The Race to Find Split Higgsino Dark Matter

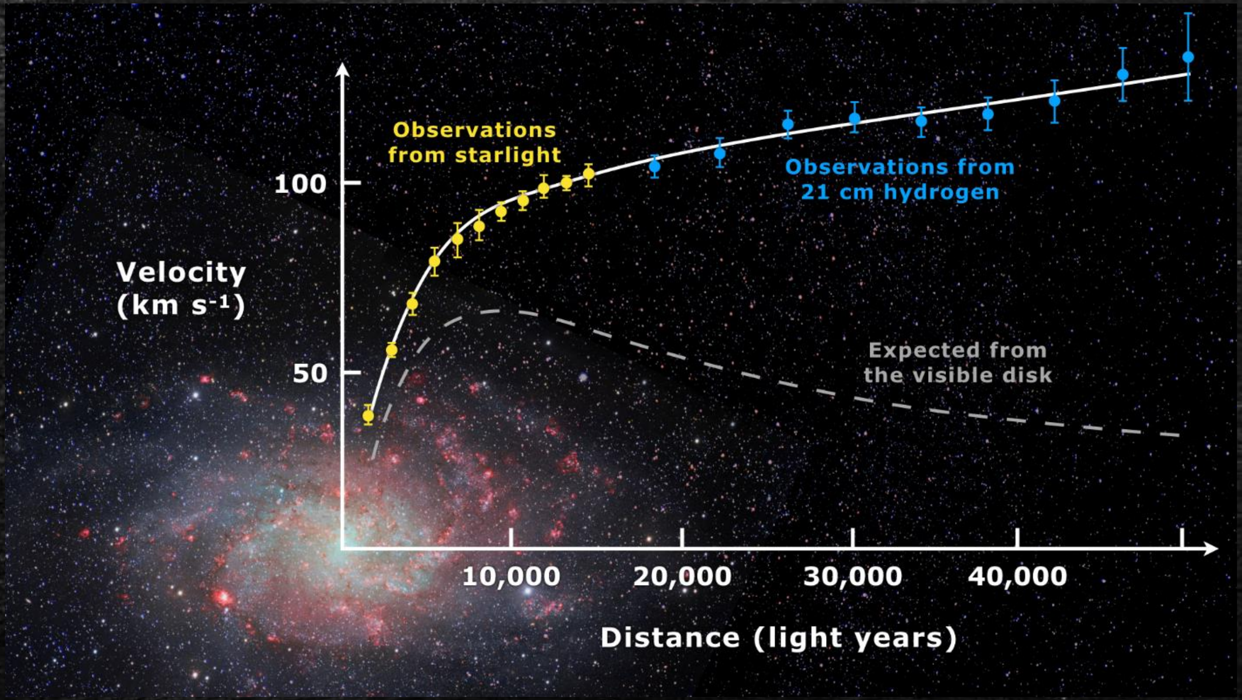
arXiv:2105.12142

SUSY 2021, 8/24/2021

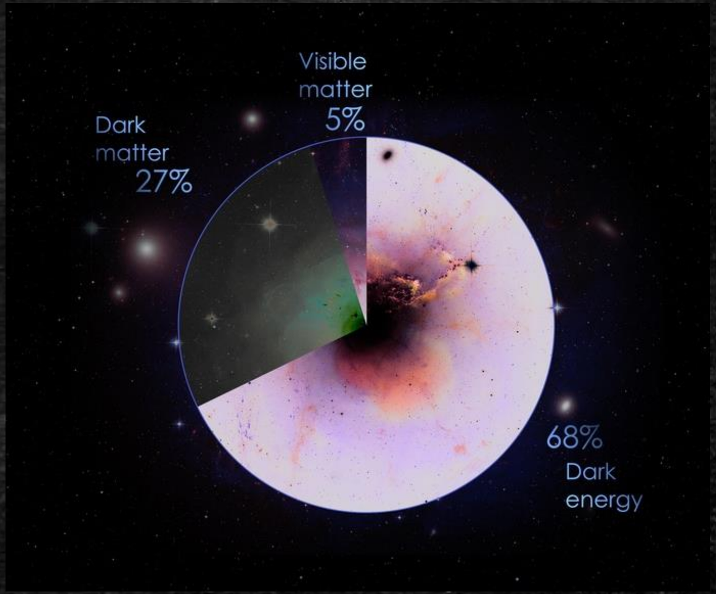
Ben Sheff – University of Michigan

Based on work in collaboration with
Raymond Co – University of Minnesota, James Wells – University of Michigan

Why Dark Matter



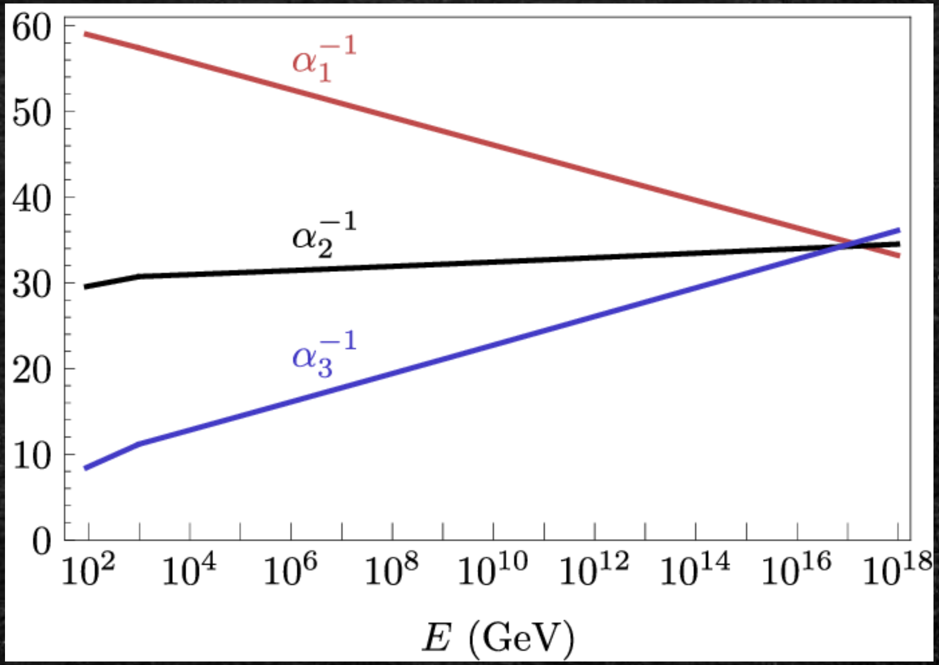
By Mario De Leo - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=74398525



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

Why *Higgsino* 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



Illustrative example

A Brief History

- 1998 – Conformal anomaly leads to anomaly mediated SUSY breaking (AMSB), possibly with high mass scalars

  Randall, Sundrum hep-th/9810155

  Giudice, et al. hep-ph/9810442

- 2004 – Early proposal of split SUSY, PeV scalars

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

- 2012-2013 – Natural models built with AMSB

  Constraints on thermal wino imply higgsino LSP of particular interest

  Baer, et al. hep-ph/1203.5539

  Baer, et al. hep-ph/1207.3343

  Cohen, et al. hep-ph/1307.4082

- 2018-2021 – Higgsino LSP combined with AMSB in Split SUSY

  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

Anomaly Mediation

- Some scalar in a hidden sector
  - $\Phi = 1 + F_\Phi \theta^2$
  - vev breaks SUSY
- Consider Super-Weyl transformation
  - Sends vev of Φ to zero
  - 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
  - Some room to maneuver in sfermion masses

Randall, Sundrum hep-th/9810155

- General result: gaugino masses follow a ratio of their beta functions
  - $M_3 \approx 10M_2 \approx 3M_1$
  - Expect 300 $M_2 \sim -F_\Phi \sim m_{3/2} \sim m_0$
- Remaining degrees of freedom
  - M_2, μ, m_0
  - Can set μ assuming thermal Higgsino DM

The Model

$$-\mathcal{L}_{\rm eff} = \frac{M_2}{2}\tilde{W}^a\tilde{W}^a + \frac{M_1}{2}\tilde{B}\tilde{B} + \mu\tilde{H}_u\epsilon\tilde{H}_d + \frac{H^\dagger}{\sqrt{2}}\left(\tilde{g}_u\sigma^a\tilde{W}^a + \tilde{g}'_u\tilde{B}\right)\tilde{H}_u + \frac{H^T\epsilon}{\sqrt{2}}\left(\tilde{g}_d\sigma^a\tilde{W}^a + \tilde{g}'_d\tilde{B}\right)\tilde{H}_d + h.c.$$

- Decouple scalars
  - Masses set to m_0=O(PeV)

Wells hep-ph/0411041

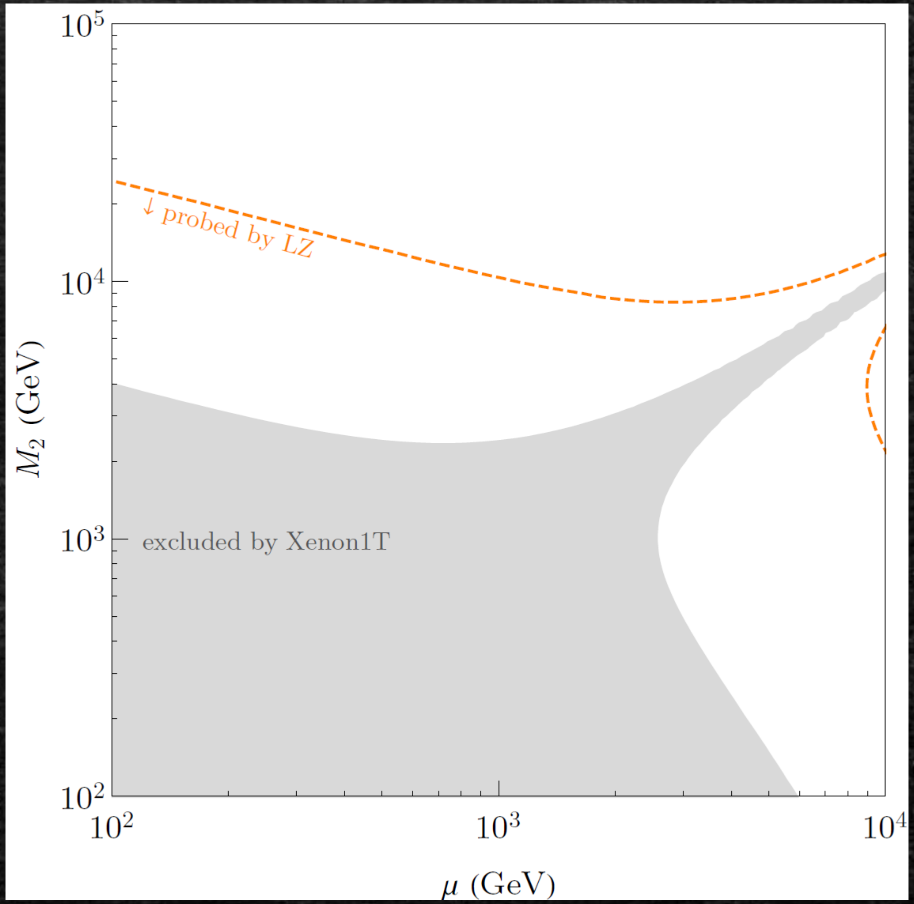
- Anomaly generated gaugino masses
  - $M_3 \approx 10M_2 \approx 3M_1$
  - $m_0 \sim 300\ M_2$
- Higgsino DM as WIMP DM
  - Standard freeze-out WIMP scenario
  - Mass set to $m_{DM} \sim \mu \approx 1.2$ TeV

Profuno, Yaguna hep-ph/0407036

Limited Accessibility to Usual Approaches

- Colliders are very limited for heavy, non-colored 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)   Galli, et al. 0905.0003
  - CTA can reach near μ = 1 TeV

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^{-38} e cm
  - Current limit is at 1.1 x 10^{-29} e cm

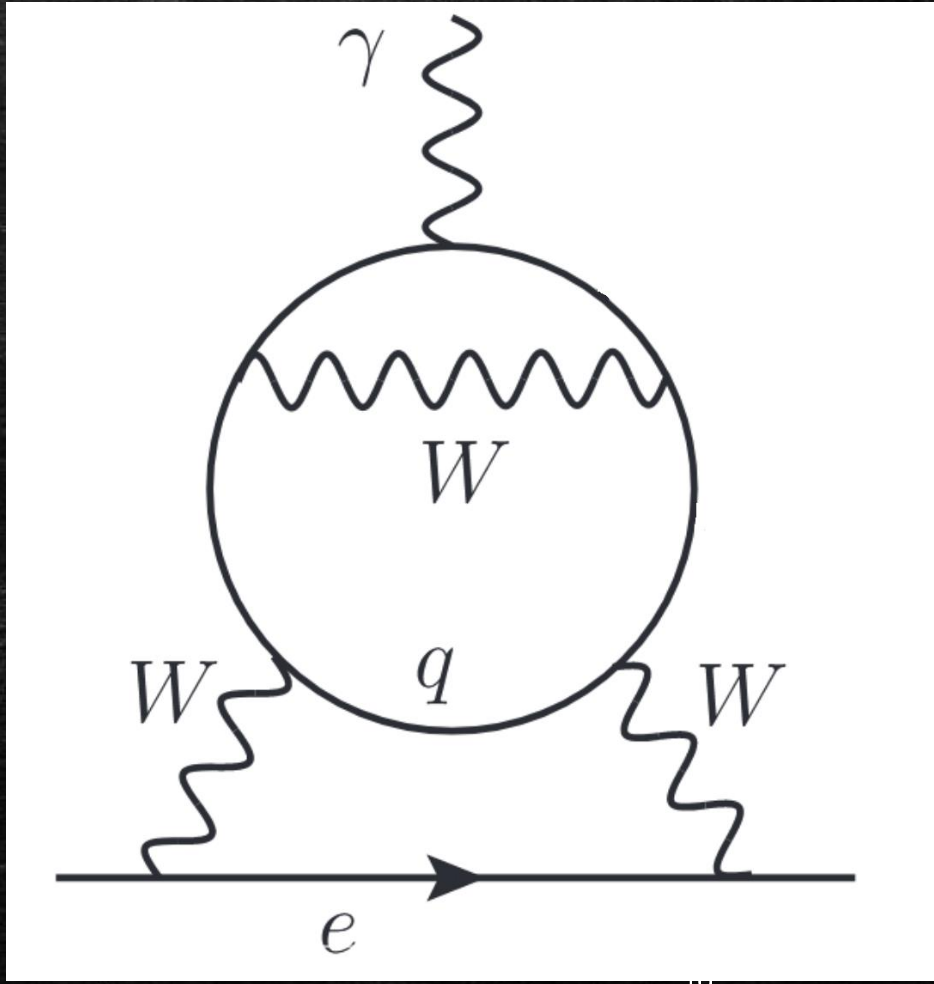
ACME II limit, 2018

Scale reference for EDM:

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

What's going on in the SM?

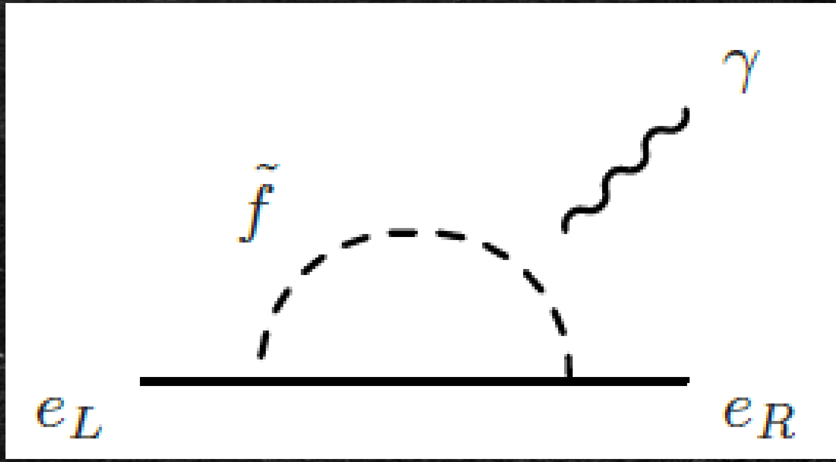
- Need to involve CKM matrix
  - Need all three doublets involved
- 3 loop diagrams are all that work



What about SUSY?

- CP phase can be large
- Limit can be (for O(1) phases)

$M_{SUSY} > 10$ TeV   Cesarotti, et al. 1810.07736



Electron EDM in Split SUSY

- Heavy scalars suppresses previous slide loops
- No 1 loop EDM
  - Non-trivial to find CP phase that can't be absorbed
  - Move to two loop

Barr-Zee Diagram

- Leading order diagrams for EDM

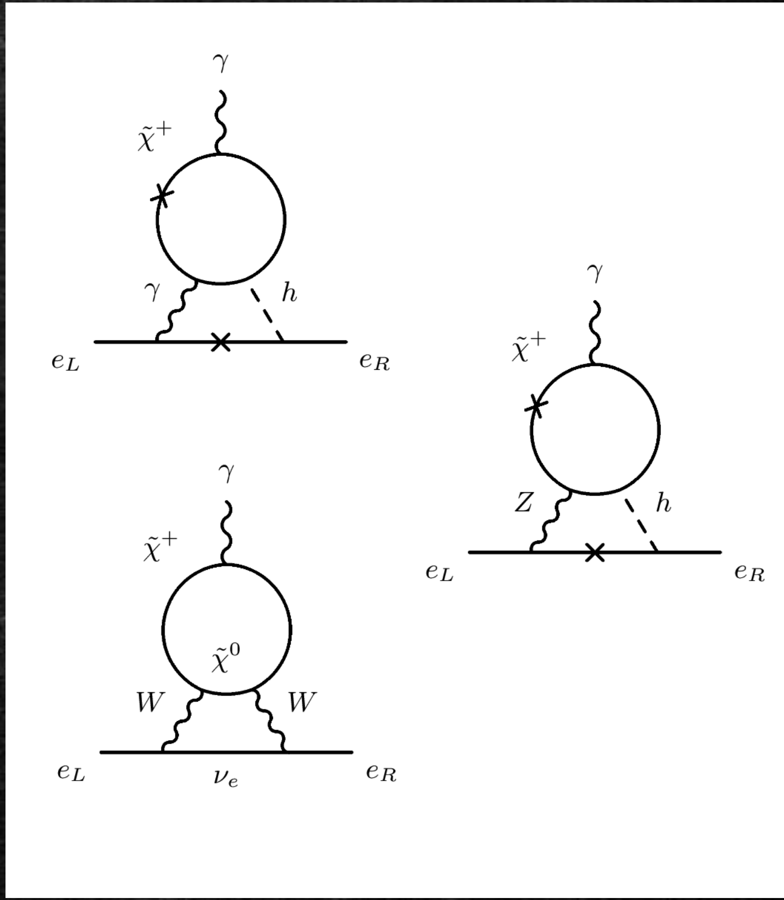
$M_2, \mu >> m_Z$ gives:

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

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

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

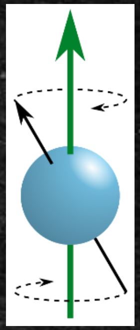
Giudice, Romanino hep-ph/0510197



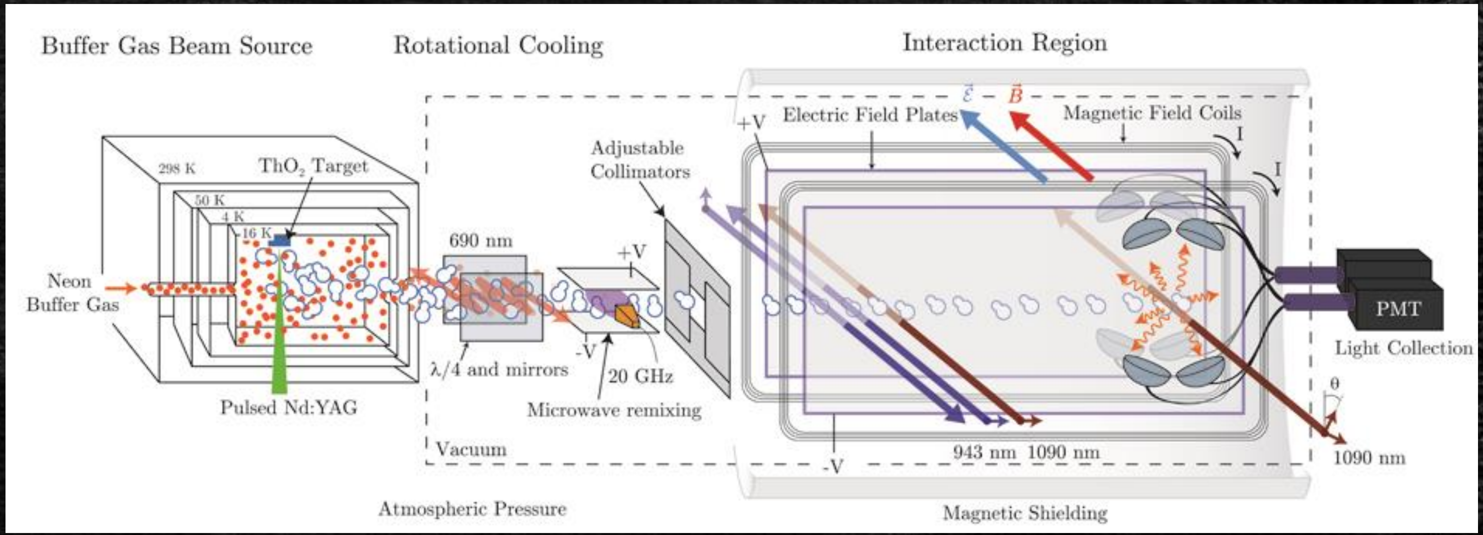
DOI: 10.1038/s41586-018-0599-8

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 1.1×10^{-29} e-cm



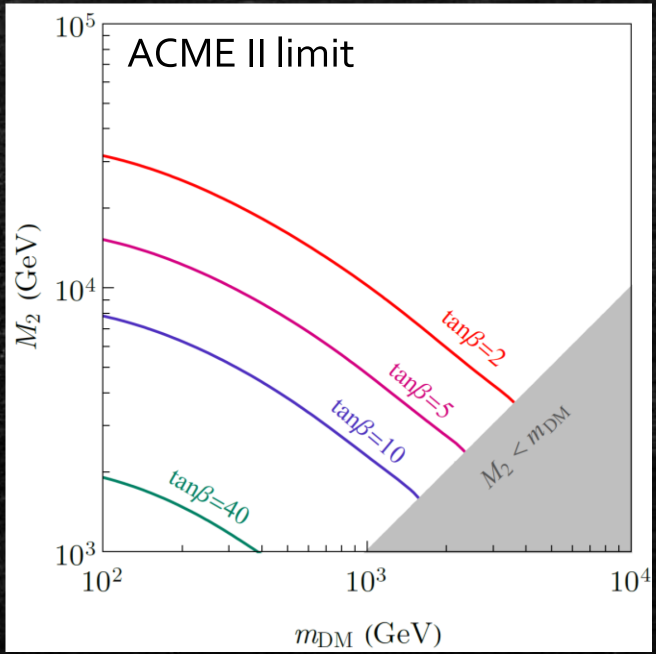
By Mario De Leo - https://commons.wikimedia.org/wiki/File:Precession_in_magnetic_field.svg

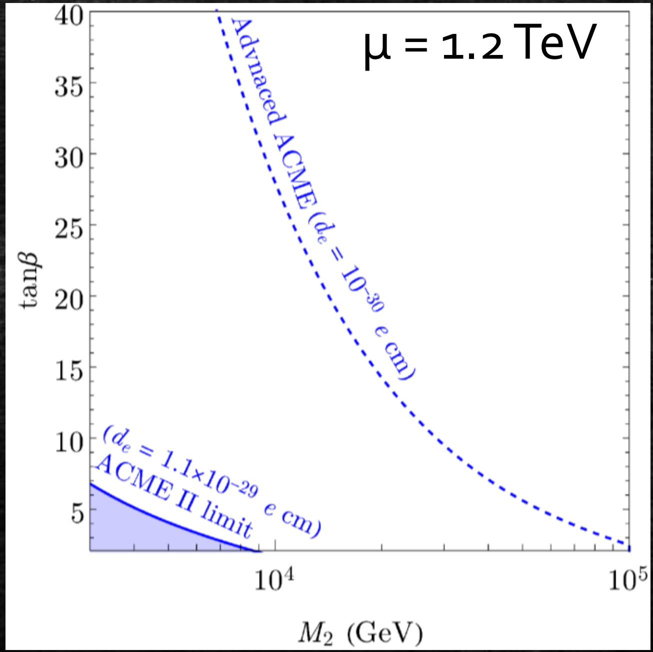


https://www.danielang.net/2016/10/16/guide-to-the-acme-edm-experiment-a-simple-overview/

EDM Results

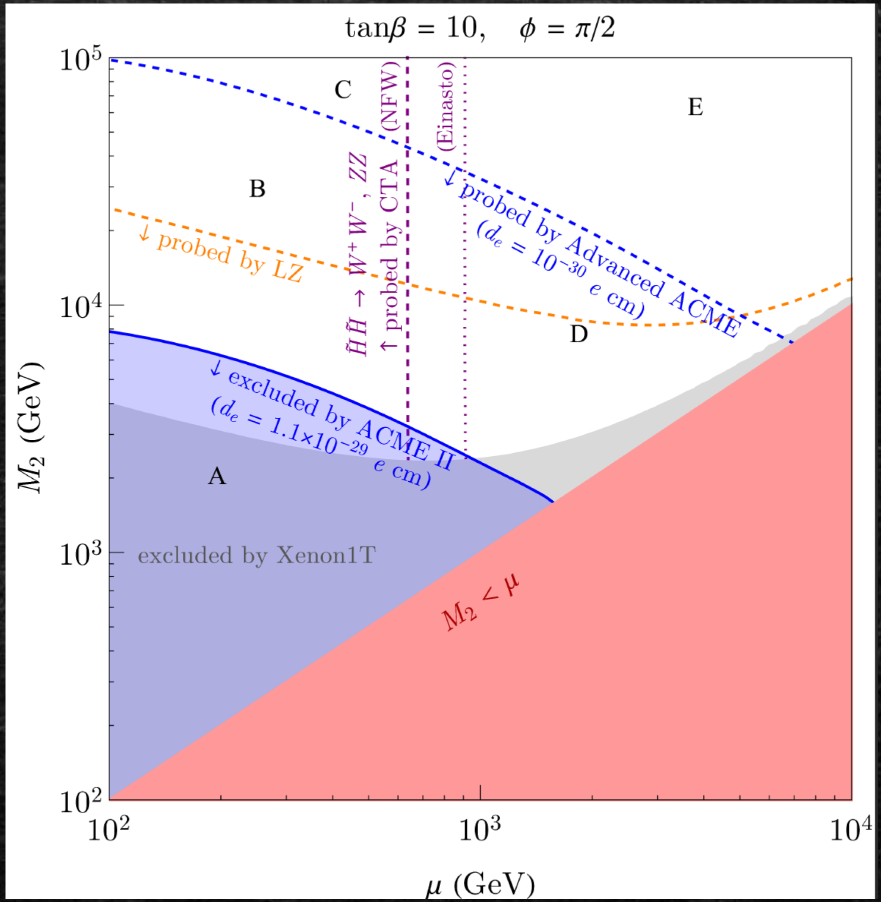
- Current limits confined to low tanβ or low ($M_2\mu$)
- Advanced ACME expected to be an order of magnitude more sensitive
  - Would reach, for μ = 1.2 TeV, M2 ~ O(10 TeV), tanβ ~ O(30) covering our region of interest





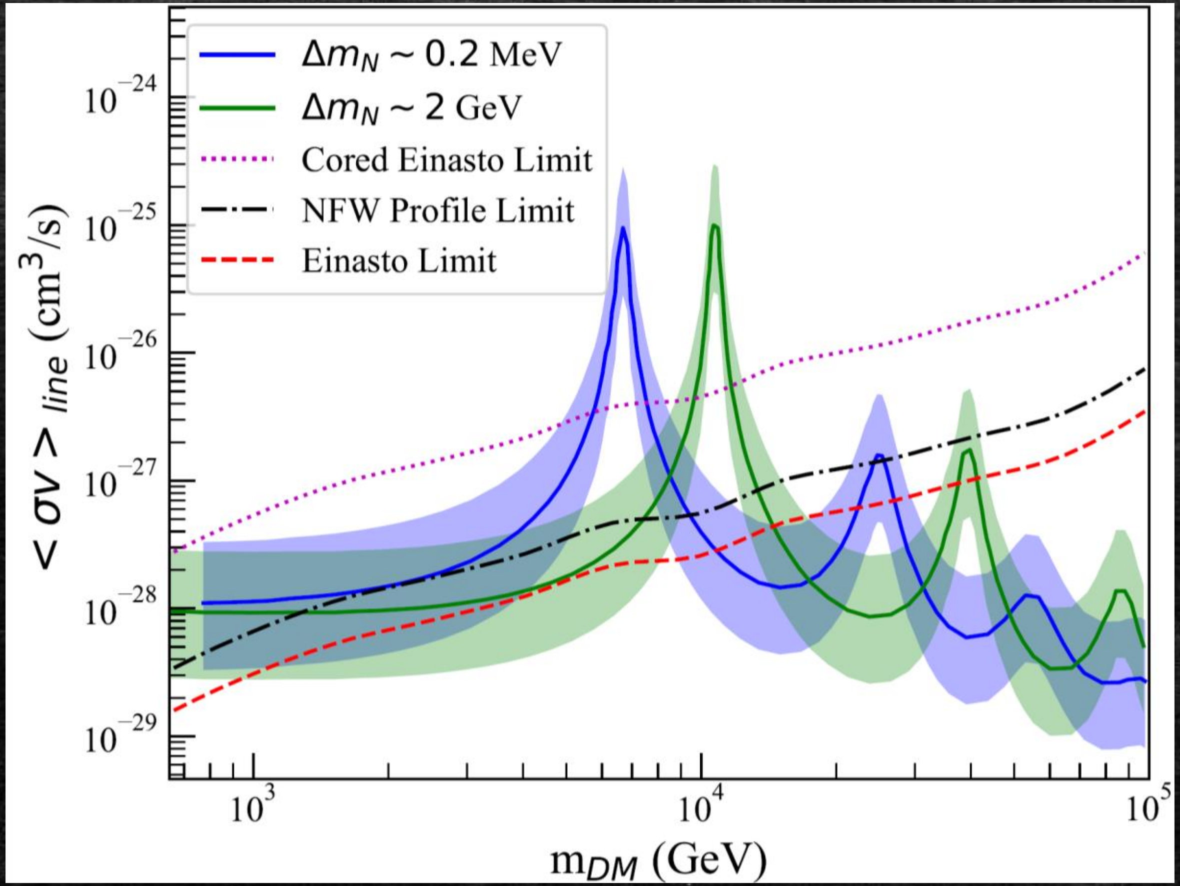
Results in Context

- A bit of a race between approaches
  - LZ could significantly increase DD limits, but limited by M_2^2 scaling
  - CTA can have reach in ID search, dependent on astrophysical unknowns
  - e-EDM reach is fairly robust
    - Up to complex phase or large M_2



Thank you!

Line photon indirect detection searches



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