Thoughts on Neutralino Dark Matter

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Old Results in Dark Matter

Observations

- Galactic Rotation Curves
- Cluster Dynamics (incl. collisions)
- Velocity dispersions of galaxies - dark matter extends beyond the visible matter
- Weak Gravitational Lensing (distribution of dark matter)
- CMB (+ Type 1A SNe, plus BAO) all agree on LambdaCDM
- Structure Formation

Summary

- Some explanation is necessary for observed gravitational phenomena.
- It's largely non-relativistic (cold).
- Its abundance is $\Omega_{DM} \approx 0.26$.
- It's stable or very long-lived.
- It's non-baryonic (BBN+CMB, structure).
- It's neutral (heavy isotope abundances).

Current Situation

- Abundance of experimental data!
  - We're exploring dark matter with unprecedented and growing precision - both experimentally and theoretically.
- Theoretical approaches:

Totally Data-Driven

↕

Totally Theory-Driven

Current Situation

- Abundance of experimental data!
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↕

Hybrid / Simplified Models

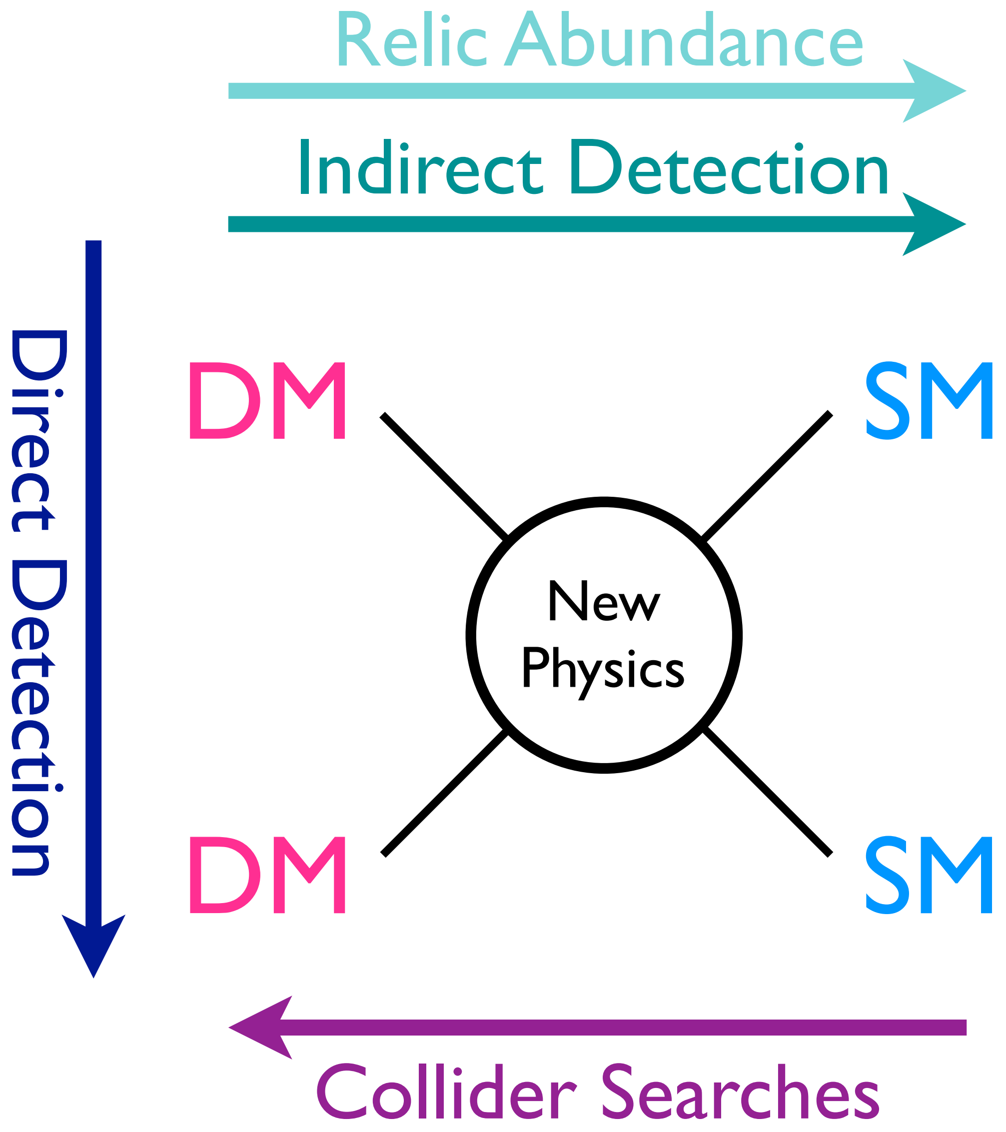
↕

Totally Theory-Driven

Effective Theories

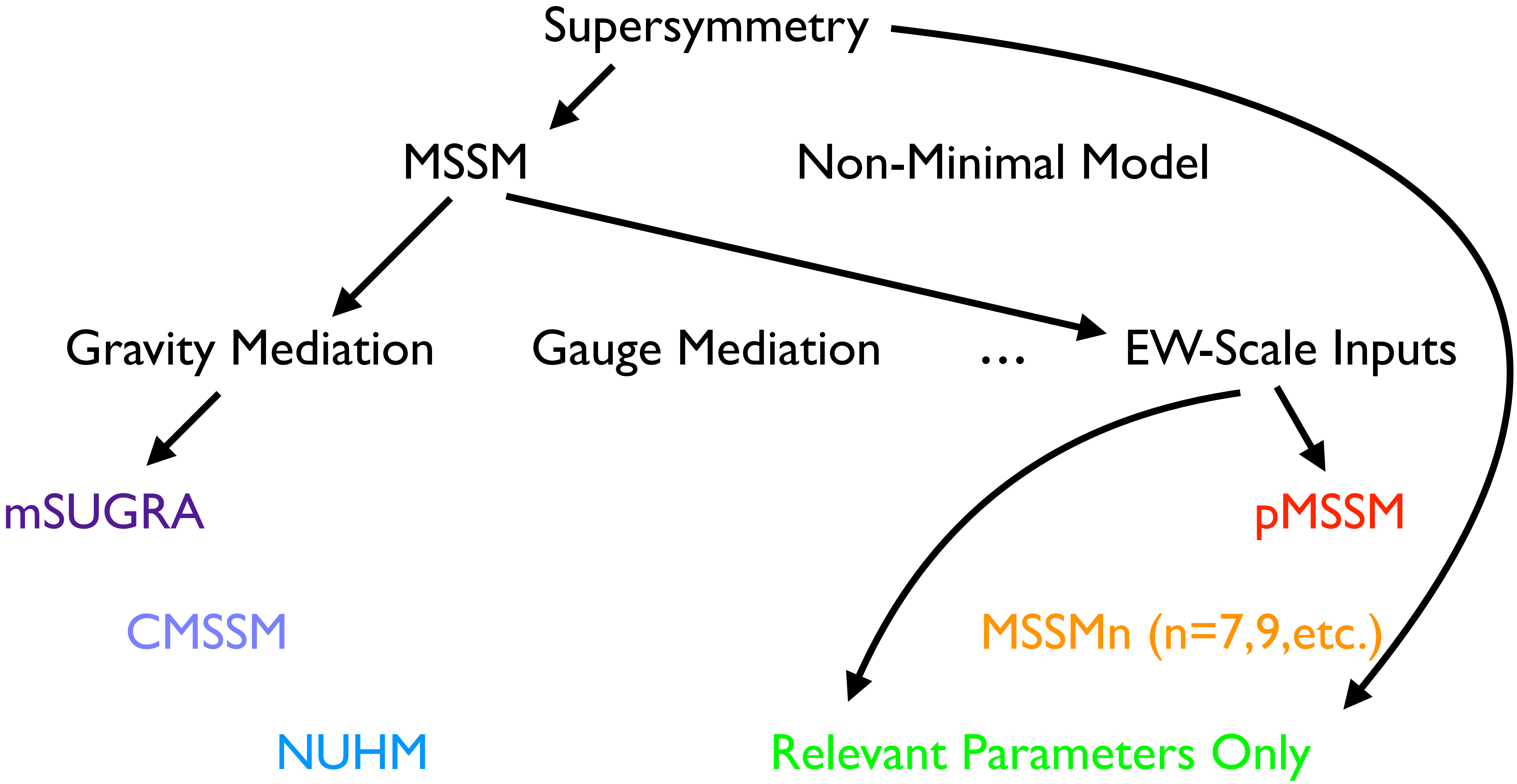
(McCabe talk on Monday)

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{X}\gamma^\mu\partial_\mu X - M_X\bar{X}X + \sum_q\sum_{i,j}\frac{G_{qij}}{\sqrt{2}}\ [\bar{X}\Gamma_i^X X]\,[\bar{q}\Gamma_q^j q]$$



- Idea: Reduce DM-SM interaction to a contact interaction.
- Universe of possible interactions is small (can enumerate)
- Utility in evaluating complementarity of detection techniques (good)
- Range of validity (careful)

Fundamental Theory



Supersymmetry

MSSM

Non-Minimal Model

Gravity Mediation

Gauge Mediation

…

EW-Scale Inputs

mSUGRA

CMSSM

NUHM

pMSSM

MSSMn (n=7,9,etc.)

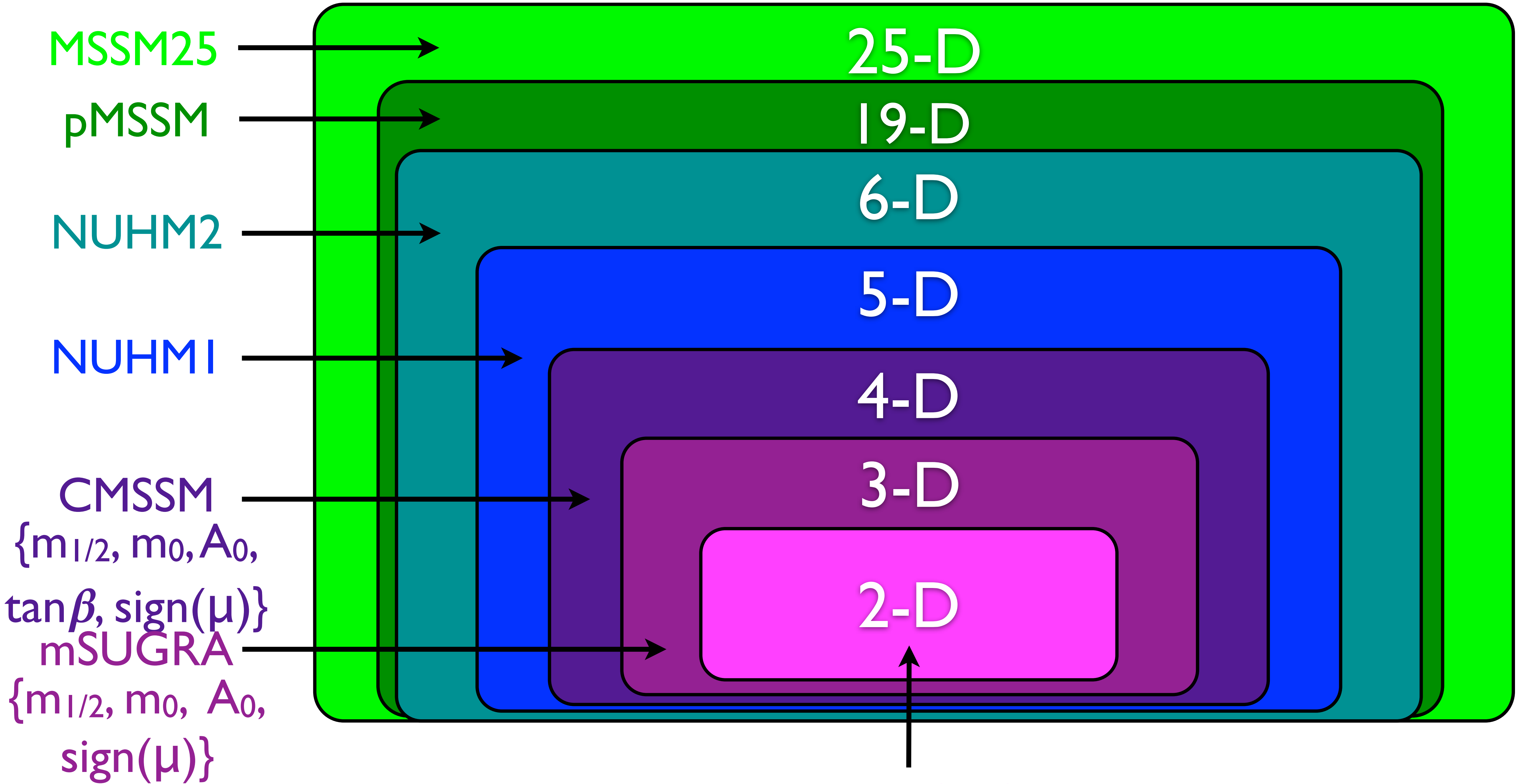
Relevant Parameters Only

SUSY Dark Matter

1. What is predicted within the SUSY framework?
    - specific realization or more general possibilities
2. What are the data really telling us?
    - Priors on model ➔ different interpretations
3. When will we know for sure?
    - Direct Dark Matter Searches

$$\tilde{\chi}_i = N_{i1}\tilde{B} + N_{i,2}\tilde{W} + N_{i3}\tilde{H}_d + N_{i,4}\tilde{H}_u$$

Dimensionality



MSSM25

25-D

pMSSM

19-D

NUHM2

6-D

NUHM1

5-D

4-D

CMSSM

$\{m_{1/2}, m_0, A_0, \tan\beta, \mathrm{sign}(\mu)\}$

3-D

mSUGRA

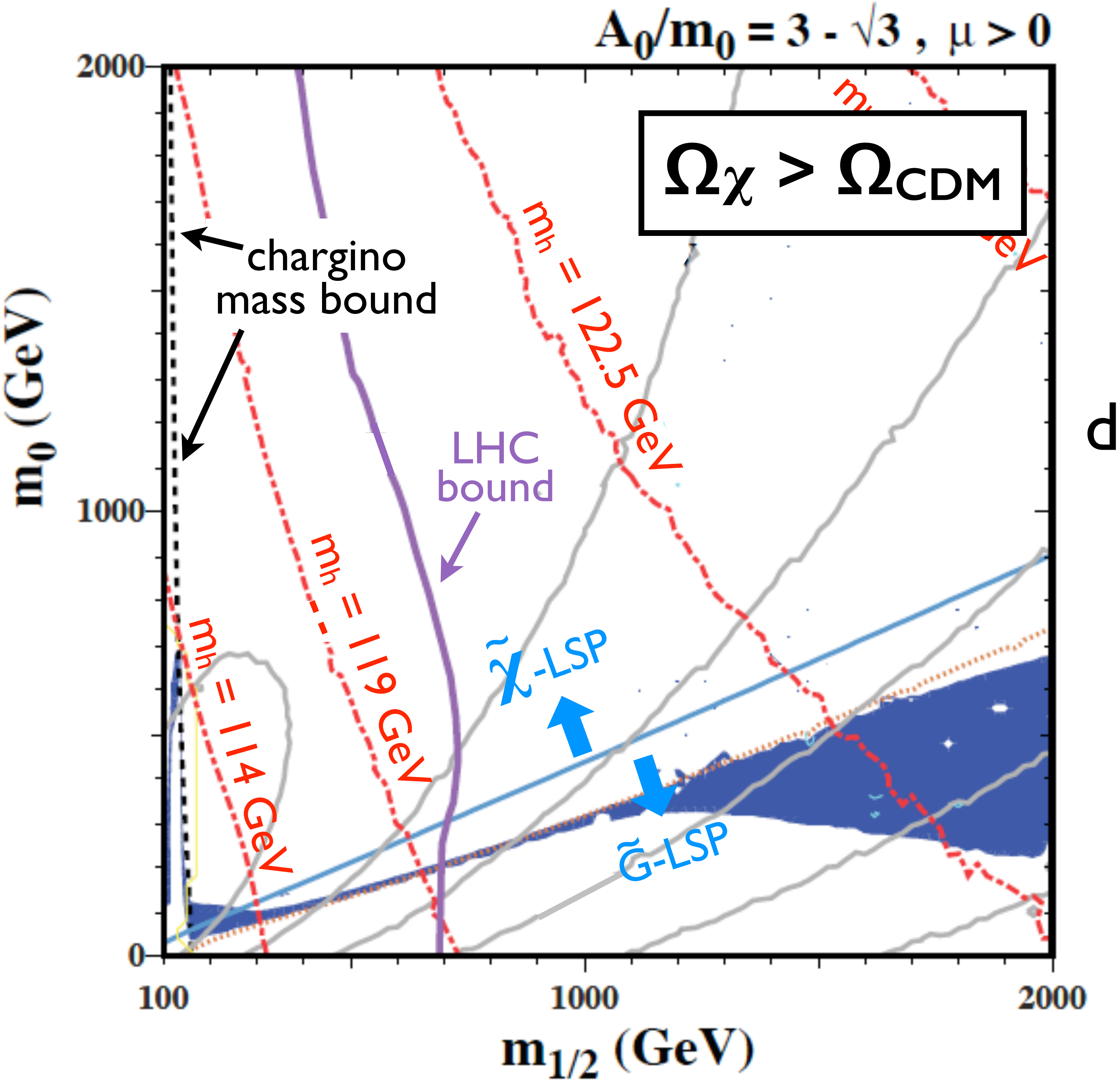
$\{m_{1/2}, m_0, A_0, \mathrm{sign}(\mu)\}$

2-D

Polonyi mSUGRA

$A_0 = (3 - \sqrt{3})m_{3/2}$ ➡ $\{m_{1/2}, m_0, \mathrm{sign}(\mu)\}$

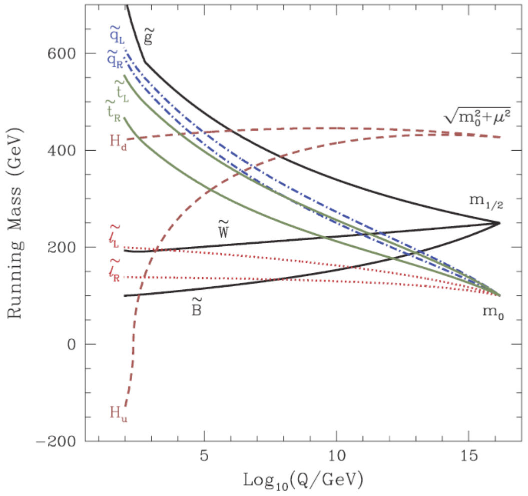
Polonyi mSUGRA



Increase dimensionality?

Ellis, Luo, Olive, Sandick (2013)

Universality Scale



- Input universality scale, M_{in}, assumed to be M_{GUT}
- Could be larger: “superGUT”
  - SUSY breaking and mediation characterized by Planck or string scale

Polonsky & Pomarol (1994)
For recent analyses, see Ellis, Mustafayev, & Olive (2010,2011)

- Could be smaller: “subGUT/GUTless”, “Mirage”, or “TGM”

Ellis, Olive, & **Sandick**
(2006, 2007, 2008);
Ellis, Luo, Olive,
& **Sandick** (2013)

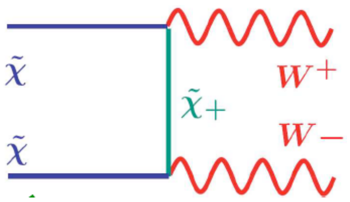
Choi et al. (2004, 2005),
Kachru et al. (2003),
and others

Monaco et al.
(2011)

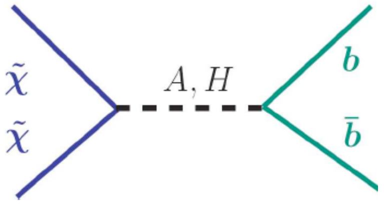
  - Lowest dynamical scale in the Polonyi/hidden sector where SUSY is broken, or scale of interactions that transmit breaking to observable sector

Dark Matter Abundance

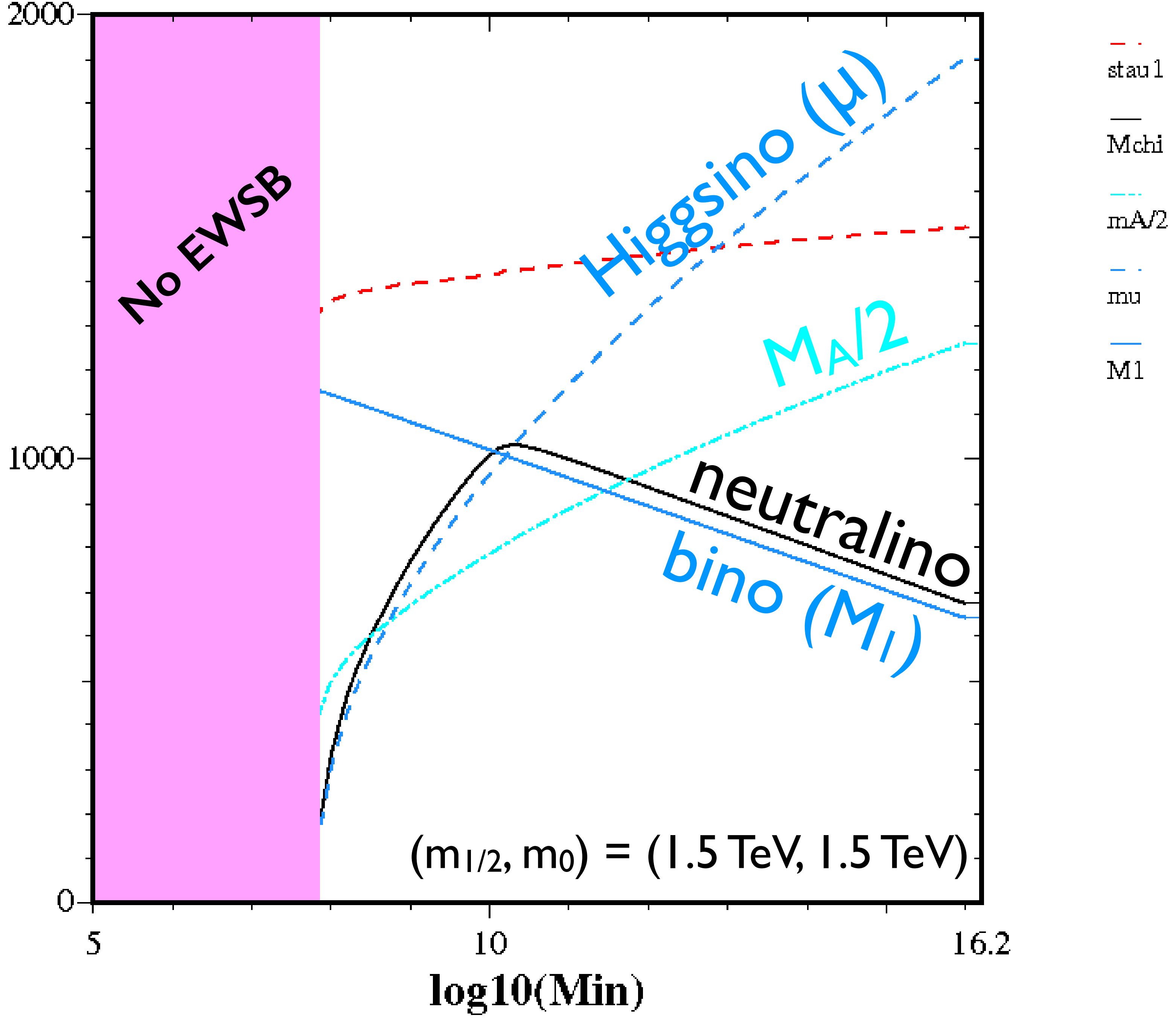
1. neutralino LSP becomes Higgsino-like at low M_{in}



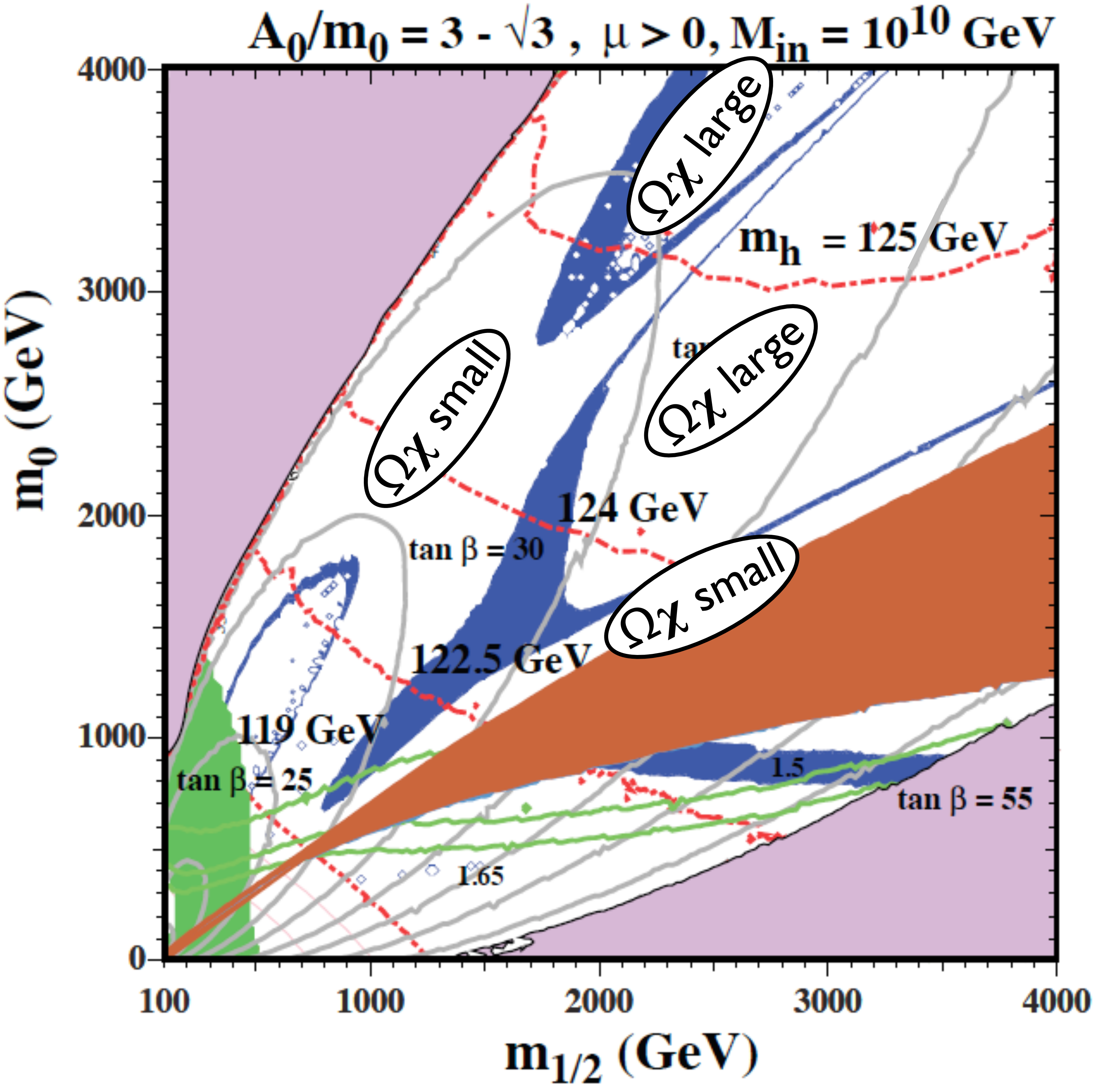
2. m_A decreases with M_{in} → appearance of rapid annihilation funnel



(2-loop results)



sub-GUT mSUGRA



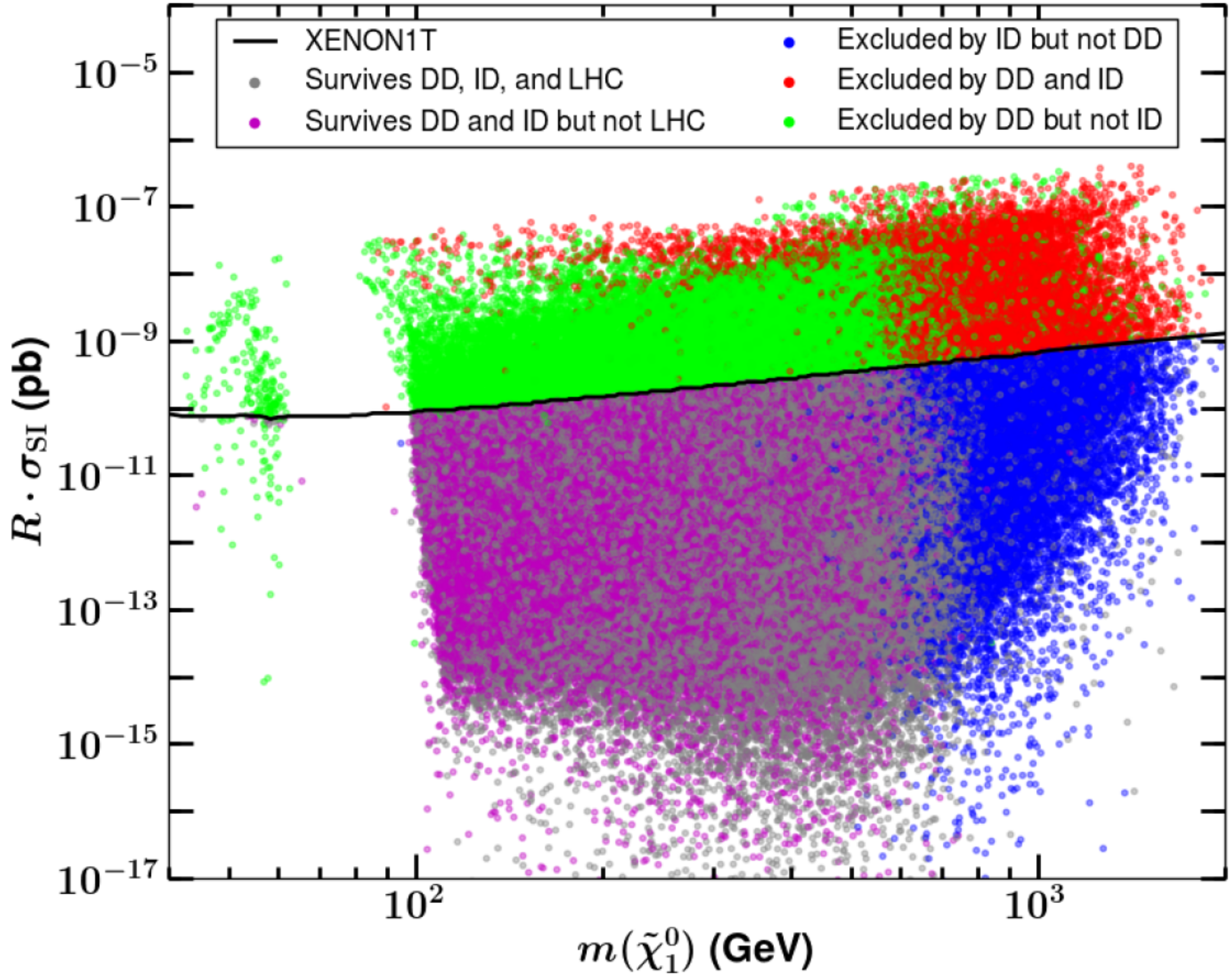
Ellis, Luo, Olive,
Sandick (2013)

To Higher Dimensions…

- There are still viable, few-parameter models motivated by high-scale physics.
  - Strength: one of these models might actually describe our Universe!
  - Strength: understand how observables change in the parameter space!
  - Weakness: may be missing important model classes
- Higher dimensional models more fully explore the possible combinations of observables (if sampling of the model space is adequate!).

pMSSM

Cahill-Rowley et al. (2013)

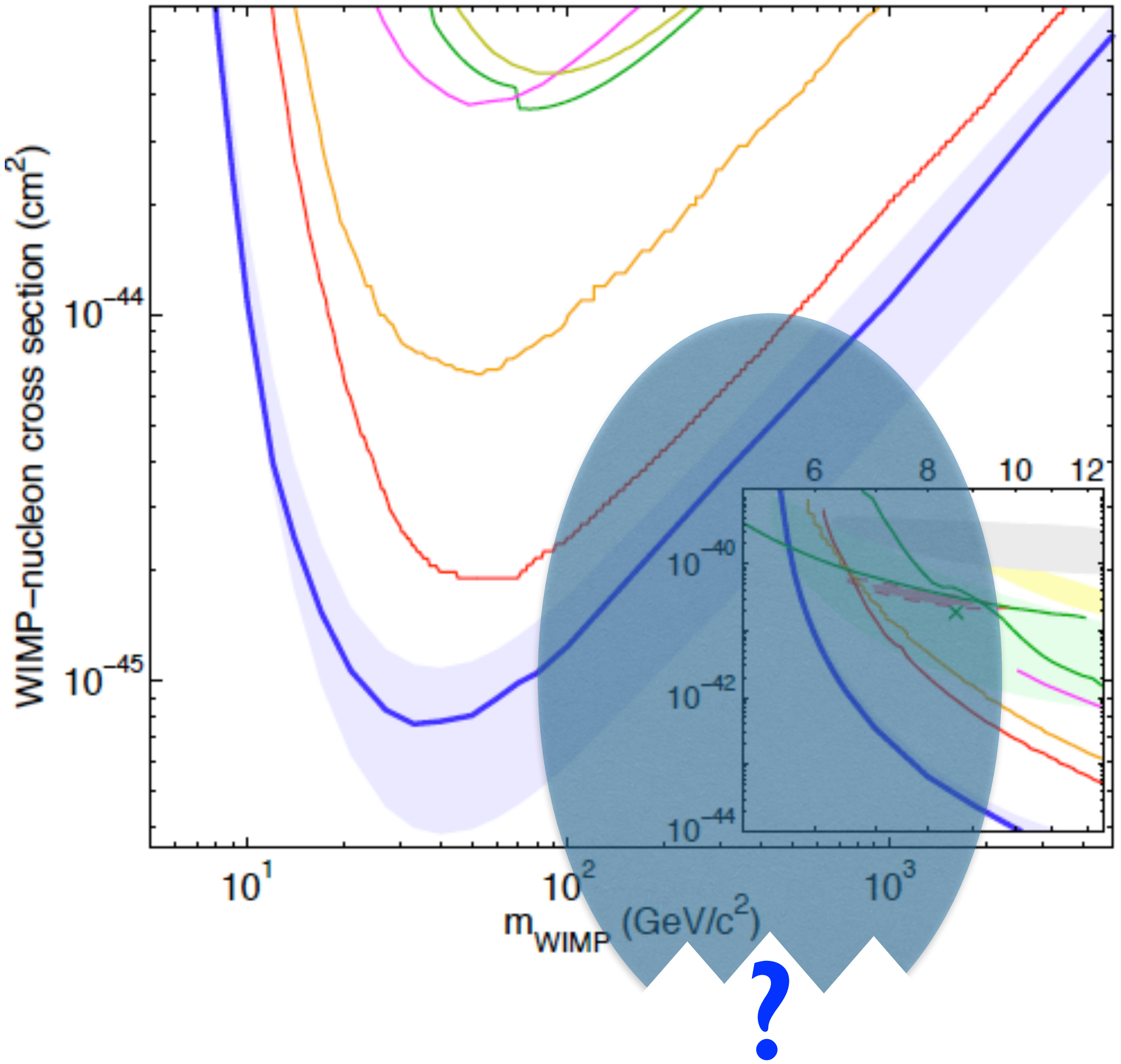


3. When will we know for sure?

Future Prospects

- Timeline for discovery/exclusion?

Akerib *et al.* (LUX Collaboration), 2013



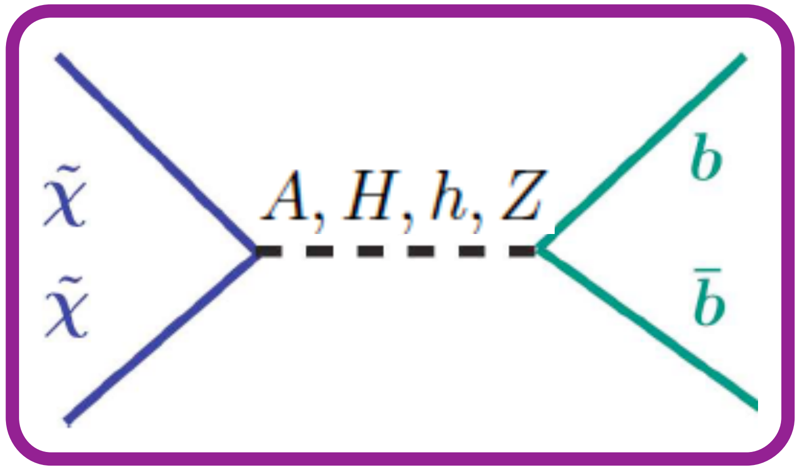
Could answer within a low-dimensional model (not general), or within the MSSM (not conclusive).

Simplified models can help you construct a definite, model-independent answer.

Resonance Models

- Neutralino: $\tilde{\chi}_1^0 = \underset{M_1}{\alpha \tilde{B}} + \beta \tilde{W}^0 + \underset{\mu}{\gamma \tilde{H}_d^0 + \delta \tilde{H}_u^0}$

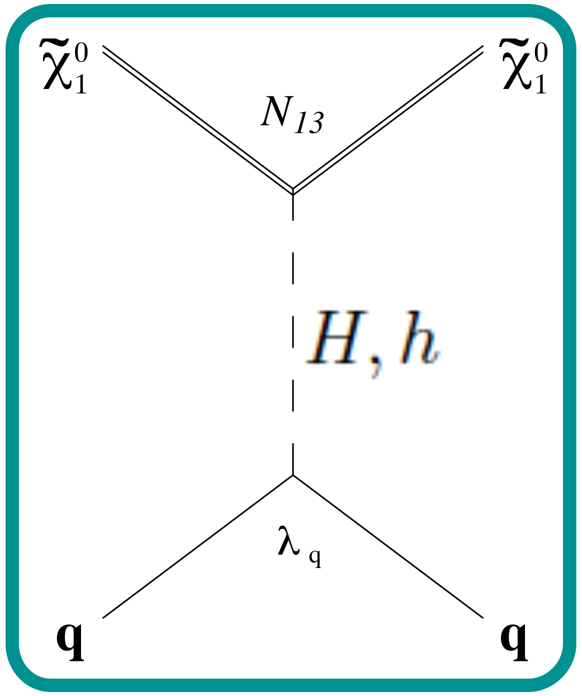
- s-channel resonance annihilations occur when $2m_{\tilde{\chi}_1^0} \approx m_{A,H,h,Z}$



- As $(\sigma_{ann.} v)$ increases, $\Omega_{\tilde{\chi}_1^0}$ decreases
  - If $\Omega_{\tilde{\chi}_1^0}$ too large, increase Higgsino content: μ

- Scattering with quarks is governed by $M_1,\ \mu,\ m_A,\ \tan\beta$

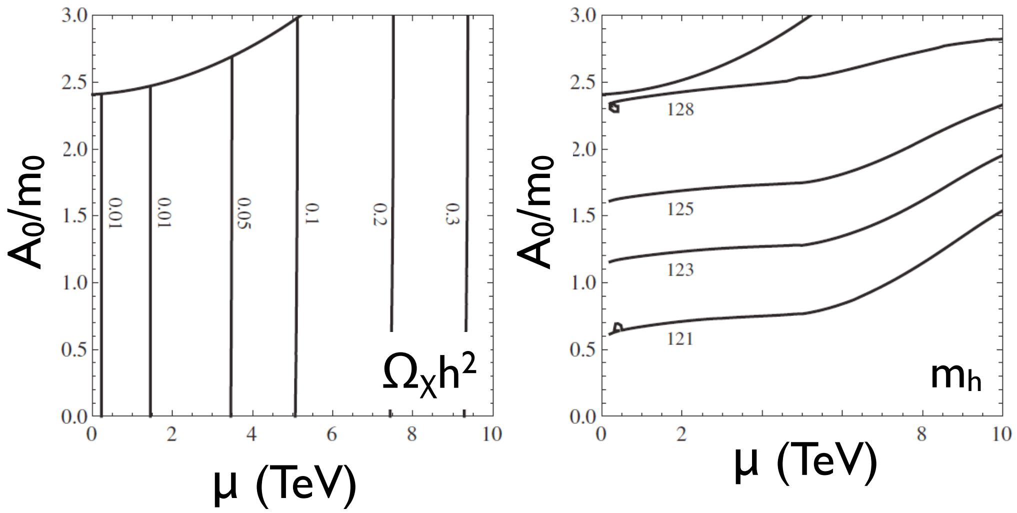
- Relevant parameters: $\{M_1,\ \mu,\ m_A,\ \tan\beta,\ M_0,\ A_0\}$

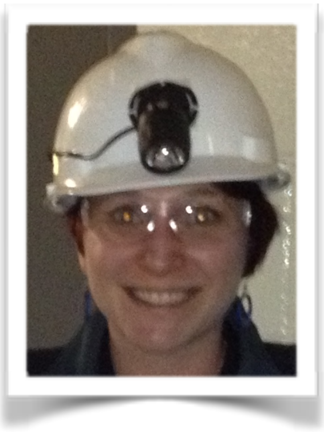


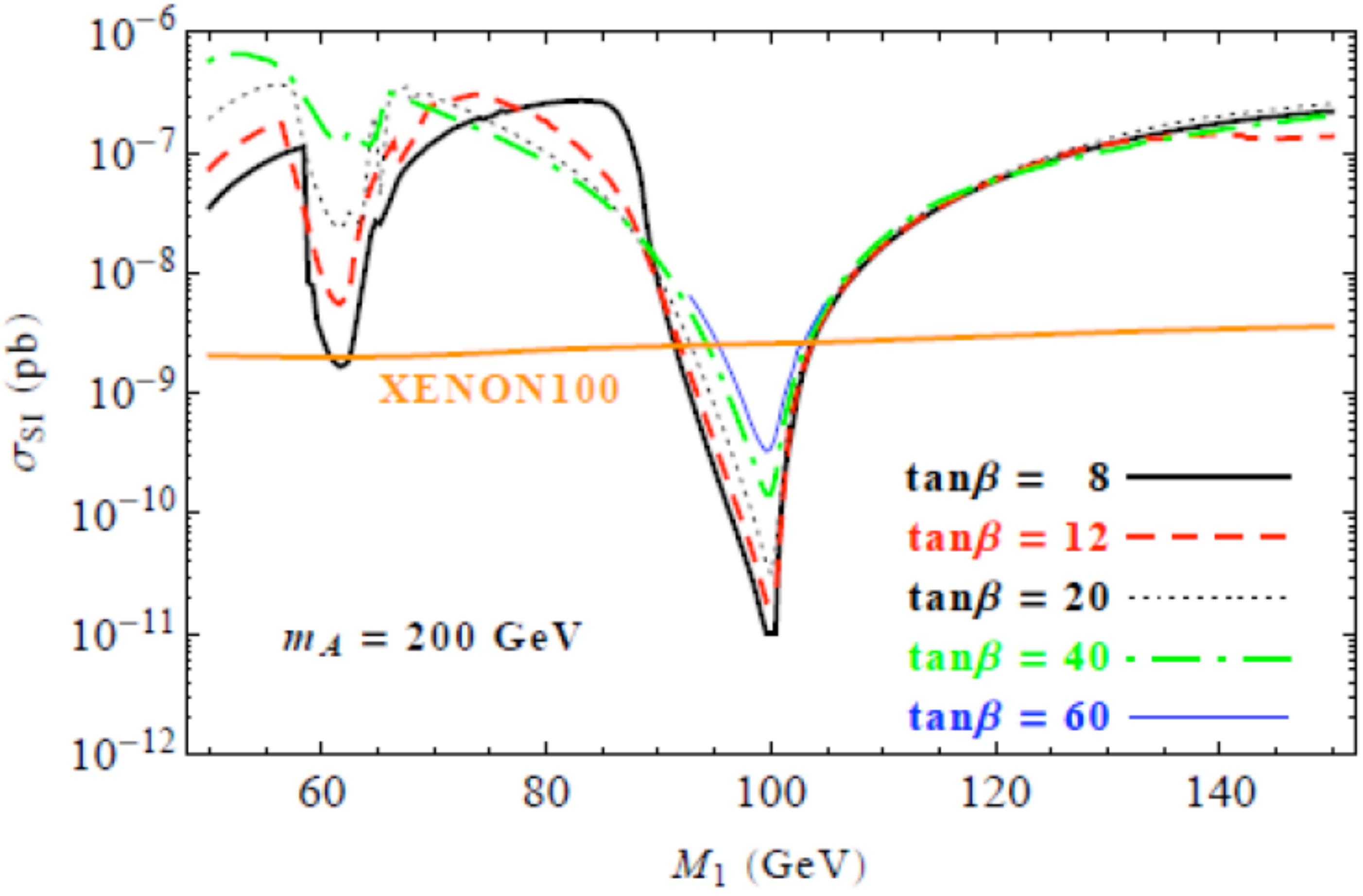
If DM abundance is achieved through a resonance, how small could σ_{SI} possibly be?

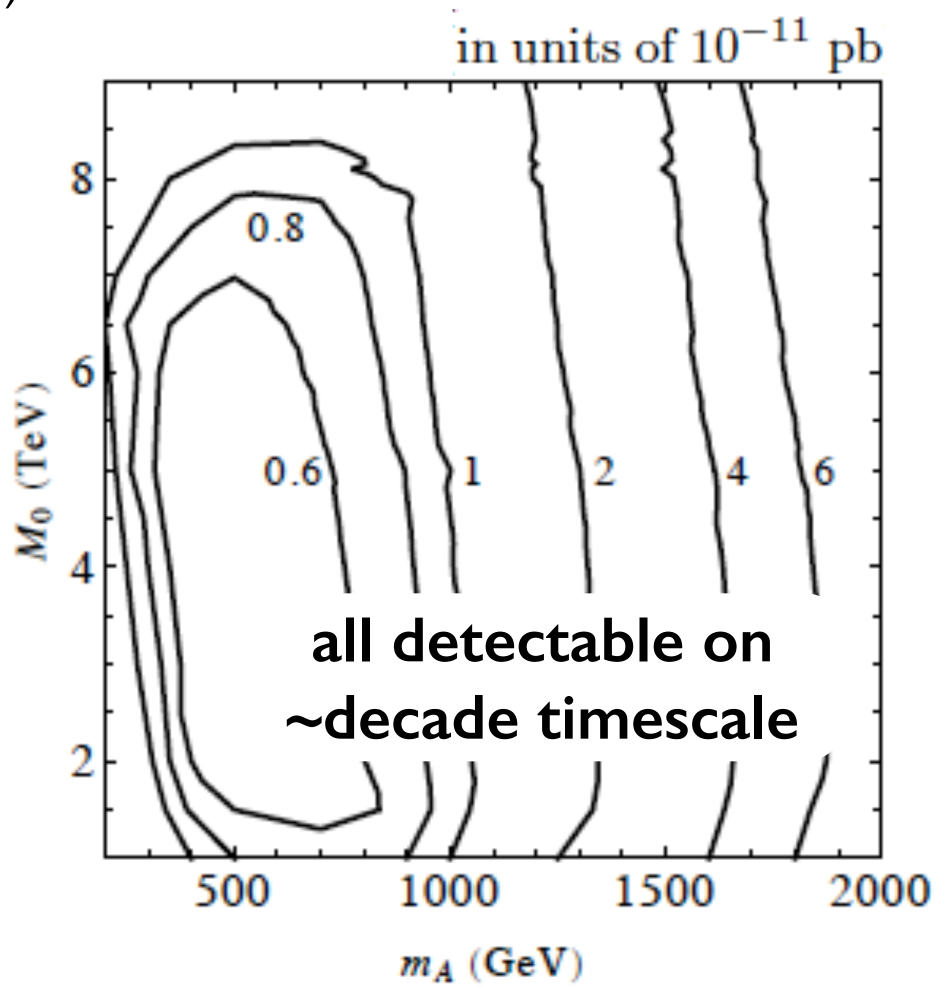
Hooper, **Kelso, Sandick,** & Xue, PRD 2013

- Relic Abundance: μ
- Higgs mass: A_0
- Free parameters: (m_0, M_1, m_A, $\tan\beta$)









all detectable on ~decade timescale

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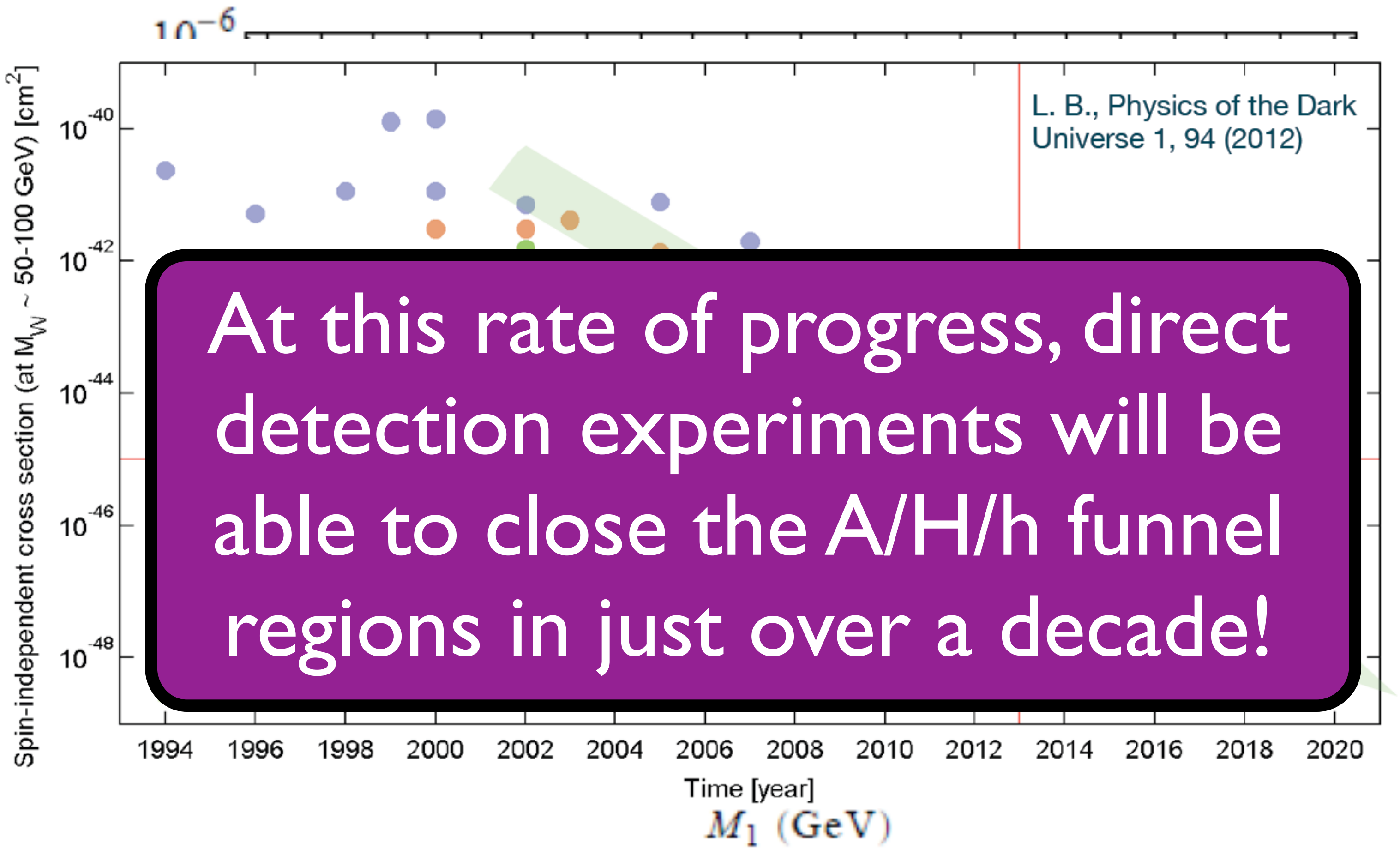
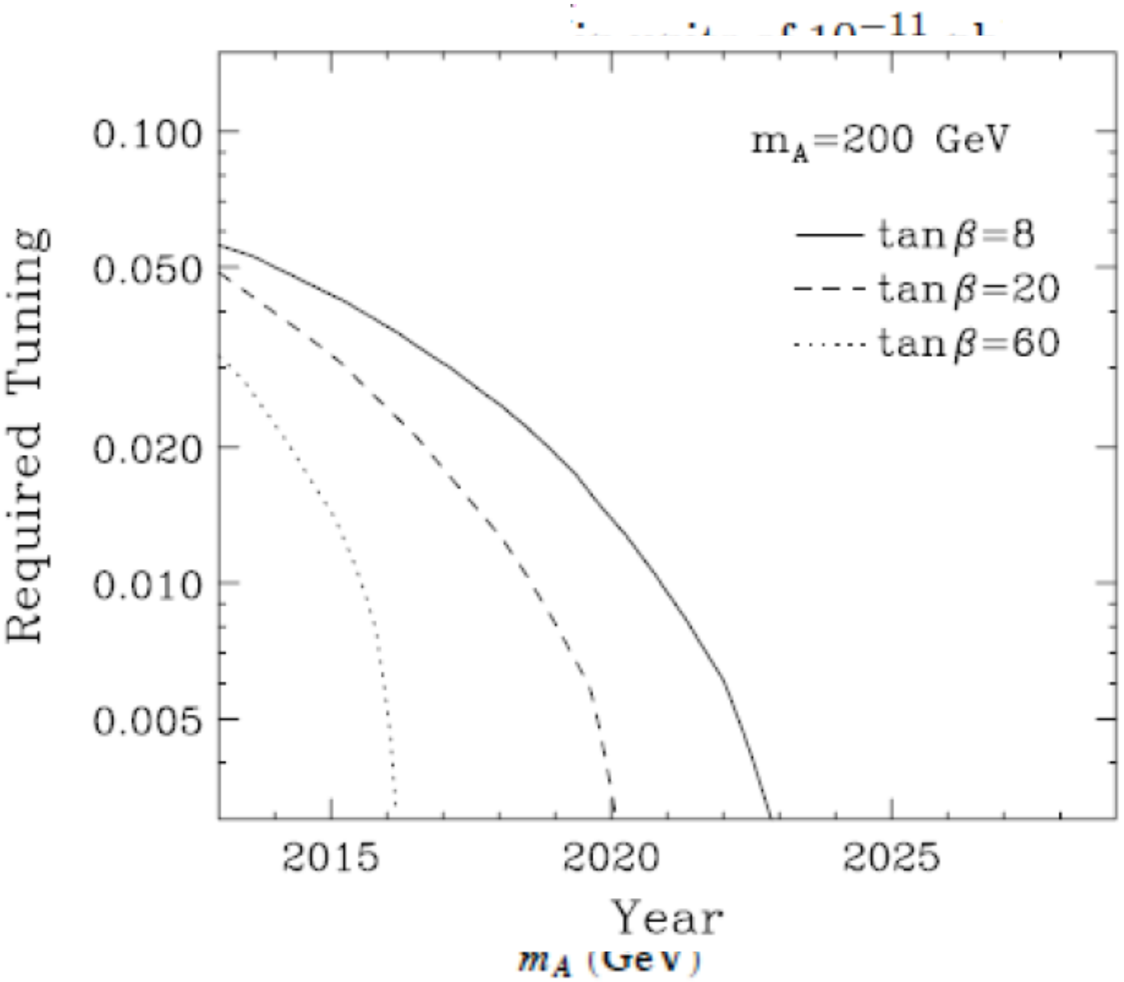
- Relic Abundance: μ
- Higgs mass: A_0
- Free parameters: $(m_0, M_1, m_A, \tan\beta)$

If Nature is MSSM-like, and neutralino dark matter at a resonance makes up all the dark matter in the Universe, then direct detection experiments are pushing the resonance to be more and more exact.



At this rate of progress, direct detection experiments will be able to close the A/H/h funnel regions in just over a decade!



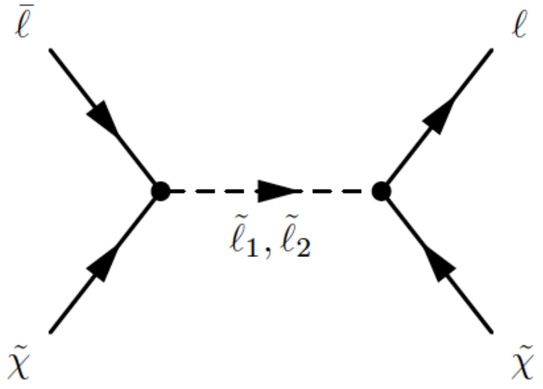
Data-Driven SUSY

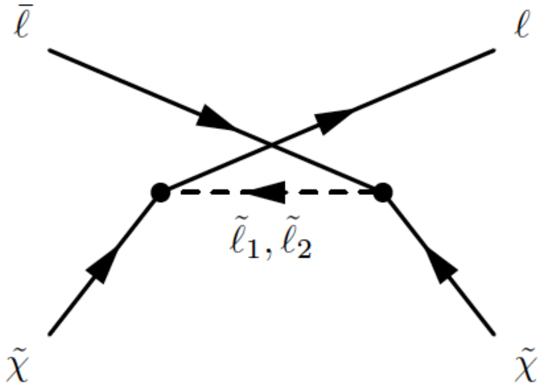
- 2. What are the data telling us?
  - Investigate parameter space near current constraints.
  - Dramatically different answers, depending on assumptions!
- What we really know about sparticles: sleptons, charginos, and 3rd gen. squarks heavier than ~100 GeV, 1st/2nd gen. squarks heavier than ~1.1 TeV, gluino heavier than ~1 TeV
- Other constraints: Higgs ~126 GeV, dark matter, rare B decays, electric dipole moments, anomalous magnetic moments
- Simple model: bino-like LSP and light sleptons (everything else heavy)
  - $m_{\tilde{\chi}_1}, m_{\tilde{l}_1}, m_{\tilde{l}_2}, \alpha, \varphi$

Fukushima, Kelso, Kumar,
Sandick, & Yamamoto (in prep.)

Light Sleptons

- Relic Abundance:





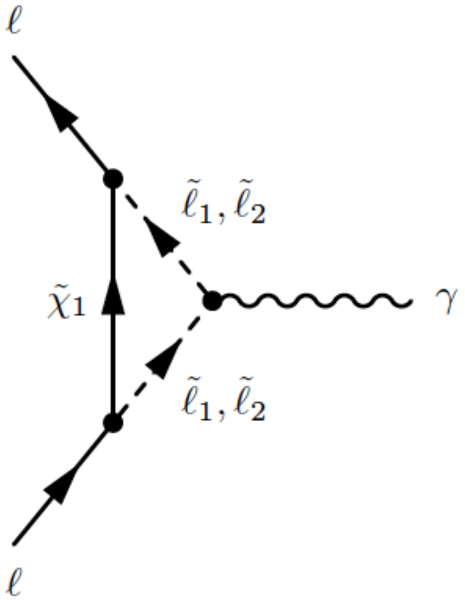
$$\langle \sigma v \rangle \sim c_0 + c_1 \left(\frac{T}{m_\chi} \right)$$

$$c_0 = \frac{m^2_{\tilde{\chi}}}{2\pi} g^4 Y_L^2 Y_R^2 \cos^2\alpha \sin^2\alpha \left(\frac{1}{m^2_{\tilde{\ell}_1} + m^2_{\tilde{\chi}}} - \frac{1}{m^2_{\tilde{\ell}_2} + m^2_{\tilde{\chi}}} \right)^2$$

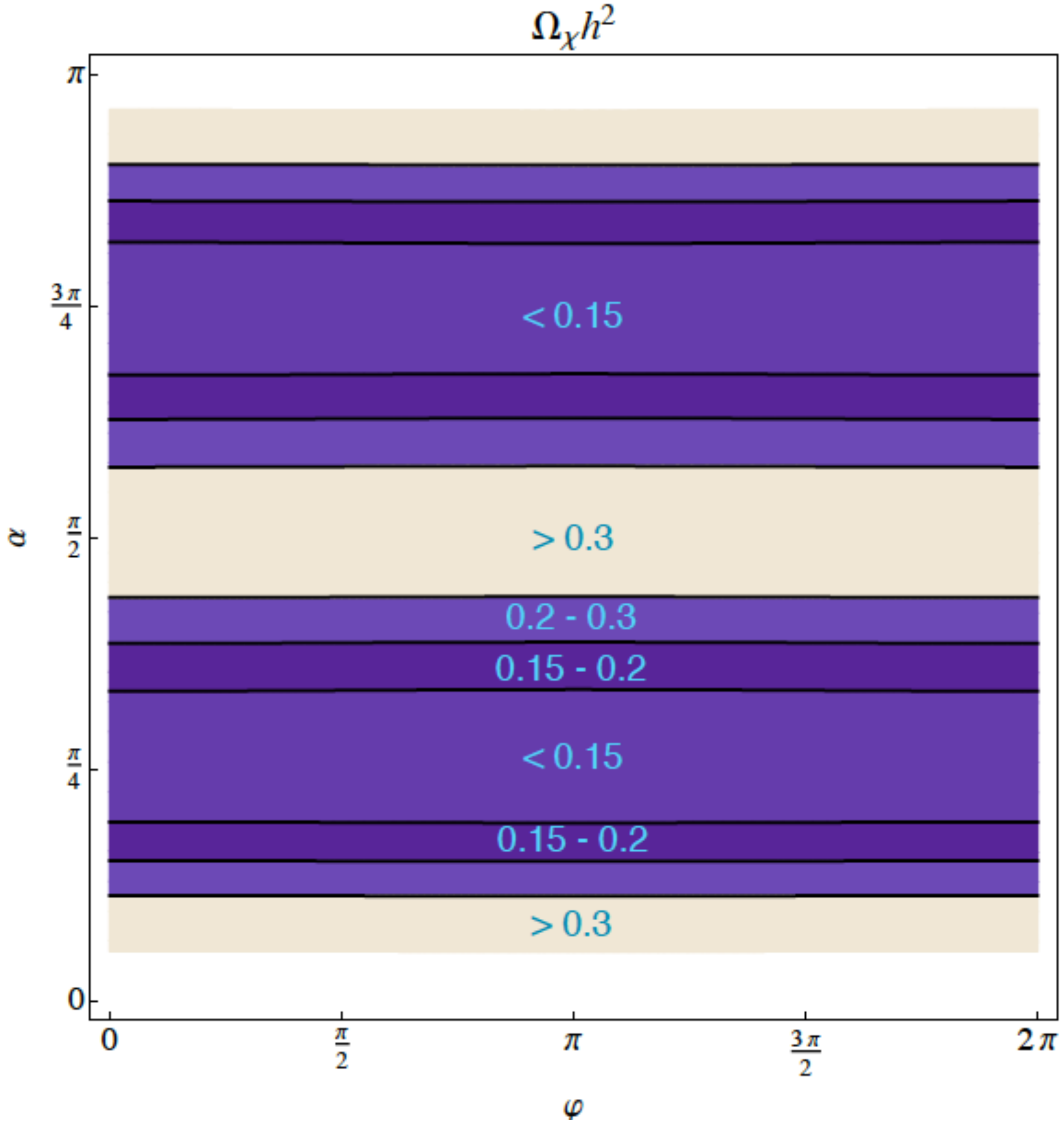
- Dipole Moments:

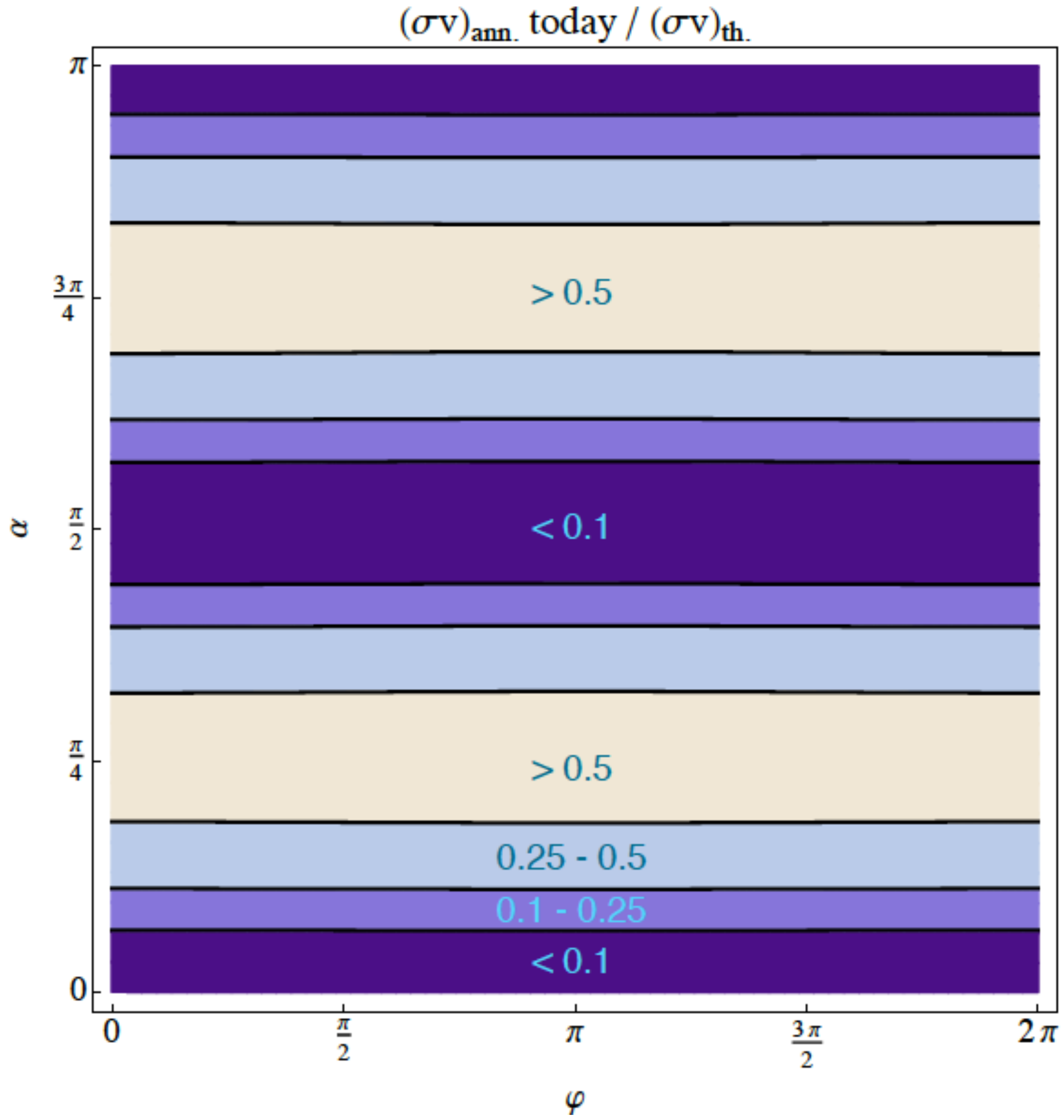
$$\Delta a = \frac{m_\ell m_{\tilde{\chi}}}{4\pi^2 m^2_{\tilde{\ell}_1}} g^2 Y_L Y_R \cos\varphi \cos\alpha \sin\alpha \left[\frac{1}{2(1-r_{\tilde{\ell}_i})^2} \left(1 + r_{\tilde{\ell}_i} + \frac{2 r_{\tilde{\ell}_i} \ln r_{\tilde{\ell}_i}}{1 - r_{\tilde{\ell}_i}} \right) \right] - (\tilde{\ell}_1 \to \tilde{\ell}_2)$$

$$\frac{d}{|e|} = \frac{m_{\tilde{\chi}}}{8\pi^2 m^2_{\tilde{\ell}_1}} g^2 Y_L Y_R \sin\varphi \cos\alpha \sin\alpha \left[\frac{1}{2(1-r_{\tilde{\ell}_i})^2} \left(1 + r_{\tilde{\ell}_i} + \frac{2 r_{\tilde{\ell}_i} \ln r_{\tilde{\ell}_i}}{1 - r_{\tilde{\ell}_i}} \right) \right]$$
$$-(\tilde{\ell}_1 \to \tilde{\ell}_2)$$



Light Smuons Scenario ($M_1 \neq M_2$)

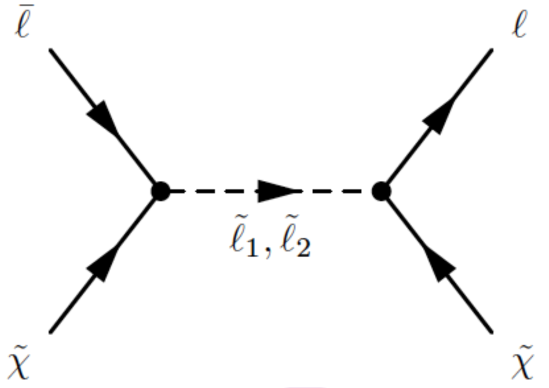


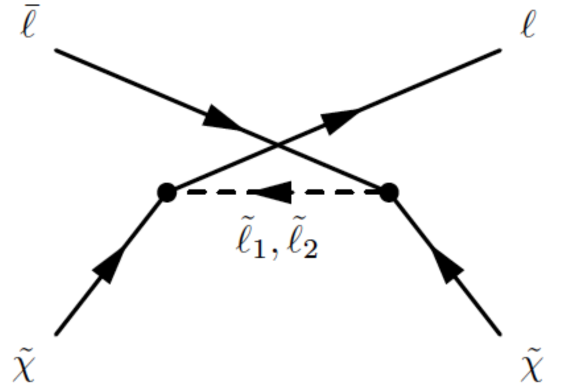


Fukushima, Kelso, Kumar, Sandick, & Yamamoto (in prep.)

Light Sleptons

- Annihilation Cross Section:





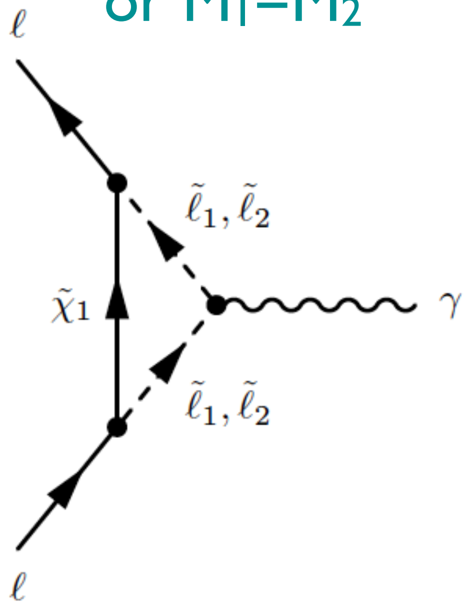
$$\langle\sigma v\rangle \sim c_0 + c_1\left(\frac{T}{m_\chi}\right)$$

$$c_0 = \frac{m_{\tilde\chi}^2}{2\pi} g^4 Y_L^2 Y_R^2 \cos^2\alpha \sin^2\alpha \left(\frac{1}{m_{\tilde\ell_1}^2 + m_{\tilde\chi}^2} - \frac{1}{m_{\tilde\ell_2}^2 + m_{\tilde\chi}^2}\right)^2$$

maximal when
$\alpha = n\pi/4$, n odd

- Dipole Moments:

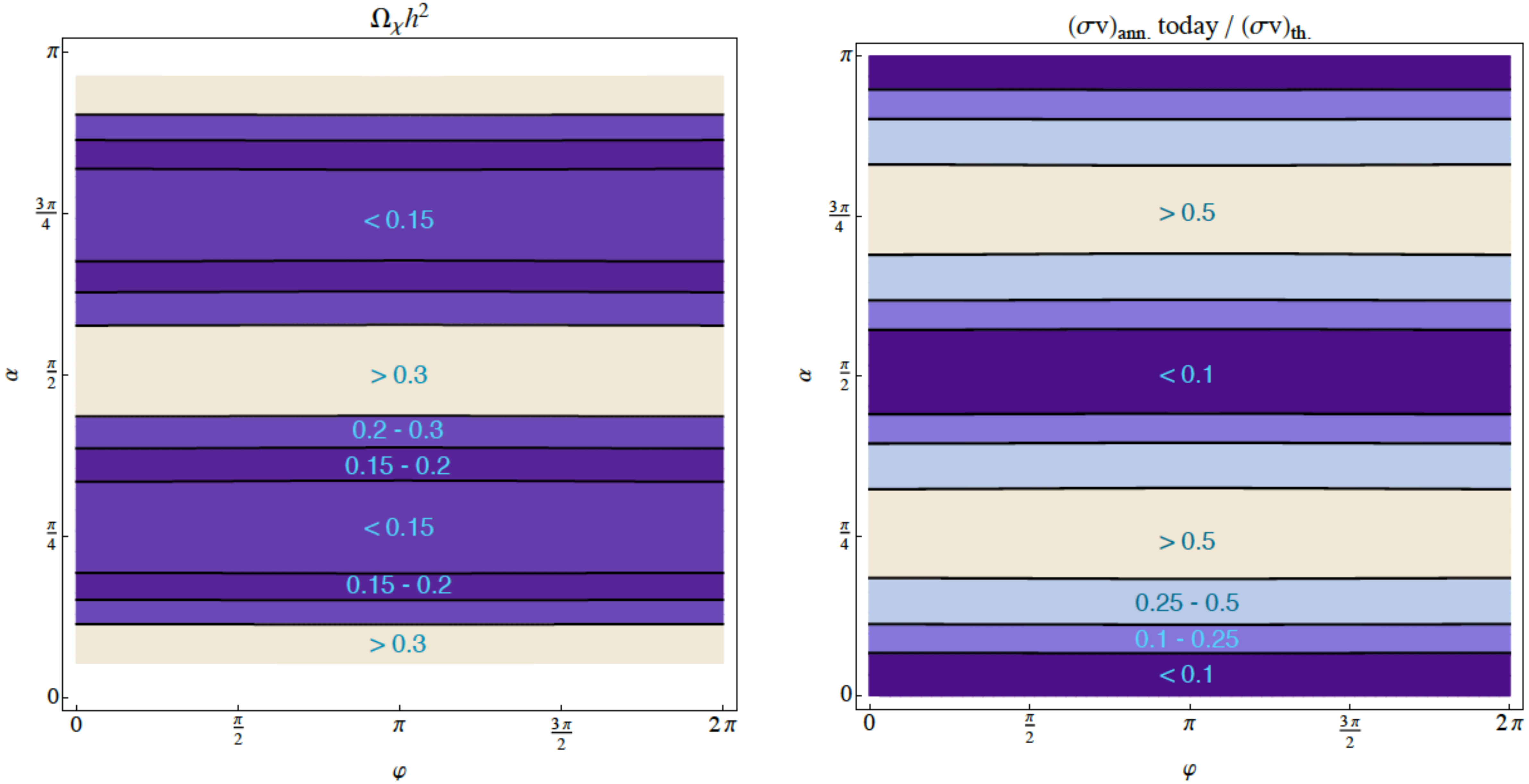
zero when
$\alpha = n\pi/2$, n integer
or $M_1 = M_2$



$$\Delta a = \frac{m_\ell m_{\tilde\chi}}{4\pi^2 m_{\tilde\ell_1}^2} g^2 Y_L Y_R \cos\varphi \cos\alpha \sin\alpha \left[\frac{1}{2(1-r_{\tilde\ell_i})^2}\left(1 + r_{\tilde\ell_i} + \frac{2 r_{\tilde\ell_i} \ln r_{\tilde\ell_i}}{1 - r_{\tilde\ell_i}}\right)\right] - (\tilde\ell_1 \to \tilde\ell_2)$$

$$\frac{d}{|e|} = \frac{m_{\tilde\chi}}{8\pi^2 m_{\tilde\ell_1}^2} g^2 Y_L Y_R \sin\varphi \cos\alpha \sin\alpha \left[\frac{1}{2(1-r_{\tilde\ell_i})^2}\left(1 + r_{\tilde\ell_i} + \frac{2 r_{\tilde\ell_i} \ln r_{\tilde\ell_i}}{1 - r_{\tilde\ell_i}}\right)\right]$$
$$-(\tilde\ell_1 \to \tilde\ell_2)$$

Light Smuons Scenario ($M_1 \neq M_2$)



Fukushima, Kelso, Kumar, Sandick, & Yamamoto (in prep.)

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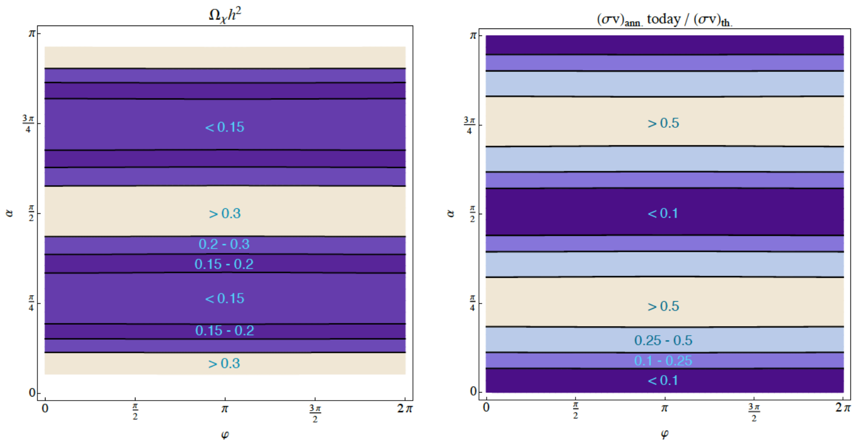
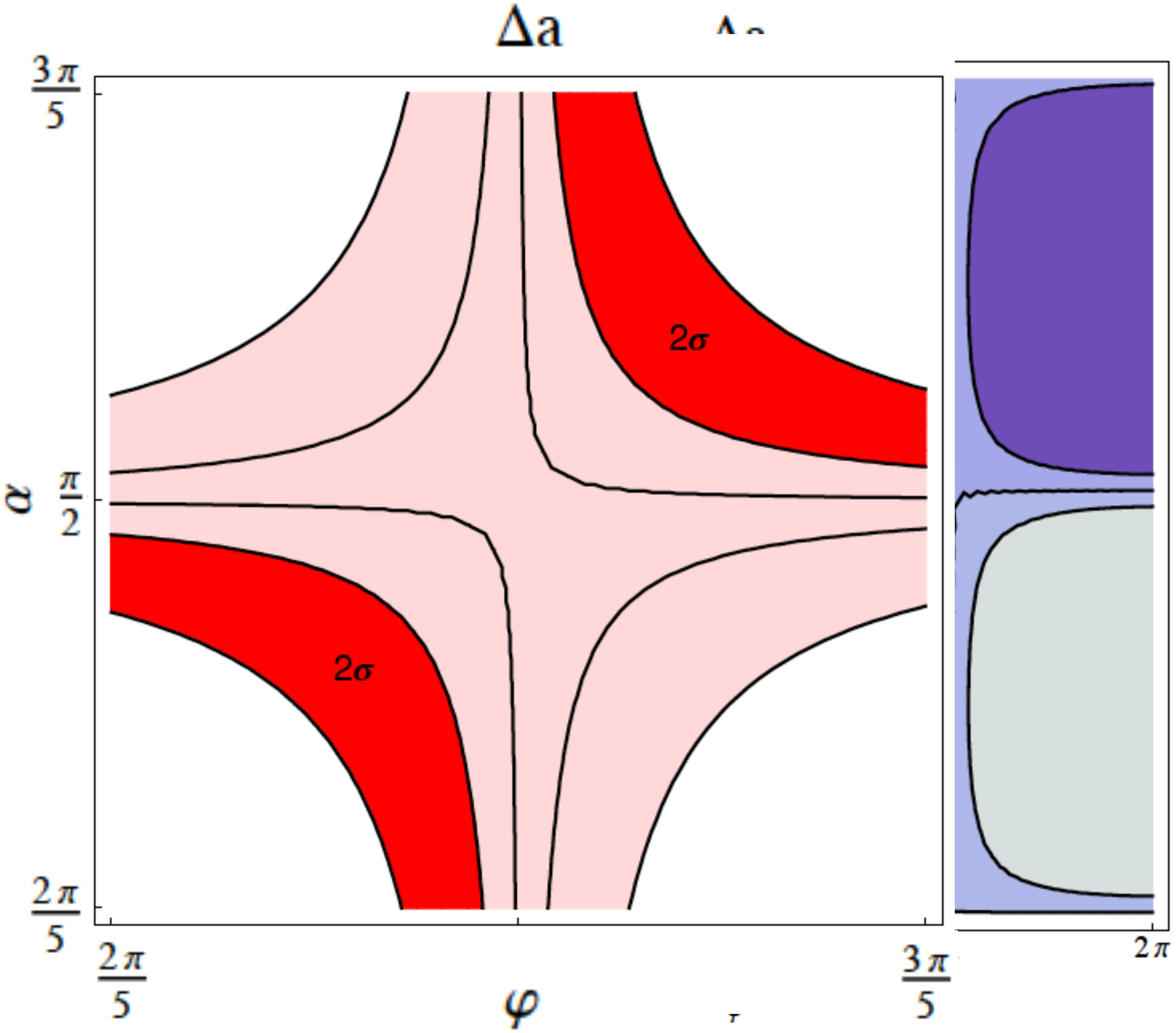
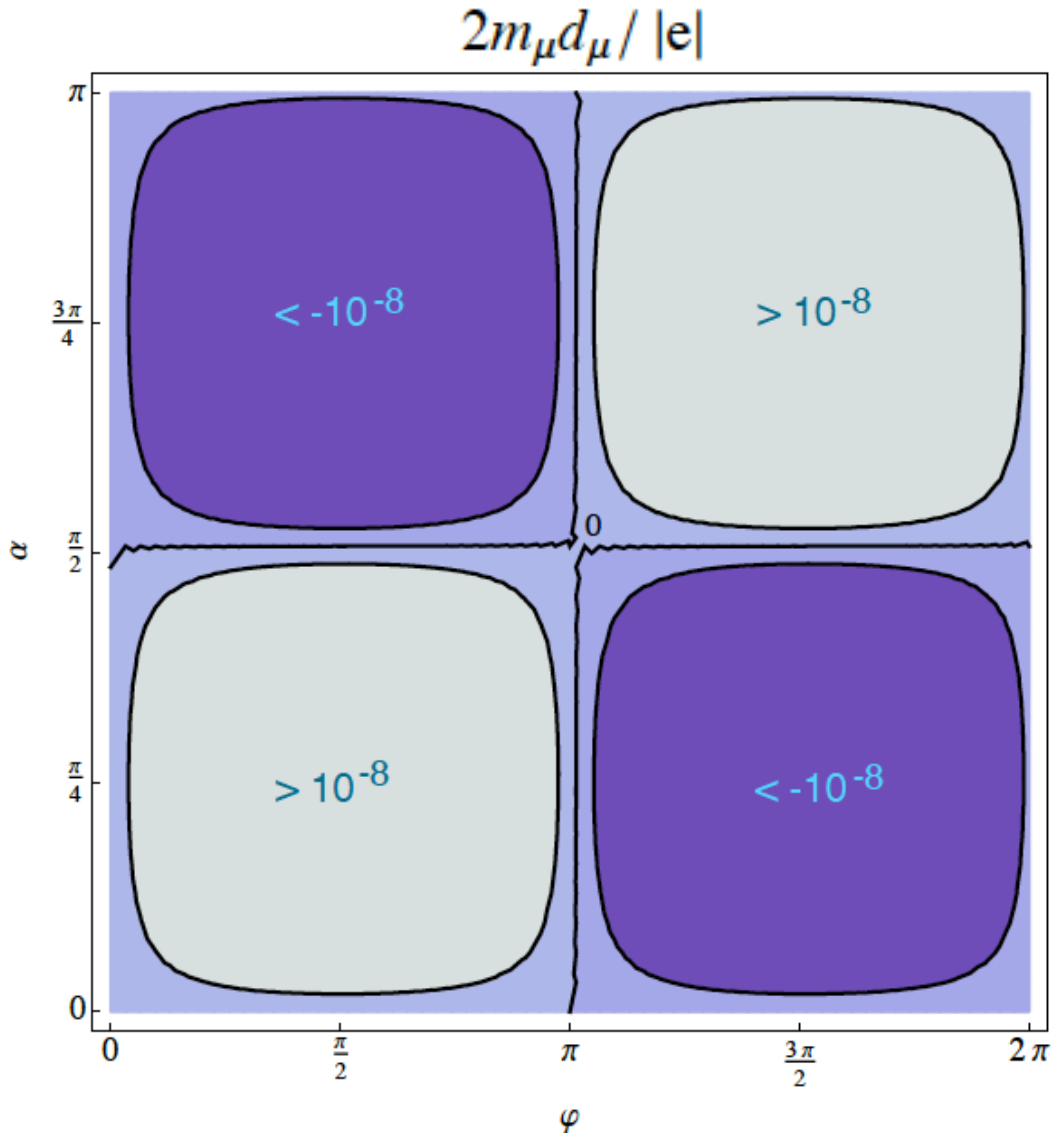
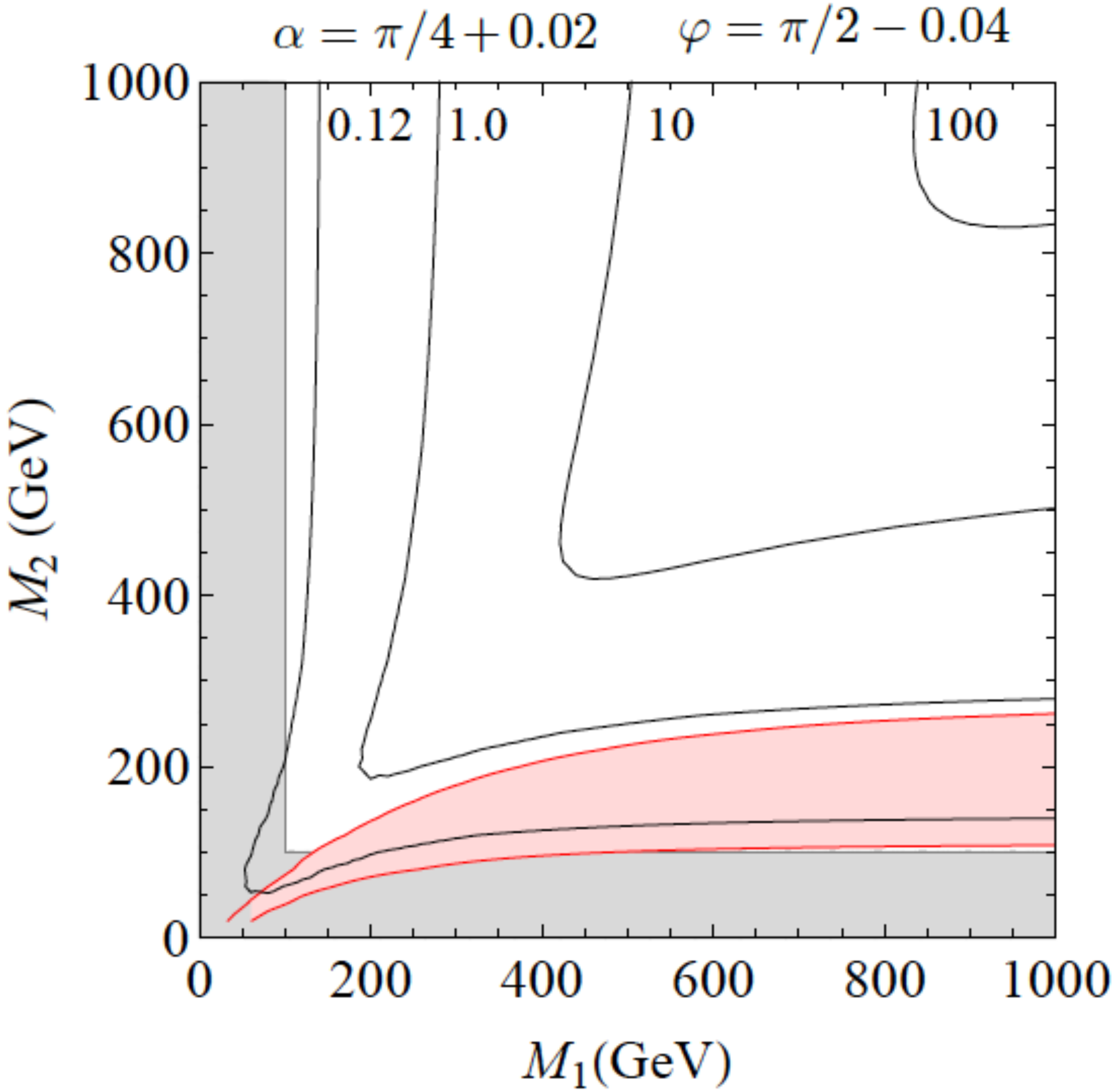


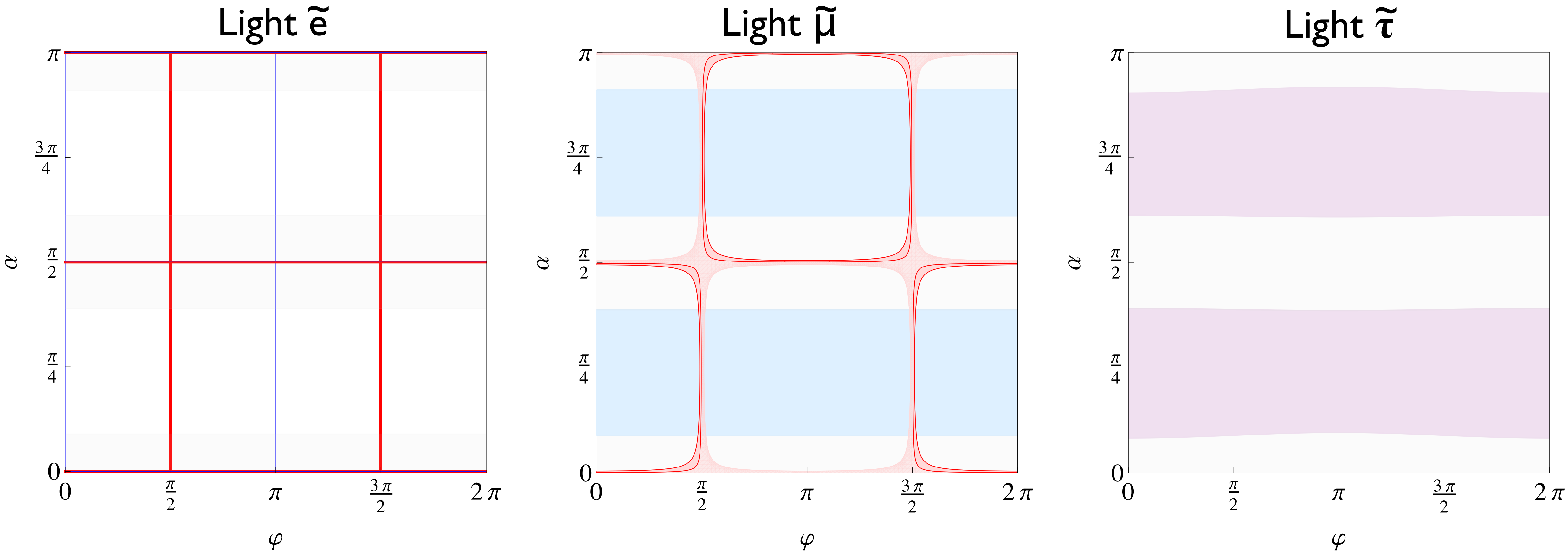




Light Smuons Scenario



Light Sleptons ($M_1 \neq M_2$)



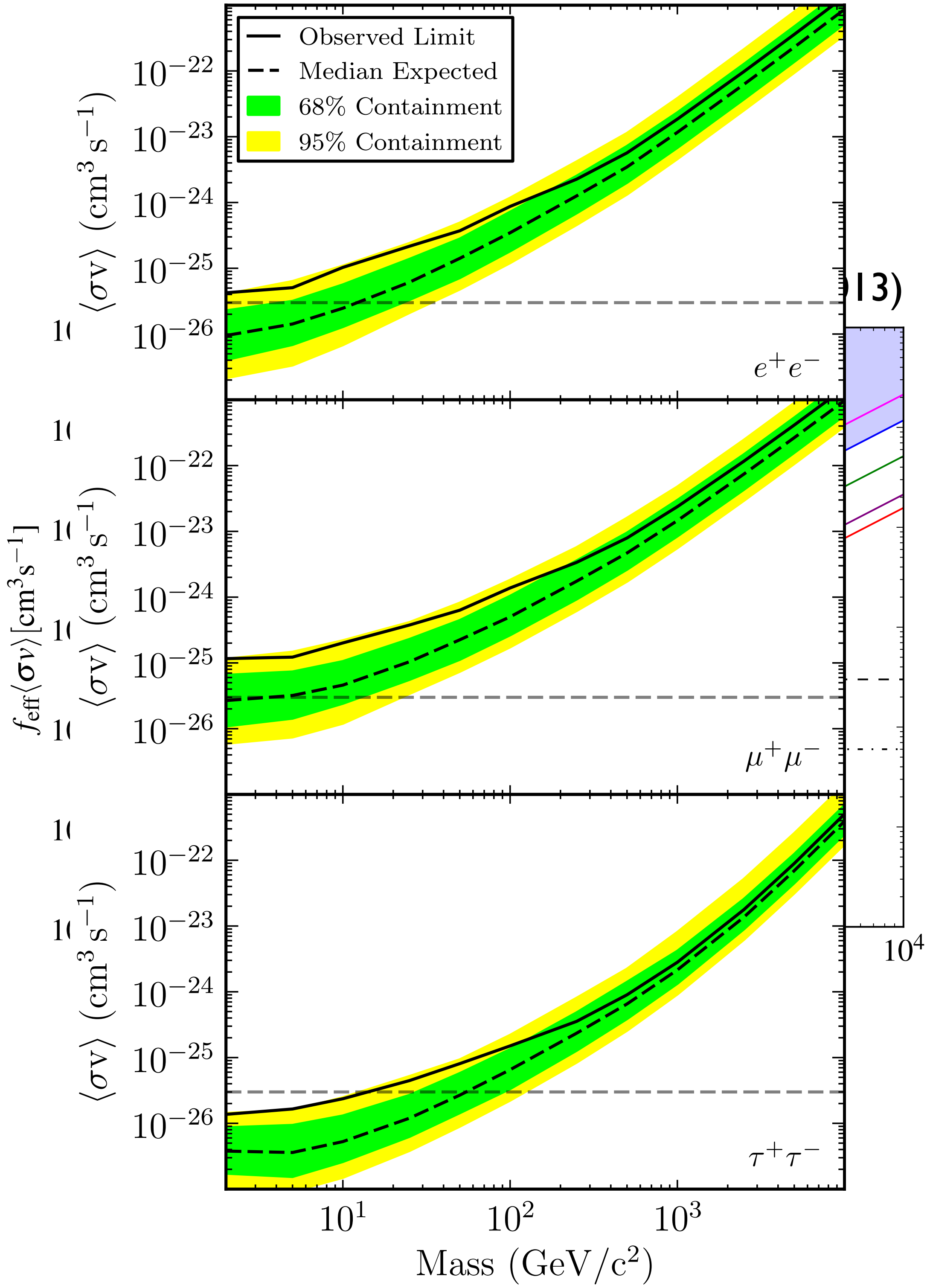
- If $M_1=M_2$, dipole moments vanish, but too much dark matter.
- Light $\tilde{e}$: Angles must be tuned to $\alpha \lesssim 10^{-3}$ and $\varphi \lesssim 10^{-6}$, but relic abundance is too large
- Light $\tilde{\mu}$: Possible to obey dipole moment constraints (or explain Δa), and have thermal dark matter (for small range of φ)
- Light $\tilde{\tau}$: Relic abundance is the only constraint (see also Pierce, et al.; Hagiwara et al., 2013)

Fukushima, Kelso, Kumar, Sandick, & Yamamoto (in prep.)

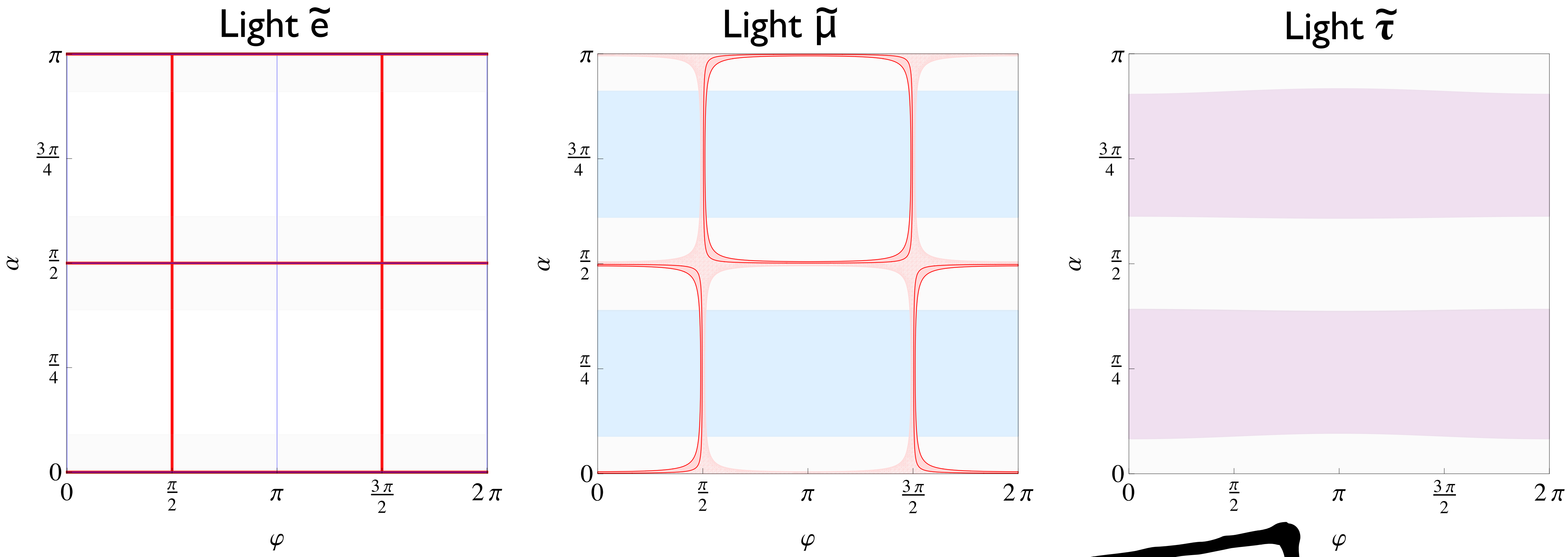
Other Signatures

- Indirect Detection:
    - Best Case Scenario is annihilation to taus. Possibly within reach of Fermi (dSphs).
    - Annihilation to neutrinos: Unconstrained by dipole moments, but annihilation rate is small (relic abundance too large). Probably not detectable at IceCube or SK.
- CMB: not currently constrained for annihilations to muons or taus, and will remain just out of reach, even for CVL experiment

Ackermann et al. (2014)



Light Sleptons ($M_1 \neq M_2$)



- If $M_1=M_2$, dipole moments vanish, but too much dark
- Light ẽ: Angles must b … o large
- Li … rmal dark
  ma
- Ligh … ly constraint (see also Pierce, et al.; Hagiwara et al., 2013)

Viable scenarios with bino-like dark matter and light smuons/staus.

Fukushima, Kelso, Kumar, Sandick, & Yamamoto (in prep.)

Summary

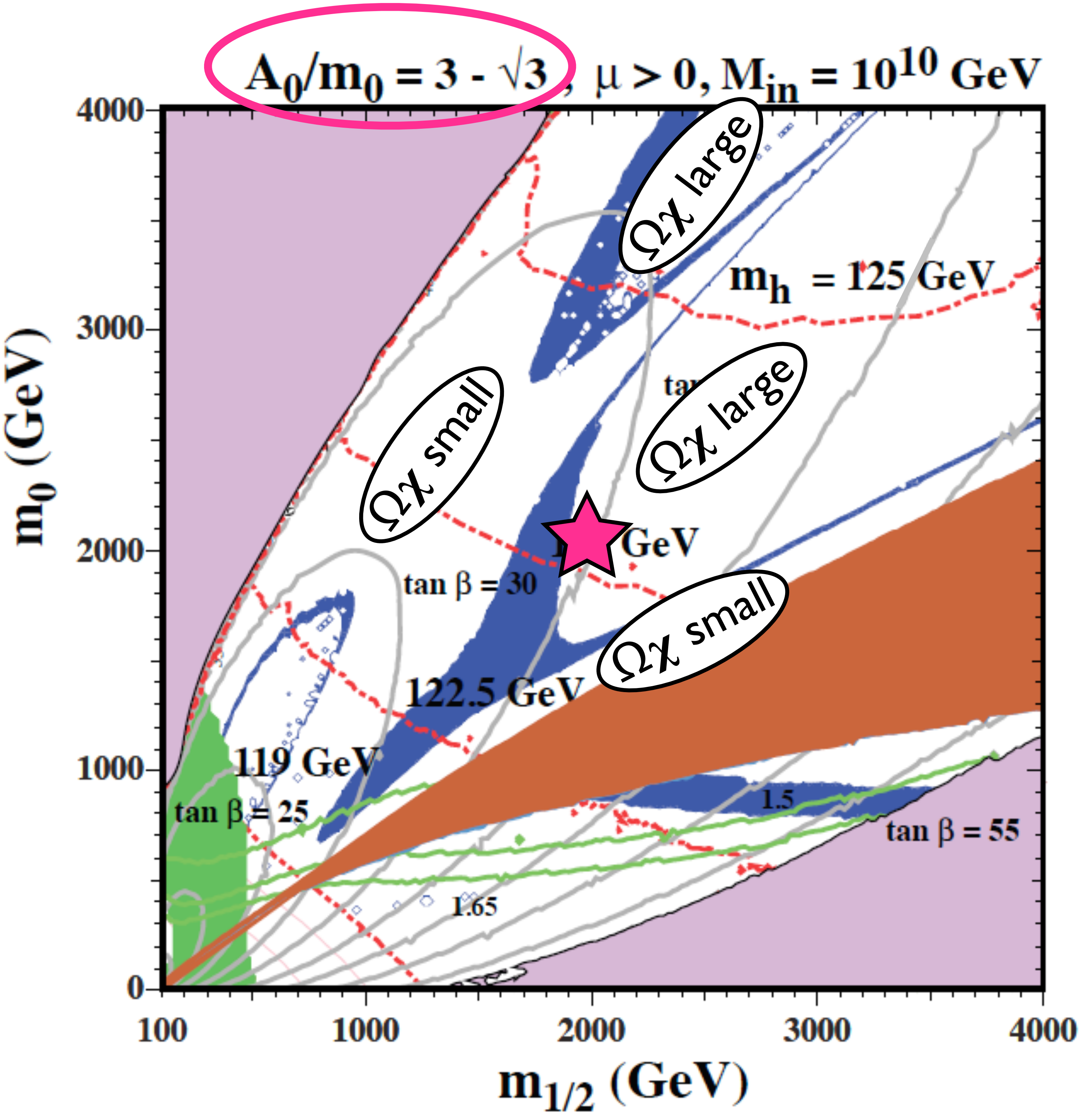
- Finite distinct ways to observe dark matter:
    - Abundance, Annihilation Today, Decay Today, Production at Colliders, Direct Detection
- A spectrum of theoretical approaches to particle dark matter

Extra Slides

Looking Forward

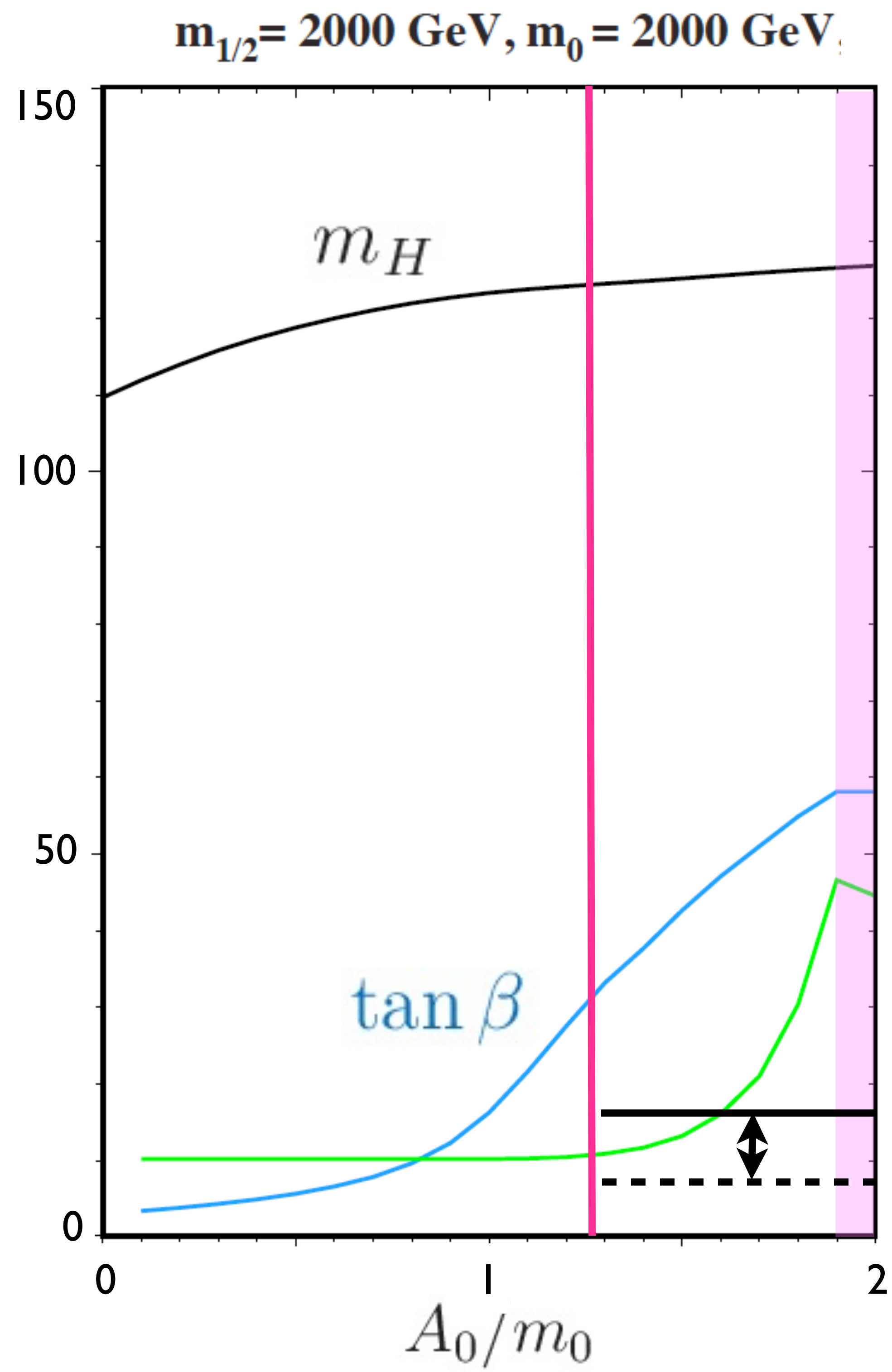
- Direct dark matter searches - towards the neutrino background! and directional searches!
- Indirect dark matter searches
  - Fermi, HAWK, VERITAS, AMS-02, GAPS, CTA GAMMA-400…
- LHC - SUSY/DM discovery potential at 14 TeV
- 100 TeV Hadron Collider
- Linear Collider - ILC at 500 GeV, CLIC at 3TeV

sub-GUT mSUGRA



Ellis, Luo, Olive, Sandick (2013)

sub-GUT mSUGRA



At large tanβ,

$$\mathrm{BR}(B_s \to \mu^+\mu^-) \sim \tan\beta^6$$

A_0 { large enough: $m_H \approx 126$ GeV
small enough: $\mathrm{BR}(B_s \to \mu^+\mu^-) \lesssim 1.5$ SM value

Polonyi Model seems to be the sweet spot!