RETURN OF THE WIMP

AN ABUNDANCE OF ANOMALIES

Southern California BSM
University of California Irvine
Irvine, CA
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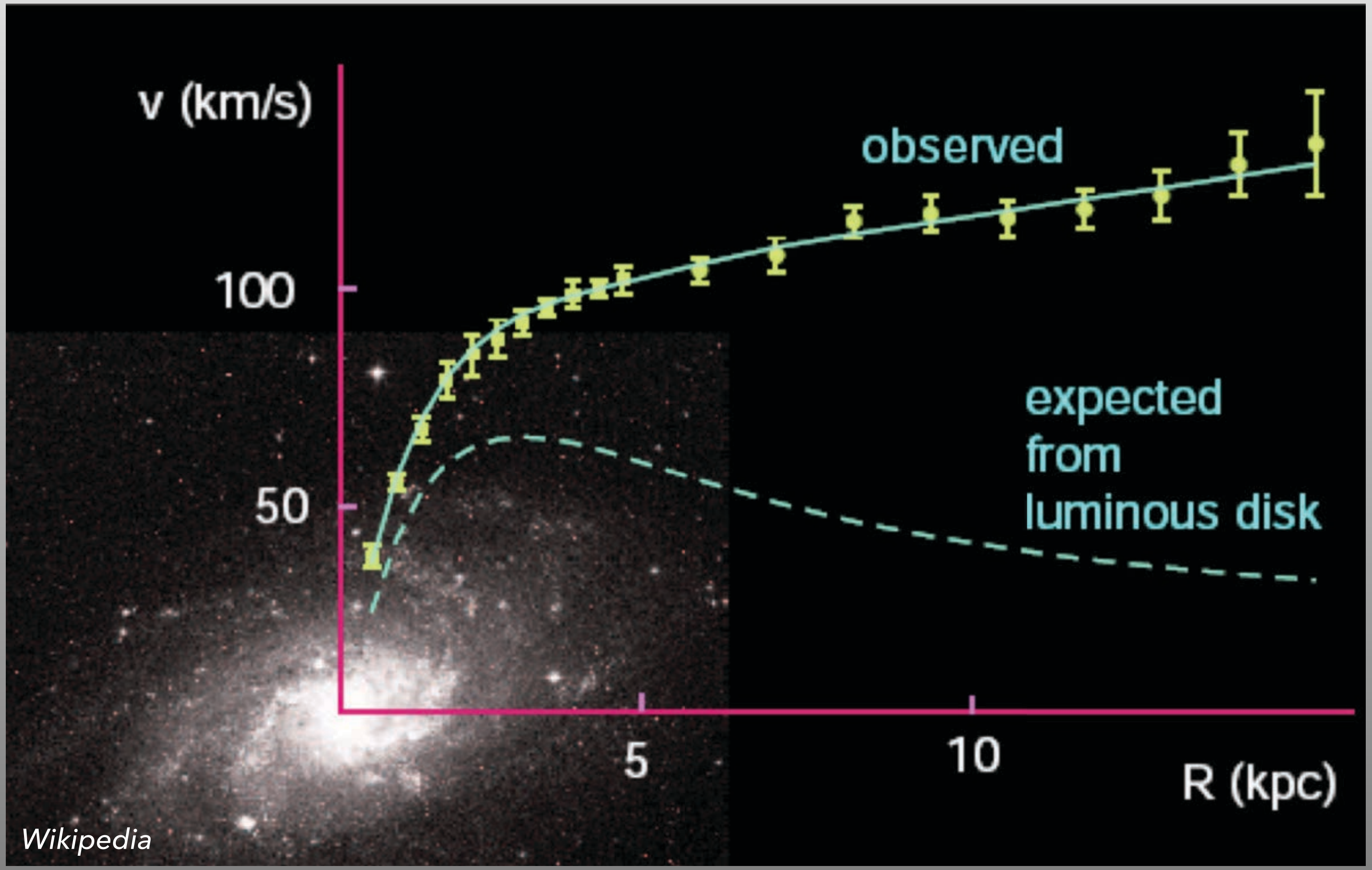
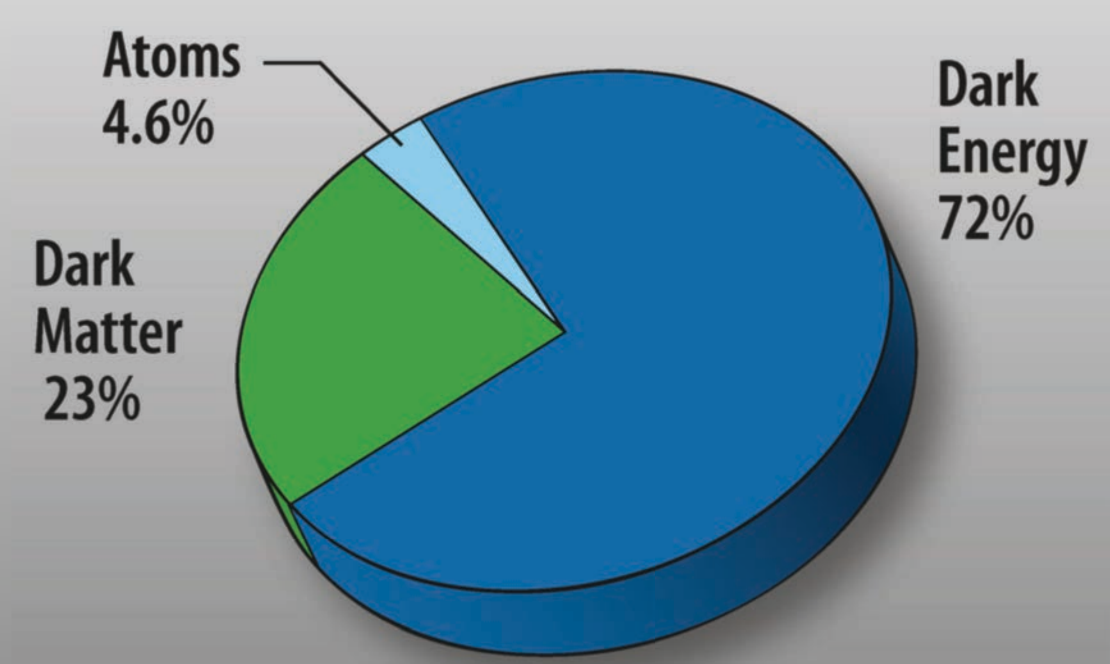
UC San Diego

THE STORY SO FAR...





- Plenty of evidence for dark matter interacting gravitationally.
- ~5x as much dark matter as ordinary matter in the universe.
- Present day abundance: $\Omega h^2 = 0.1188 \pm 0.0011$ (Planck, 2015)

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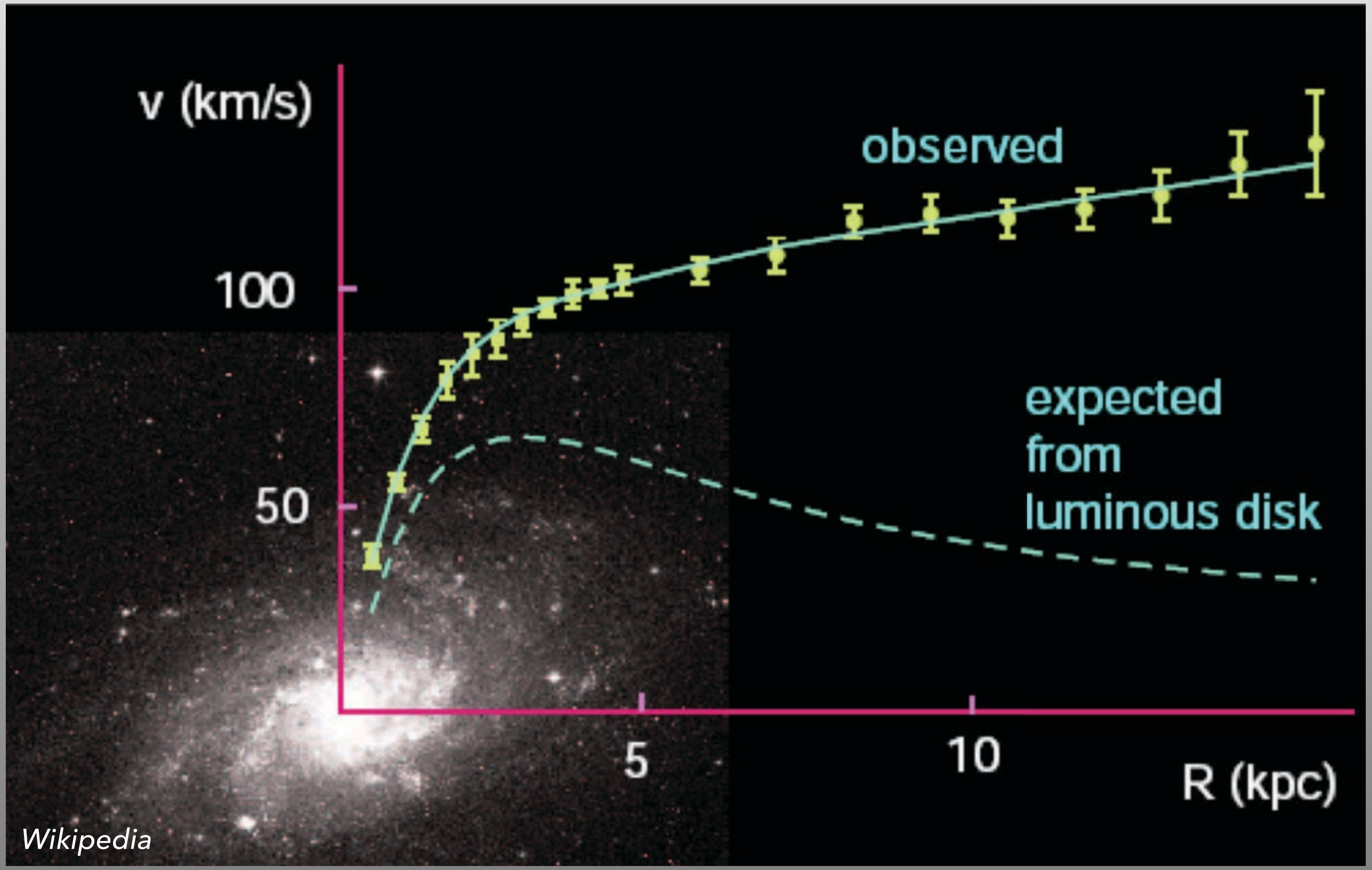

How does dark matter fit into the Standard Model?

- Not baryonic.
- Not electrically charged.
- Stable on the scale of the lifetime of the universe.
- Neutrinos are too hot, no large-scale structure.

- Plenty of evidence for dark matter interacting gravitationally.
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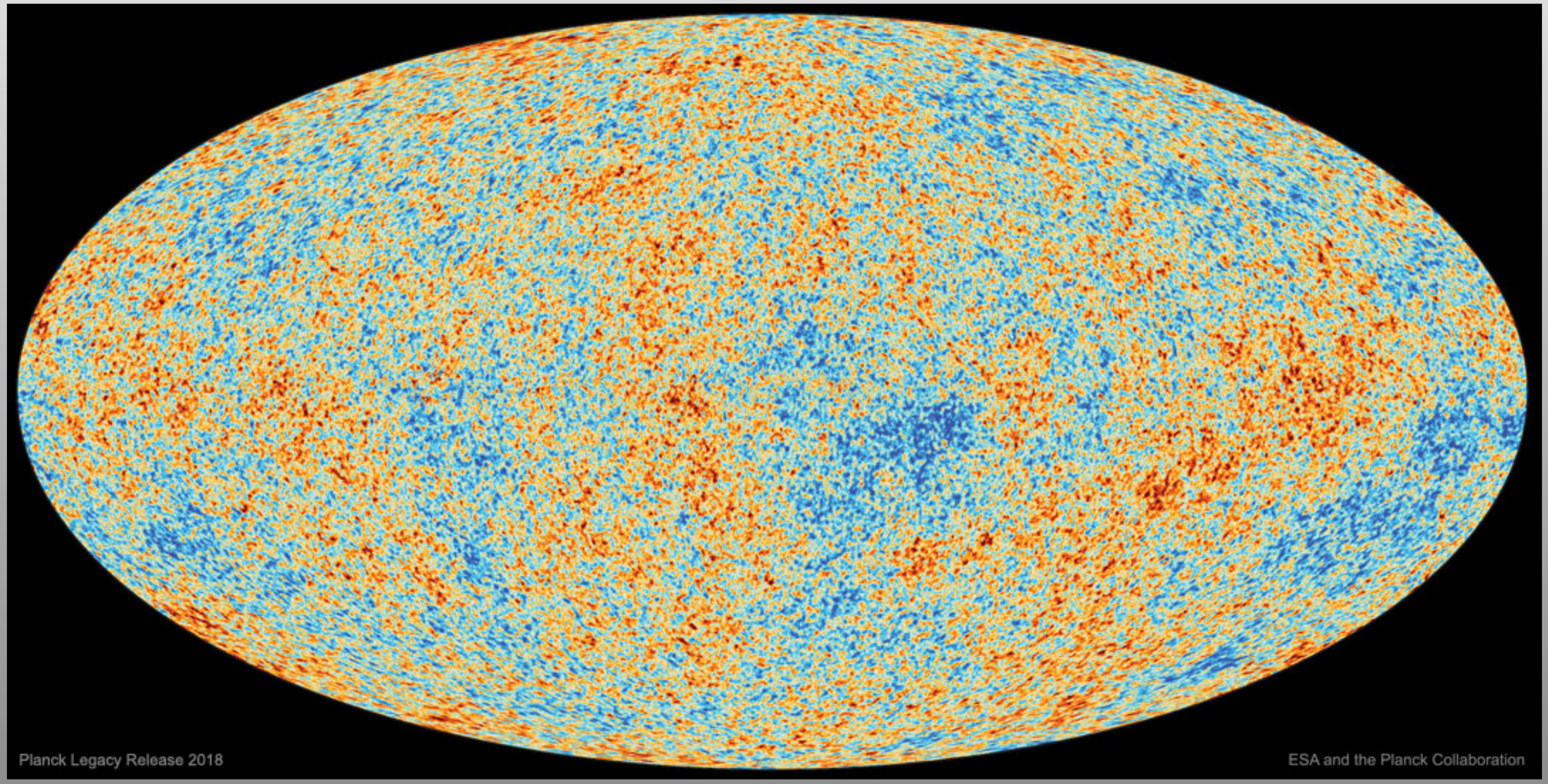
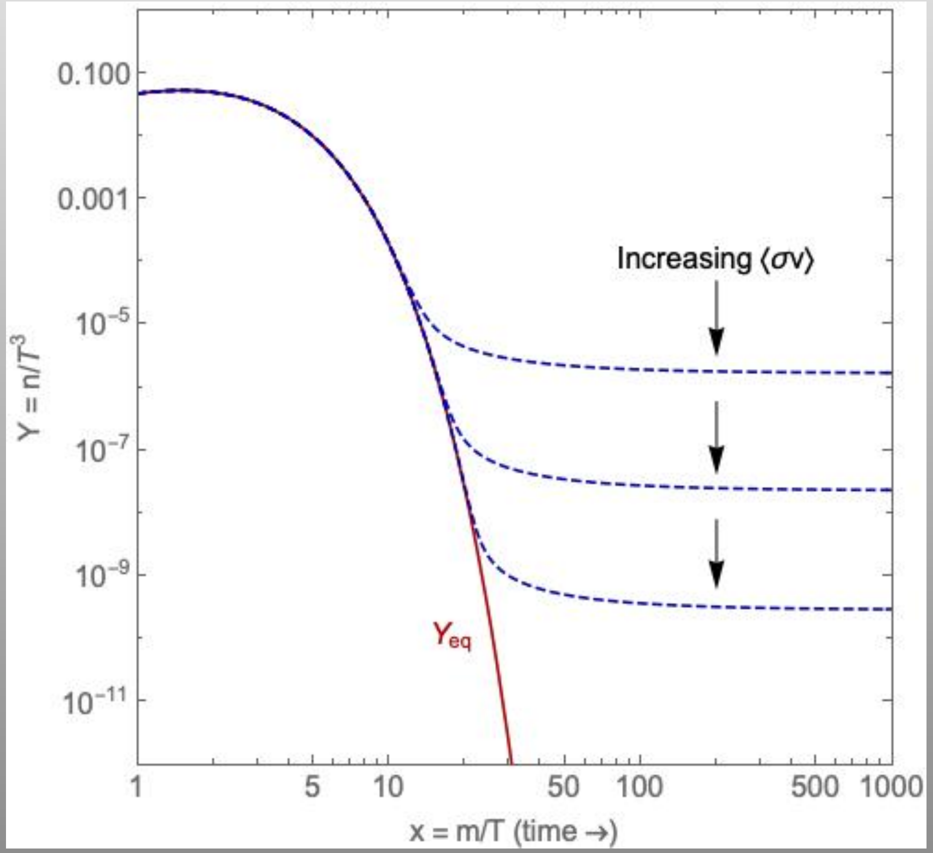




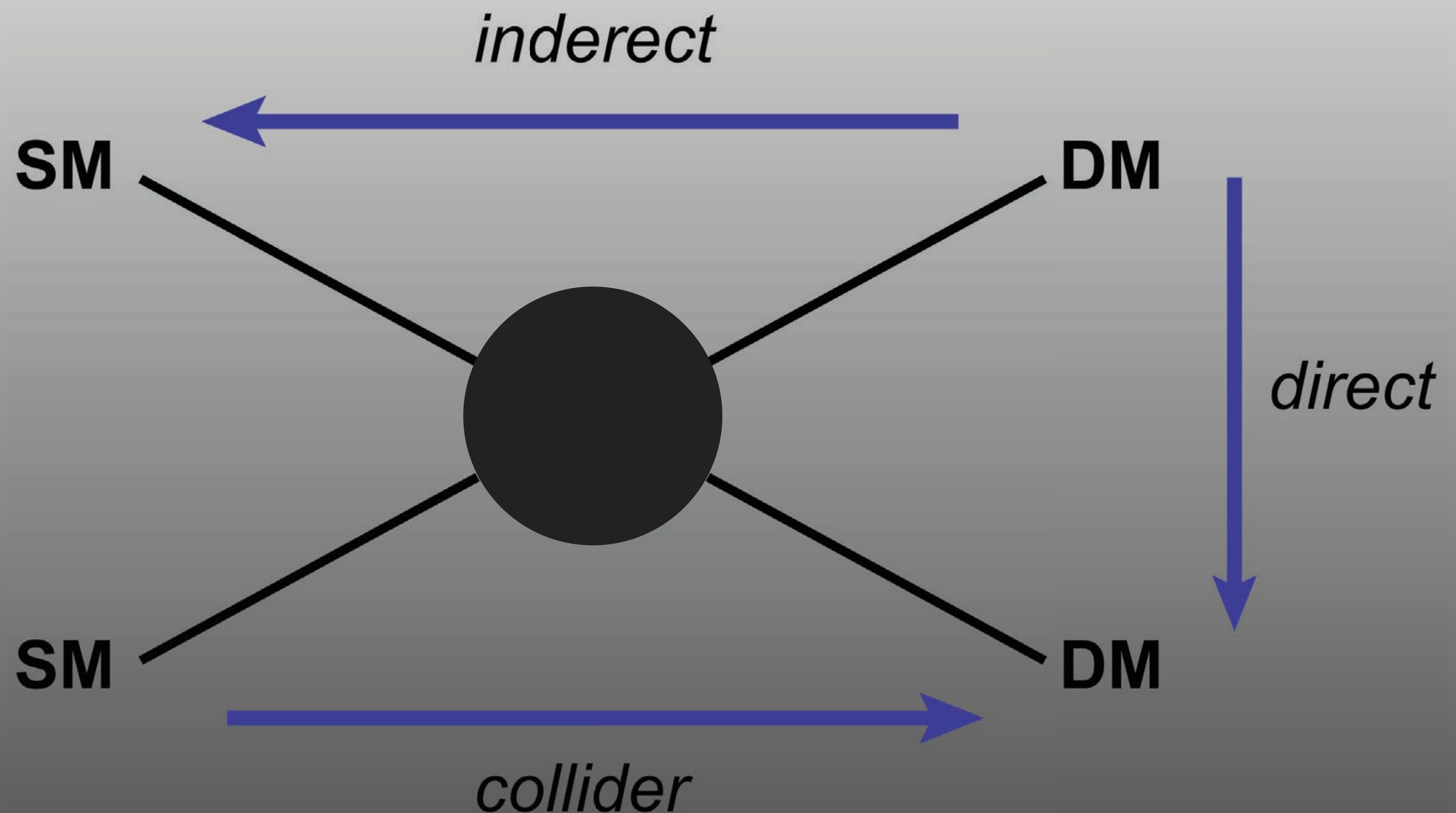
$$\Omega h^2 = 0.1188 \pm 0.0011\,, \qquad \sigma \propto \alpha^2/m^2$$

Weakly Interacting Massive Particles and the "WIMP miracle"

- In the standard freeze-out scenario, the observed relic density is obtained for weak-scale interaction strengths and masses $\mathcal{O}(100$ GeV$)$!

THE STORY SO FAR...

So off we go searching for WIMPs



Deliyergiyev, 2016

SUPERSYMMETRIC DARK MATTER

- Possible solution to the electroweak hierarchy problem.
- Predicts a WIMP-like dark matter candidate, stable due to R-parity.
- LHC probes strong dynamics well $\longrightarrow$ heavy squarks & gluinos.
- Relatively, the electroweak sector of SUSY is poorly constrained.

Minimal Supersymmetric Standard Model (MSSM)

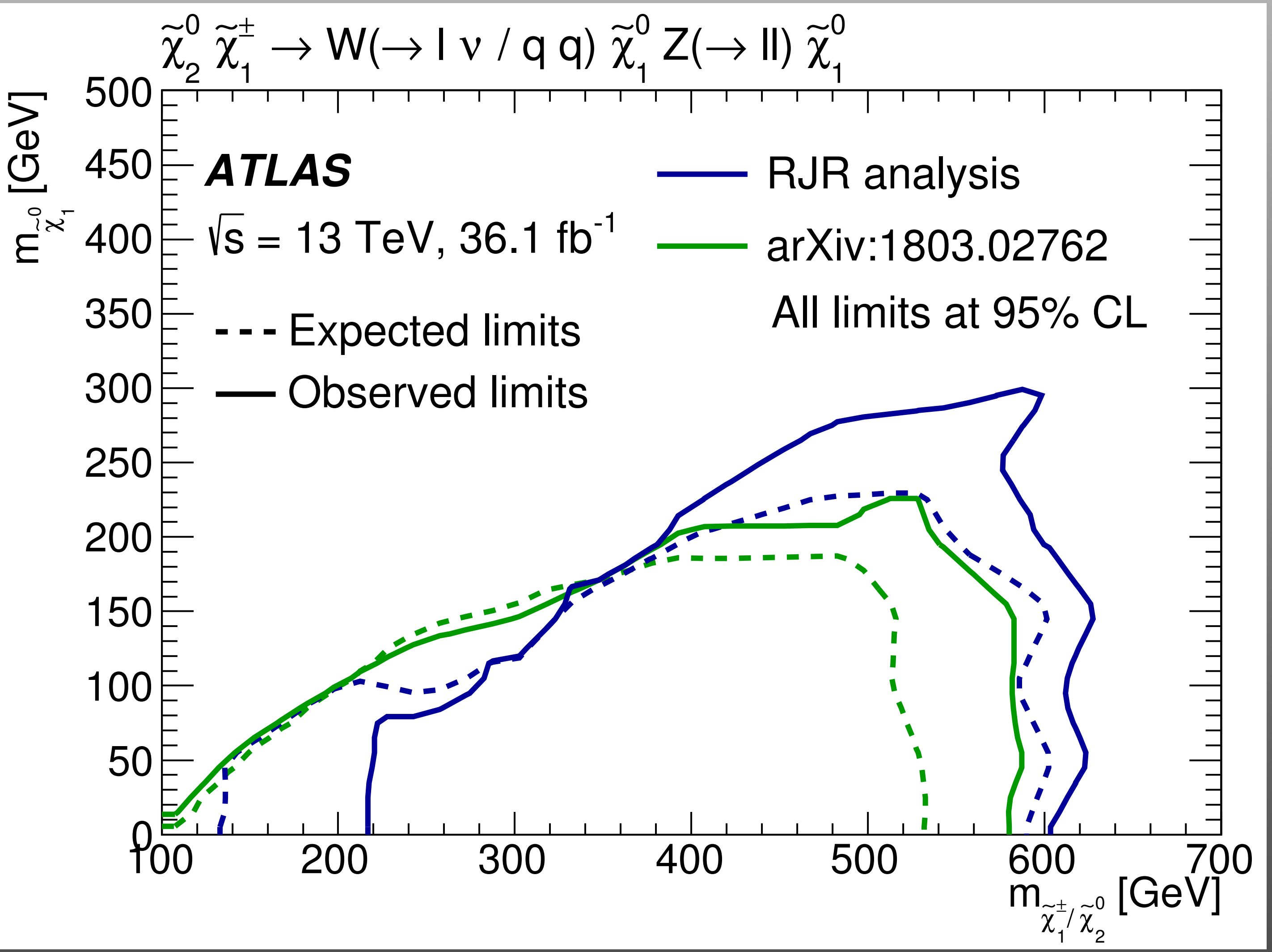
- 4 Majorana neutralinos, mixtures of $\{\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0\}$.
- Relevant parameters: M_1, M_2, μ, and $\tan\beta$.
- Also 2 charginos, mixtures of charged wino and Higgsinos.

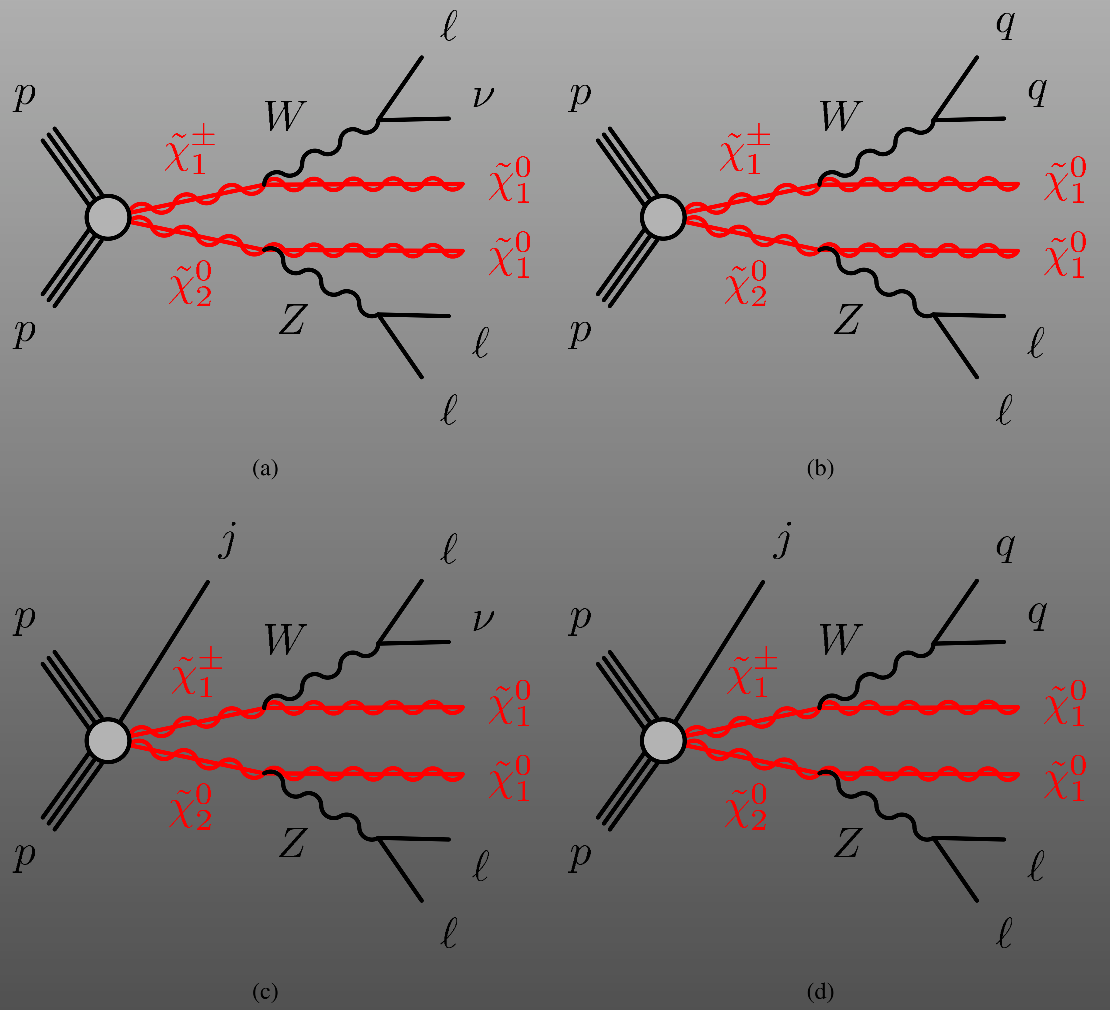
$$\chi = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_d^0 + N_{14}\tilde{H}_u^0$$

A NEW HOPE AT THE LHC

ATLAS search for chargino-neutralino production using "Recursive Jigsaw Reconstruction" (RJR), RAZOR-like variables. [Run 2, $36.1\ \mathrm{fb}^{-1}$]

- Jackson, Rogan, and Santoni, 2016 [arXiv:1607.08307]
- ATLAS Collaboration, 2018 [arXiv:1806.02293]

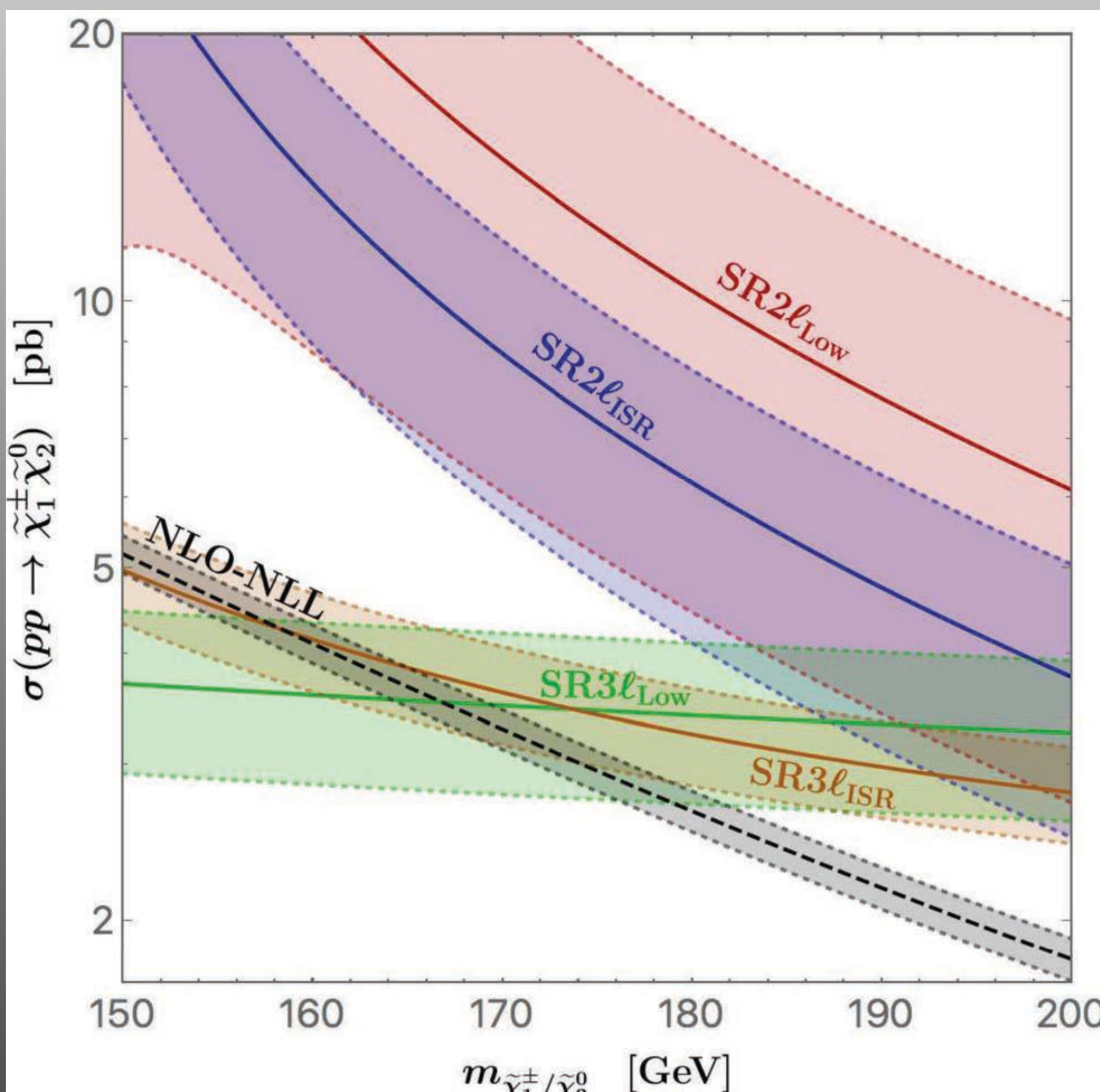




ANATOMY OF THE ATLAS EXCESS

What can this tell us about the MSSM and dark matter?

- Carena, Osborne, Shah, and Wagner, 2018 [arXiv:1809.11082]



Signal Region	Observed Events	BG Events	Signi cance (Z)
$SR2\ell_{Low}$	19	8 4 5 8	1.39
$SR2\ell_{ISR}$	11	$2\ 7^{+2\ 8}_{-2\ 7}$	1.99
$SR3\ell_{Low}$	20	10 2	2.13
$SR3\ell_{ISR}$	12	3 9 1 0	3.02

- Heavy colored sector
- Wino-like cross-sections
- Bino-like LSP
- Low mass regime
- Degenerate $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$
- Compressed Spectrum

$$\Delta m \equiv m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim 100 \text{ GeV}$$

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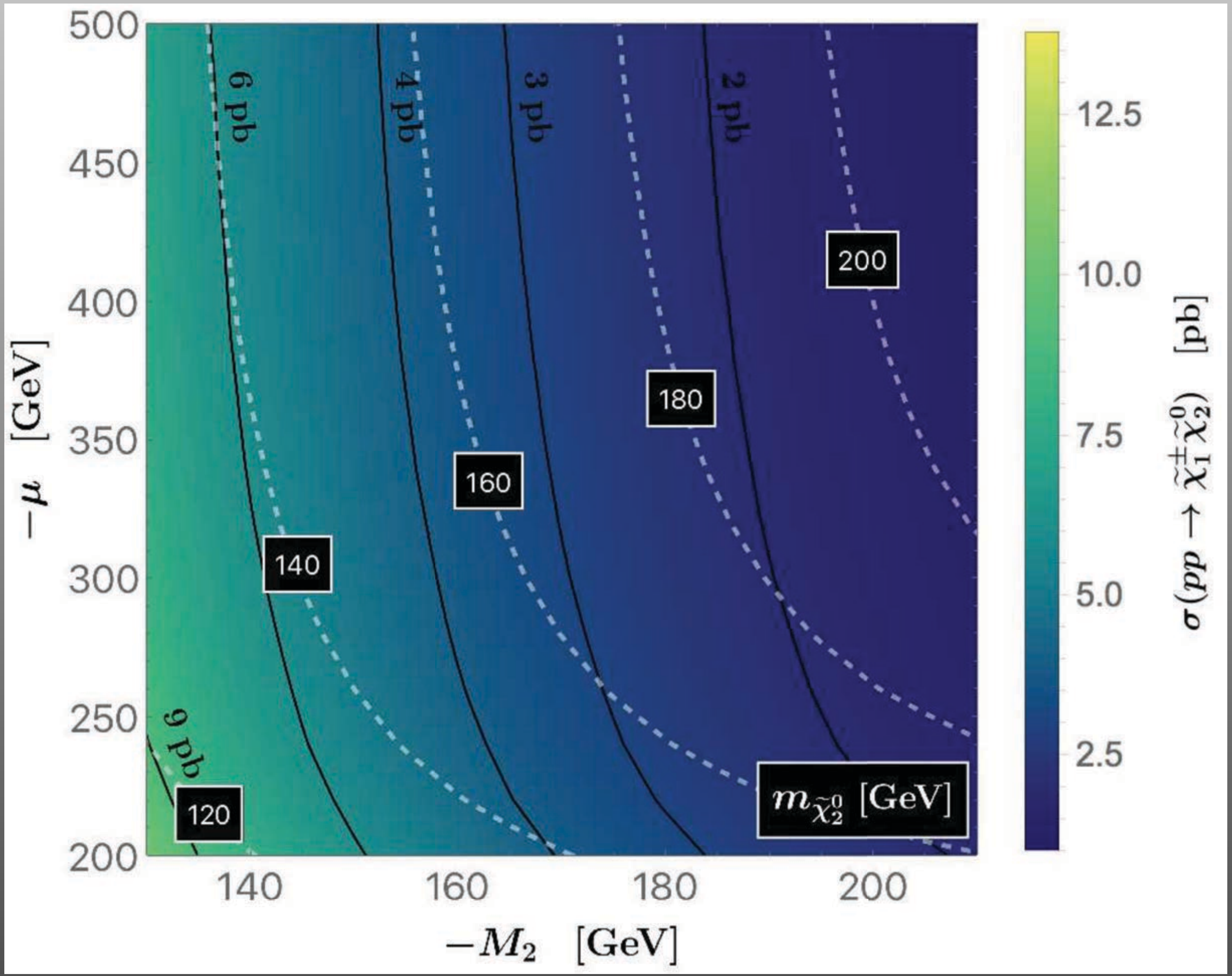
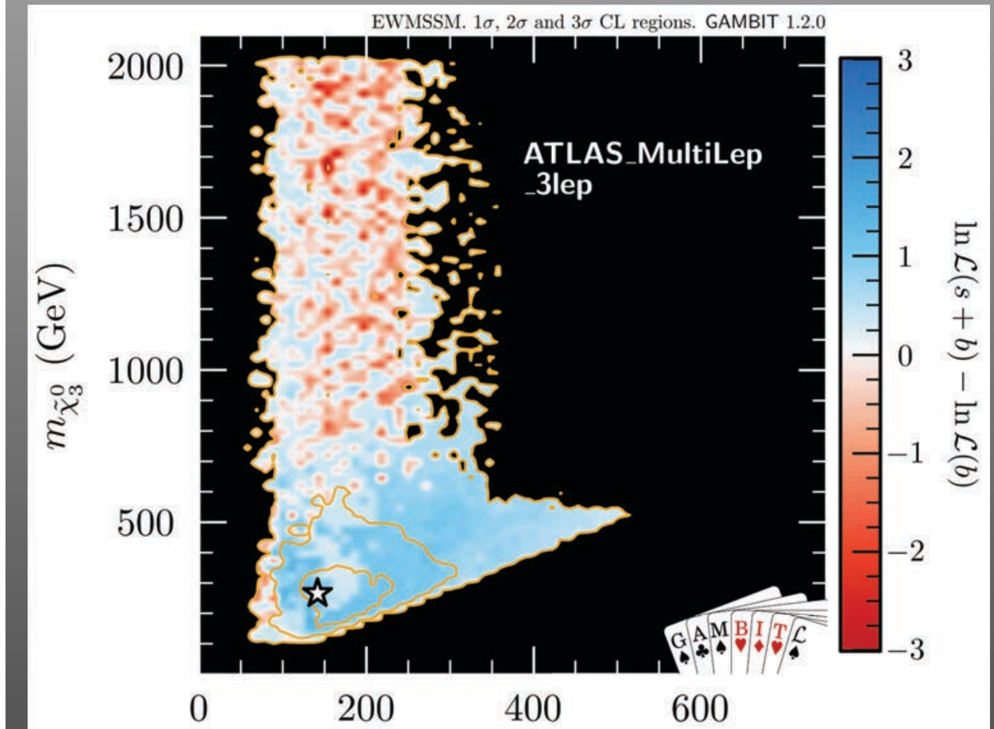


- Mixing reduces cross section
- Additional light states contaminate searches
- 3ℓ searches want $\sigma \sim 3$ pb



Gambit [arXiv:1809.02097]

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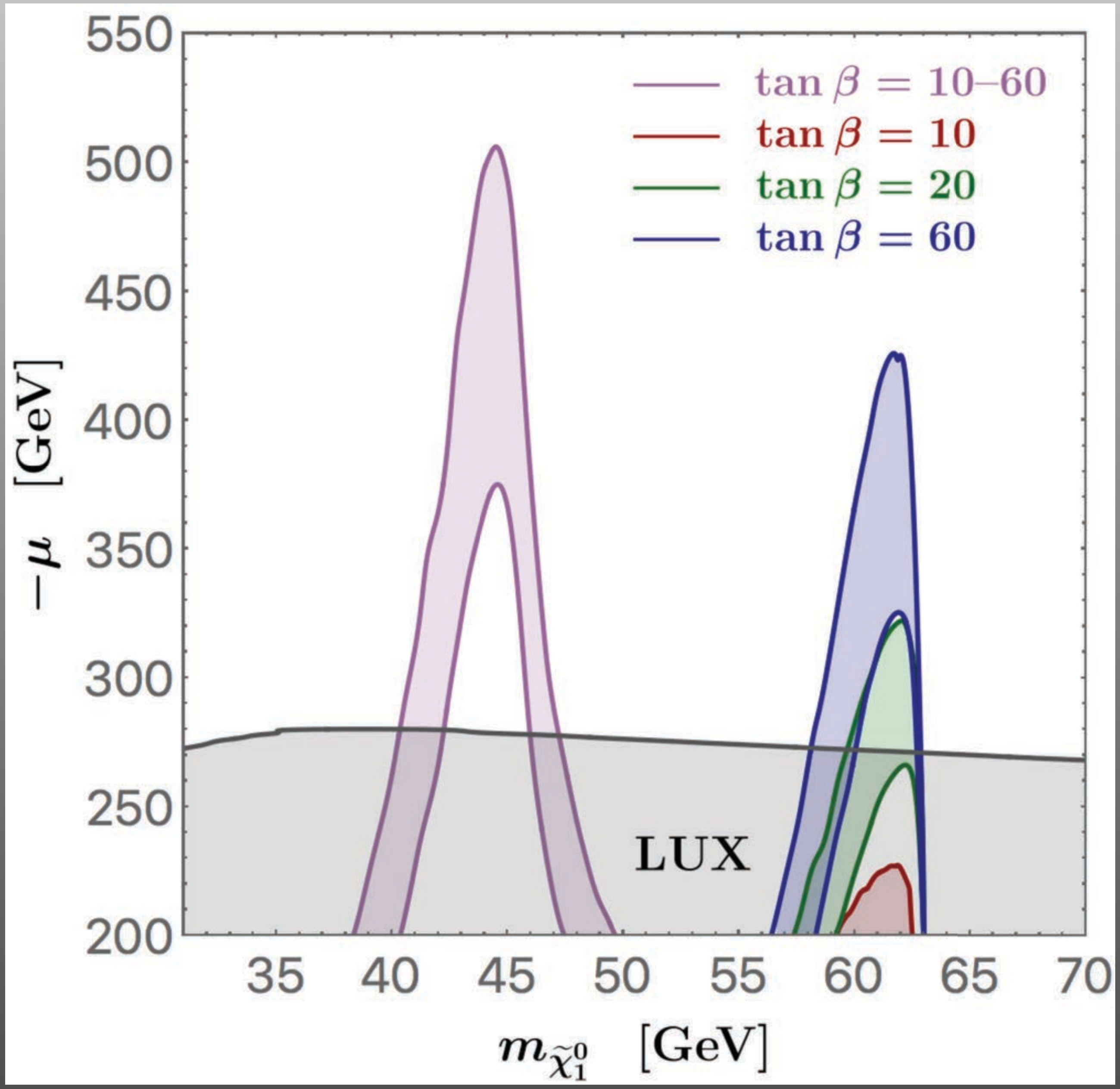

- SIDD blind spot:

$$\sigma_p^{\text{SI}} \propto \frac{m_Z^4}{\mu^4}\left[\frac{2}{m_h^2}\left(m_{\tilde{\chi}_1^0} + 2\frac{\mu}{\tan\beta}\right) + \mathcal{O}\left(\frac{1}{m_{\text{heavy}}^2}\right)\right]^2$$

- $m_{\tilde{\chi}_1^0} \approx M_1 \quad \rightarrow \quad M_1 > 0,\ \mu < 0$
- Z resonance: $m_{\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0} \sim 145$ GeV, tension with previous searches?
- h resonance: large $\tan\beta$
- SDDD constrains $\mu \lesssim -275$ GeV
- Independent of M_2

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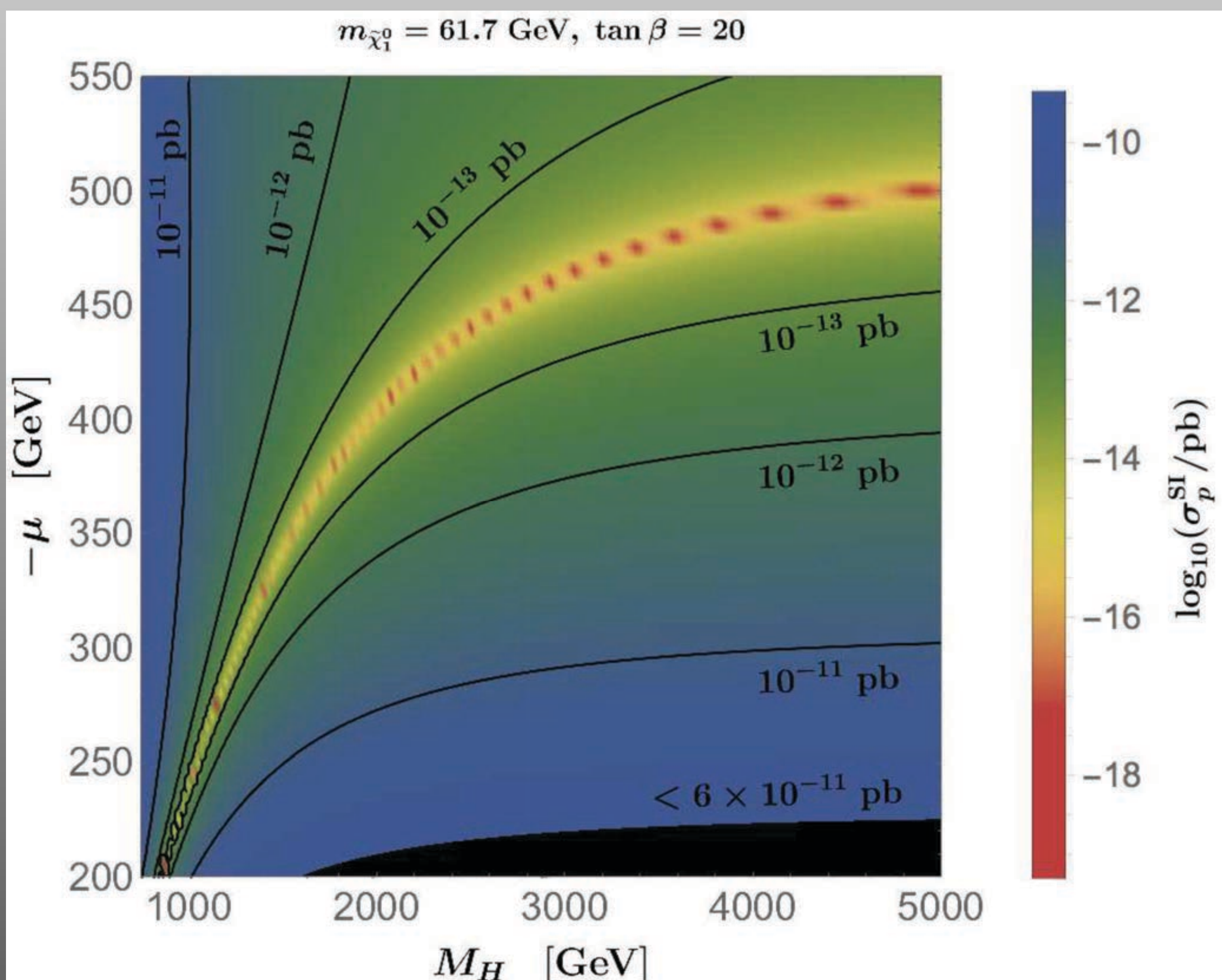

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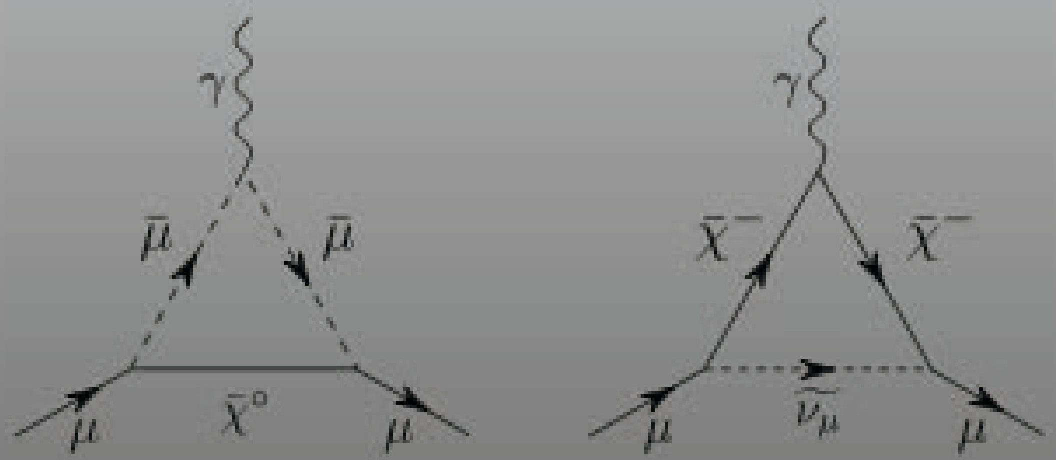
MUON ANOMALOUS MAGNETIC MOMENT

- Longstanding Brookhaven anomaly, $\sim 3.5\ \sigma$.
- Fermilab $(g-2)_\mu$ experimental results expected soon.

$$\delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{theory}} = 268(63)(43) \times 10^{-11}$$

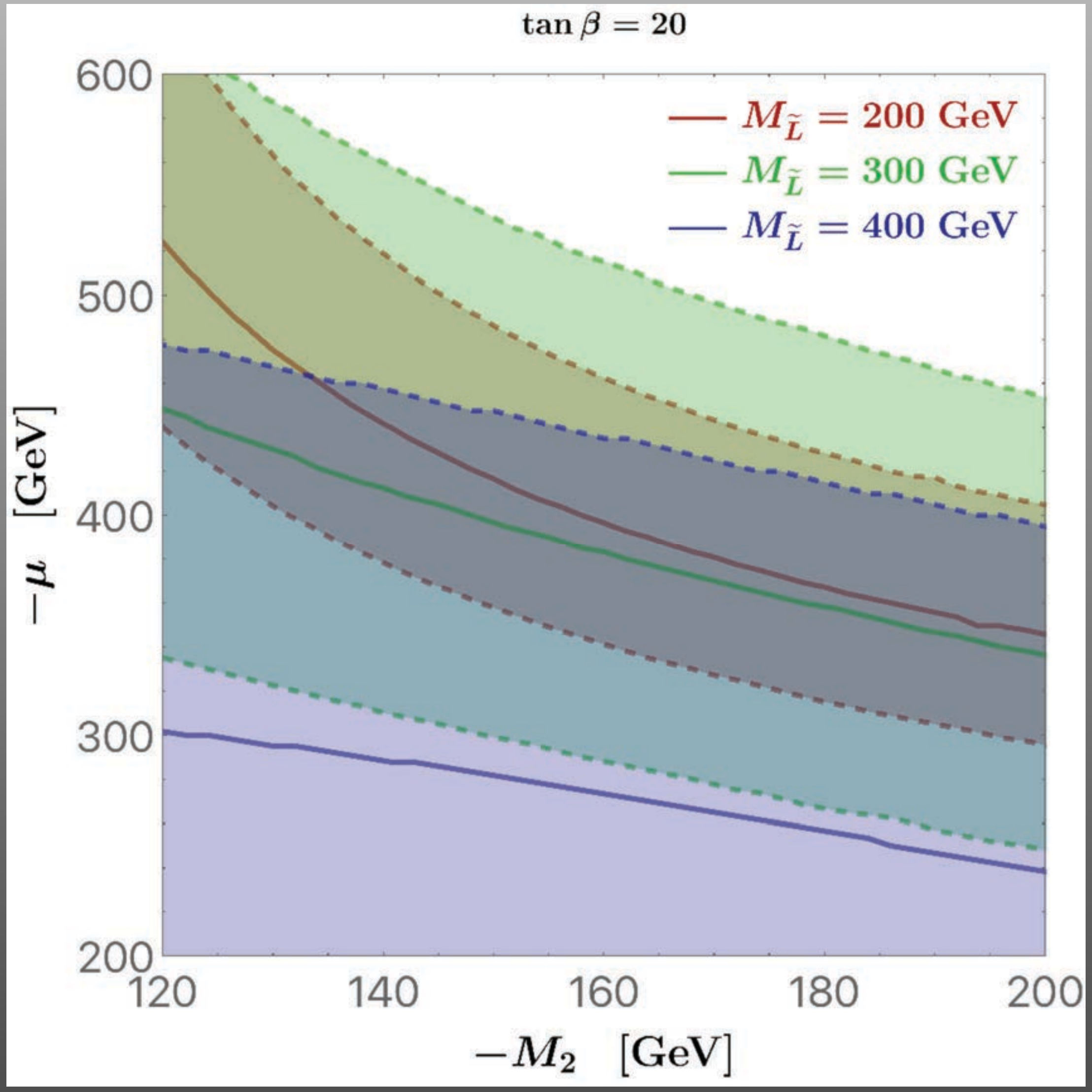


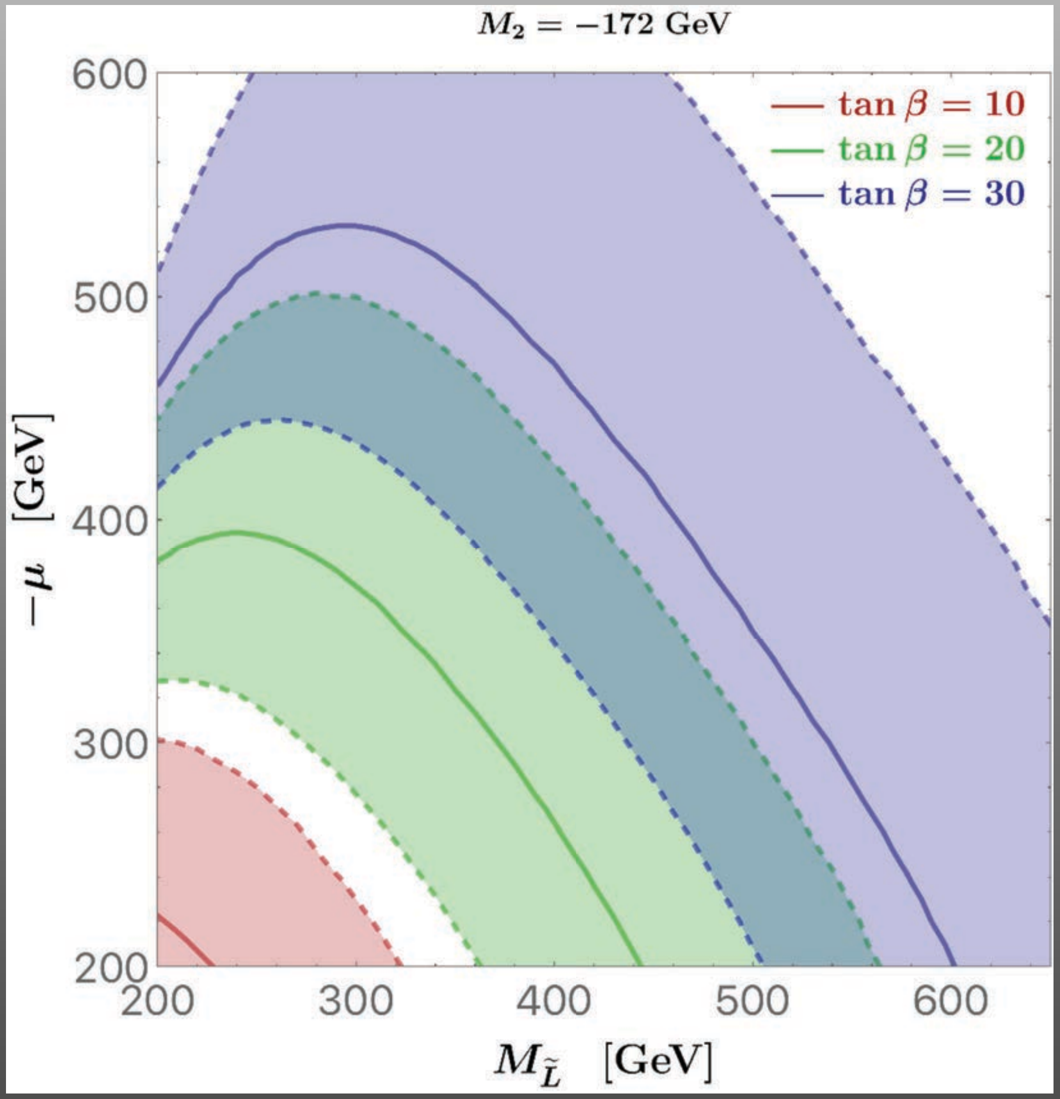
$$\delta a_\mu \simeq \frac{\alpha}{8\pi s_W^2}\frac{m_\mu^2}{\tilde{m}^2}\,\text{Sgn}(\mu M_2)\tan\beta \simeq 130 \times 10^{-11}\left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^2 \text{Sgn}(\mu M_2)\tan\beta$$

- Requires slepton masses of order a few hundred GeV

ANATOMY OF MUON G−2

- Requires $\mu \times M_2 > 0 \quad \rightarrow \quad \mu < 0, M_2 > 0$.
- Left-handed sleptons cascade decay, reducing LHC constraints.
- $M_{\tilde{L}} \sim 400$ GeV





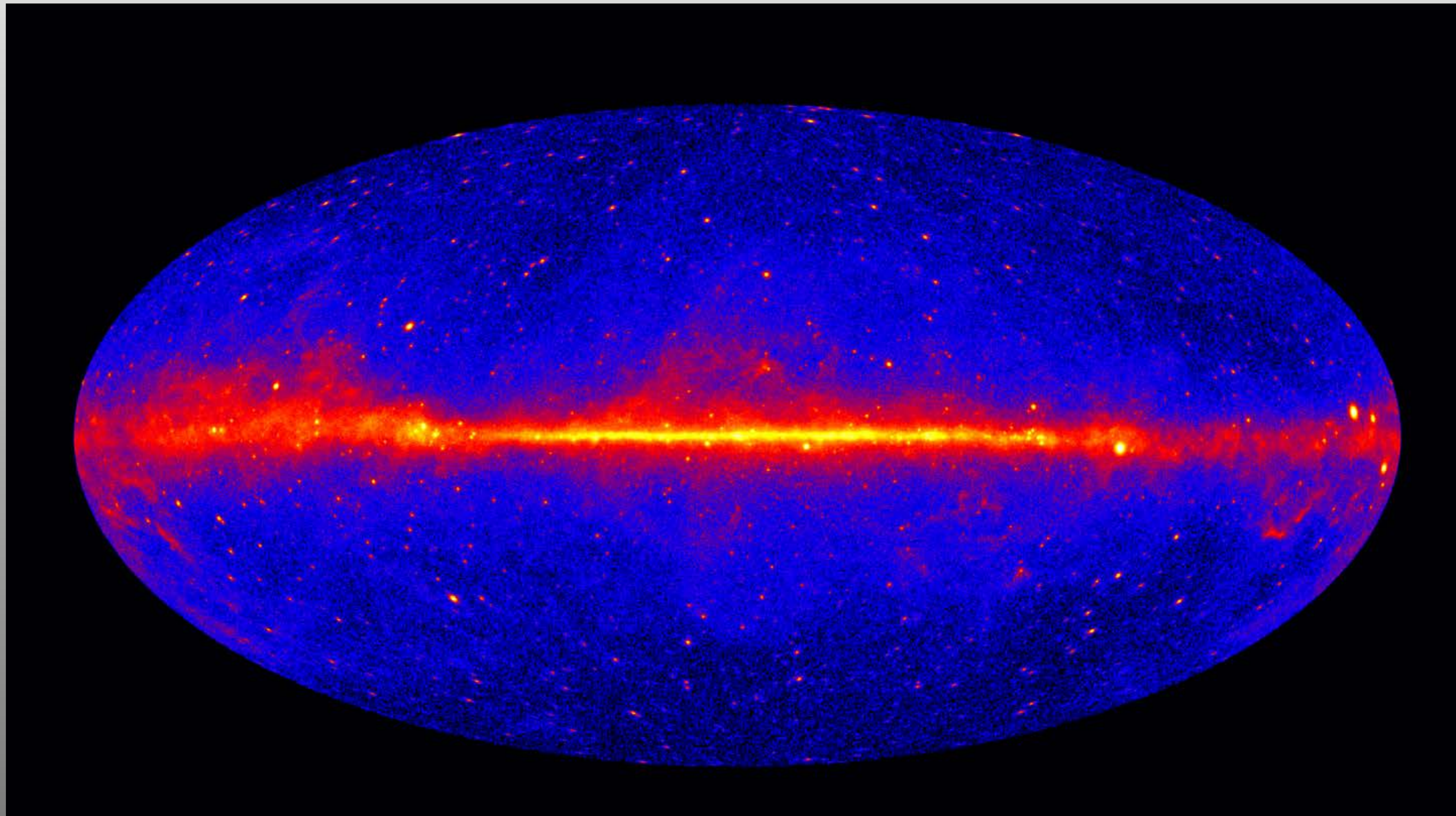
ANOMALIES BENCHMARK

Param.	[GeV]	Param.	[GeV]	Param.	[GeV]	Param.	[GeV]
μ	-300	M_2	-172	$M_{\widetilde{L}}$	400	M_H	1500
M_1	63.5	M_3	2000	$M_{\widetilde{Q}}$	2000	A_t	3000

Degenerate soft parameters between generations and chiralities for simplicity only.

Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]
h	125.84	$\widetilde{\chi}_1^\pm$	165.0	$\widetilde{\nu}_e$	395.0	$\widetilde{u}_R$	2069.8
H	1500.03	$\widetilde{\chi}_2^\pm$	333.6	$\widetilde{\nu}_\mu$	395.0	$\widetilde{u}_L$	2069.5
H_3	1500.00	$\widetilde{\tau}_1$	389.5	$\widetilde{\nu}_\tau$	395.0	$\widetilde{d}_R$	2070.3
$H^\pm$	1502.38	$\widetilde{\tau}_2$	415.0	$\widetilde{g}$	2129.2	$\widetilde{d}_L$	2071.0
$\widetilde{\chi}_1^0$	61.7	$\widetilde{e}_R$	402.4	$\widetilde{t}_1$	1927.7	$\widetilde{s}_R$	2070.3
$\widetilde{\chi}_2^0$	164.8	$\widetilde{e}_L$	402.6	$\widetilde{t}_2$	2131.6	$\widetilde{s}_L$	2071.0
$\widetilde{\chi}_3^0$	314.2	$\widetilde{\mu}_R$	402.4	$\widetilde{b}_1$	2067.1	$\widetilde{c}_R$	2069.8
$\widetilde{\chi}_4^0$	331.2	$\widetilde{\mu}_L$	402.6	$\widetilde{b}_2$	2074.1	$\widetilde{c}_L$	2069.5

GALACTIC CENTER EXCESS

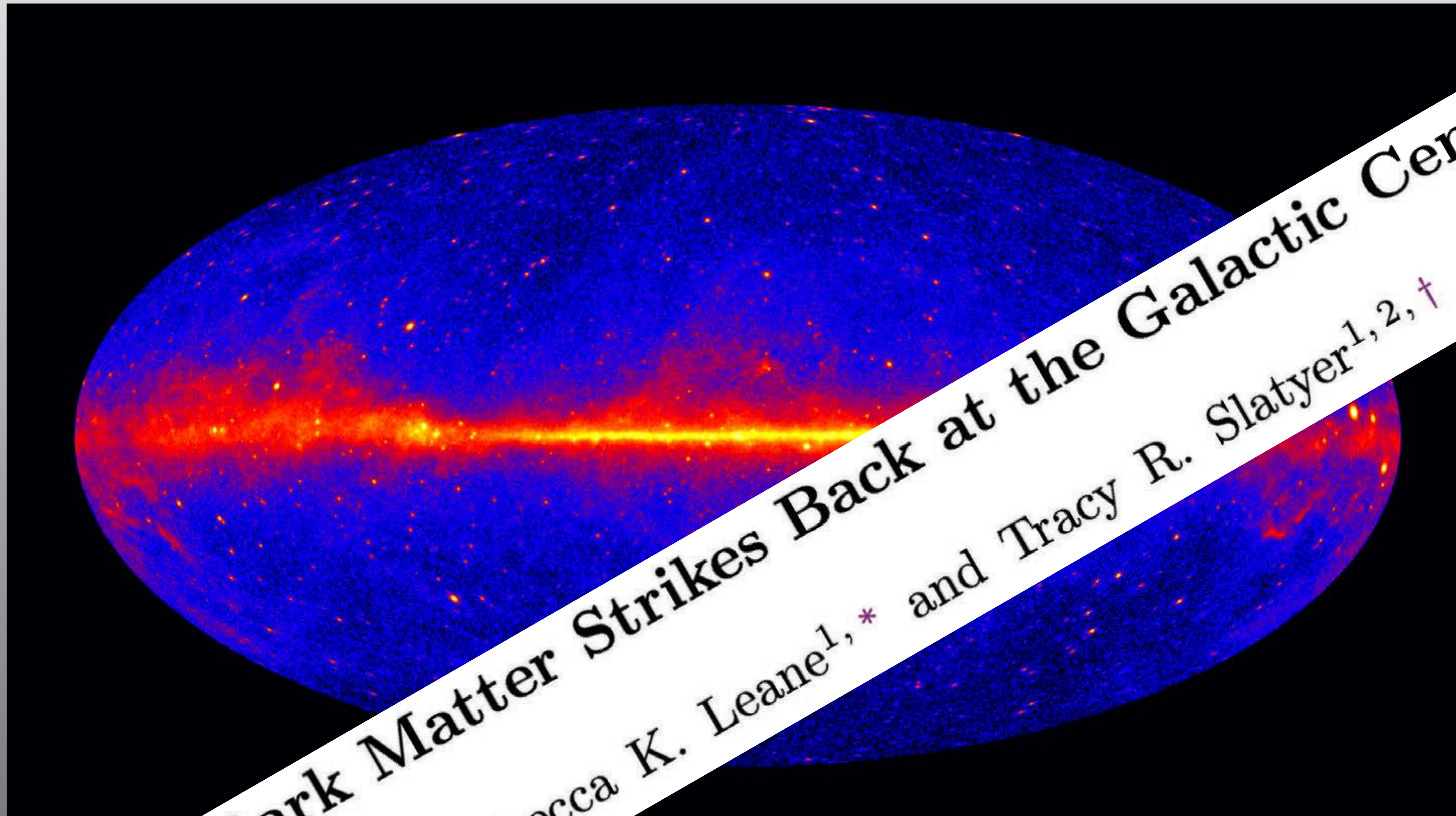


Fermi-LAT sees gamma ray excess, AMS sees anti-proton excess. Both are consistent with $\tilde{\chi}\tilde{\chi} \to \bar{b}b$.

Gamma ray excess $\sim$ few GeV. [arXiv:1511.02938]

- Dark matter annihilation? [arXiv:1010.2752, etc.]
- Point-like sources, unknown population of millisecond pulsars? [arXiv:1506.05104, etc.]

GALACTIC CENTER EXCESS



Dark Matter Strikes Back at the Galactic Center

Rebecca K. Leane[1,*] and Tracy R. Slatyer[1,2,†]

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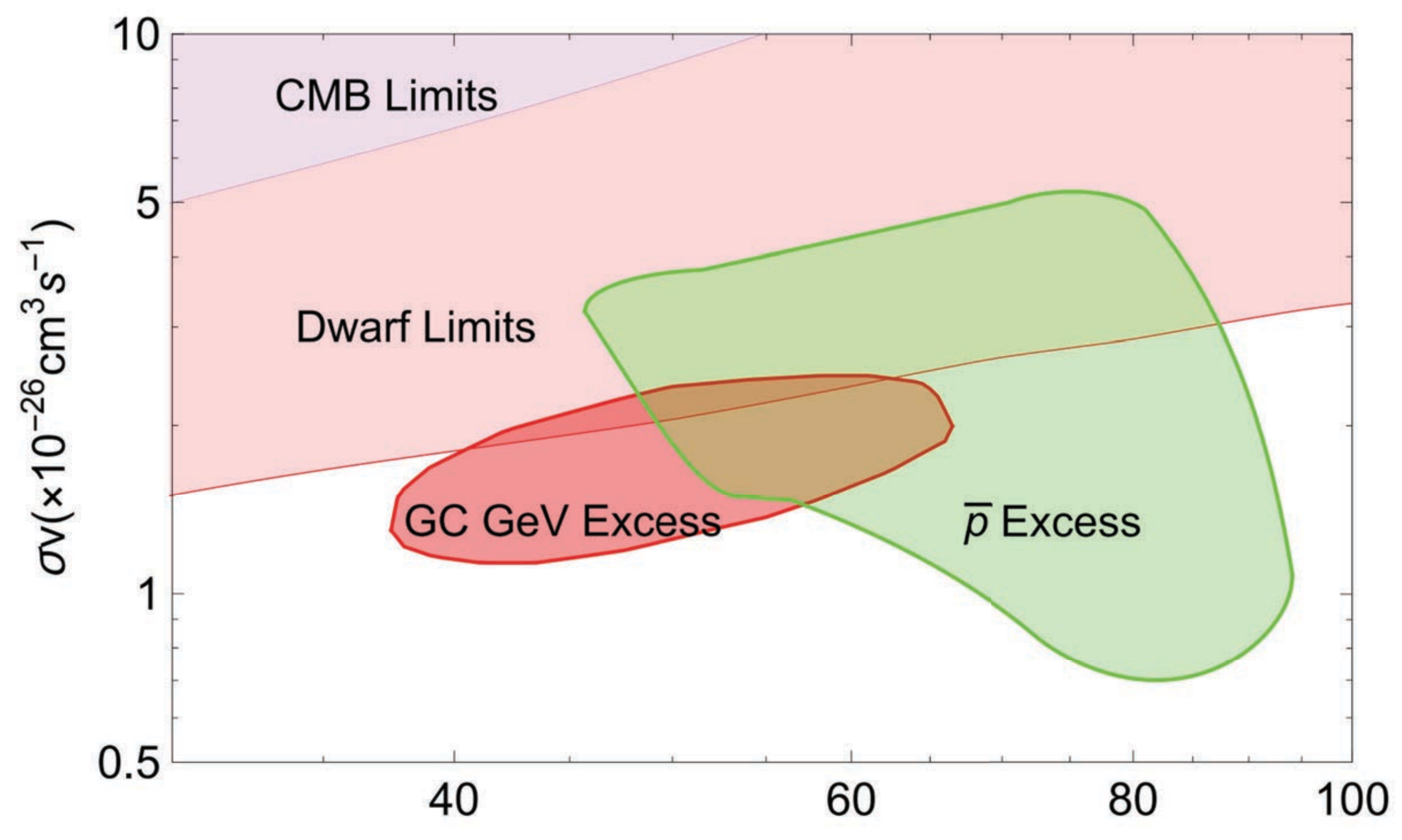
ANATOMY OF THE GCE

What can we infer from the GCE if we take the ATLAS excess as signal?

- Carena, Osborne, Shah, and Wagner, 2019 [arXiv:1905.03768]



Cholis, Linden, Hooper, 2019 [arXiv:1903.02549]

Rest of the story stays the same!

- $m_{\tilde{\chi}_1^0} \sim 60$ GeV.
- MSSM doesn't work: requires $m_\chi > 60$ GeV.
- Mismatch between relic resonance at finite temp. and indirect detection at 0 temp.
- CPV-MSSM: complex M_1 leads to s-wave component to h-mediated annihilation.
- NMSSM: Additional CP-odd singlet A_1 boosts resonant annihilation at 0 temp.

ANATOMY OF THE GCE

What can we infer from the GCE if we take the ATLAS excess as signal?

- Carena, Osborne, Shah, and Wagner, 2019 [arXiv:1905.03768]

- CPV-MSSM: complex M_1 introduces electric dipole moments (EDMs).
- Scales as the inverse of slepton mass squared $\longrightarrow$ no $(g-2)_\mu$ contribution.

Param.	Value	Param.	[GeV]	Param.	[GeV]	Param.	[GeV]
$\arg[M_1]$	5.8°	μ	-300	M_3	3000	A_t	2500
$\tan\beta$	20	M_1	63.425	$M_{\widetilde{L}}$	3000	A_b	2500
$M_{H^\pm}$	1500 GeV	M_2	-185	$M_{\widetilde{Q}}$	3000	A_τ	1000

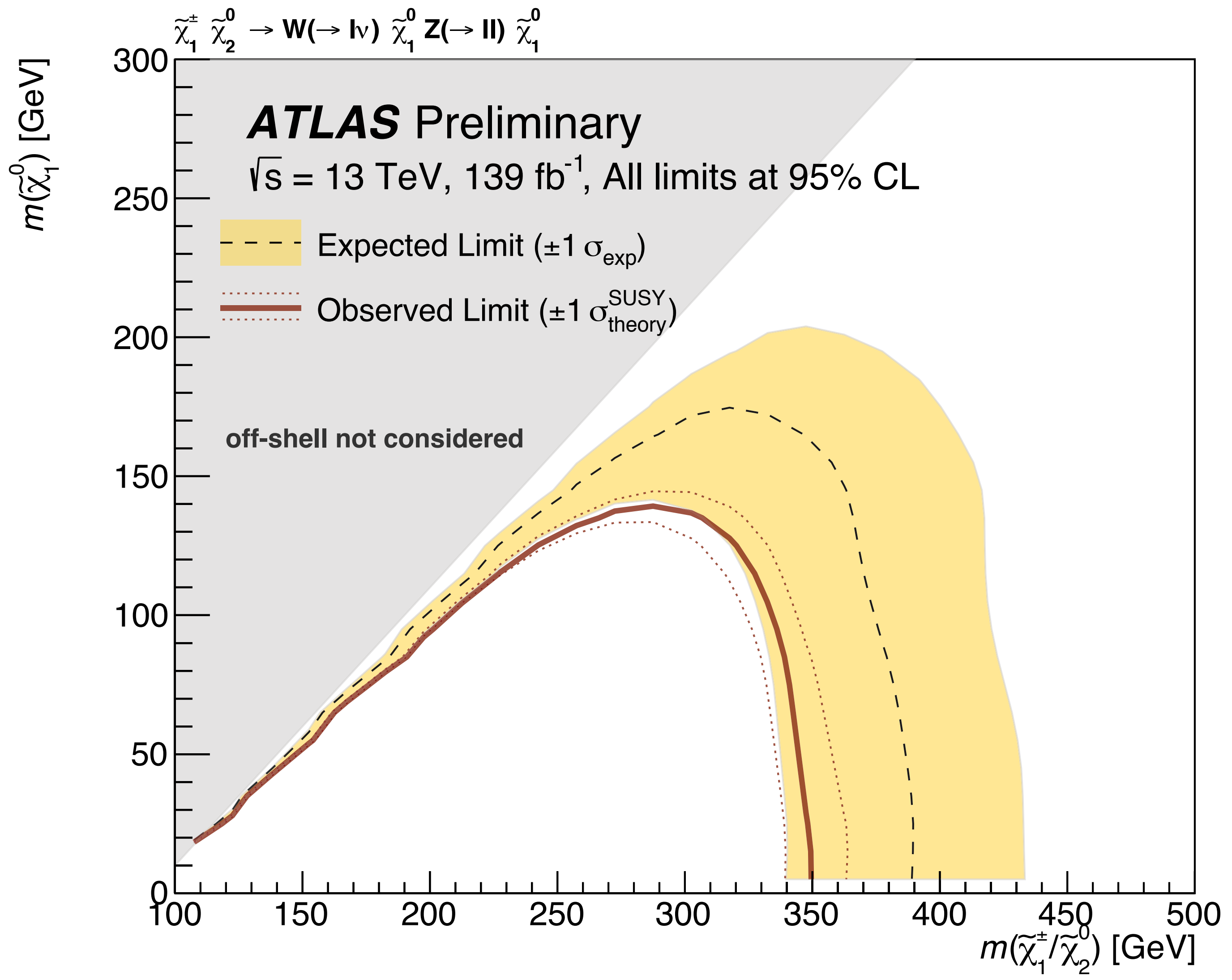
- NMSSM: no problem accommodating $(g-2)_\mu$.

Param.	Value	Param.	[GeV]	Param.	[GeV]	Param.	[GeV]
$\tan\beta$	20	$\mu_{\rm eff}$	-300	M_3	3000	A_λ	-1260
λ	0.15	M_1	62.62	$M_{\widetilde{L}}$	450	A_κ	-10.8
κ	-0.55	M_2	-171.	$M_{\widetilde{Q}}$	3000	A_t	4000

A NEW HOPE AT THE LHC (?)

ATLAS search for chargino-neutralino production using "emulated Recursive Jigsaw Reconstruction" (eRJR). [Run 2, $139\ \mathrm{fb}^{-1}$]

- Confirms $3\ \sigma$ excess with $36\ \mathrm{fb}^{-1}$ data set, full Run 2 data set excess reduced to $\sim 1\ \sigma$.
- ATLAS Collaboration, 2019 [ATLAS-CONF-2019-020]



Signal channel	N_{obs}	N_{exp}	$p(s=0)\ (Z)$
SR-low	51	46 ± 5	0.27 (0.60)
SR-ISR	30	23.0 ± 2.2	0.10 (1.27)

- Emulated search using traditional variables.
- Correlation between search variables good for some, not all.
- Awaiting RJR analysis of full Run 2 data, CMS equivalent.

RETURN OF THE WIMP

- Dark matter picture only cares about M_1 and μ for SIDD: $M_1 \times \mu < 0$.
- Excess fit for wino-like $m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} \sim 160$ GeV, bino-like $m_{\tilde{\chi}_1^0} \sim 60$ GeV.
- LHC cross sections depend on M_2 and mixing. Higgsino cross sections $\sim 1/4$ smaller than wino, unconstrained by LHC.
- Muon $(g-2)$ suggests light sleptons, $M_{\tilde{L}} \sim 400$ GeV, which avoid LHC bounds by cascade decaying first to heavier charginos and neutralinos.
- Light spectrum is important to understand, as it can dramatically alter the interpretation of LHC SUSY searches.
- GCE may hint that an extended SUSY model is needed: CPV-MSSM or NMSSM to decouple relic density and indirect detection.

CONCLUSIONS

Low energy SUSY may still be waiting to be discovered at the LHC! Electroweak sector with a rich spectrum, not tightly constrained.

WIMP paradigm is still alive! Anomalies paint a detailed picture of what we might expect in the future.

LHC Run 3 and next generation astrophysical probes may finally begin to illuminate WIMP dark matter.

Thank You!