

Detecting Dark Matter with DarkSide-50

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Thursday, January 21, 2015

quarks leptons

u	c	t
d	s	b

e	μ	τ
ν_e	ν_μ	ν_τ

g	Z	W^+	W^-	γ	H
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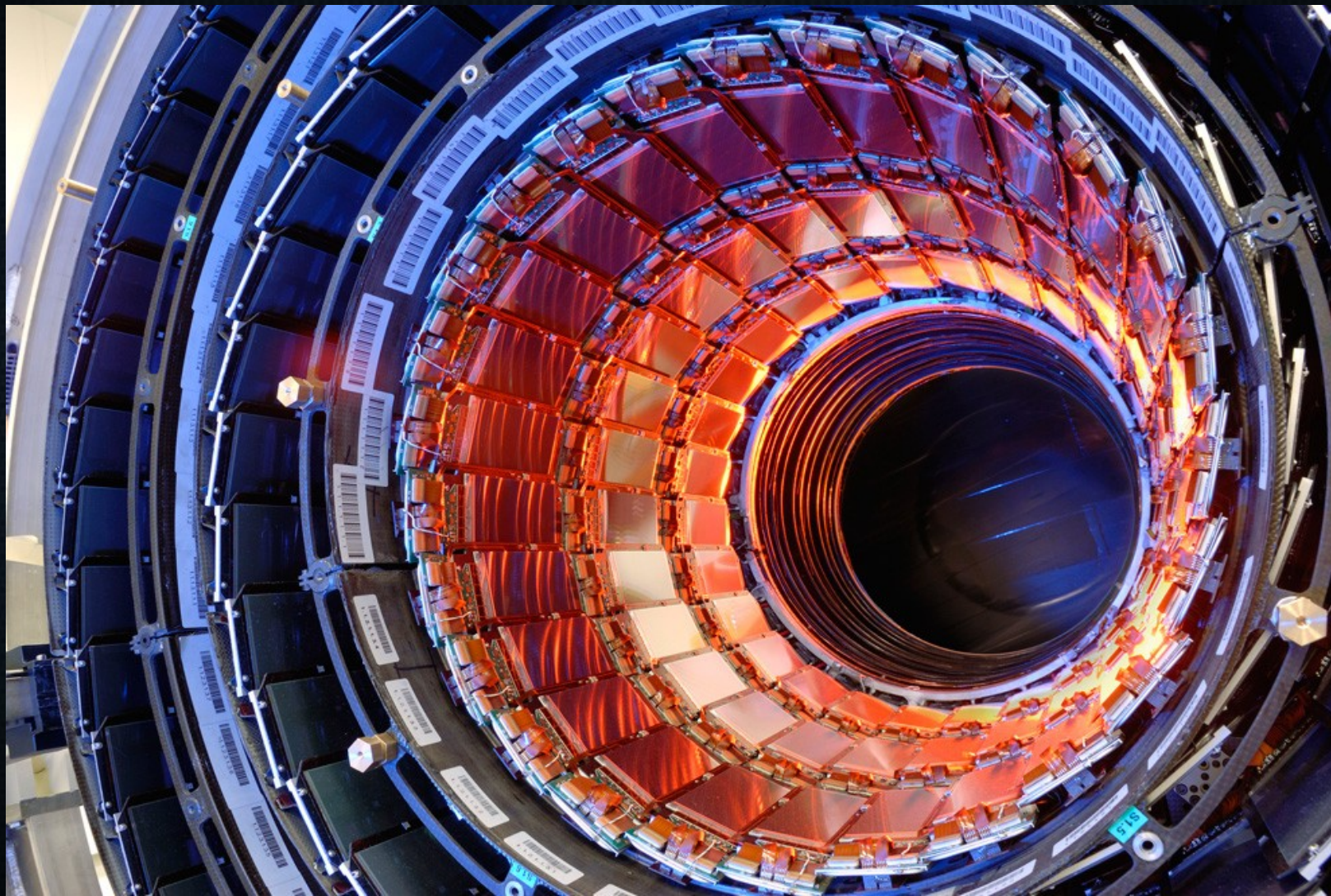
bosons

$$\begin{aligned}
\mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \\
& \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
& \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + \\
& g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
& M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \\
& \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \\
& \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
& M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
& \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \right. \\
& \left. \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - \\
& igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
& Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + \\
& Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \\
& igs_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
& A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + \\
& A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \\
& \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
& \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \\
& g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + \\
& g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - \\
& A_\mu A_\mu W_\nu^+ W_\nu^-) + \\
& g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
& 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + \\
& 2H\phi^+ \phi^-] - \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + \\
& 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- +
\end{aligned}$$

$$\begin{aligned}
& 2(\phi^0)^2 H^2] - gMW_\mu^+ W_\mu^- H - \\
& \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig[W_\mu^+ (\phi^0 \partial_\mu \phi^- - \\
& \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \\
& \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g[W_\mu^+ (H \partial_\mu \phi^- - \\
& \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \\
& \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - \\
& ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
& igs_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
& ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
& igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
& \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
& \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - \\
& 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w^2} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - \\
& W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - \\
& W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
& g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \\
& \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + \\
& m_d^\lambda) d_j^\lambda + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \\
& \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \\
& \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - \\
& 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \\
& \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \\
& \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 +
\end{aligned}$$

$$\begin{aligned}
& \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \\
& \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \\
& \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \\
& \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{gm_e^\lambda}{2M} [H (\bar{e}^\lambda e^\lambda) + \\
& i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \\
& \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
& m_u^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \\
& \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
& m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \frac{gm_u^\lambda}{2M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
& \frac{g}{2M} m_d^\lambda H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2M} m_u^\lambda \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
& \frac{ig}{2M} m_d^\lambda \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \\
& \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \\
& \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
& \partial_\mu \bar{X}^+ X^0) + igs_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
& \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
& \partial_\mu \bar{X}^0 X^+) + igs_w W_\mu^- (\partial_\mu \bar{X}^- Y - \\
& \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \\
& \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
& \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \\
& \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
& igM s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
& \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}$$

Heavily Tested



http://inapcache.boston.com/universal/site_graphics/blogs/bigpicture/lhc_11_20/l11_00000001.jpg

And many others...⁴

And it checks out!

quarks leptons

u	c	t	e	μ	τ
d	s	b	ν_e	ν_μ	ν_τ

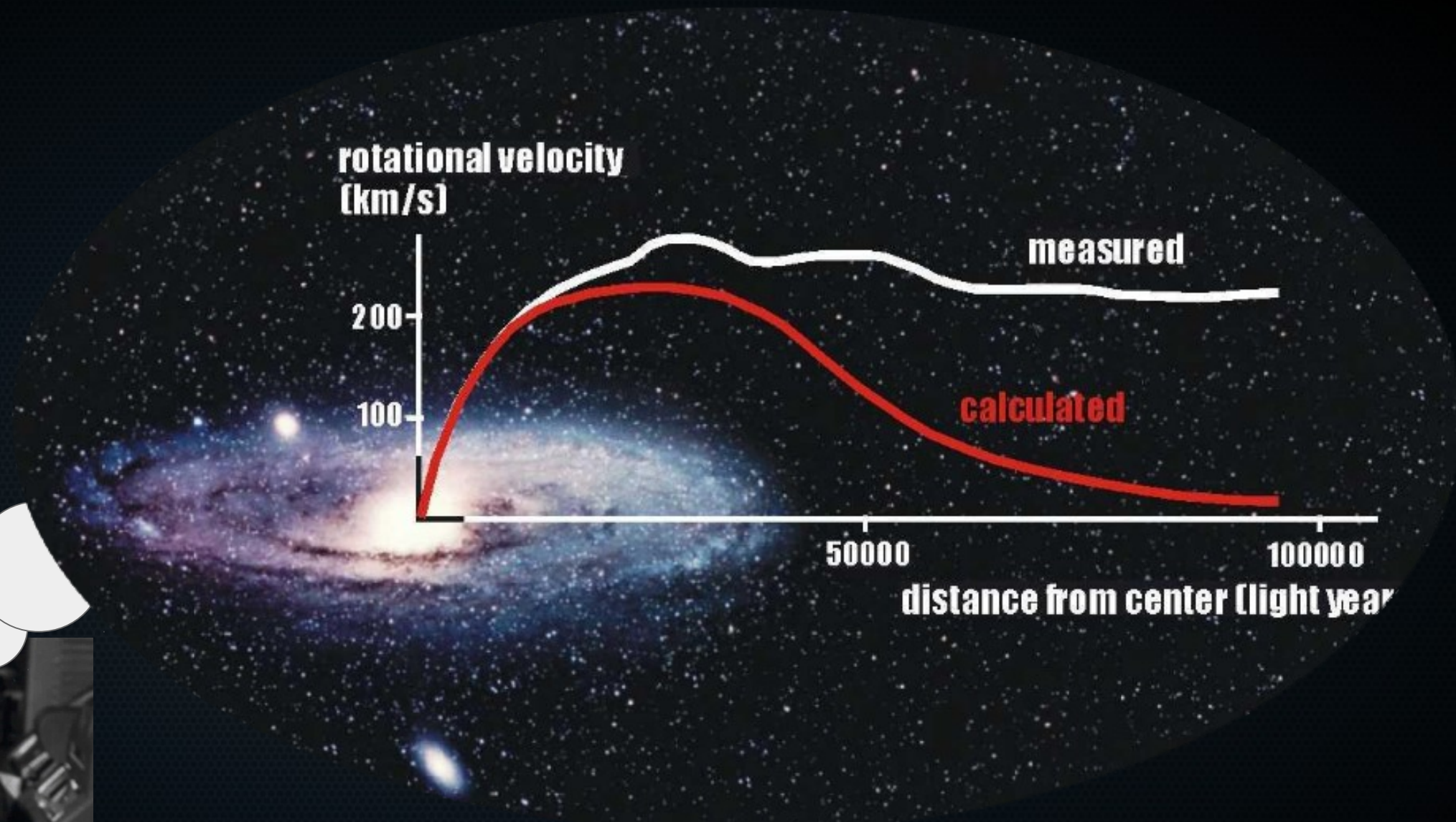
bosons

g	Z	W^+	W^-	γ	H
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$$\mathcal{L}_{SM} =$$

$$-\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\mu \gamma^\mu q_j^\mu) g_\mu^a + G^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G_\mu^b g_\mu^c - \partial_\mu W_\nu^+ \partial_\mu W_\nu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2}M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_H^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}m_\phi^2 \phi^0 \phi^0 - \frac{1}{2}M^2 \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\mu Z_\mu^0 (W_\mu^+ W_\mu^- - W_\mu^- W_\mu^+) - Z_\mu^0 (W_\mu^+ \partial_\mu W_\mu^- - W_\mu^- \partial_\mu W_\mu^+) - Z_\mu^0 (W_\mu^- \partial_\mu W_\mu^+ - W_\mu^+ \partial_\mu W_\mu^-)] - ig_s w [\partial_\mu A_\mu (W_\mu^+ W_\mu^- - W_\mu^- W_\mu^+) - A_\mu (W_\mu^+ \partial_\mu W_\mu^- - W_\mu^- \partial_\mu W_\mu^+) + A_\mu (W_\mu^- \partial_\mu W_\mu^+ - W_\mu^+ \partial_\mu W_\mu^-)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\mu^+ W_\mu^- + \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\mu^- W_\mu^+ + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\mu^0 W_\mu^- - Z_\mu^0 Z_\mu^0 W_\mu^+ W_\mu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\mu W_\mu^- - A_\mu A_\mu W_\mu^+ W_\mu^-) + g^2 s_w c_w [A_\mu Z_\mu^0 (W_\mu^+ W_\mu^- - W_\mu^- W_\mu^+) - 2A_\mu Z_\mu^0 W_\mu^+ W_\mu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \frac{1}{2}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - gMW_\mu^+ W_\mu^- H - \frac{1}{2}g\frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig[W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}ig[W_\mu^+ (H\partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w} (Z_\mu^0 (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig\frac{s_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig_s w MA_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig\frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig_s w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 (\phi^+ \phi^- + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - e^\lambda (\gamma \partial + m_\lambda^2) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_\lambda^2) u_j^\lambda - d_j^\lambda (\gamma \partial + m_\lambda^2) d_j^\lambda + ig_s w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda k} d_k^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda C_{\lambda k}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} M [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{gm_\lambda^2}{2M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_\lambda^2 (\bar{u}_j^\lambda C_{\lambda k} (1 - \gamma^5) d_k^\lambda) + m_\lambda^2 (\bar{u}_j^\lambda C_{\lambda k} (1 + \gamma^5) d_k^\lambda) + \frac{ig}{2M\sqrt{2}} \phi^- [m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda k}^\dagger (1 + \gamma^5) u_j^\lambda) - m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda k}^\dagger (1 - \gamma^5) u_j^\lambda) - \frac{gm_\lambda^2}{2M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{gm_\lambda^2}{2M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + Y \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig_s w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig_s w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \partial_\mu \bar{X}^- X^+) + ig_s w A_\mu (\partial_\mu \bar{X}^+ X^- - \partial_\mu \bar{X}^- X^+) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^- - \bar{X}^- X^0 \phi^+] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igMs_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]$$

kind of...



cdms.phy.queensu.ca/Public_Docs/Pictures/Rotationcurve_3.jpg

~15%

quarks			leptons		
u	c	t	e	μ	τ
d	s	b	ν_e	ν_μ	ν_τ
g	Z	W ⁺	W ⁻	γ	H
bosons					

~85%

DARK MATTER



...and the evidence piled up...

quarks leptons

u	c	t
d	s	b

e	μ	τ
ν_e	ν_μ	ν_τ

g	Z	W^+	W^-	γ	H
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bosons

+

DARK MATTER

DARK MATTER



?

?
 ν_s

?
axions

?

WIMPs

- Massive Compact Halo Objects
- Microlensing measurements
- CMB Measurements

- Cold sterile neutrinos

- Predicted by Peccei-Quinn theory
- May solve the Strong CP problem

- Weakly Interacting Massive Particles
- Predicted by SUSY, Kaluza-Klein, ...

DARK MATTER



?

?

ν_s

?

axions

?

WIMPs

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• Cold sterile neutrinos

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WIMPs: Thermal Relics

Cosmological requirements:

- $\langle \sigma v \rangle \sim 10^{-26} \text{ cm}^3/\text{s}$
- Mass $\sim 100 \text{ GeV}/c^2$

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WIMPs: Thermal Relics

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- Mass $\sim 100 \text{ GeV}/c^2$

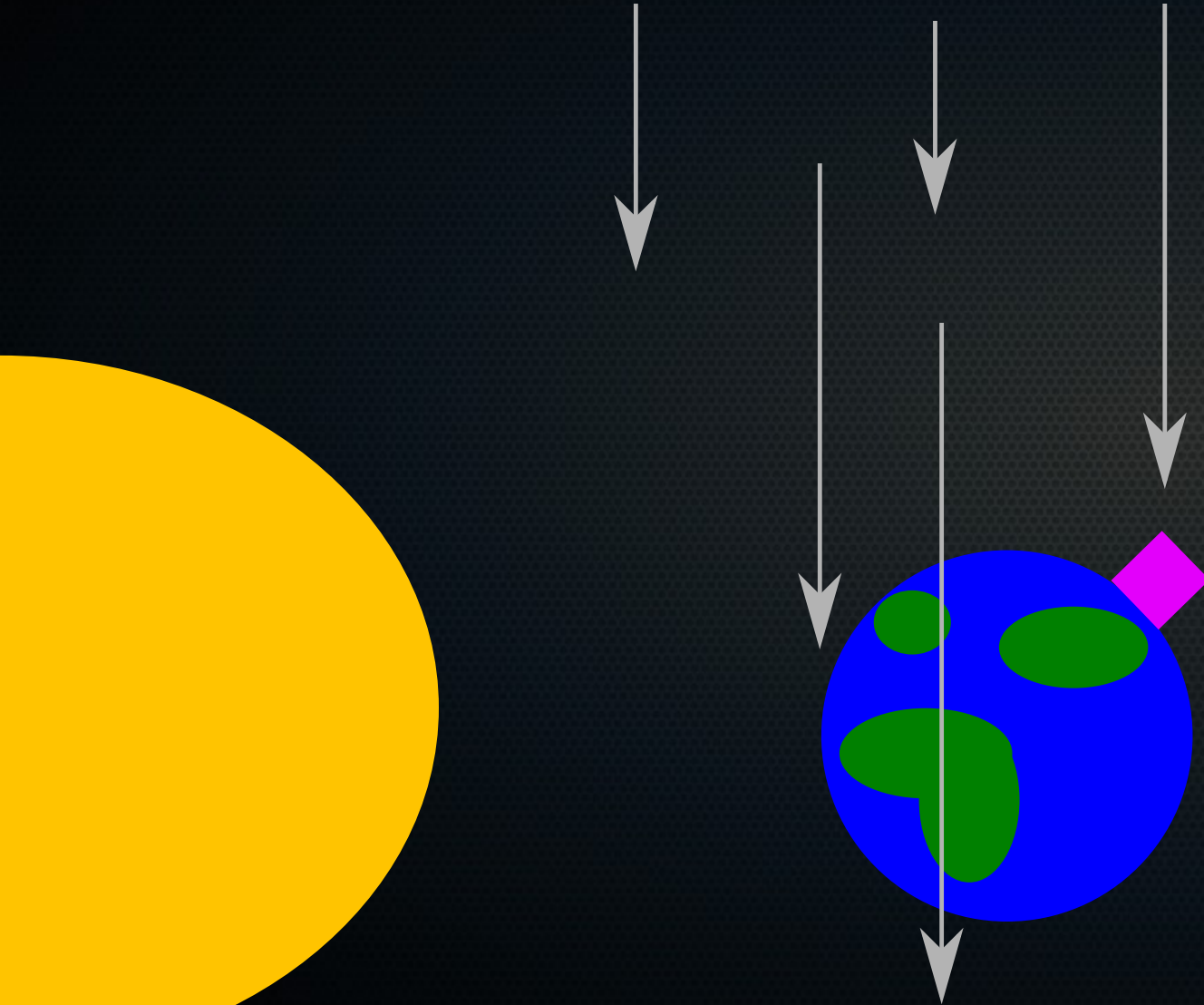
} Weak interaction scale



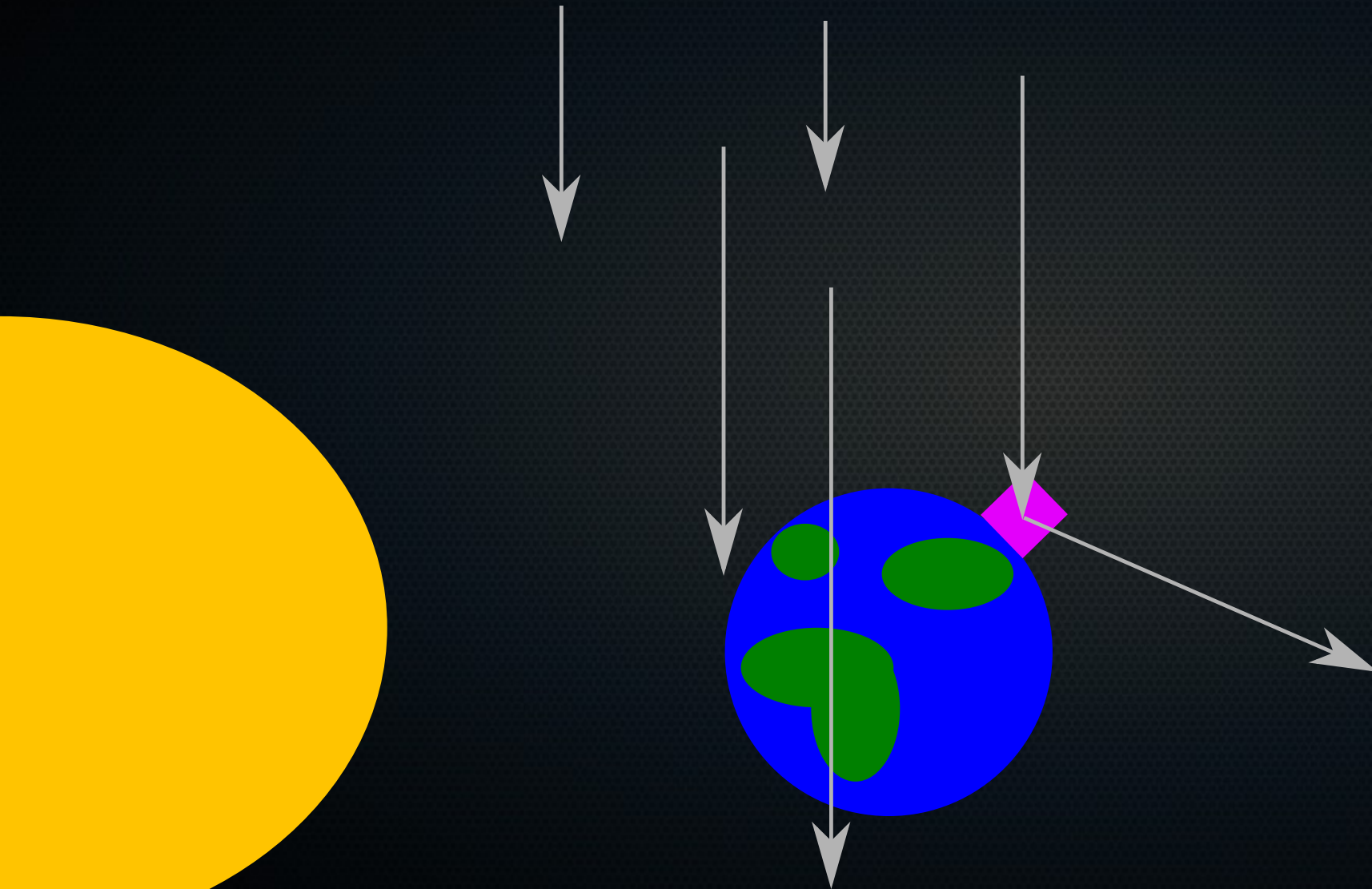
Interactions with non-WIMPs will be very rare

WIMP Detection

- Earth moves through WIMP wind

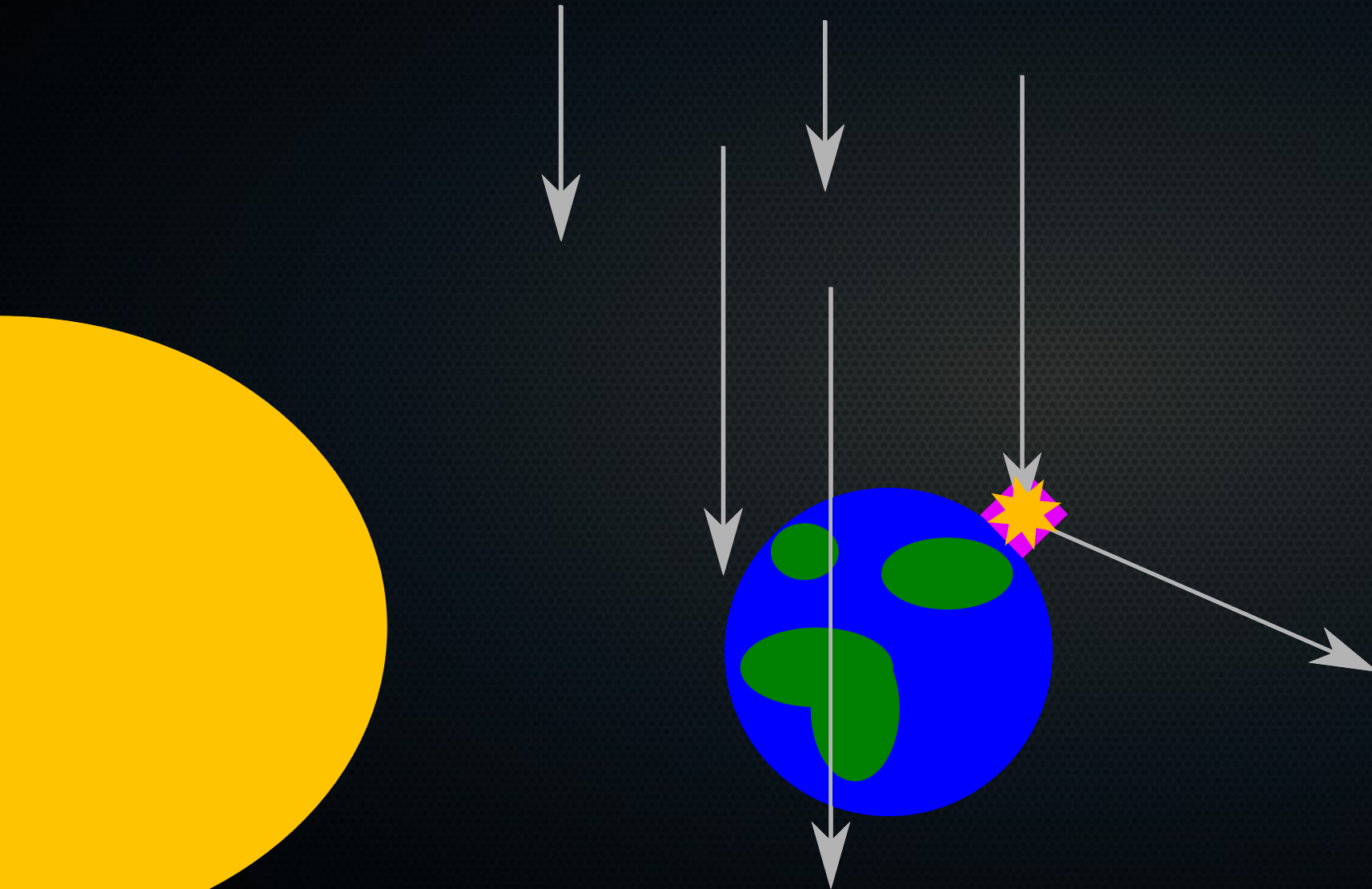


WIMP Detection



- Earth moves through WIMP wind
- WIMP scatters in detector

WIMP Detection



- Earth moves through WIMP wind
- WIMP scatters in detector
- Detector produces a signal

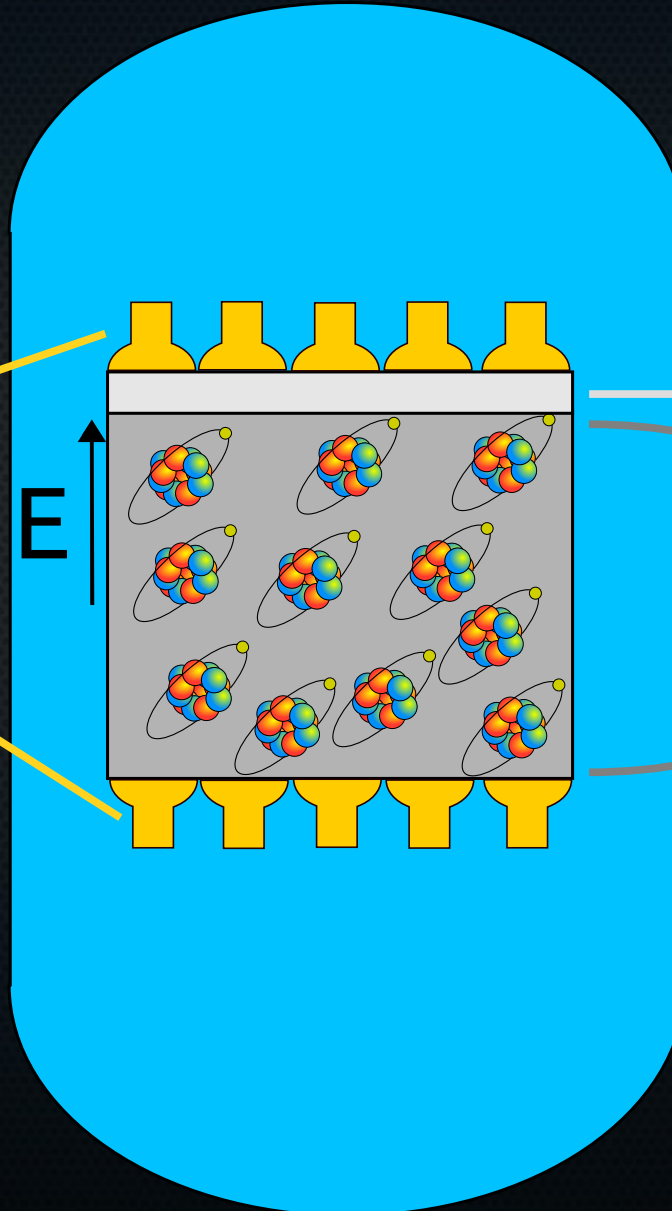
The DarkSide-50 Detector



DarkSide-50

Photo
Multiplier
Tubes

Cryostat



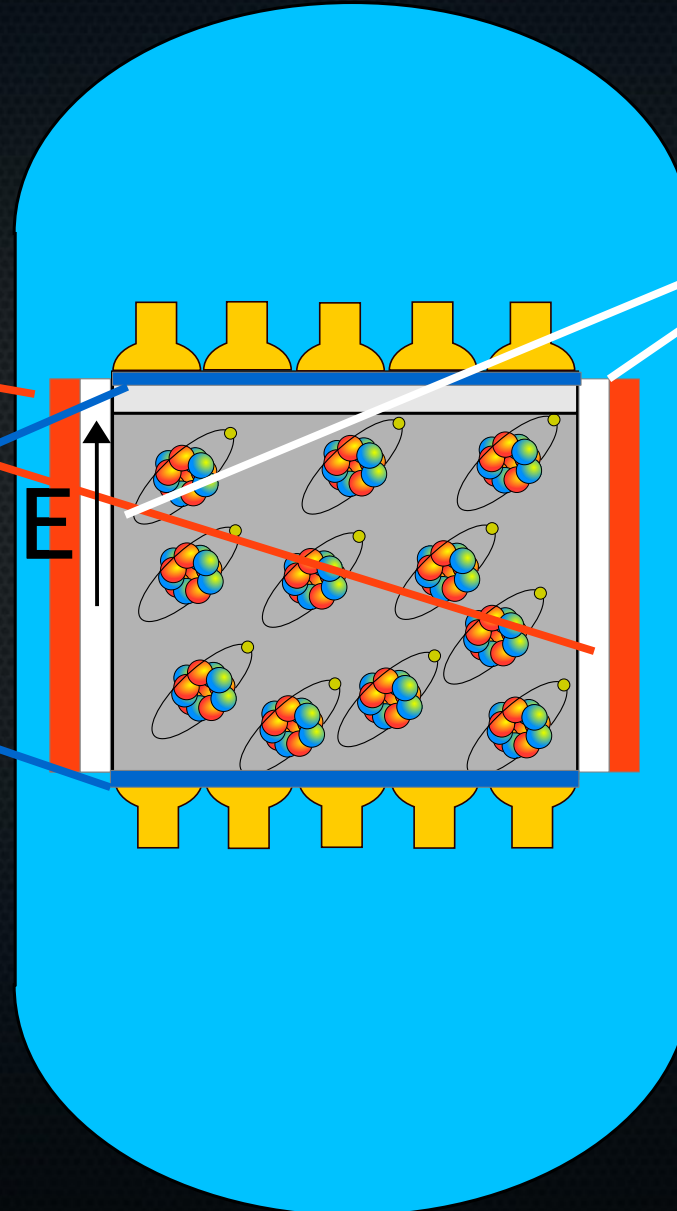
Gaseous
argon
50 kg liquid
argon

DarkSide-50

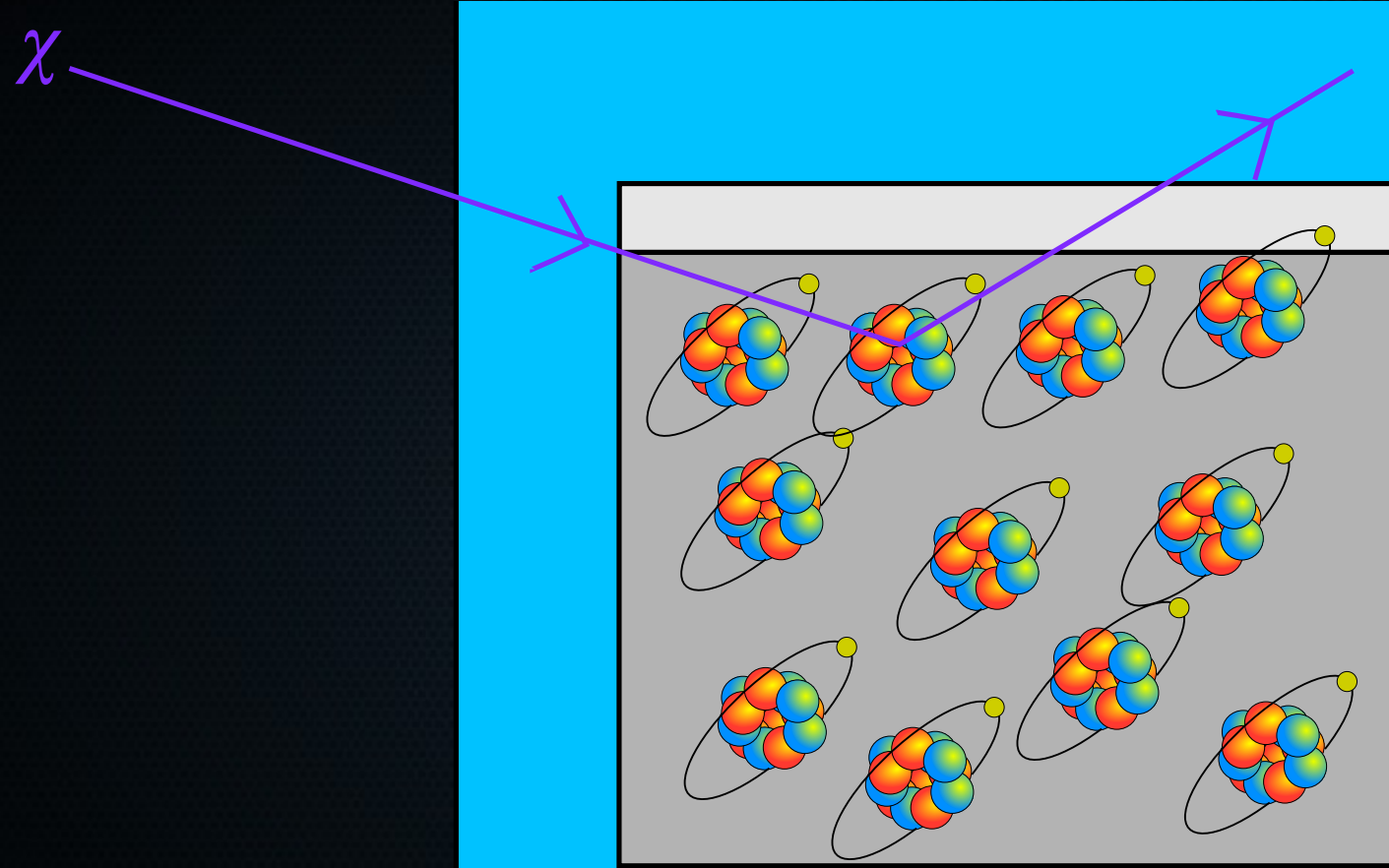
Copper field cage

Quartz windows
(coated with wavelength shifter)

Teflon reflector
(coated with wavelength shifter)

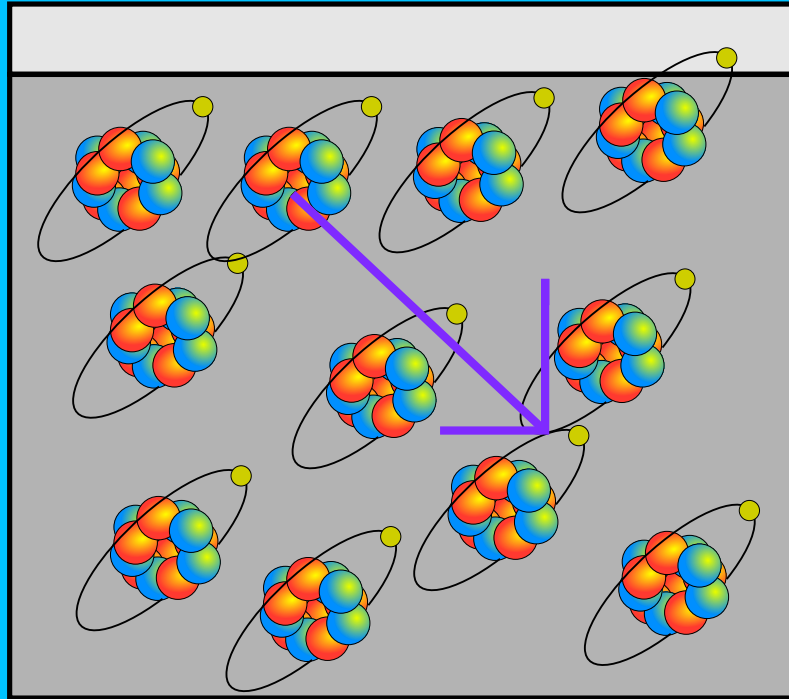


Liquid Argon Scintillation



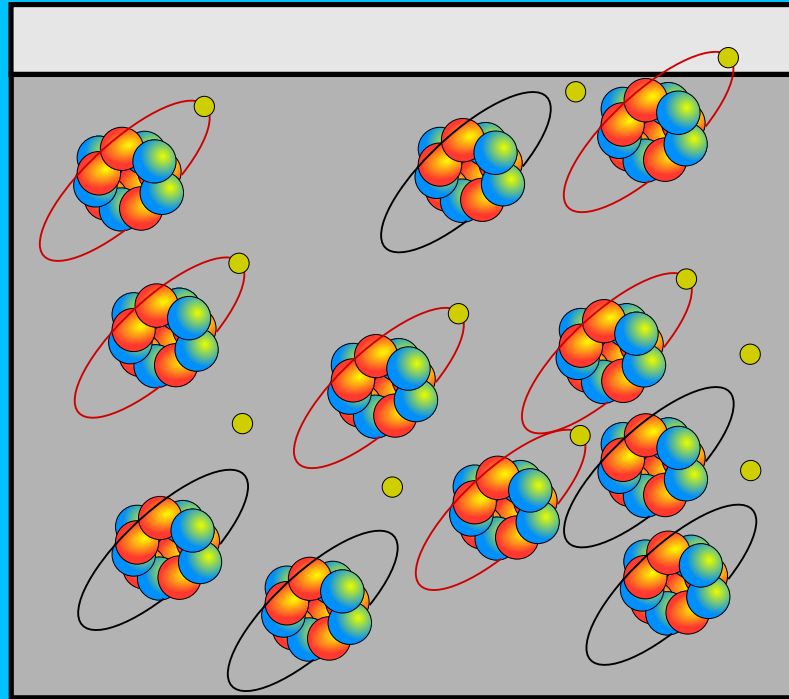
- WIMP scatters of Ar nucleus

Liquid Argon Scintillation



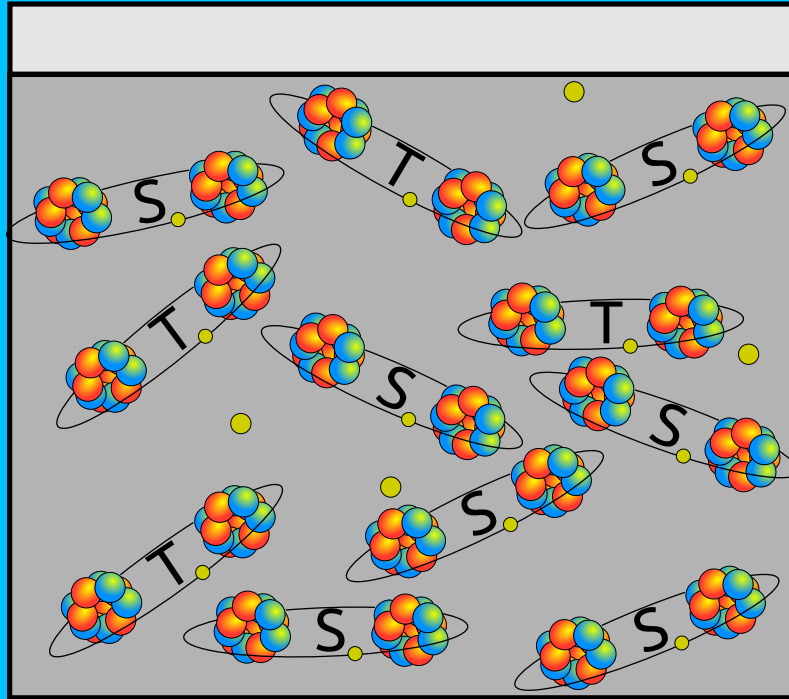
- WIMP scatters off Ar nucleus
- Ar nucleus recoils and scatters off of other Ar nuclei

Liquid Argon Scintillation



- WIMP scatters off Ar nucleus
- Ar nucleus recoils and scatters off of other Ar nuclei
- Ar atoms become excited or ionized

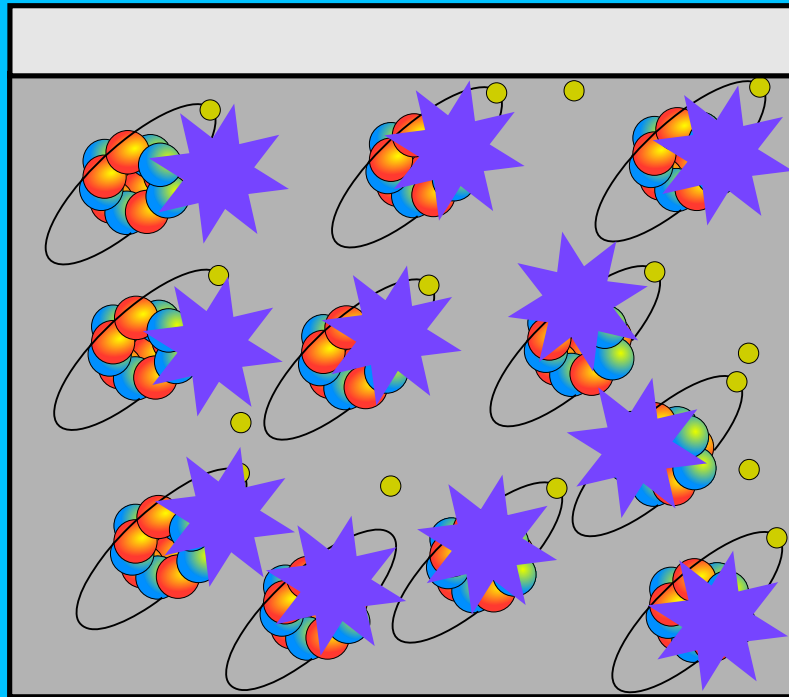
Liquid Argon Scintillation



- WIMP scatters off Ar nucleus
- Ar nucleus recoils and scatters off of other Ar nuclei
- Ar atoms become excited or ionized
- Ionized and excited Ar form dimers with ground state Ar

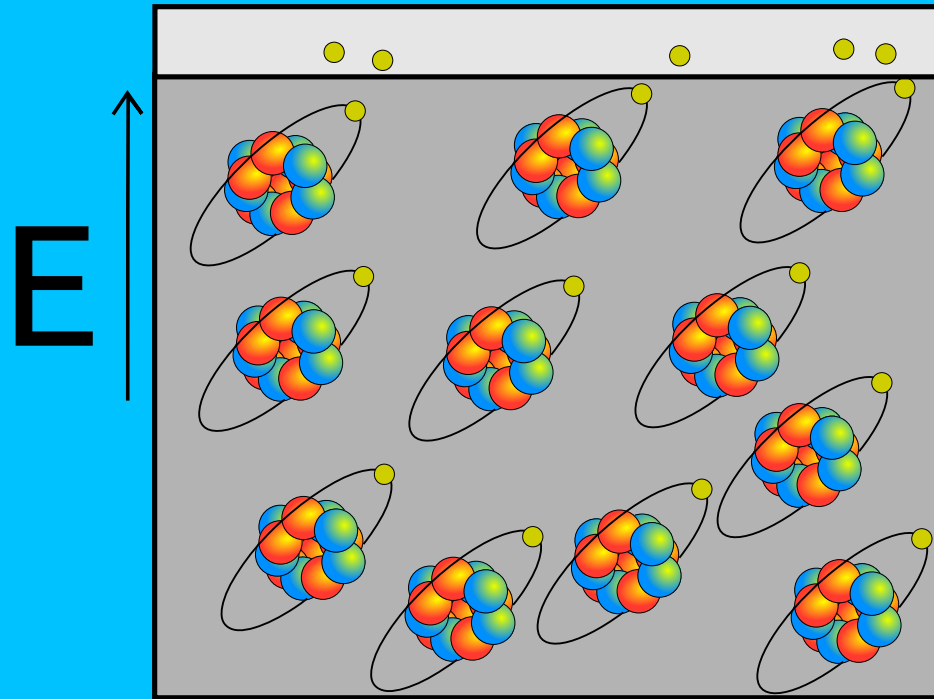
Liquid Argon Scintillation

S1 Signal



- WIMP scatters off Ar nucleus
- Ar nucleus recoils and scatters off of other Ar nuclei
- Ar atoms become excited or ionized
- Ionized and excited Ar form dimers with ground state Ar
- Dimers split apart and release light

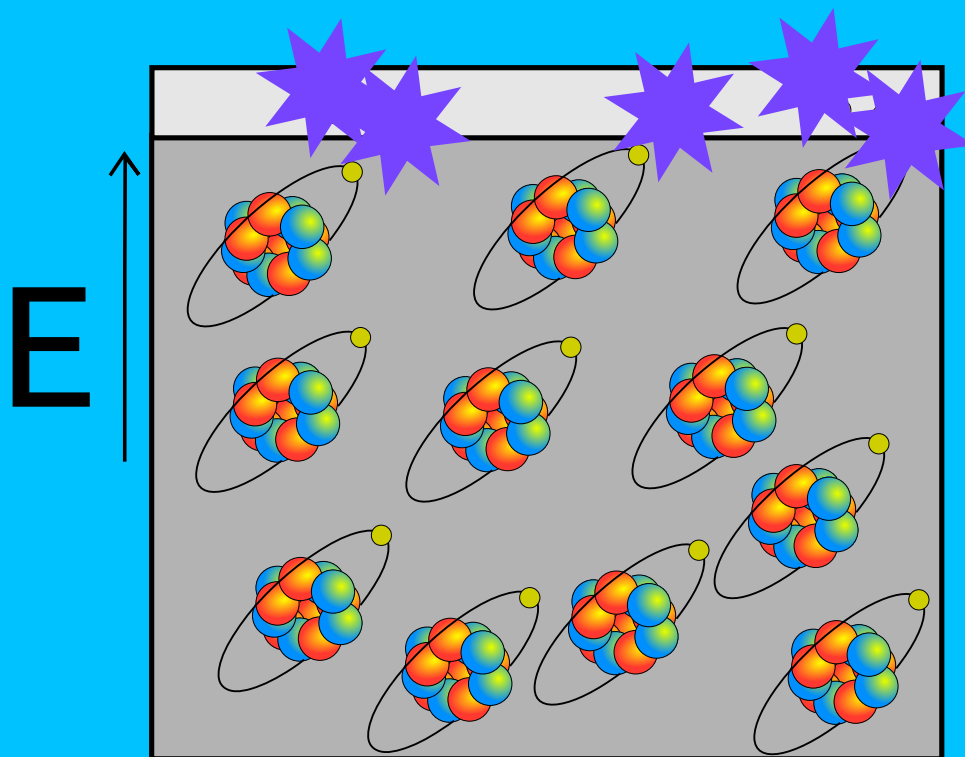
Liquid Argon Scintillation



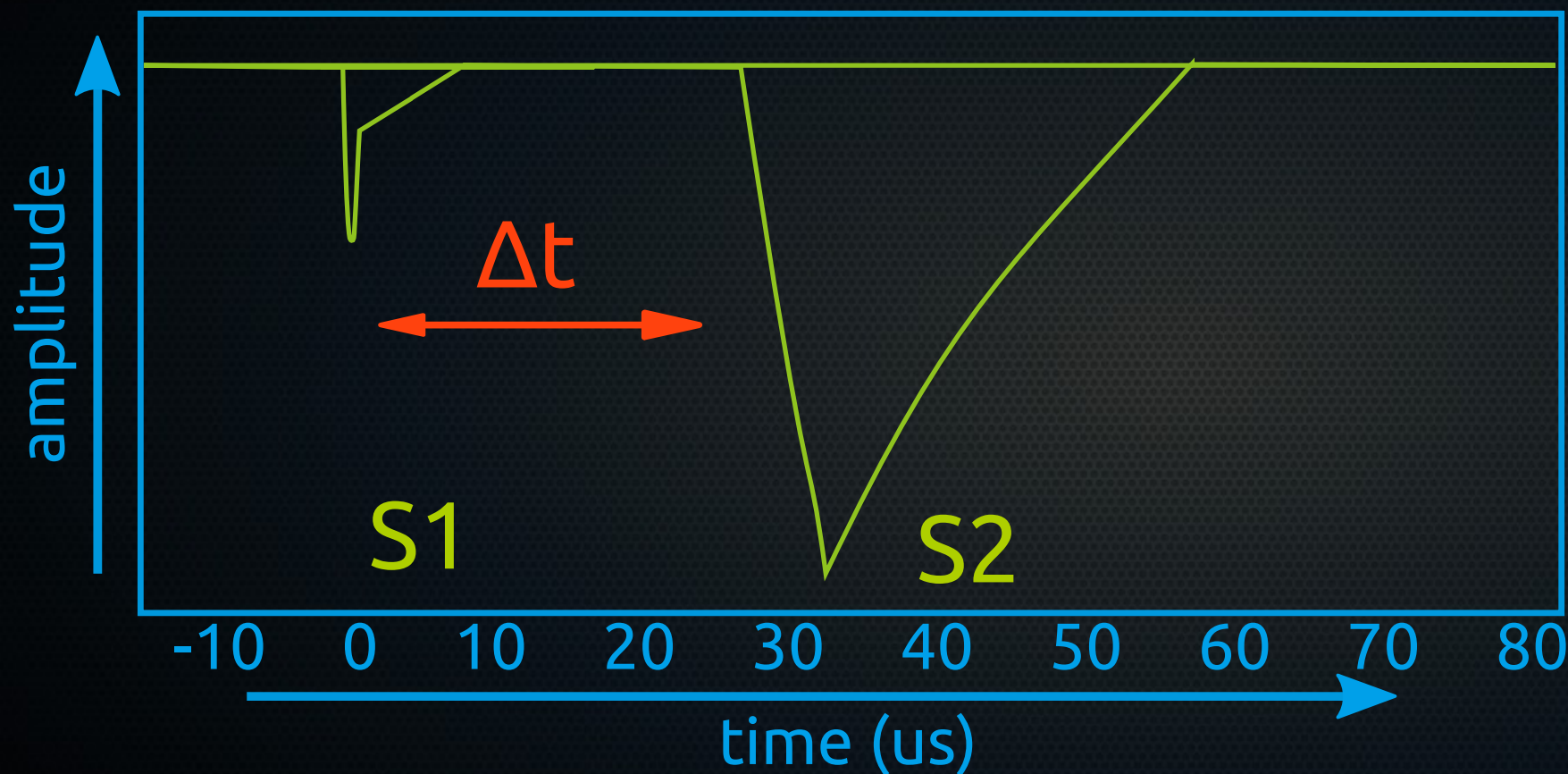
- WIMP scatters off Ar nucleus
- Ar nucleus recoils and scatters off of other Ar nuclei
- Ar atoms become excited or ionized
- Ionized and excited Ar form dimers with ground state Ar
- Dimers split apart and release light
- Ionized e^- drifted to gas layer

Liquid Argon Scintillation

S2 Signal



- WIMP scatters off Ar nucleus
- Ar nucleus recoils and scatters off of other Ar nuclei
- Ar atoms become excited or ionized
- Ionized and excited Ar form dimers with ground state Ar
- Dimers split apart and release light
- Ionized e^- drifted to gas layer
- e^- scintillate in gas layer



What we can learn:

- S1 → Recoil energy
- Δt → z-coordinate
- S2 PMT distribution → x,y-coordinates
- S2/S1 and S1 pulse shape → recoil type

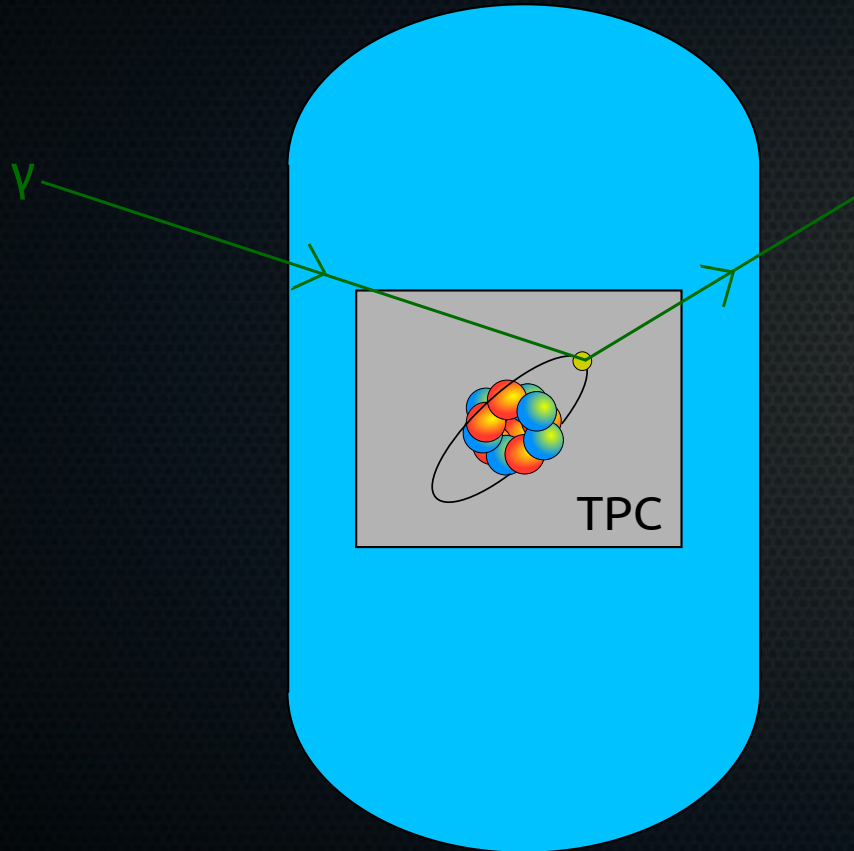
WIMP events are rare

WIMP events are rare

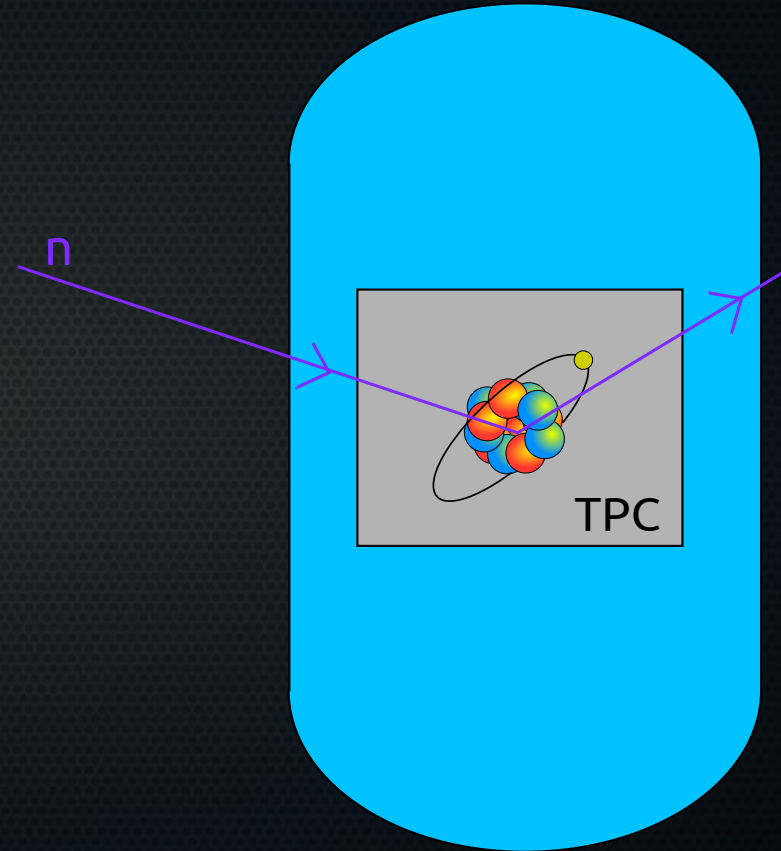
Any backgrounds can easily hide a WIMP if we are not careful

Backgrounds: 2 Types

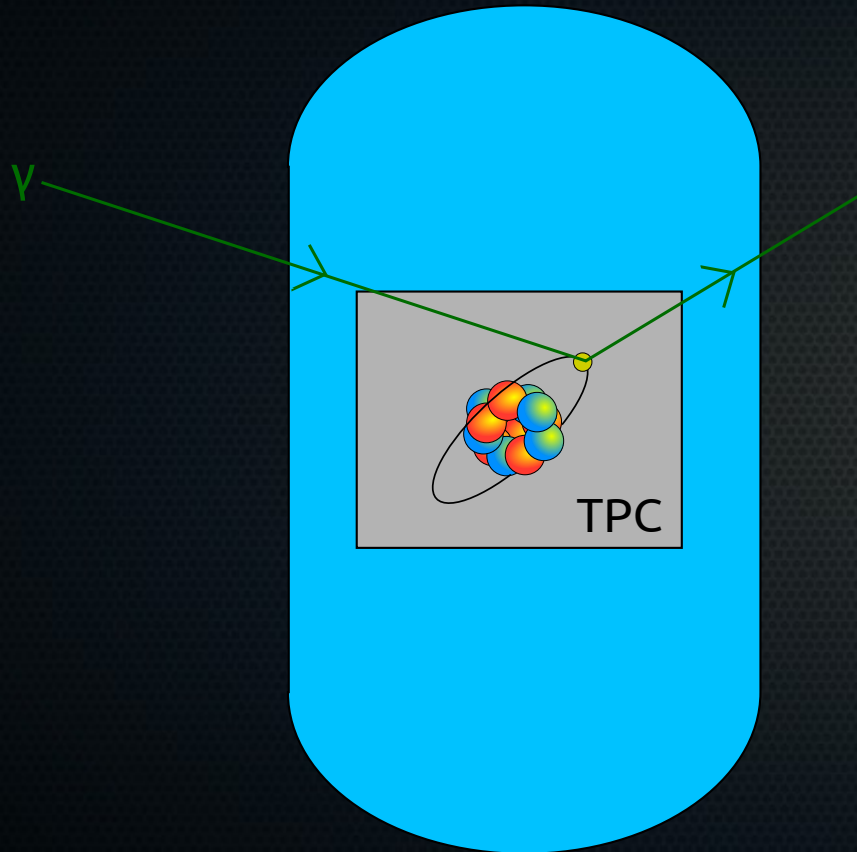
Electron Recoils



Nuclear Recoils

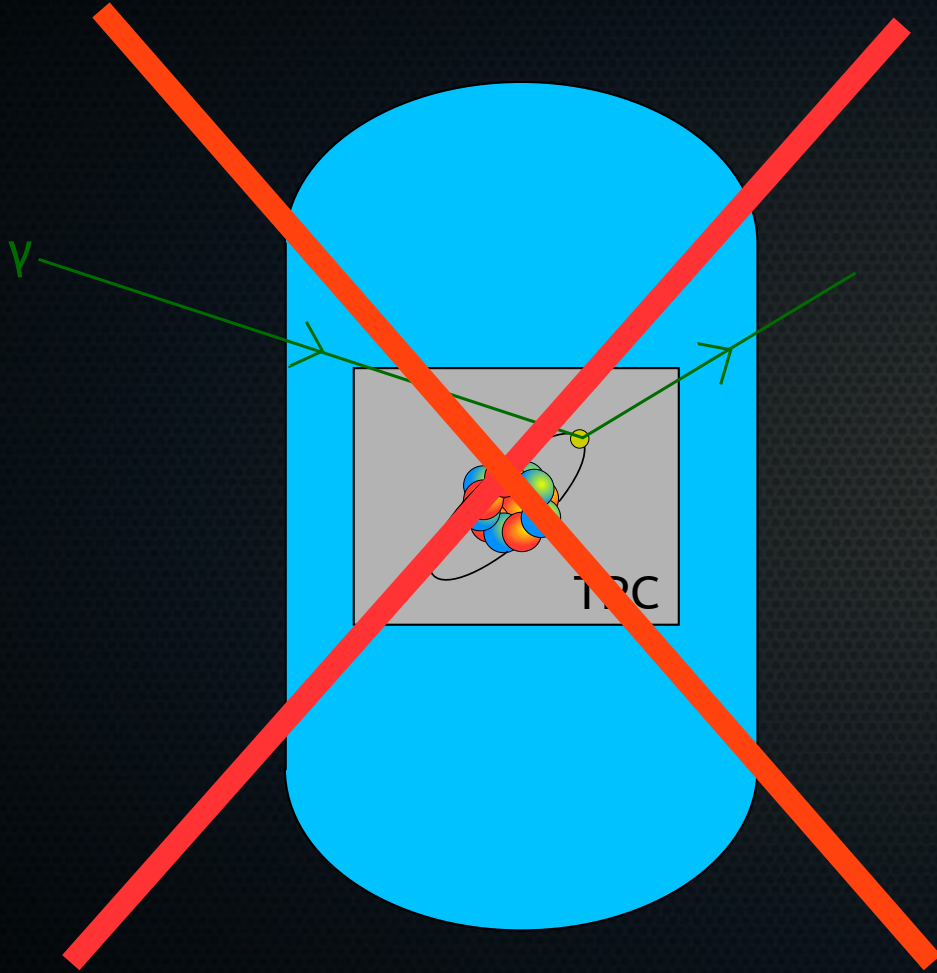


Electron Recoils



- Produced by β decay of ^{39}Ar or from incident γ rays
- Eliminate with pulse shape discrimination in LAr
- Ionization/scintillation signal ratio offers suppression

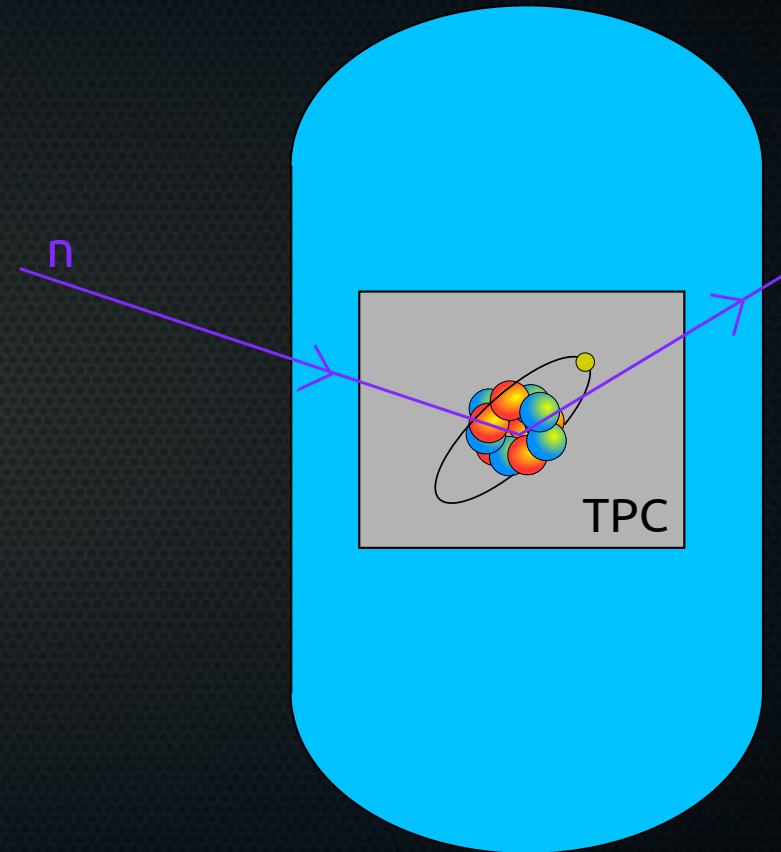
Electron Recoils



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Nuclear Recoils

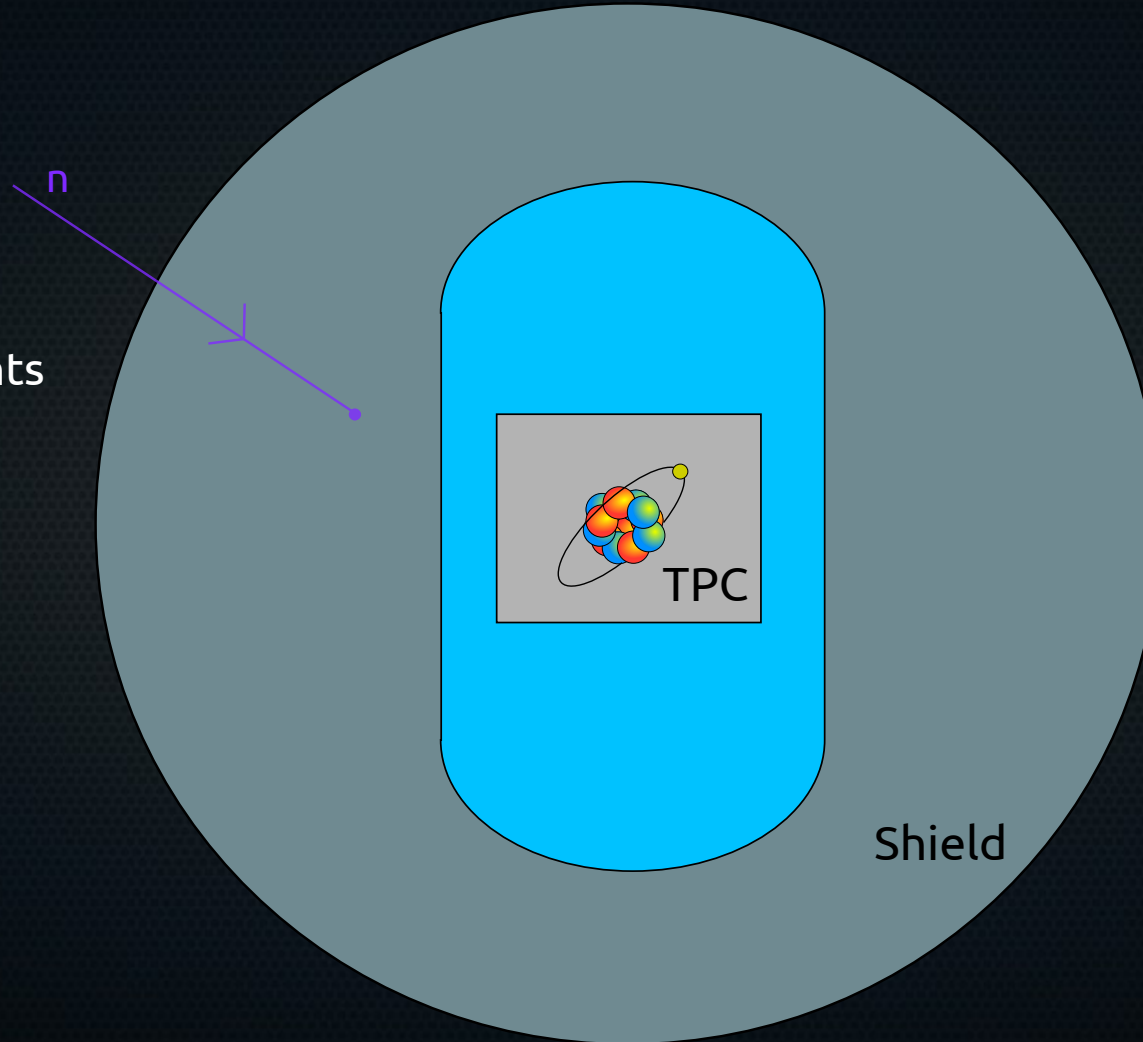
- From surface background α decays
 - Eliminated with fiducial cuts
- Neutron scatters
 - Radiogenic (fission and (α, n) reactions)
 - From surrounding environment
 - In detector components
 - Cosmogenic (muon spallation)
- Cannot be rejected with pulse shape discrimination



So how can we remove
neutron backgrounds?

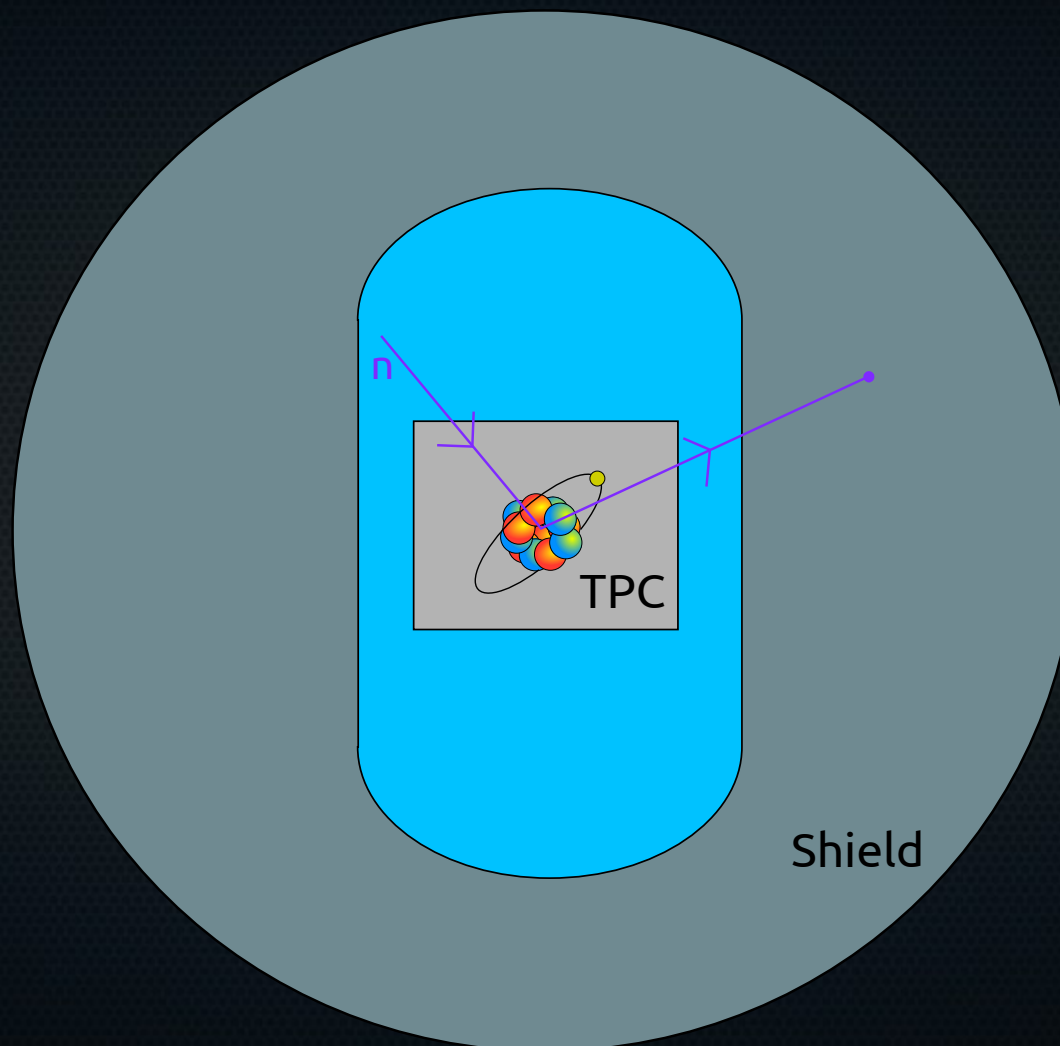
Passive Shielding?

- Radiogenic (fission and α, n reactions)
 - From surrounding environment
 - In detector components
- Cosmogenic (muon spallation)



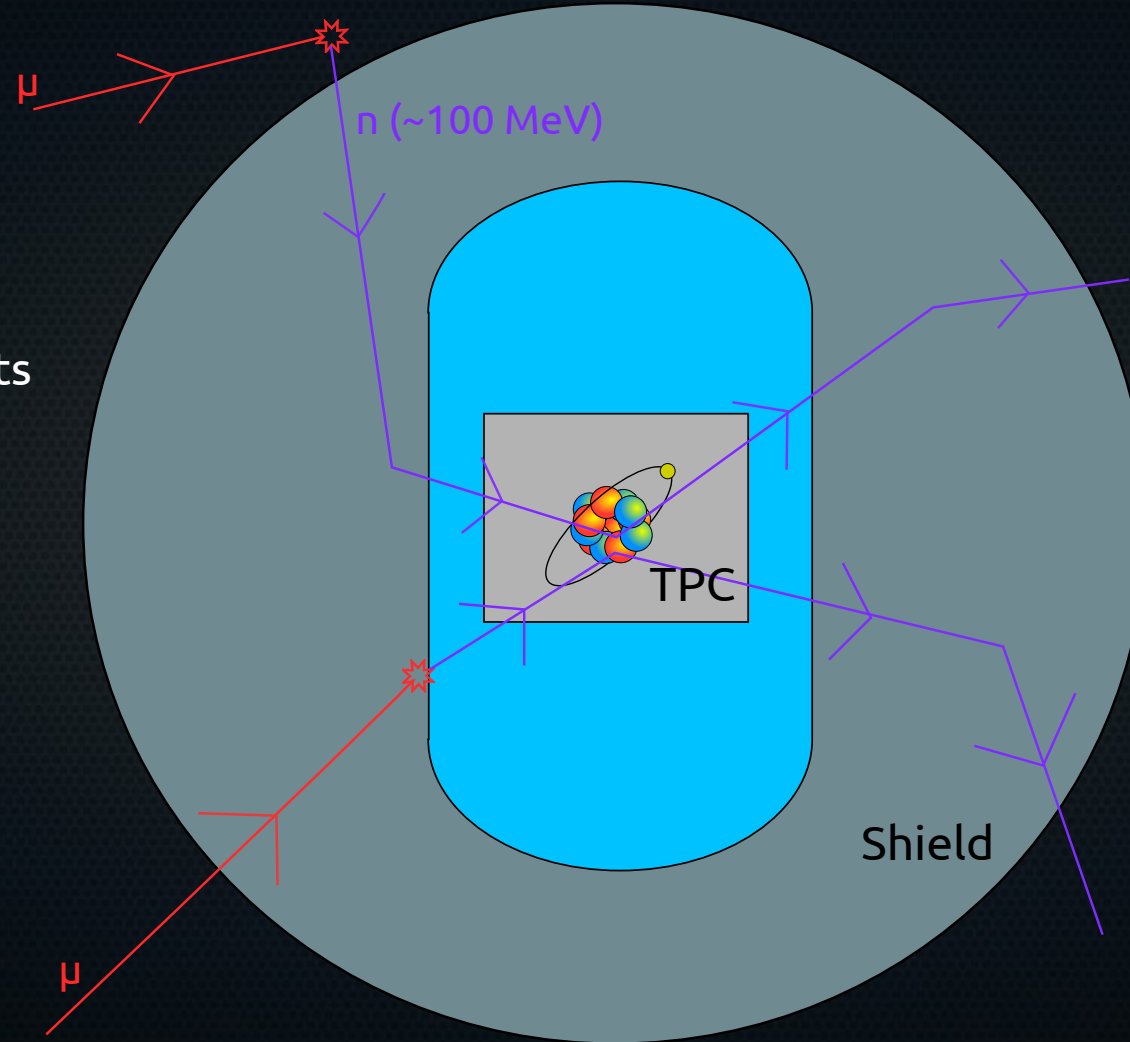
Passive Shielding?

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Passive Shielding?

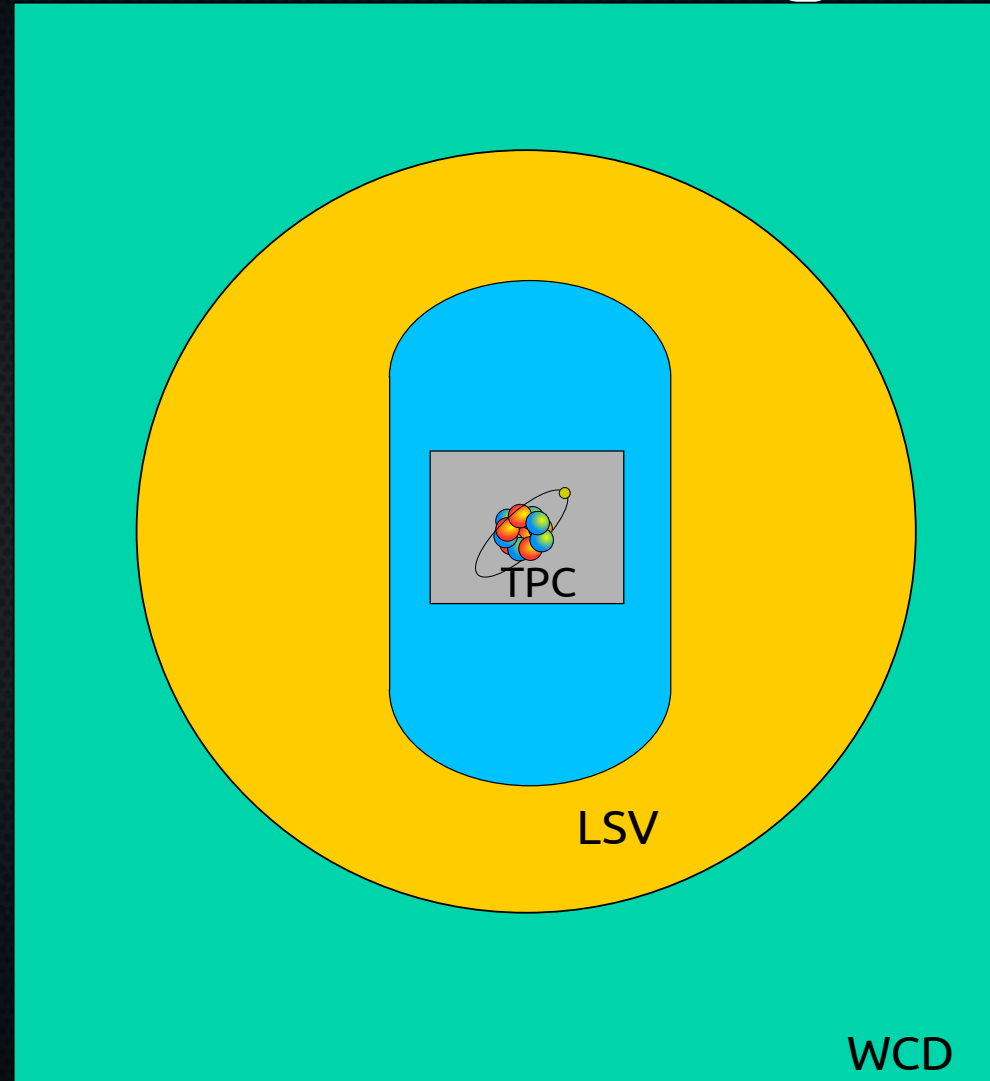
- Radiogenic (fission and (α, n) reactions)
 - From surrounding environment
 - In detector components
- Cosmogenic (muon spallation)



Active Shielding

Water Cherenkov Detector

- Provides shielding to the LSV
- Can detect passing muons that may produce a cosmogenic neutron

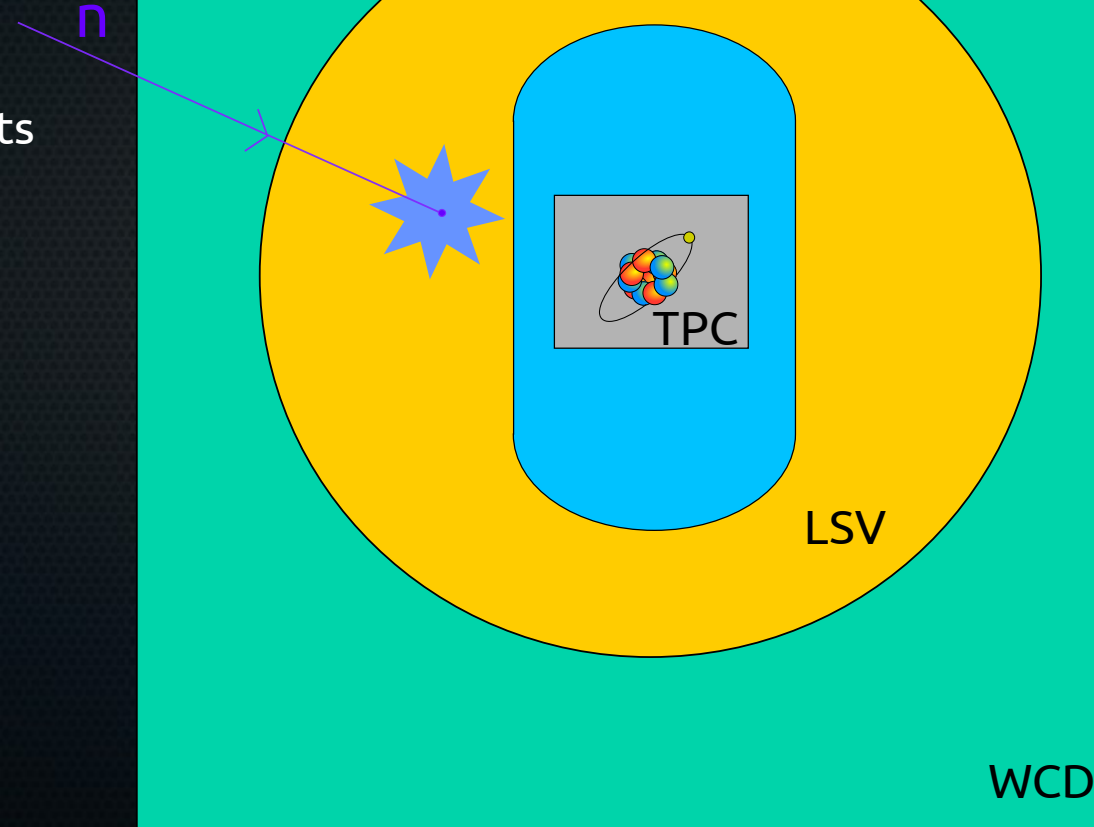


Liquid Scintillator Vessel

- Boron-loaded to improve neutron capture cross section
- Detects neutrons and γ rays in coincidence with TPC
- Provides shielding and *vetoing* of backgrounds
- Allows for *in situ* background measurements

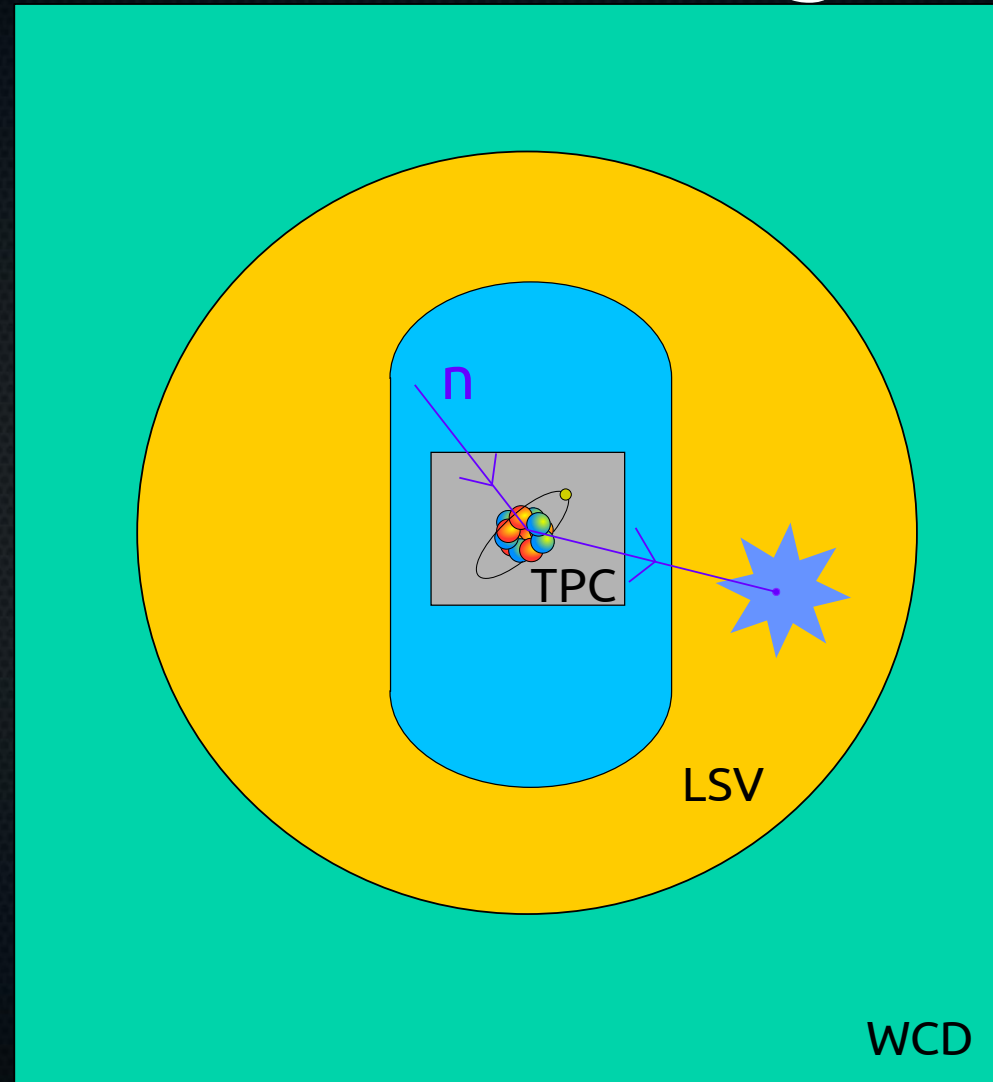
Active Shielding

- Radiogenic (fission and α, n reactions)
 - From surrounding environment
 - In detector components
- Cosmogenic (muon spallation)



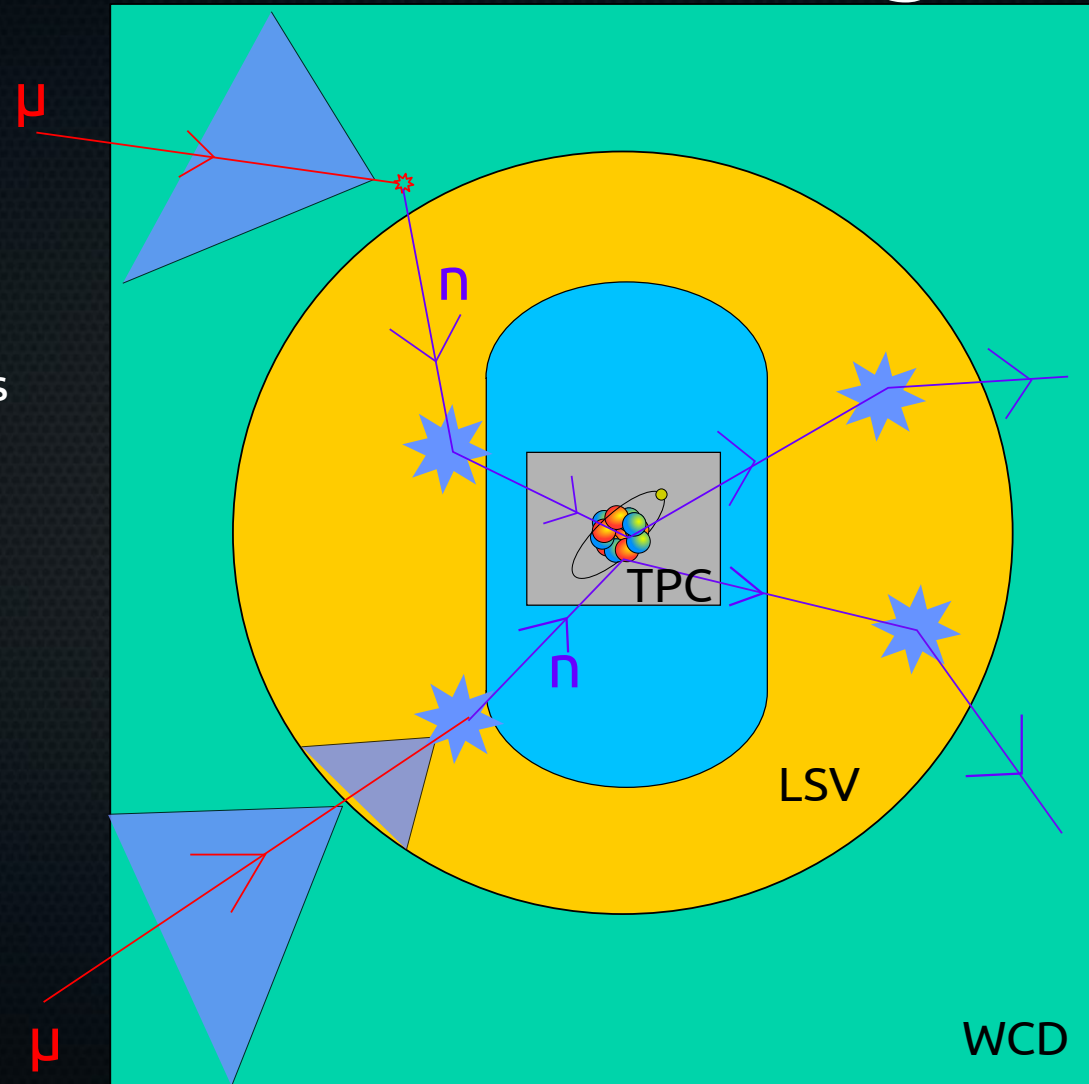
Active Shielding

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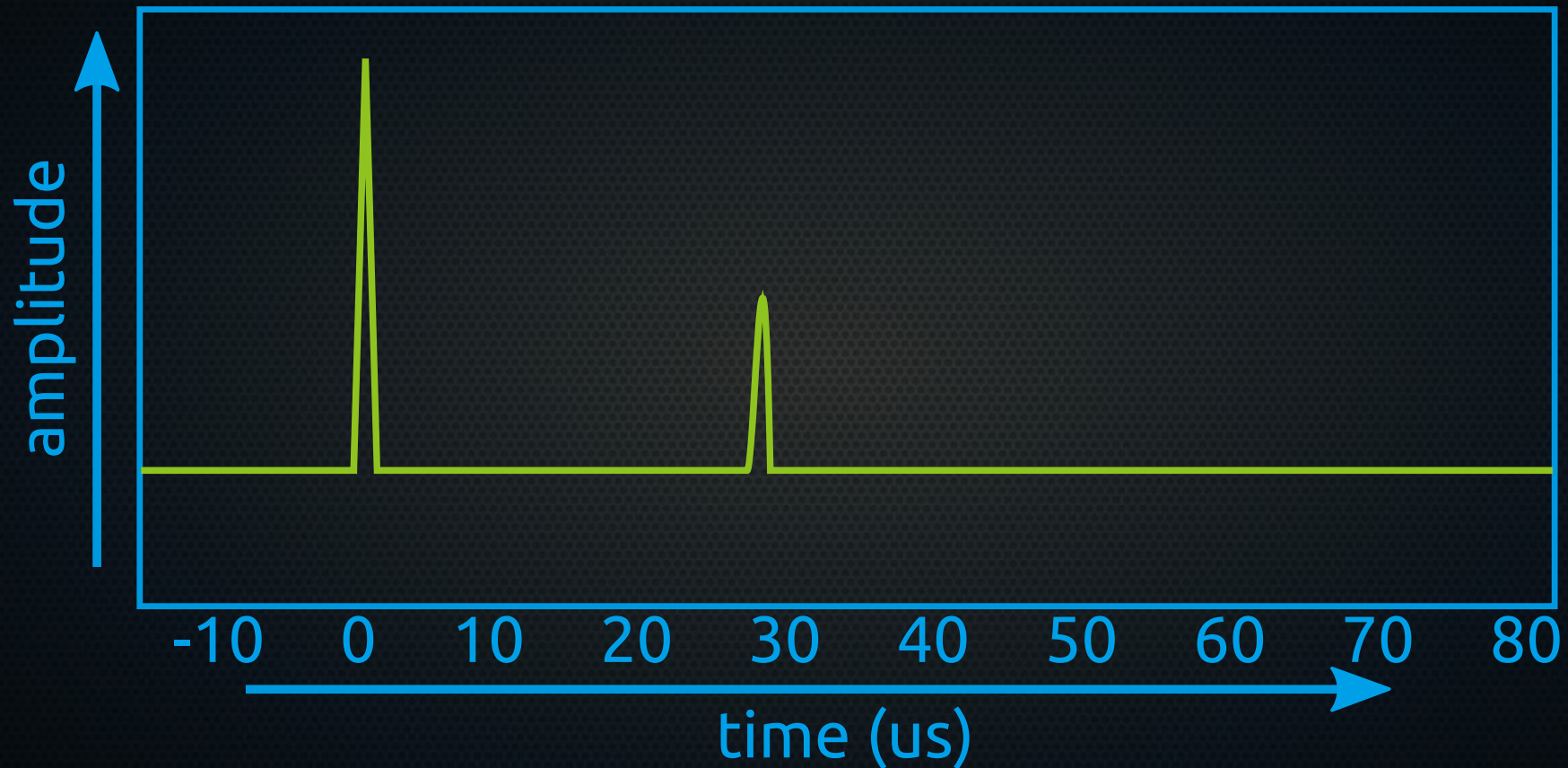


Active Shielding

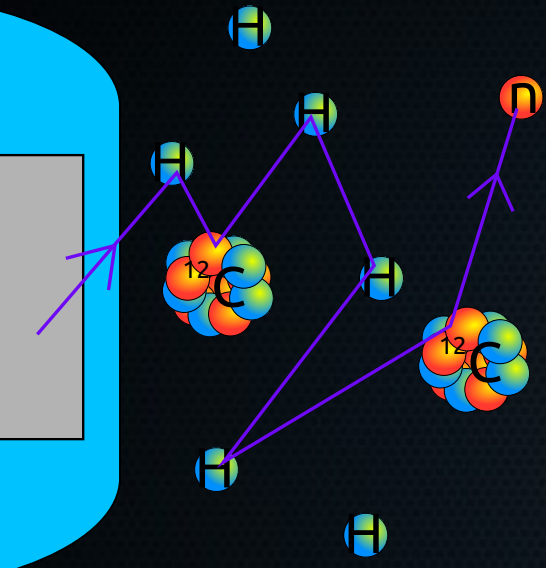
- Radiogenic (fission and (α, n) reactions)
 - From surrounding environment
 - In detector components
- Cosmogenic (muon spallation)



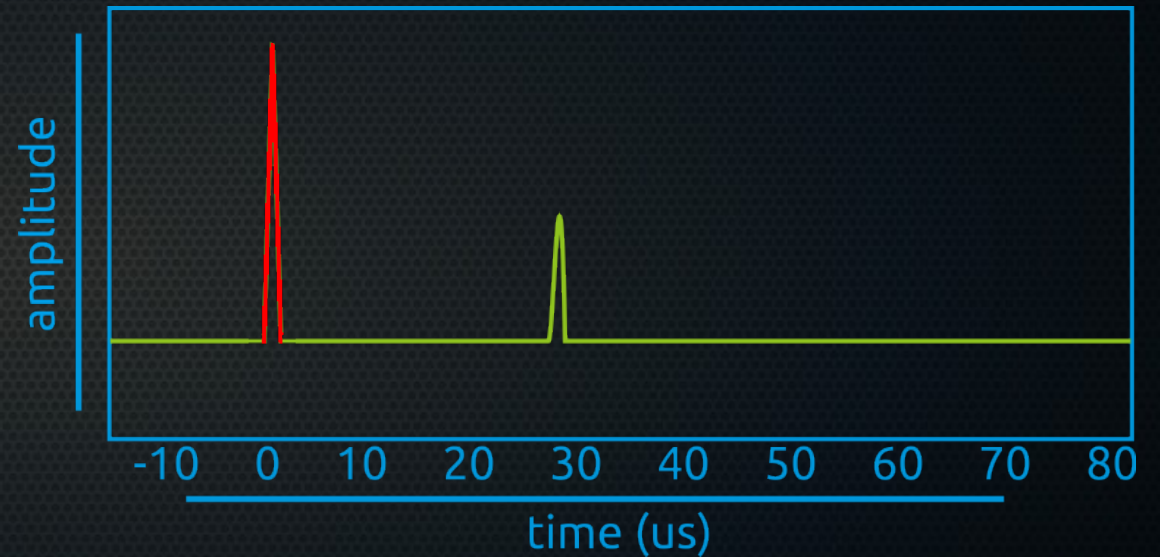
Vetoing Neutrons with the LSV



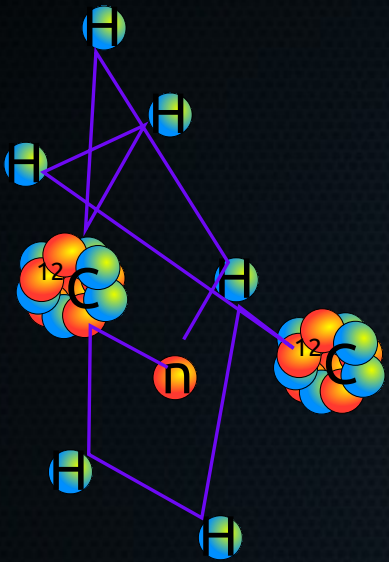
Neutron Detection: Prompt Signal



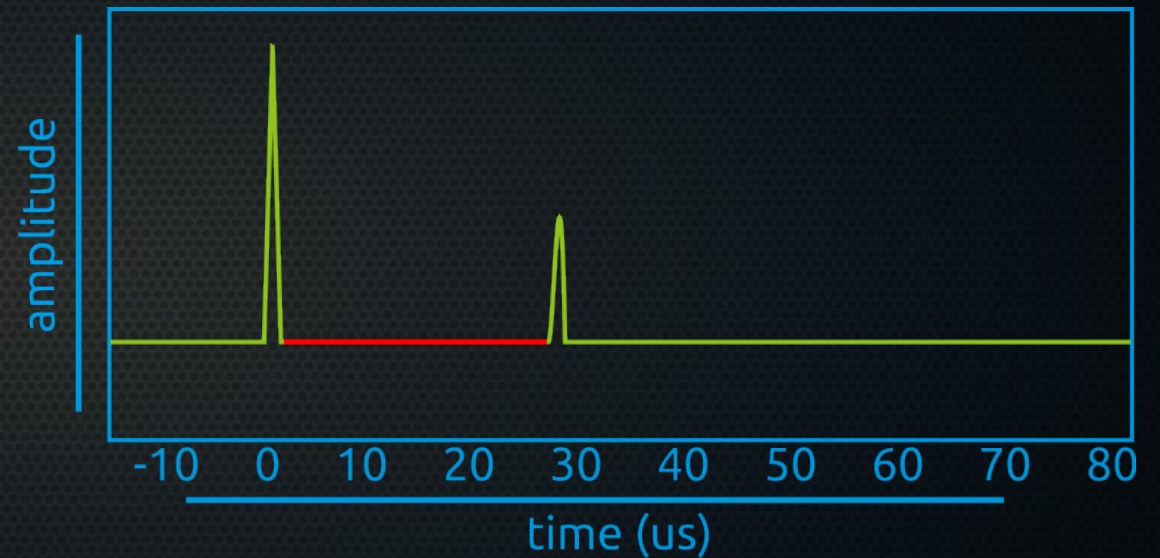
- **Neutron thermalization**
 - Very fast (< 100 ns)
 - Prompt time cut $\rightarrow$ low background
 $\rightarrow$ can cut with low threshold
 - Signal size depends on neutron energy



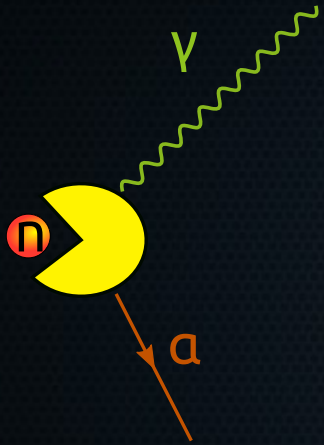
Neutron Detection: Quiet Time



- **Neutron random walk**
 - No signal produced
 - Neutron random walks at thermal energies



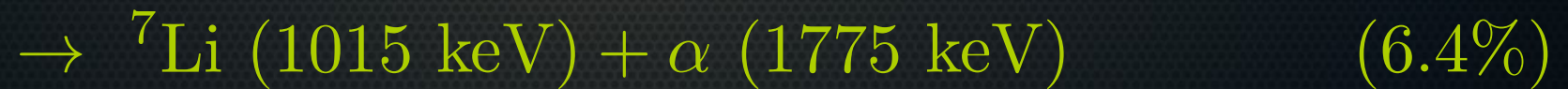
Neutron Detection: Capture Signal



- Neutron capture
 - Neutron captures on
 - ^{10}B : $\sigma = 3837 \text{ b}$
 - ^1H : $\sigma = 0.33 \text{ b}$
 - Produces $2.2 \text{ MeV } \gamma$



Neutron Capture on ^{10}B



Neutron Capture on ^{10}B



Relatively high energy, easy to see
But ~8% chance it will go back into
cryostat unseen

Neutron Capture on ^{10}B



Highly quenched to a total signal equivalent to an electron energy of ~50-60 keVee
Will always deposit all energy into the scintillator
If we can reliably see these, we can see neutrons

Target vetoing efficiency: $> 99.5\%$

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The key to high efficiency is to efficiently detect
the $\alpha + \text{Li}$

Target vetoing efficiency: $> 99.5\%$

The key to high efficiency is to efficiently detect
the $\alpha + \text{Li}$

The key to detecting the $\alpha + \text{Li}$ is a high light yield

Designing the LSV



Designing the LSV



Designing the LSV

Scintillator Cocktail:

- Pseudocumene [PC] (50%)
- Trimethyl borate [TMB] (50%)
- PPO (3 g/L)

Reflector: Lumirror E6SR

Designing the LSV

Scintillator Cocktail:

- Pseudocumene [PC] (50%)
- Trimethyl borate [TMB] (50%)
- PPO (3 g/L)

Primary scintillator



Reflector: Lumirror E6SR

Designing the LSV

Scintillator Cocktail:

- Pseudocumene [PC] (50%)
- Trimethyl borate [TMB] (50%)
- PPO (3 g/L)

Boron-loading agent
Mixes well with PC

Reflector: Lumirror E6SR

Designing the LSV

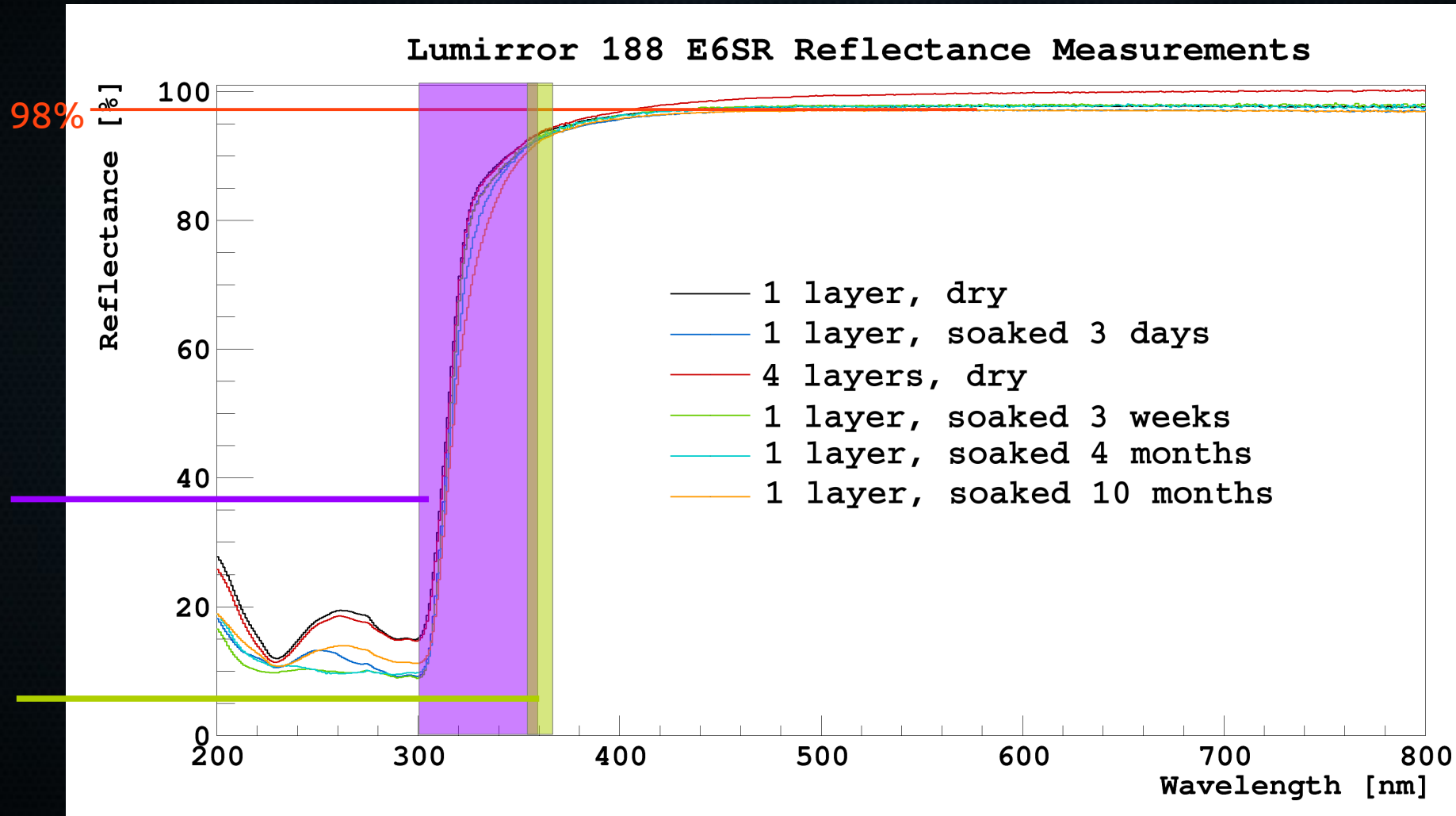
Scintillator Cocktail:

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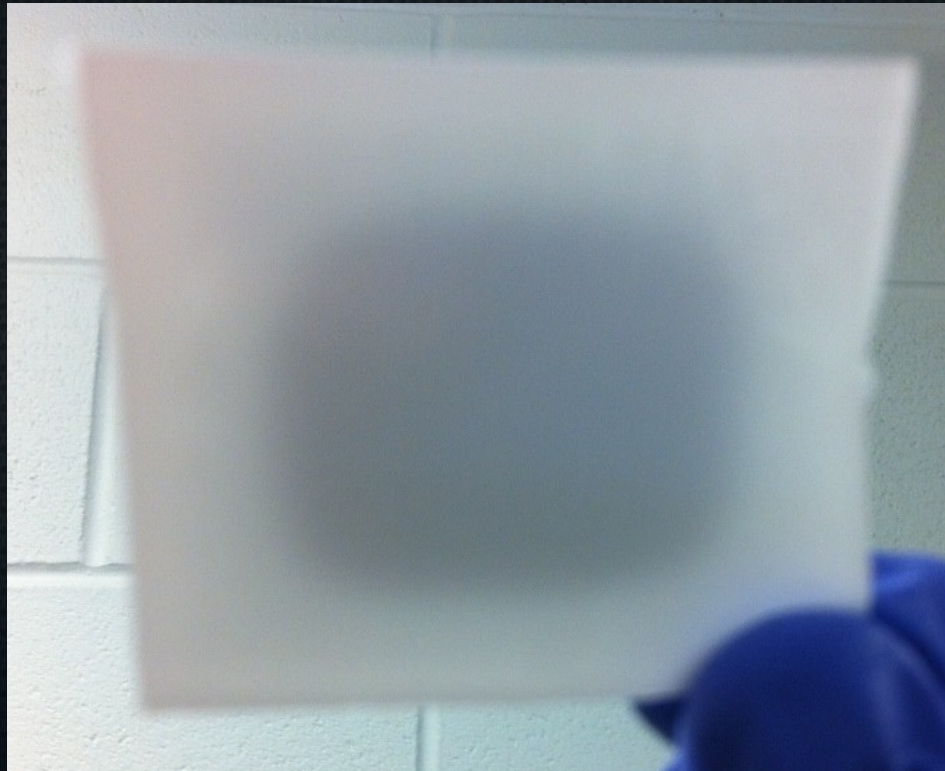
Reflector: Lumirror E6SR

Wavelength shifter
Shifts scintillation light to visible
Improves scintillator response

Designing the LSV



Designing the LSV



Prototype Tests

Measurements

- Light yield: 0.47 PE/keV
- Decreased by 0.52%/week

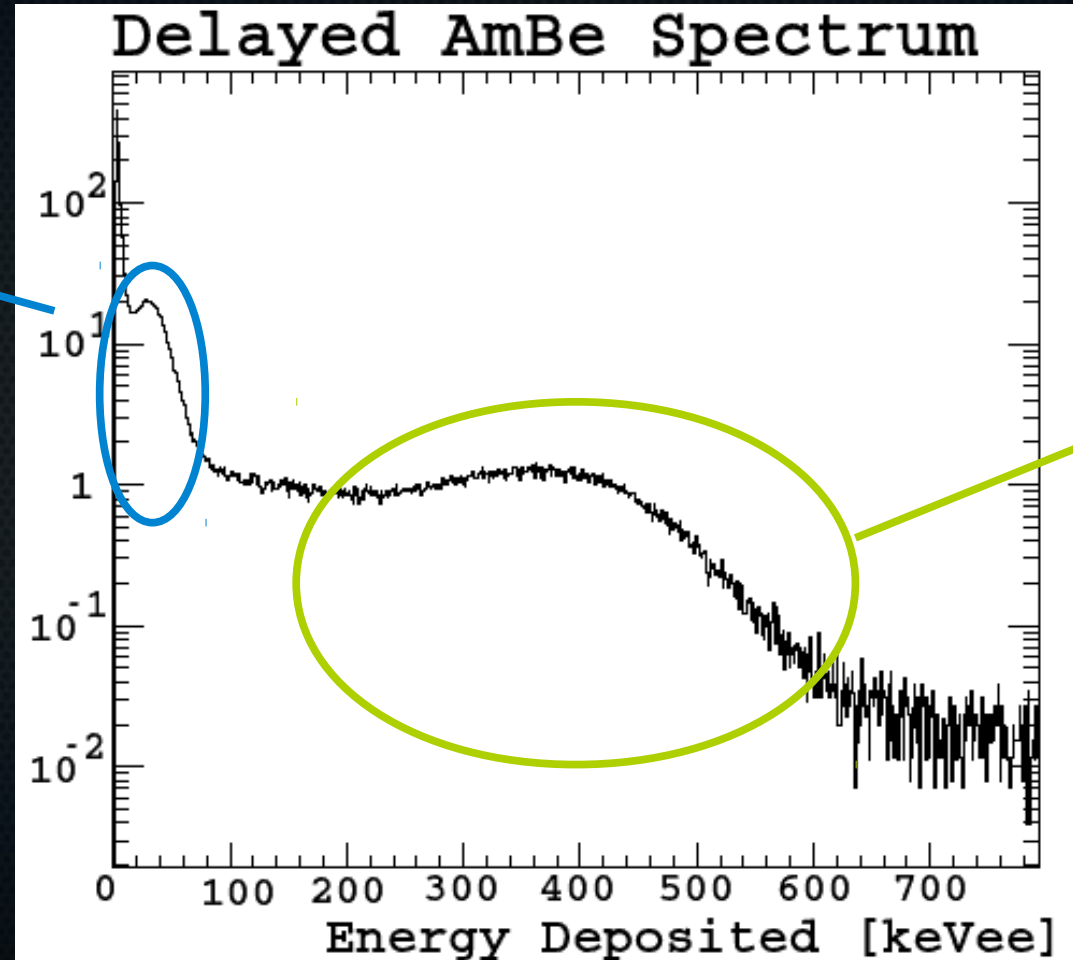


Optical Monte Carlo

- Light yield: 0.46 PE/keV
- Scaled to DS-50 geometry
- Light yield: 0.48 PE/keV
- High enough to detect α +Li

Prototype Tests

$\alpha + \text{Li}$



$\alpha + \text{Li} + \gamma$

☒ Neutron capture products are detectable

☐ Prompt signal is detectable

Testing Prompt Response

$$F = E \cdot LY \cdot QF(E)$$

Testing Prompt Response

$$F = E \cdot LY \cdot QF(E)$$

Light output by scintillation event

Testing Prompt Response

$$F = E \cdot LY \cdot QF(E)$$

Incident particle energy

Testing Prompt Response

$$F = E \cdot LY \cdot QF(E)$$

High energy electron recoil light yield

Testing Prompt Response

$$F = E \cdot LY \cdot QF(E)$$

Quenching factor
(depends on particle type and kinetic energy)

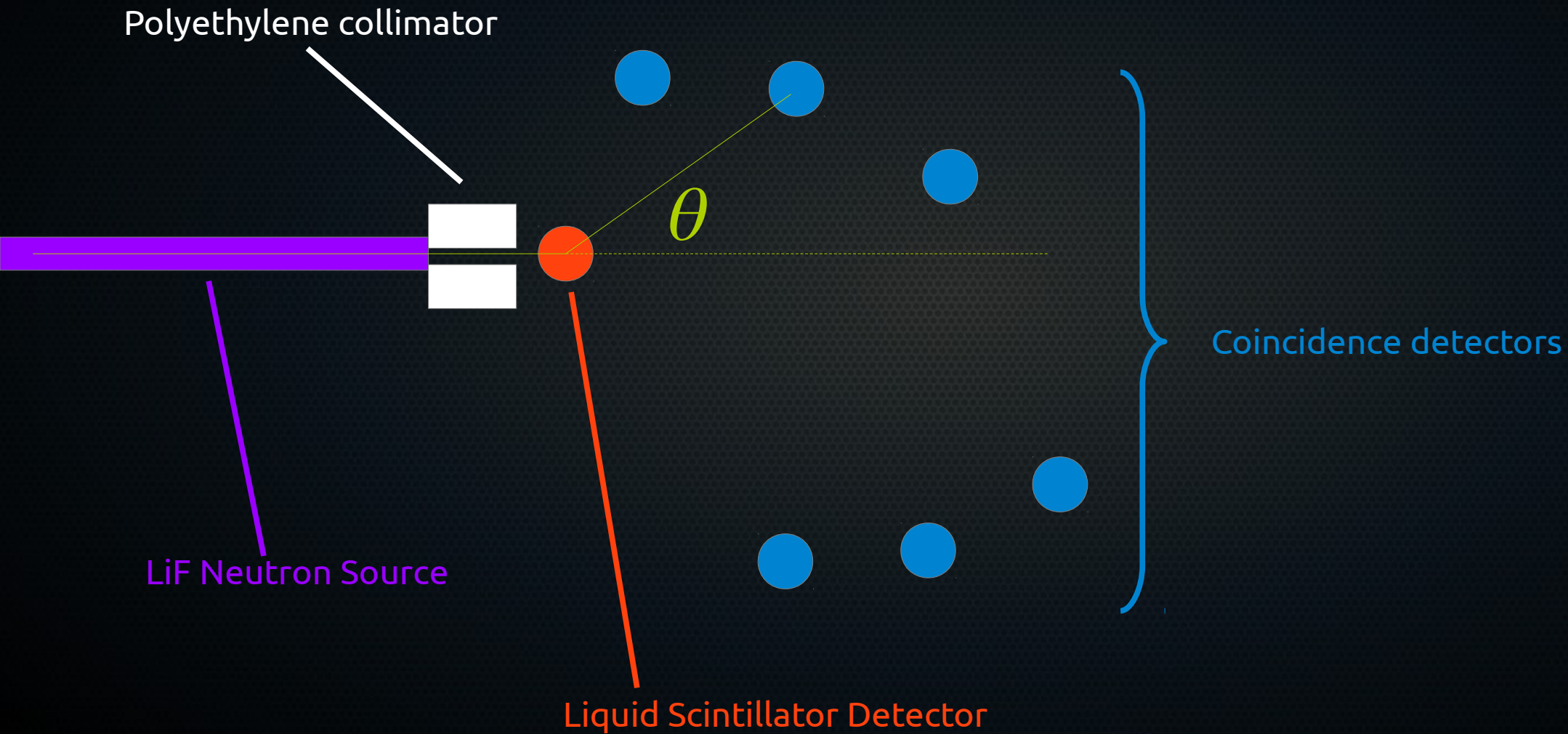
Testing Prompt Response

$$F = E \cdot LY \cdot \frac{1}{1 + kb \cdot \frac{dE}{dx}}$$

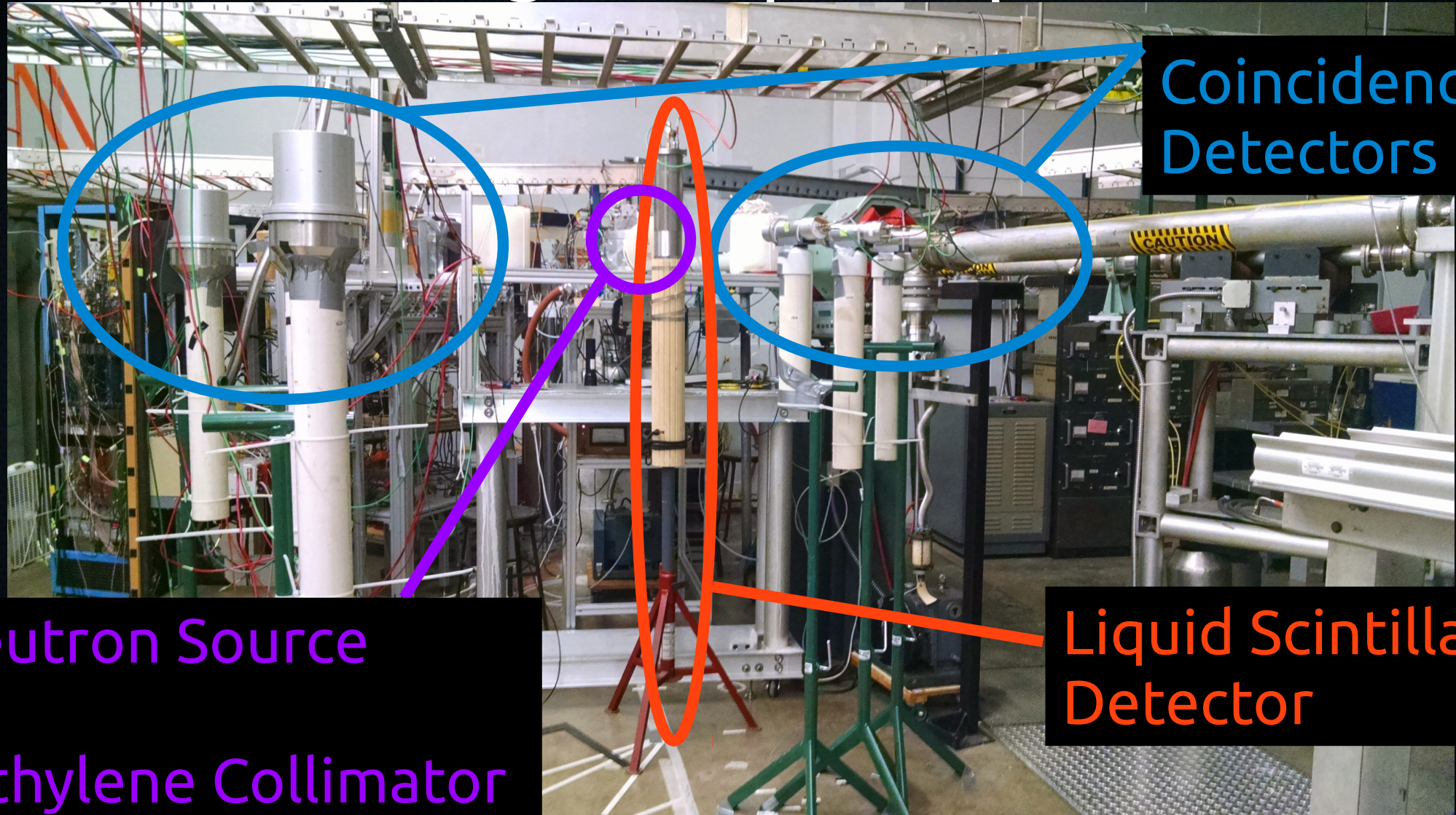
Quenching factor

Introduces substantial non-linearity for
nuclear recoils

Testing Prompt Response



Testing Prompt Response



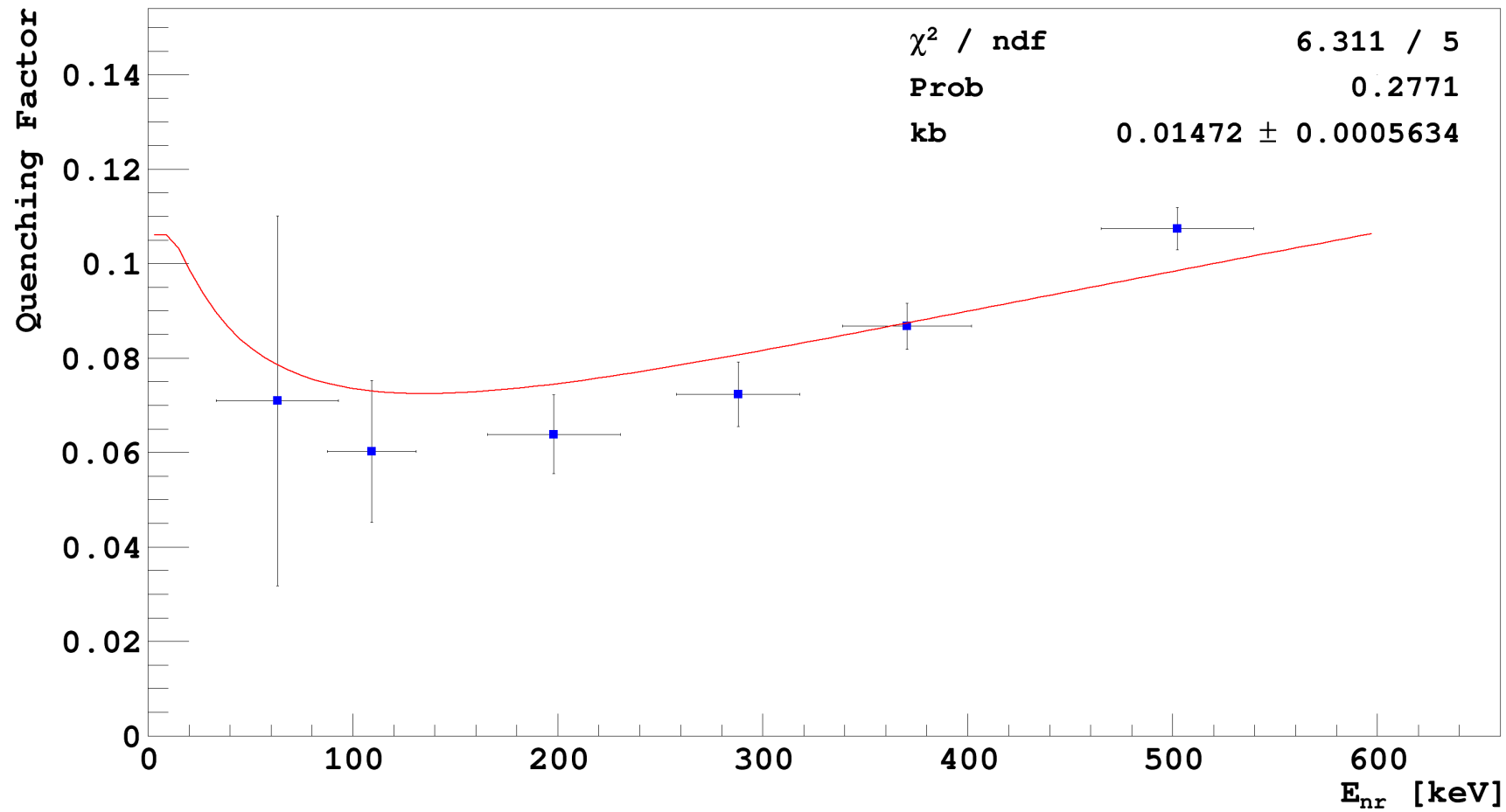
Coincidence
Detectors

LiF Neutron Source
and
Polyethylene Collimator

Liquid Scintillator
Detector

At University of Notre Dame

Testing Prompt Response

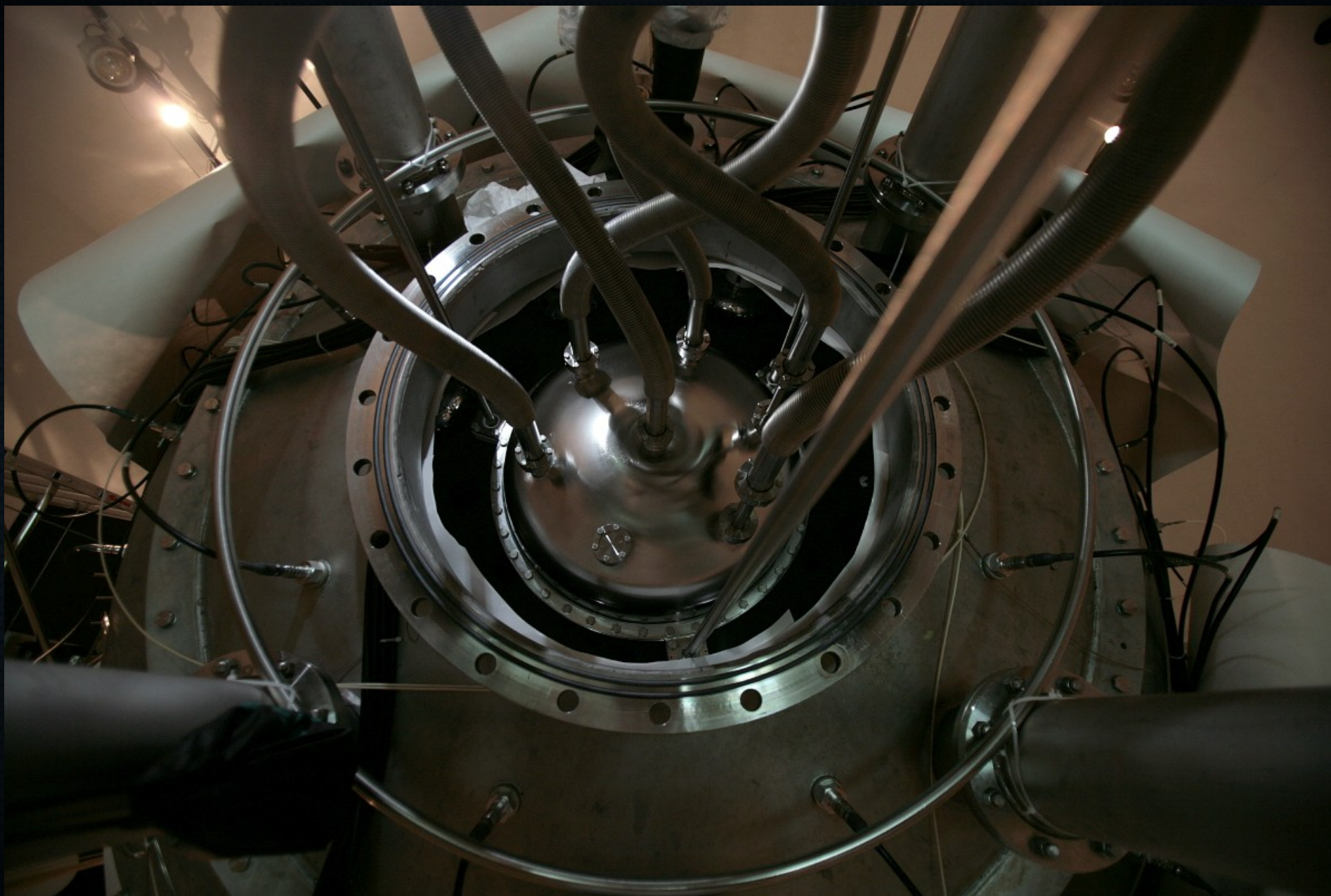


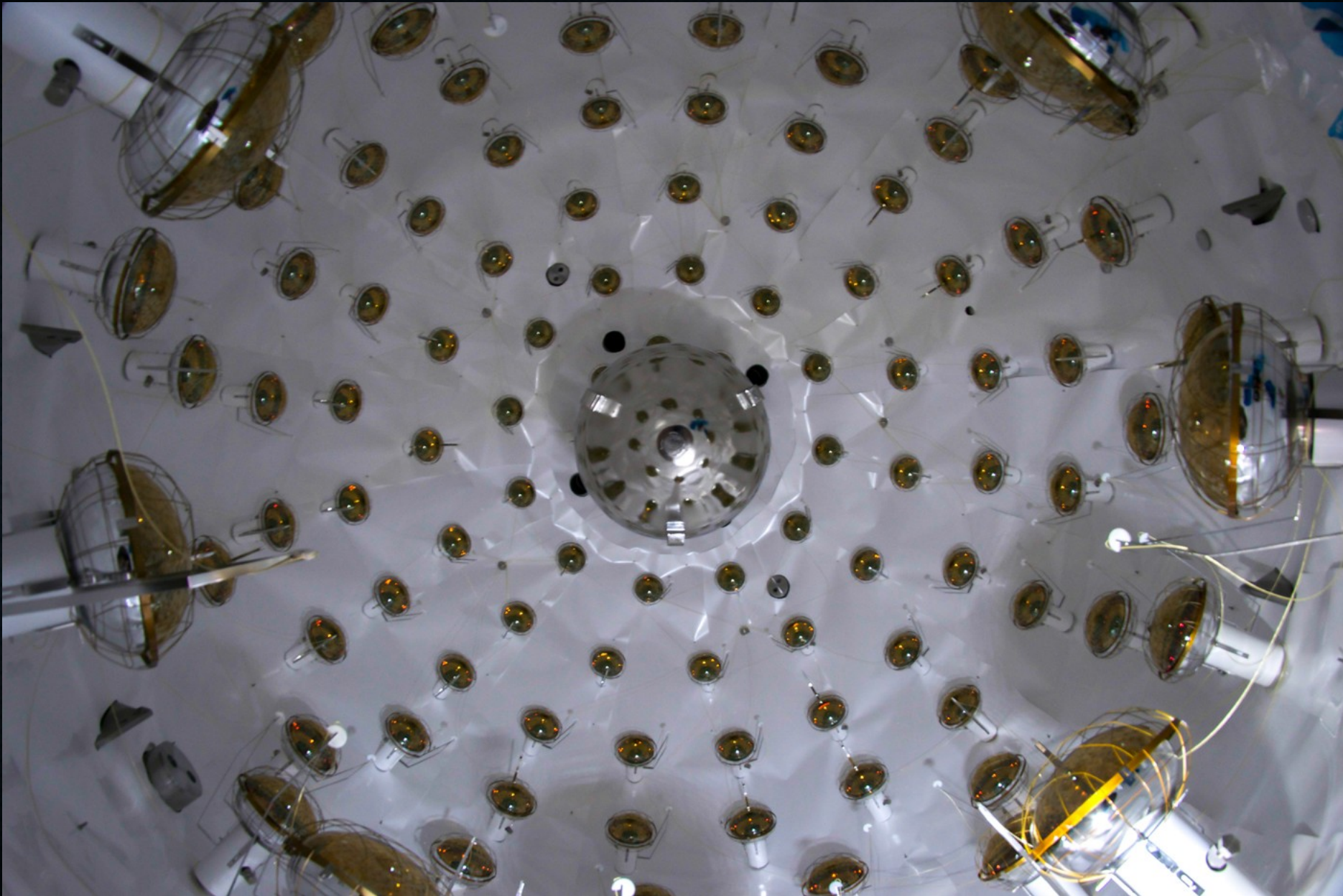
☒ Neutron capture products are detectable

☒ Prompt signal is detectable

Begin: The DarkSide







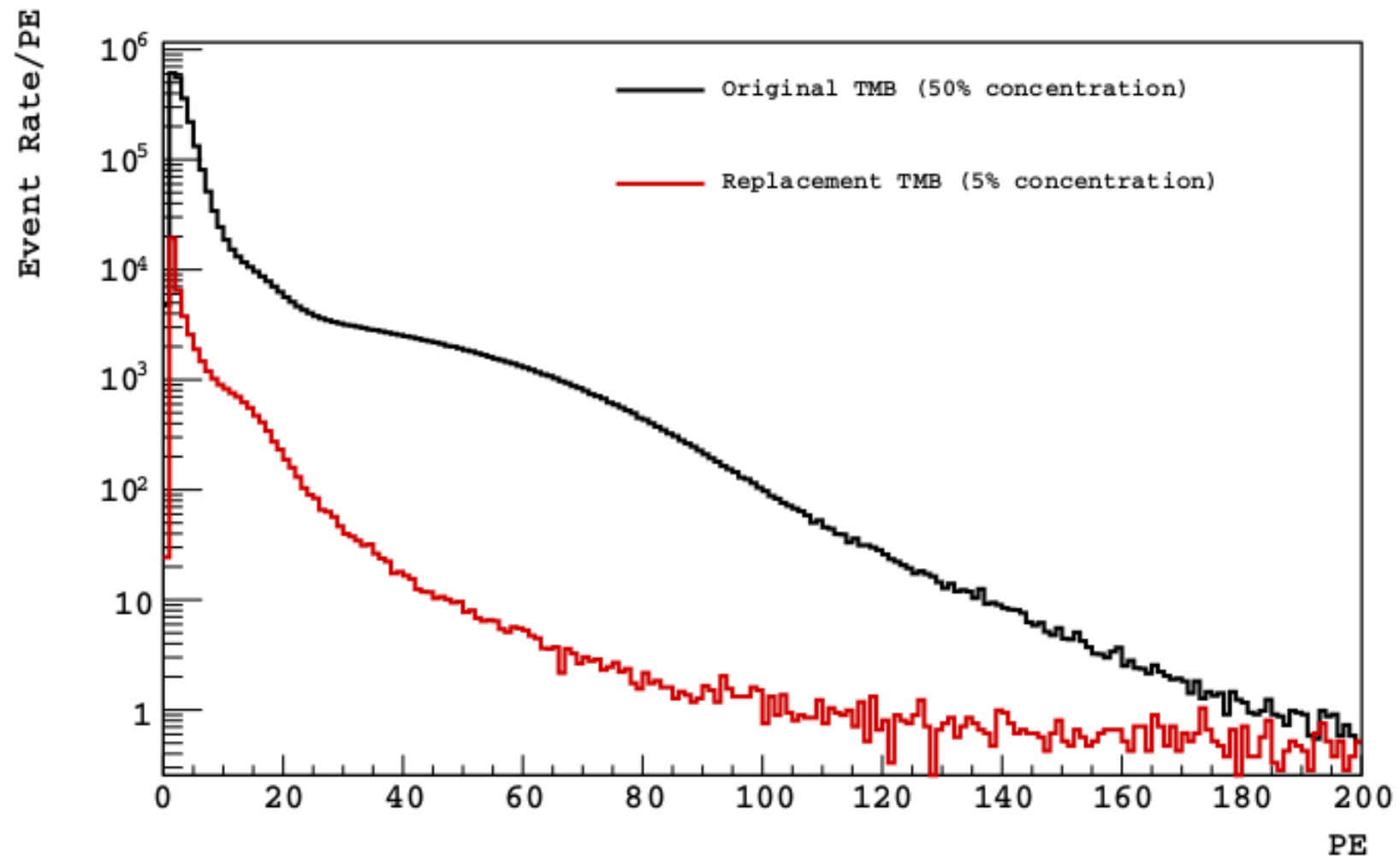
The LSV: A Tale of Two Cocktails

- Phase I

- Nov 2013 – Jun 2014
- 50% PC, 50% TMB
- 2.5 g/L PPO
- Overwhelming ^{14}C contamination from TMB ~200 kBq from atmospheric ^{14}C
- Neutron capture time ~2.2 us
- High light yield >0.5 PE/keV

- Phase II

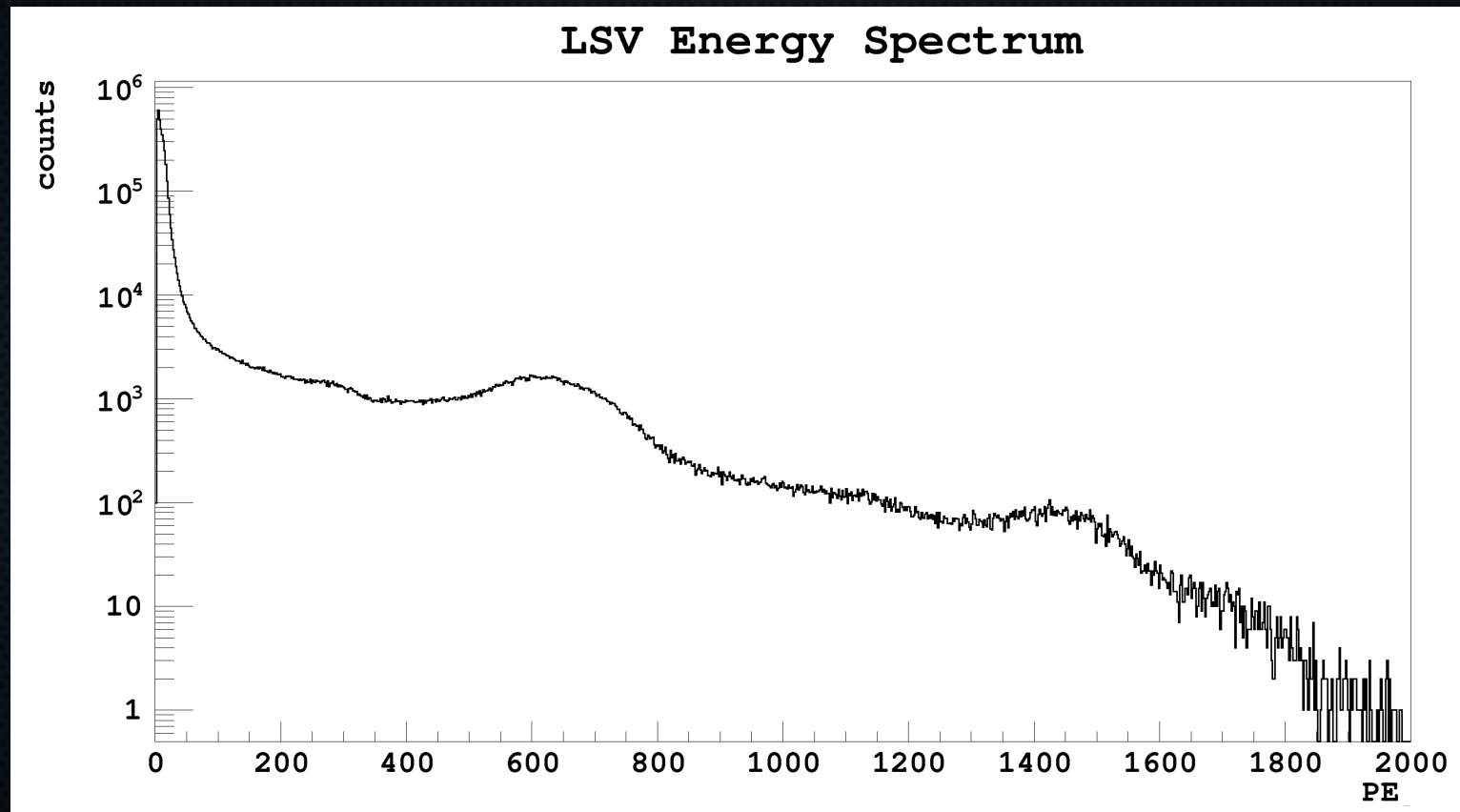
- Apr 2015 – Present
- 95% PC, 5% TMB
- 1.4 g/L PPO
- New TMB made from petroleum – much lower ^{14}C rate ~250 Bq (measured ^{14}C contamination of new TMB at the LLNL accelerator mass spectrometer to be below background)
- Neutron capture time ~22 us
- High light yield > 0.5 PE/keV



Phase I rate: ~200 kBq

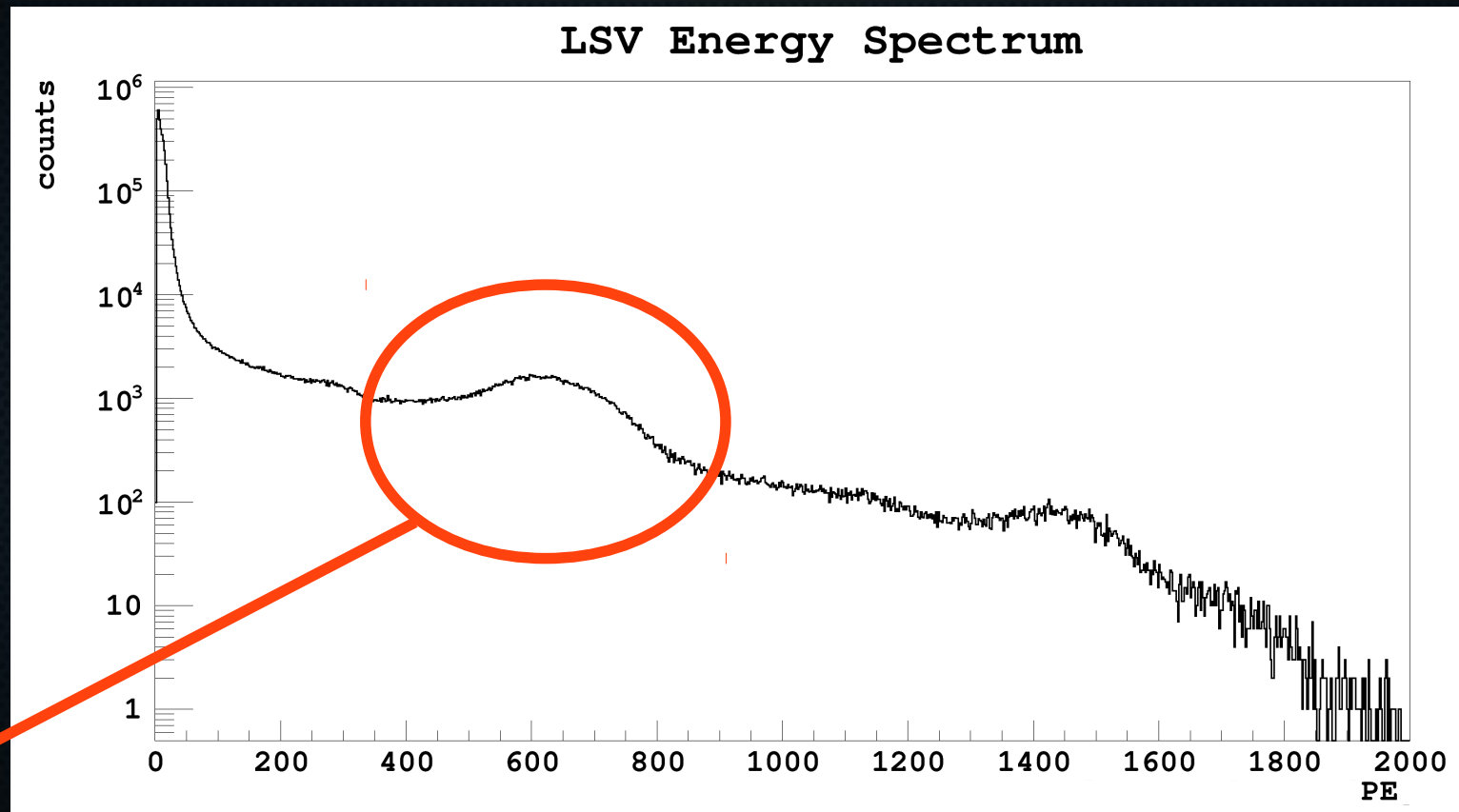
Phase II rate: 245 Bq

Prompt LSV-TPC Coincidence



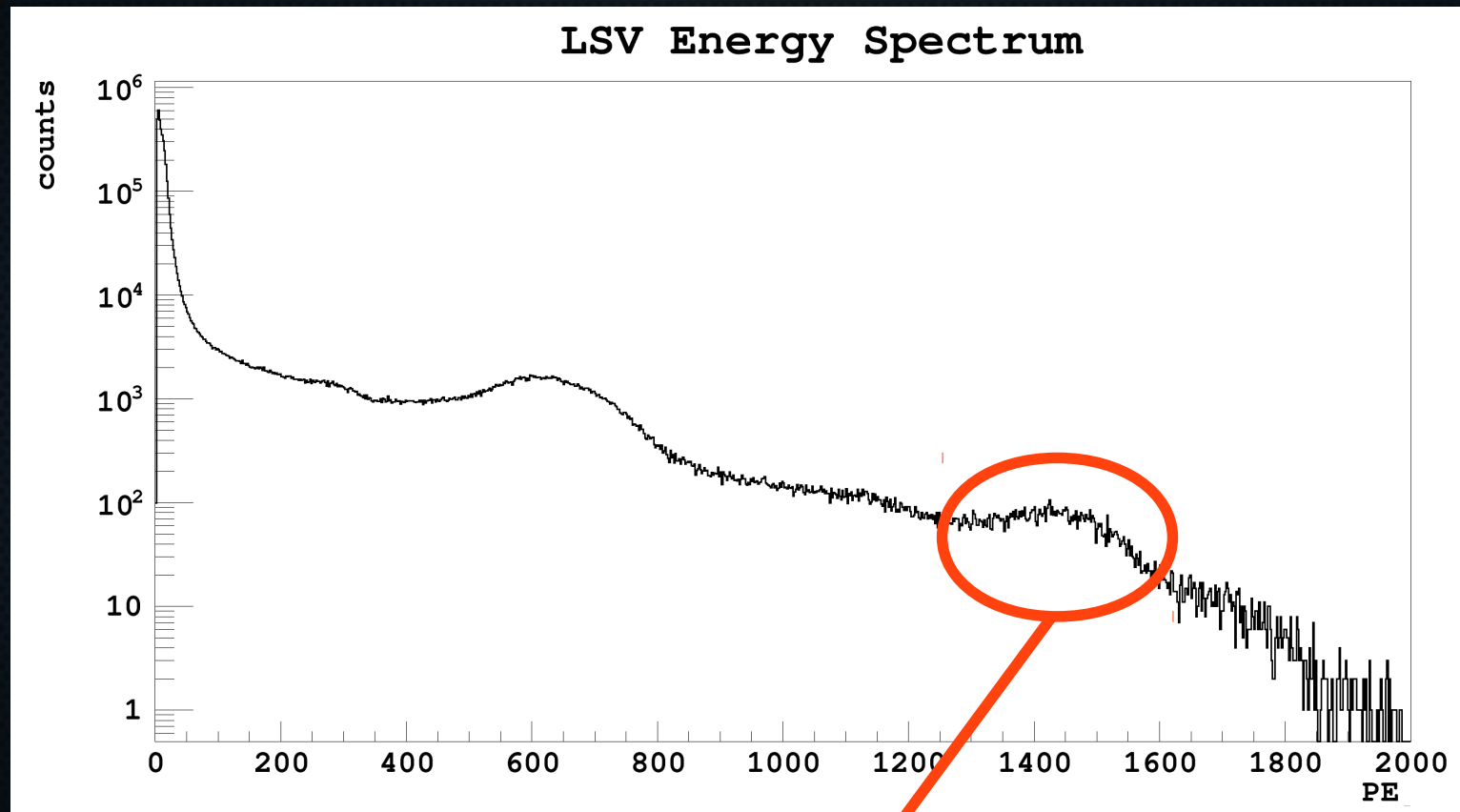
Note: these are
mostly γ rays

Prompt LSV-TPC Coincidence



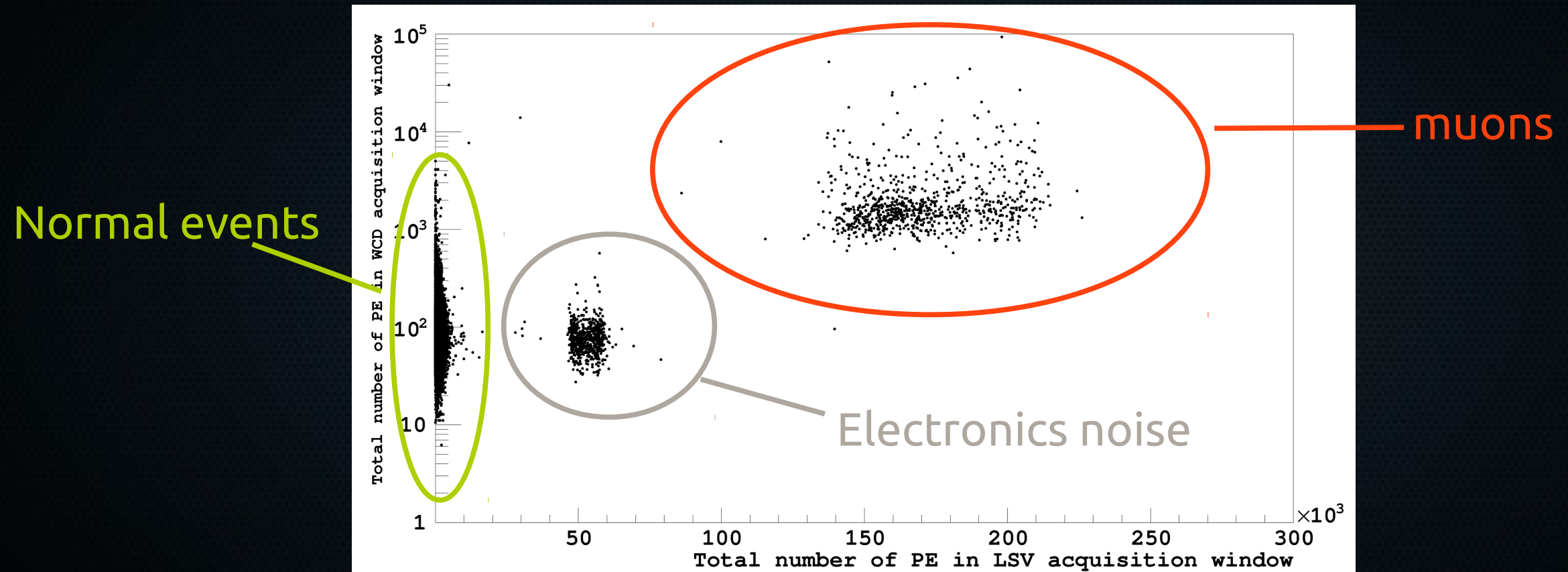
$^{60}\text{Co}: \gamma (1.17 \text{ MeV}, 1.33 \text{ MeV}) \rightarrow 0.59 \text{ PE/keV}$

Prompt LSV-TPC Coincidence

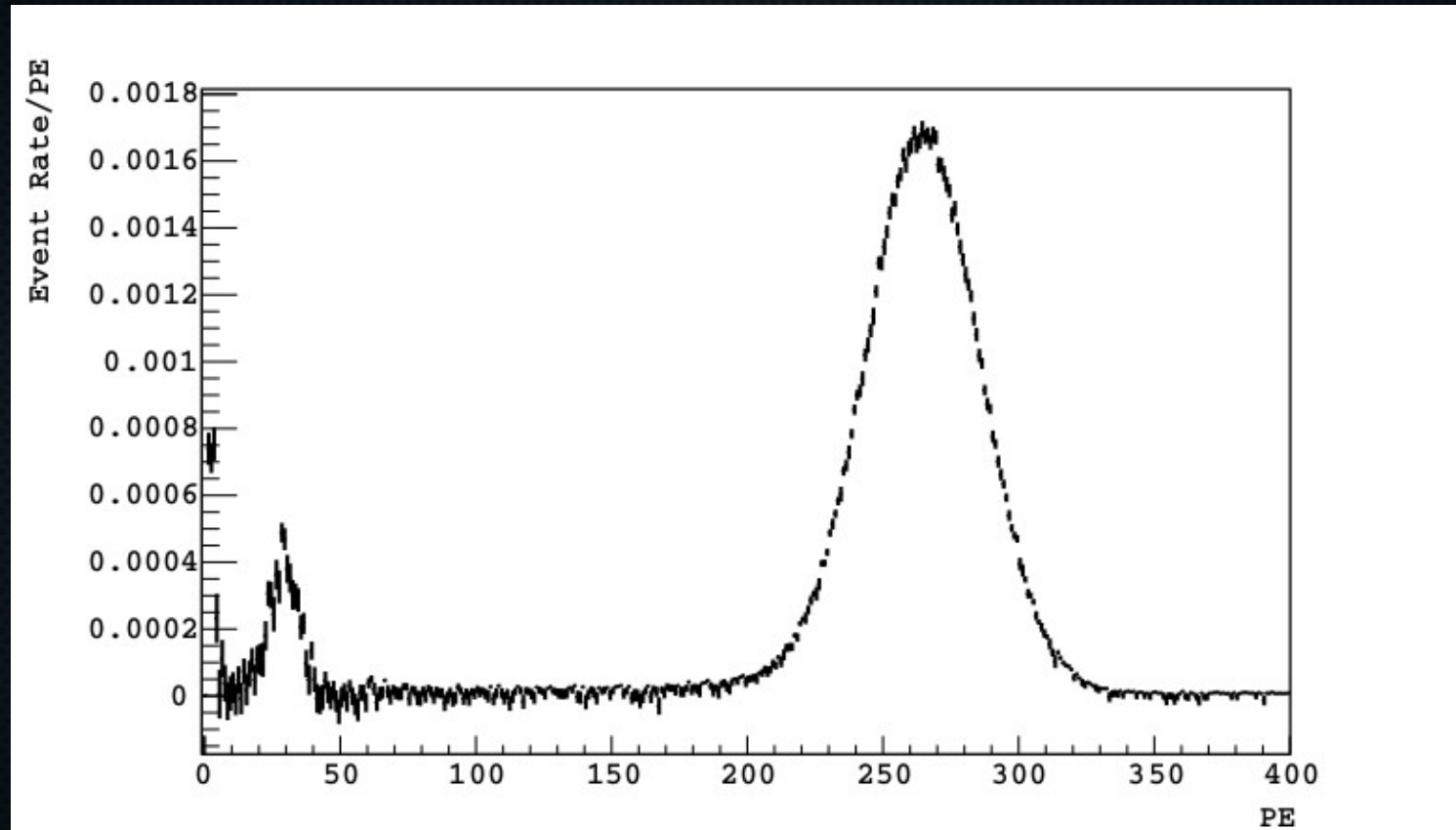


$^{208}\text{Tl}: \gamma (2.6 \text{ MeV}) \rightarrow 0.55 \text{ PE/keV}$

Muons

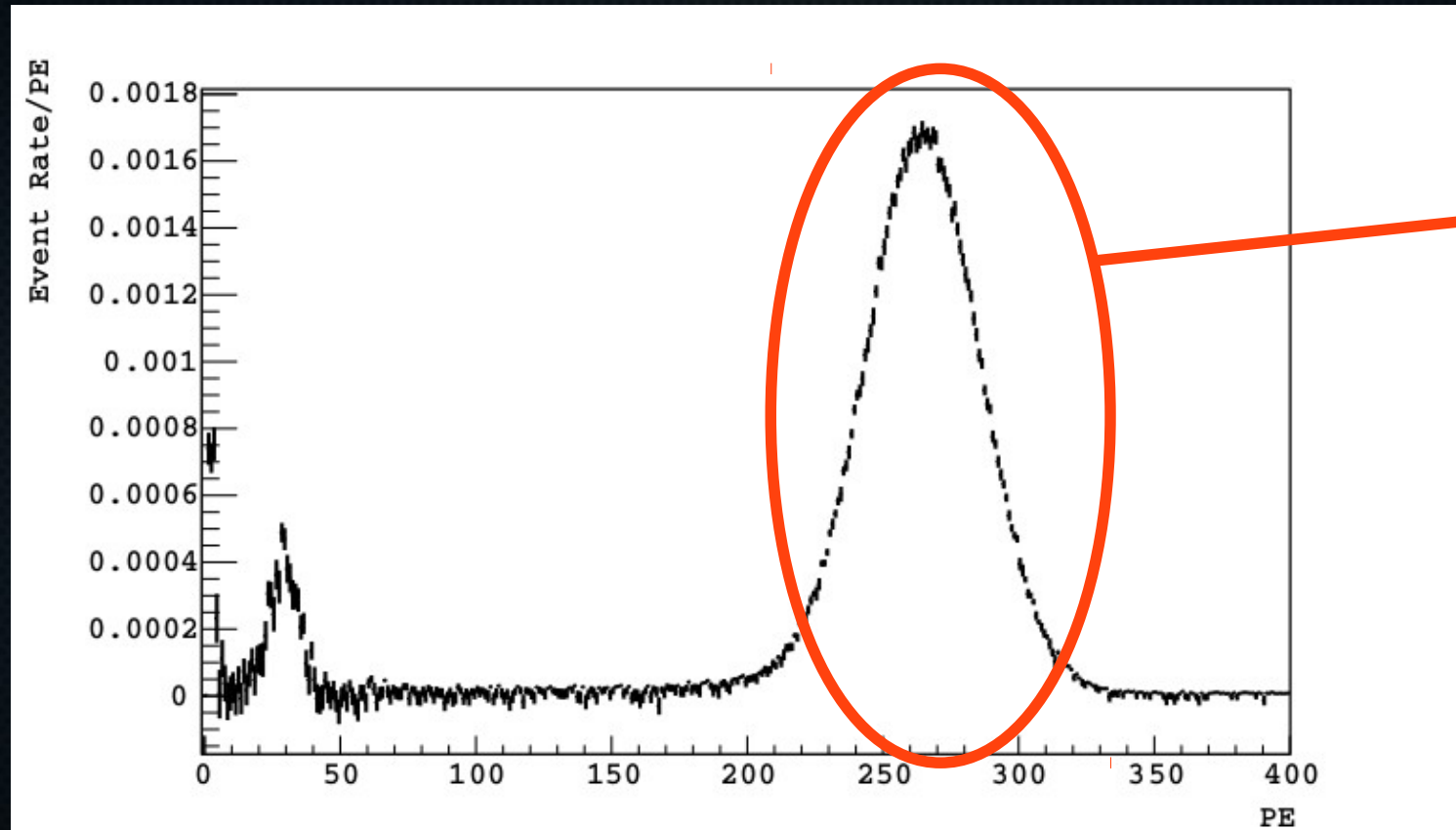


Neutron Capture Signal



$^{241}\text{Am}^9\text{Be}$ Calibration Run

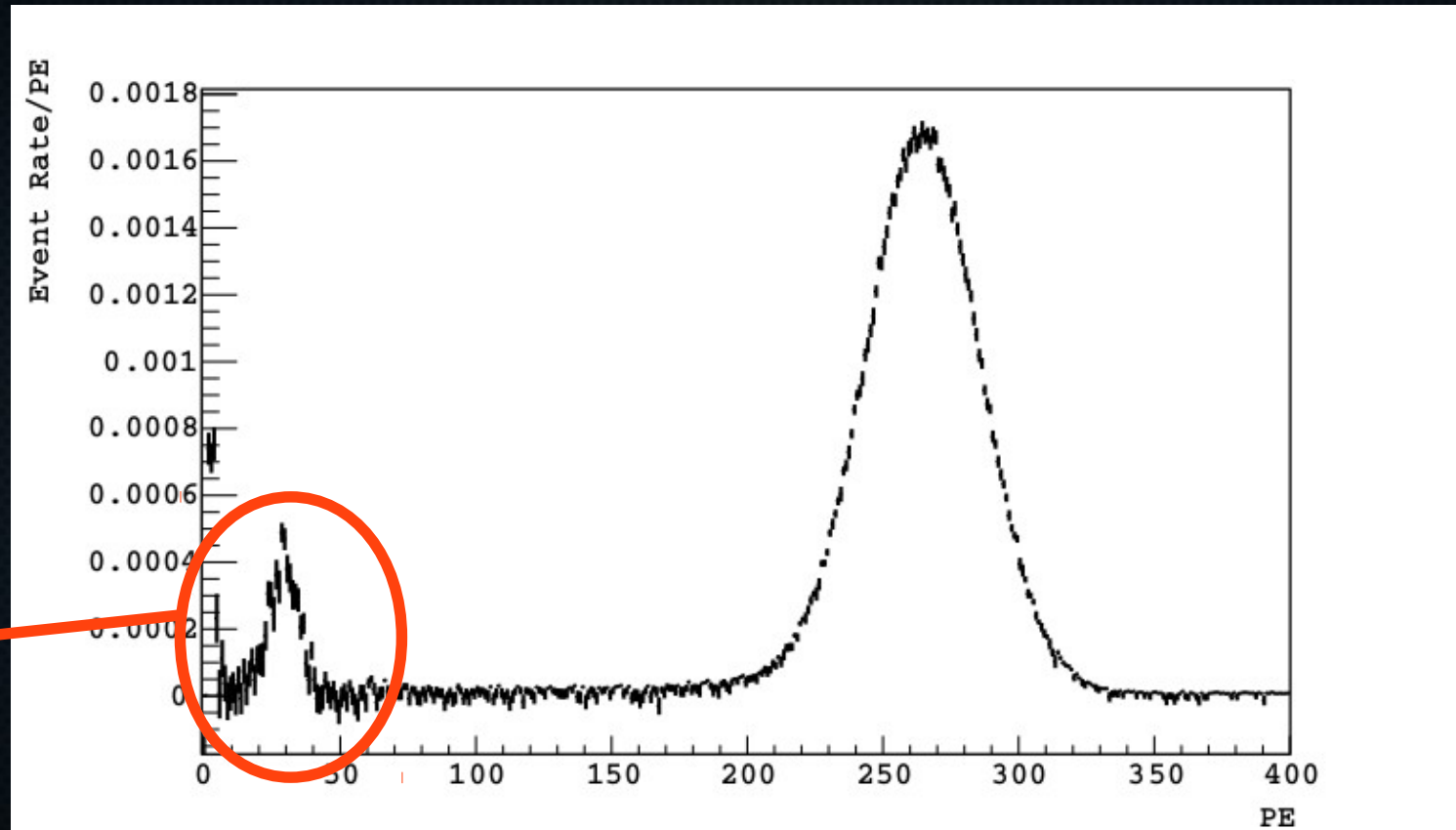
Neutron Capture Signal



$\alpha + \text{Li} + \gamma$

$^{241}\text{Am}^9\text{Be}$ Calibration Run

Neutron Capture Signal



$\alpha + \text{Li}$

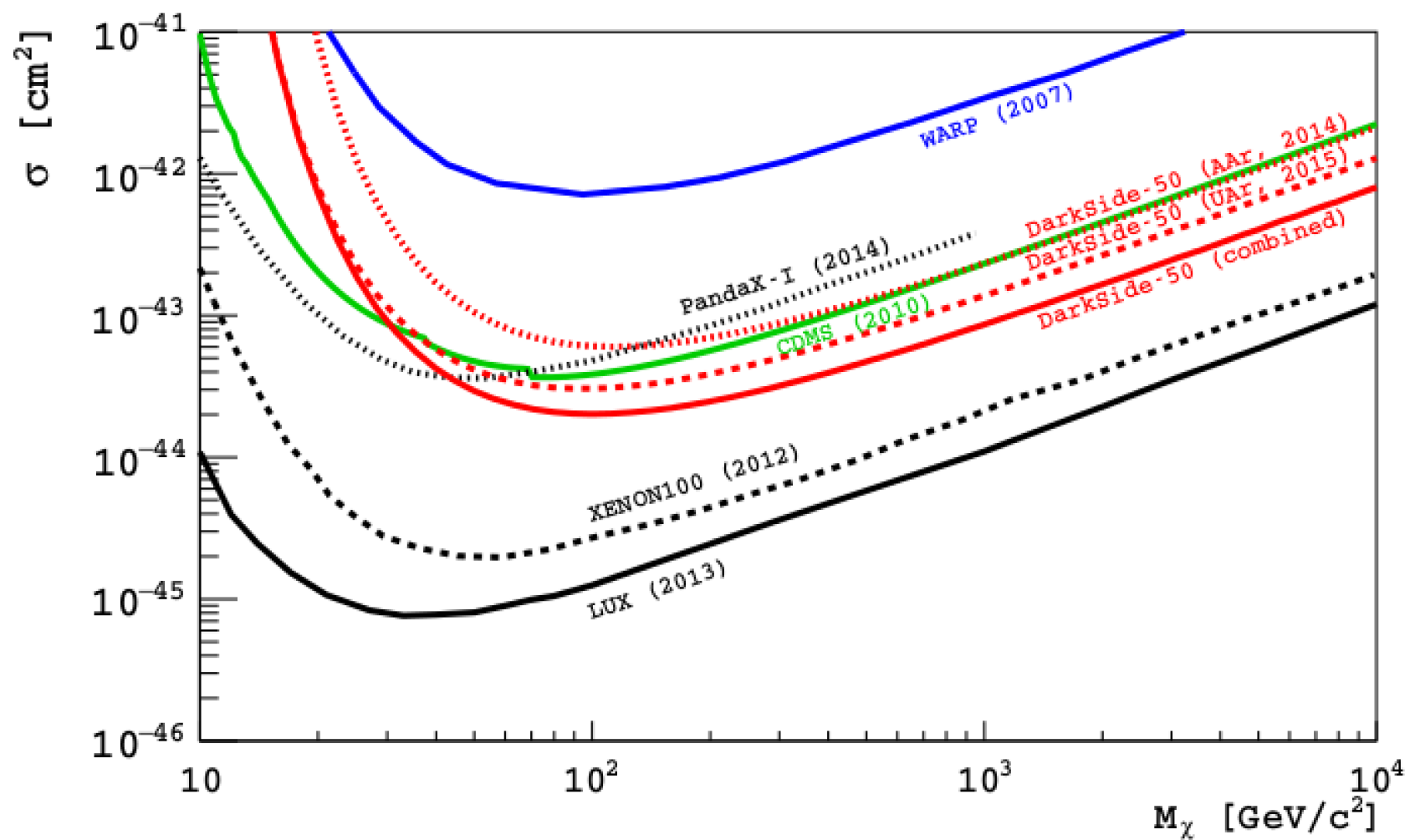
$^{241}\text{Am}^9\text{Be}$ Calibration Run

Neutron Vetoing Efficiency

- Calibrations and simulations: vetoing efficiency **from capture signal alone** is **> 99.1%**
 - ~7.7% of neutrons capture on ^1H ; 2.2 MeV γ lost ~8% of the time
 - 0.62% loss from this channel
 - ~0.23% capture after the LSV acquisition window has closed
 - ~0.05% leave no signal in LSV at all
- Total efficiency is even larger due to thermalization signal
 - Low background → cut with 1 PE threshold (~0.9% acceptance loss)
 - Will evaluate using $^{241}\text{Am}^{13}\text{C}$ source

Results

- 118 live days of running
 - "First Results from the DarkSide-50 Dark Matter Experiment at Laboratori Nazionali del Gran Sasso"
 - "Low radioactivity argon dark matter search results from the DarkSide-50 experiment"
- 2 neutrons vetoed that otherwise passed all cuts
 - 1 radiogenic
 - 1 cosmogenic
- 0 remaining backgrounds!



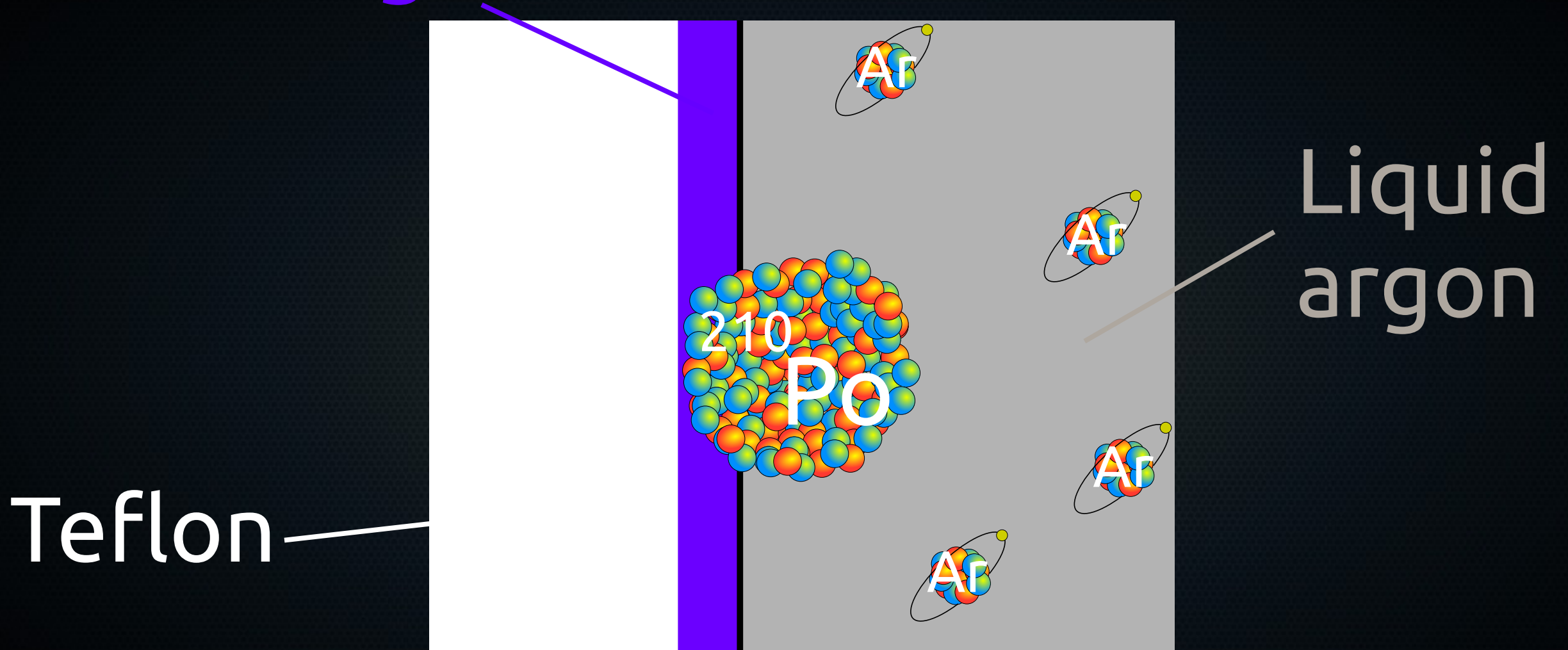
Summary

- Detecting WIMPs requires extraordinarily low backgrounds
- Electron recoil backgrounds can be effectively removed using pulse shape discrimination
- Nuclear recoil backgrounds from surface radioactivity can be removed with position cuts
- Nuclear recoil backgrounds from neutrons can be removed with our highly efficient neutron veto
- DarkSide has collected 118 days of data background free

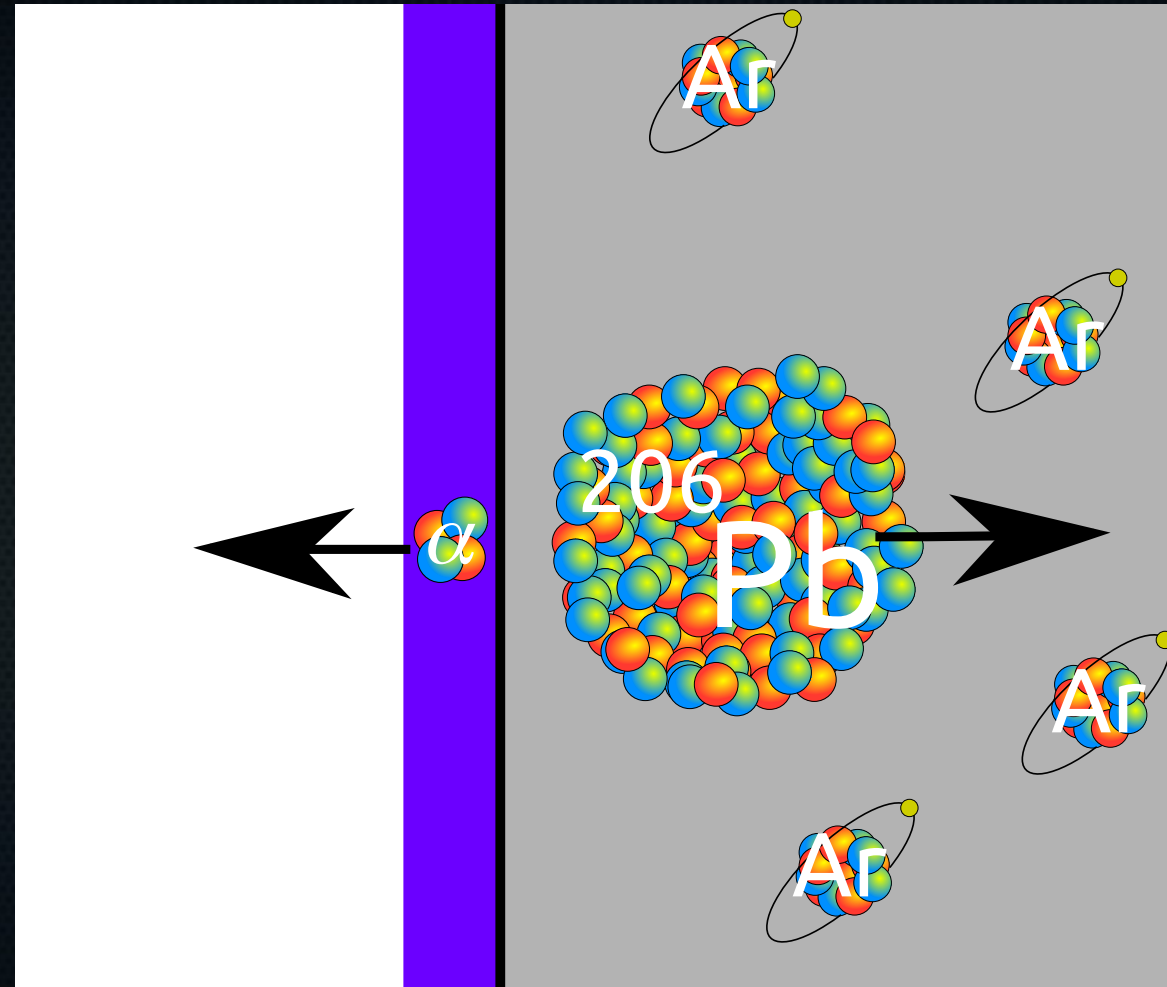
Further R&D

Surface backgrounds: The other nuclear recoil

Wavelength shifter

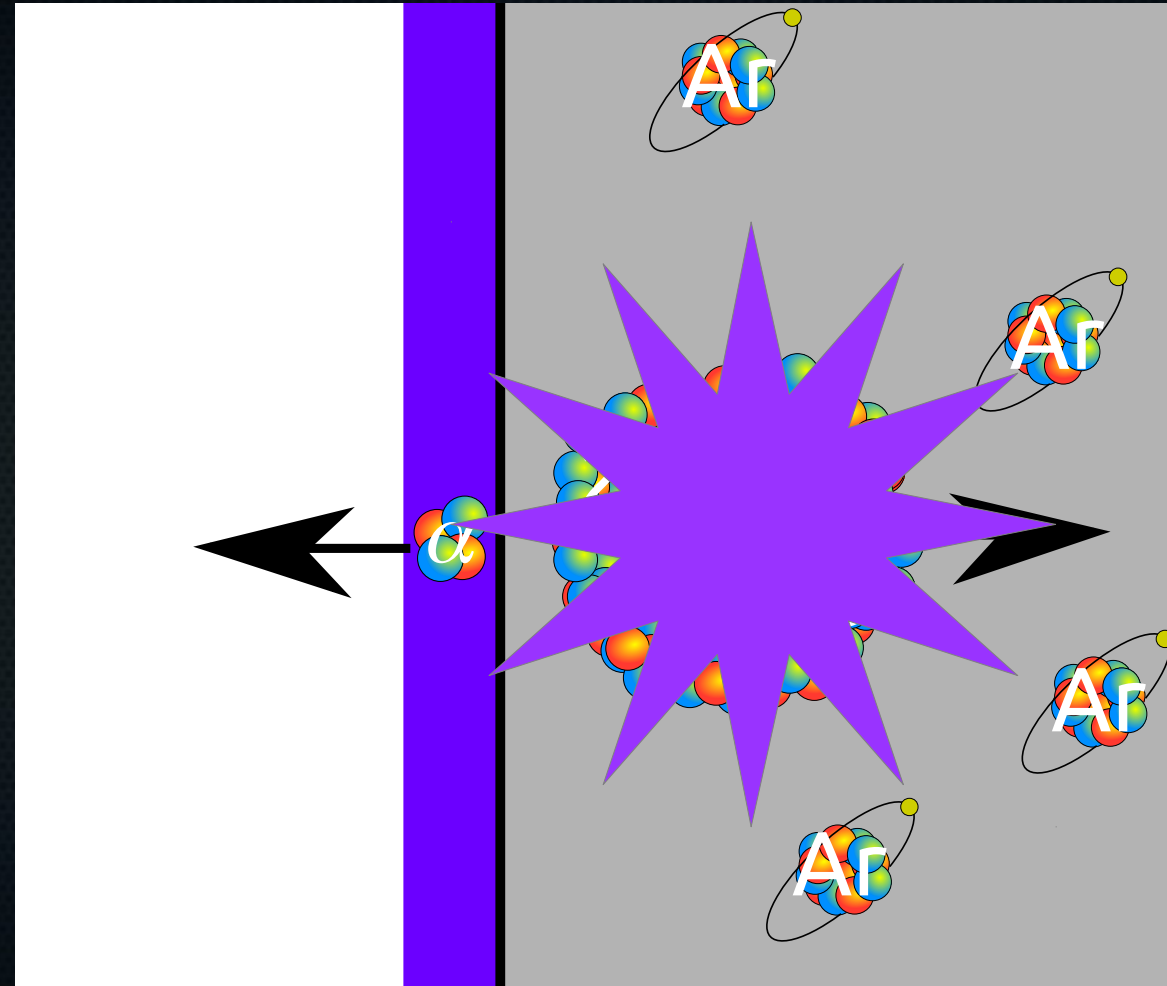


- $T_{\text{Po-210}}^{1/22} = 138 \text{ d}$
- $E(\alpha) = 5.304 \text{ MeV}$
- $E(^{206}\text{Po}) = 103 \text{ keV}$



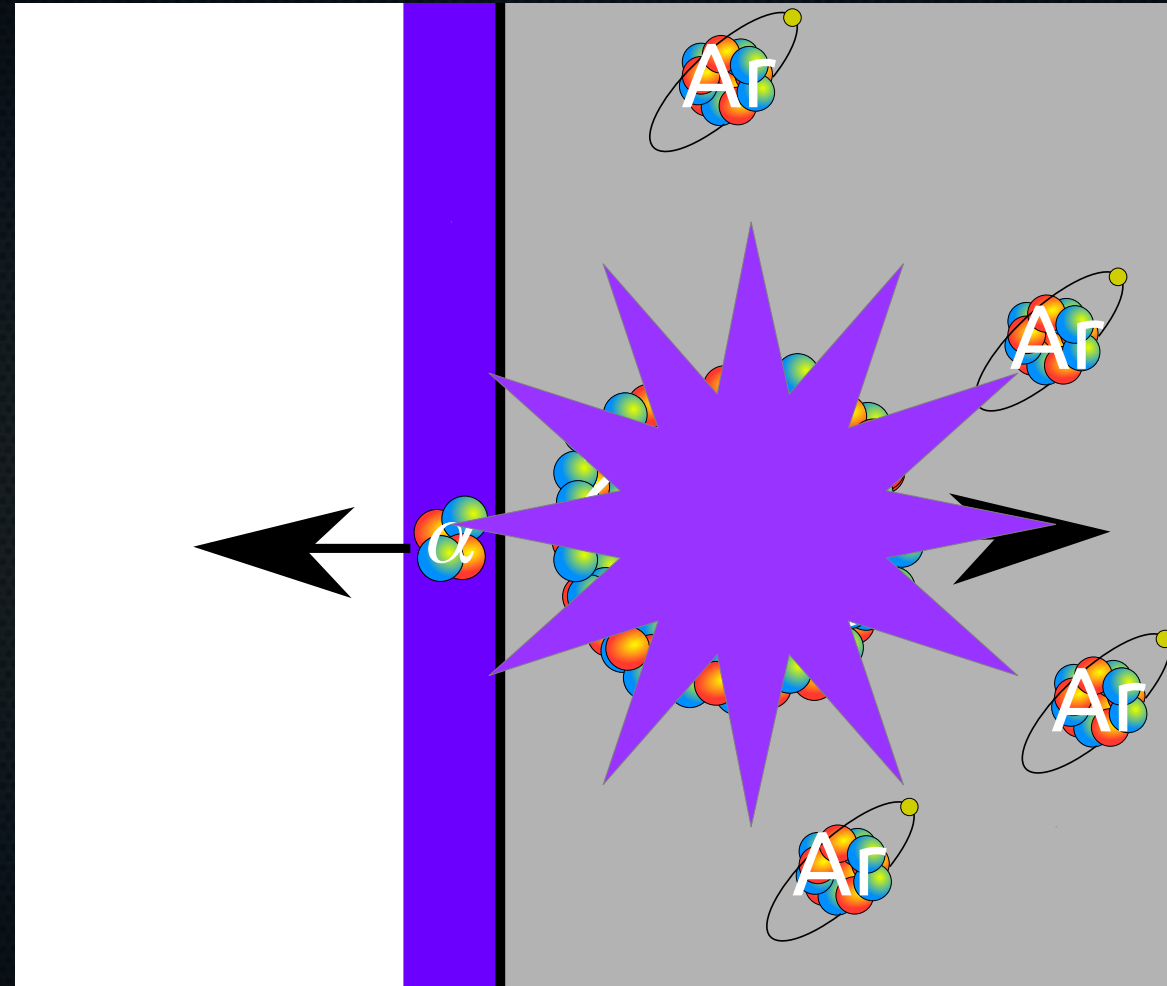
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Nuclear
recoil!



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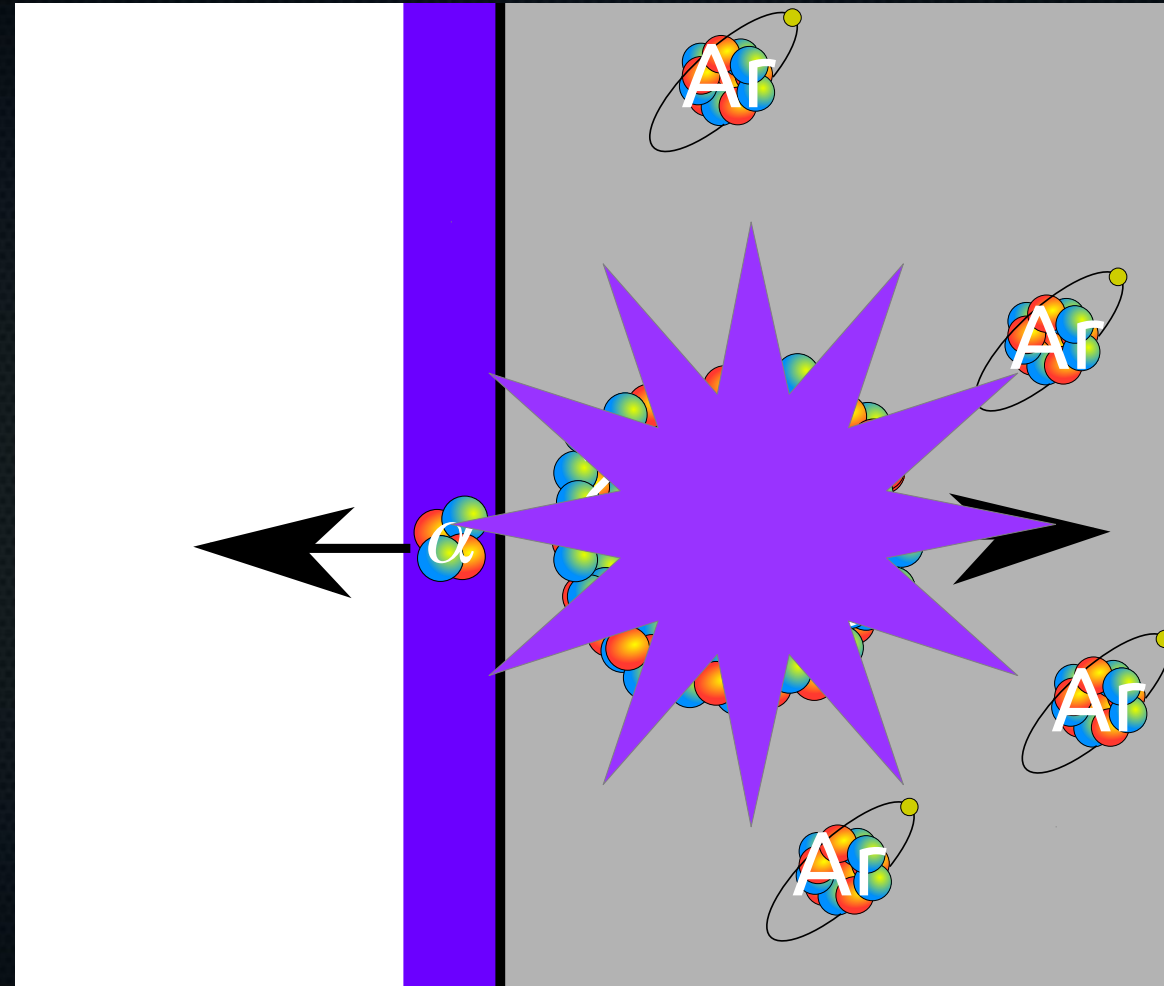
Nuclear
recoil!



Usual strategy:
Position cuts

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Nuclear
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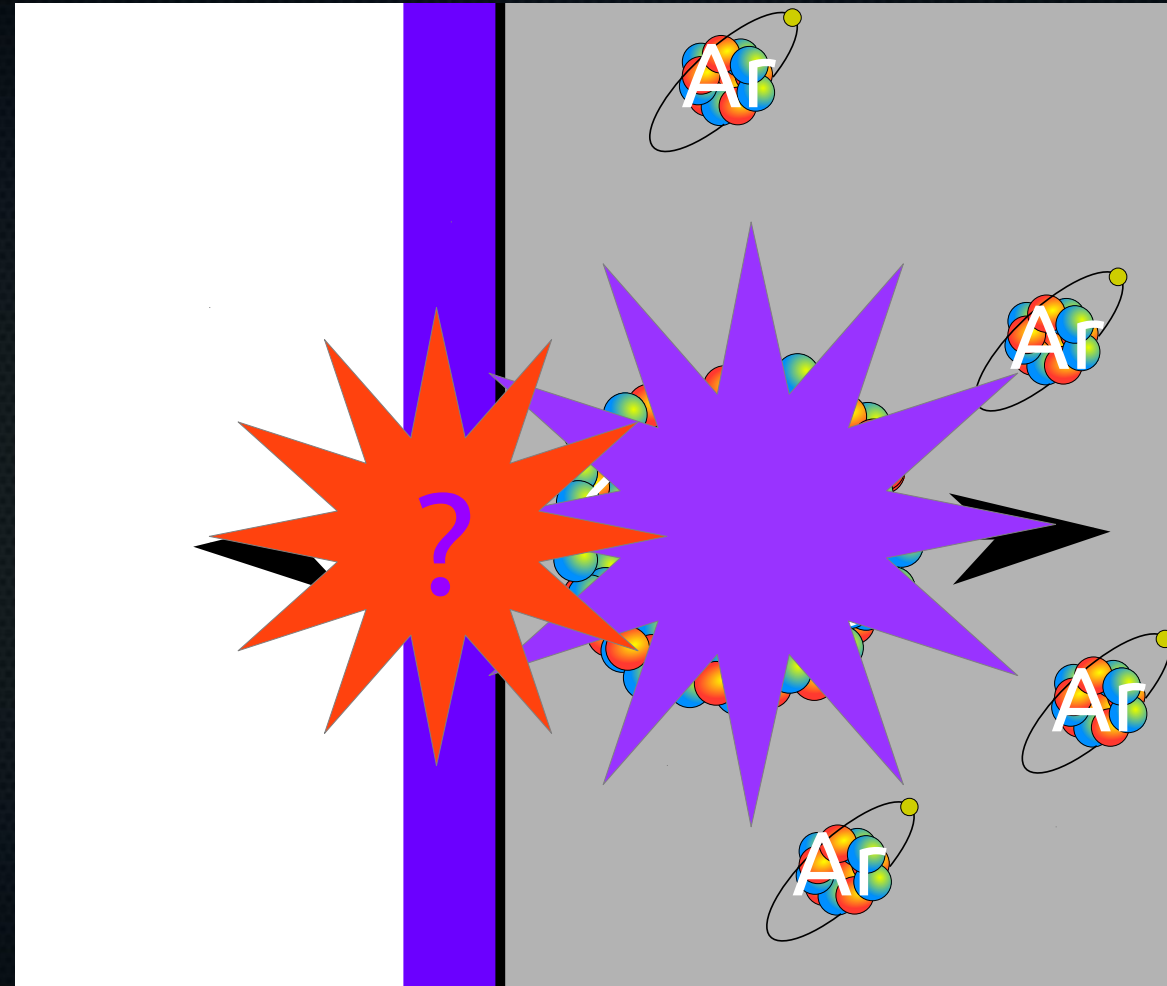


Usual strategy:
Position cuts

The problem:

- (x,y) reconstruction is hard
- Reduces exposure

Our solution:





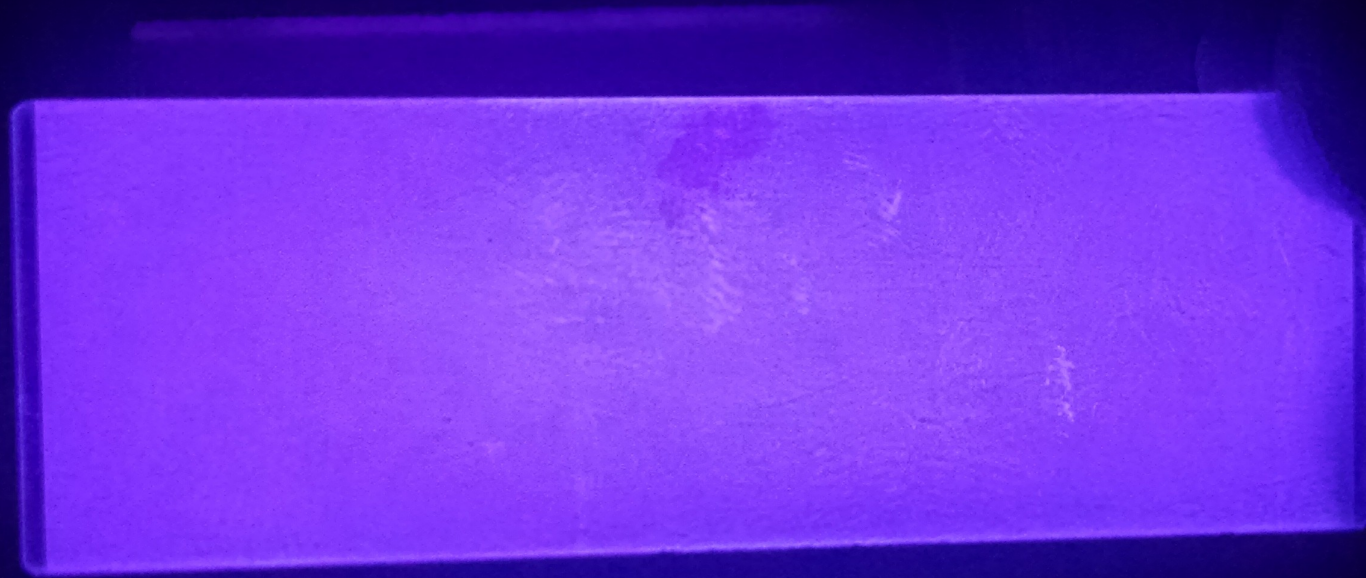
PMT



Contains spectralon cup

Tested wavelength shifters:

- Tetraphenyl butadiene (TPB)
- P-Terphenyl (pTP)

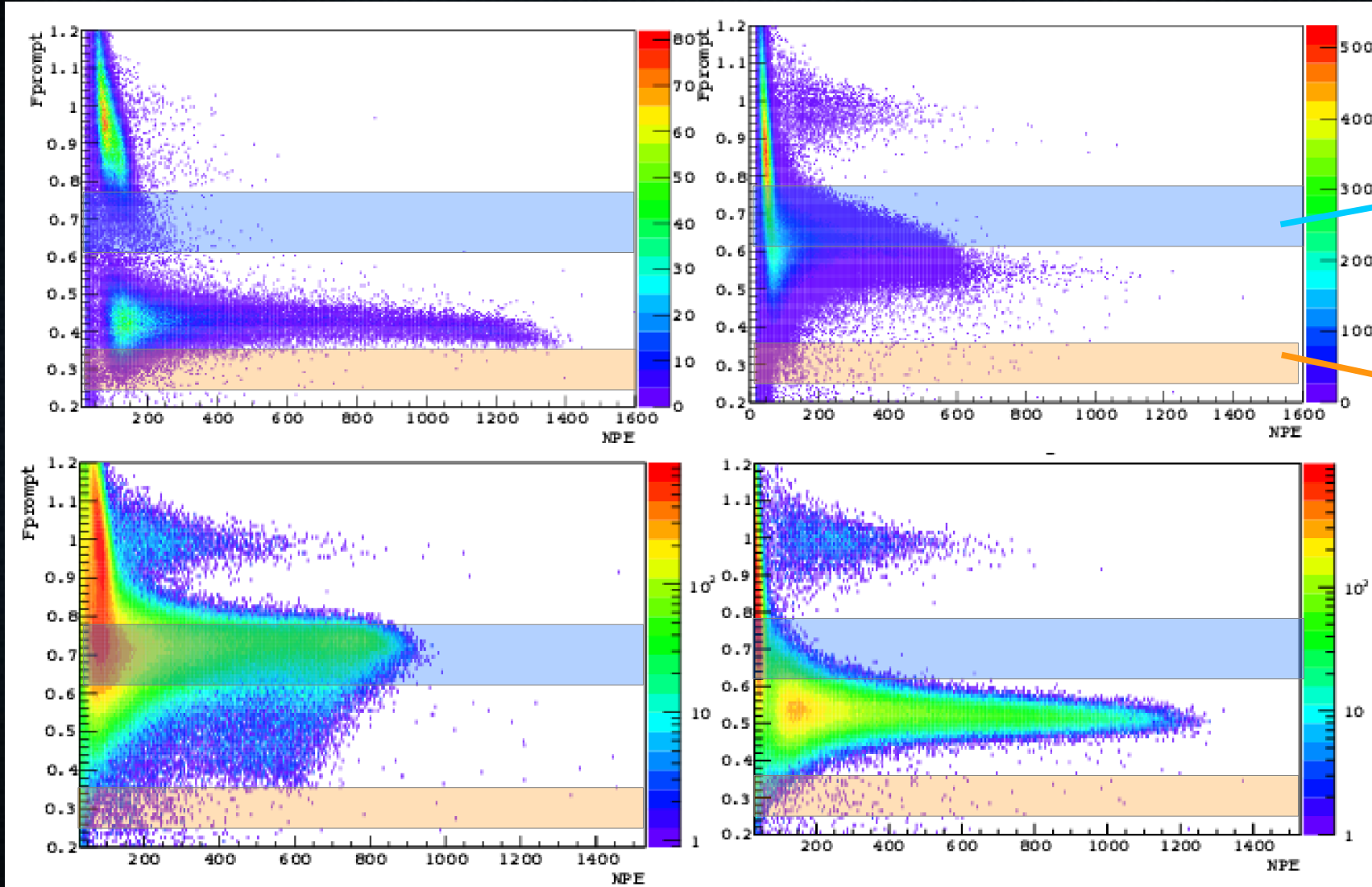


20°C

-190°C

TPB

pTP



Nuclear recoils

Electron recoils

Using a ^{210}Po needle source

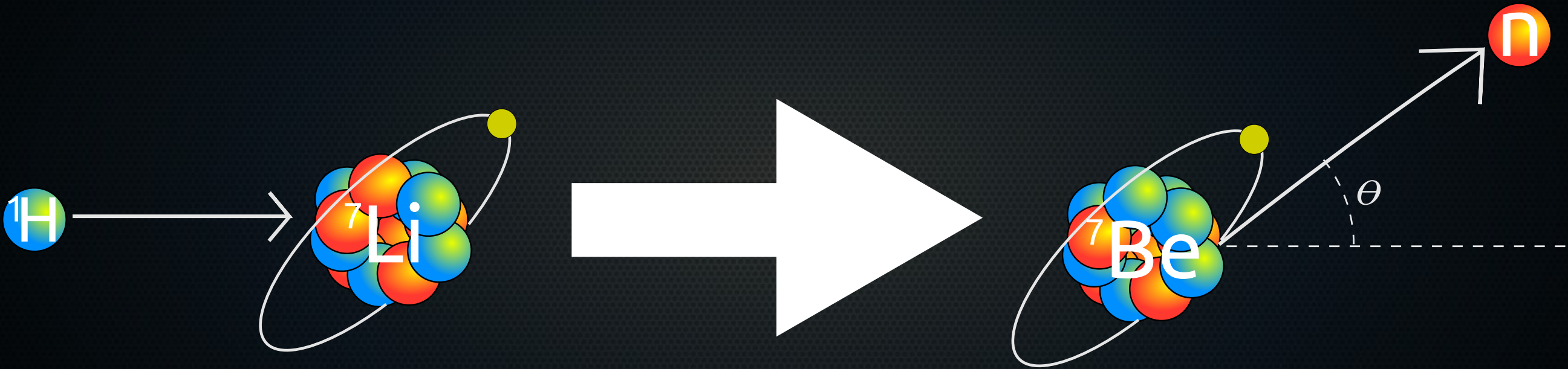


THE END

Neutron Rates

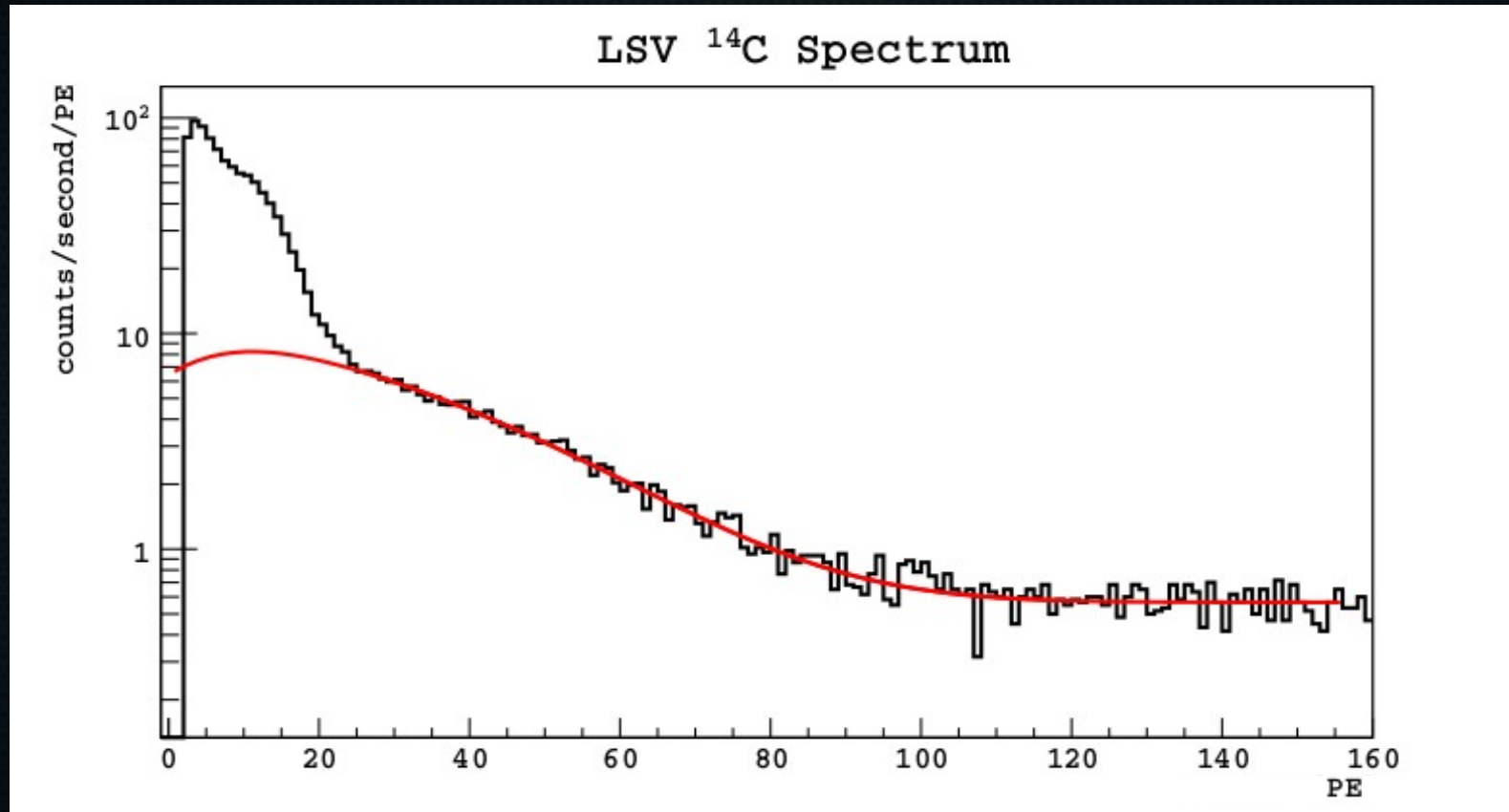
- Expect ~10 radiogenic neutron single scatters in the TPC per year
- Expect ~581 cosmogenic neutrons to enter the TPC per year (far fewer will produce single scatters in the WIMP search region)
 - FLUKA simulations show no events in 34 years where a cosmogenic neutron reaches the TPC and the LSV or WCD fails to trigger
 - A. Empl et al. *A Fluka study of underground cosmogenic neutron production*. JCAP, Aug. 2014.

Testing Prompt Response: Li(p,n)Be reaction



^{14}C Measurement

Phase II



Assumed:
 $k_B = 0.012 \text{ cm/MeV}$

Measured:
 $LY = 0.56(1) \text{ PE/keV}$
 $\text{Rate} = 245 \pm 27 \text{ Bq}$

Detection Mechanisms

