Next Phase of Split Supersymmetry with Thermal Dark Matter

arXiv:2105.12142
2205.xxxxx

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Based on work in collaboration with
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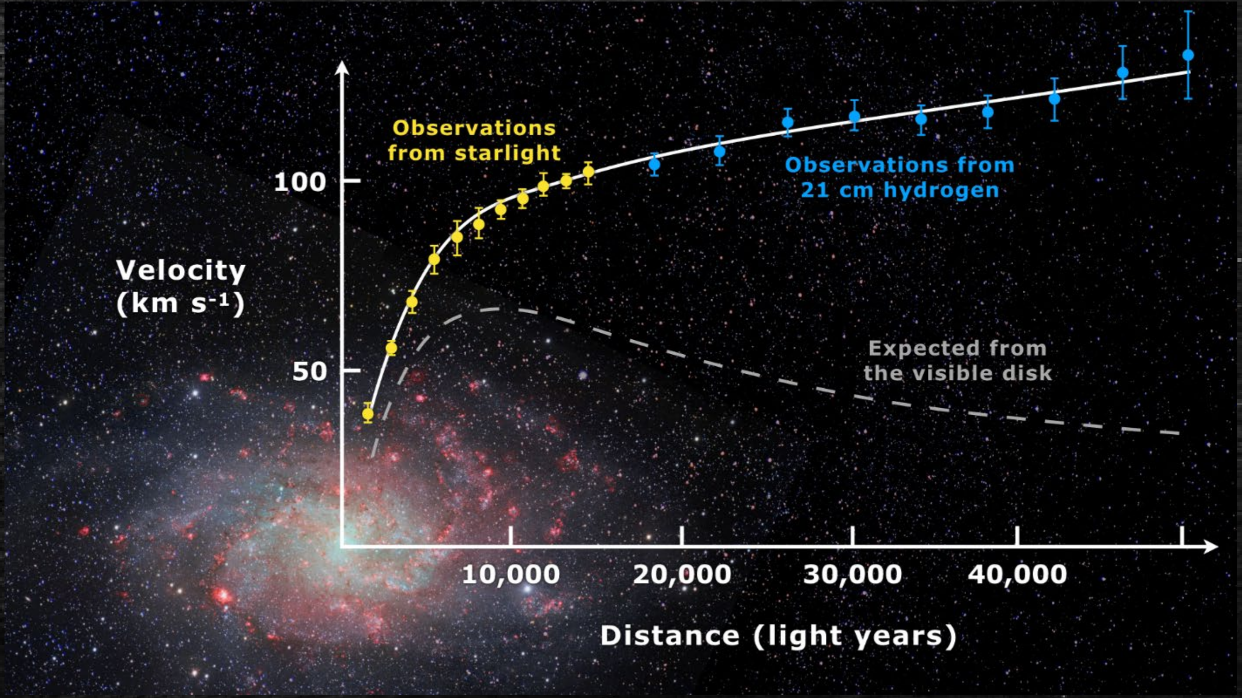
Why Dark Matter



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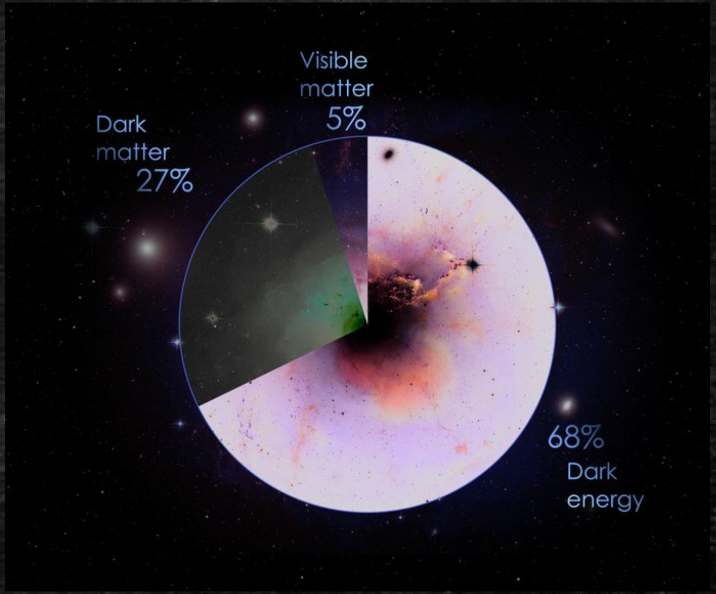
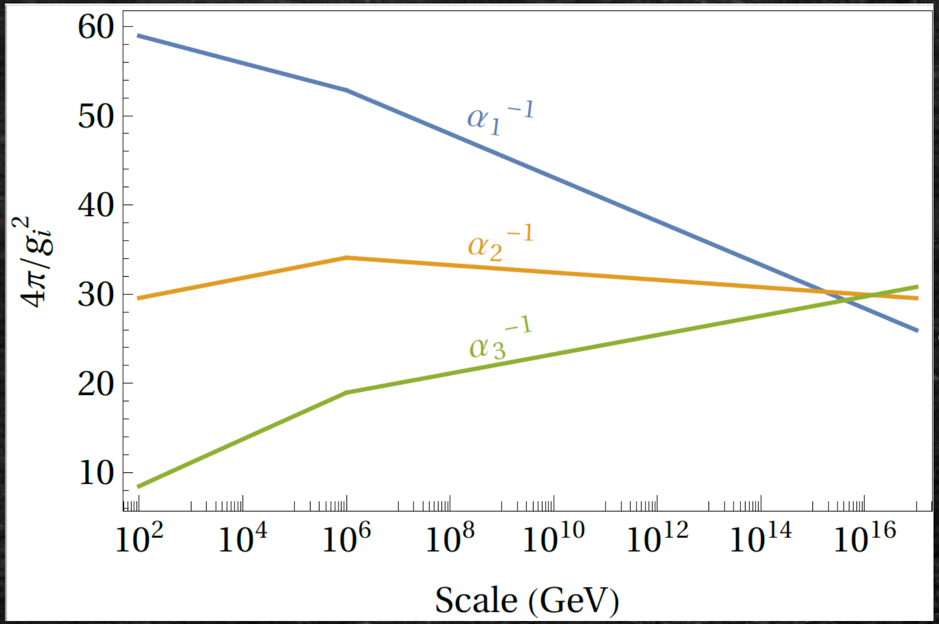


credit to NASA's Goddard Space Flight Center https://svs.gsfc.nasa.gov/12307

Why Split SUSY Dark Matter

- Most of the advantages of SUSY, with very few parameters
  - Gauge coupling unification
  - Electroweak scale stabilization
- Unify scalar masses at high scale and give SUSY breaking gaugino masses by anomaly mediation



Anomaly Mediation

- Some scalar in a hidden sector
  - $\Phi = 1 + F_\Phi \theta^2$
  - vev breaks SUSY
- Consider Super-Weyl transformation
  - Gives rise to an anomaly, leading to a shift in the gauge terms
    - $-2\,\beta_\lambda \ln(\Phi)$
  - Anomaly balanced by gaugino masses: $m_\lambda = -\beta_\lambda g_\lambda^2 F_\Phi$
- Can also get terms $\Phi^2\phi^2$ and $\Phi\psi^2$ in Lagrangian
  - Sfermions (ϕ) and gauginos (ψ) get mass enhanced by $|F_\Phi|$
  - If Φ has any charge, the latter is forbidden, so only sfermions get high mass

Randall, Sundrum hep-th/9810155
Gherghetta, Giudice, Wells hep-ph/9904378

A More Abstract Picture

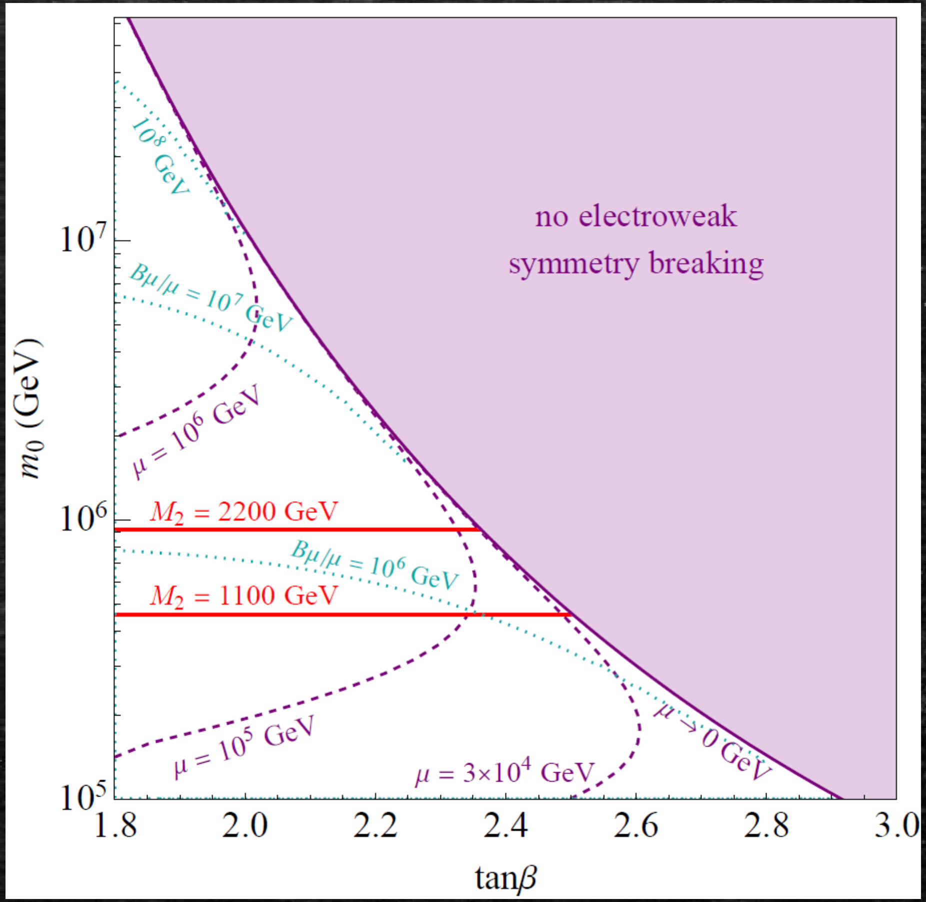
- Not the only way this story comes about
  - Strings story and more discussion on this story in literature

Randall, Sundrum hep-th/9810155

- General result: gaugino masses follow a ratio of their beta functions
  - $M_3 \approx 10 M_2 \approx 3 M_1$
  - Expect 300 $M_2 \sim -F_\Phi \sim m_{3/2} \sim m_0$
- Remaining degrees of freedom
  - $\tan\beta$, m_0, μ, $B\mu$
  - Can set μ or m_0 assuming thermal Higgsino or Wino DM
    - $\mu = 1.1$ TeV for Higgsino
    - $m_0 = 0.9$ PeV for Wino
  - Lose two degrees of freedom from EW symmetry breaking requirements

EW Symmetry Breaking Requirements

- Scalar mass unification at GUT scale sets m_{Hu}, m_{Hd}
  - Use measured m_Z
  - Set tanβ arbitrarily
- $\mu \ll m_o$ gives narrow band based on tuning m_{Hu}, m_{Hd} against one another
  - e.g. Higgsino DM curve, for $\mu = 1.1$ TeV, is invisible here
  - $B\mu/\mu$ can get large wrt m_o

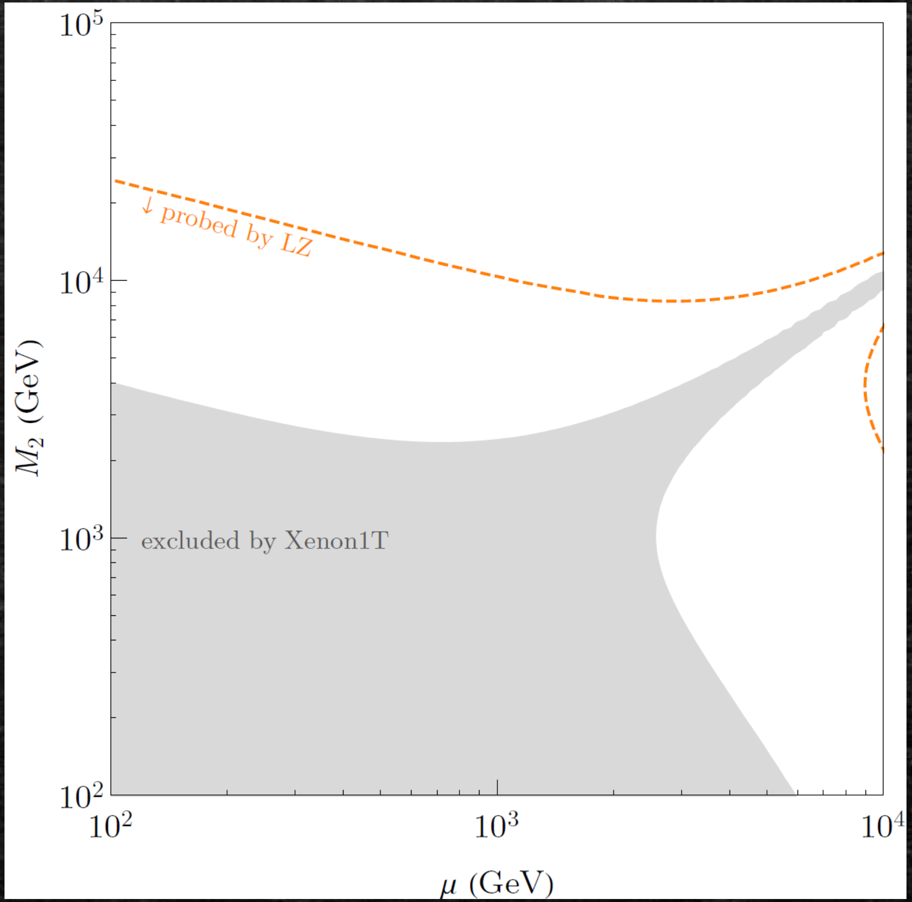


Limited Accessibility to Usual Approaches

- Colliders are very limited for heavy, non-strongly coupled particles
- Direct detection cross section falls rapidly as the higgsino-gaugino mixing angle
- Indirect detection has limited reach on higgsino mass
  - CMB measurements limited to O(100 GeV)
  - CTA can reach near μ = 1 TeV

Galli, et al. 0905.0003

Rinchiuso, et al. 2008.00692



Electron Electric Dipole Moments

- SUSY is well understood
  - Generically has large complex phases
  - Lead to charge parity violations
- Very little background to worry about
  - Electron EDM can come from SUSY charge parity breaking
  - In SM it's at most ~10^{-35} e cm
  - Current limit is at 1.1×10^{-29} e cm

ACME II limit, 2018

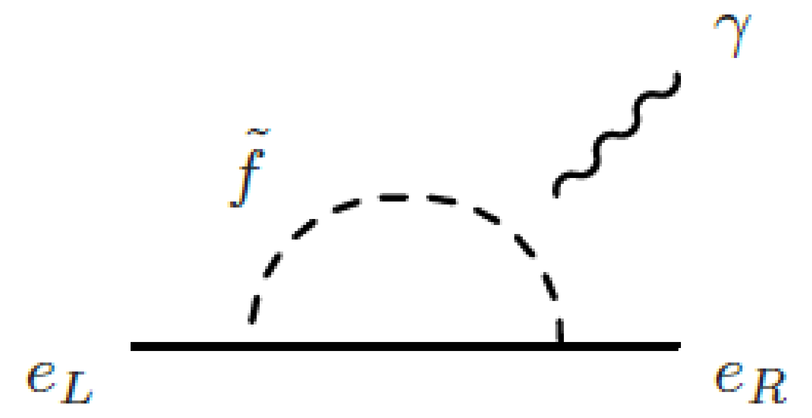
Scale reference for EDM:

Water: 3.9×10^{-9} e cm
Naïve neutron: 4×10^{-14} e cm
Neutron limit: 10^{-26} e cm

Electron EDM in Split SUSY

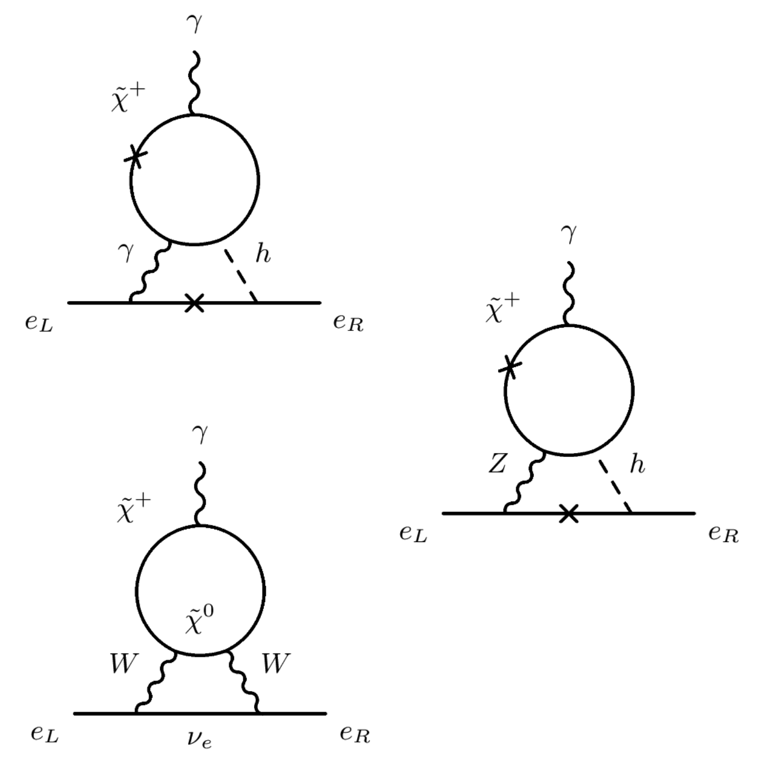
- Heavy scalars suppresses previous slide loops
- No 1 loop EDM
  - for O(1) phases, $m_0 > 10$ TeV suppresses EDM below current limits
  - Move to two loop

Cesarotti, et al. 1810.07736



Barr-Zee Diagram

- Leading order diagrams for EDM



M_2, $\mu >> m_Z$ gives:

$$d_{\gamma h} \simeq \frac{-e\alpha m_e}{8\pi^3}\frac{\tilde g_u \tilde g_d}{M_2\mu}\sin\phi_2 F_{\gamma h}\left(\frac{M_2^2}{\mu^2},\frac{M_2\mu}{m_h^2}\right)$$

$$d_{Zh} \simeq \frac{e\left(4\sin^2\theta_W-1\right)\alpha m_e}{32\pi^3\cos^2\theta_W}\frac{\tilde g_u \tilde g_d}{M_2\mu}\sin\phi_2 F_{Zh}\left(\frac{m_Z^2}{m_h^2},\frac{M_2^2}{\mu^2},\frac{M_2\mu}{m_h^2}\right)$$

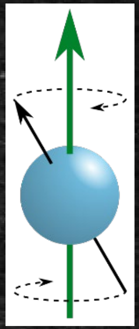
$$d_{WW} \simeq \frac{-e\alpha m_e}{32\pi^3\sin^2\theta_W}\left(\frac{\tilde g_u \tilde g_d}{M_2\mu}\sin\phi_2 F_{WW}^{(2)}\left(\frac{M_2^2}{\mu^2},\frac{M_2\mu}{m_h^2}\right)+\frac{\tilde g'_u \tilde g'_d}{M_1\mu}\sin\phi_1 F_{WW}^{(1)}\left(\frac{M_1^2}{\mu^2},\frac{M_1\mu}{m_h^2}\right)\right)$$

Giudice, Romanino hep-ph/0510197

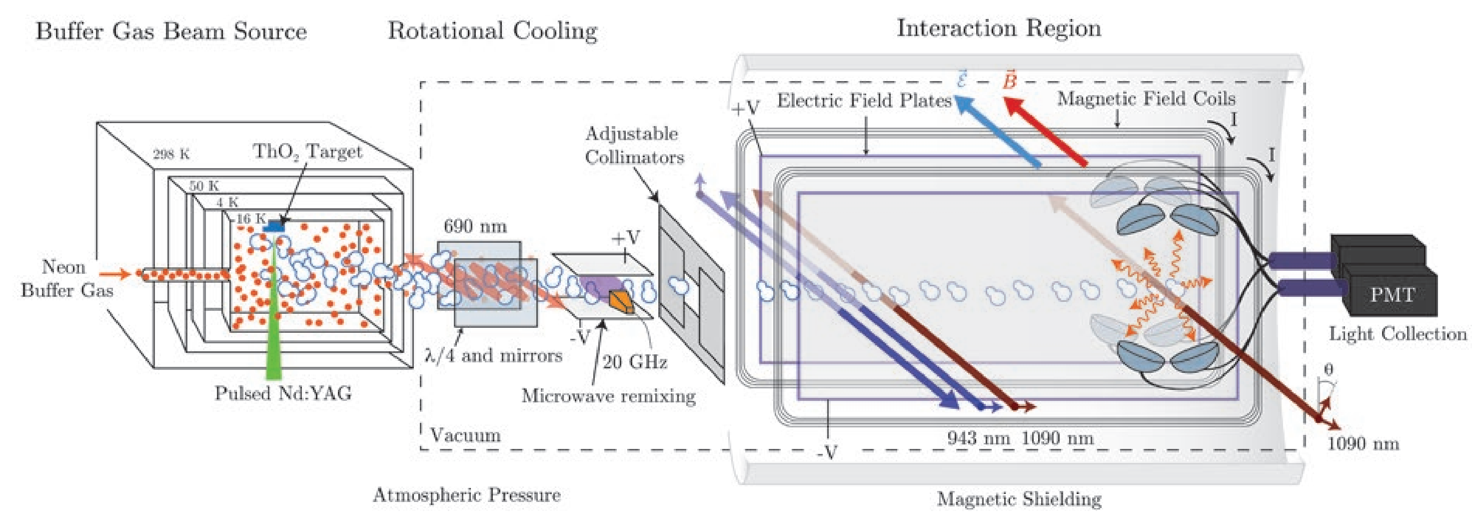
DOI: 10.1038/s41586-018-0599-8

How to measure EDM: ACME II

- Precession of EDM in a strong electric field
  - Field inside ThO molecule is one of the strongest known: 80 GV/cm
- Propagate molecules through shielded chamber
  - Known time-of-flight
  - excite electron to particular spin angle in xy-plane at start
  - measure final angle with fluorescence by linearly polarized laser
- Current measurements at 1.1 x 10^{-29} e-cm



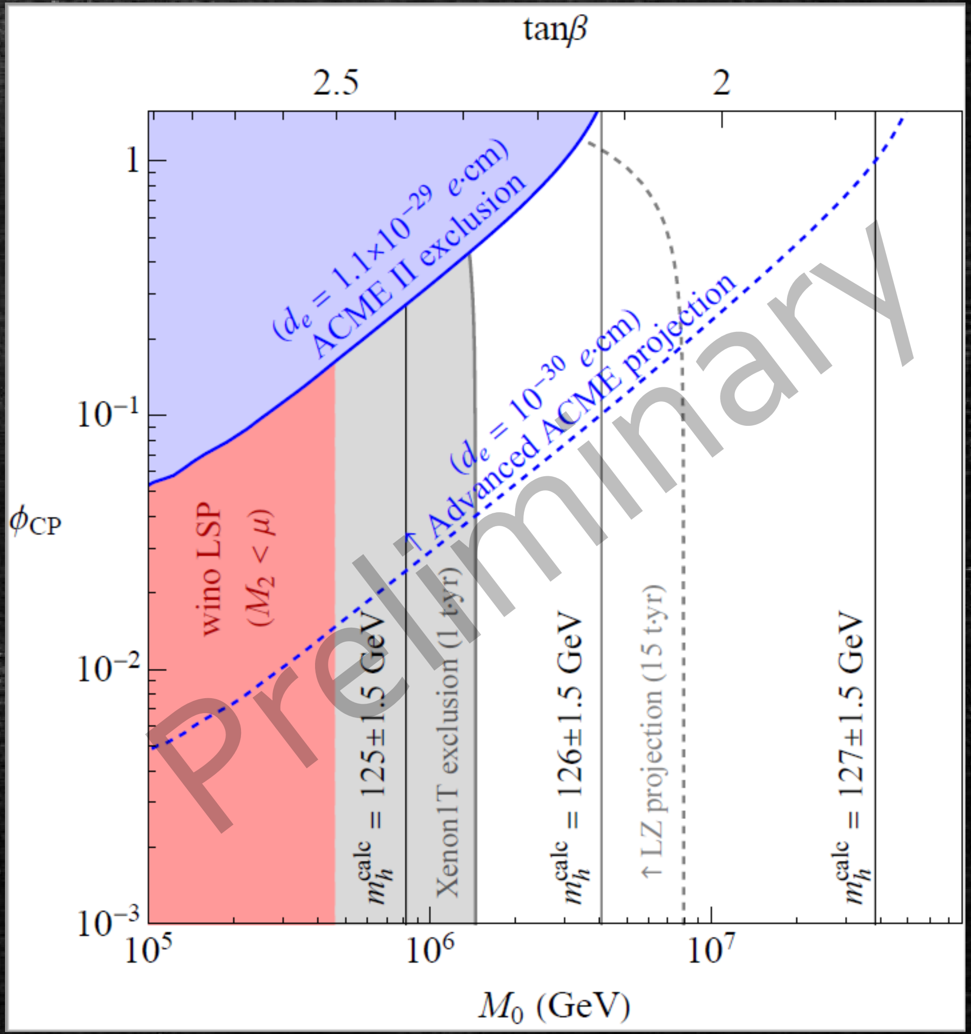
By Mario De Leo - https://commons.wikimedia.org/wiki/File:Precession_in_magnetic_field.svg



https://www.danielang.net/2016/10/16/guide-to-the-acme-edm-experiment-a-simple-overview/

Higgsino Like Dark Matter Limits

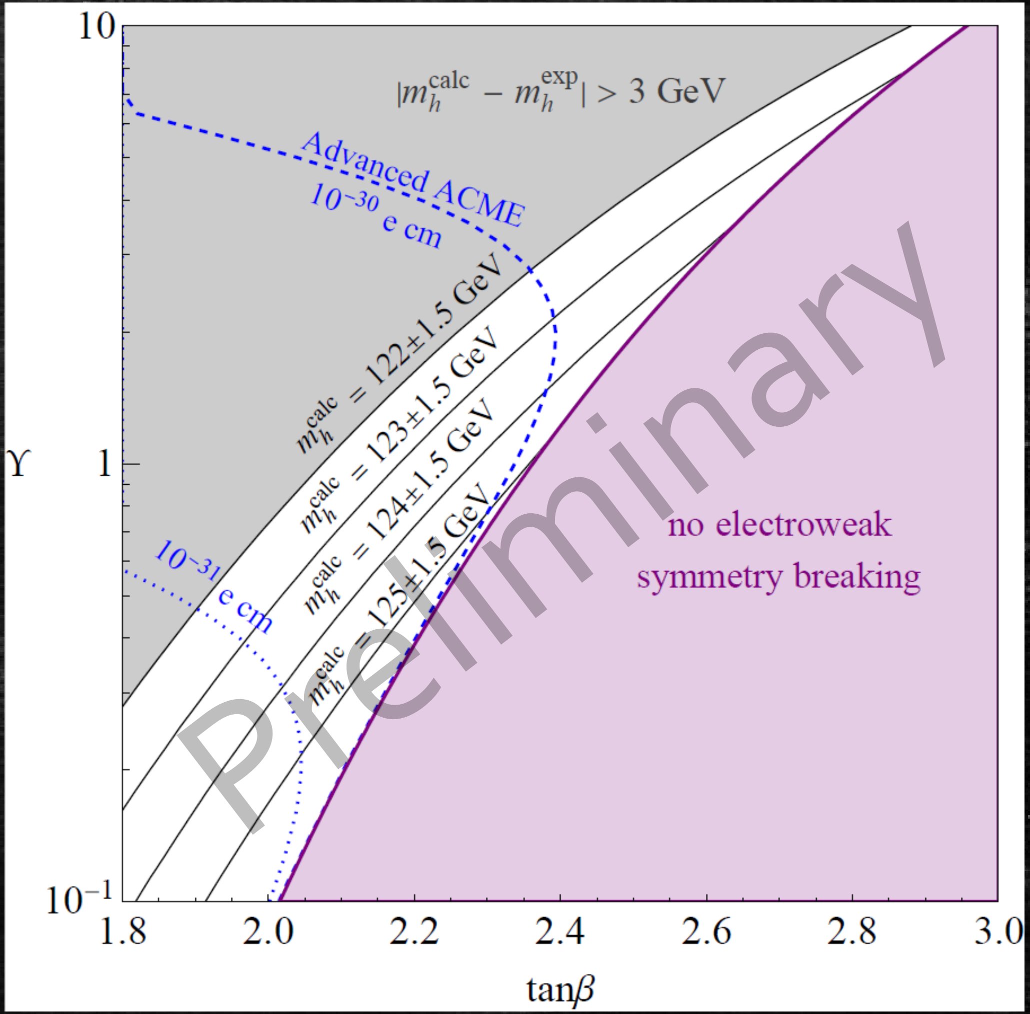
- A bit of a race between approaches
  - LZ gives broad coverage in DD limits, limited by M_2^2 scaling
  - e-EDM reach is very wide
    - Up to complex phase or large M_2
- Complementary Higgs Mass Constraints
  - Upper bound can be limited by Higgs mass
  - Dependence on future top quark mass measurements



Wino Like Dark Matter Limits

- Υ is a relative enhancement of gaugino masses wrt scalar masses
- Direct Detection limits are fairly weak in this regime
  - Suppression of nucleon scattering below LZ reach by large μ
- Next to next generation electron EDM has discovery potential
- Significant discovery and exclusion already from indirect detection limits

Cohen, et al. 1307.4082



Thank you!

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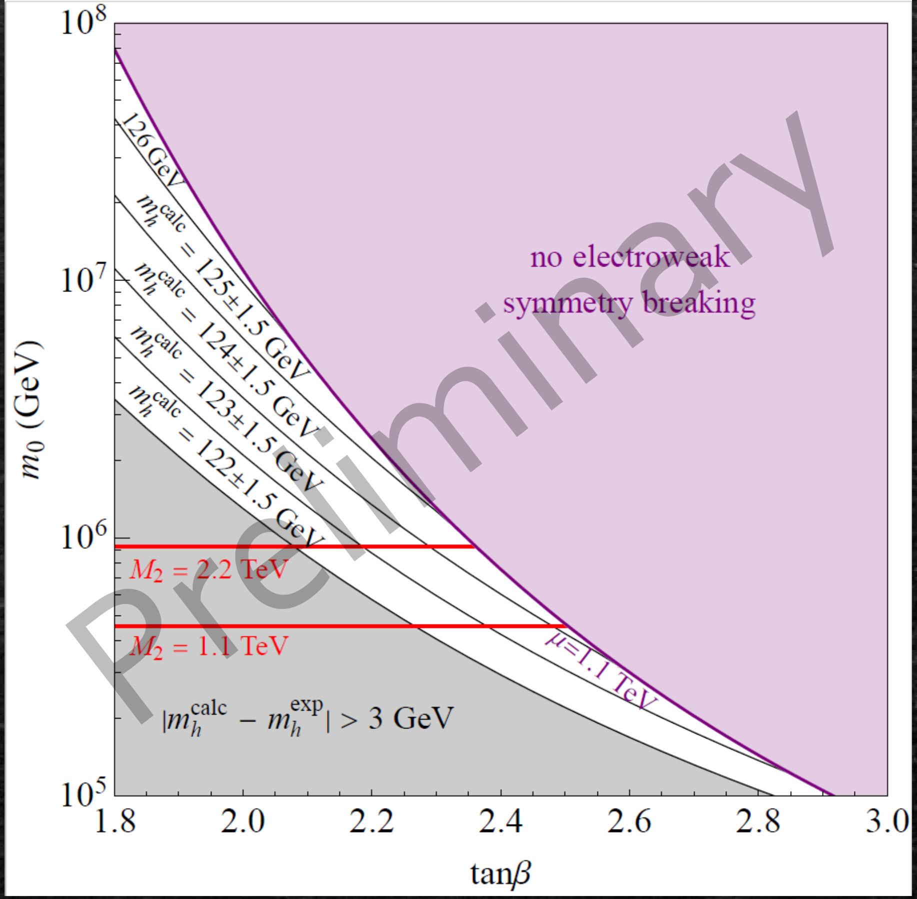
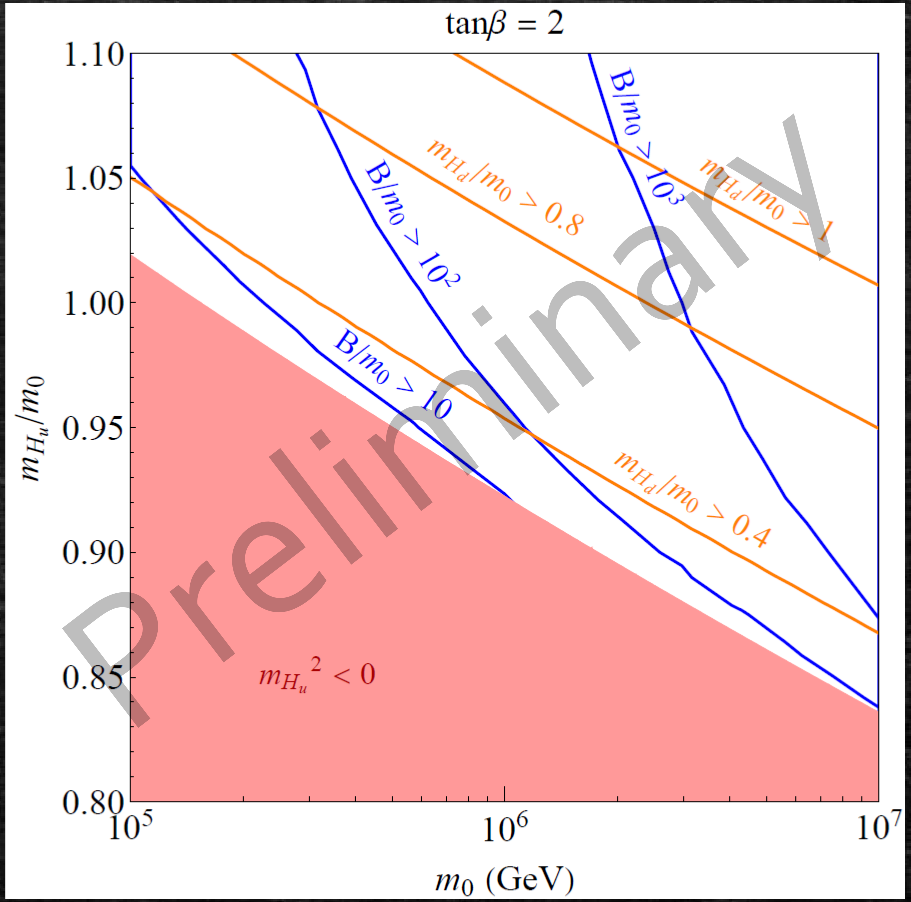
Higgs Mass over the full parameter space

- Error bars in roughly equal measure from
  - Theory errors
  - Precision on top quark mass

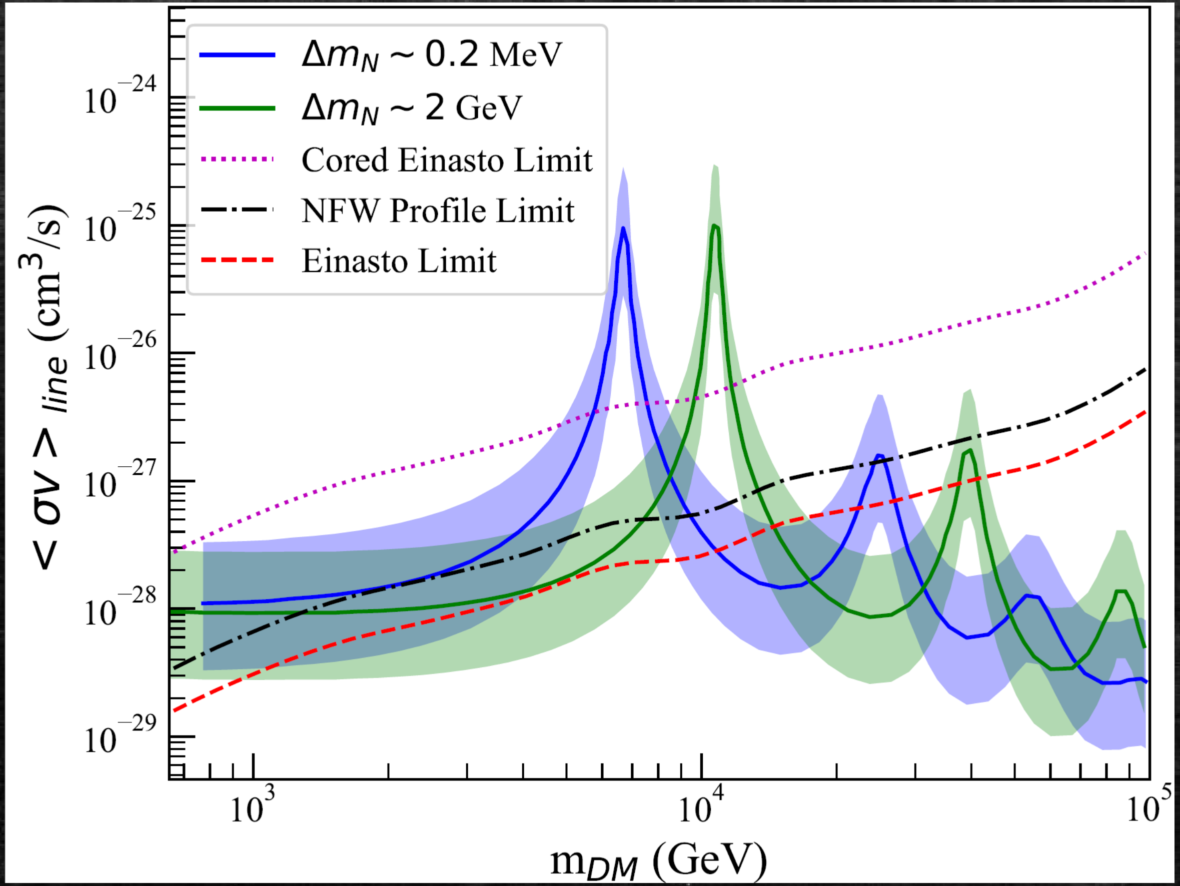


Easing the EW symmetry breaking conditions

- Allow the Higgs masses to vary from the unified value at GUT scale



Line photon indirect detection searches for Higgsinos



Data for curves courtesy of Rinchiuso, et al. 1905.00315, Hryczuk, et al 2008.00692

A Brief History

- 1998 – Conformal anomaly leads to anomaly mediated SUSY breaking (AMSB), possibly with high mass scalars
- 2004 – Early proposal of split SUSY, PeV scalars
- 2012-2013 – Natural models built with AMSB

  Constraints on thermal wino imply higgsino LSP of particular interest
- 2018-2022 – Higgsino LSP combined with AMSB in Split SUSY

Randall, Sundrum hep-th/9810155

Giudice, et al. hep-ph/9810442

Wells hep-ph/0411041
Arkani-Hamed, et al. hep-ph/0409232

Baer, et al. hep-ph/1203.5539

Baer, et al. hep-ph/1207.3343

Cohen, et al. hep-ph/1307.4082

Baer, Barger, Sengupta hep-ph/1801.09730

Cesarotti, et al. hep-ph/1810.07736

Tata hep-ph/2002.04429

Co, Sheff, Wells hep-ph/2105.12142