Dark Matter Theory and Searches

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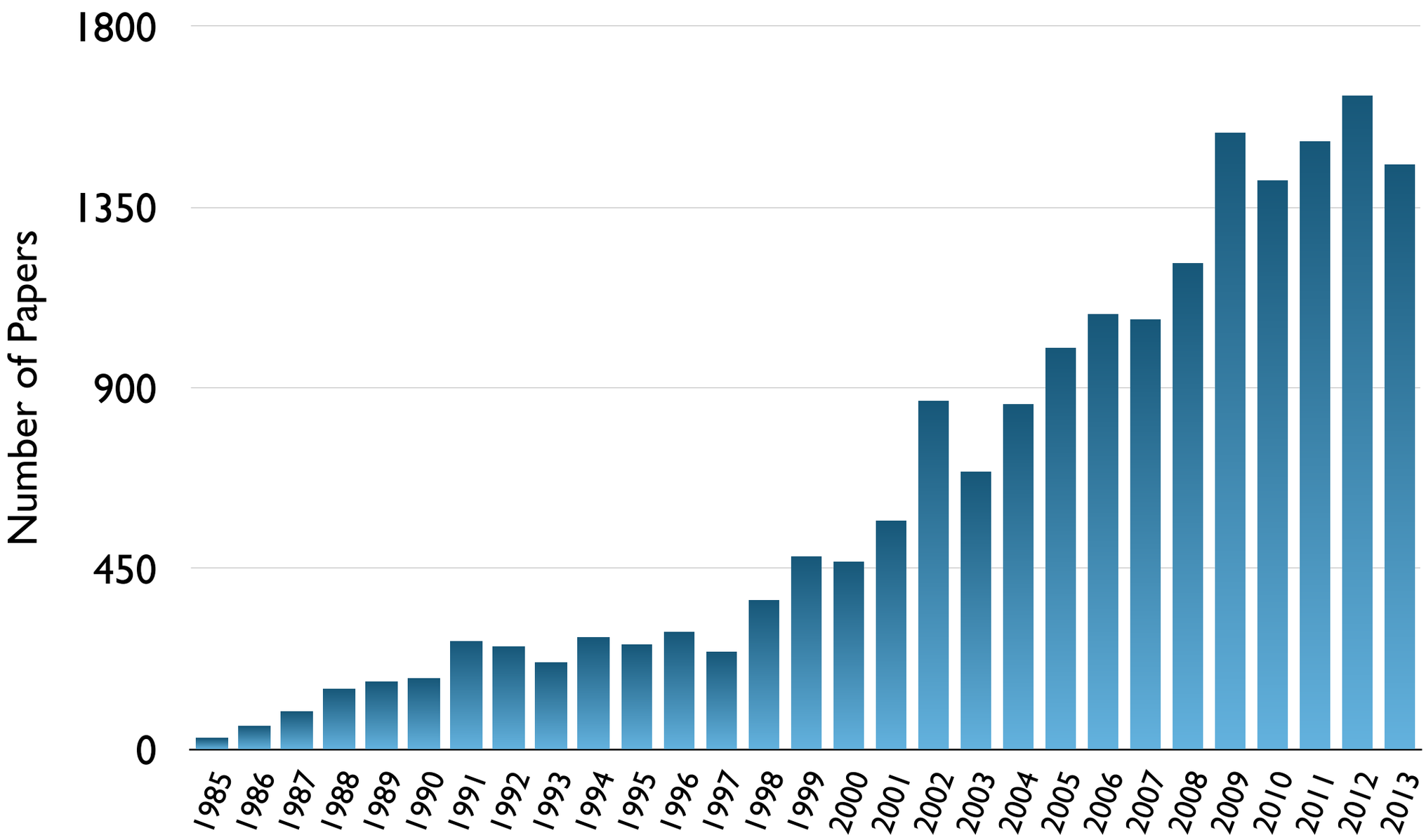
University of Utah

DM Papers (inSPIRE)



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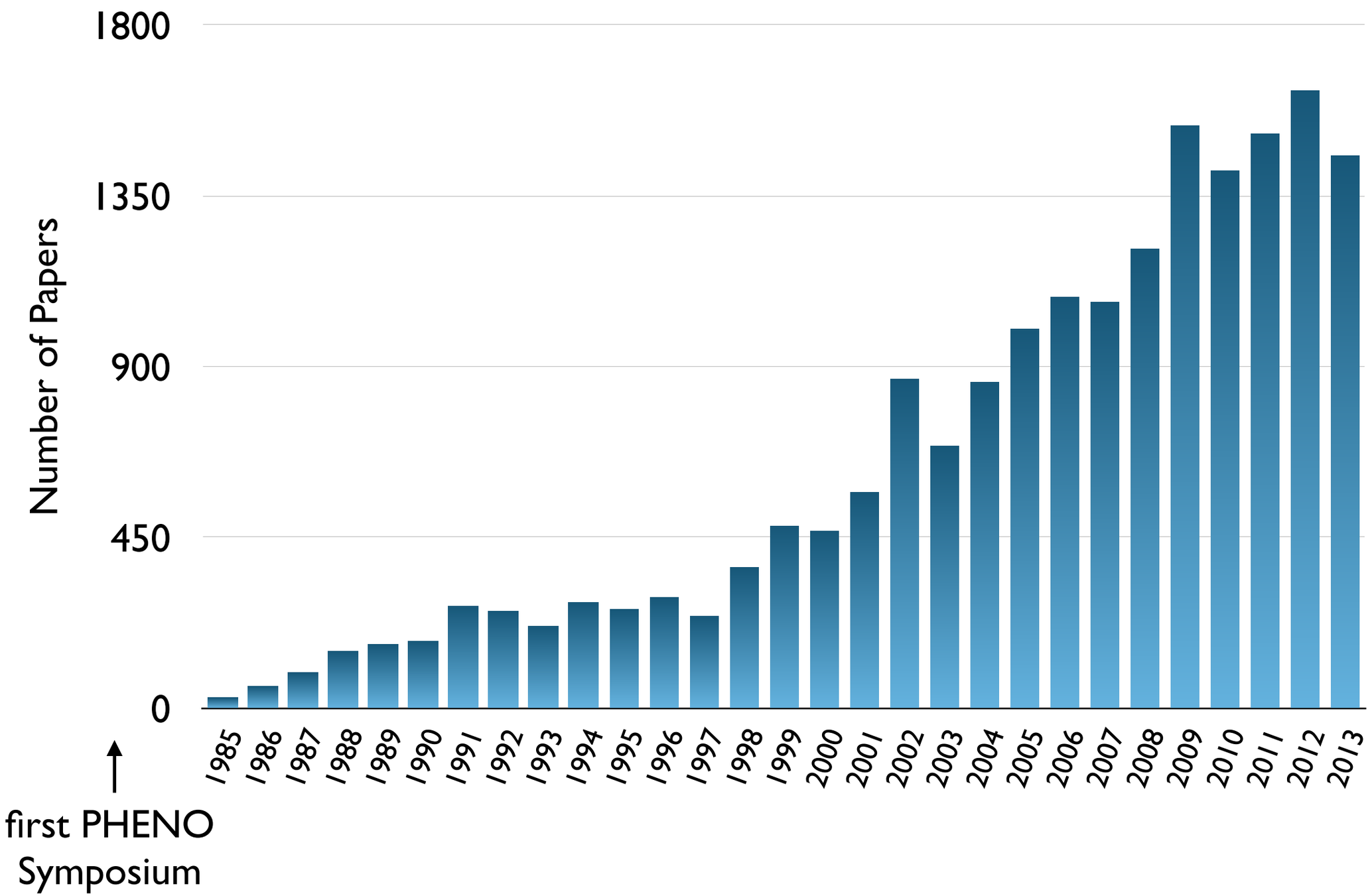

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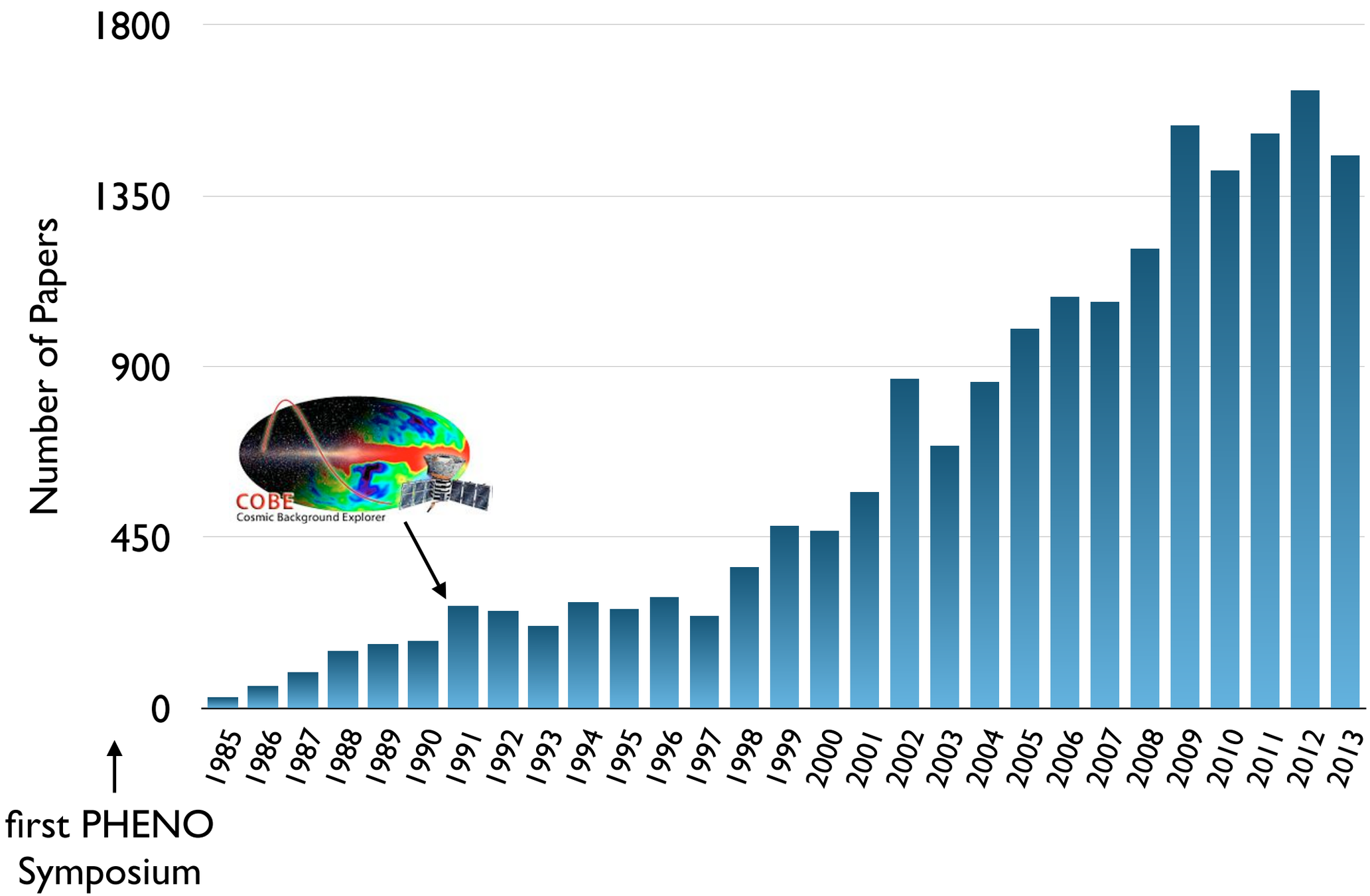

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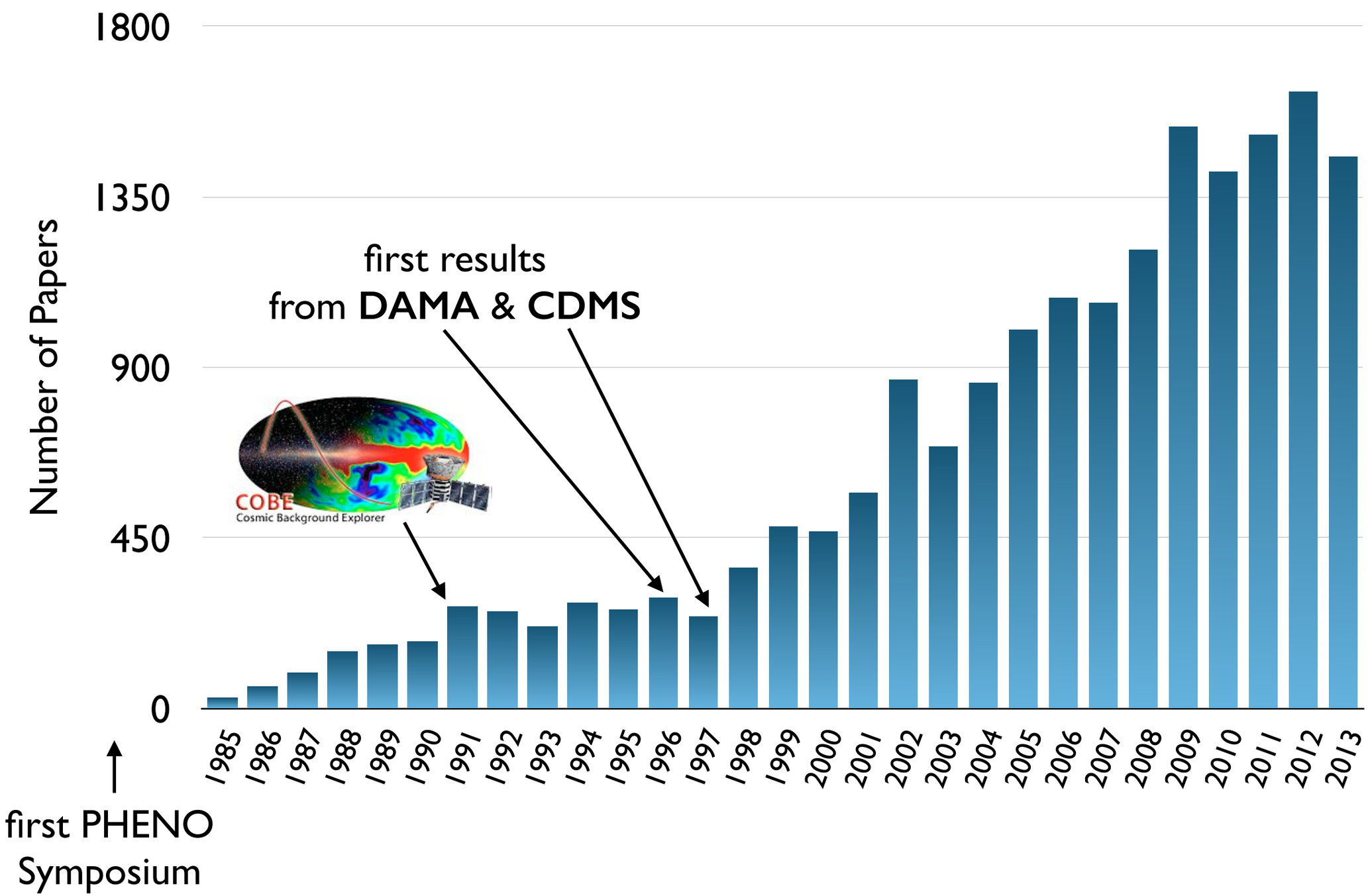

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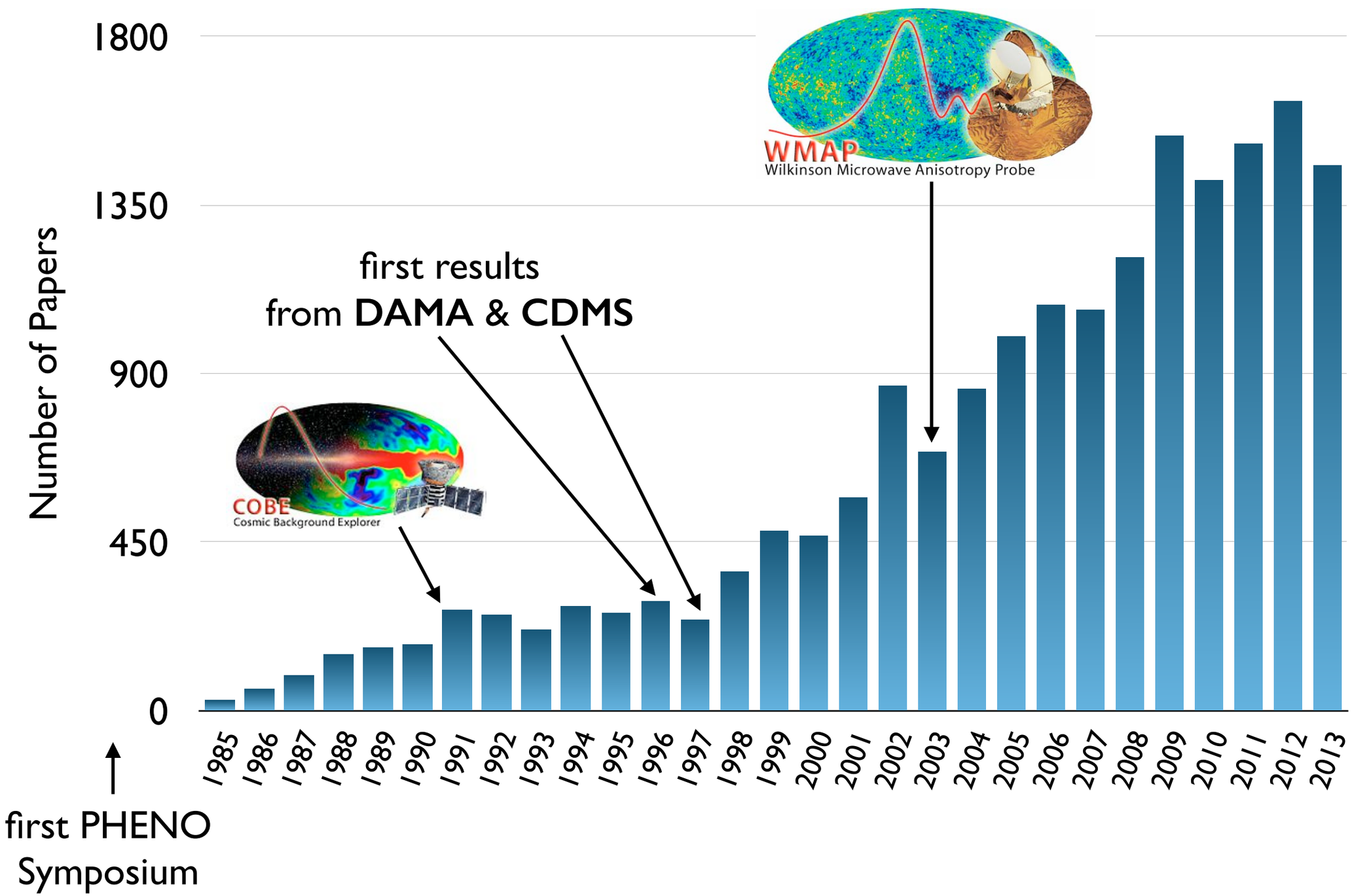

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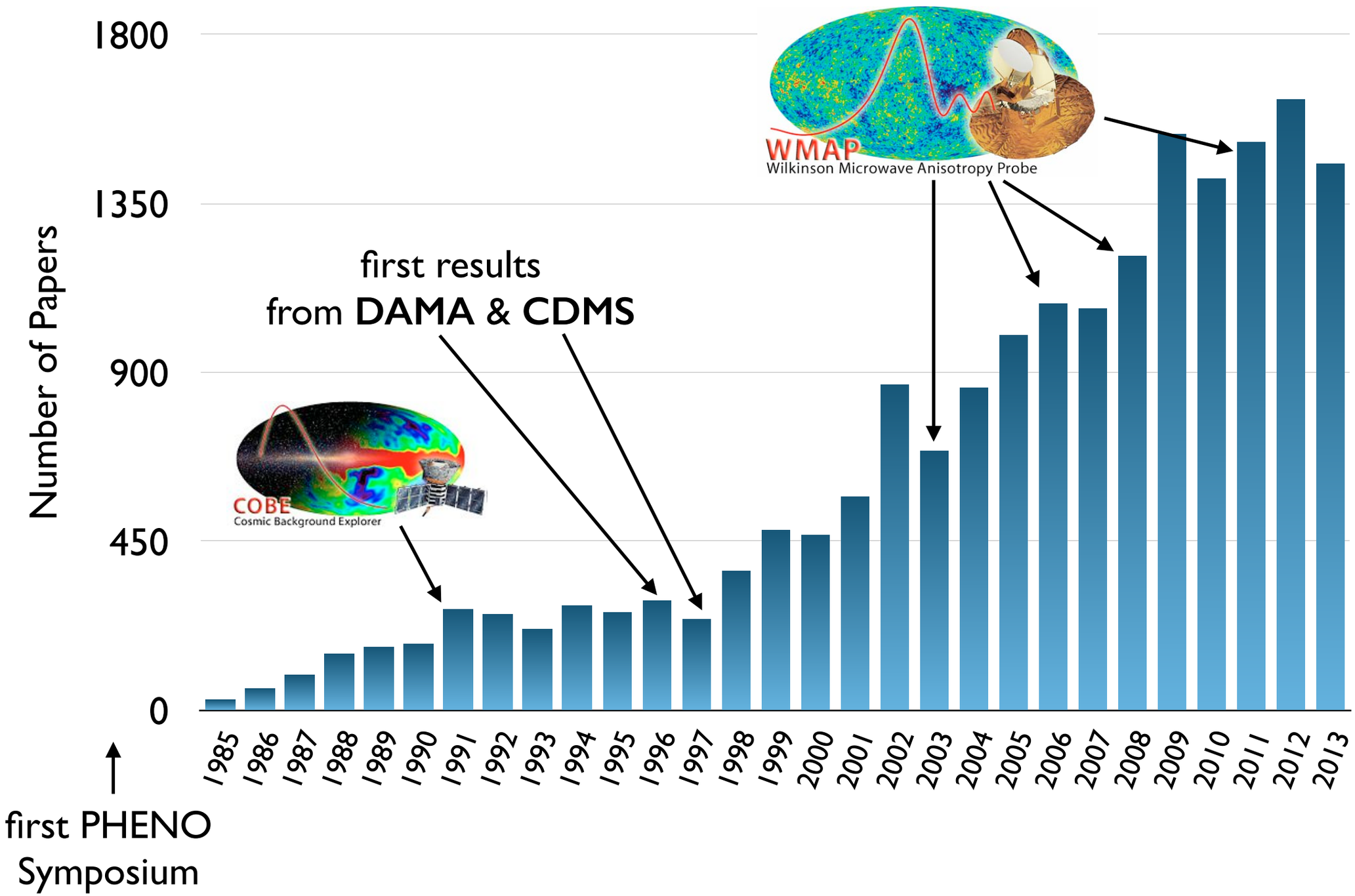

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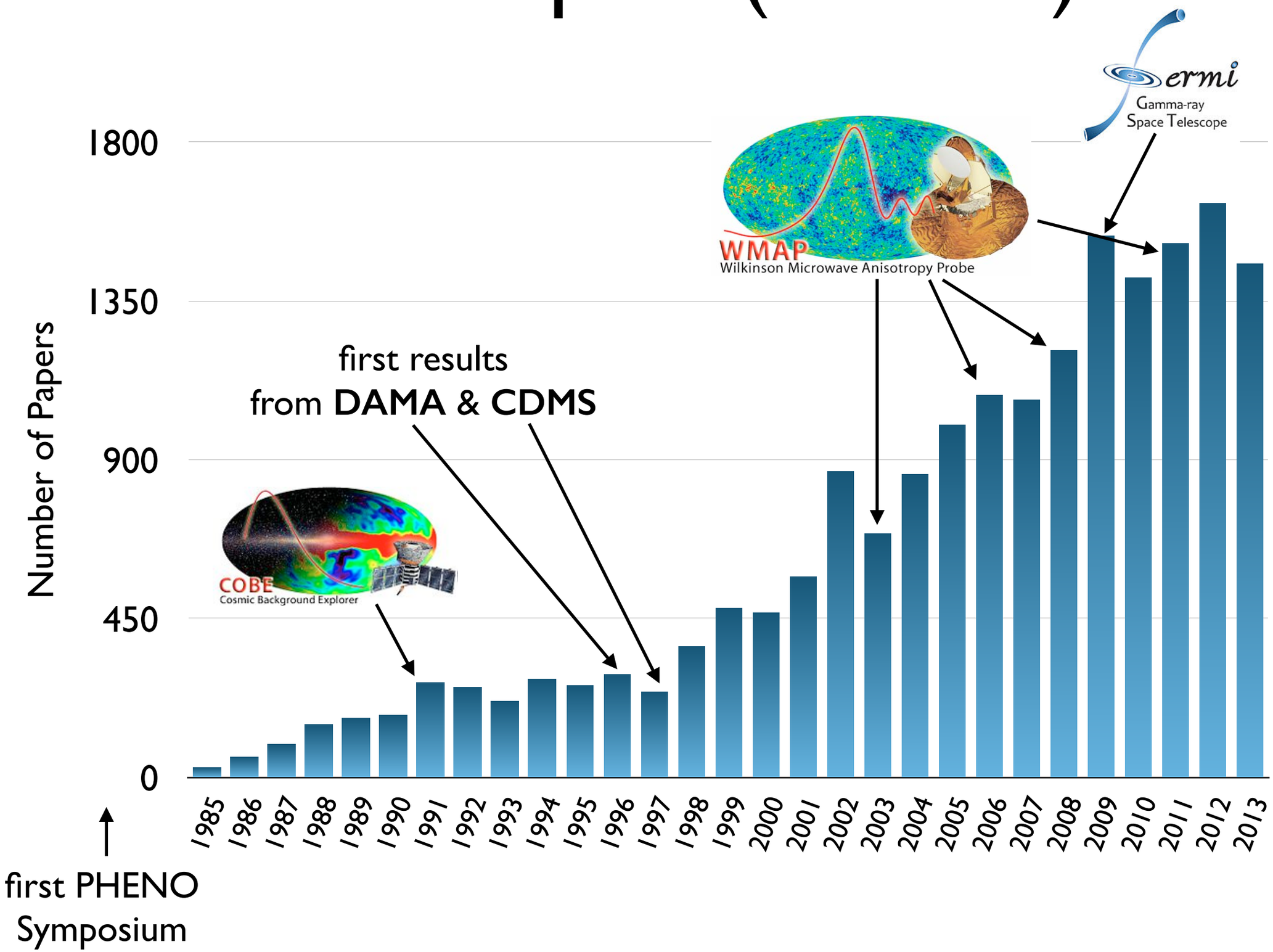


Old Results in Dark Matter

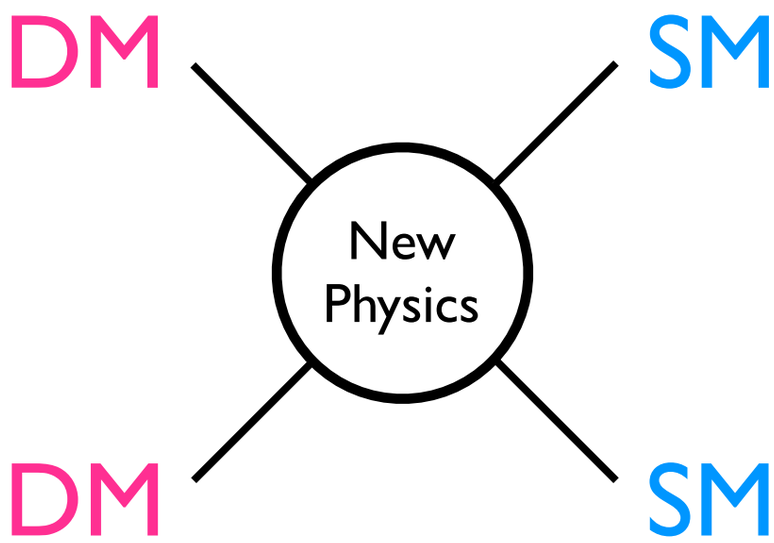
Observations

- 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).

If dark matter is a particle:



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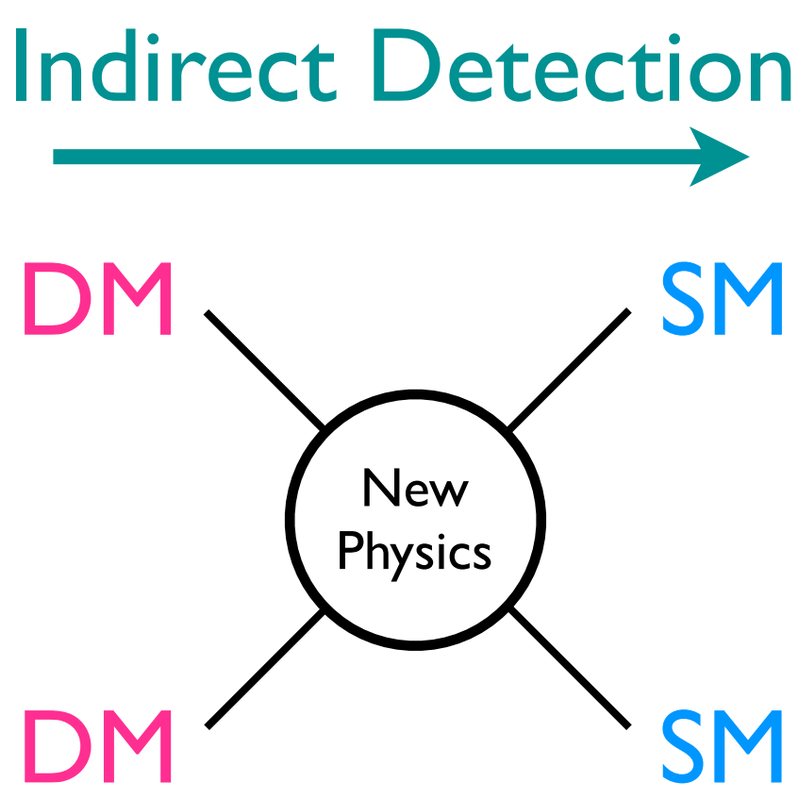

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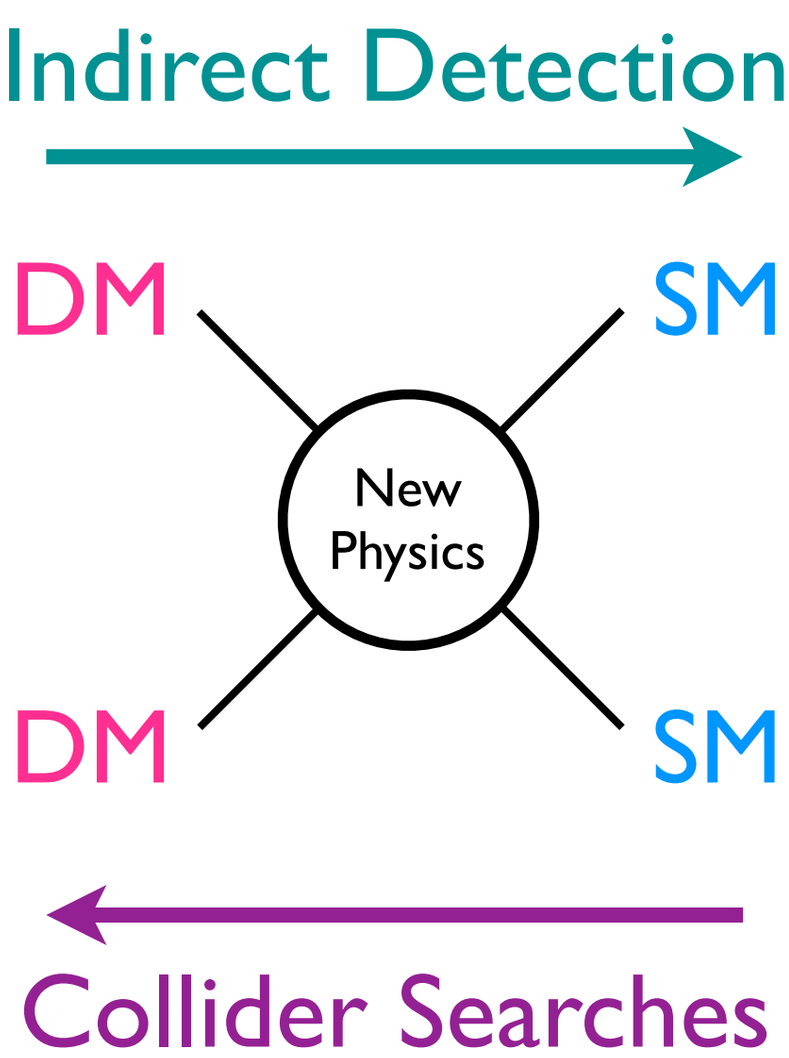

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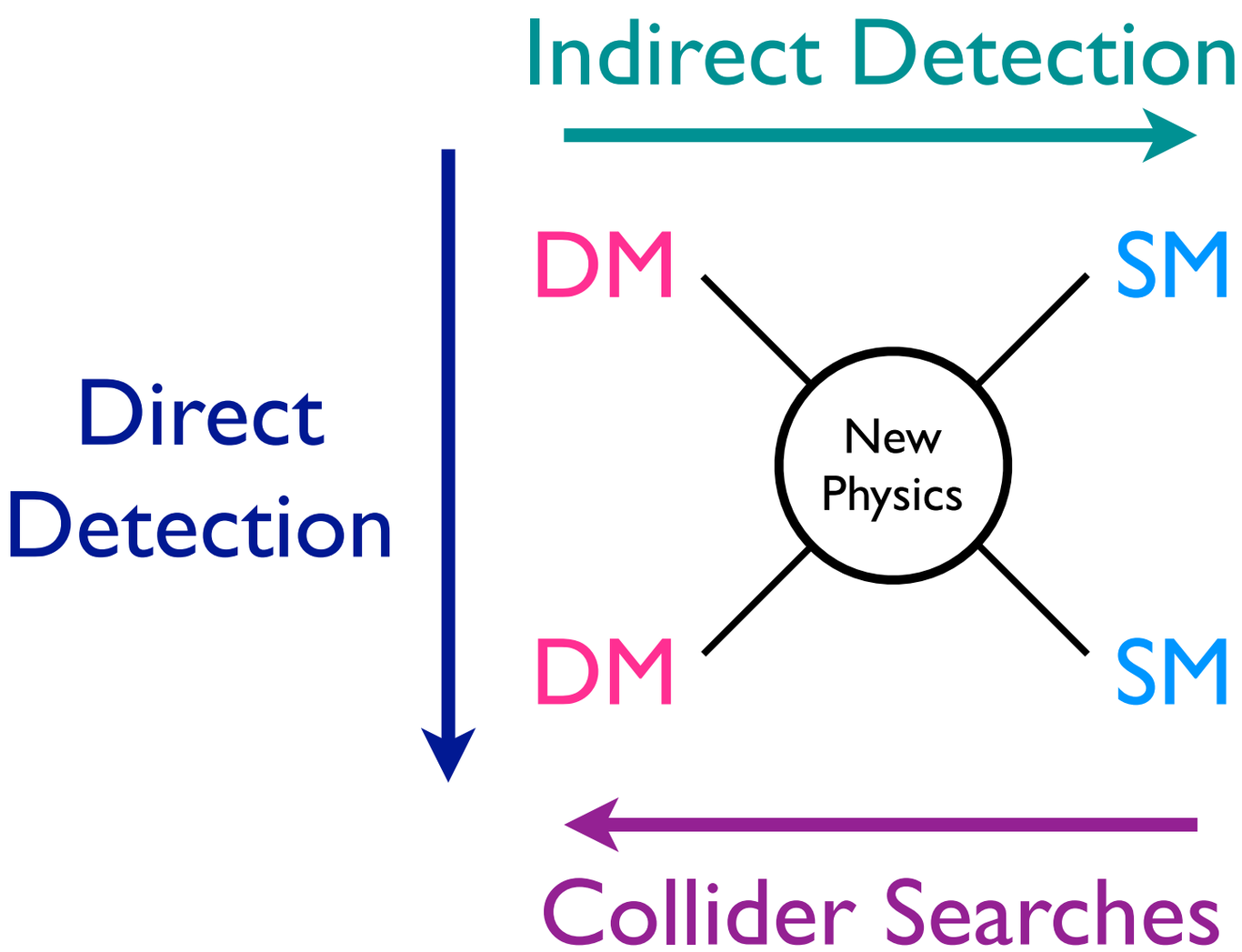

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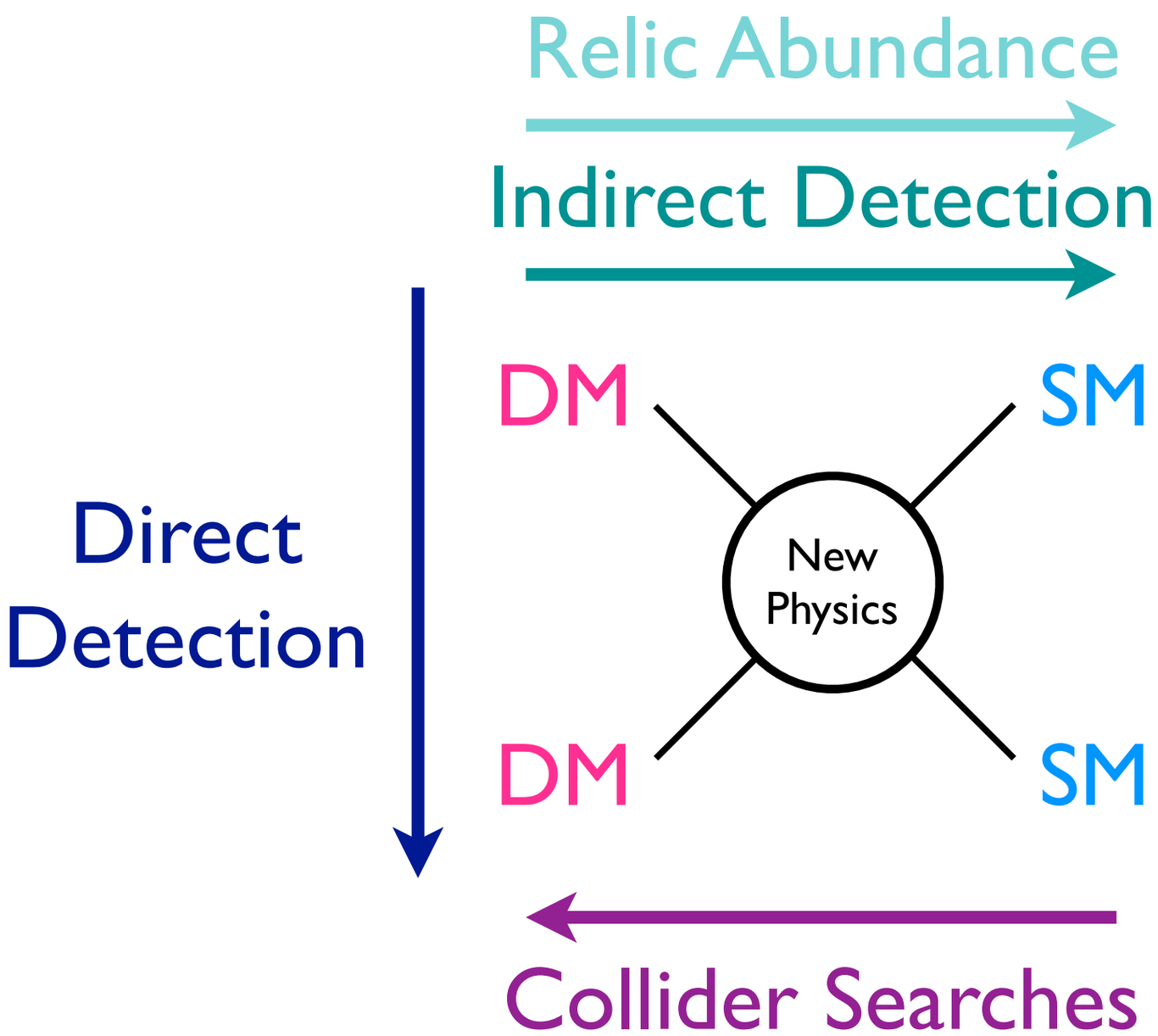

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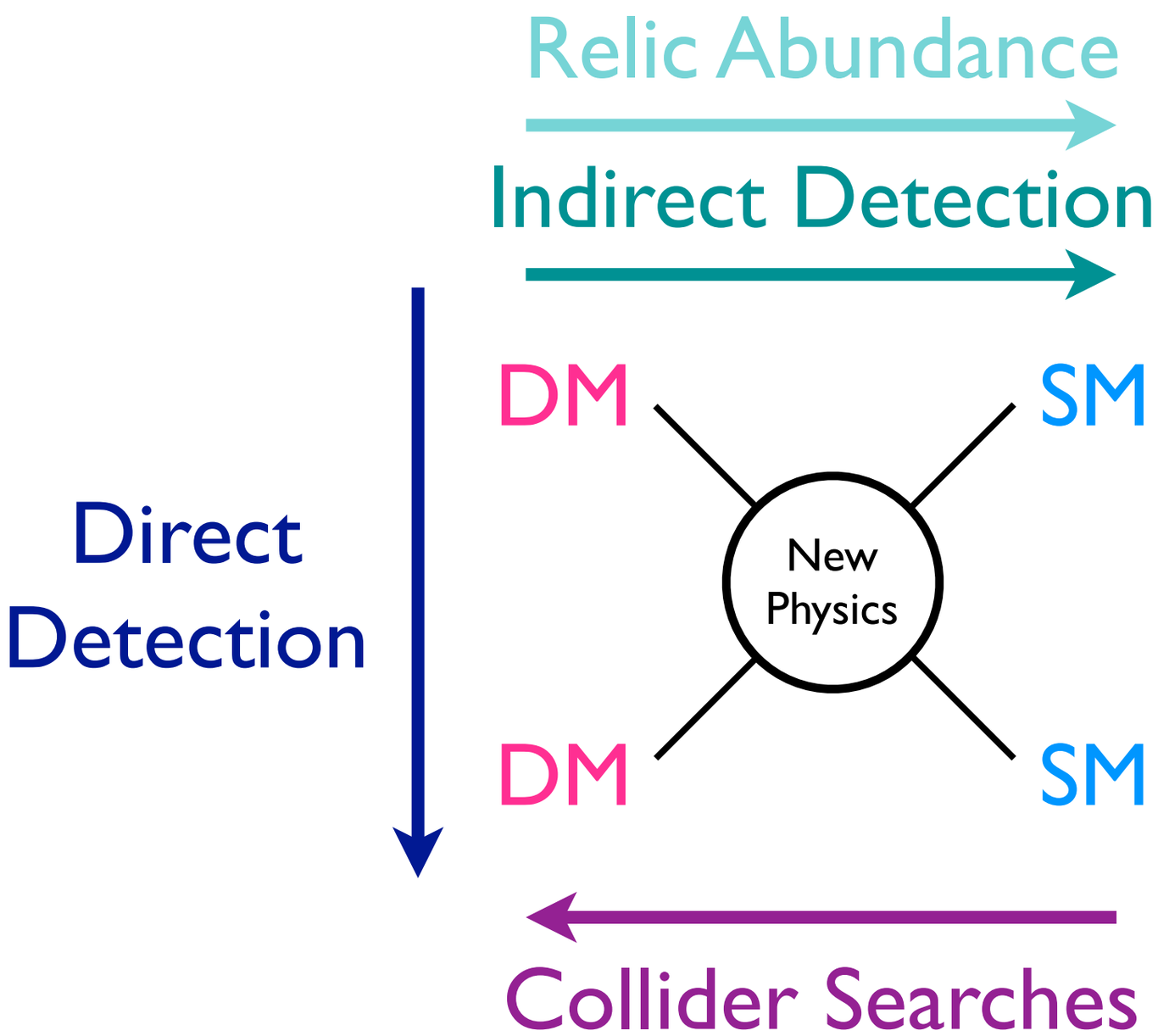

- ✓ Unambiguous evidence of the particle nature of dark matter
- ✓ Connection between terrestrially-observed DM and cosmological DM
- ✓ Confirm the theory of new physics and measure dark matter's properties

Current Situation

- Abundance of experimental data!
  - "We're exploring dark matter with unprecedented and growing precision." -Zhen Liu
- Theoretical approaches:

Totally Data-Driven

$\updownarrow$

Totally Theory-Driven

Current Situation

- Abundance of experimental data!
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Totally Data-Driven

↕

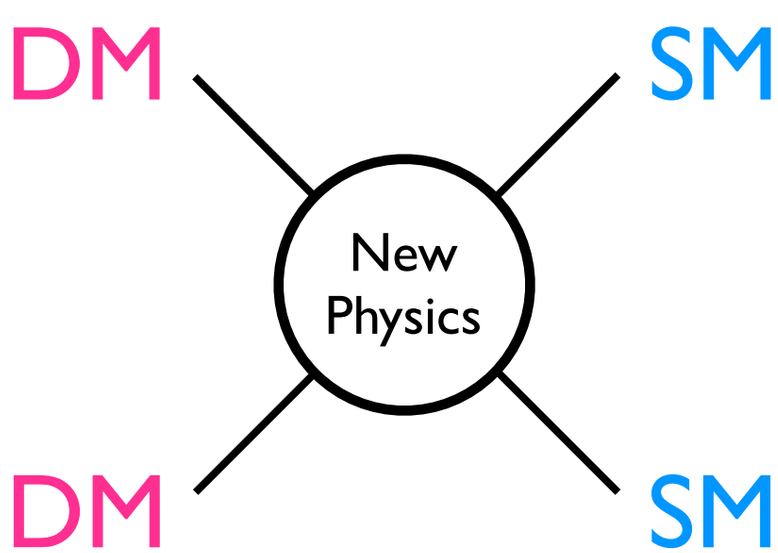
Hybrid / Simplified Models

↕

Totally Theory-Driven

Effective Theories

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



- 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

Fundamental Theory

Supersymmetry

MSSM

Non-Minimal Model

Fundamental Theory

Supersymmetry

MSSM

Non-Minimal Model

Gravity Mediation

Gauge Mediation

…

EW-Scale Inputs

Fundamental Theory

Supersymmetry

MSSM

Non-Minimal Model

Gravity Mediation

Gauge Mediation

…

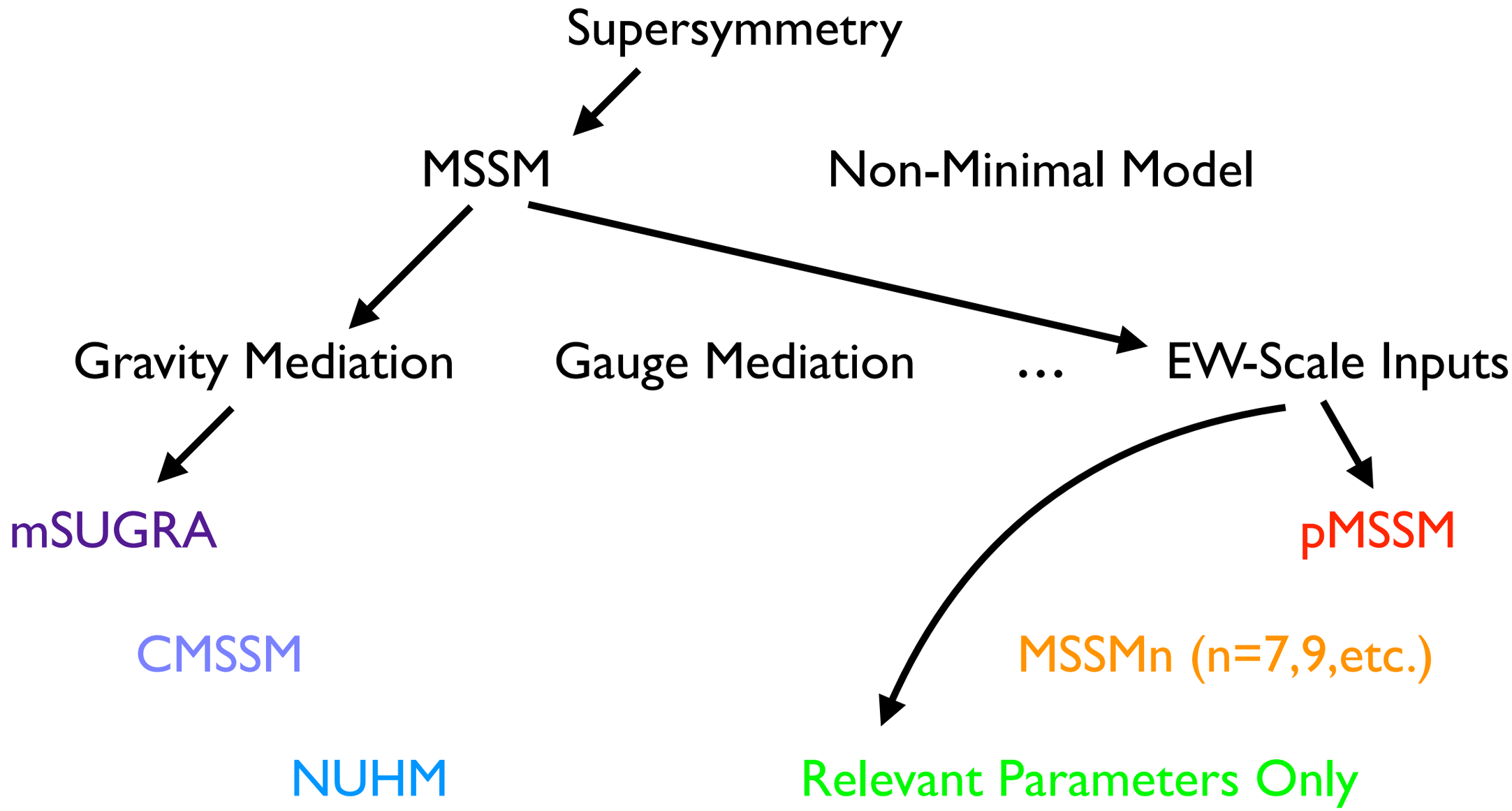
EW-Scale Inputs

mSUGRA

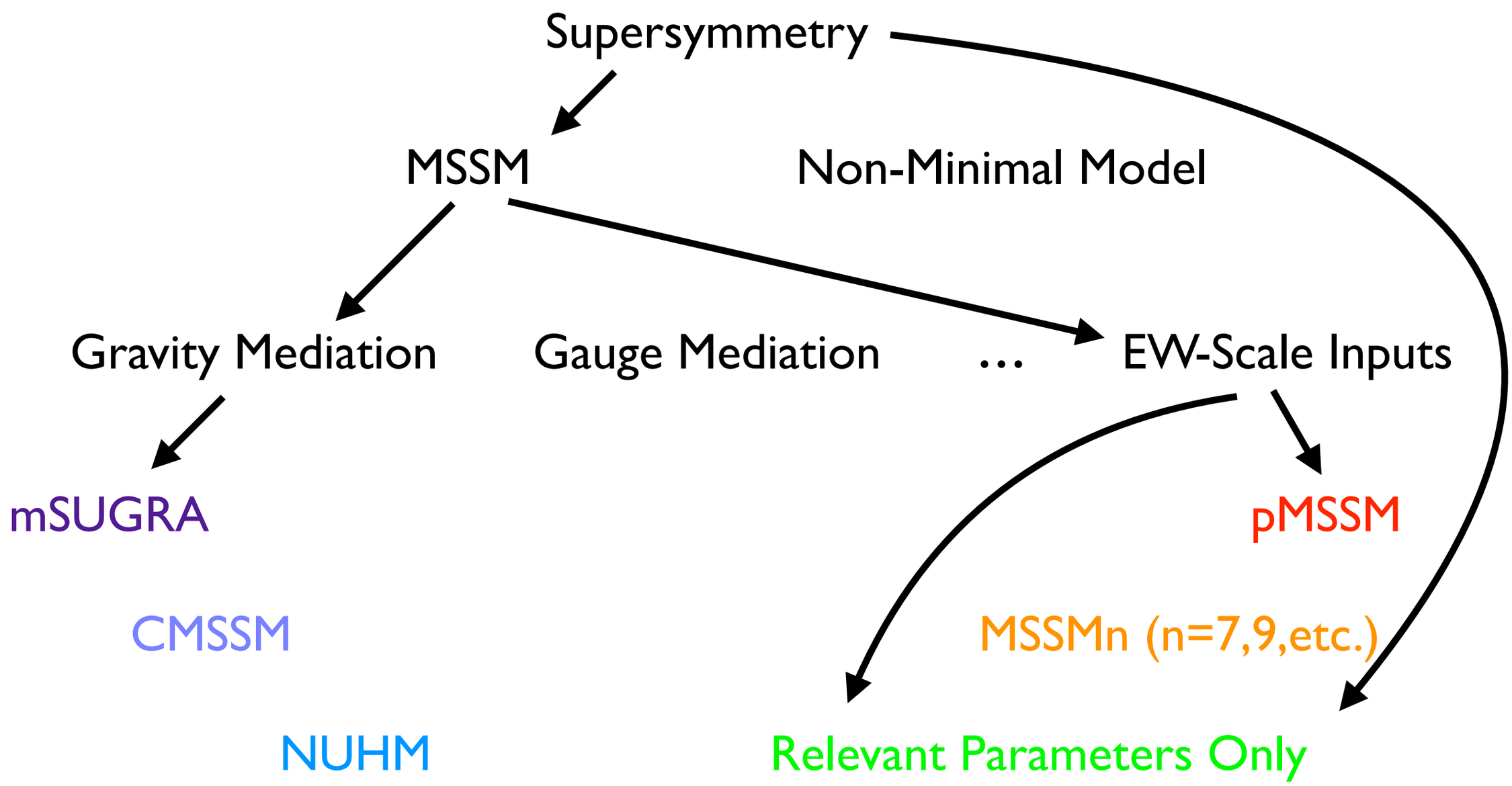
CMSSM

NUHM

Fundamental Theory



Fundamental Theory



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

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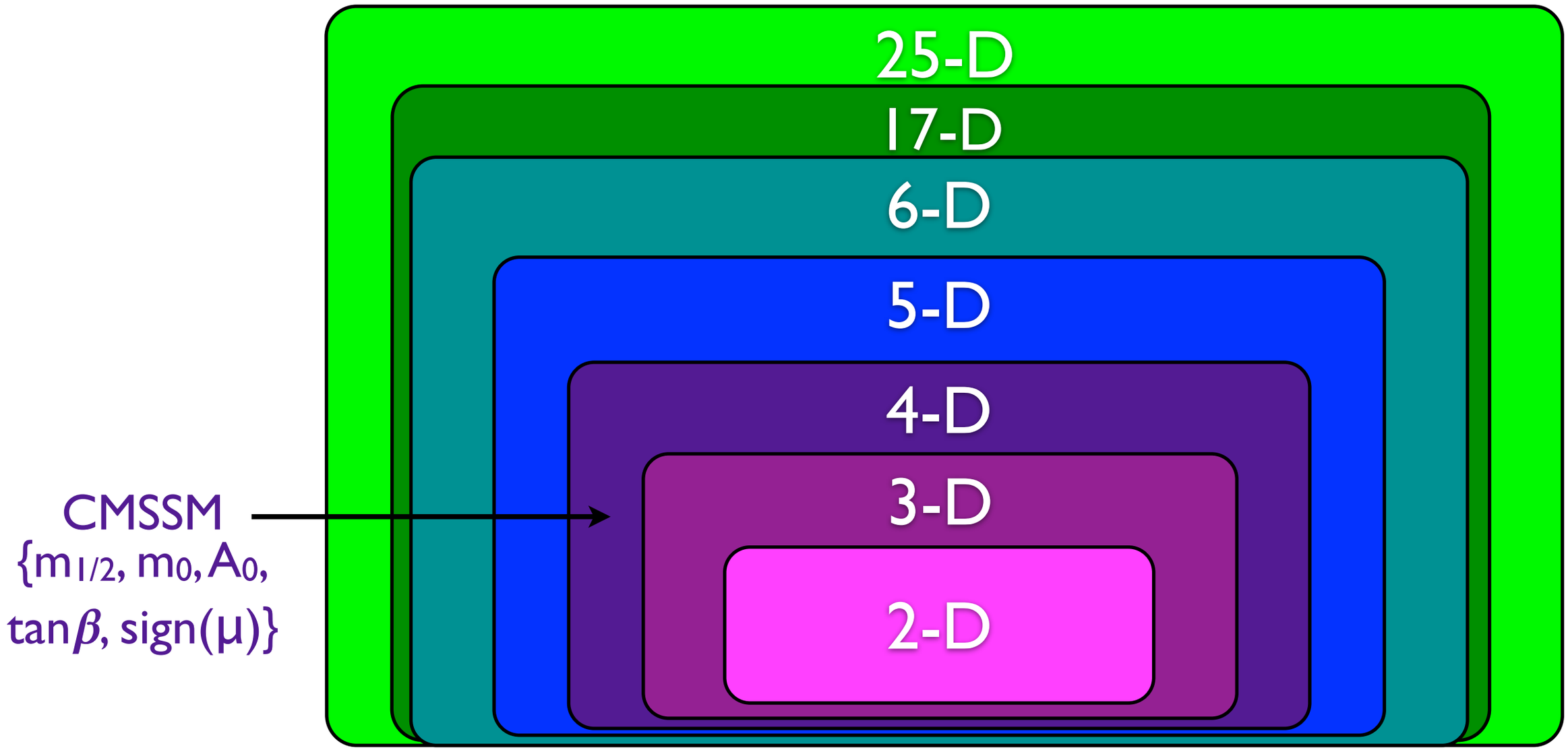
$$\tilde{\chi}_i = N_{i1}\tilde{B} + N_{i,2}\tilde{W} + N_{i3}\tilde{H}_d + N_{i,4}\tilde{H}_u$$

Dimensionality



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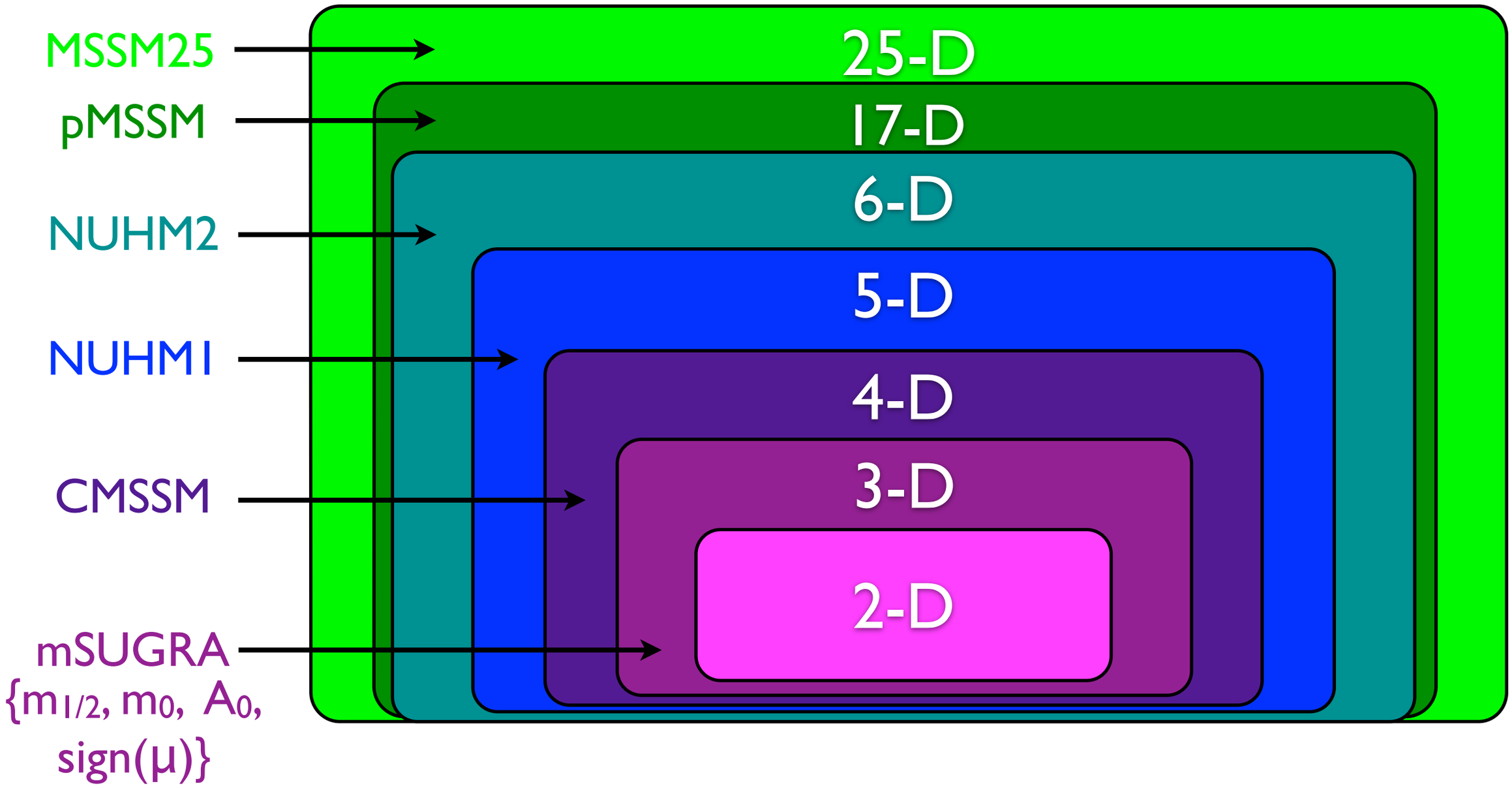

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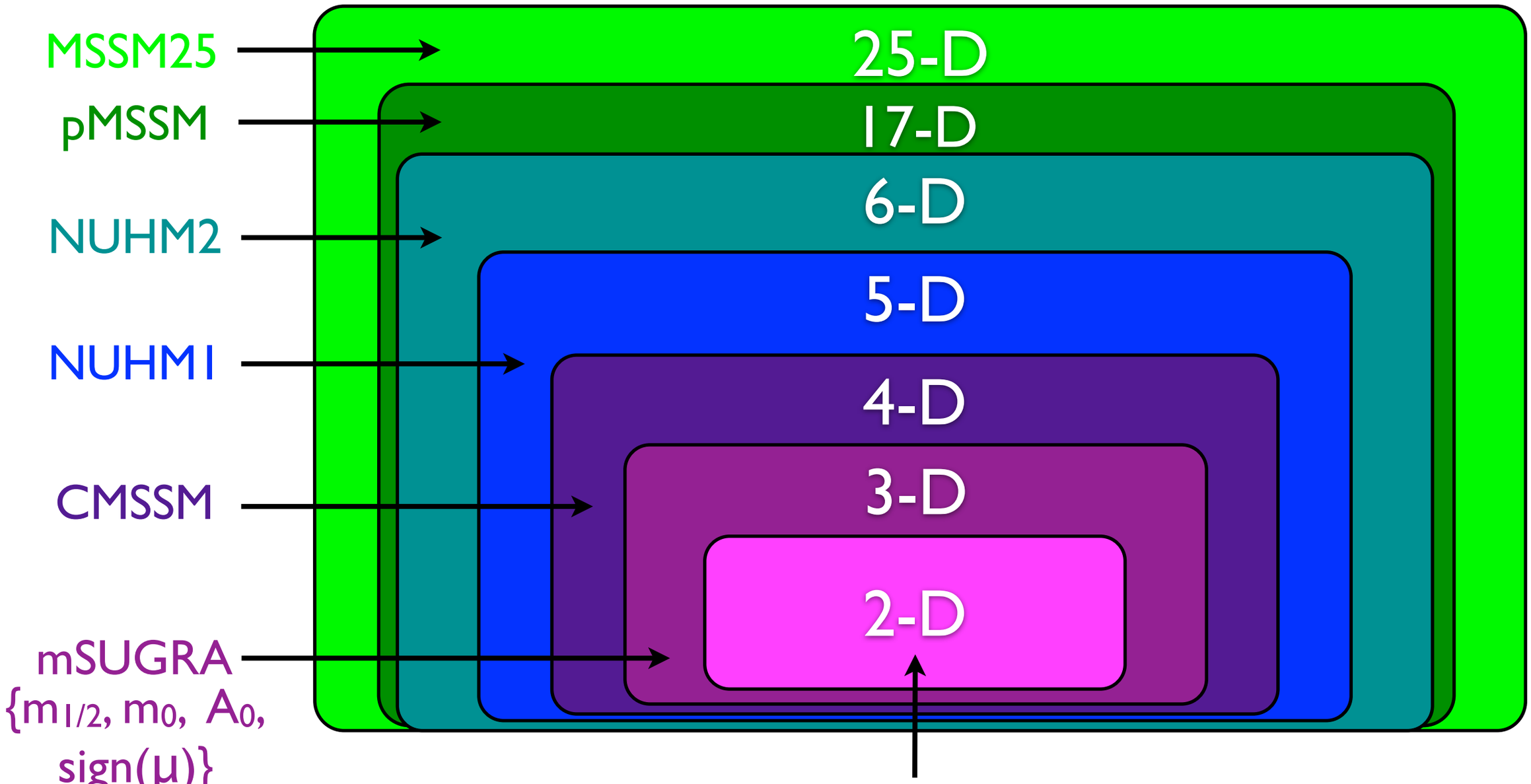
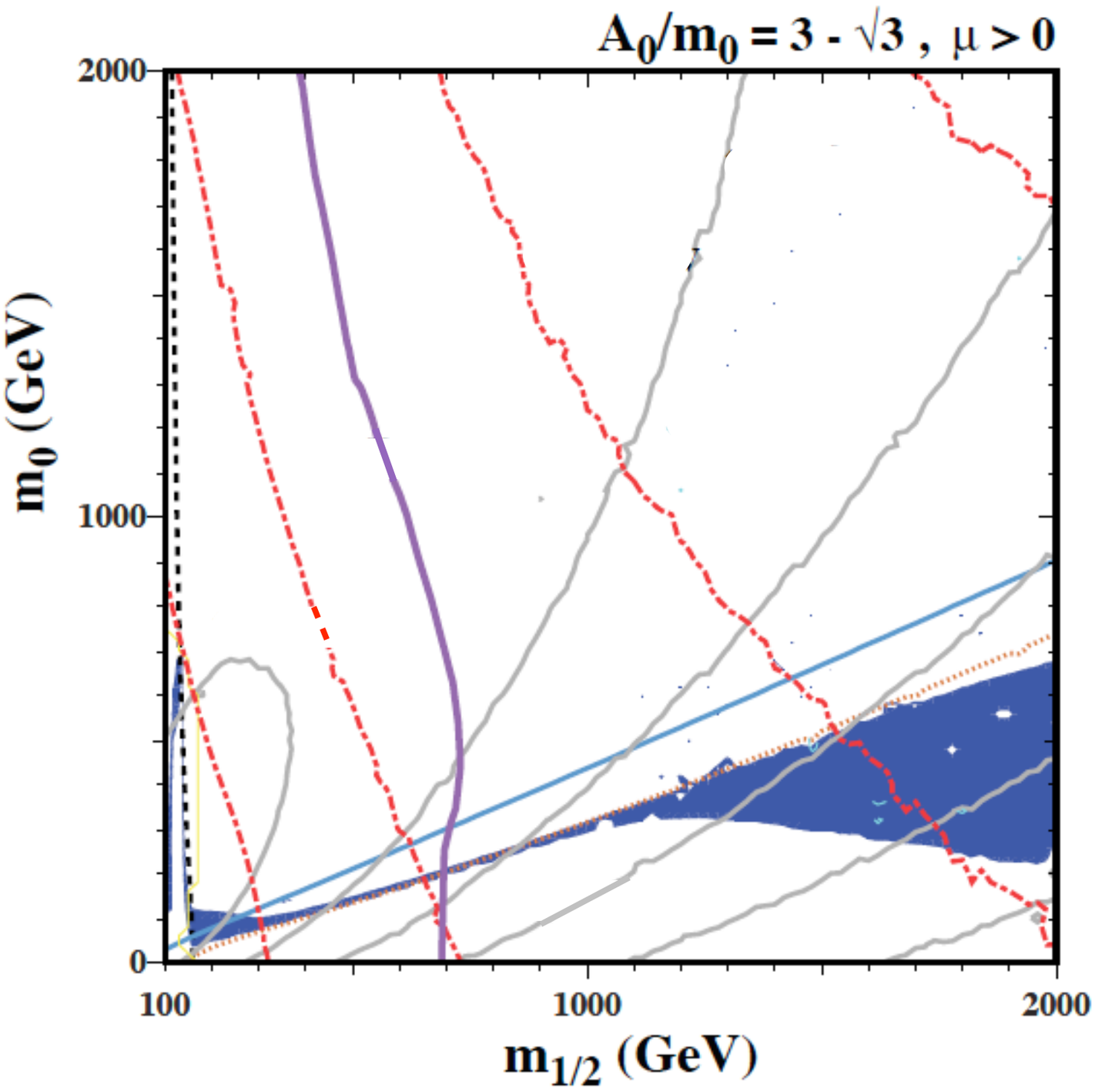


Polonyi mSUGRA

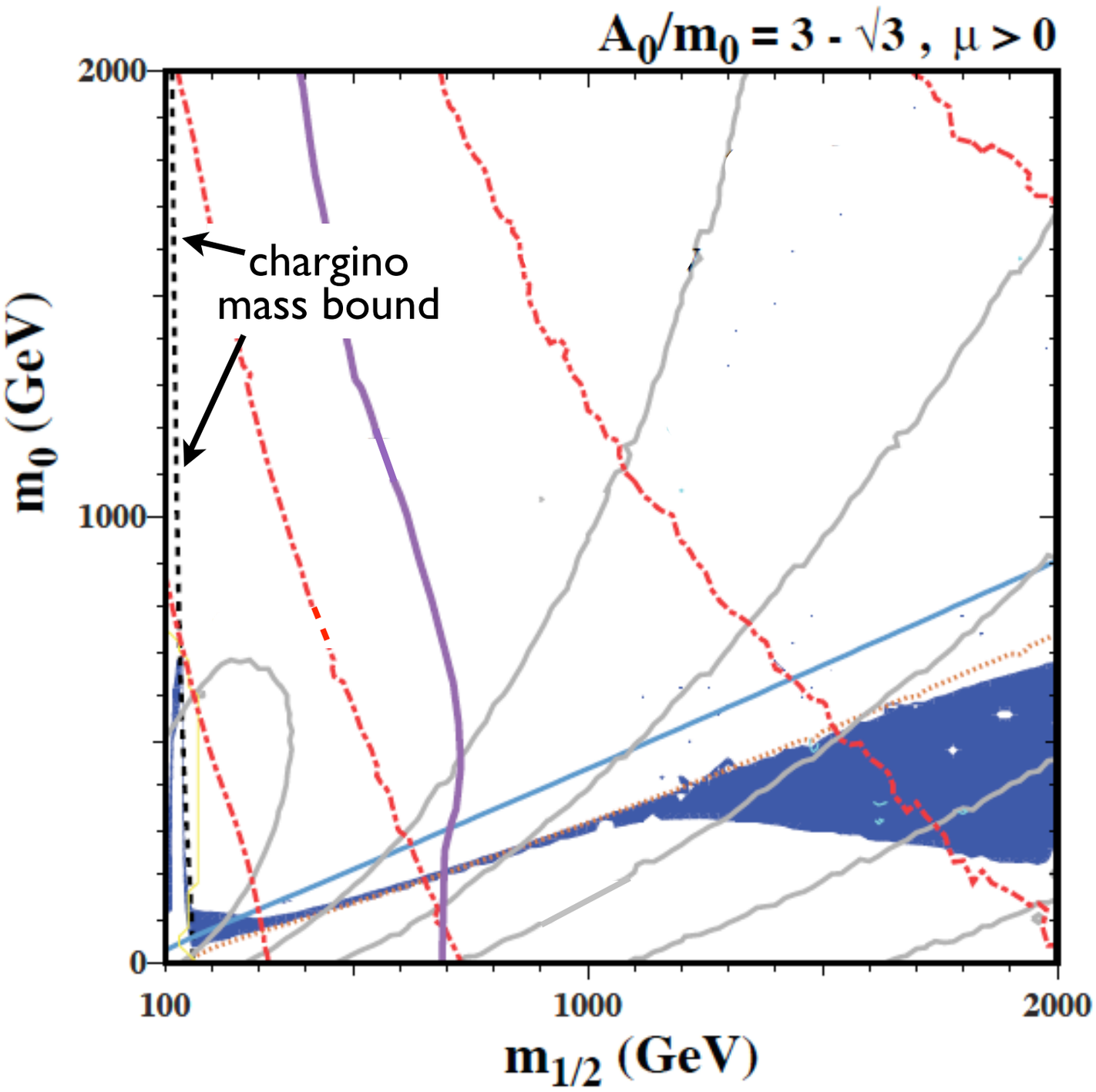
$A_0 = (3 - \sqrt{3}) m_{3/2}$ ➡ $\{m_{1/2}, m_0, \mathrm{sign}(\mu)\}$

Polonyi mSUGRA



Ellis, Luo, Olive, Sandick (2013)

Polonyi mSUGRA



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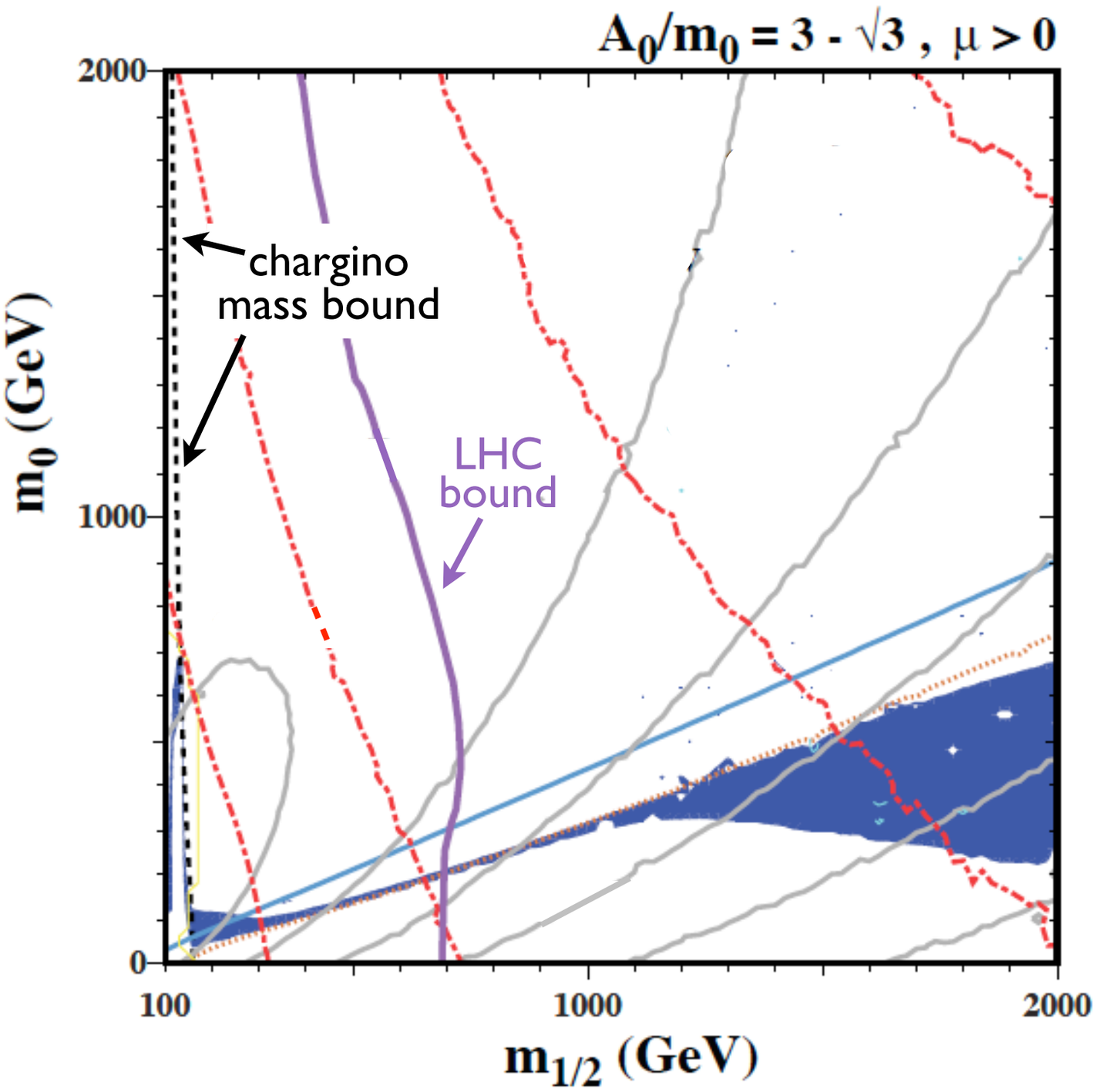

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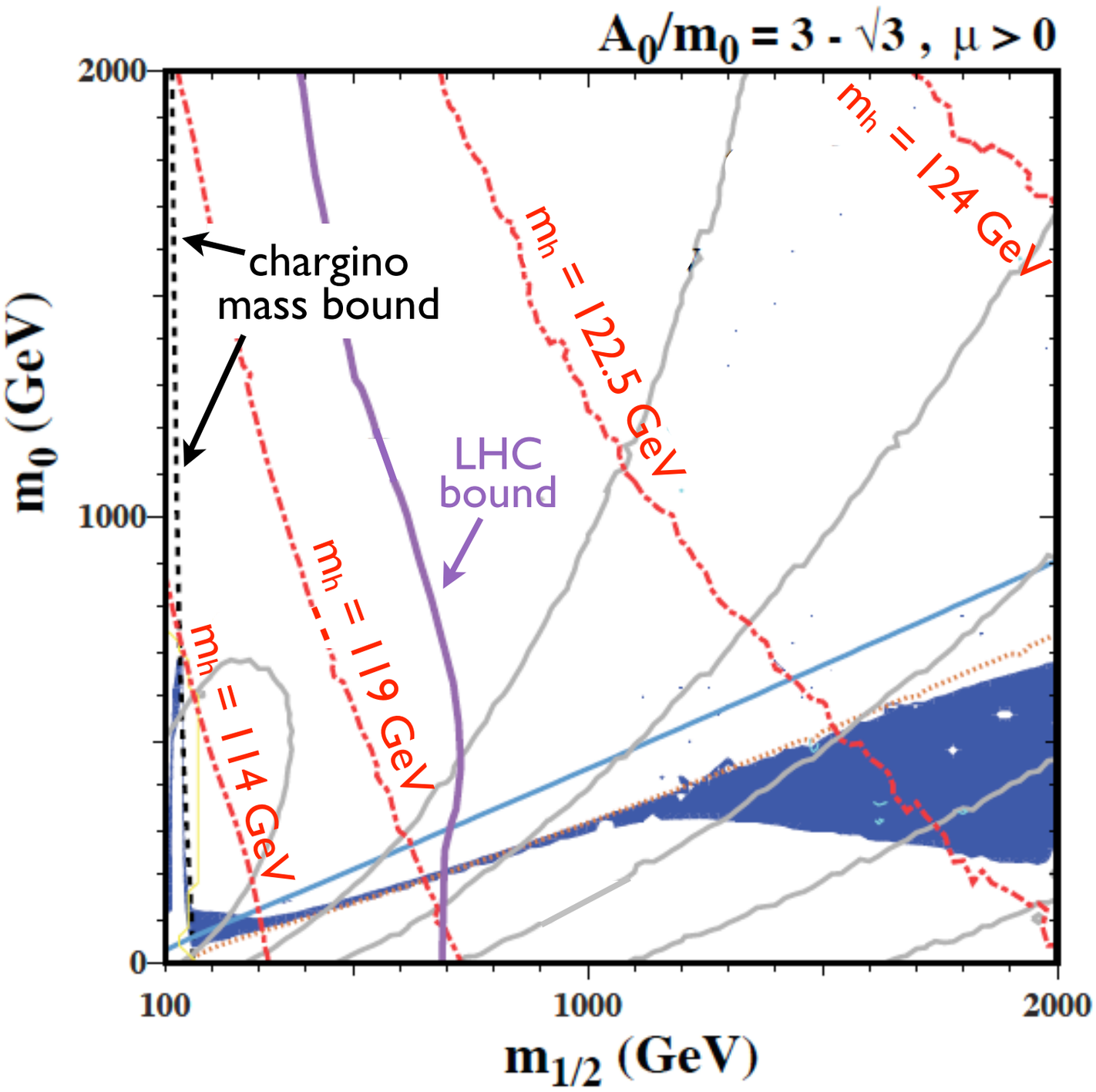

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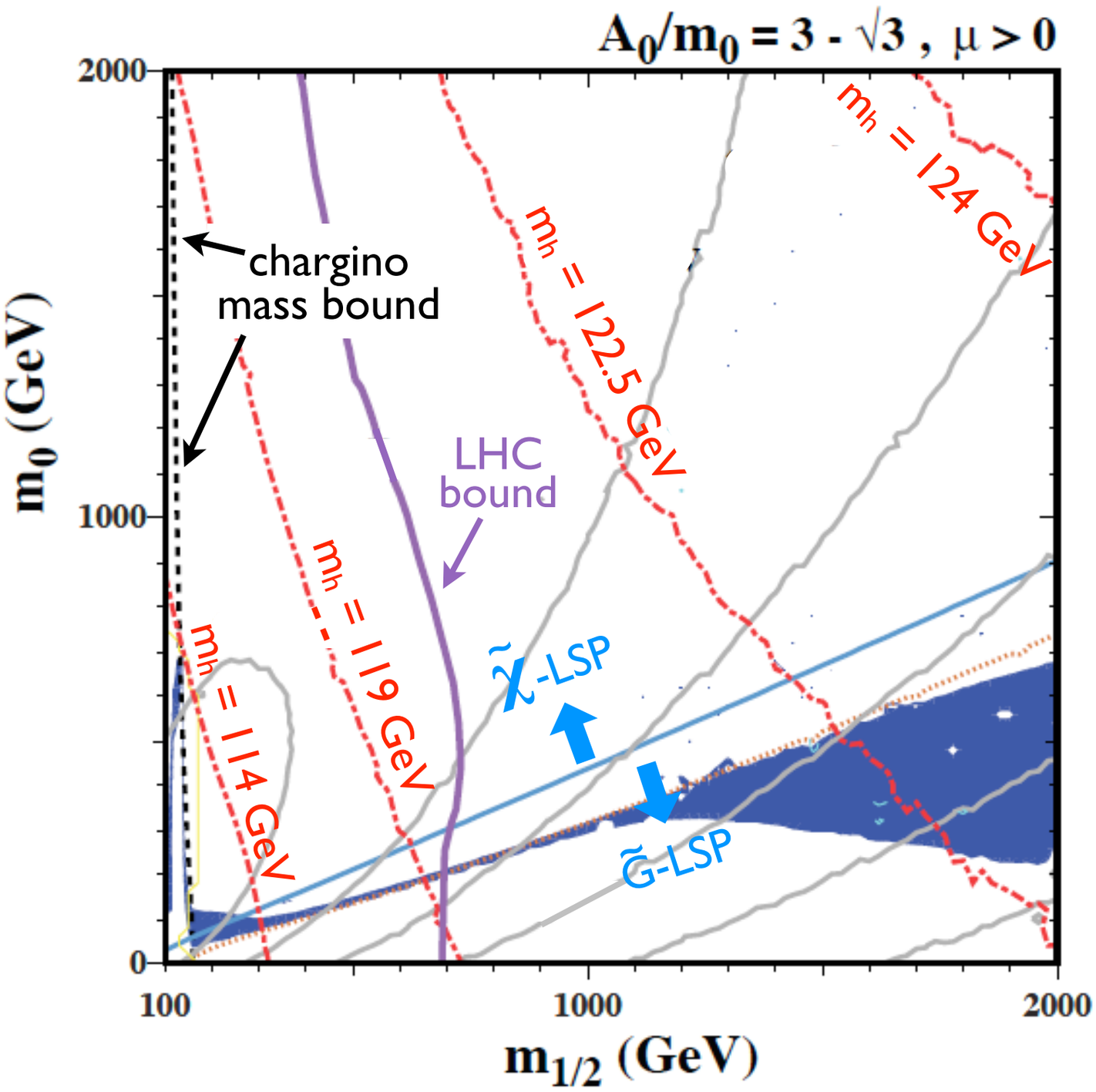

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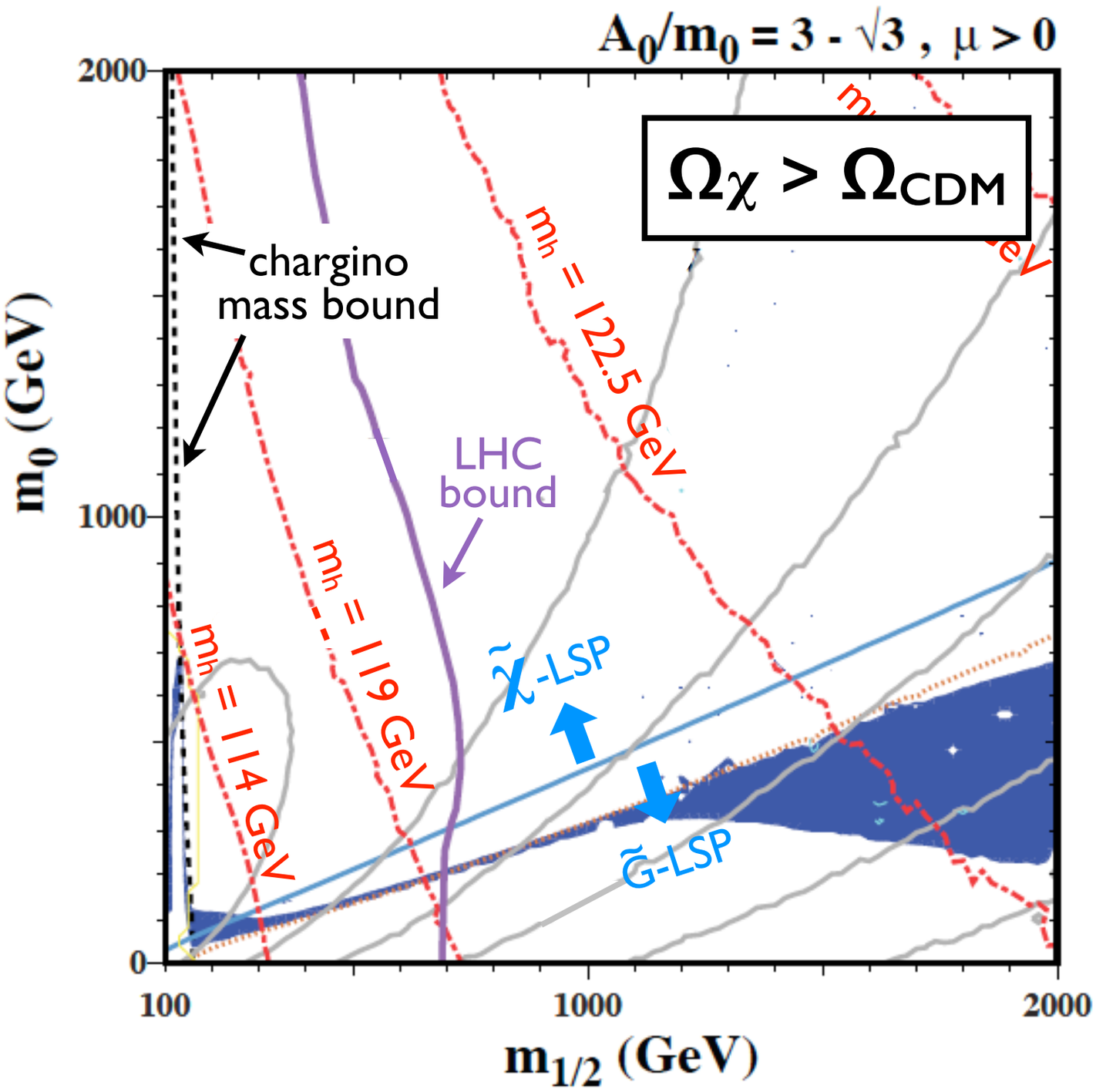

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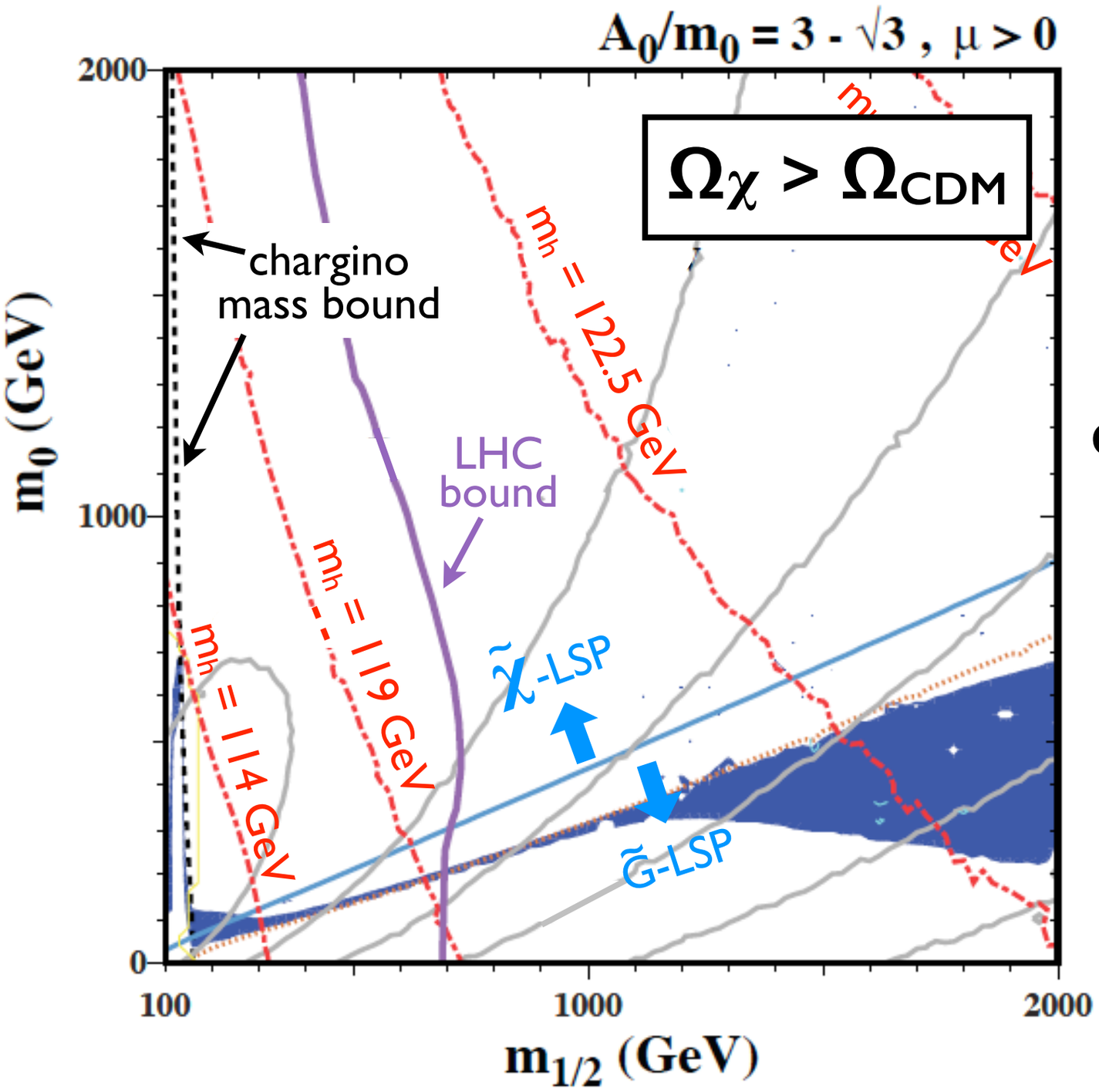
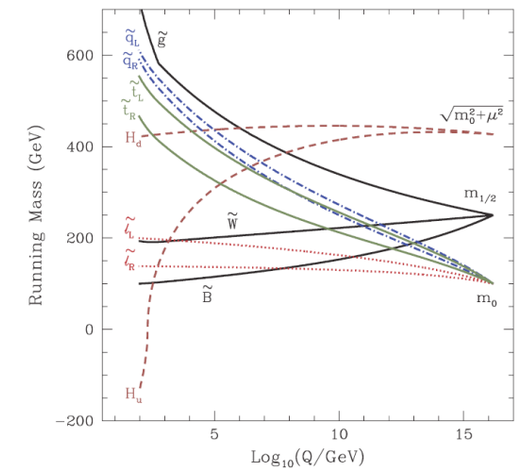


Increase dimensionality?

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)

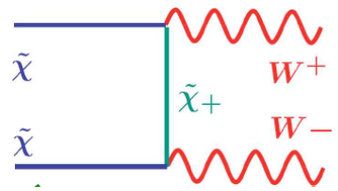
Choi et al. (2004, 2005), Kachru et al. (2003), and others

Monaco et al. (2011)

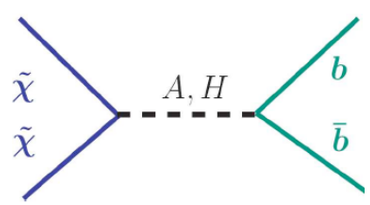
  - Lowest dynamical scale in the Polonyi/hidden sector where SUSY is broken, or scale of interactions that transmit breaking to observable sector

Dark Matter Abundance

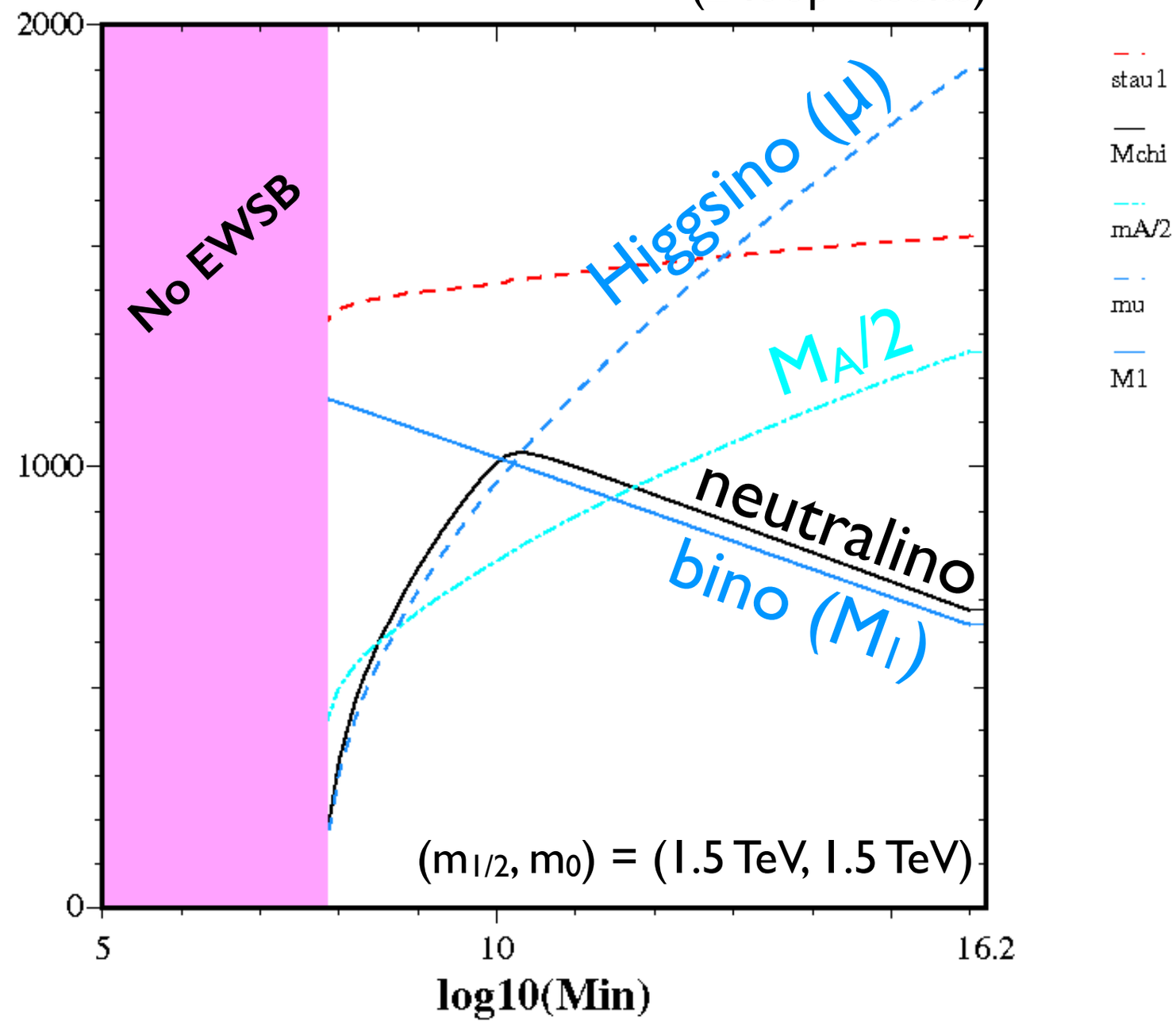
1. neutralino LSP becomes Higgsino-like at low M_{in}



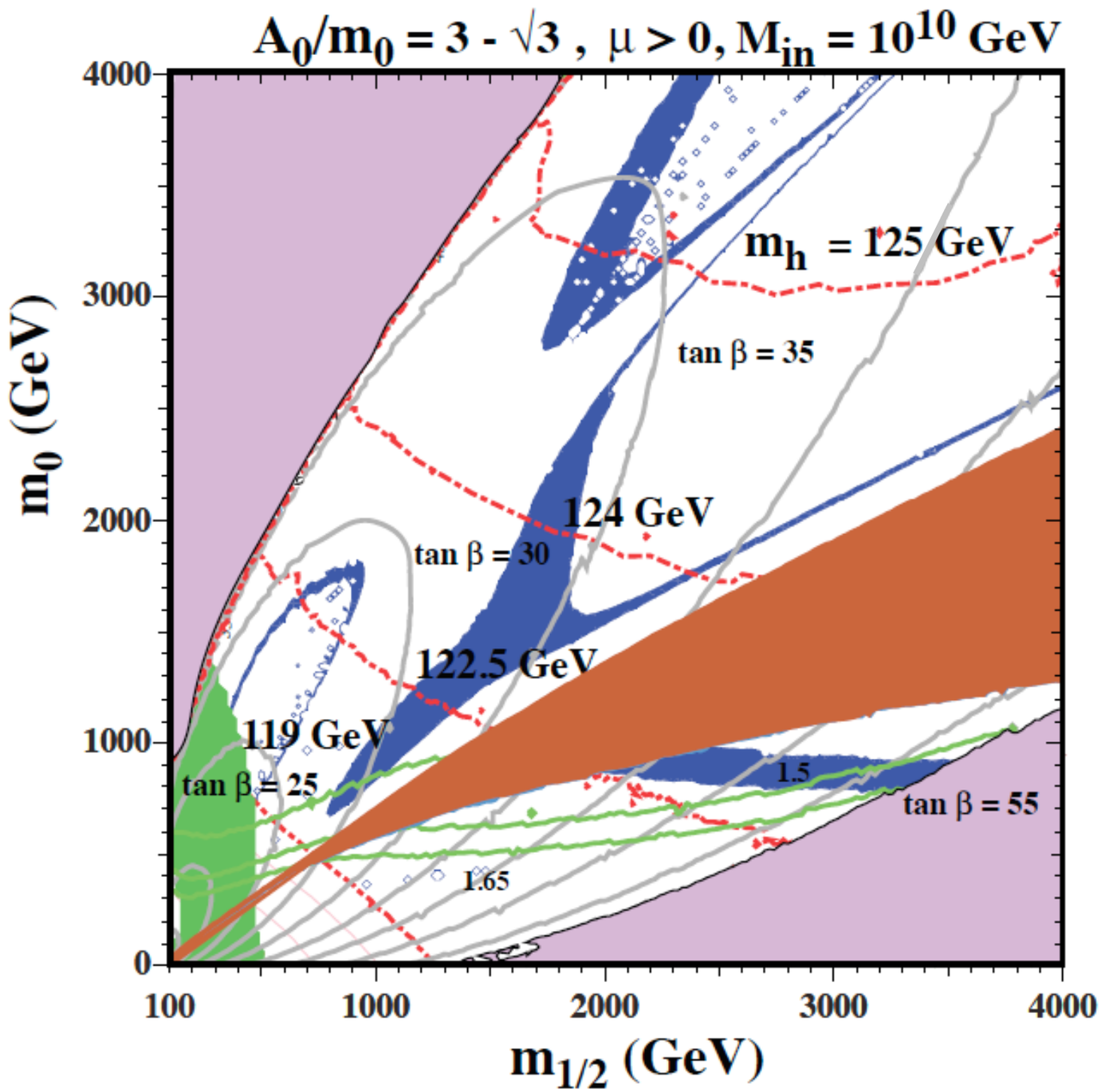
2. m_A decreases with M_{in} → appearance of rapid annihilation funnel



(2-loop results)



sub-GUT mSUGRA



Ellis, Luo, Olive, Sandick (2013)

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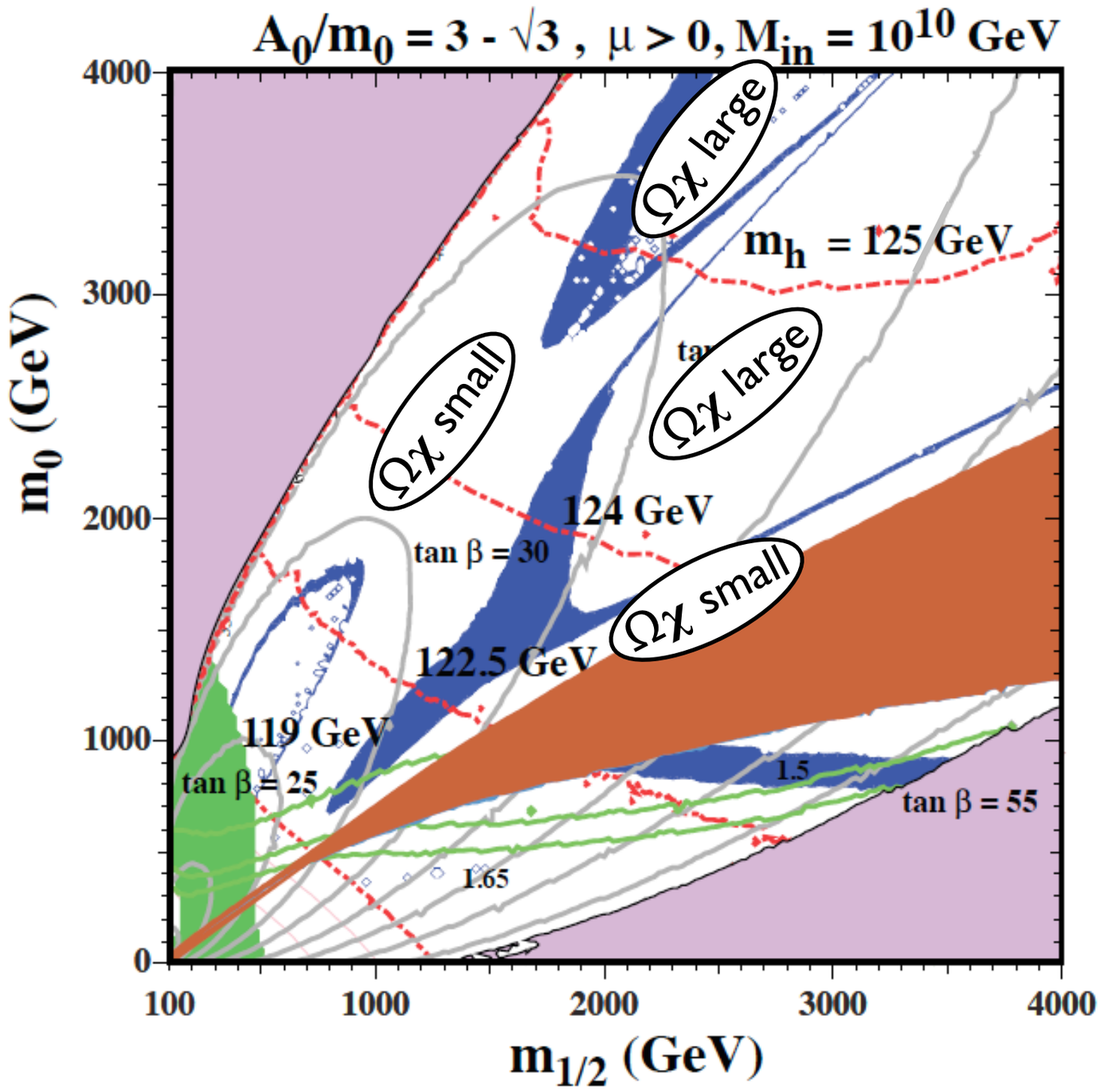


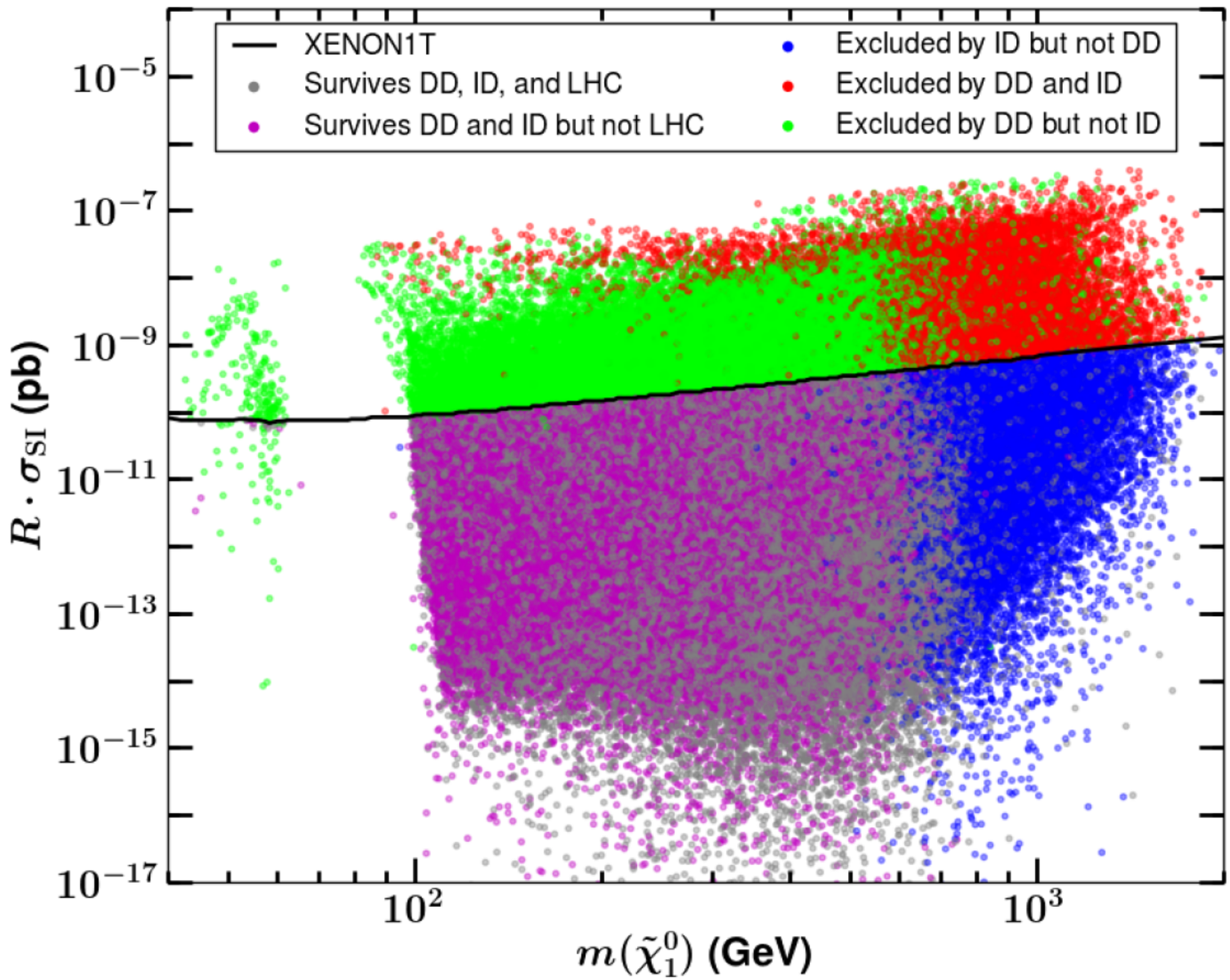
Ellis, Luo, Olive, Sandick (2013)

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)

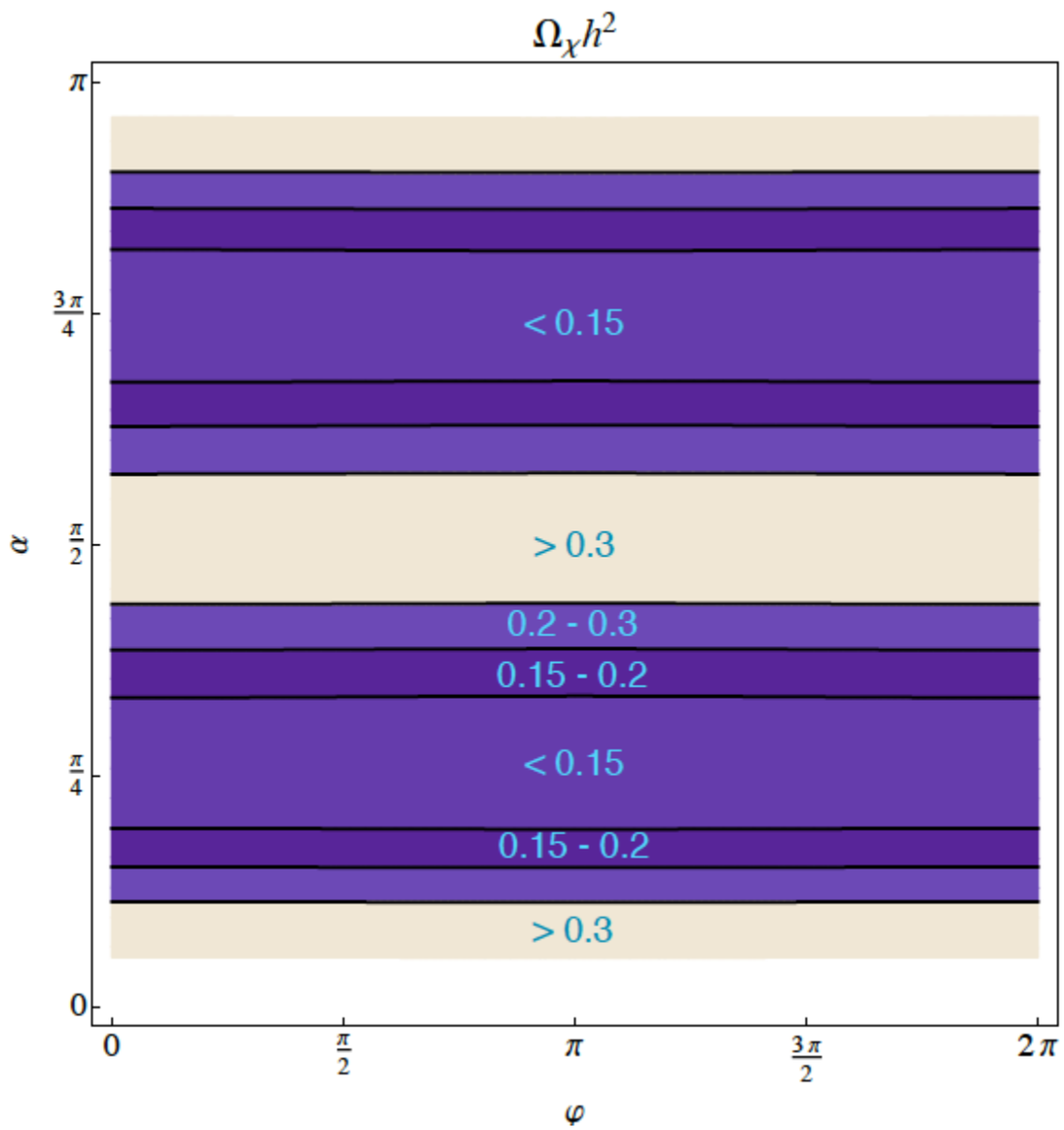


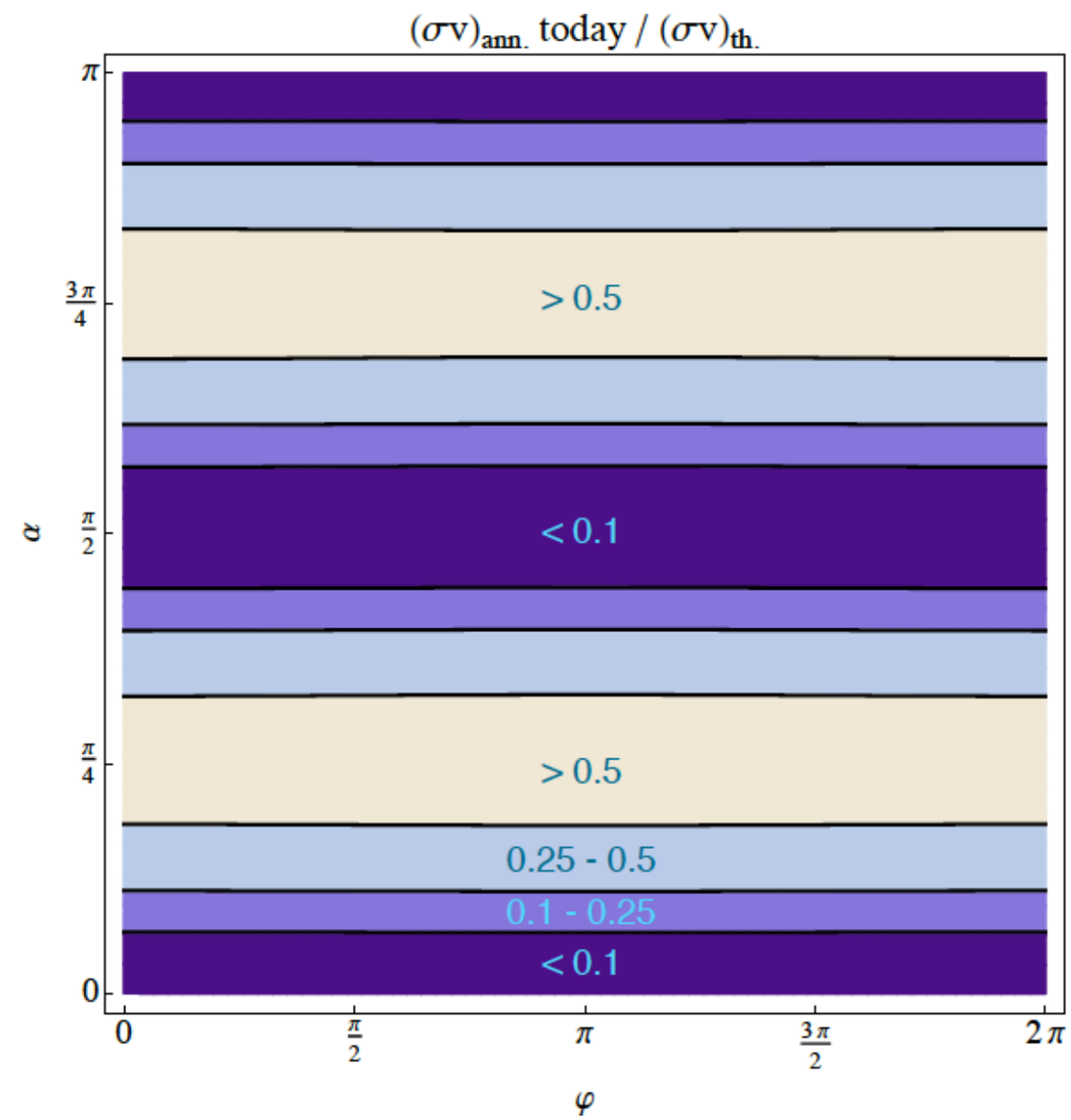
Data-Driven SUSY

- 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 Smuons Scenario ($M_1 \neq M_2$)





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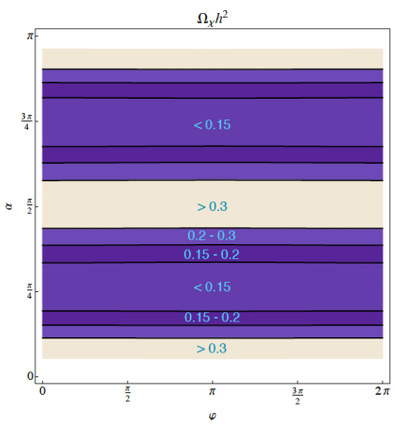

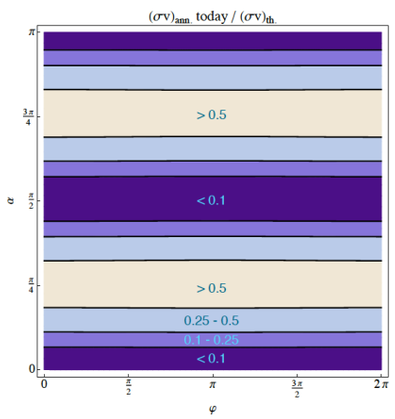

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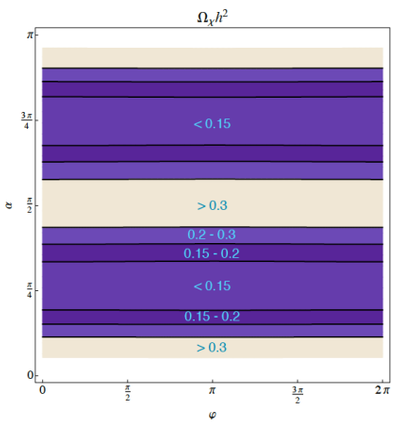

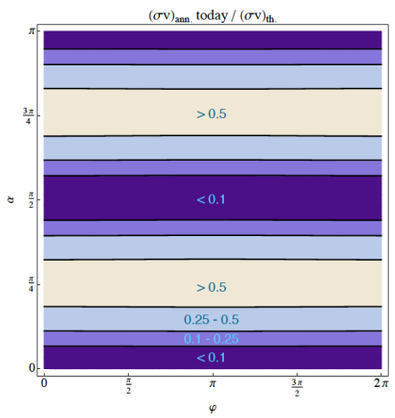

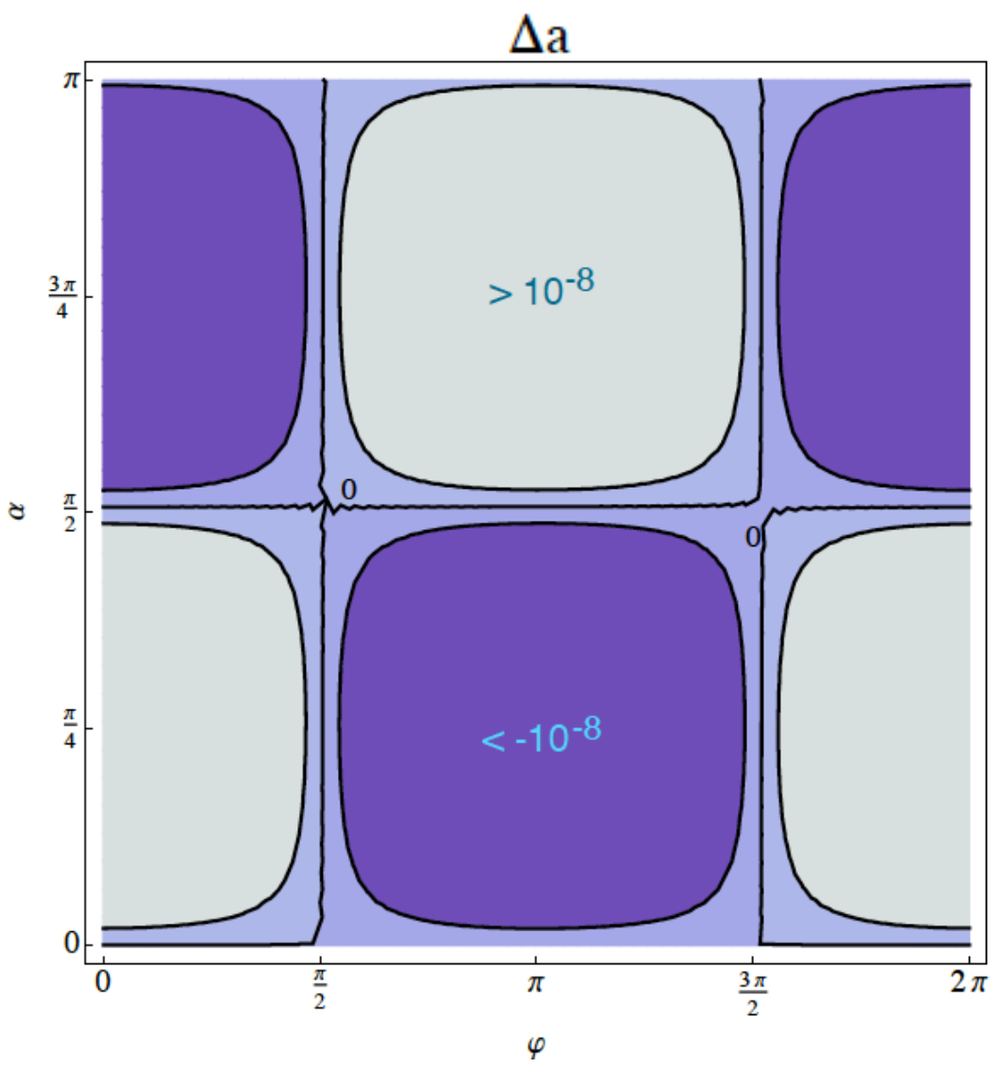

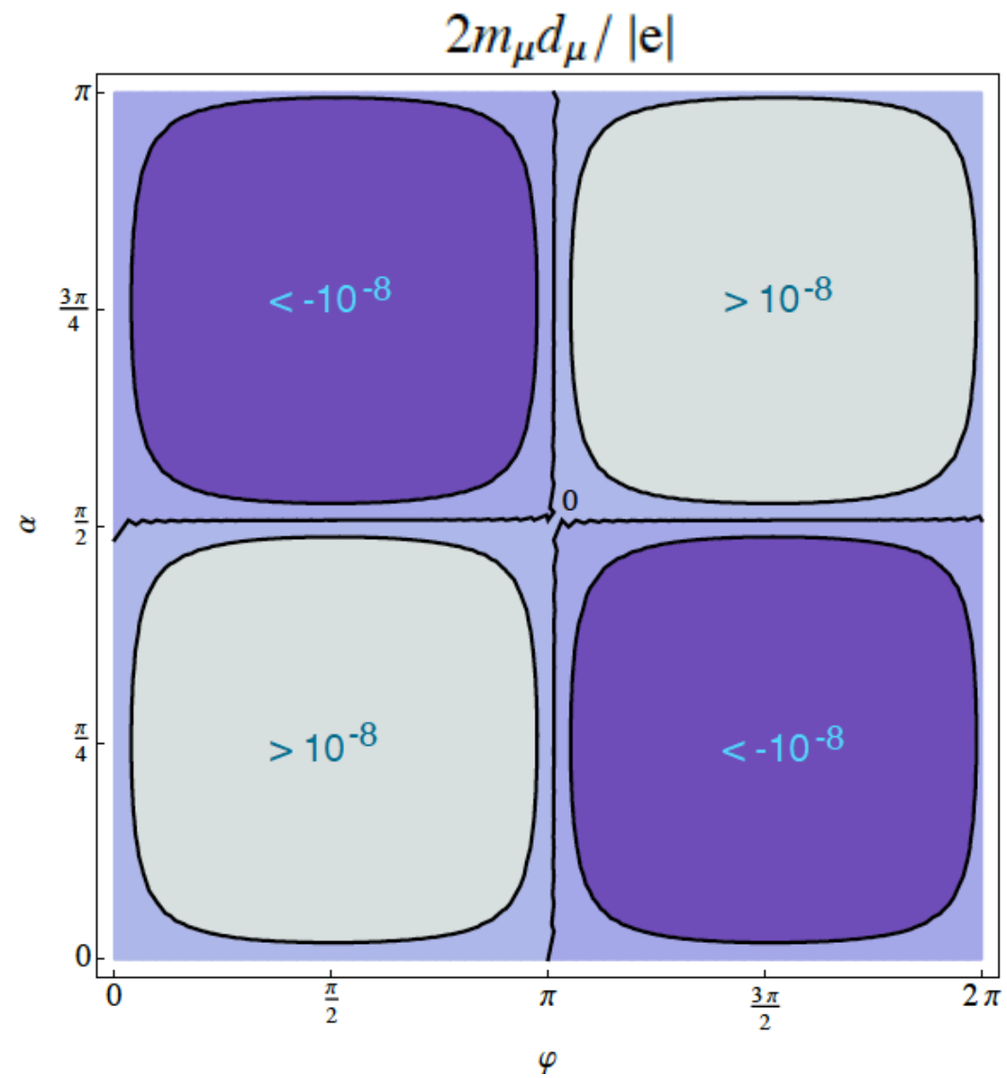

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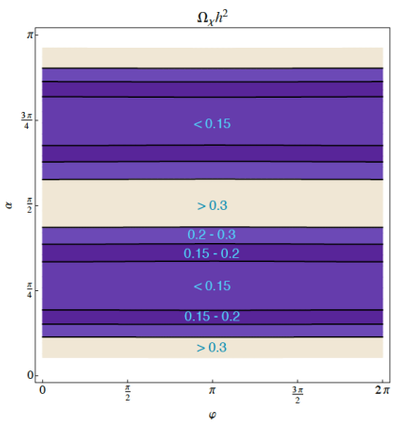
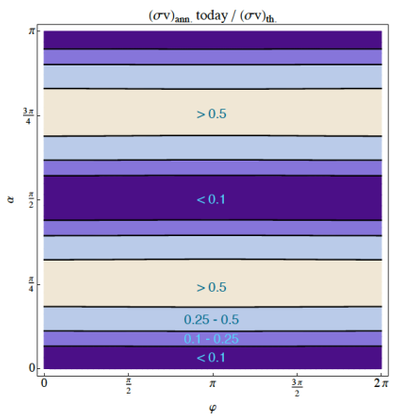
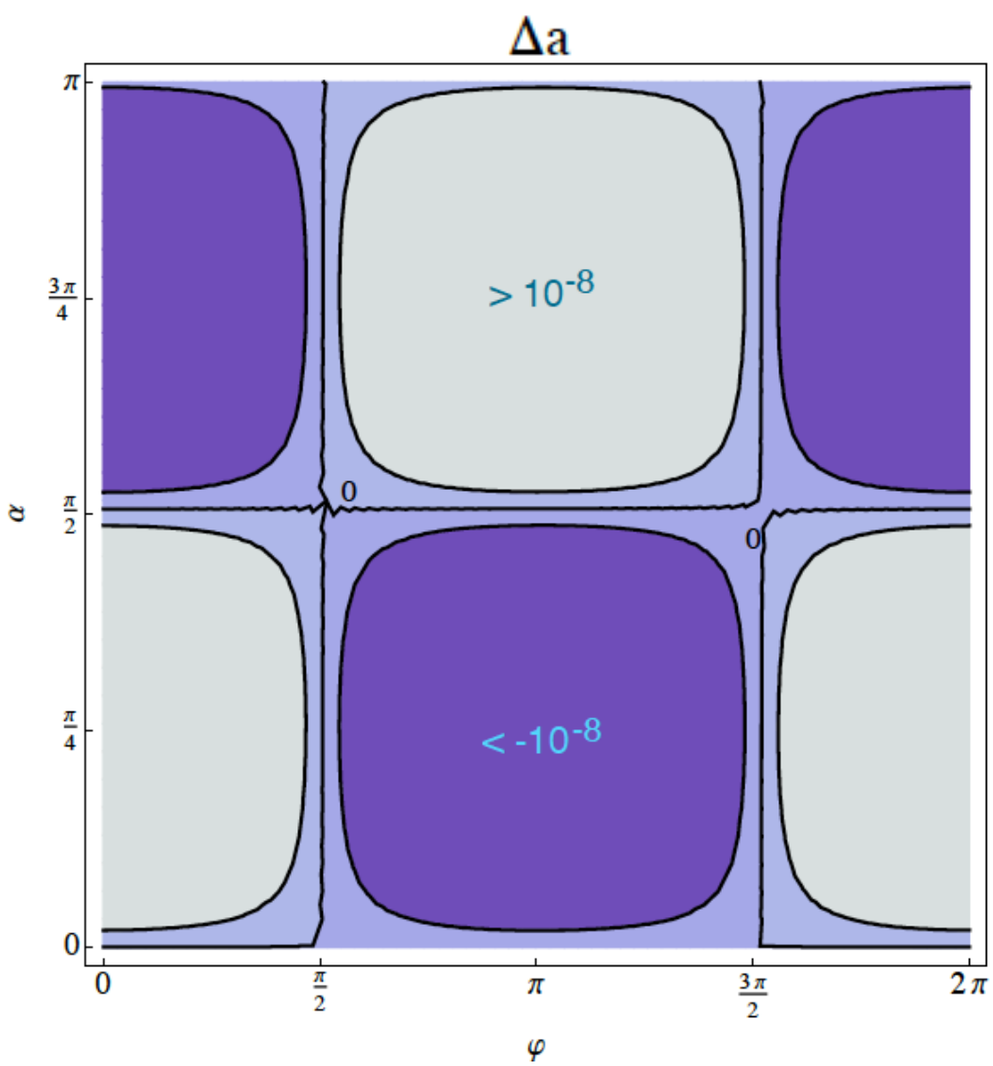
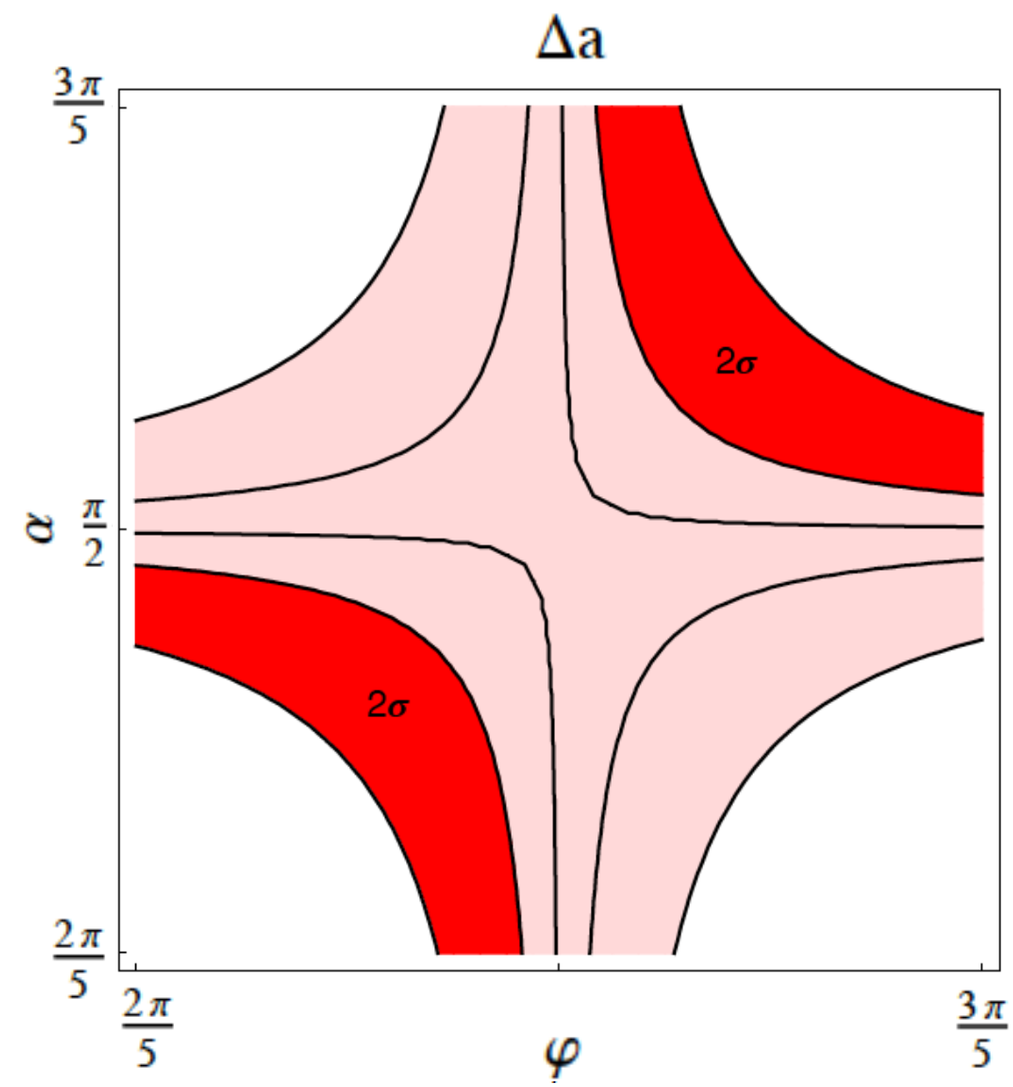
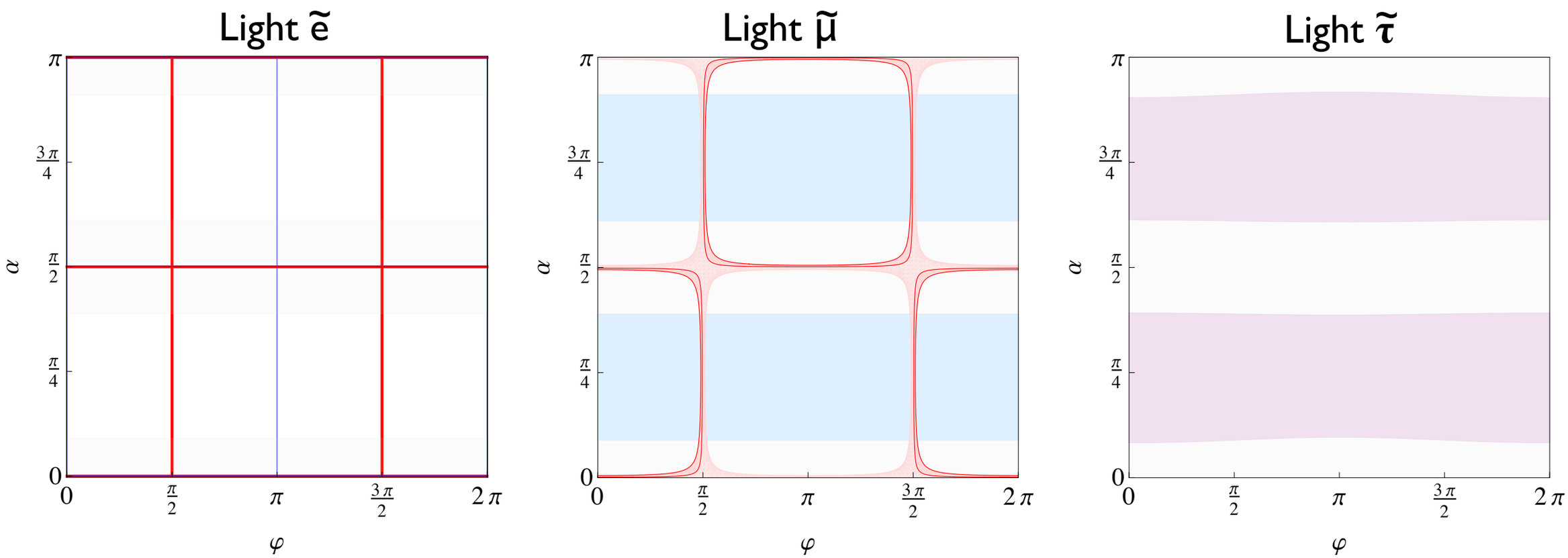








Light Sleptons ($M_1 \neq M_2$)



- 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.)

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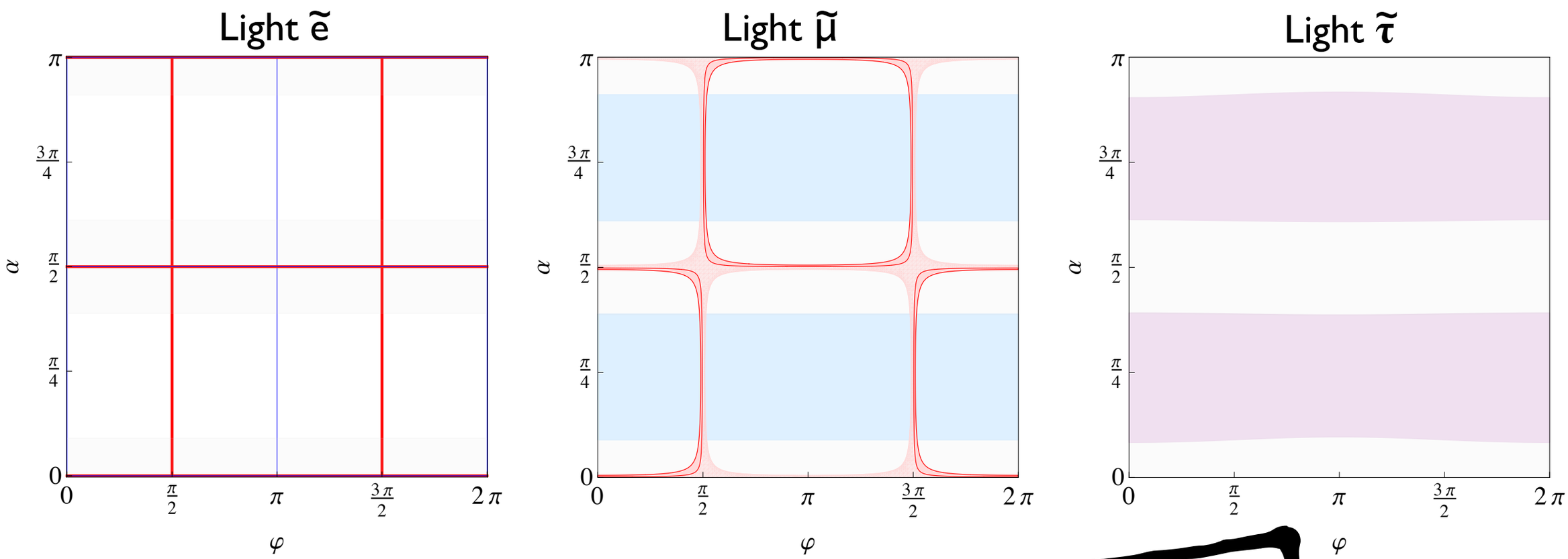

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- Li rmal dark ma
- Ligh constraint (see also Pierce, et al.; Hagiwara et al., 2013)

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

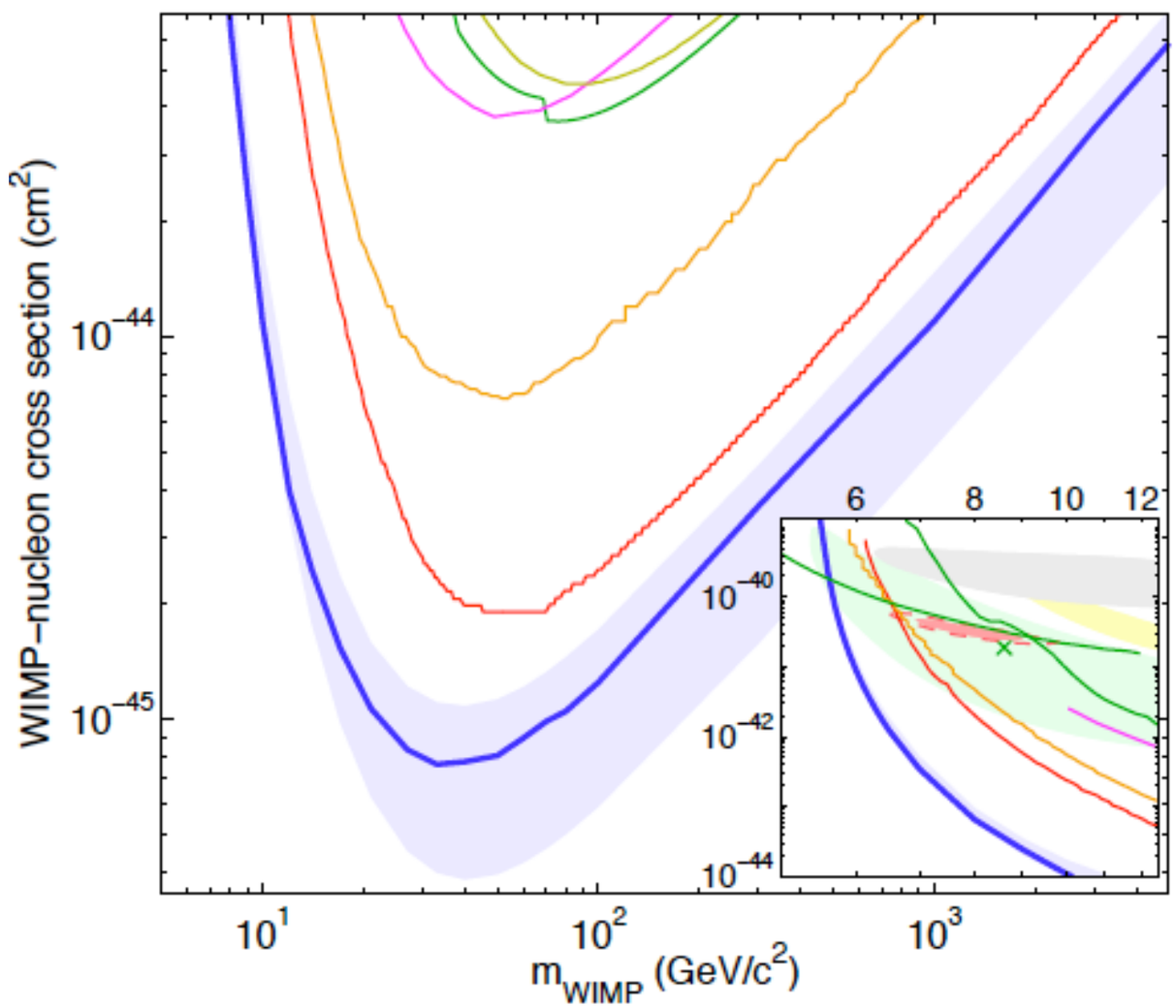
Fukushima, Kelso, Kumar, Sandick, & Yamamoto (in prep.)

3. When will we know for sure?

Future Prospects

- Timeline for discovery/exclusion?

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



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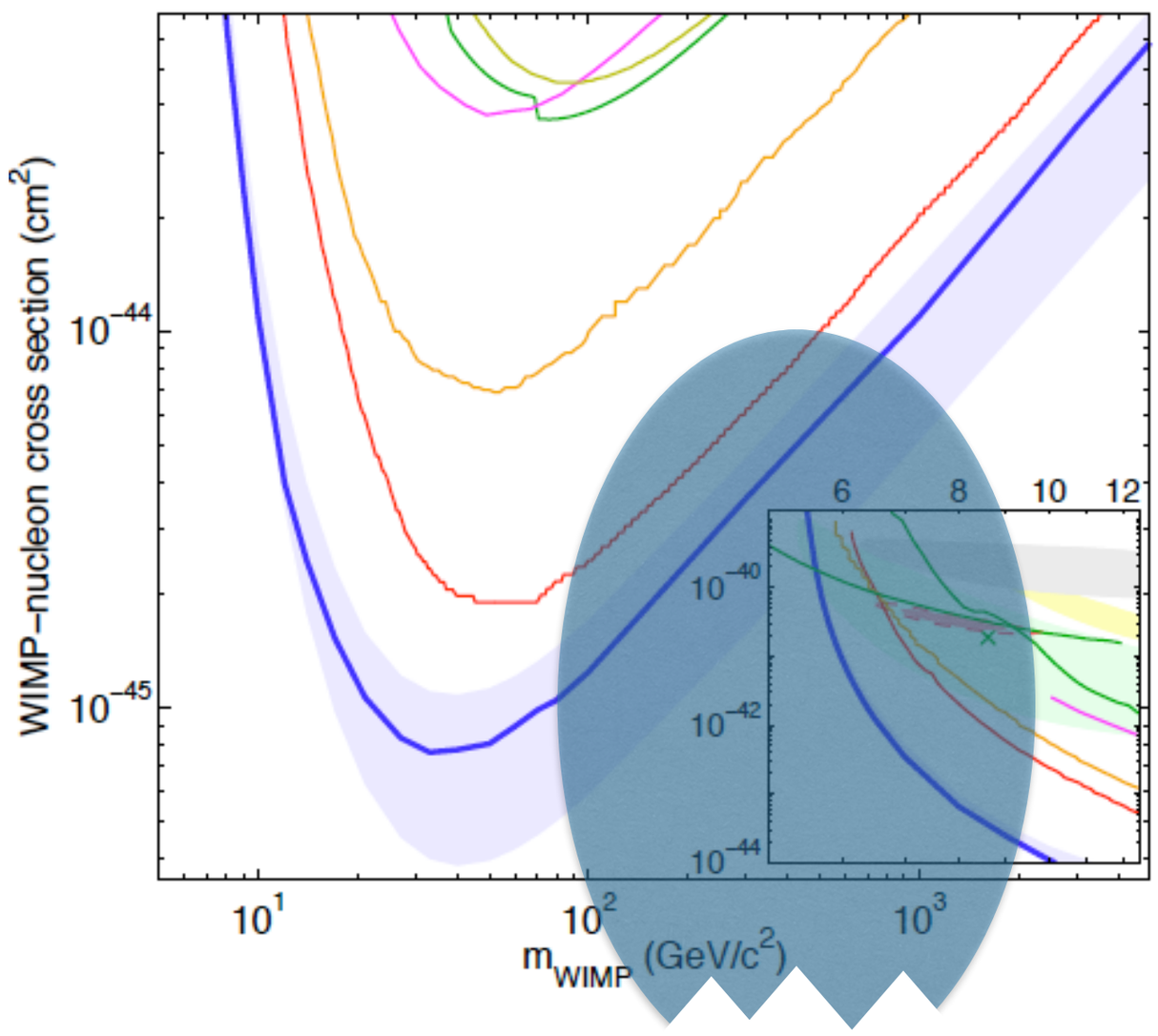

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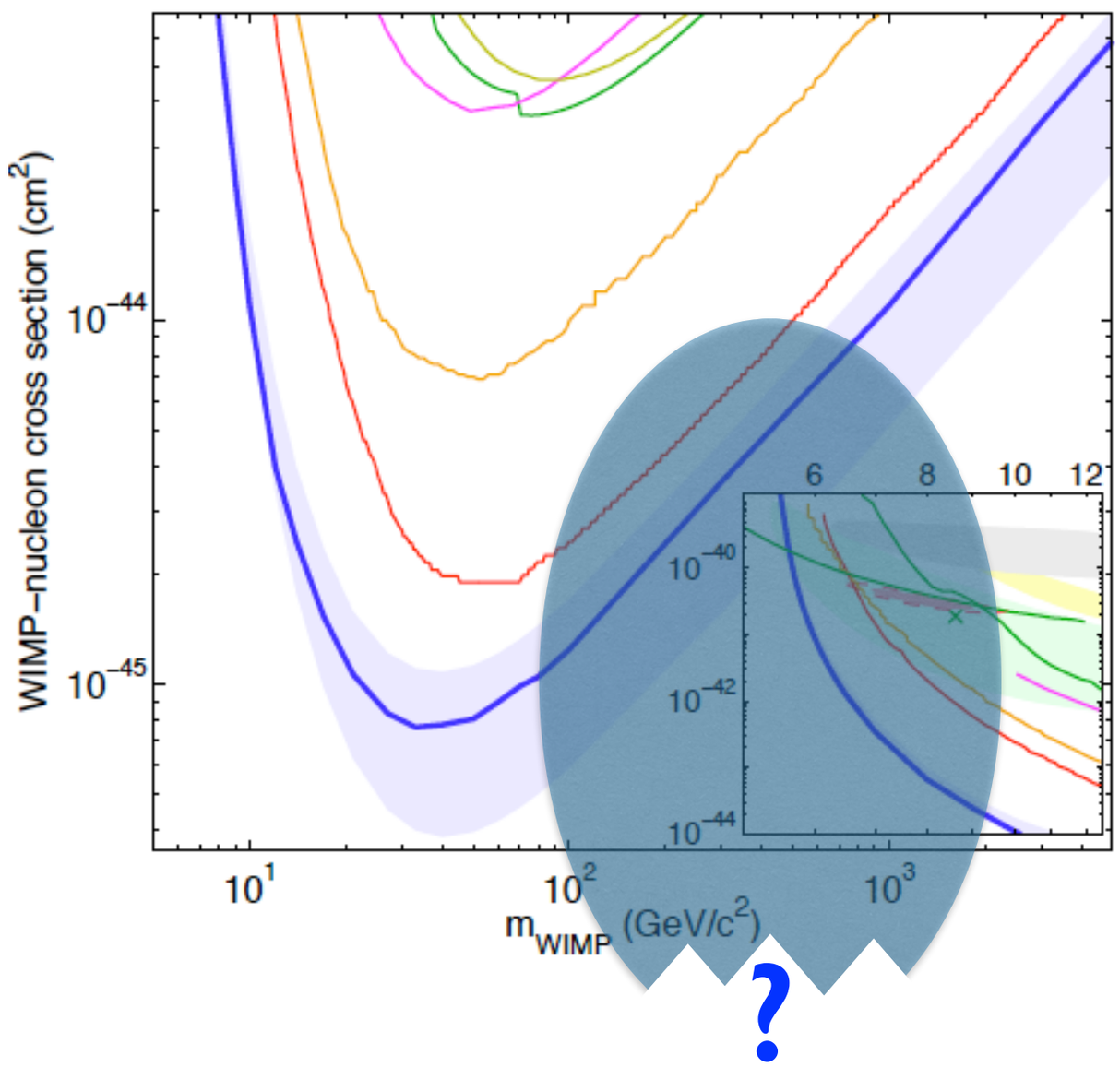

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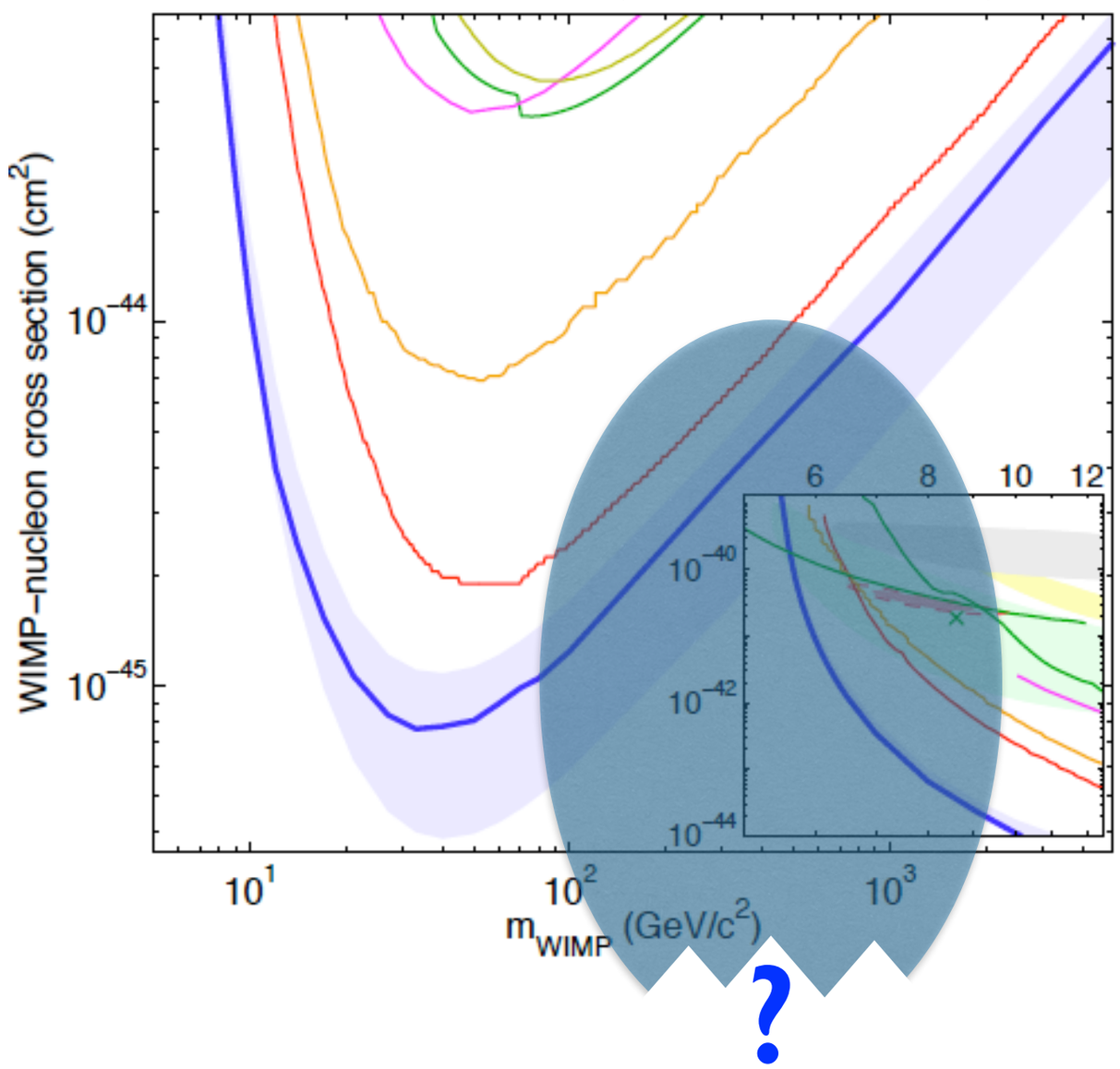

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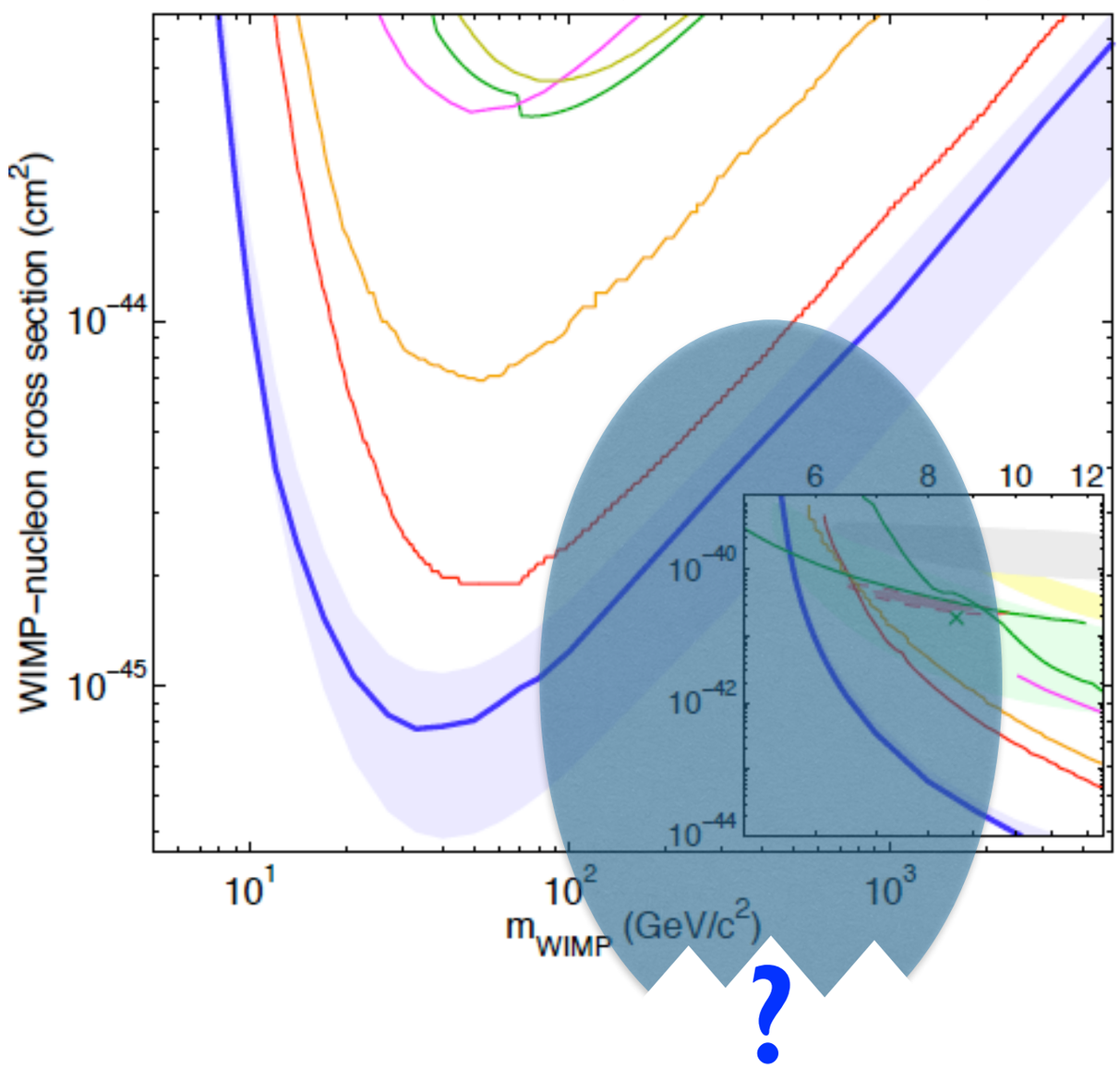

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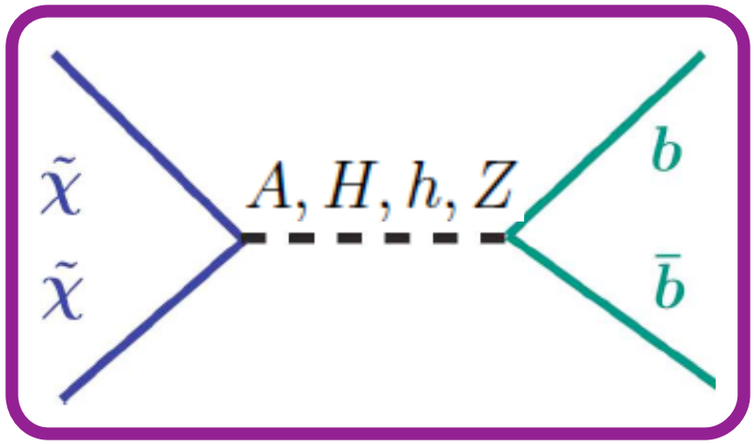
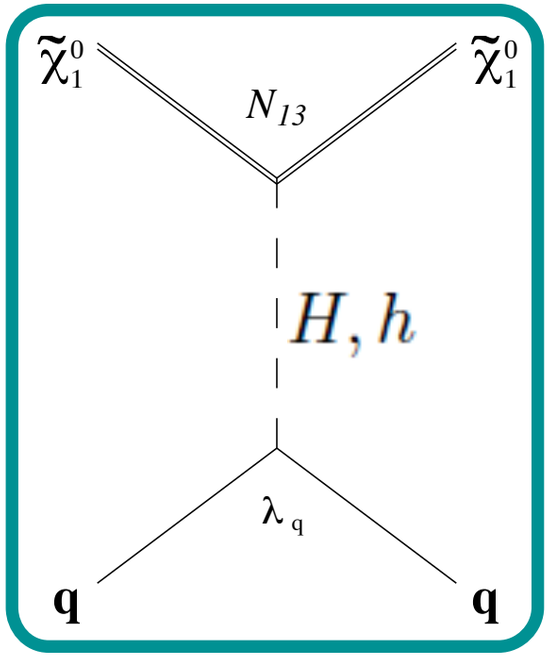
Simplified models can help you construct a definite, model-independent answer.

Resonance Models

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



- 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



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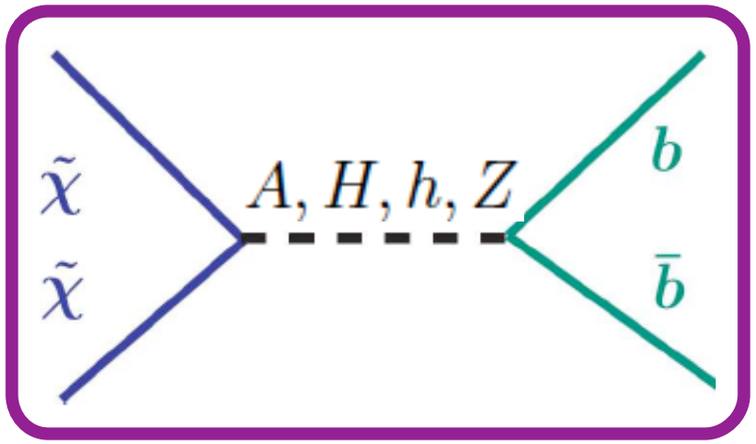

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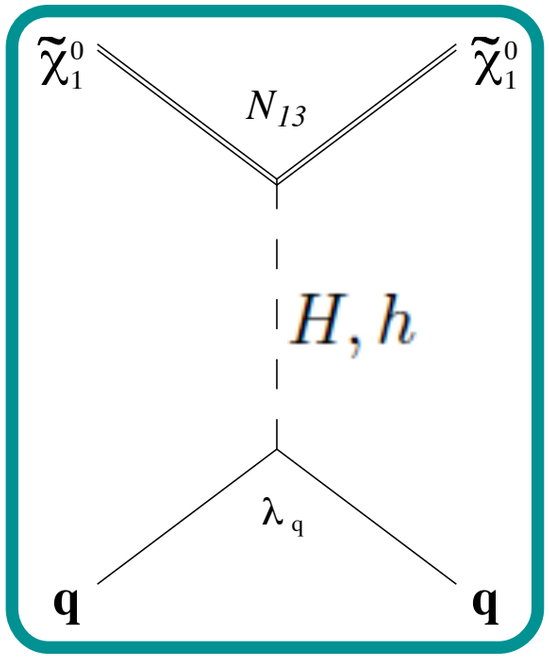

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Hooper, **Kelso, Sandick,** & Xue, PRD 2013

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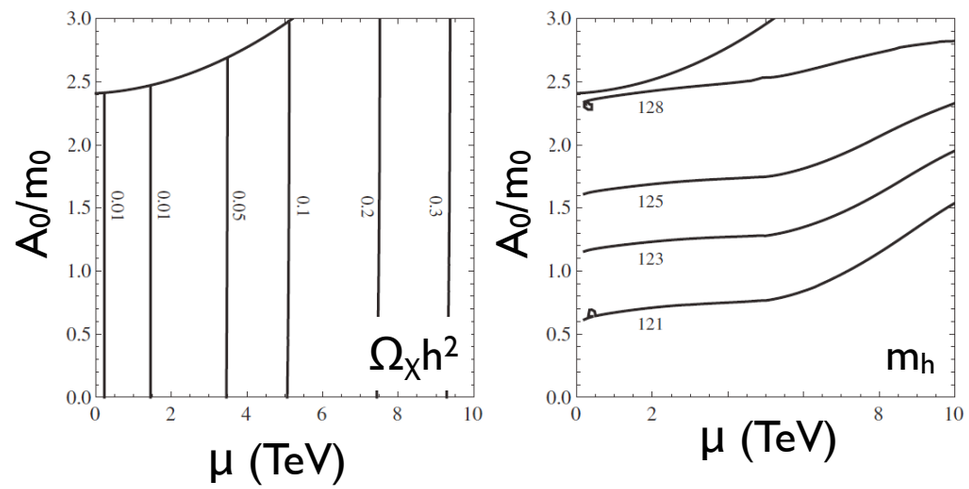

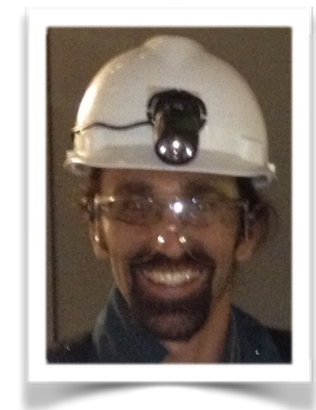

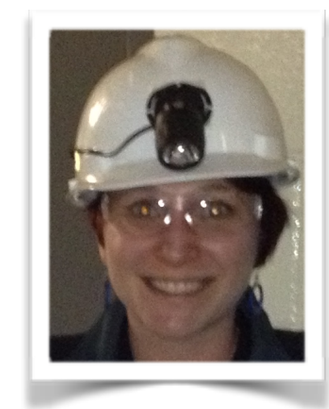

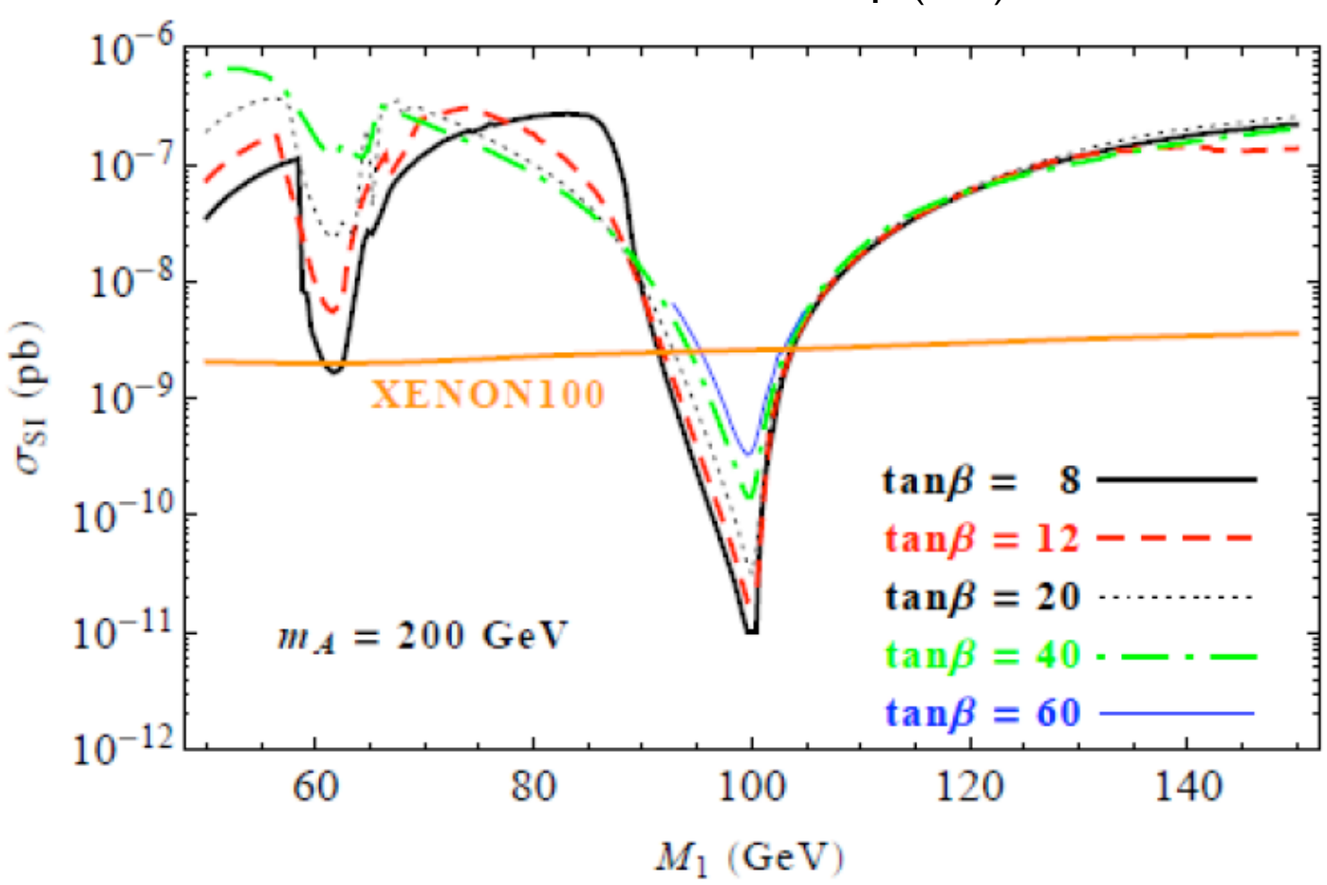

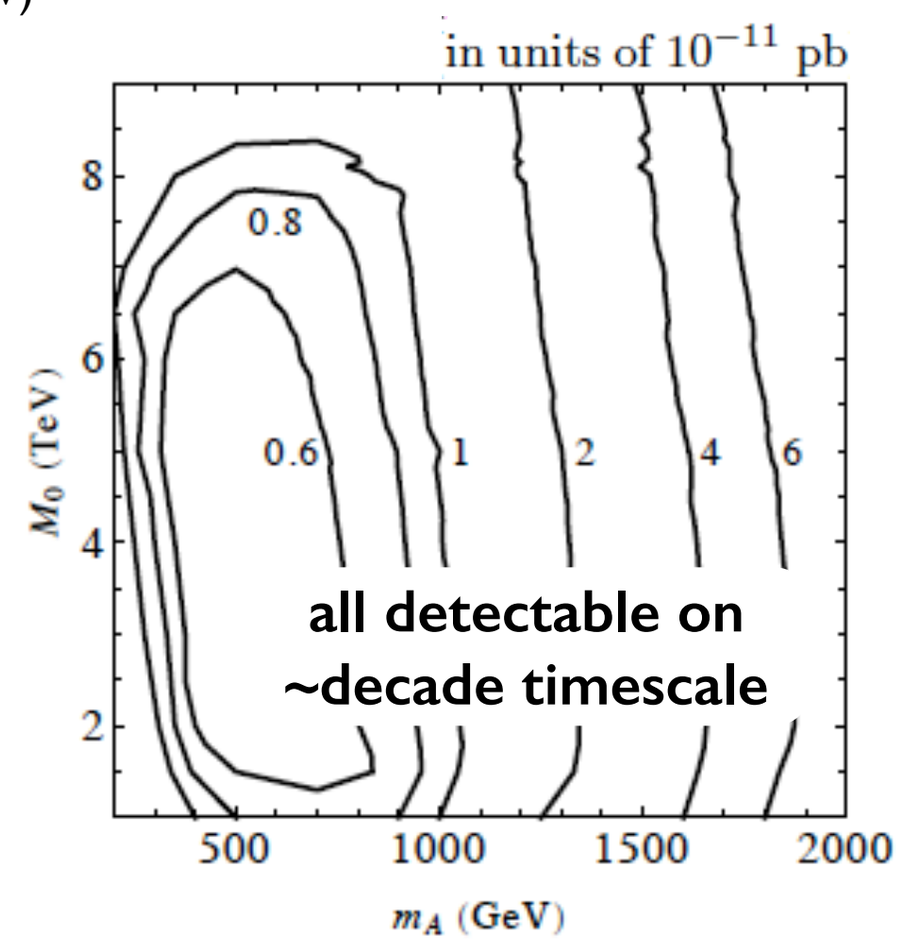

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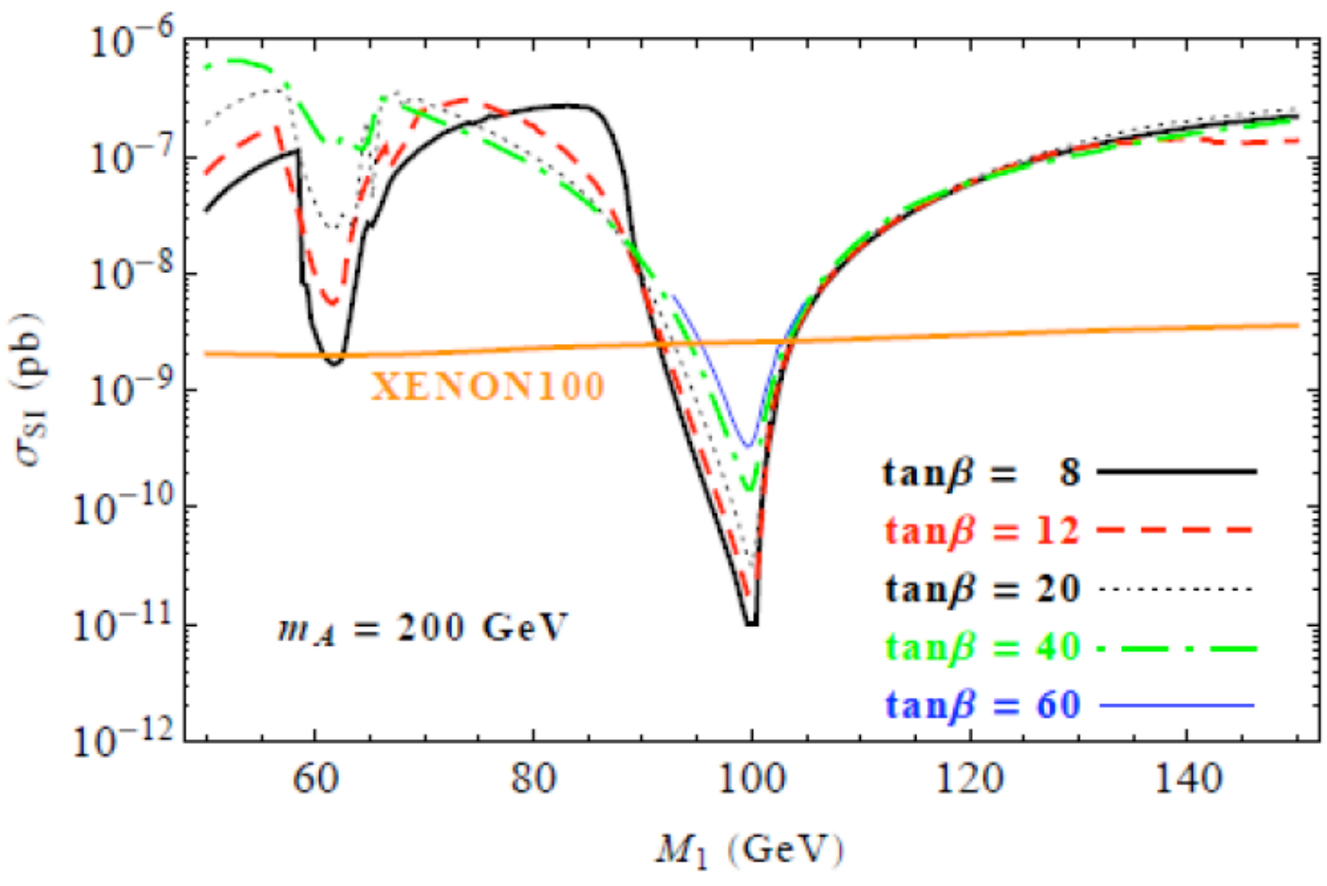

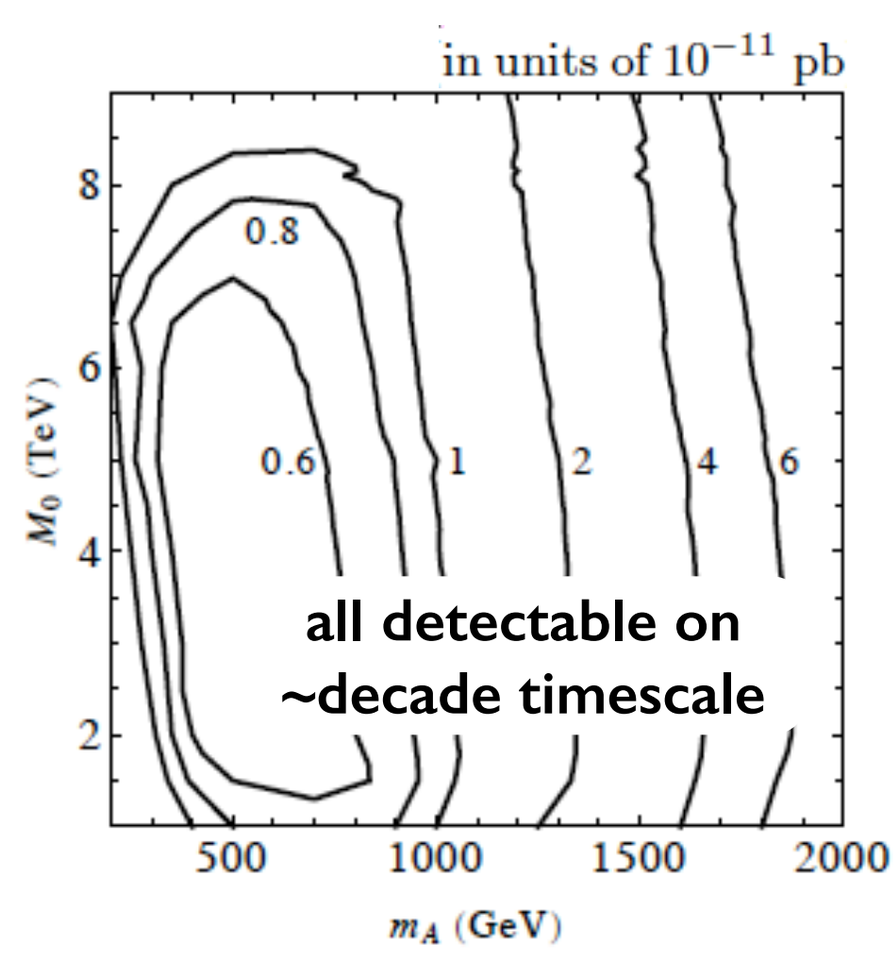

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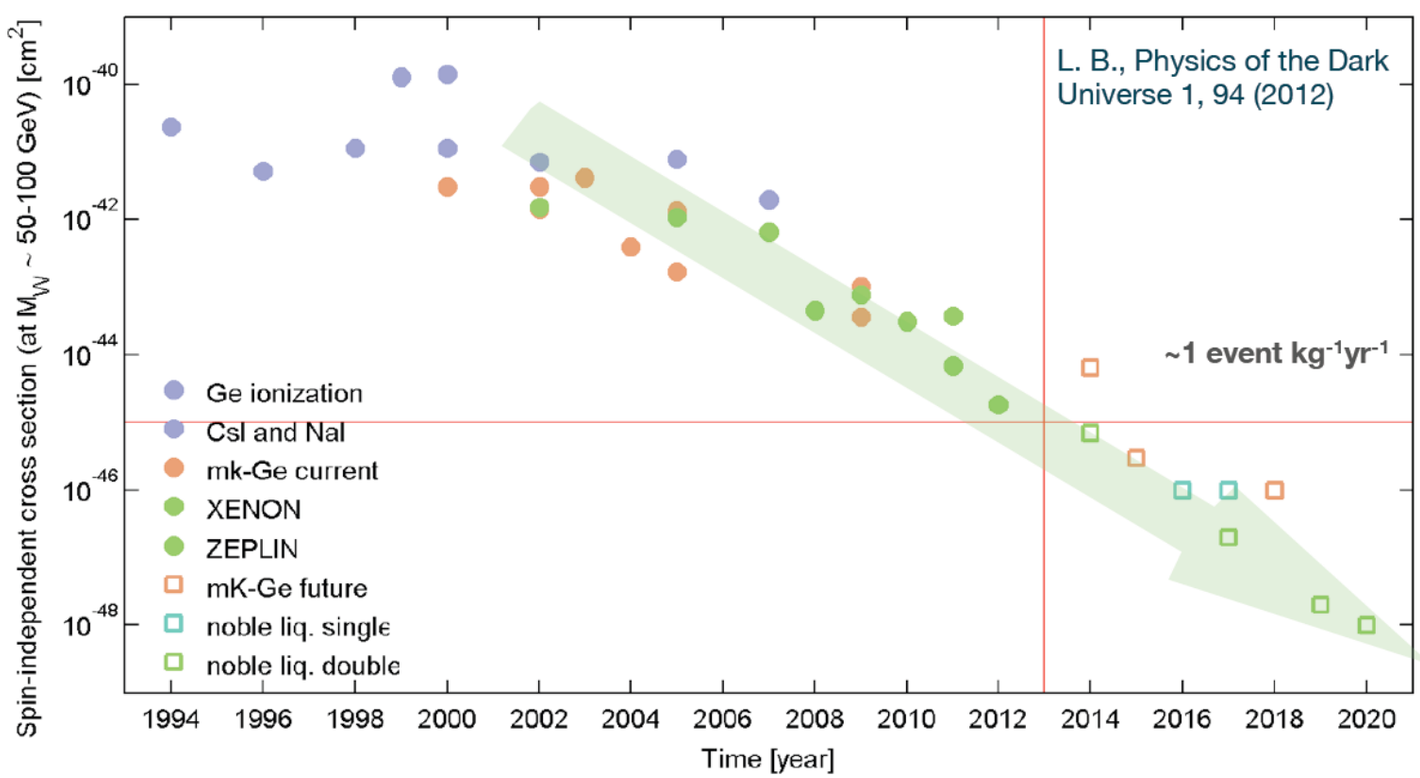

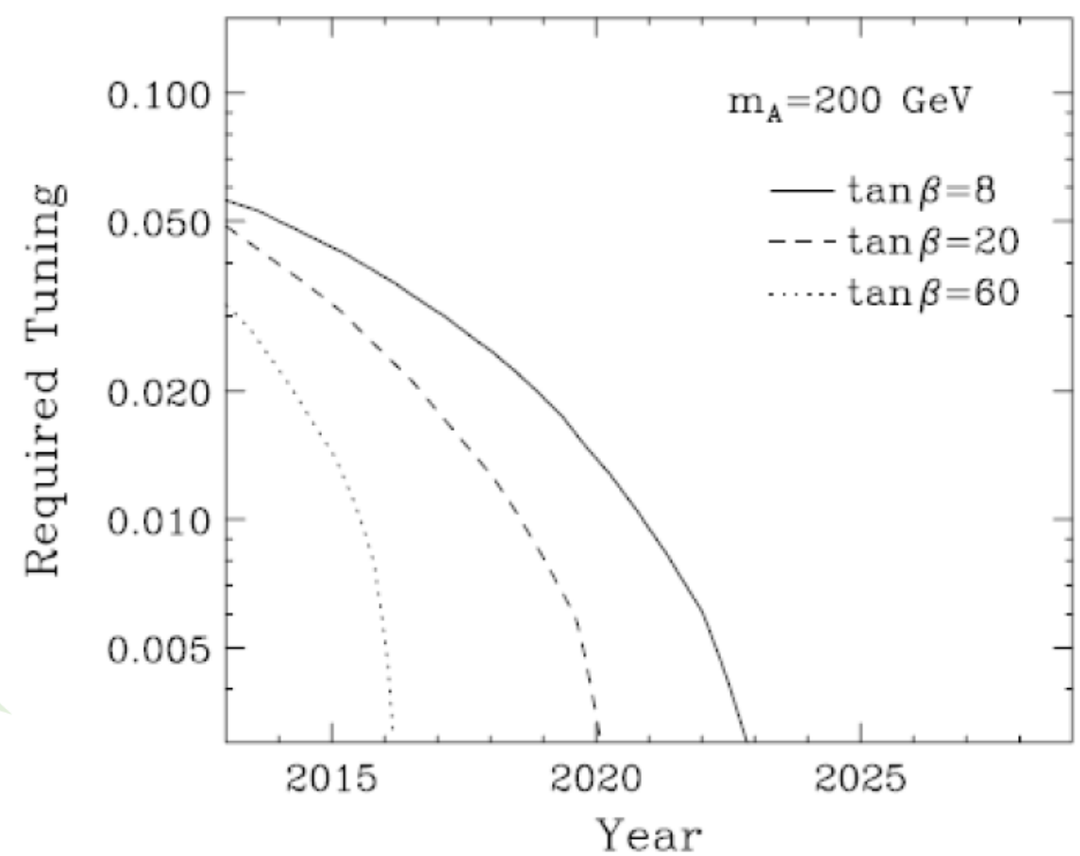

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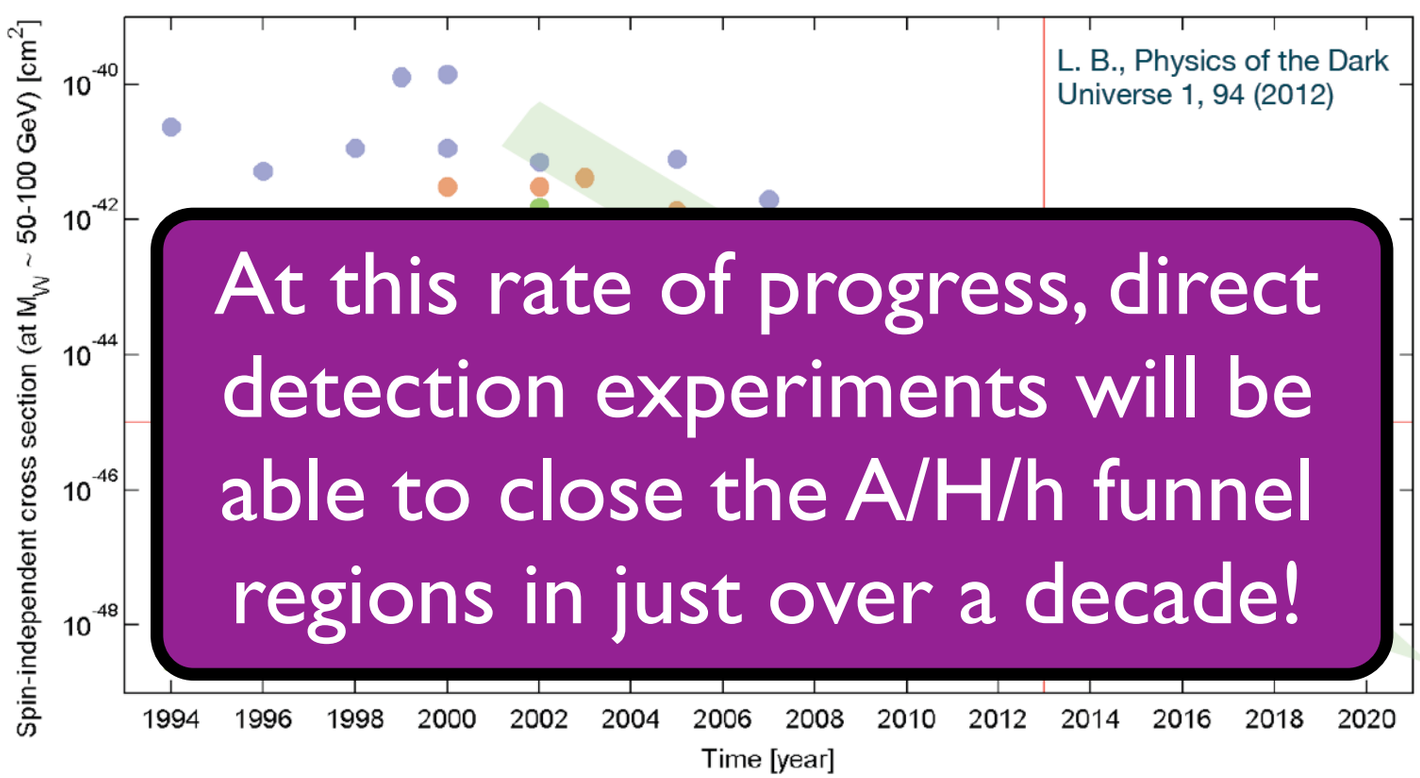
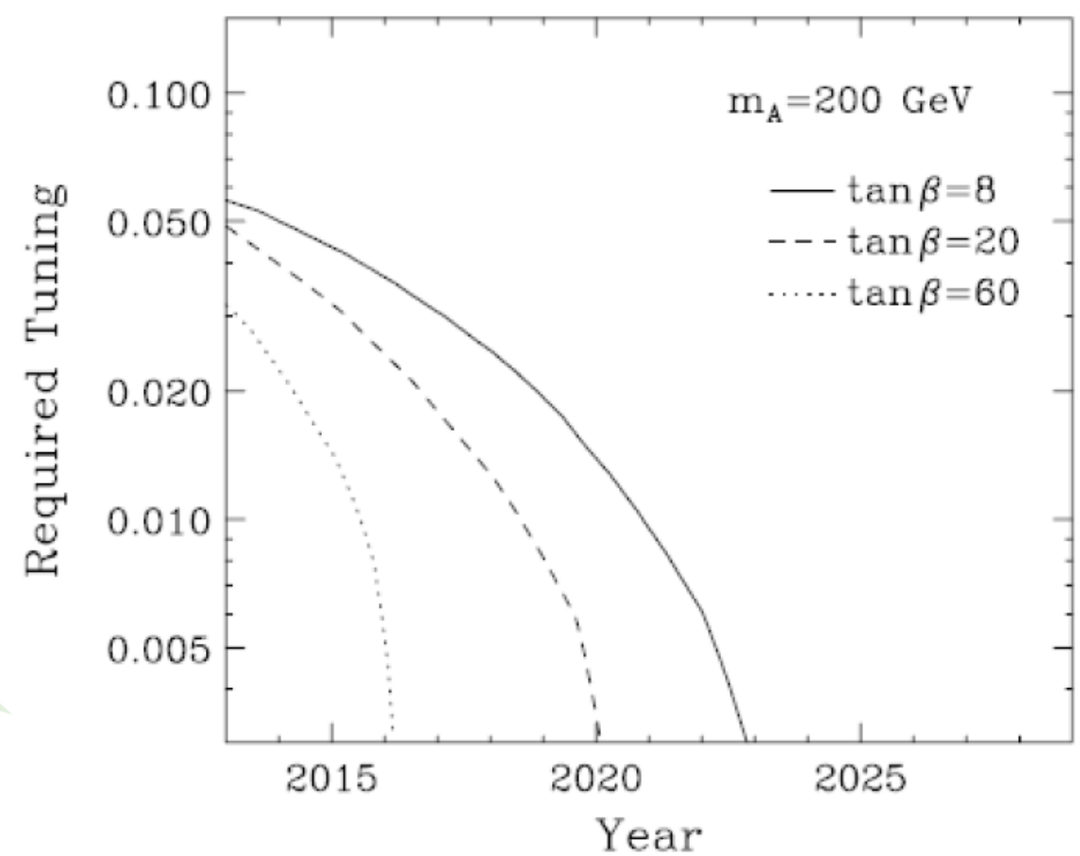


At this rate of progress, direct detection experiments will be able to close the A/H/h funnel regions in just over a decade!



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- Finite distinct ways to observe dark matter:
  - Abundance, Annihilation Today, Decay Today, Production at Colliders, Direct Detection
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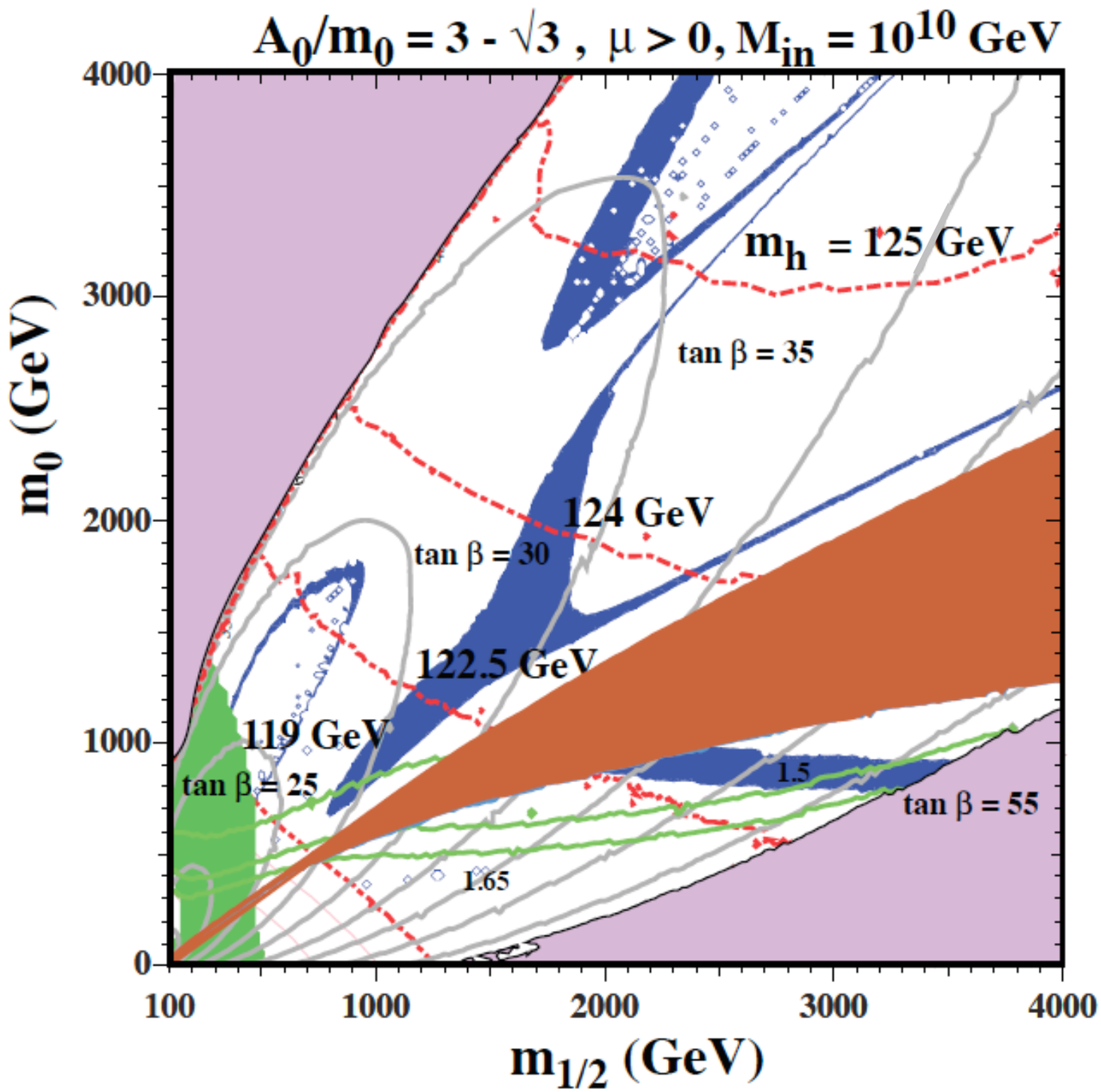
Extra Slides

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)

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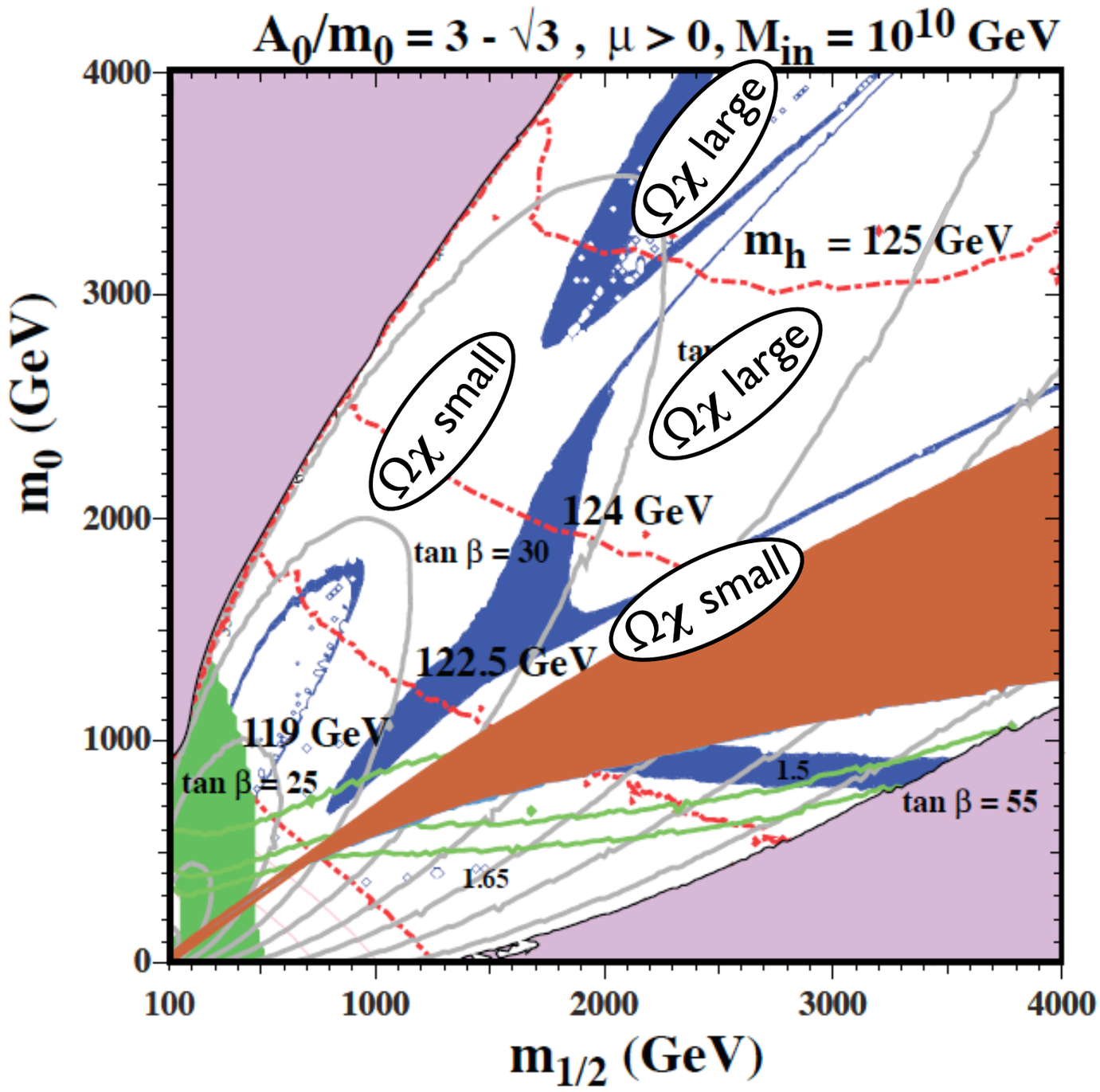

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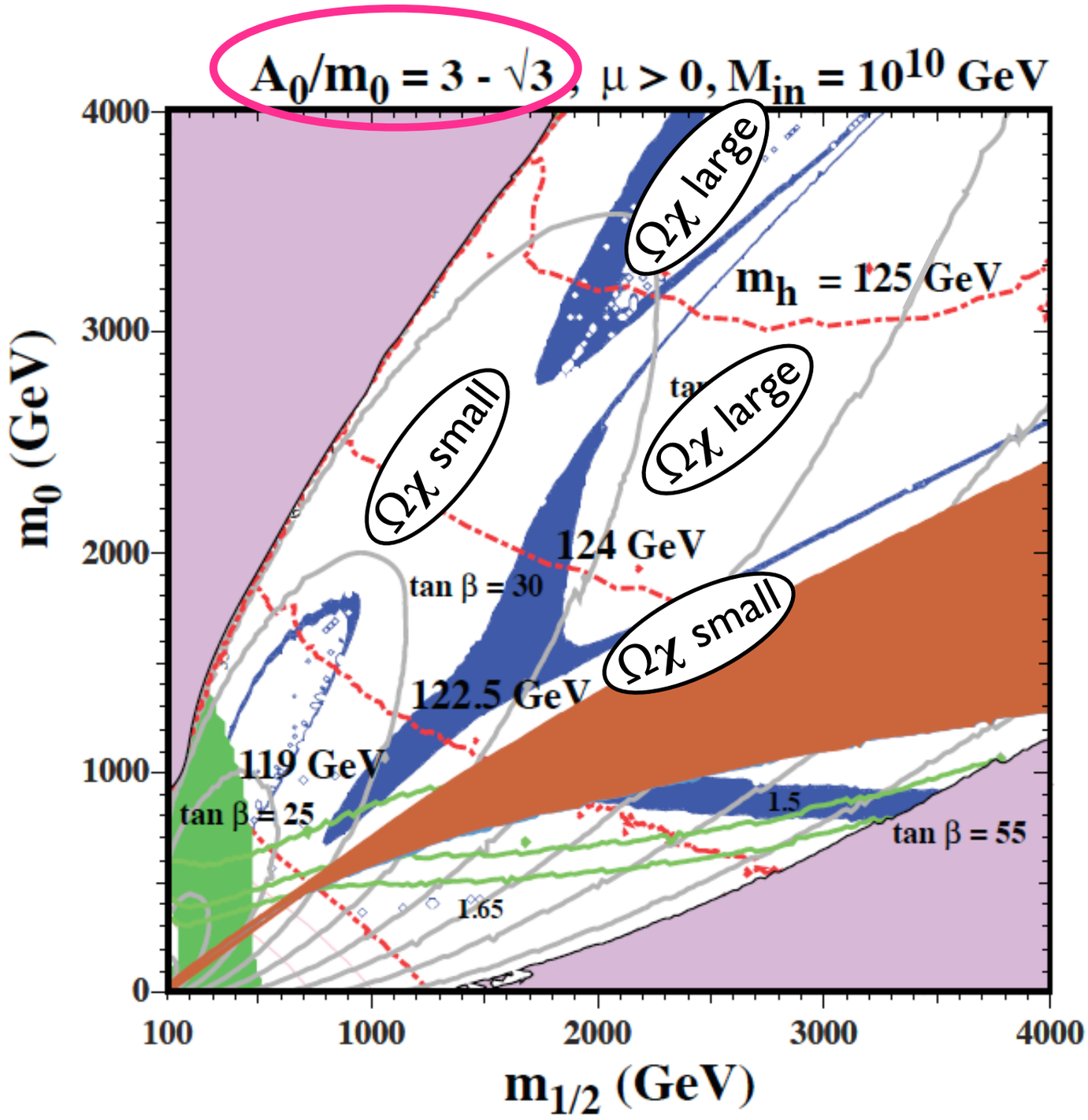

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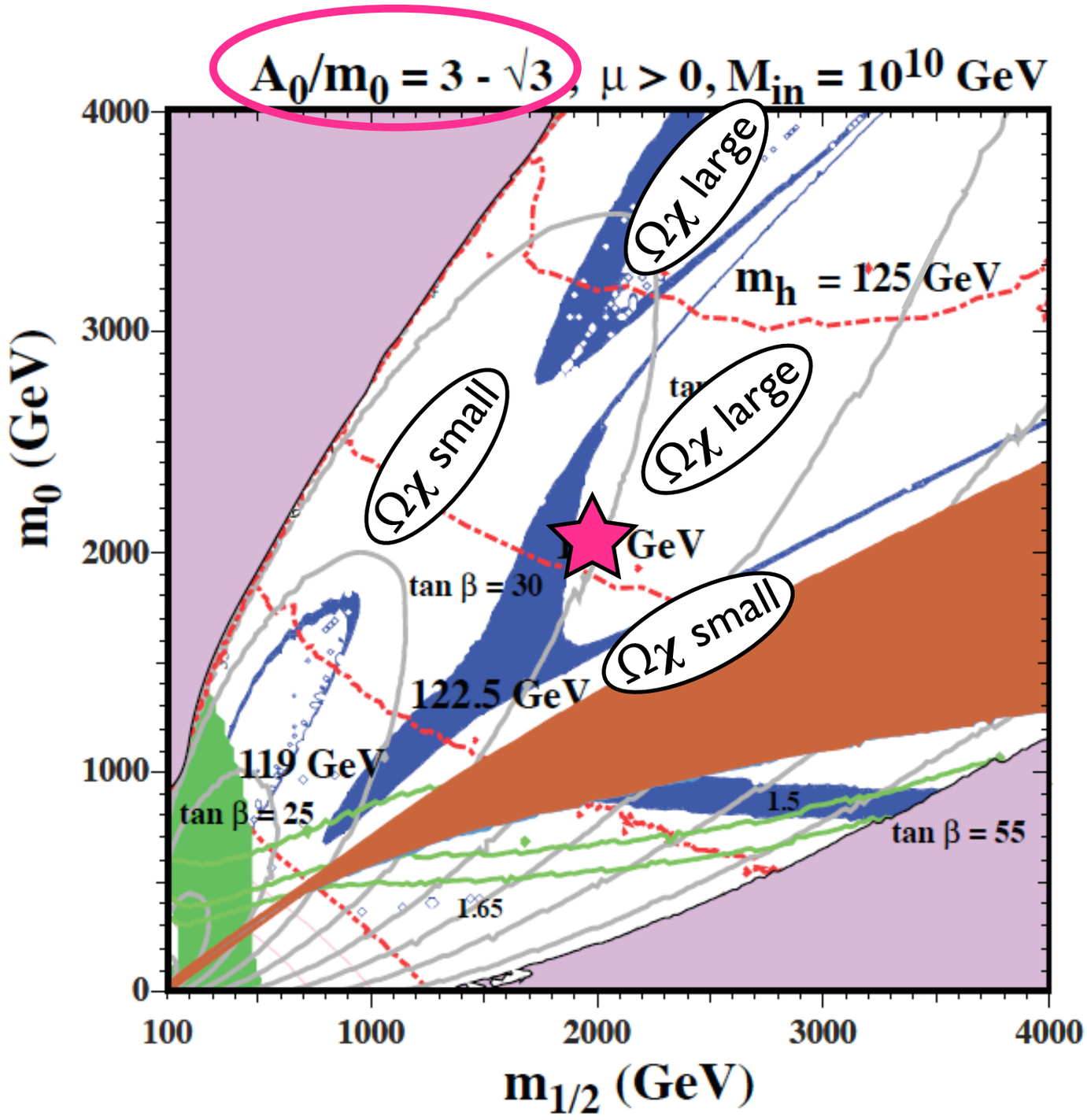

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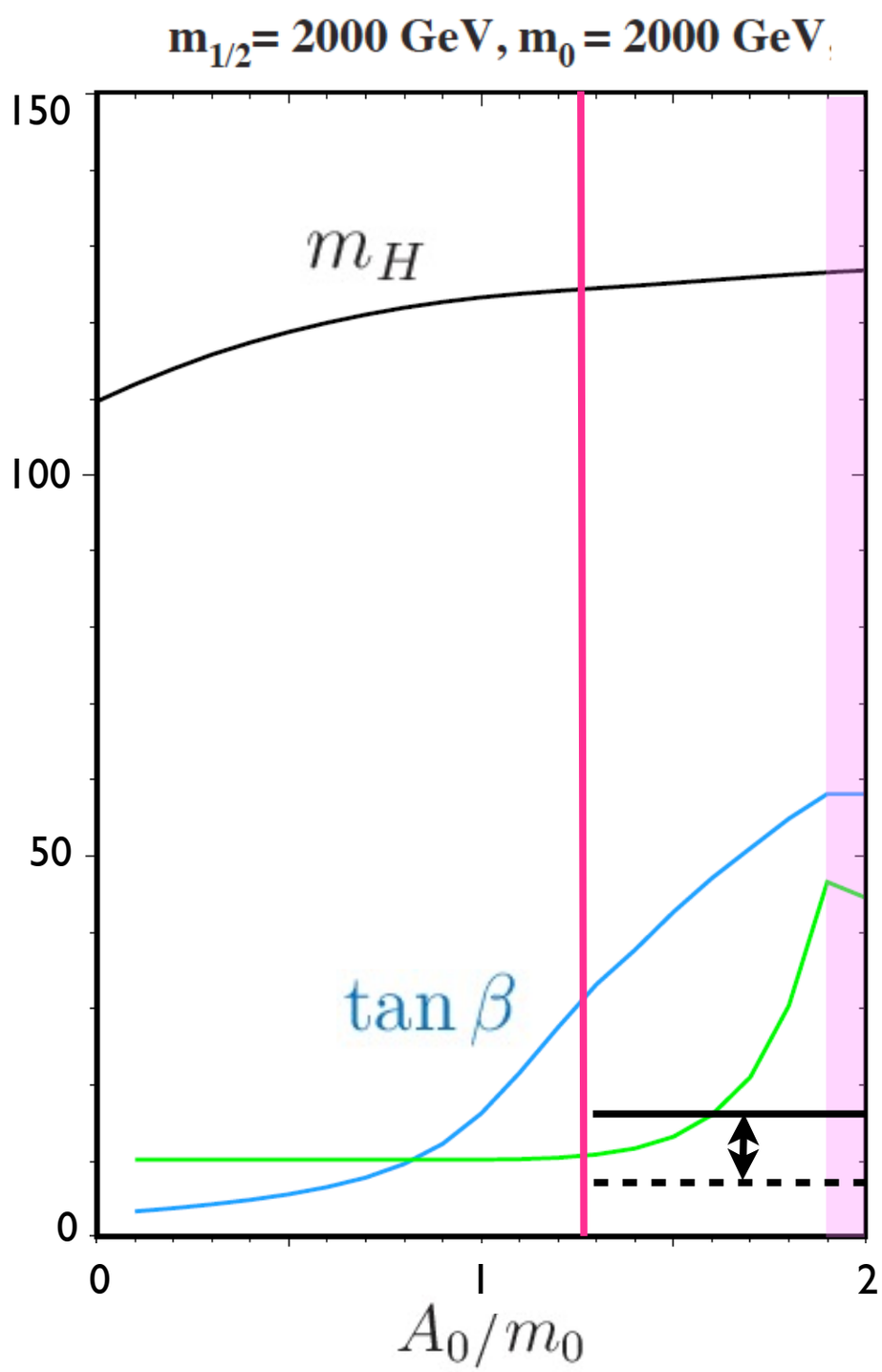

At large tanβ,

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

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

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95% CL

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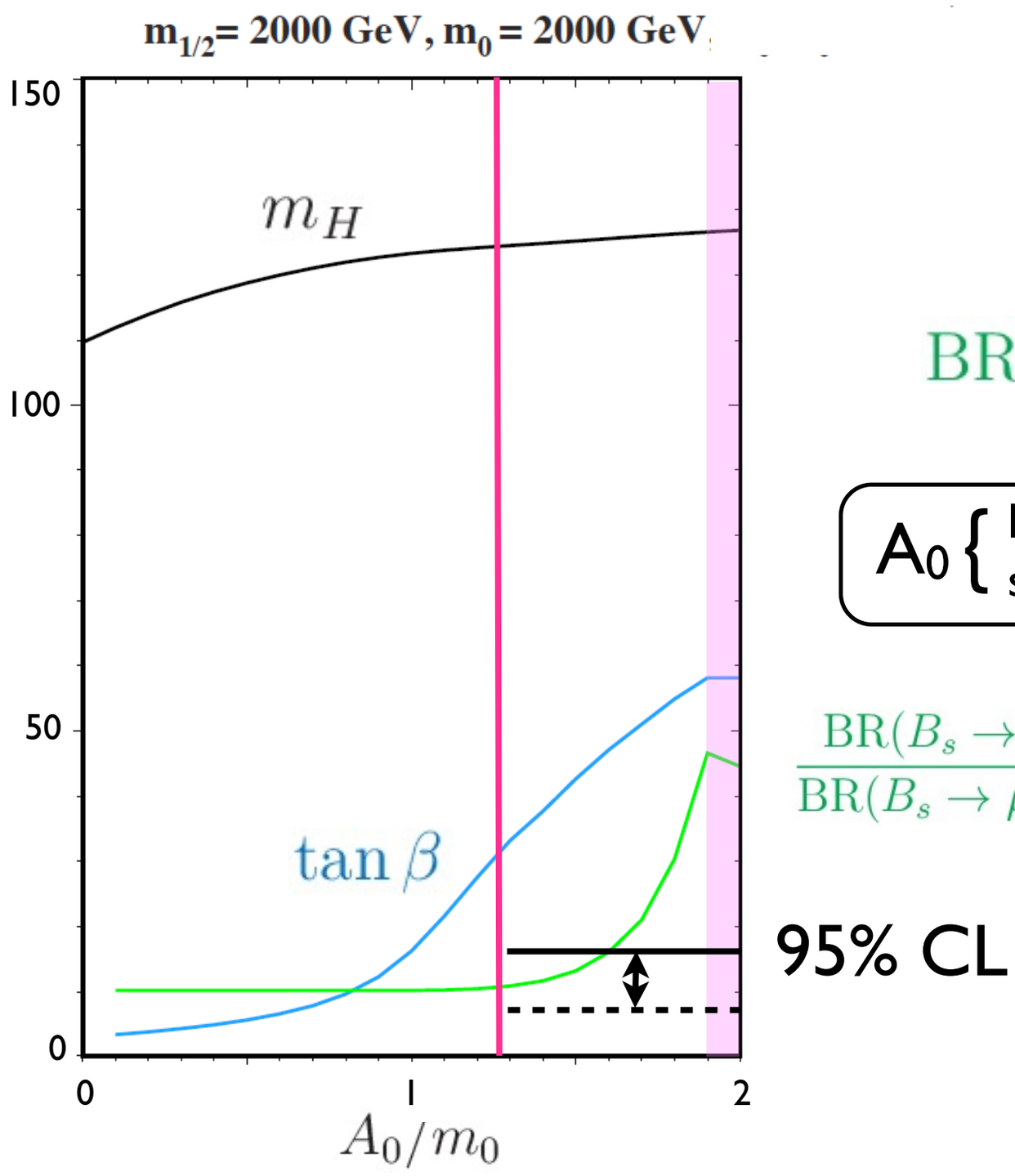

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Polonyi Model seems to be the sweet spot!