Title: Improving prospects for the direct detection of Higgsino dark matter

Speakers: Harikrishnan Ramani

Collection/Series: Particle Physics

Subject: Particle Physics

Date: May 23, 2025 - 1:00 PM

URL: https://pirsa.org/25050041

Abstract:

The pseudo-Dirac Higgsino is one of the last surviving electroweak WIMPs. The LHC will not reach the 1.1 TeV target mass even with full luminosity and prospects for its indirect detection depend on a favorable dark matter density profile at the galactic center. Since it has only off-diagonal couplings at tree-level, its direct detection is possible only when the mass splitting is smaller than the initial center of mass kinetic energy. This direct detection loophole is actually more generic; going by the name 'inelastic dark matter'. In this talk I will talk about my recent efforts to reach mass splittings larger than what has been thought to be possible thus far, by invoking interesting astrophysics, elements from the end of the periodic table, and large volume neutrino detectors.

IMPROVING PROSPECTS FOR DETECTING ELECTROWEAK PSEUDO-DIRAC DARK MATTER

Harikrishnan Ramani
University of Delaware

BASED ON

Enhancing Direct Detection of Higgsino Dark Matter
P.W.Graham, H.Ramani and Samuel Wong
Phys.Rev.D 111 (2025) 5, 055030 e-Print: 2409.07768 [hep-ph]

Dark Matter Constraints from Isomeric 178Hf
D. Alves, S. Elliott, R. Massarczyk, S.J. Meijer, H. Ramani
Phys.Rev.Lett. 131 (2023) 14, 141801 [Editor's Suggestion]• e-Print: 2306.04442 [nucl-ex]

Constraints on the decay of 180Ta
Majorana Collaboration + D. Alves and H. Ramani
Phys.Rev.Lett. 131 (2023) 15, 152501 • e-Print: 2306.01965 [nucl-ex]

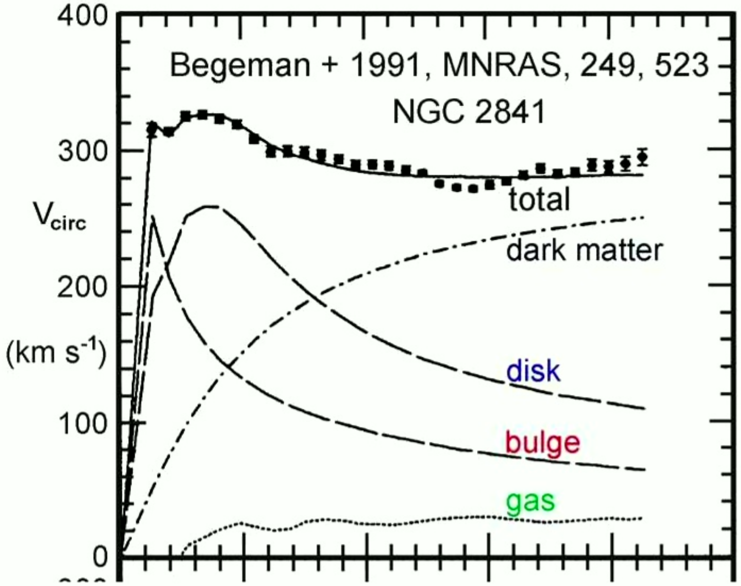
Search for Dark Matter Induced De-excitation of 180m Ta
B. Lehnert, H. Ramani, M. Hult, G. Lutter, M. Pospelov, S. Rajendran
Phys.Rev.Lett. 124 (2020) 18, 181802 • e-Print: 1911.07865 [hep-ph]

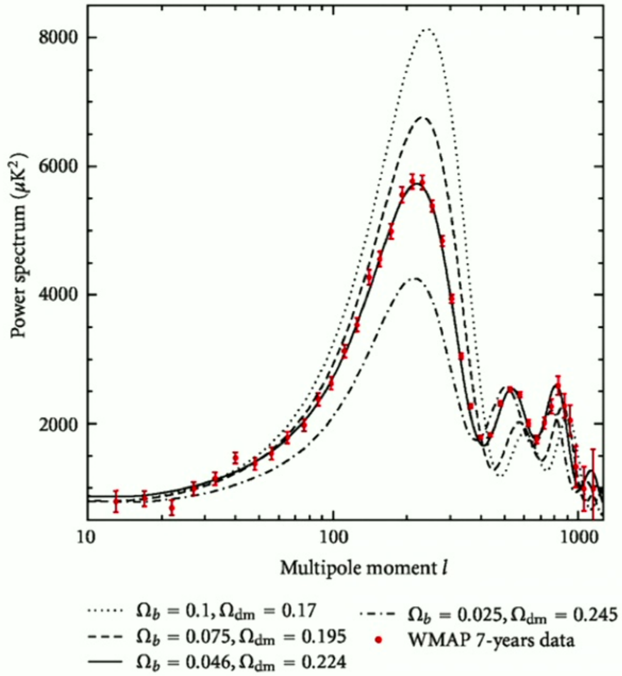
Metastable Nuclear Isomers as Dark Matter Accelerators
M. Pospelov, S. Rajendran and H.Ramani
Phys.Rev.D 101 (2020) 5, 055001 [Editor's Suggestion] • e-Print: 1907.00011 [hep-ph]

OUTLINE

- Intro To Higgsinos and summary
- Improvements in Direct Detection prospects
- Nuclear Isomers as exothermic DM detectors

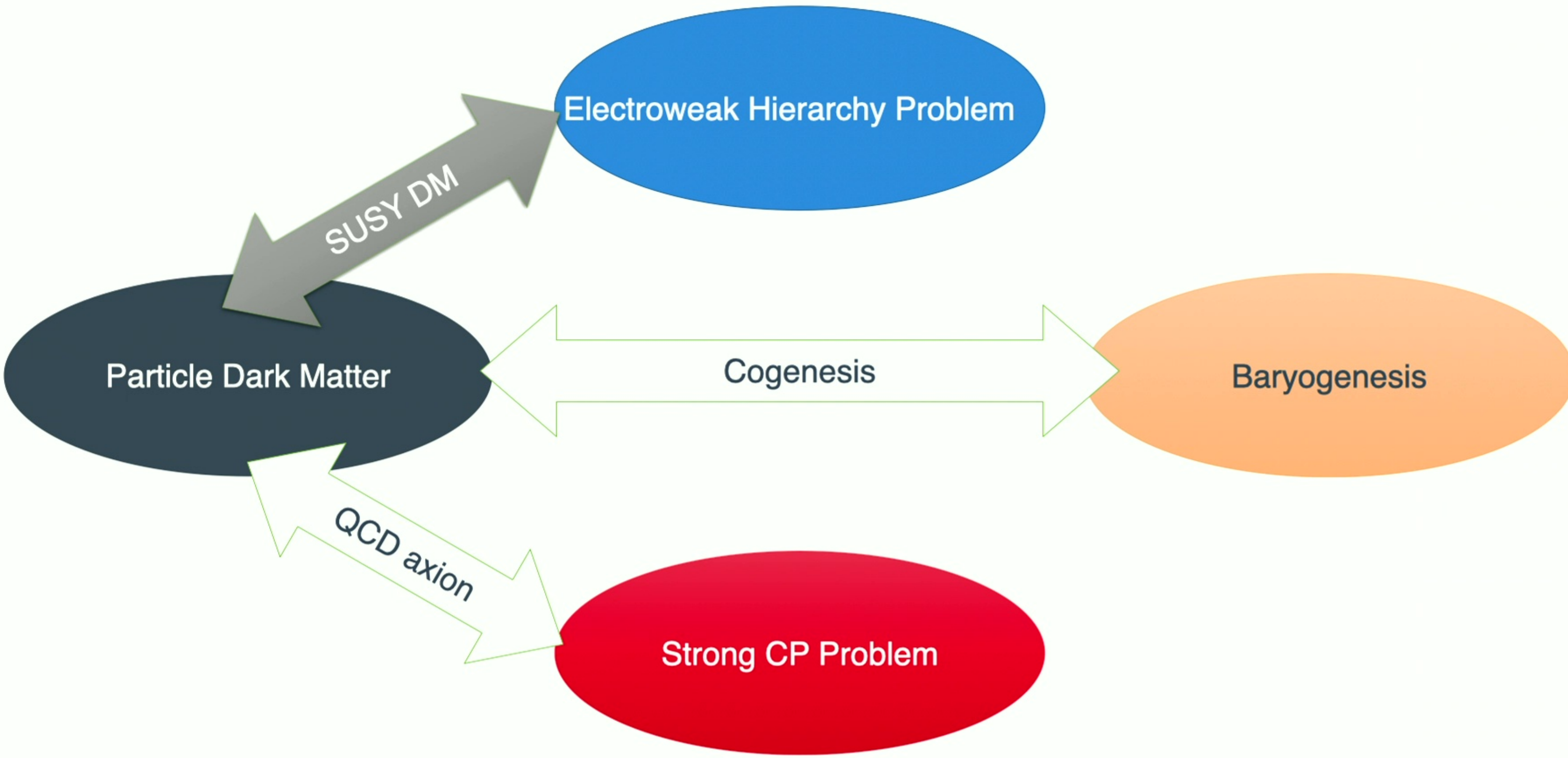
DARK MATTER





- ✦ Overwhelming evidence for Dark Matter (DM)
- ✦ Cannot be explained by the Standard Model
- ✦ Critical to galaxy/star formation $\Longrightarrow$ our very existence

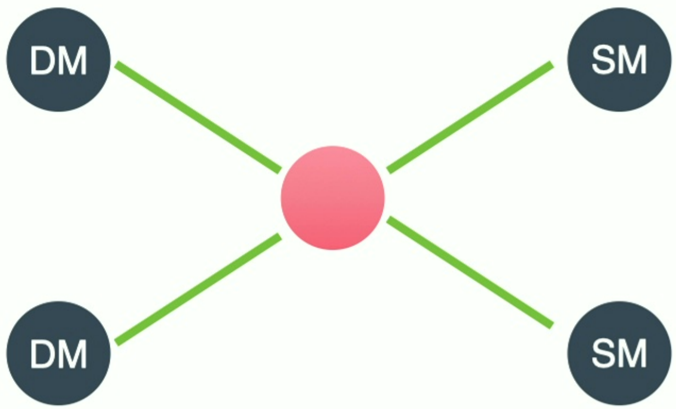
OPEN PROBLEMS

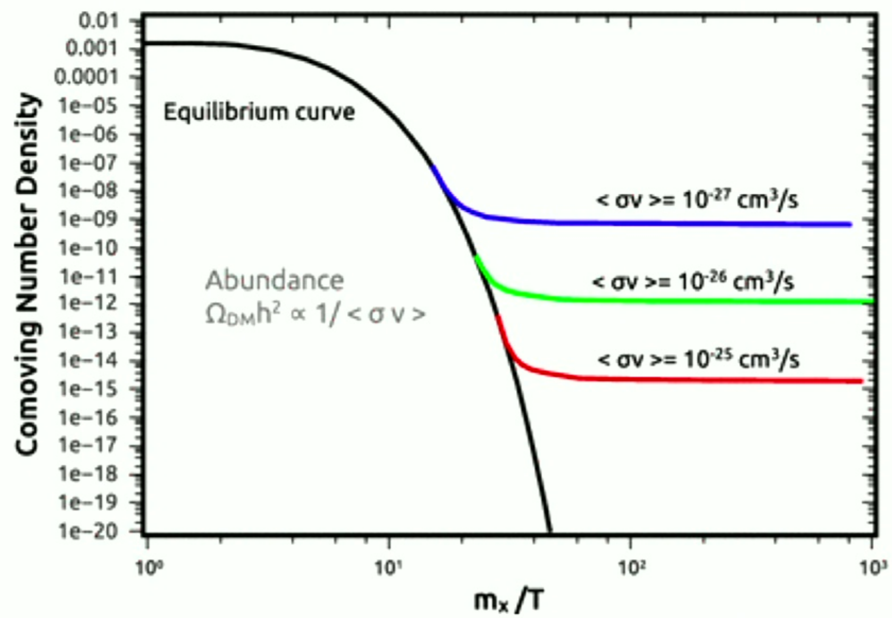


RELATED TO OTHER PROBLEMS

IN PARTICLE PHYSICS?

WIMP MIRACLE





- Thermal Equilibrium then Freeze-out
- TeV particles with weak-scale cross-sections produce the correct relic abundance!
- 1.1 TeV mass for pure Higgsino and 3 TeV mass for pure Wino

Other WIMPs?

WIMP = **Weakly** Interacting Massive Particle

Minimal Extension - Reuse Standard Model Gauge groups for Dark Matter

COMPLEX WIMPs

DM spin	n_Y	$M_{\rm DM}$ (TeV)
Dirac fermion	$2_{1/2}$	1.08 ± 0.02
	3_1	2.85 ± 0.14
	$4_{1/2}$	4.8 ± 0.3
	5_1	9.9 ± 0.7
	$6_{1/2}$	31.8 ± 5.2
	$8_{1/2}$	82 ± 8
	$10_{1/2}$	158 ± 12
	$12_{1/2}$	253 ± 20
Complex scalar	$2_{1/2}$	0.58 ± 0.01
	3_1	2.1 ± 0.1
	$4_{1/2}$	4.98 ± 0.25
	5_1	11.5 ± 0.8
	$6_{1/2}$	32.7 ± 5.3
	$8_{1/2}$	84 ± 8
	$10_{1/2}$	162 ± 13
	$12_{1/2}$	263 ± 22

Electroweak **n-plets** with non-zero hypercharge **Y**

The last Complex WIMPs standing

Salvatore Bottaro,[1,2] Dario Buttazzo,[2] Marco Costa,[1,2] Roberto Franceschini,[3] Paolo Panci,[4,2] Diego Redigolo,[5,6] and Ludovico Vittorio[1,

INDIRECT DETECTION

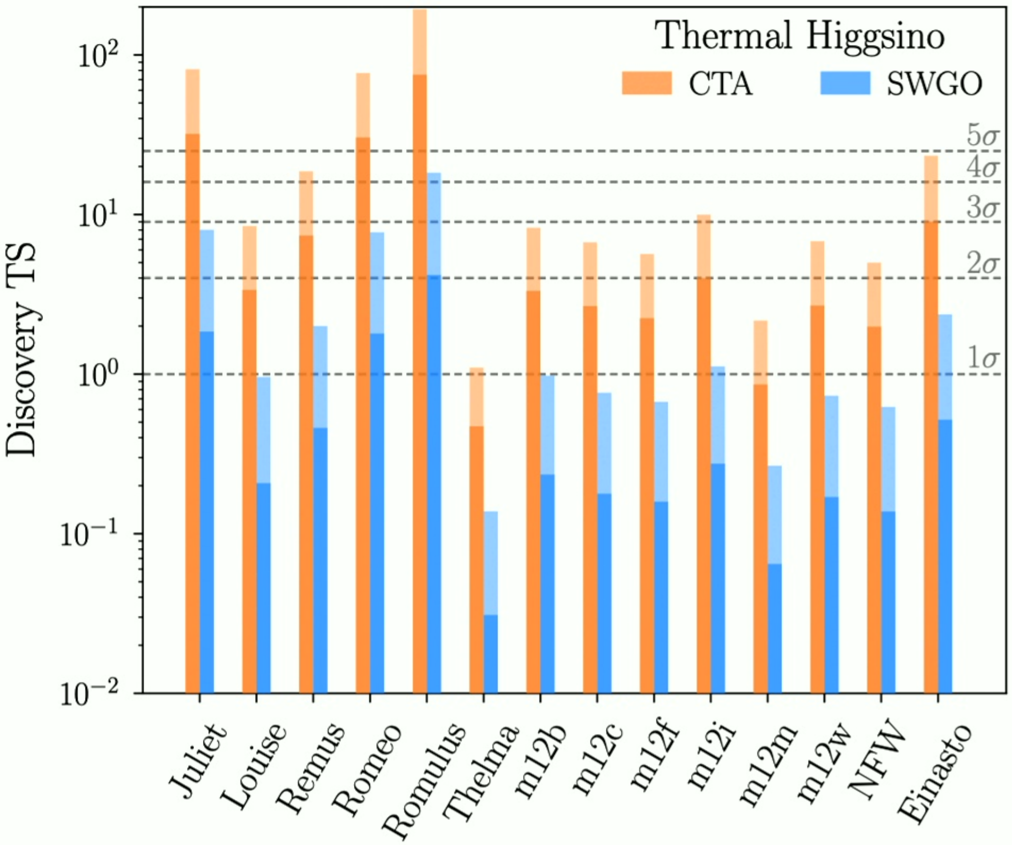
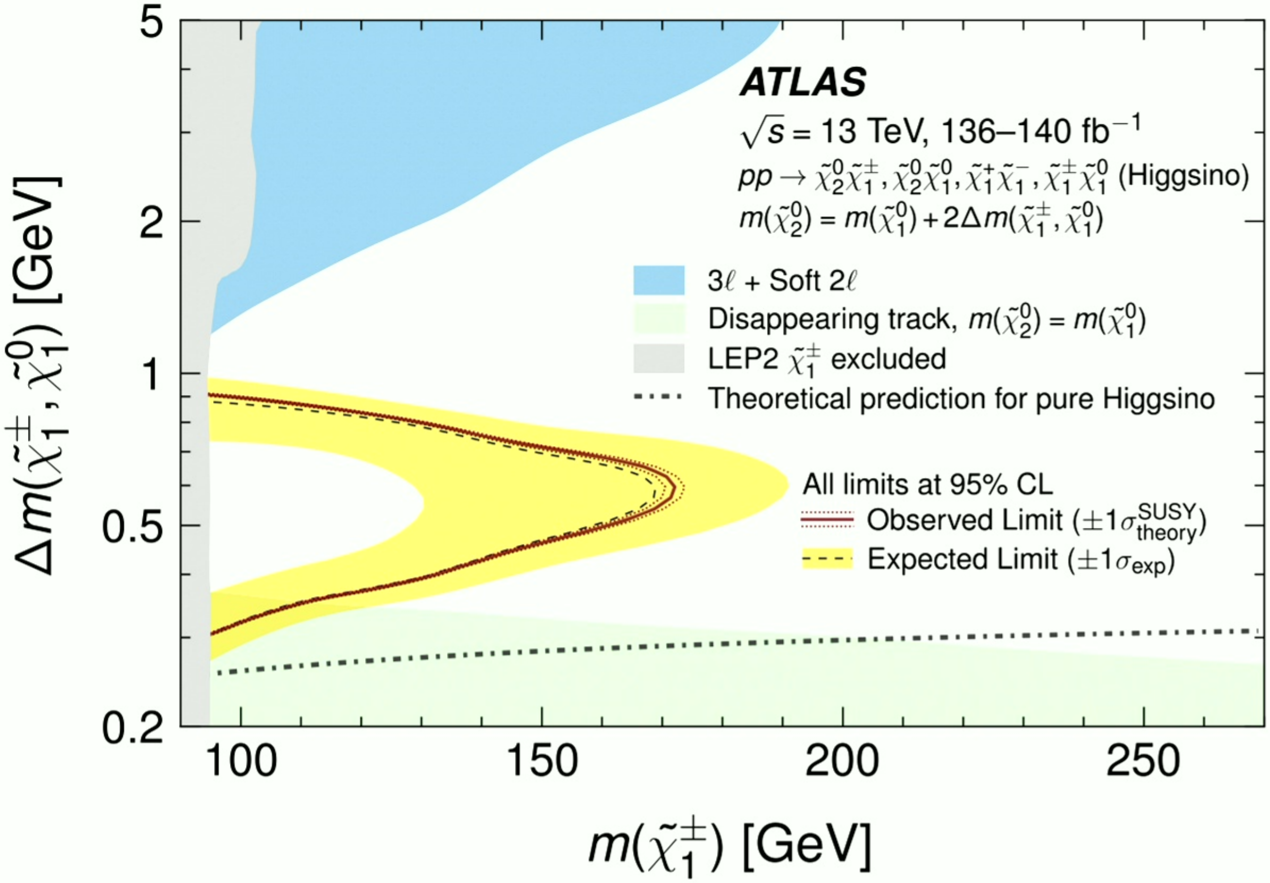


Figure 1. A projection of the expected discovery test statistics (TSs) in favor of the thermal higgsino annihilation signal for CTA (orange) and SWGO (blue). The projected reach is shown for a wide range of DM profiles and for optimal analyses (light) and more realistic analyses that account for mismodeling uncertainties (dark), as discussed in this work.

Rodd, Safdi, Xu - 2405.13104

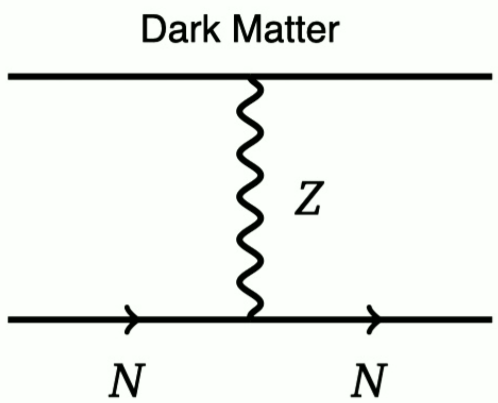
Depends on the unknown J-factor at the GC

COLLIDERS

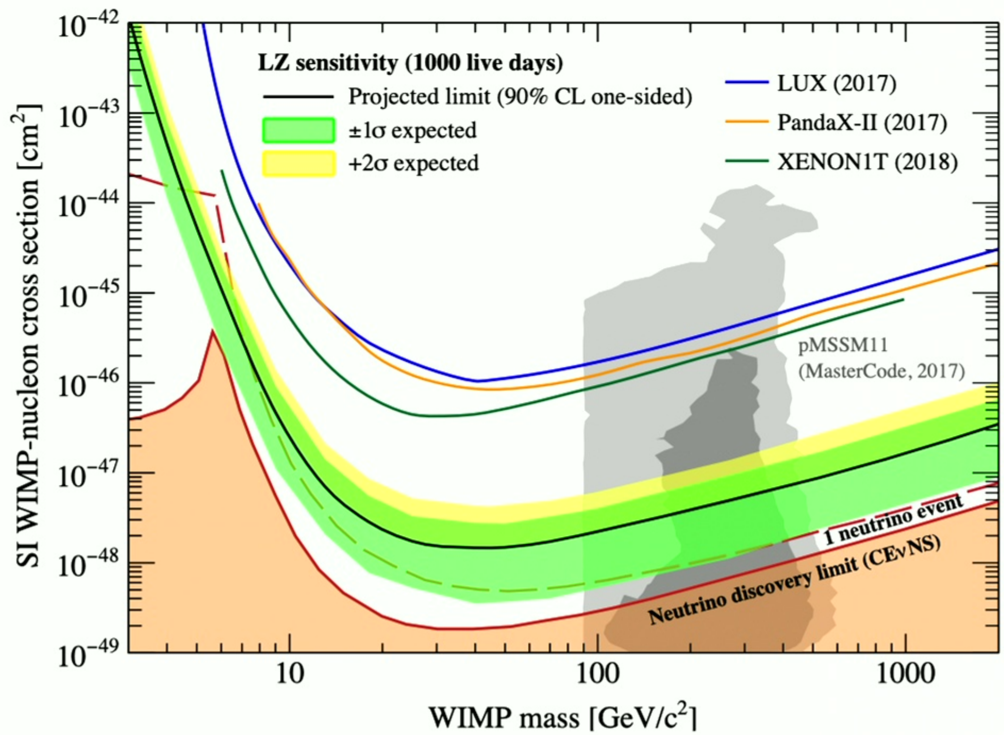


ATLAS
$\sqrt{s}$ = 13 TeV, 136–140 fb^{-1}
$pp \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm, \tilde{\chi}_2^0\tilde{\chi}_1^0, \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm\tilde{\chi}_1^0$ (Higgsino)
$m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0) + 2\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$
3ℓ + Soft 2ℓ
Disappearing track, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0)$
LEP2 $\tilde{\chi}_1^\pm$ excluded
Theoretical prediction for pure Higgsino
All limits at 95% CL
Observed Limit ($\pm 1\sigma_{\mathrm{theory}}^{\mathrm{SUSY}}$)
Expected Limit ($\pm 1\sigma_{\mathrm{exp}}$)
$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ [GeV]
$m(\tilde{\chi}_1^\pm)$ [GeV]
5
2
1
0.5
0.2
100
150
200
250

DIRECT DETECTION



- Simple Z exchange $\sigma_n \approx 10^{-39}$cm^2
- Ruled out long ago?
- Not so fast!



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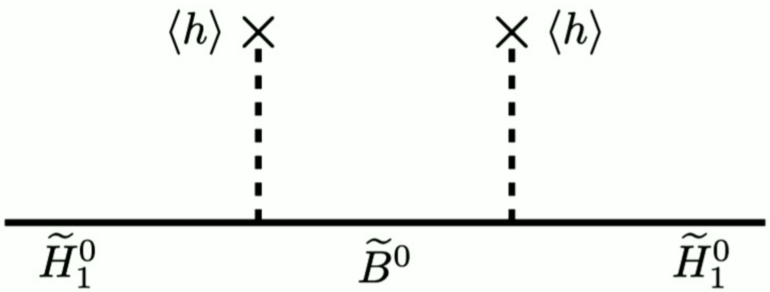
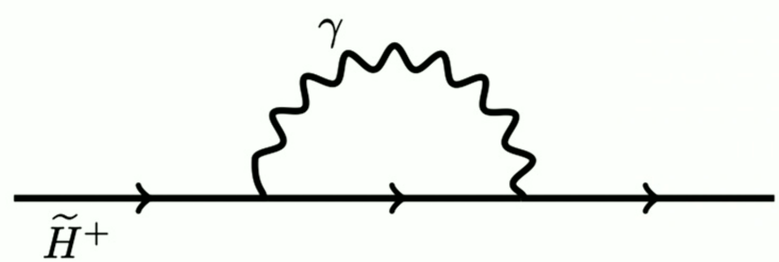
PSEUDO-DIRAC HIGGSINO

- Dirac Fermions before EWSB Mass $\mu\tilde{H}_u . \tilde{H}_d$ with $\mu \approx 1$ TeV
- After EWSB receive small Majorana mass
- Two nearly degenerate Majorana fermions aka pseudo-dirac

arXiv: 1705.04843, Krall & Reece



Majorana Mass after EWSB



Charge - Neutral Splitting ≈ 350 MeV

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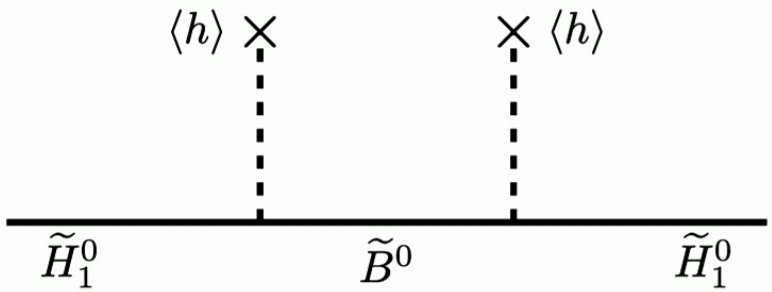
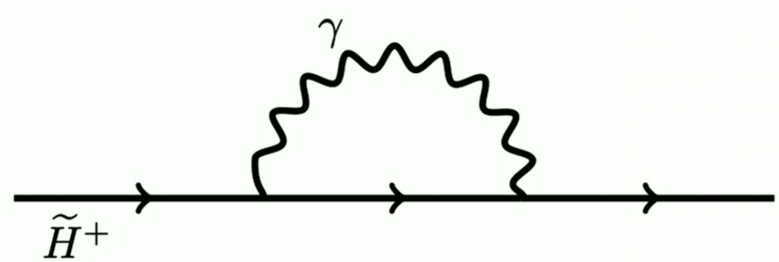


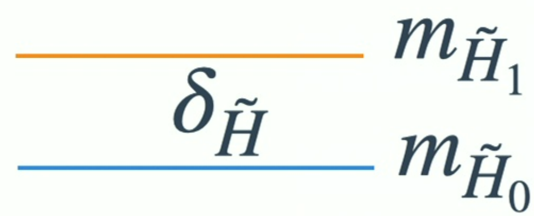
Majorana Mass after EWSB

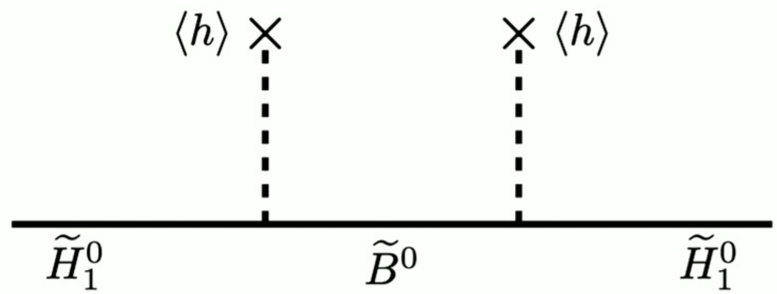


Charge - Neutral Splitting ≈ 350 MeV

PSEUDO-DIRAC HIGGSINO

- Two nearly degenerate Majorana fermions aka pseudo-dirac
- Only off-diagonal couplings with Z
- Mass splitting





Majorana Mass after EWSB

arXiv: 1608.02662, Bramante, Fox, Kribbs, Martin

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

$M_{1,2}$ mass of Bino/Wino

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PSEUDO-DIRAC HIGGSINO

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

$M_{1,2}$ mass of Bino/Wino

Bino/Wino mass is inversely proportional to the mass splitting

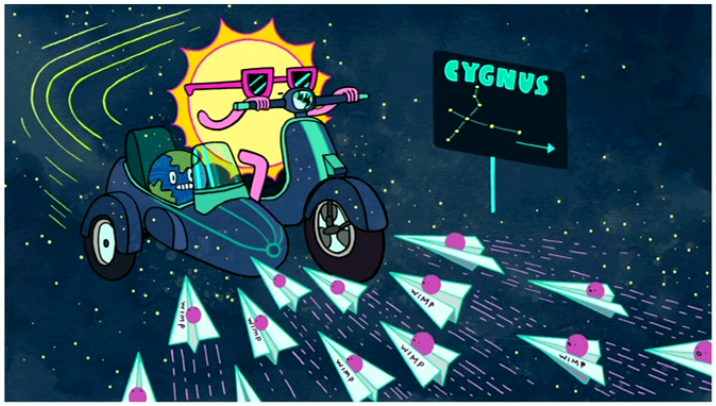
THRESHOLD CORRECTIONS

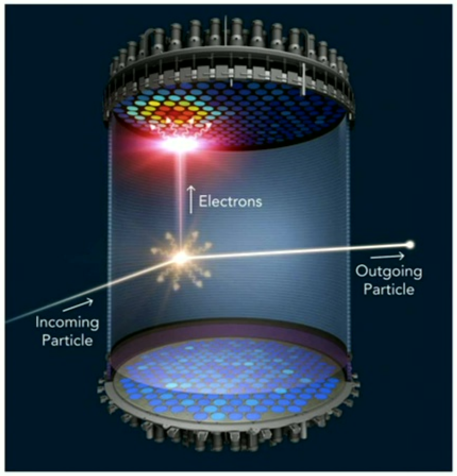
$$\Delta\mu \approx -\frac{\sin 2\beta}{32\pi^2}\left(3g^2 M_2 \log\frac{m_H}{M_2} + g'^2 M_1 \log\frac{m_H}{M_1}\right)$$

$$\begin{aligned}
\delta &\gtrsim g'^2 \sin 2\beta \sin^2\theta_W \frac{m_Z^2}{32\pi^2\mu} \log\frac{m_H}{M_1} \\
&\approx 970\ \mathrm{keV}\,\frac{1.1\ \mathrm{TeV}}{|\mu|}\,\frac{\log(m_H/M_1)}{\log(100)}\,\frac{\sin(2\beta)}{\sin(2\arctan(2))} \\
&\approx 240\ \mathrm{keV}\,\frac{1.1\ \mathrm{TeV}}{|\mu|}\,\frac{\log(m_H/M_1)}{\log(100)}\,\frac{\sin(2\beta)}{\sin(2\arctan(10))}
\end{aligned}$$

DIRECT DETECTION CONCEPT

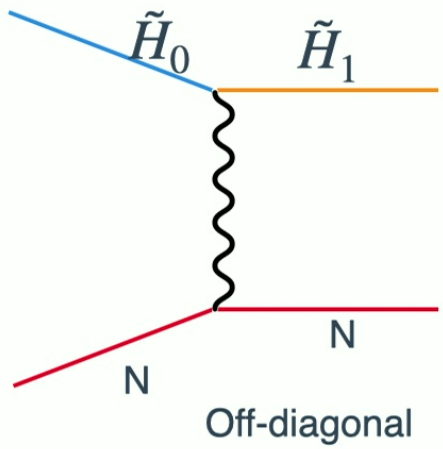
- Dark matter virial velocity relative to earth: $v_{\rm vir} = 10^{-3}$.
- Possesses CoM kinetic energy: KE $= \mu v_{\rm vir}^2/2$.
- DM scatters with SM target and deposit this KE
- 100 GeV Mass $\Longrightarrow$100 keV energy deposit





What if DM cannot supply this energy?

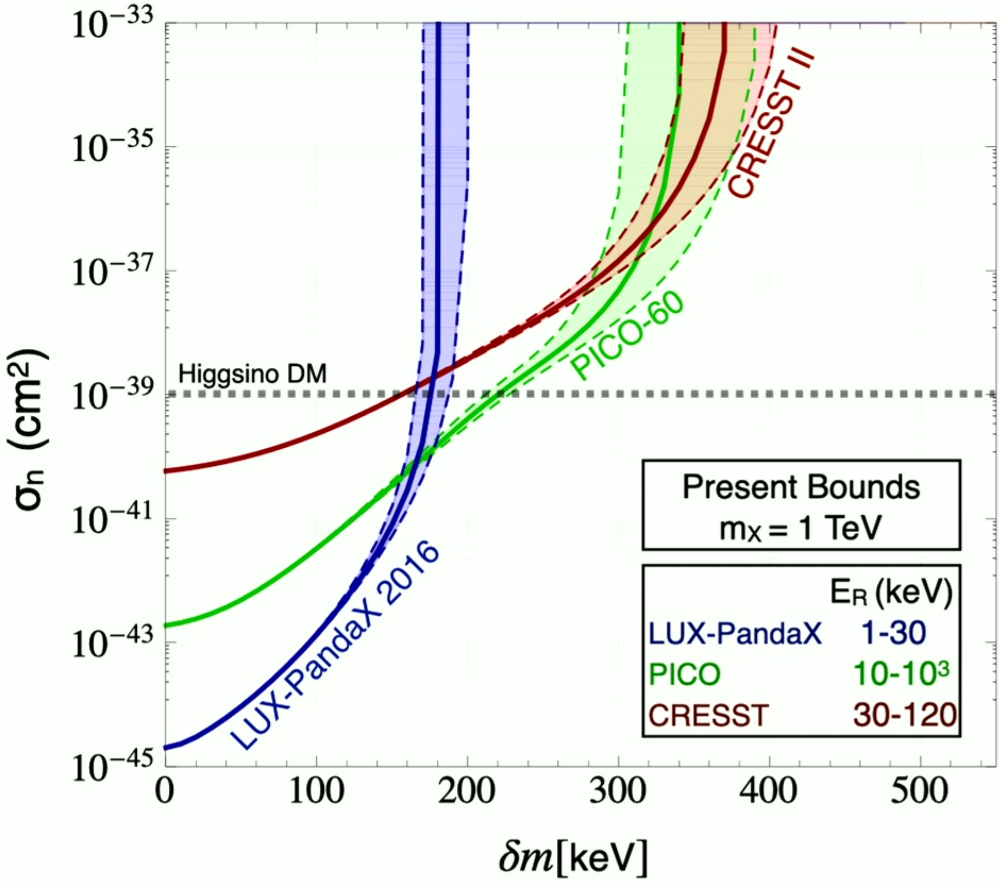
INELASTIC DARK MATTER



- ✦ Retain salient features of WIMP miracle
- ✦ Mass deficit supplied by initial KE
- ✦ $\delta m \leq \mathrm{KE} = \frac{1}{2}\mu v_{\mathrm{vir}}^2 \approx 200 - 400\ \mathrm{keV}$
- ✦ Many well-motivated models: **Higgsinos**, dark photon mediated pseudo-dirac, dipole DM etc.

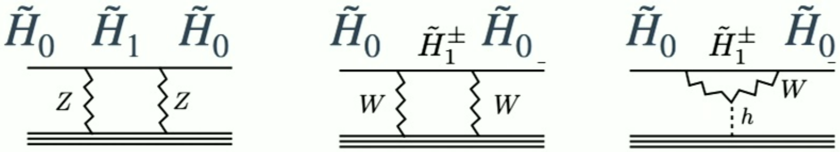
Arxiv: 1008.1988 Feldstein, Graham, Rajendran

INELASTIC DARK MATTER BOUNDS



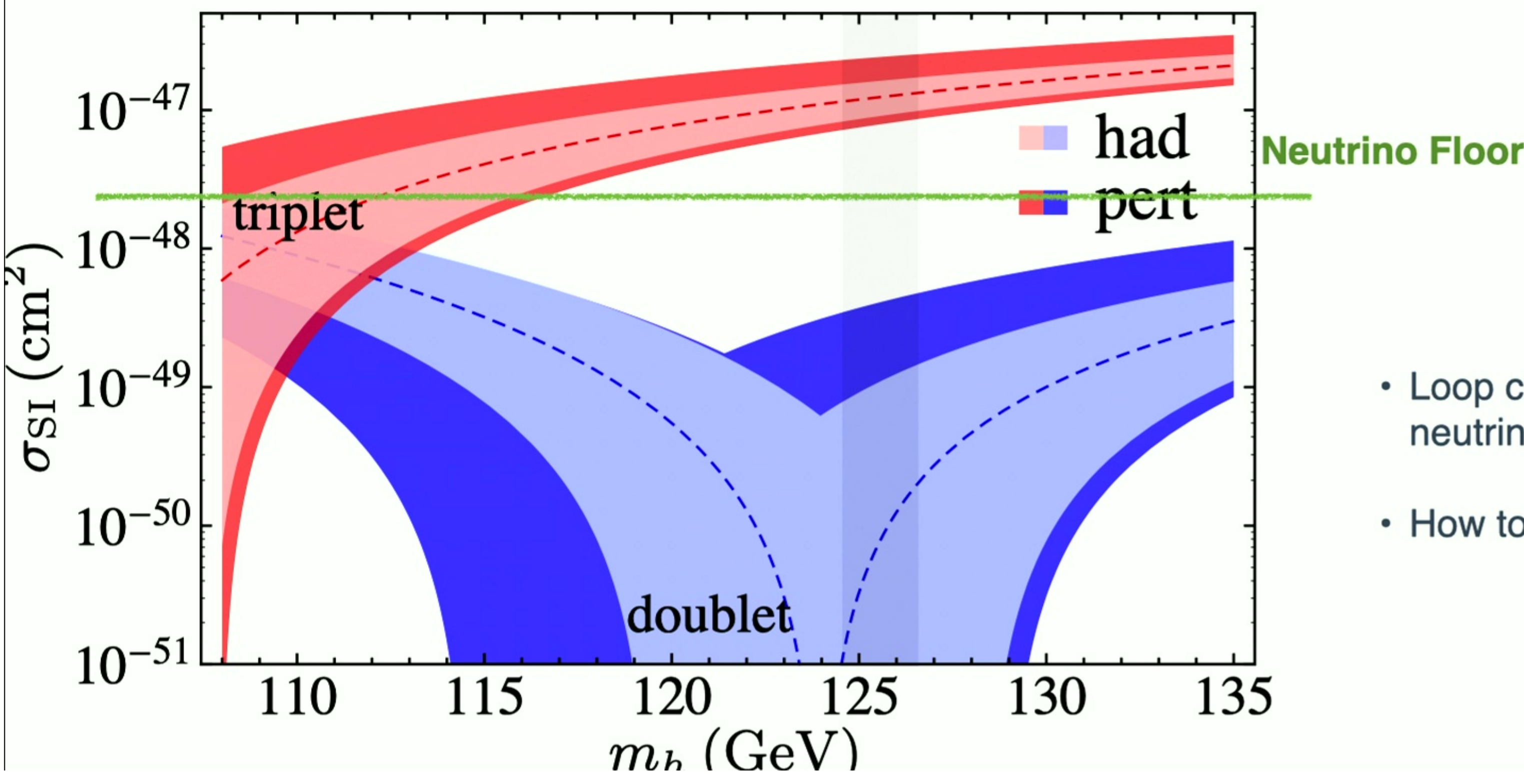
Source: arXiv: 1608.02662, Bramante, Fox, Kribs, Martin

ELASTIC LOOP



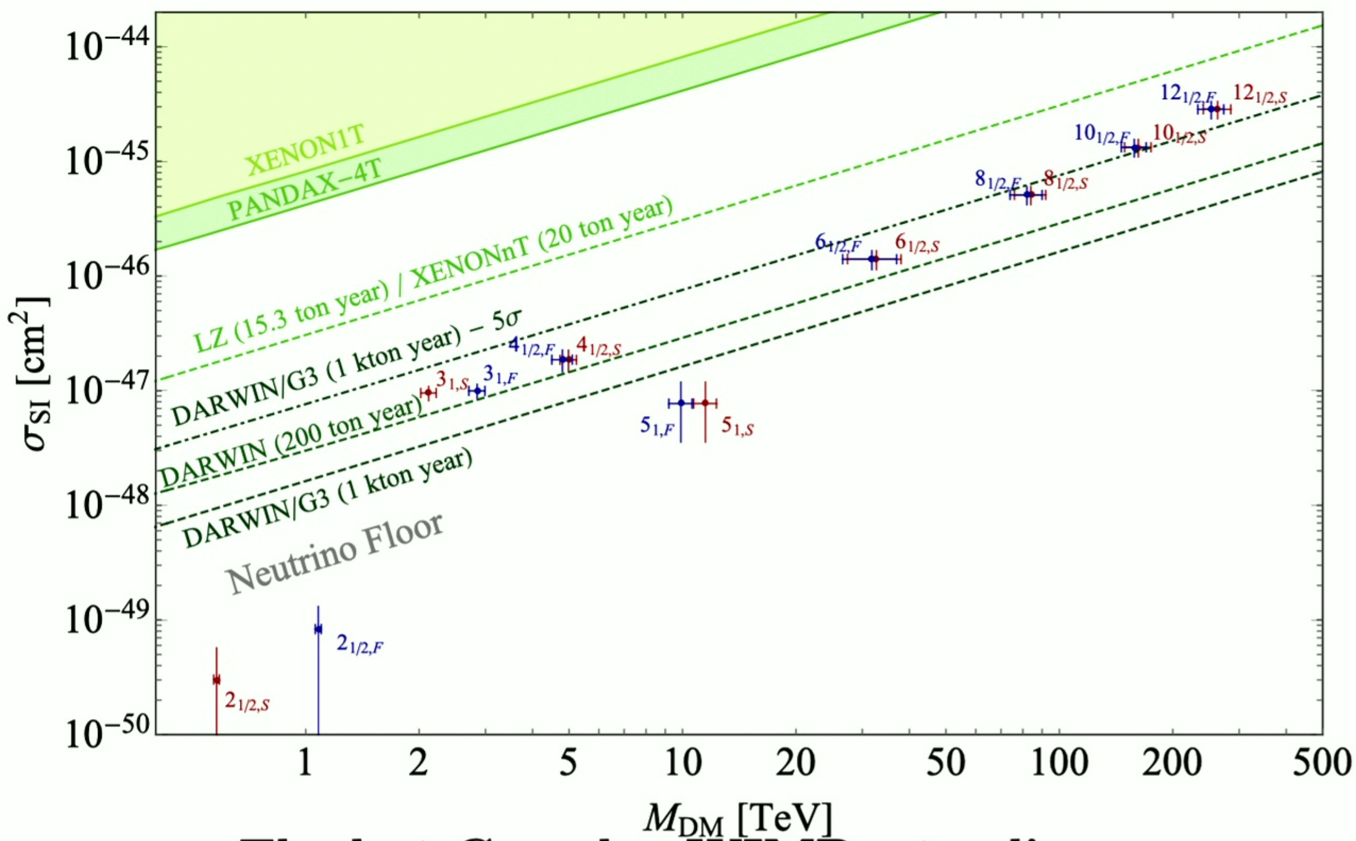
arXiv:1309.4092 Hill & Solon

Credit: Graham Kribs' slides



- Loop cross-section smaller than neutrino floor
- How to do better?

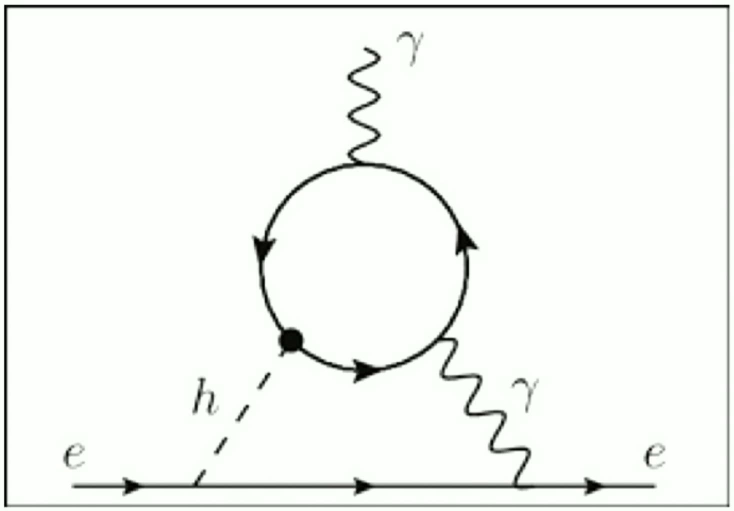
MORE GENERALLY...



The last Complex WIMPs standing

Salvatore Bottaro,[1,2] Dario Buttazzo,[2] Marco Costa,[1,2] Roberto Franceschini,[3] Paolo Panci,[4,2] Diego Redigolo,[5,6] and Ludovico Vittorio[1,2]

EDM EXPERIMENTS



$\mathcal{O}(1)$ CP violation in the Chargino sector can give rise to electron EDM

Co, Sheff, Wells arXiv: 2105.12142

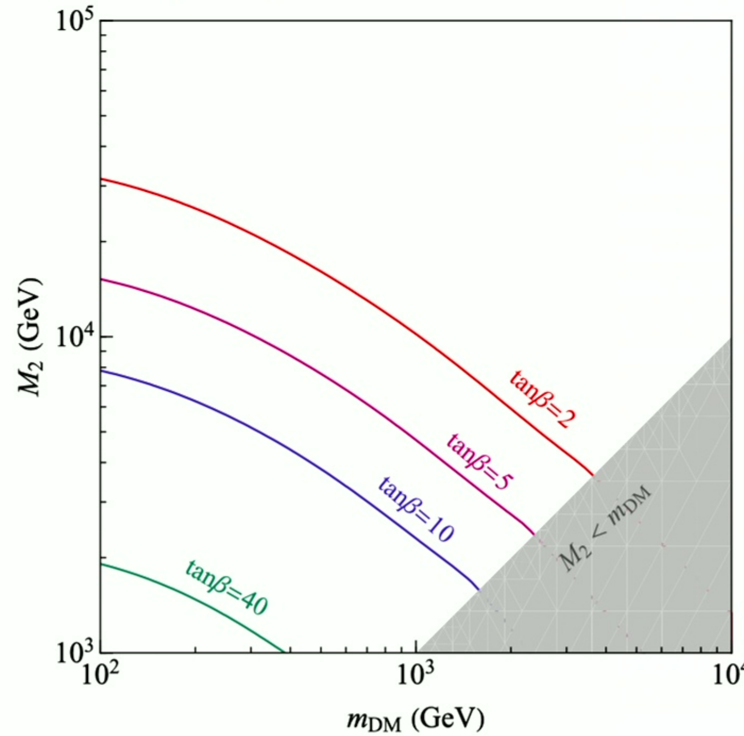
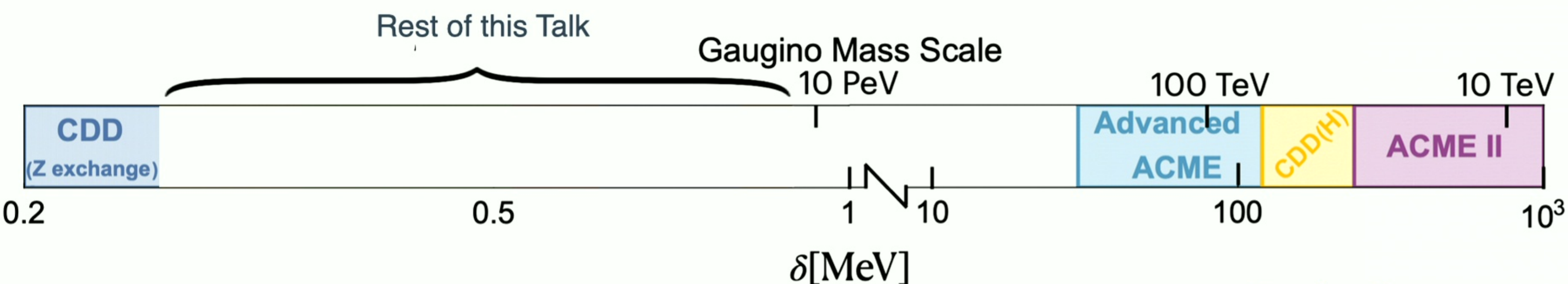


FIG. 5. Exclusion limits from the e-EDM limit, $d_e < 1.1 \times 10^{-29} e$ cm, obtained by ACME-II [61]. M_2 is assumed to be $0.3 M_1$, and $\phi = \pi/2$. The region very close to the diagonal is removed due to complications from the neutralino mass degeneracy, and below the diagonal is ignored as the wino becomes the LSP.

LIMITS ON SPLITTING



Tan $\beta = 2$

OUTLINE

- ✦ Intro To Higgsinos and summary
- ✦ Improvements in Direct Detection prospects
- ✦ Nuclear Isomers as exothermic DM detectors

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MAXIMIZE INITIAL KE

- $\delta m \leq \text{KE} = \frac{1}{2}\mu v_{\text{vir}}^2 \approx 200 - 400$ keV
- Why? μ set by Xenon or Tungsten and maximum v_{vir} set by $v_{\text{esc}} + v_{\text{E}}$
- Can we do better?

EFFECT OF LMC

- ✦Standard Halo Model does not account for satellites
- ✦The LMC 50 Myr ago made its closest pass yet of the Milky Way @ 48 kpc distance
- ✦This left high speed DM debris as well as accelerated Milky Way DM

The highest-speed local dark matter particles come from the Large Magellanic Cloud

G. Besla,[a,1] A. H. G. Peter,[b] N. Garavito-Camargo[a]

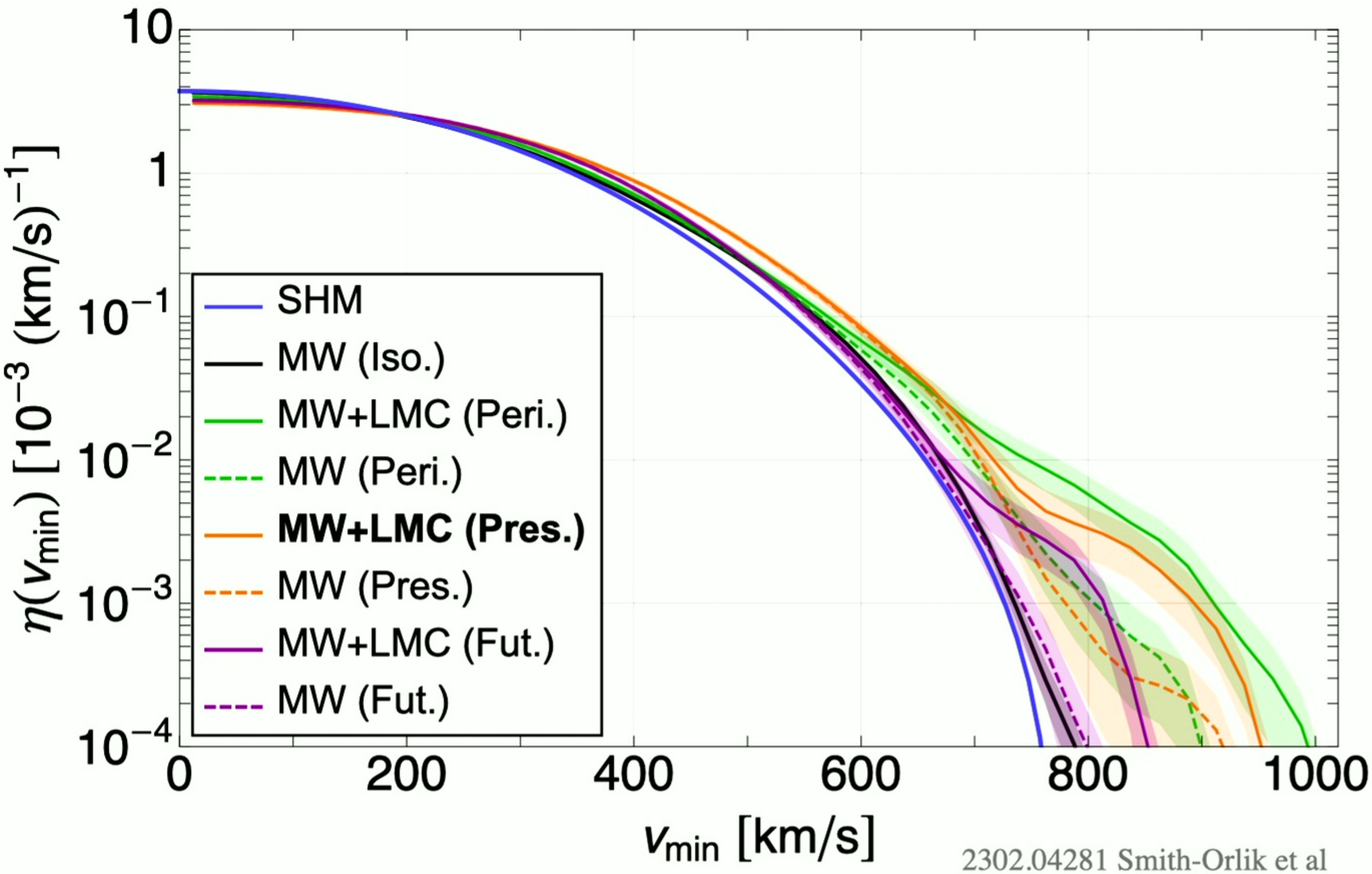
Effects on the local dark matter distribution due to the Large Magellanic Cloud

Katelin Donaldson,[1★] Michael S. Petersen,[2] Jorge Peñarrubia[1,3]

The impact of the Large Magellanic Cloud on dark matter direct detection signals

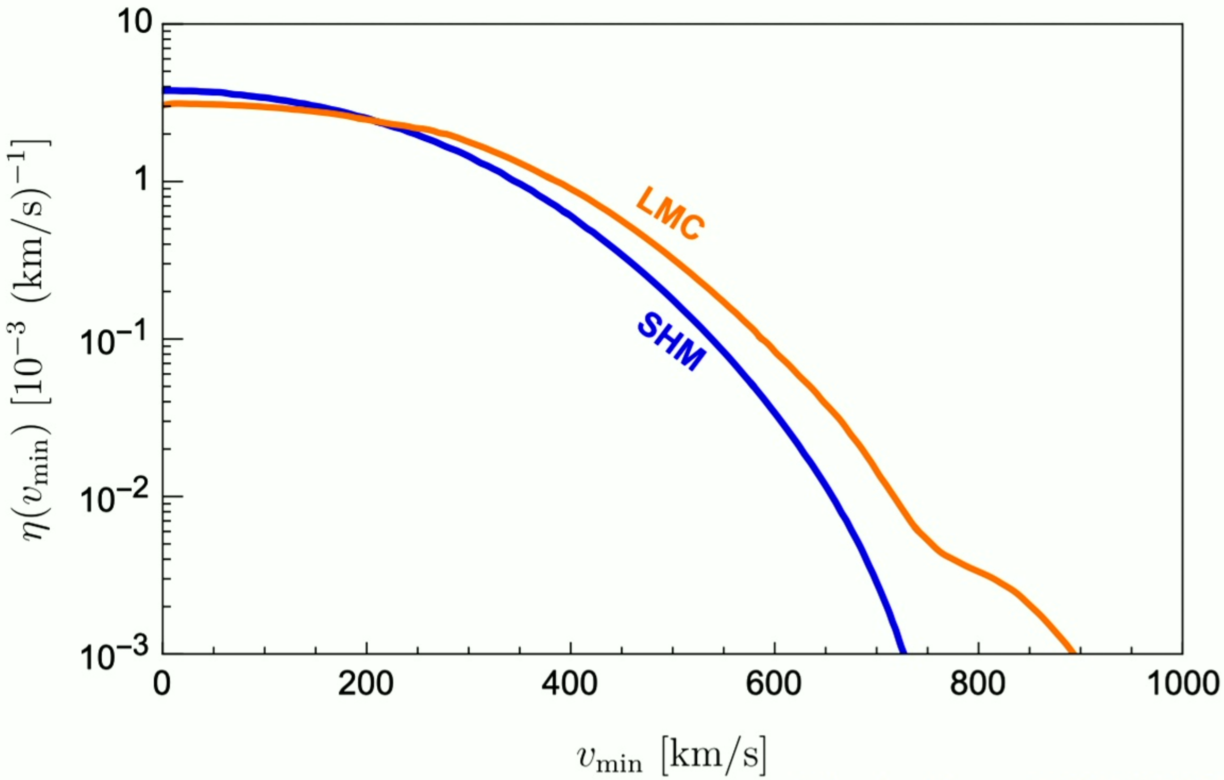
Adam Smith-Orlik,[a] Nima Ronaghi,[b] Nassim Bozorgnia,[b,c] Marius Cautun,[d] Azadeh Fattahi,[e] Gurtina Besla,[f] Carlos S. Frenk,[e] Nicolás Garavito-Camargo,[g] Facundo A. Gómez,[h,i] Robert J. J. Grand,[j,k,l] Federico Marinacci,[m] and Annika H. G. Peter[n]

LMC FLUX



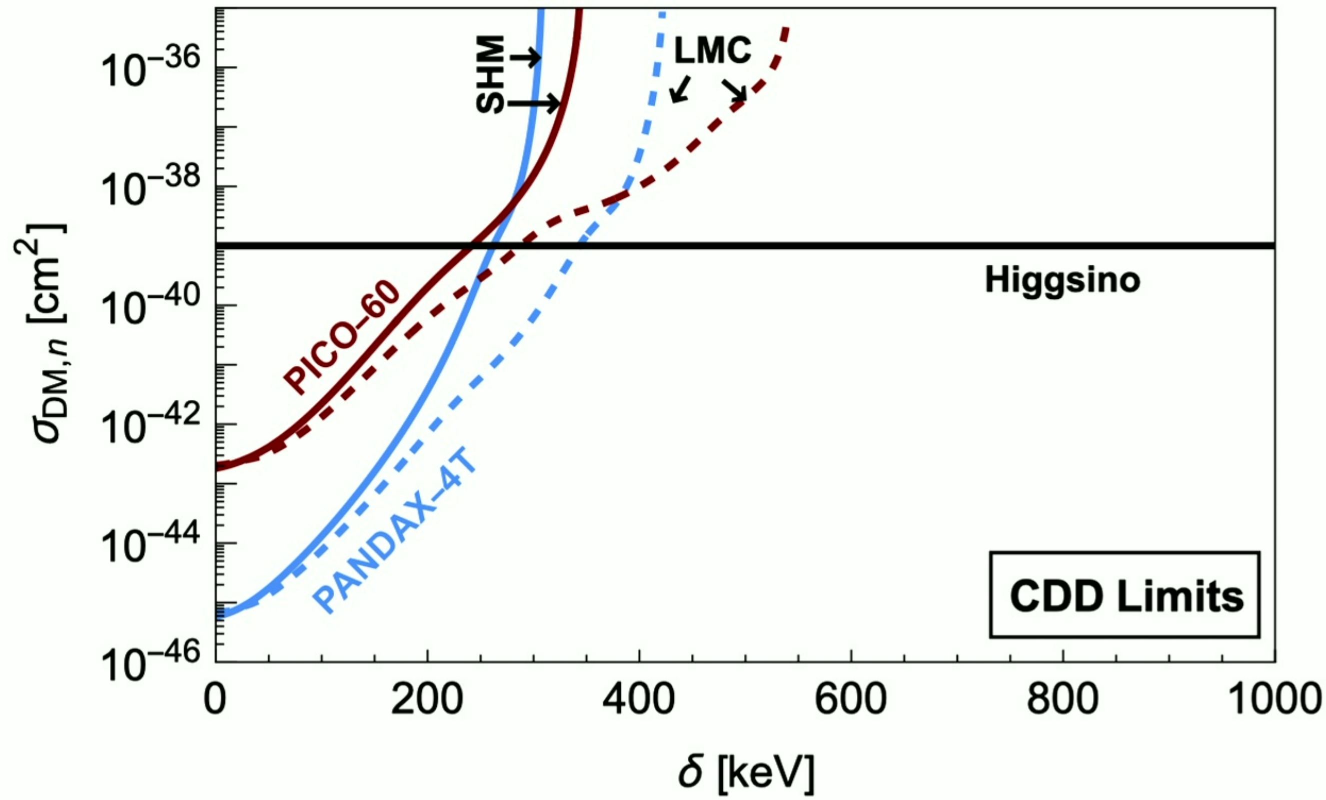
2302.04281 Smith-Orlik et al

LMC FLUX



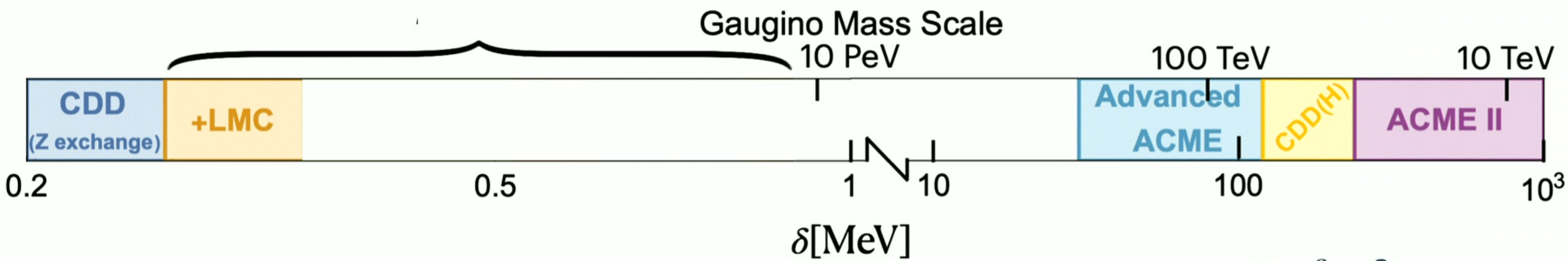
Adapted from 2302.04281 Annika Peter + other authors
Hydro-simulations of Milky Way-like Galaxies

SHM VS LMC



10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
$\sigma_{DM,n}$ [cm^2]
SHM
LMC
Higgsino
PICO-60
PANDAX-4T
CDD Limits
0
200
400
600
800
1000
δ [keV]

LIMITS ON SPLITTING



Tan $\beta = 2$

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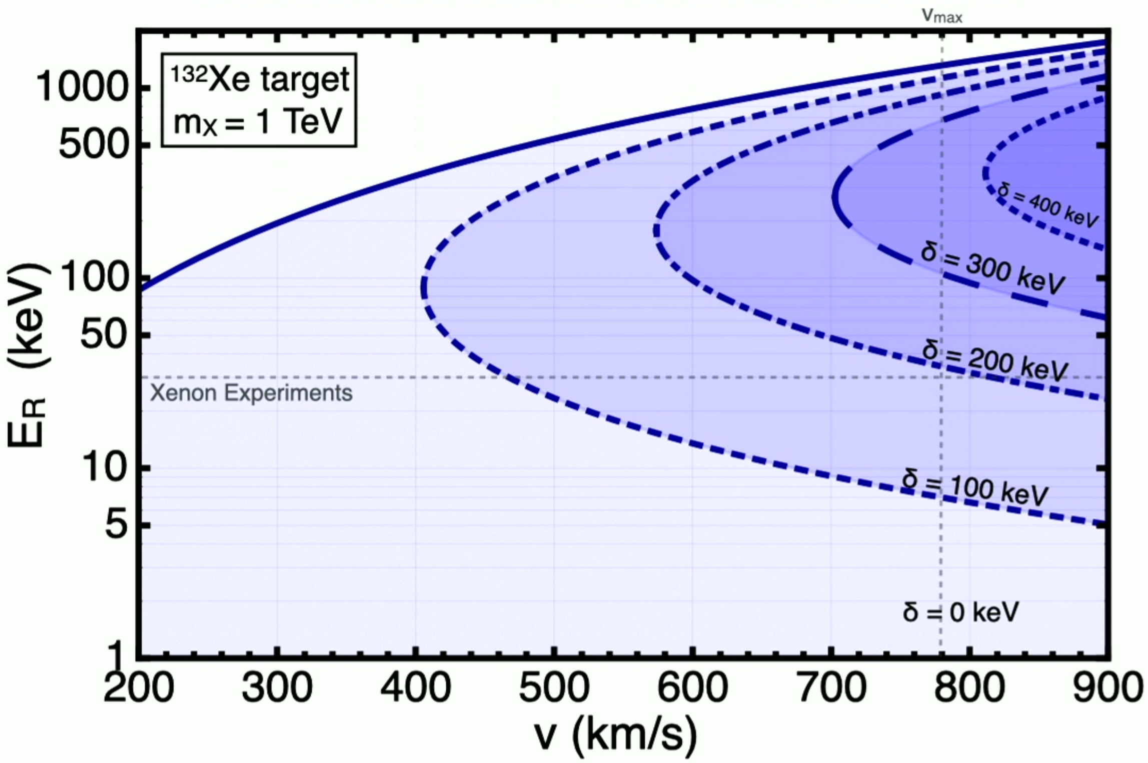
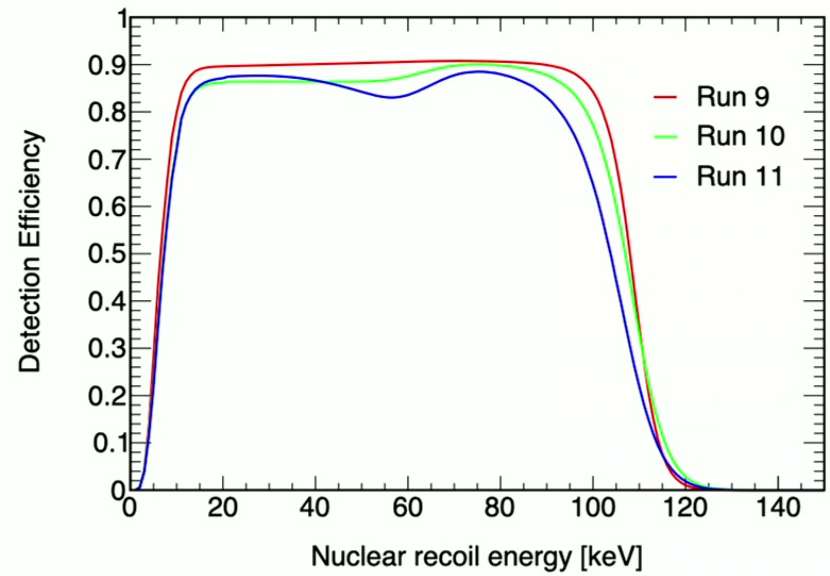
KINEMATIC MISMATCH

Bramante, Fox, Kribs, Martin, arXiv: 1608.02662



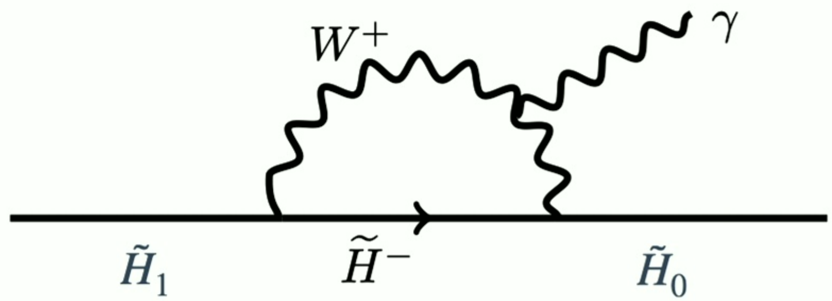
The typical recoil energy is roughly δ



PandaX-II - 2205.08066

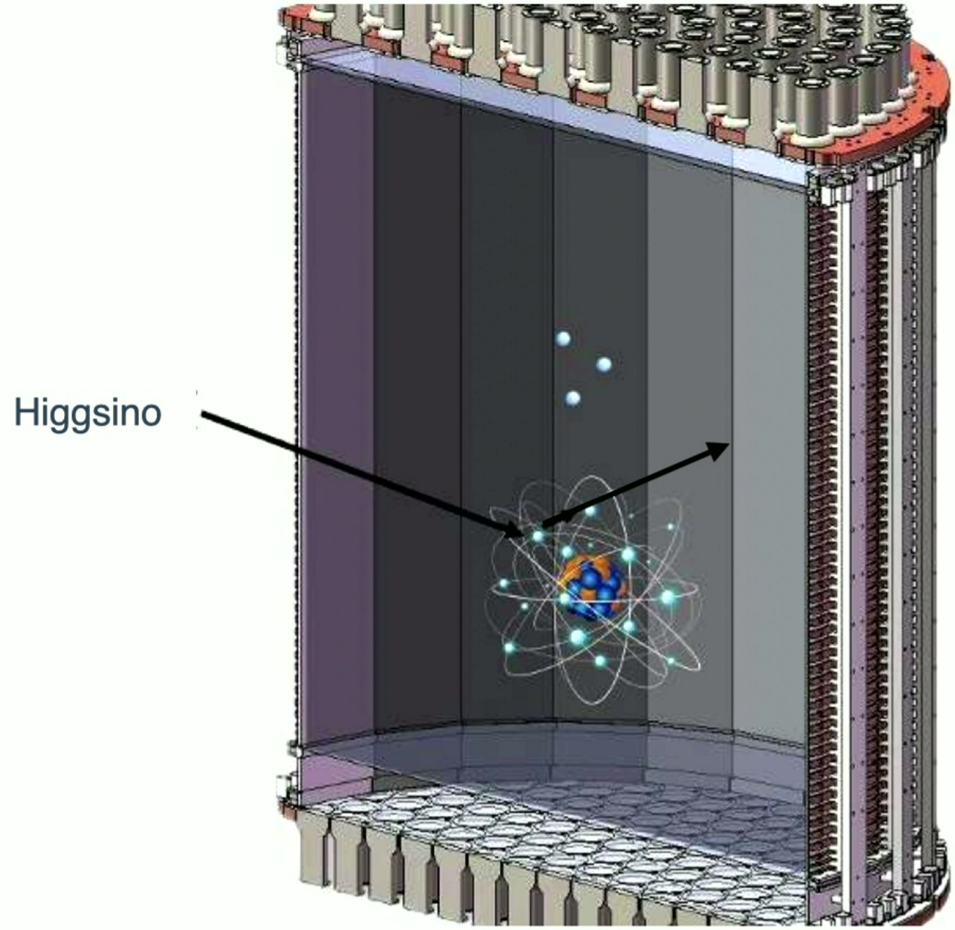
DECAY LENGTH

$$l_{\tilde{H}_2} = 7.46\ \text{km} \left(\frac{v}{400\ \text{km/s}} \right) \left(\frac{400\ \text{keV}}{\delta} \right)^3$$



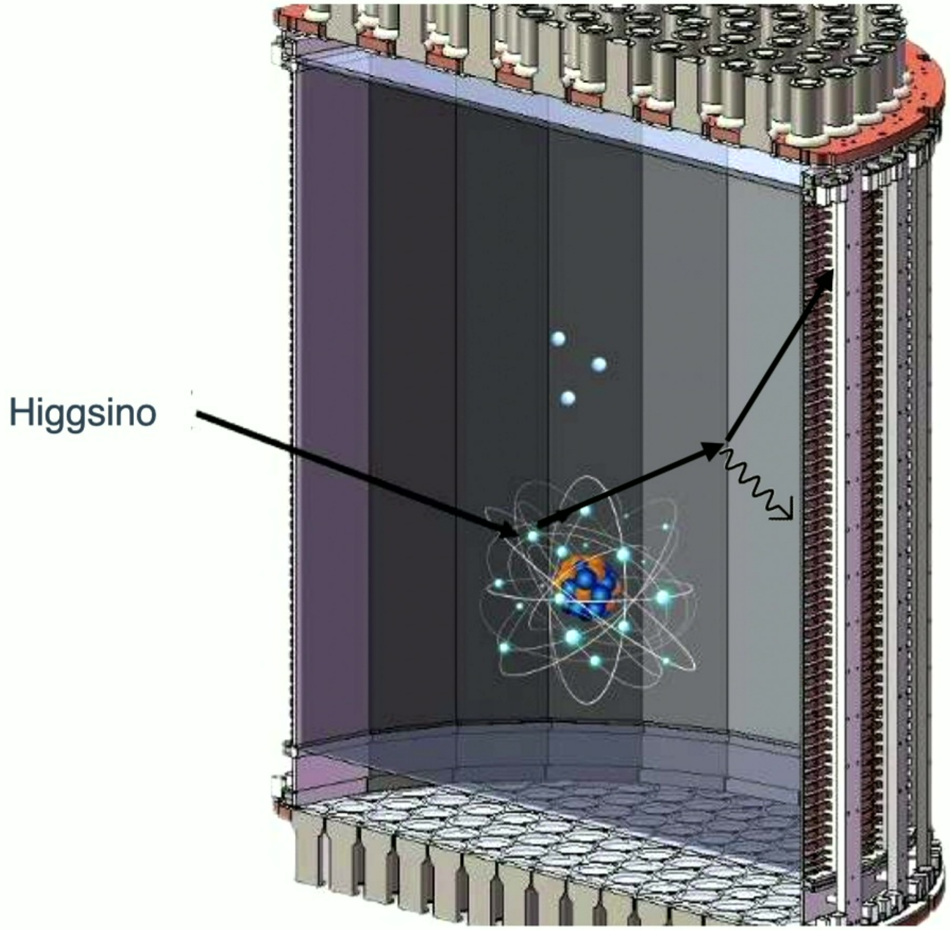
If you up-convert the Higgsino, it can decay back terrestrially!

TRIPLE COINCIDENCE?



- Usual S1-S2

TRIPLE COINCIDENCE?



- Usual S1-S2
- Additionally - S3 : In-volume excited Higgsino decay to ground state via signle photon
- What is the S1-S2-S3 Time coincident background?
- Does it do better than S1-S2 itself?
- Can we use the water veto volume?

What is the S1-S2-S3 time coincident background?

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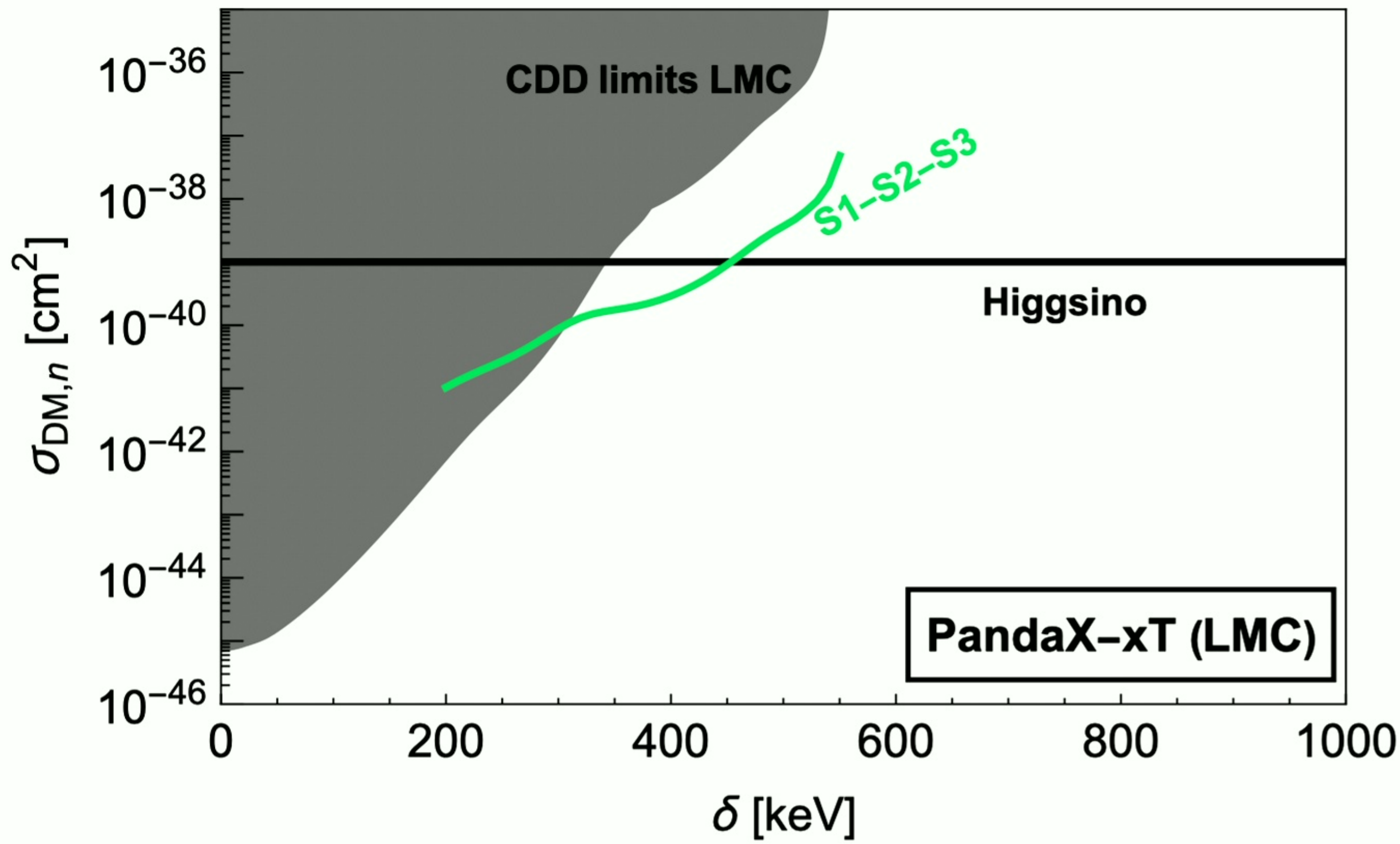
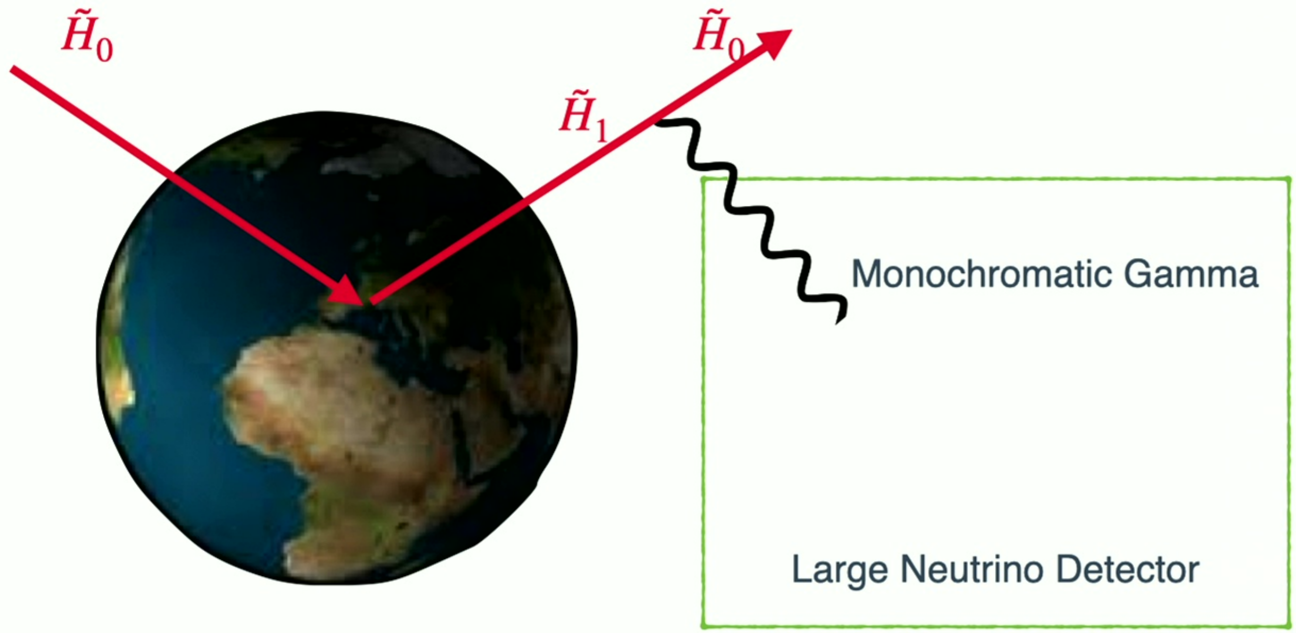
OPTIMISTIC PROJECTION



10 years - 43 ton
No background

LUMINOUS DETECTION



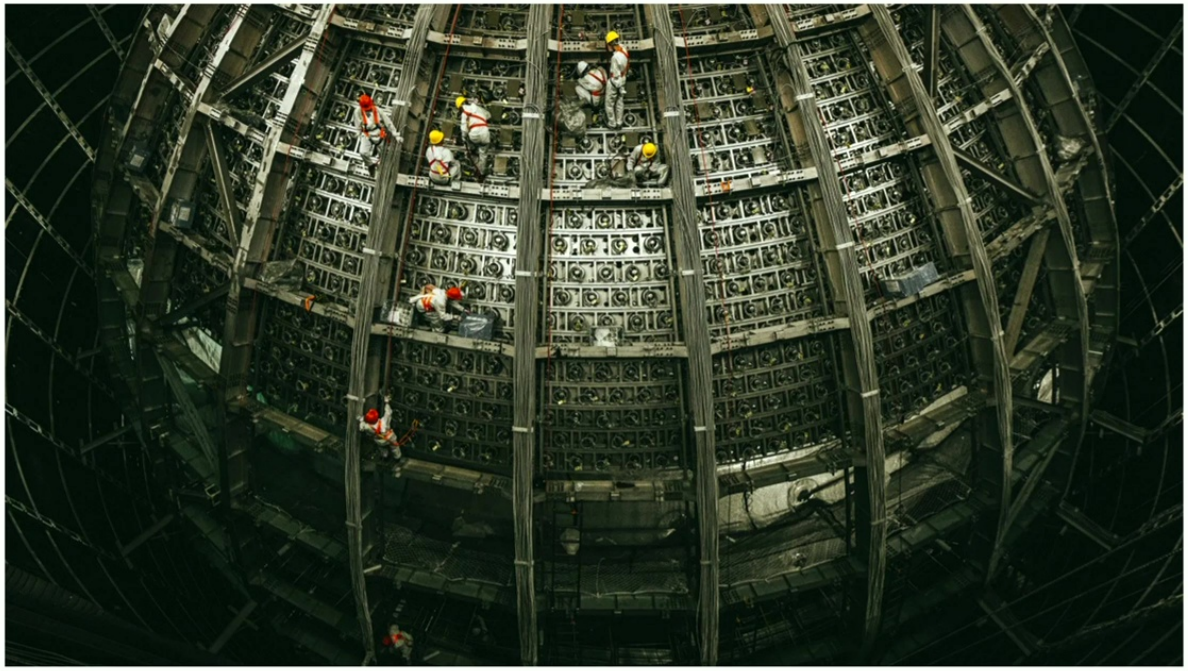
1904.09994: Eby, Fox, Harnik, Kribs

MAXIMIZE μ

element	A	n_A [km^{-3}]	a_A	relevant source	$\delta_{\mathrm{max},A}^{\mathrm{LMC}}$ [keV]	$l_{\mathrm{max},A}^{\mathrm{LMC}}$ [km]	$\delta_{\mathrm{max},A}^{\mathrm{SHM}}$ [keV]	$l_{\mathrm{max},A}^{\mathrm{SHM}}$ [km]
Ca	40.078	1.8×10^{36}	0.0261	mantle	180	180	120	150
Fe	55.85	3.0×10^{36}	0.063	mantle	250	71	160	56
Sr	87.62	6.8×10^{32}	22×10^{-6}	mantle	390	20	250	16
		6.2×10^{33}	320×10^{-6}	total crust				
Ba	137.33	1.4×10^{32}	6.85×10^{-6}	mantle	580	5.8	370	4.6
		5.7×10^{33}	456×10^{-6}	total crust				
Pb	207.2	1.4×10^{32}	17×10^{-6}	upper crust	830	2.0	530	1.6
Th	232.04	7.7×10^{31}	10.5×10^{-6}	upper crust	920	1.5	580	1.2
U	238.03	1.9×10^{31}	2.7×10^{-6}	upper crust	940	1.4	590	1.1

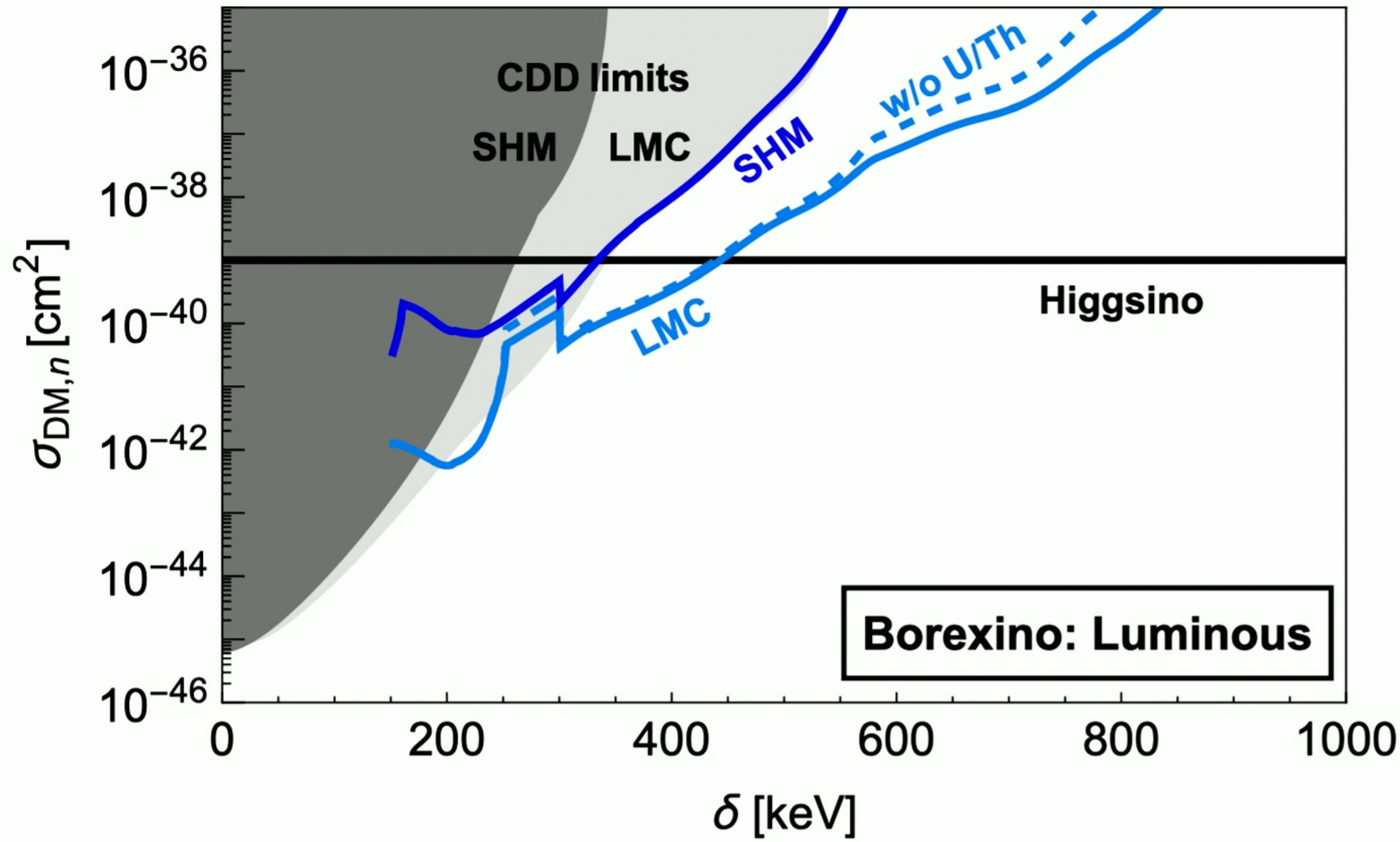
LARGE VOLUMES

detector	radius [m]	mass [t]	$E_{\rm thr}$ [keV]
Borexino	4.25	278	150
JUNO	17.5	20000	$150^{\rm a}$
SNO+	6	780	$\sim 200 - 400$



Jiangmen Underground Neutrino Observatory

Re-ANALYSIS - BOREXINO



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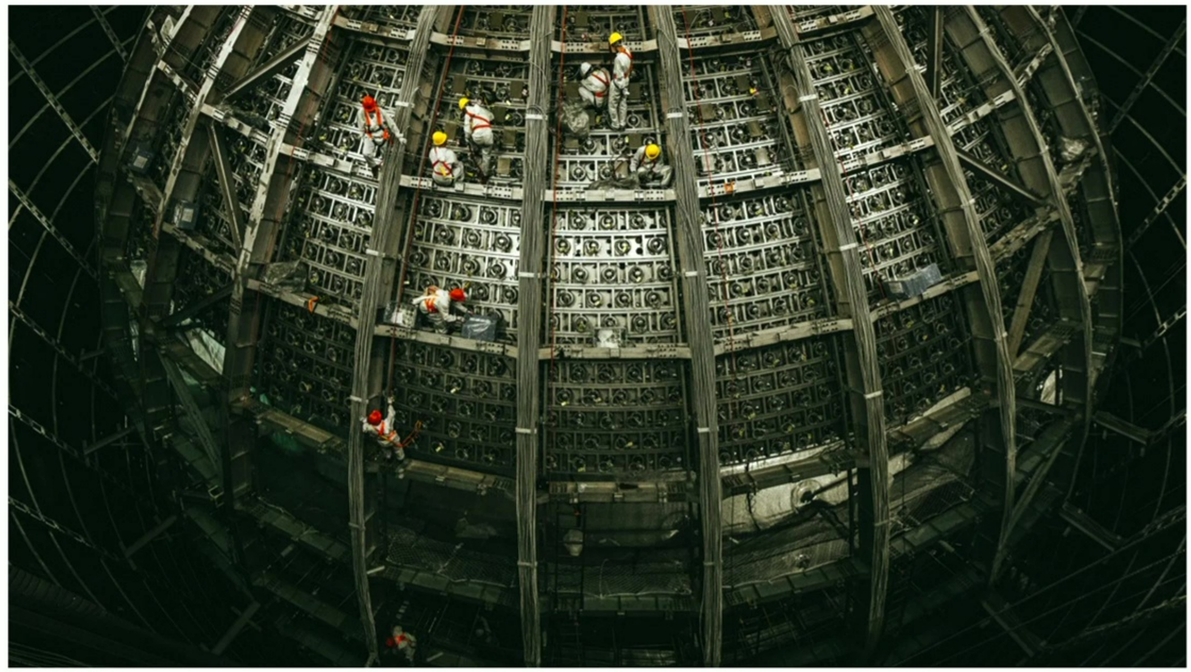
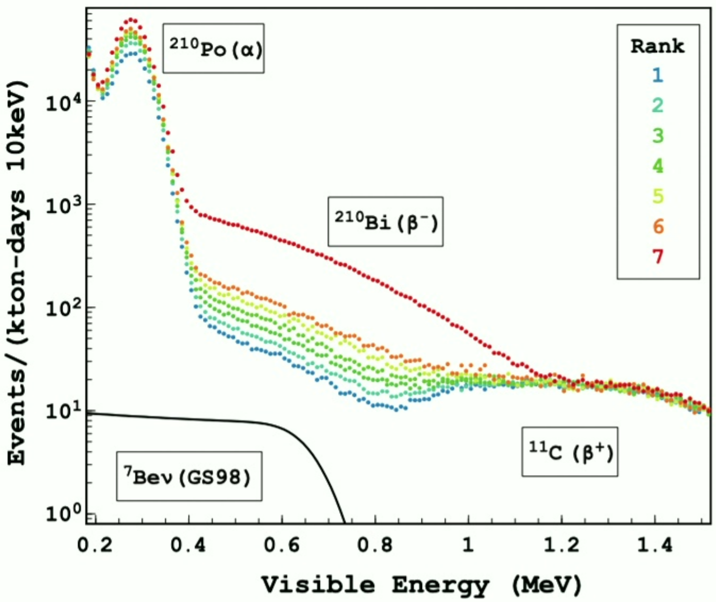
SUPPLEMENTATION



Juno Experiment

ONGOING WORK - KamLAND



- In progress: Collaboration with KamLAND experimentalists
- Using available data ≈10 years for a monochromatic photon search
- Future: KamLAND2-Zen

Masooma Sarfaraz

Spencer Axani

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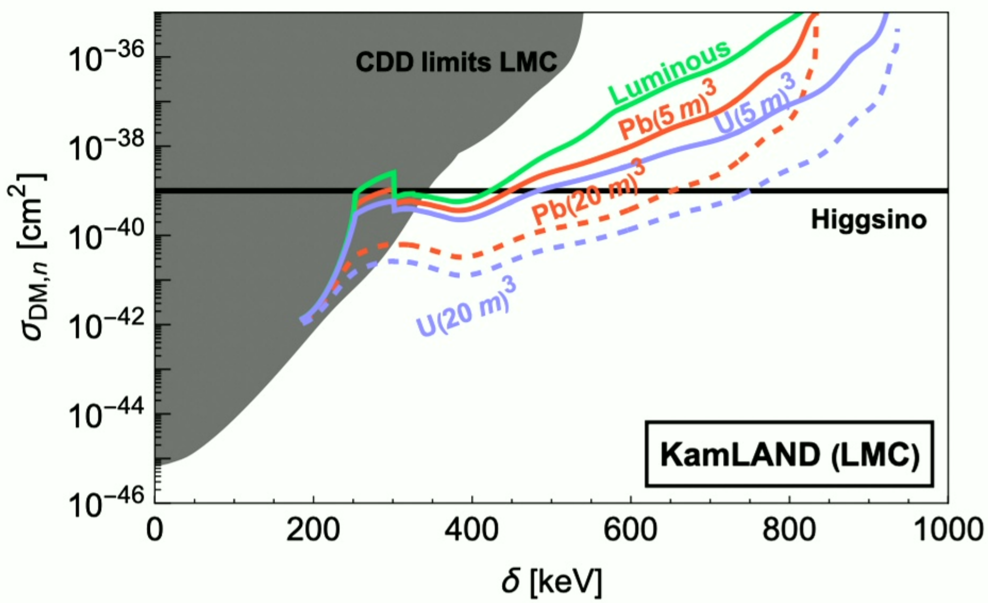
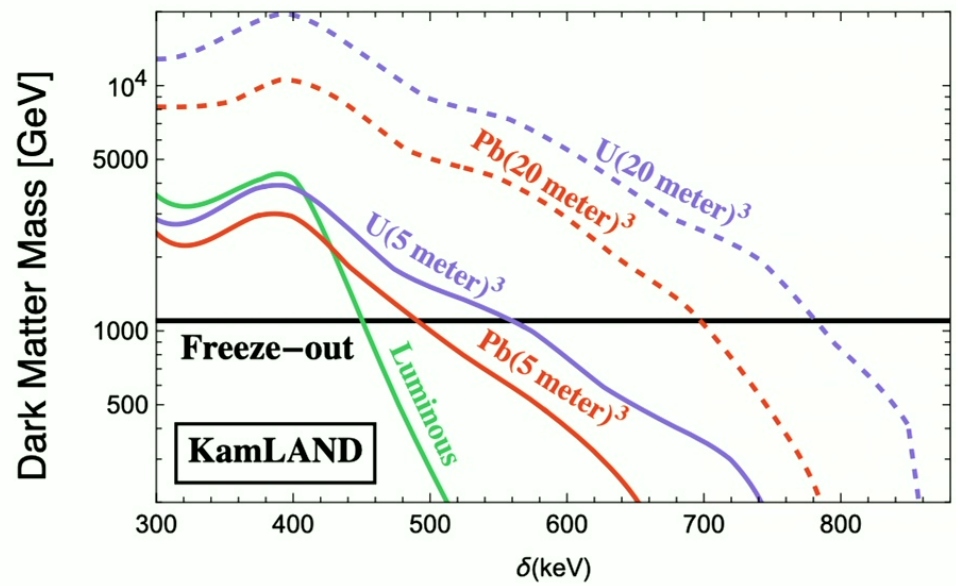
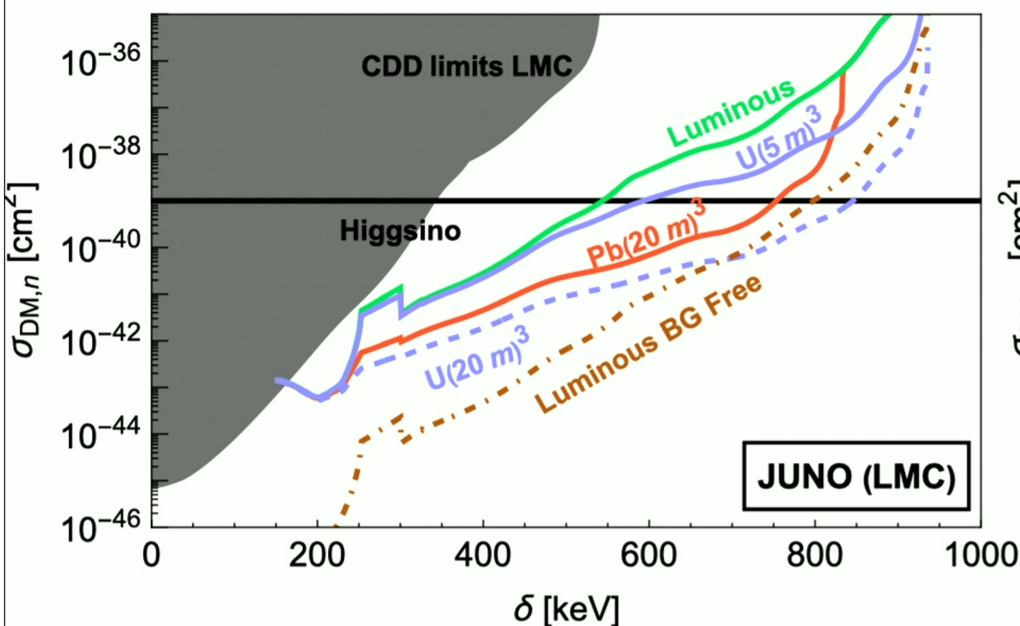
ONGOING WORK - KamLAND

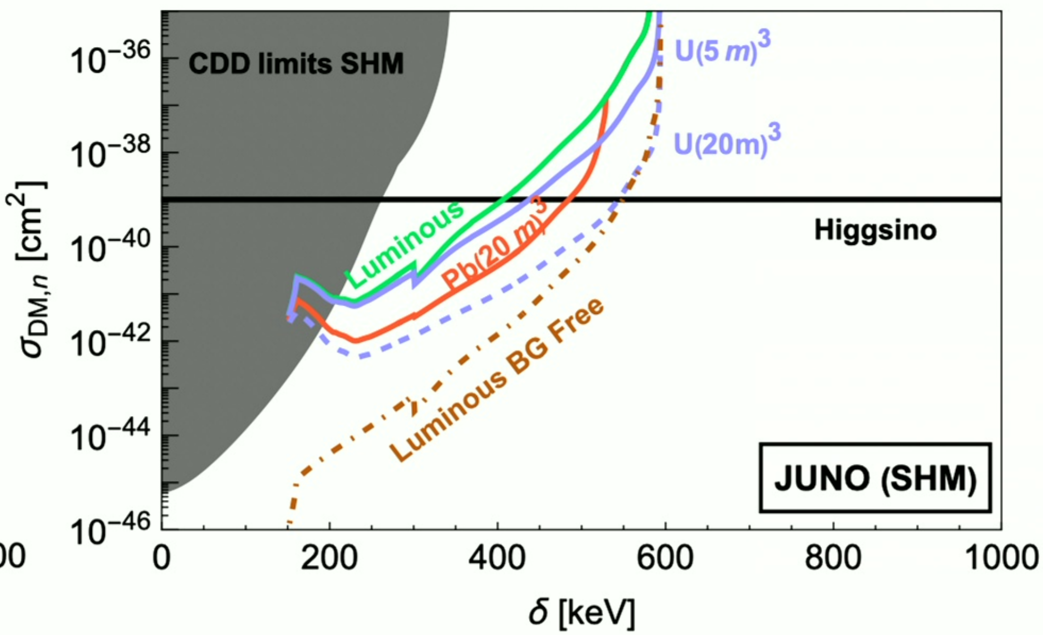




JUNO

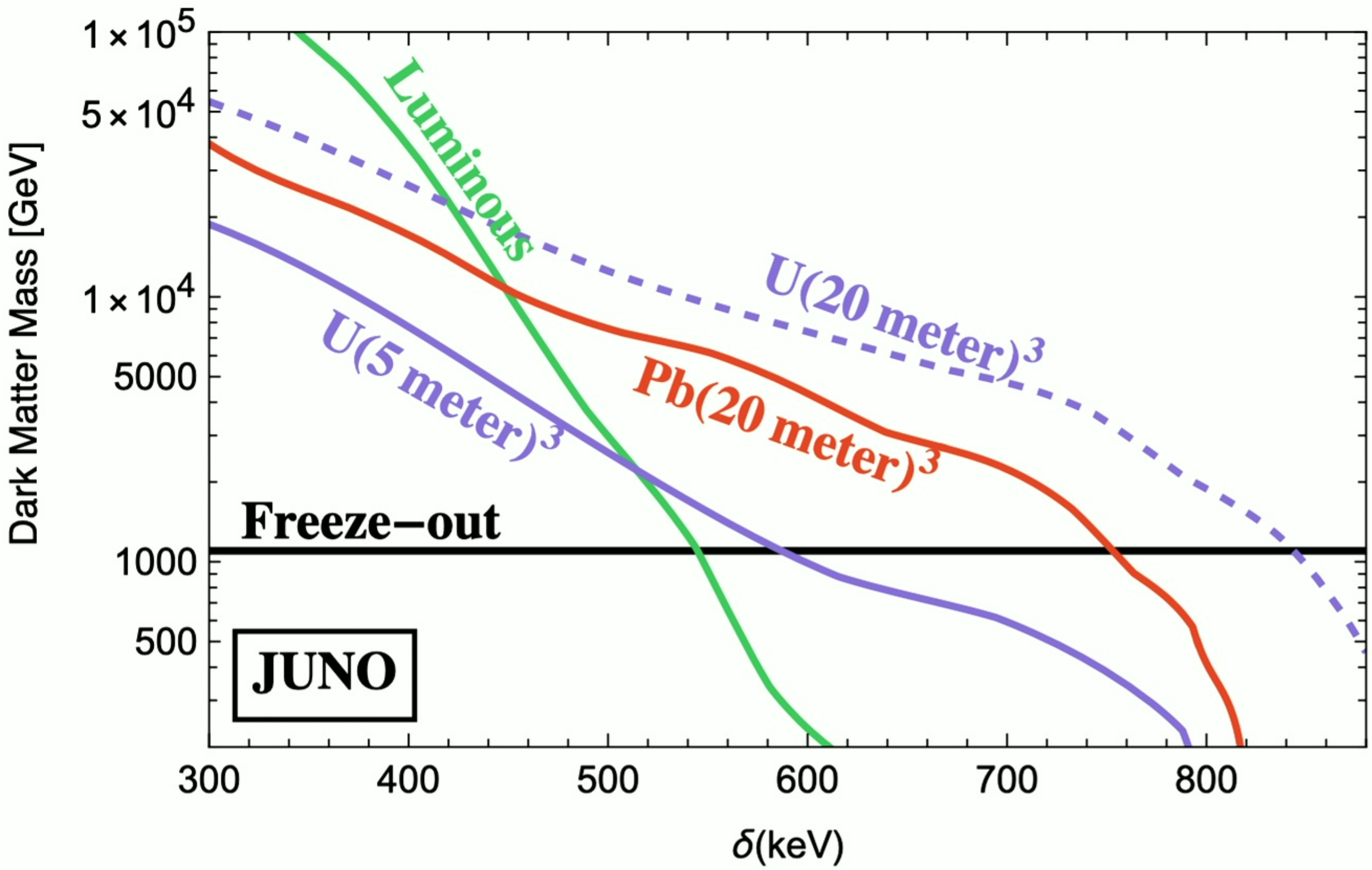


CDD limits LMC
Luminous
U(5 m)^3
Pb(20 m)^3
U(20 m)^3
Luminous BG Free
Higgsino
JUNO (LMC)
σ_DM,n [cm^2]
δ [keV]



CDD limits SHM
U(5 m)^3
U(20m)^3
Luminous
Pb(20 m)^3
Luminous BG Free
Higgsino
JUNO (SHM)
σ_DM,n [cm^2]
δ [keV]

JUNO - Arbitrary Mass



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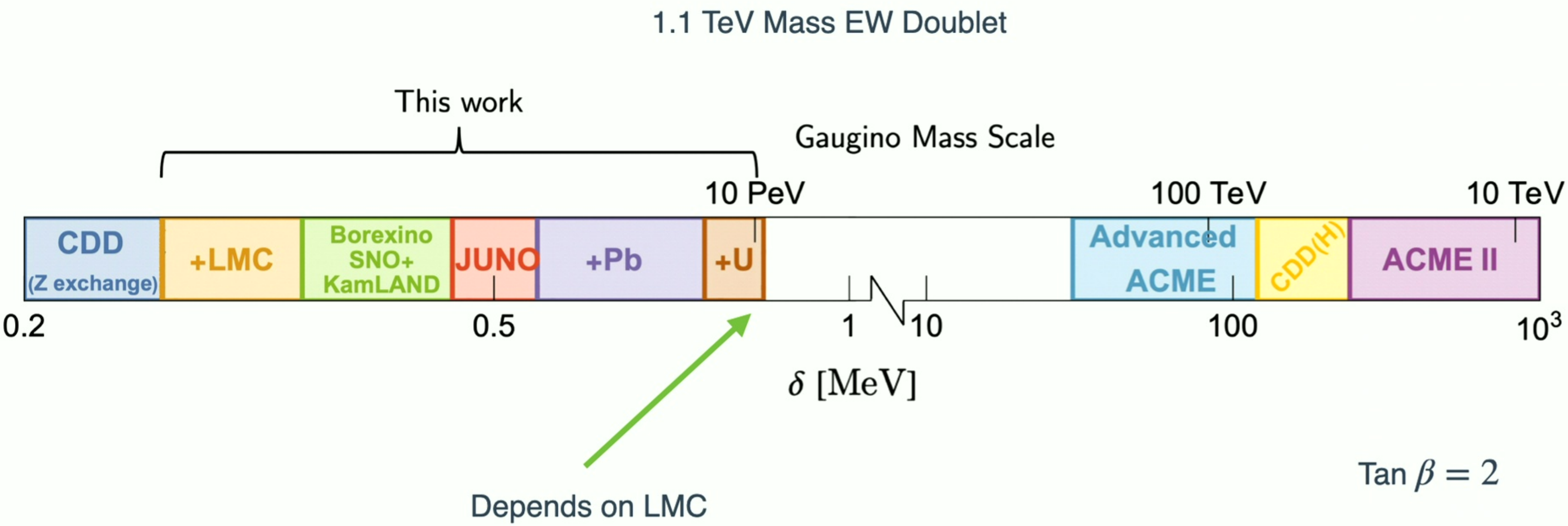
LIMITS ON SPLITTING



OUTLINE

- ✦ Intro To Higgsinos and summary
- ✦ Improvements in Direct Detection prospects
- ✦ Nuclear Isomers as exothermic DM detectors

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