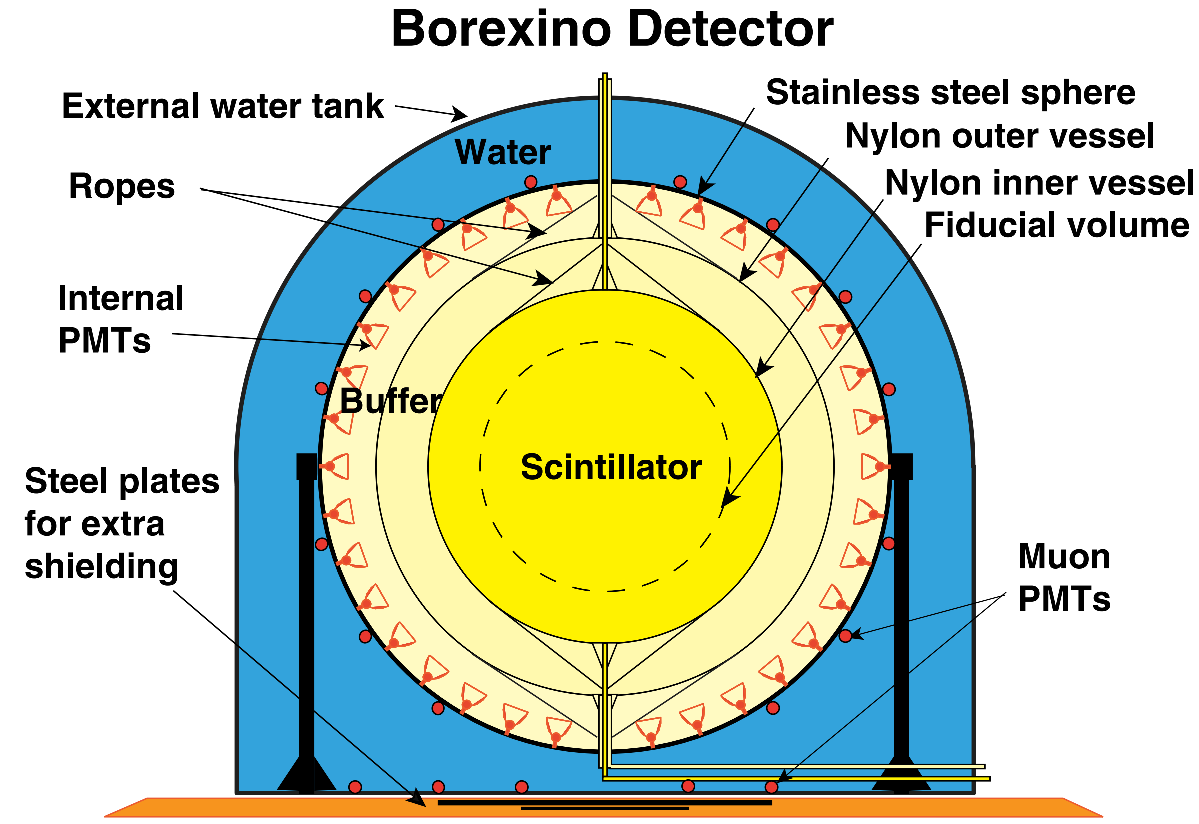
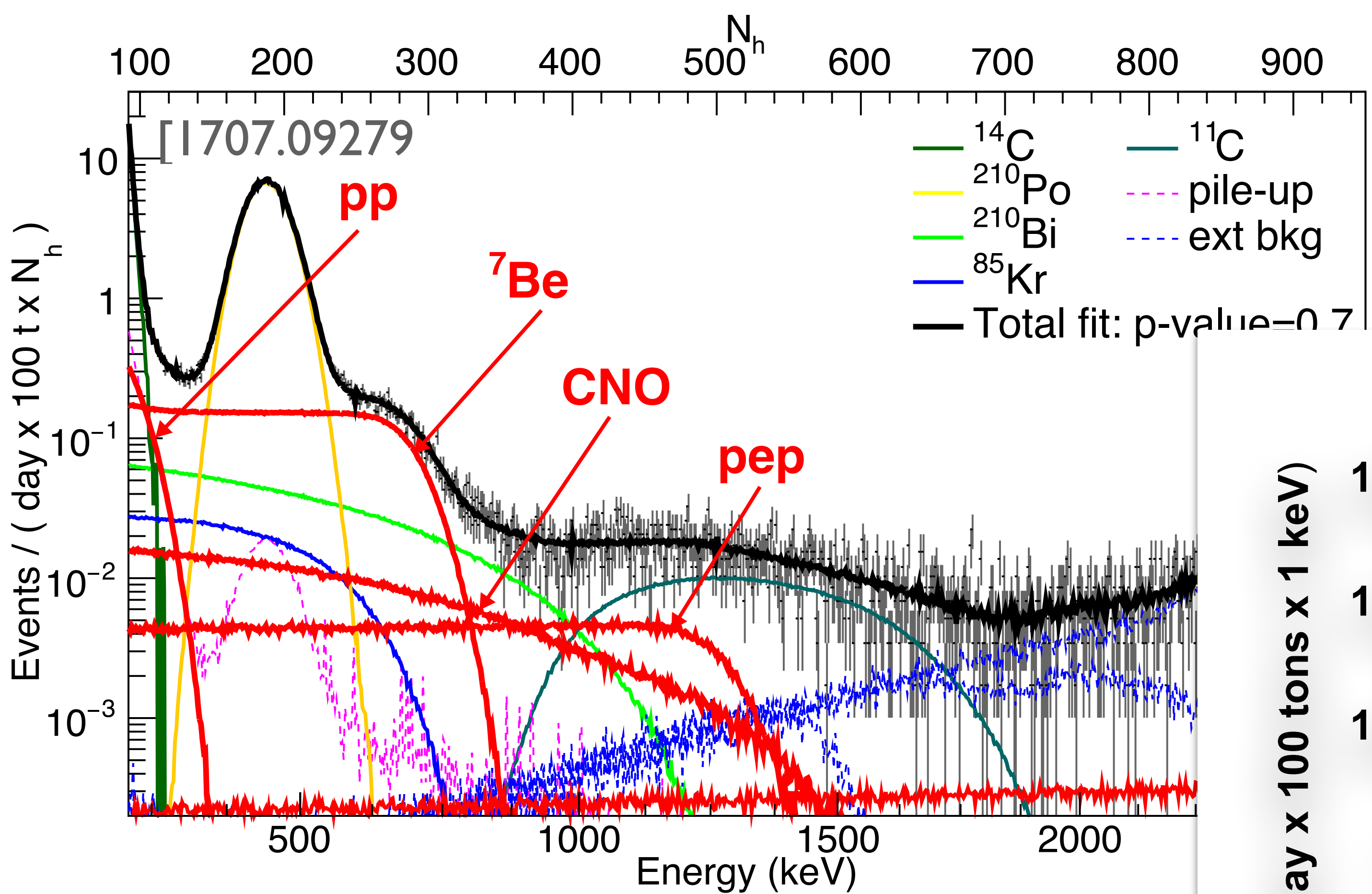
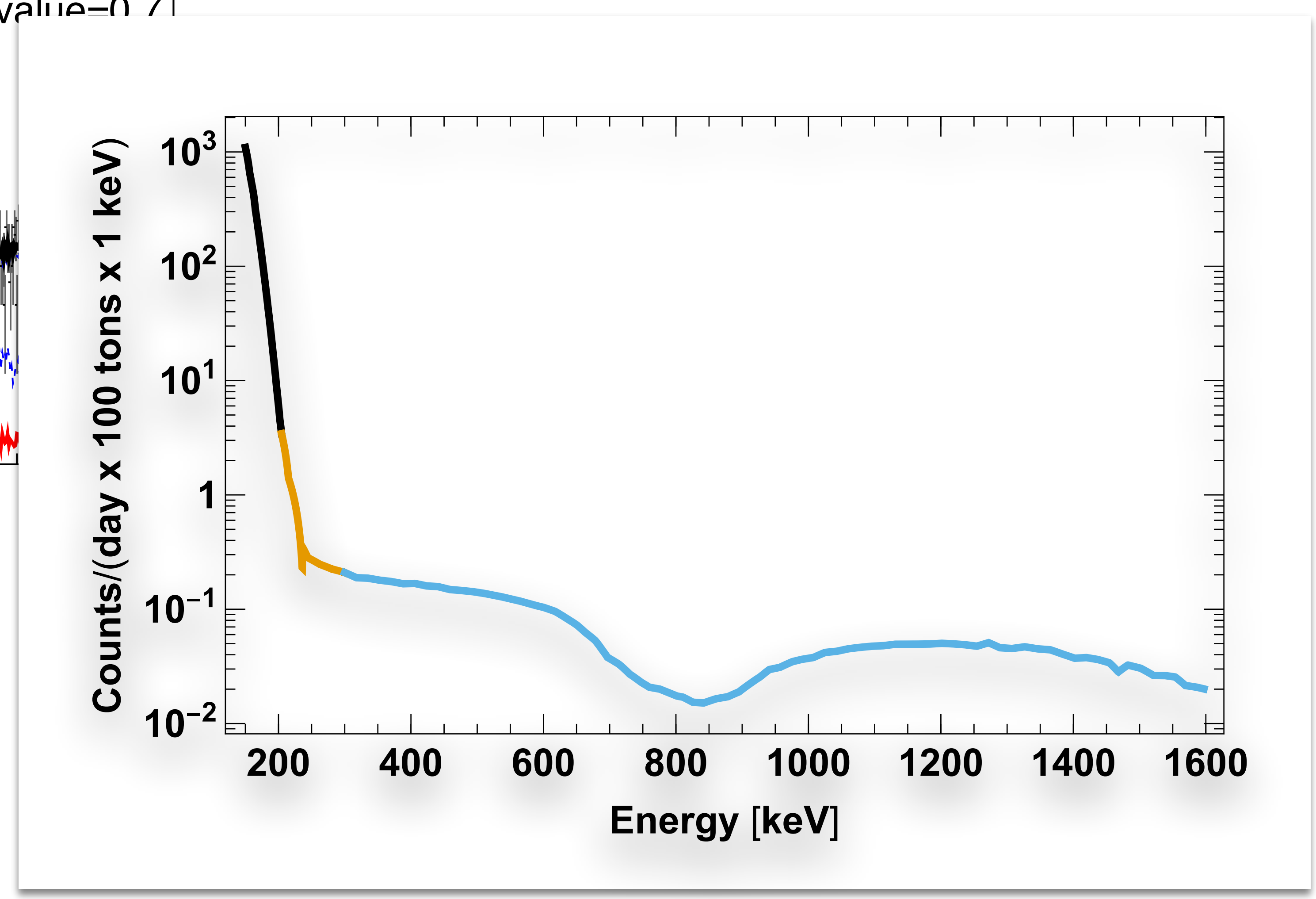


PHYSICAL REVIEW D **89**, 112007 (2014)





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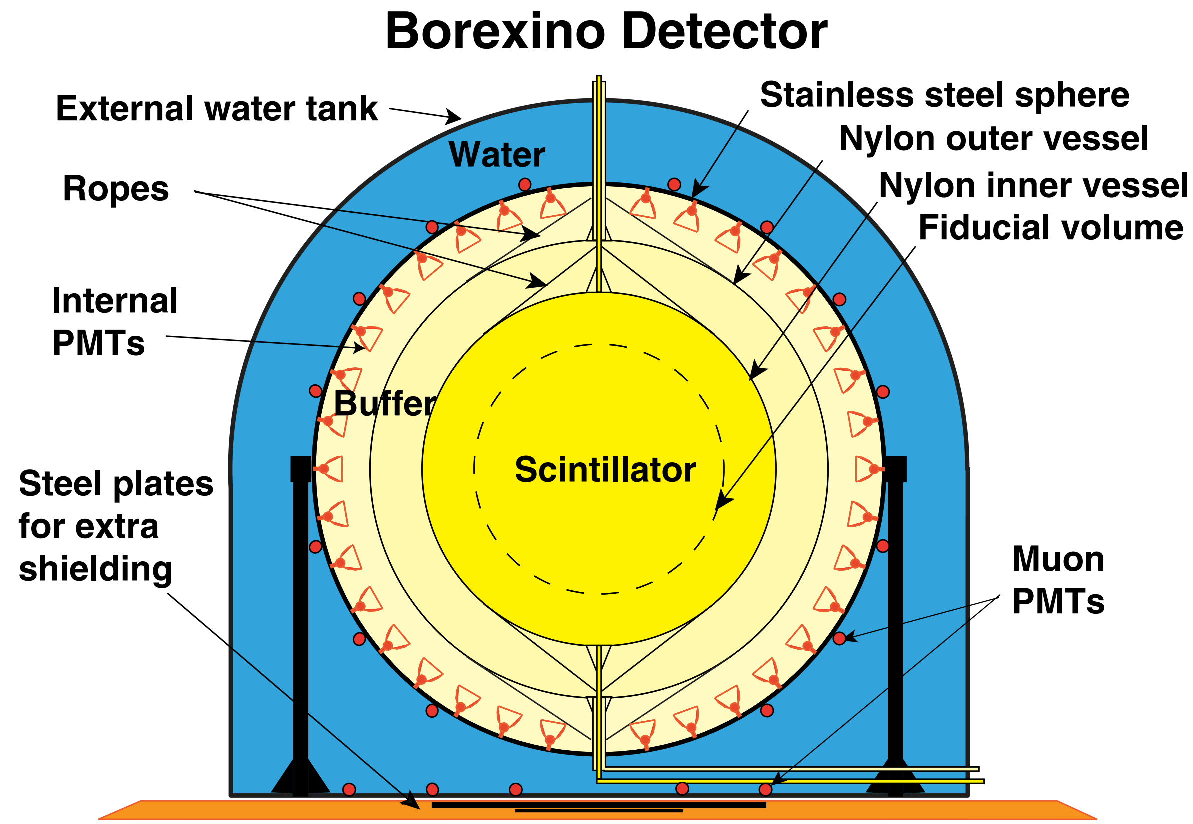
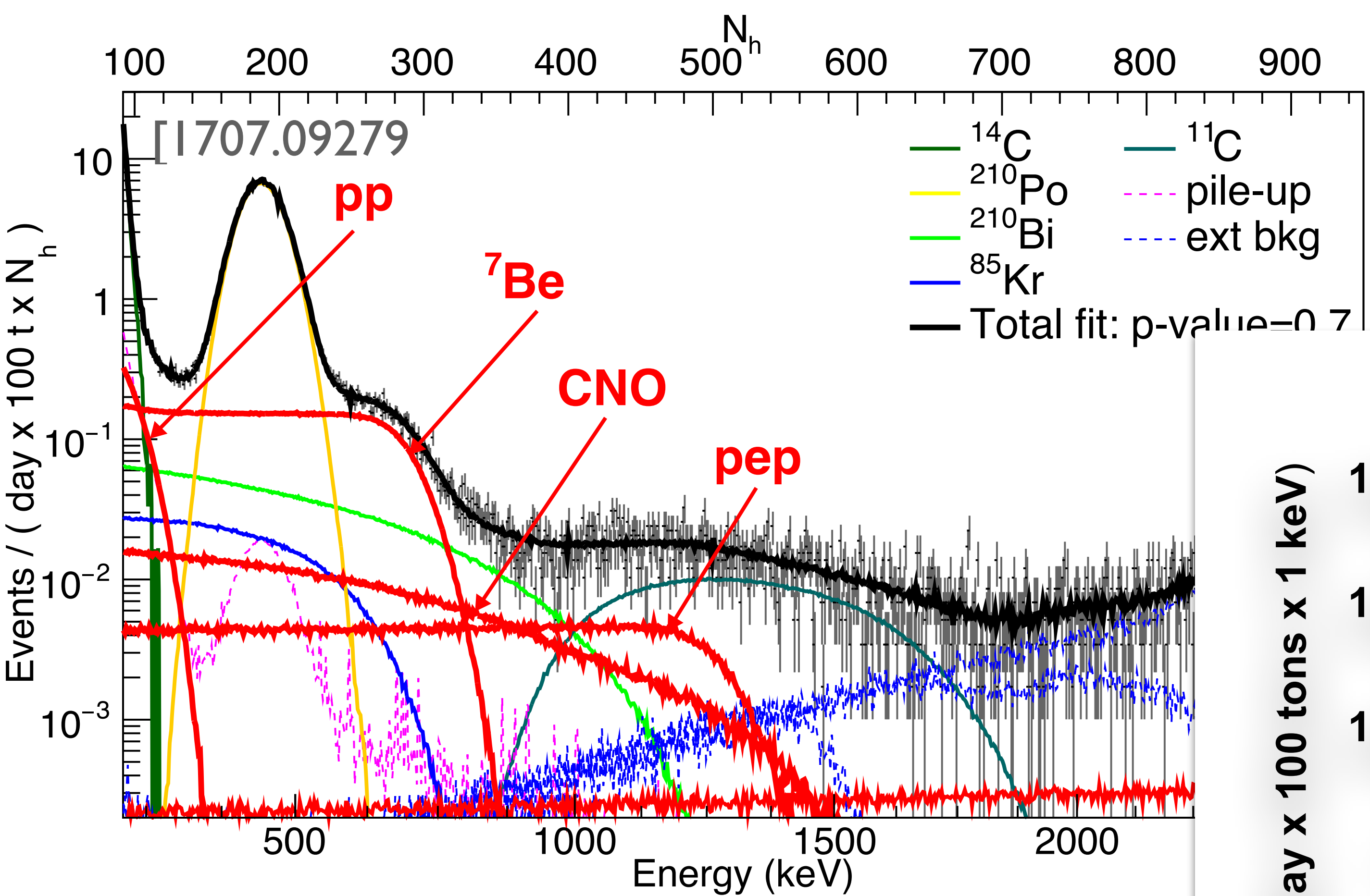
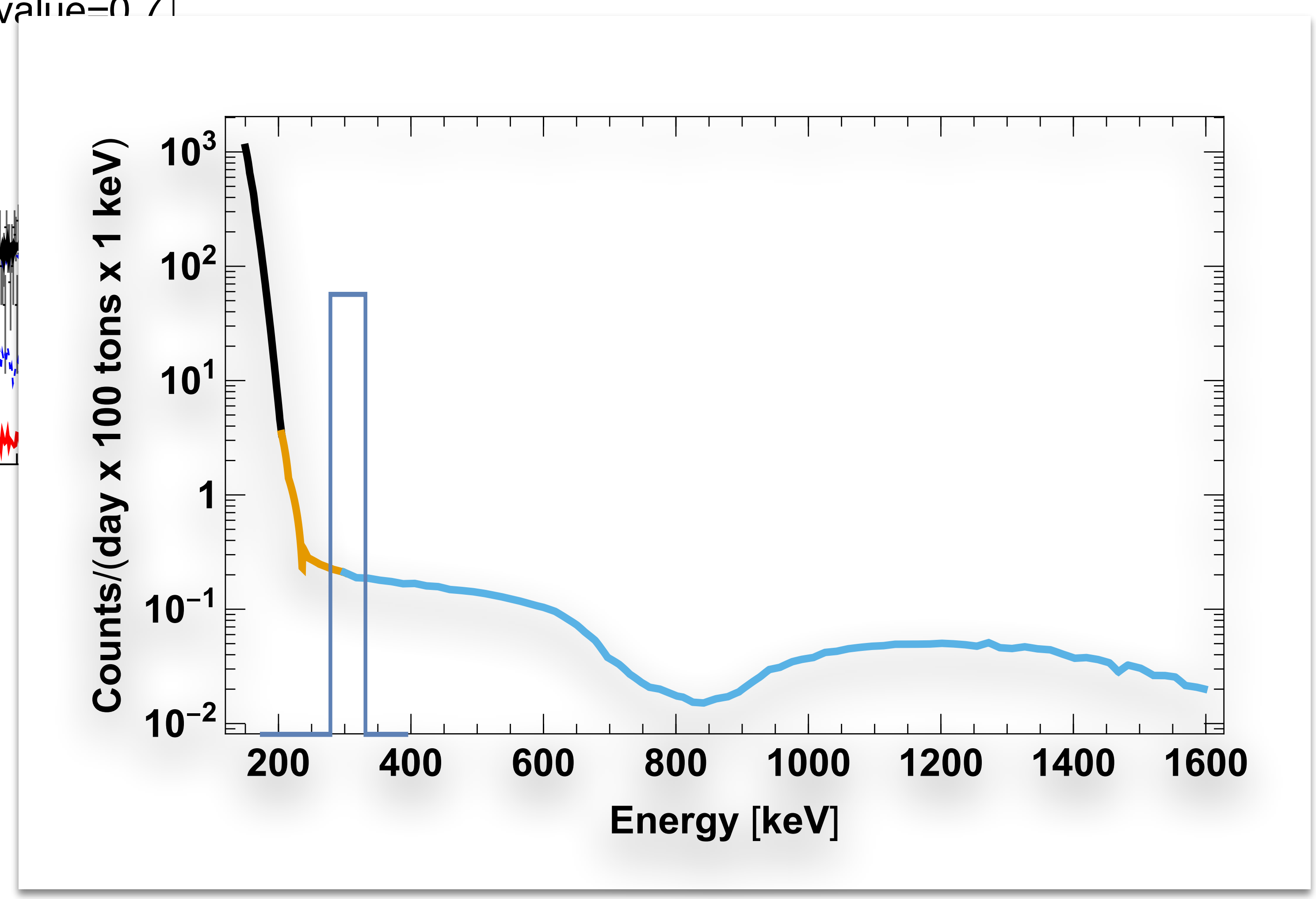


PHYSICAL REVIEW D **89,** 112007 (2014)

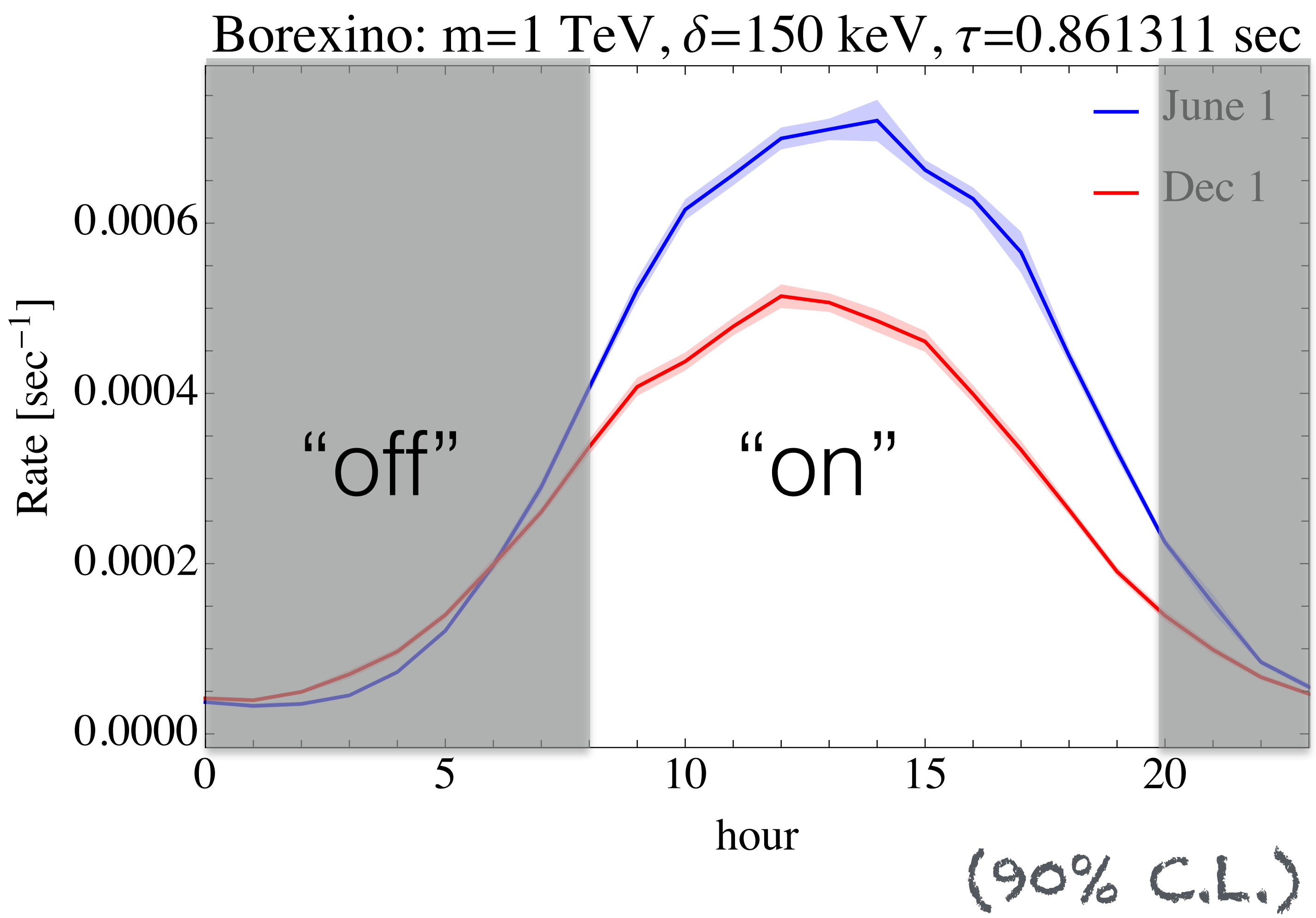




"Yesterday's signal is tomorrow's background"

A bound

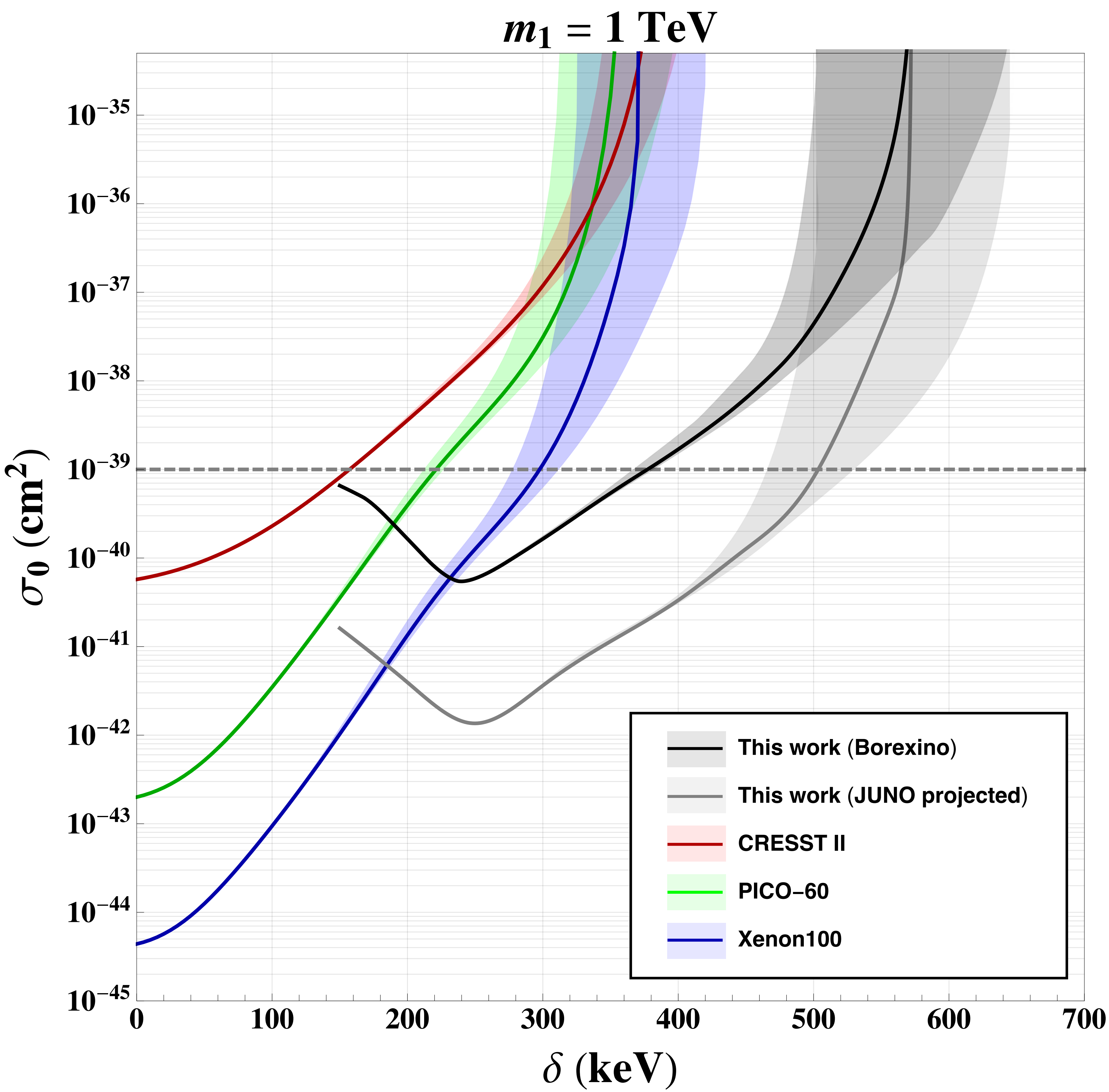
- Expect ~5 events/day—weak bound, no benefit from large exposure
- Use modulation to our advantage to measure background



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

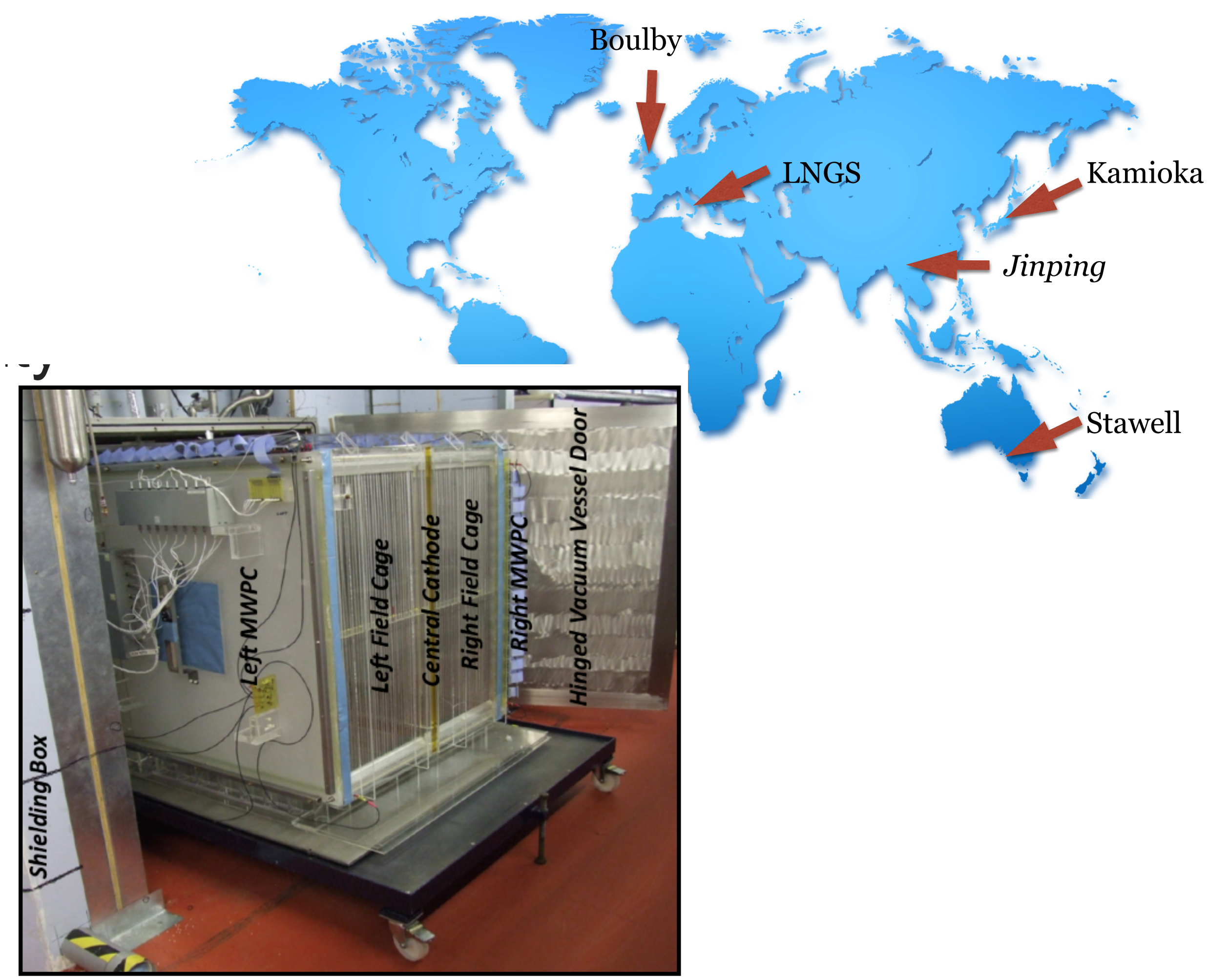
Collaboration could (should!) do a full modulation analysis (sidereal/Cygnus time)

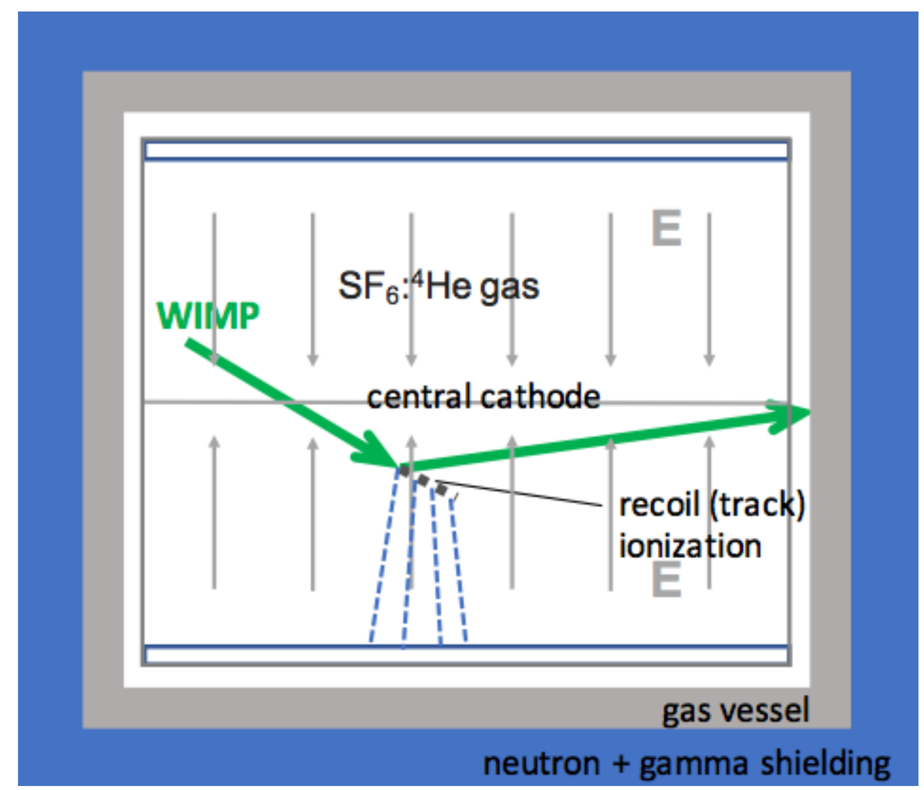
Sensitivity to the Inelastic Frontier



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

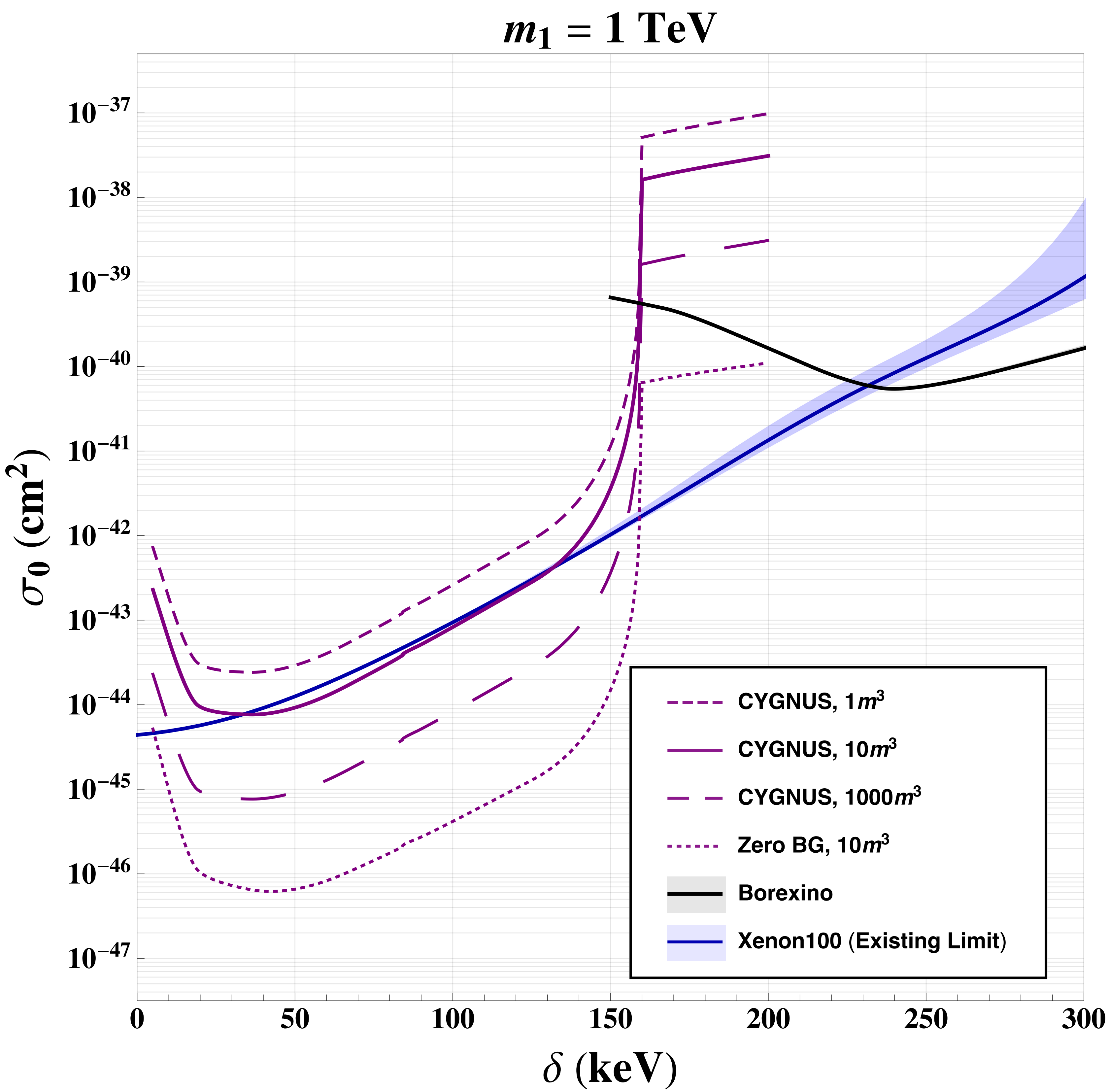
Gas drift TPC's: DMTPC, DRIFT, CYGNUS



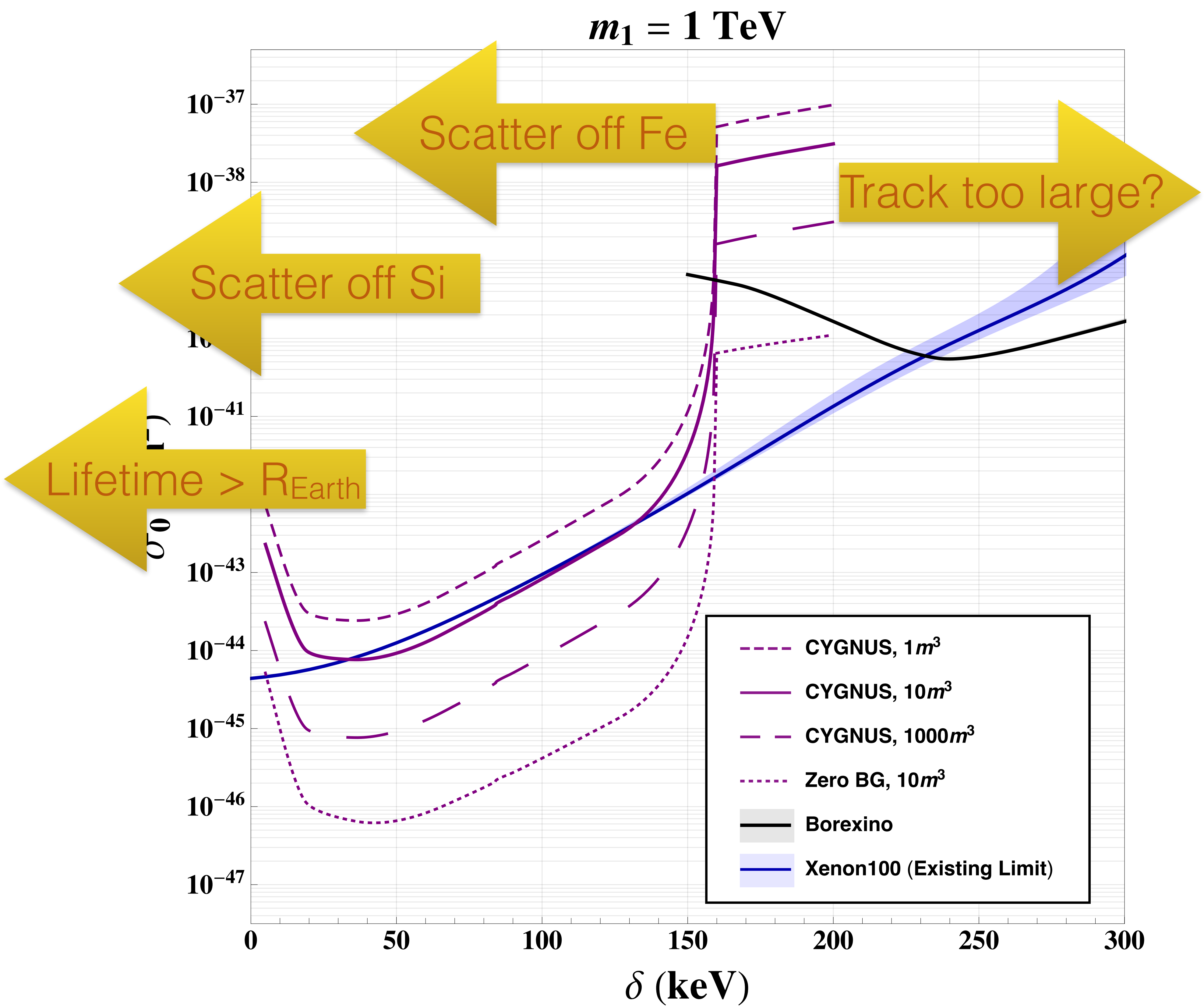


Energies ~10 keVee — ~ 200 keVee. 1m^3, 10m^3 ,1000m^3 volumes. Low mass (gass filled). No ^{14}C.

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