Cosmology and the LHC

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at the US ATLAS meeting, Seattle, August 4, 2014

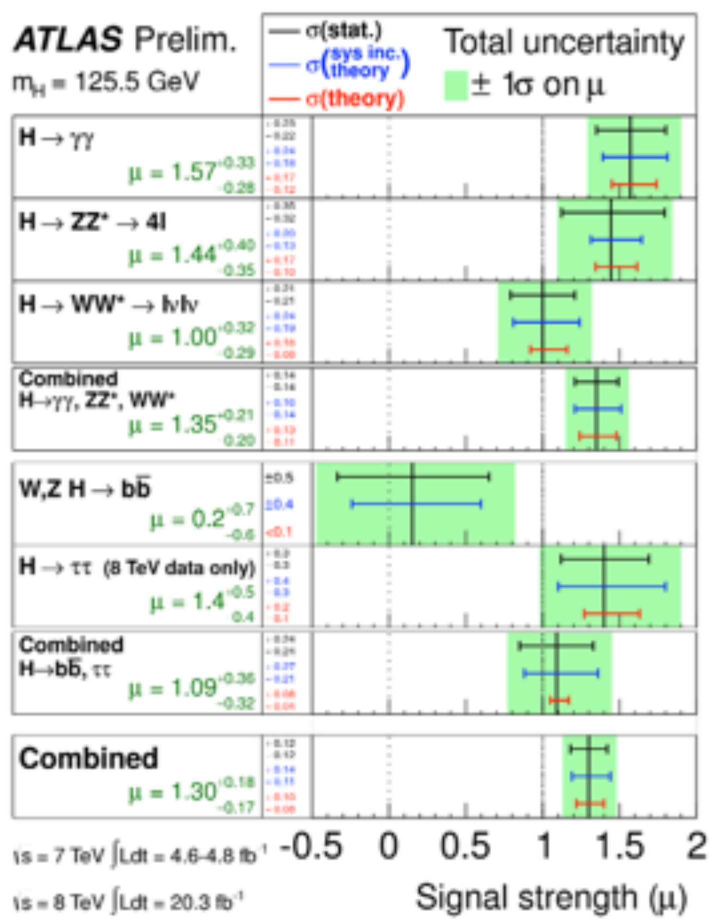
“Cosmology and the LHC”?

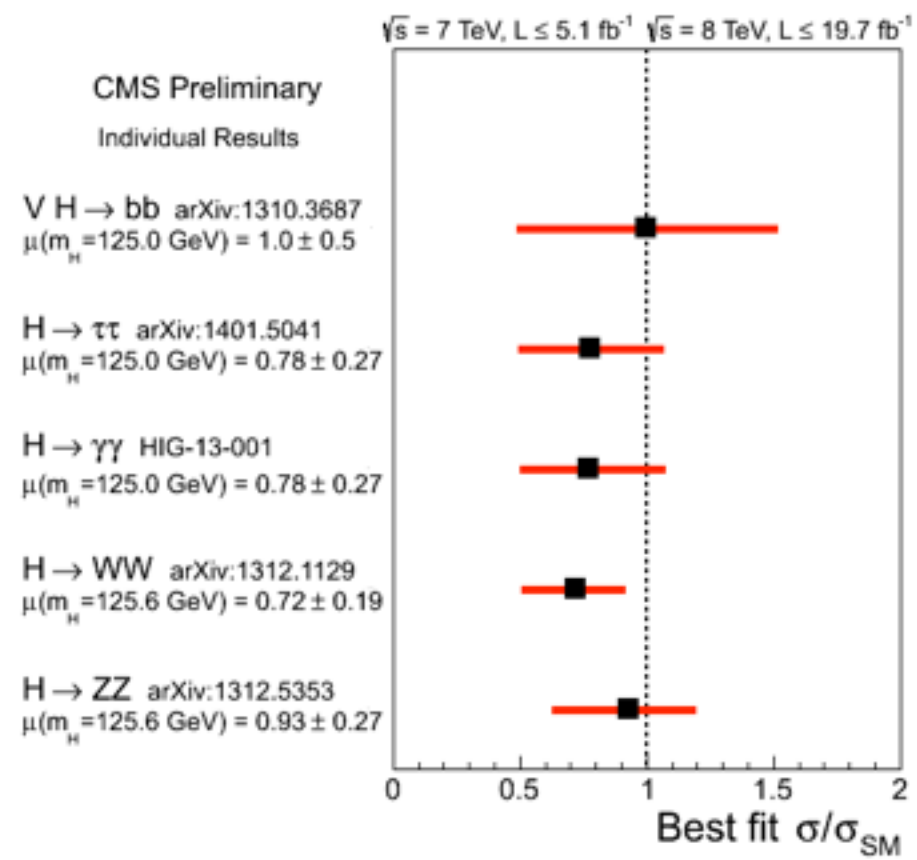
- Big topic! Lots of possible connections
- Since we don’t know anything from *either* colliders or cosmology/astrophysics about **new physics** near TeV scale, hard to say which ideas are most important
- Two possible connections I think are important:
    - Dark matter (can we make it, or related particles, at the LHC)?
    - Electroweak phase transition (what can we learn about it from colliders?)

The Electroweak Phase Transition

Dynamics of Electroweak Breaking

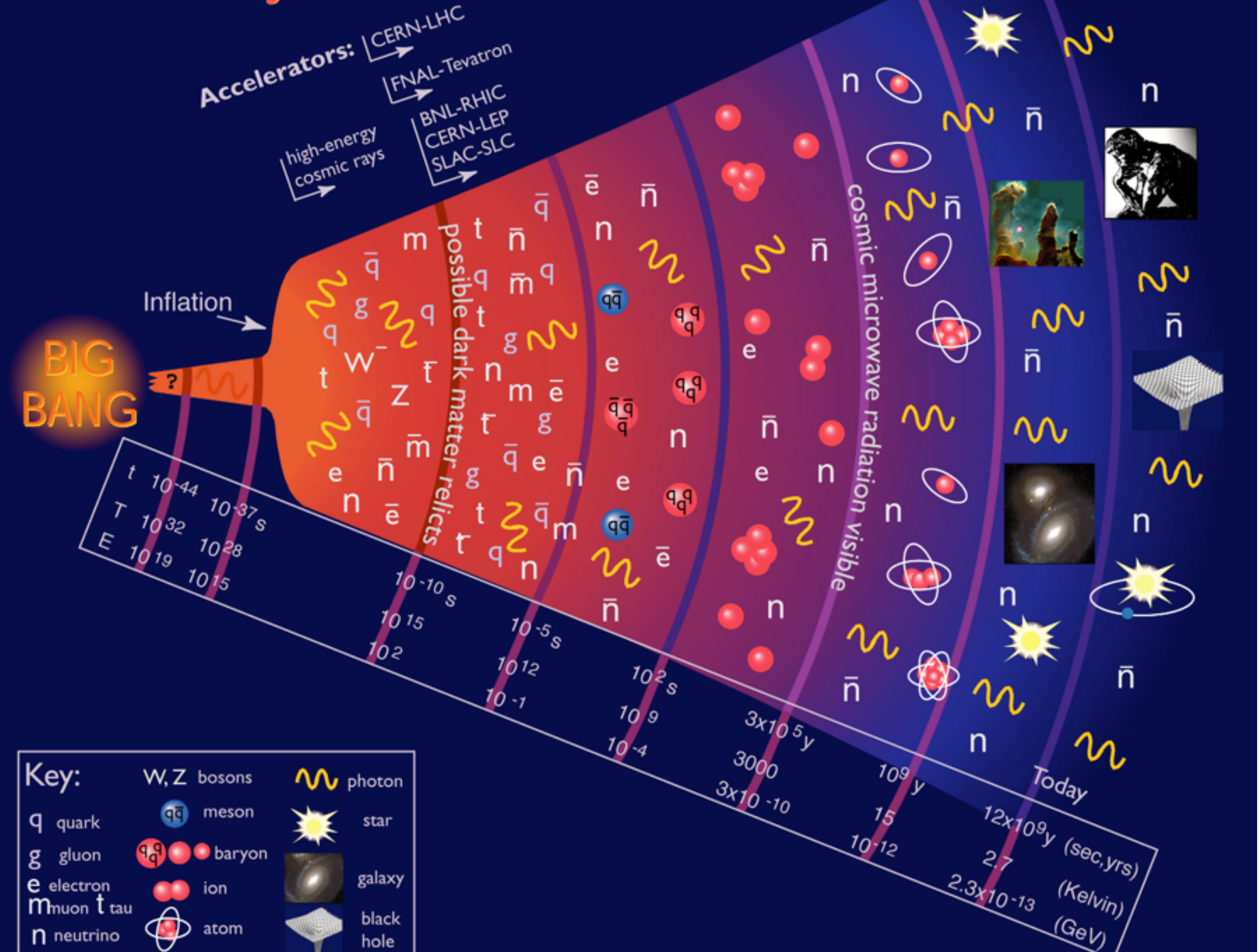
Of course, this is the major LHC discovery so far: it looks like a weakly coupled, SM-like Higgs boson!



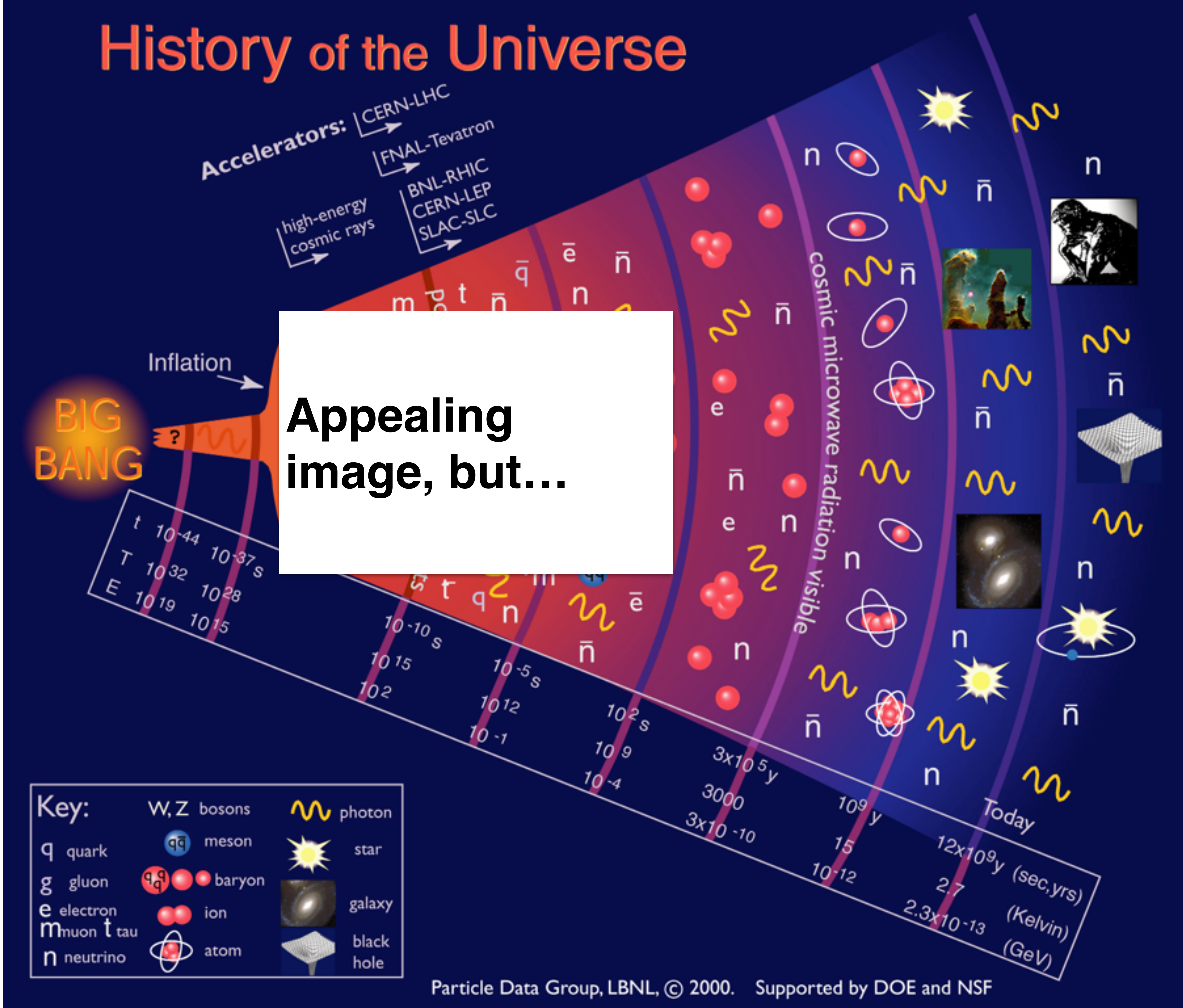


Tempting to extrapolate back and say we know something about the universe at temperatures at or above ~100 GeV.

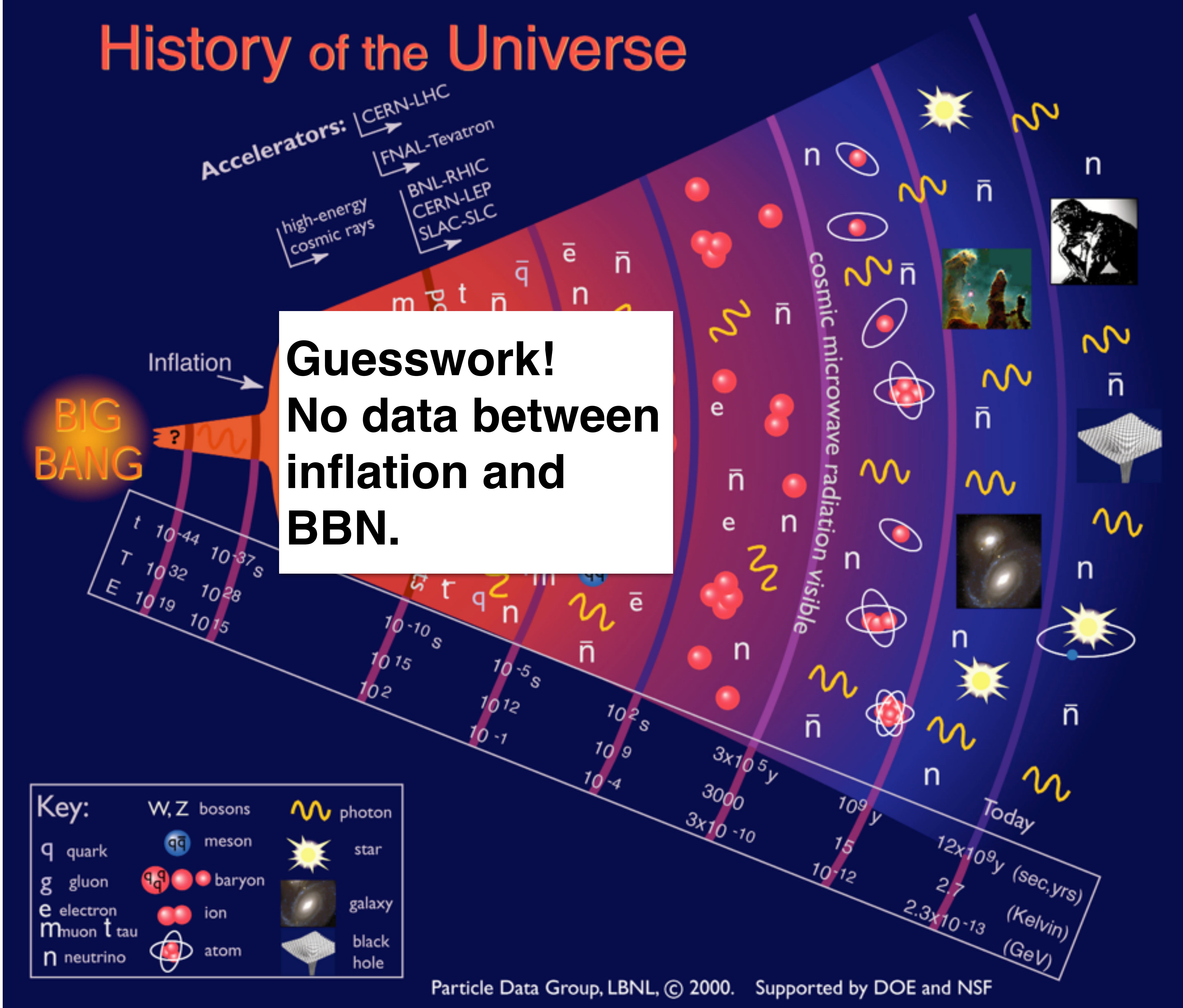
History of the Universe



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



Appealing image, but…



Guesswork!
No data between inflation and BBN.

Caveat: What the LHC *Can't* Tell Us About Cosmology

One sometimes encounters the claim (especially in popular media) that the LHC tells us about what the universe was like when the temperature was ~ 100 GeV.

In detail, this isn't true. For instance: **was most of the energy in the universe in the form of massive particles or of radiation** when the SM plasma had a temperature ~ 100 GeV? Not only do we **not know**, the LHC can't tell us.

Particle with **gravitational strength interactions** and mass ~ 100 TeV decays just before BBN: undetectable at colliders, could have dominated the universe at weak scale.

Higgs Measurements and Cosmology

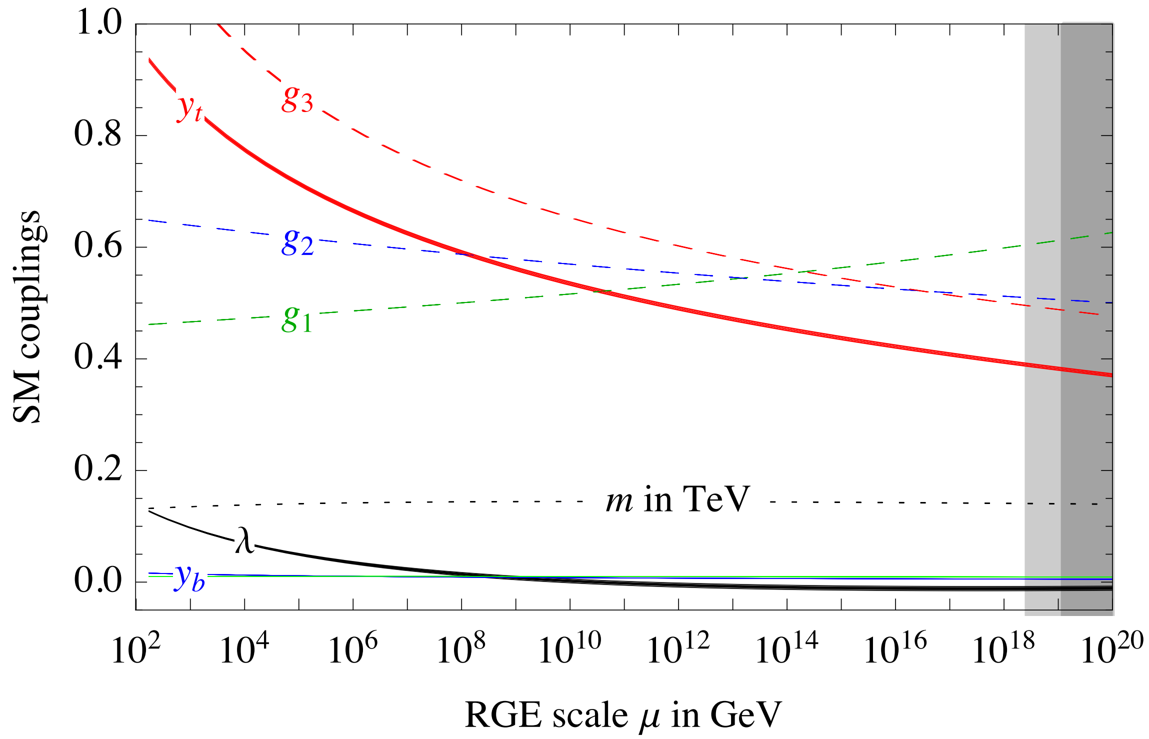
Learning about the Higgs couplings, we might extrapolate:

RG running*:* does the potential have other minima at large field values? Is there a mystery of why we're in *our* minimum?

Finite temperature*:* how does the potential change in a hot environment? What was the phase transition from unbroken to broken symmetry like?

We need ***other*** data to tell us what the early universe was like (e.g. matter or radiation-dominated, what scale inflation happened at). But LHC (+ILC, FCC-ee…?) provides key data.

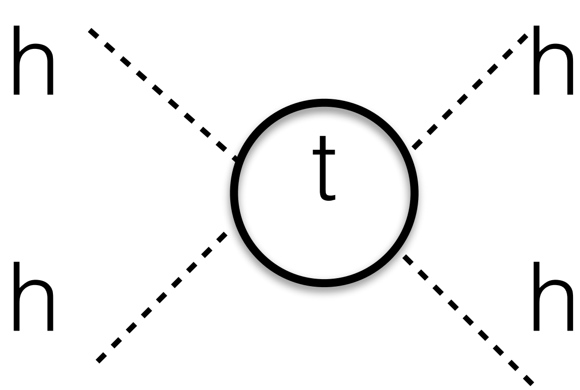
Higgs Potential Instabilities



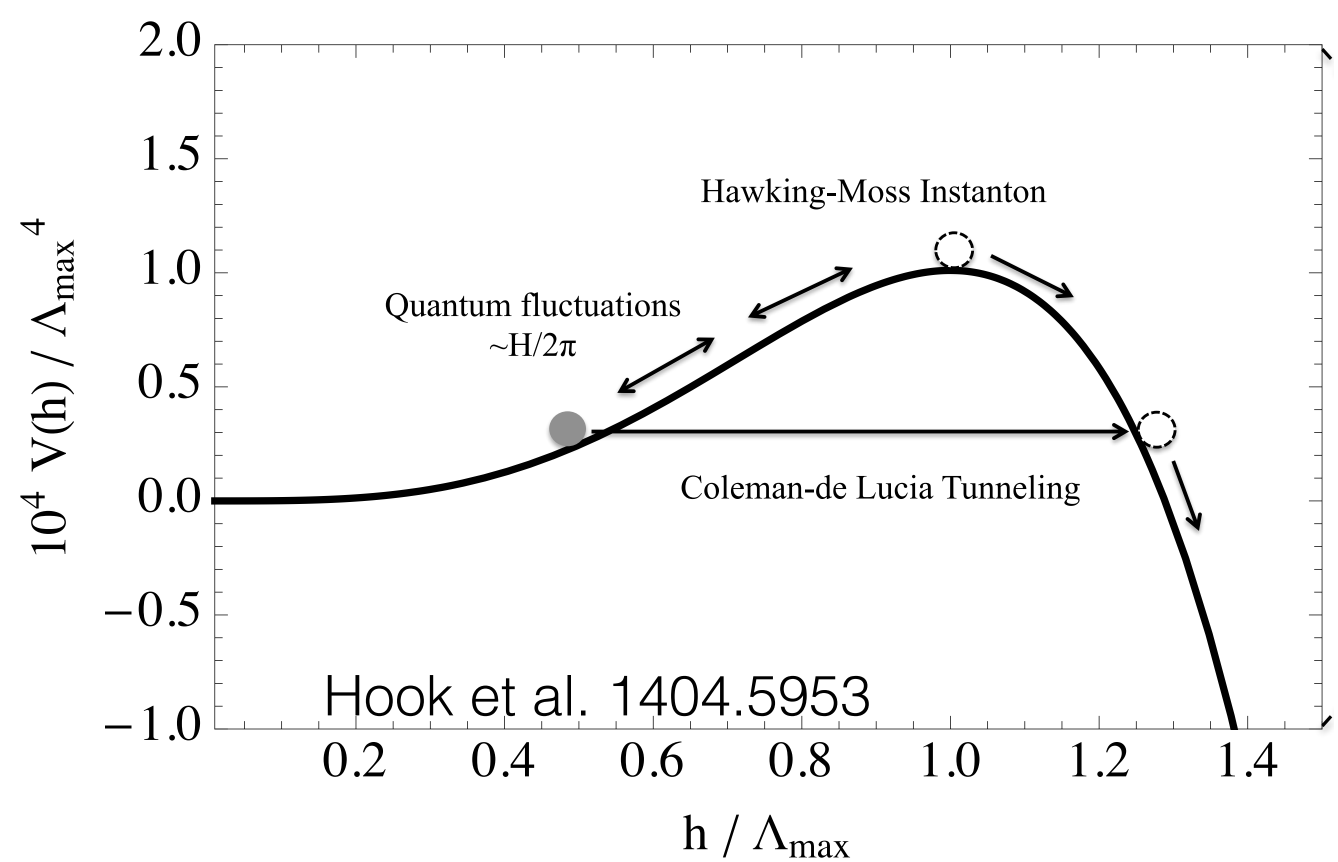
Buttazzo et al., 1307.3536

Running SM couplings: the big top Yukawa generates a rapid decrease in λ(μ).

V(h) ~ λ(μ=h) h⁴.



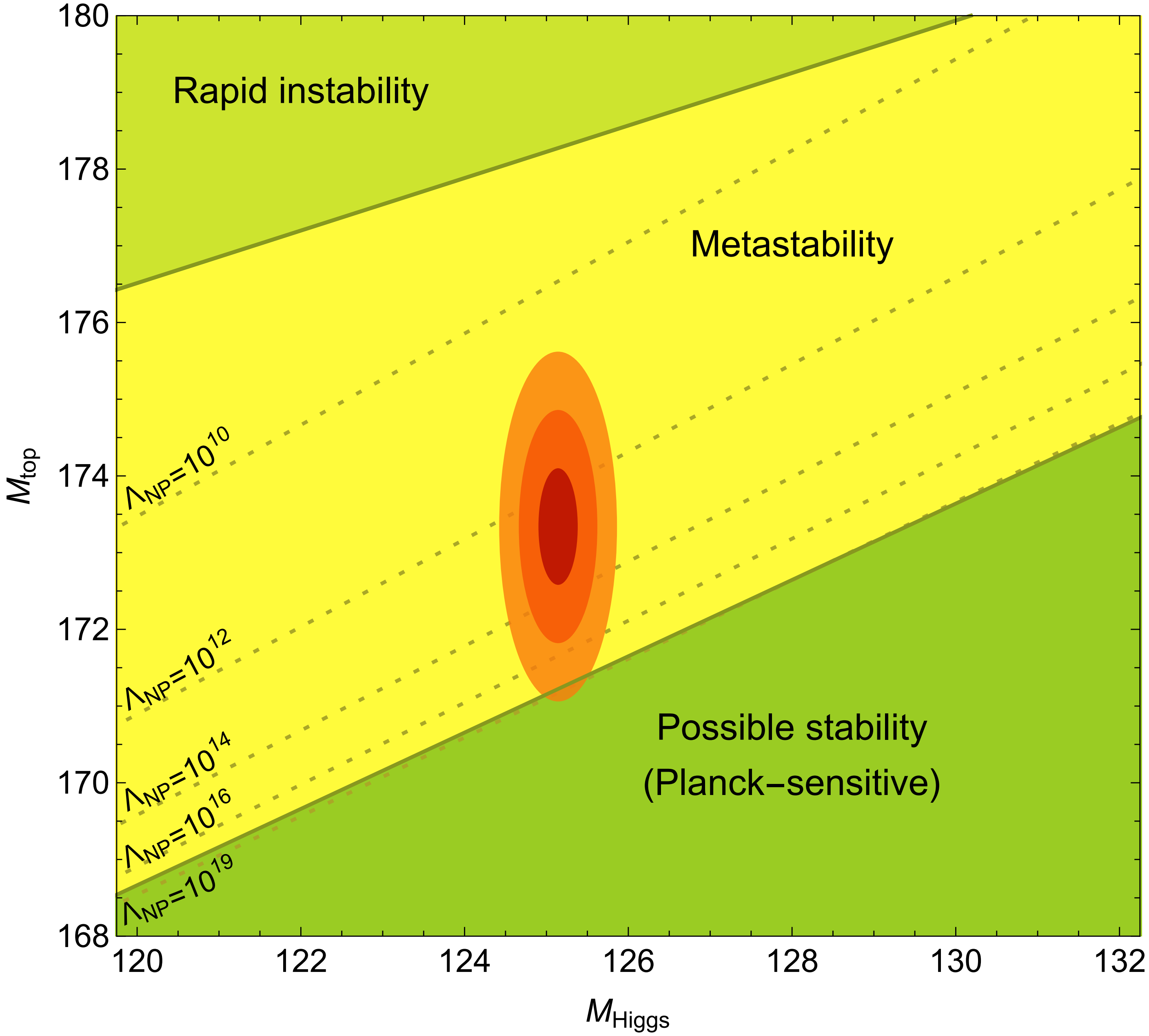
Unstable at "h"~10^9 GeV. (Careful about gauge dependence!)



Hook et al. 1404.5953

Higgs Potential Instabilities

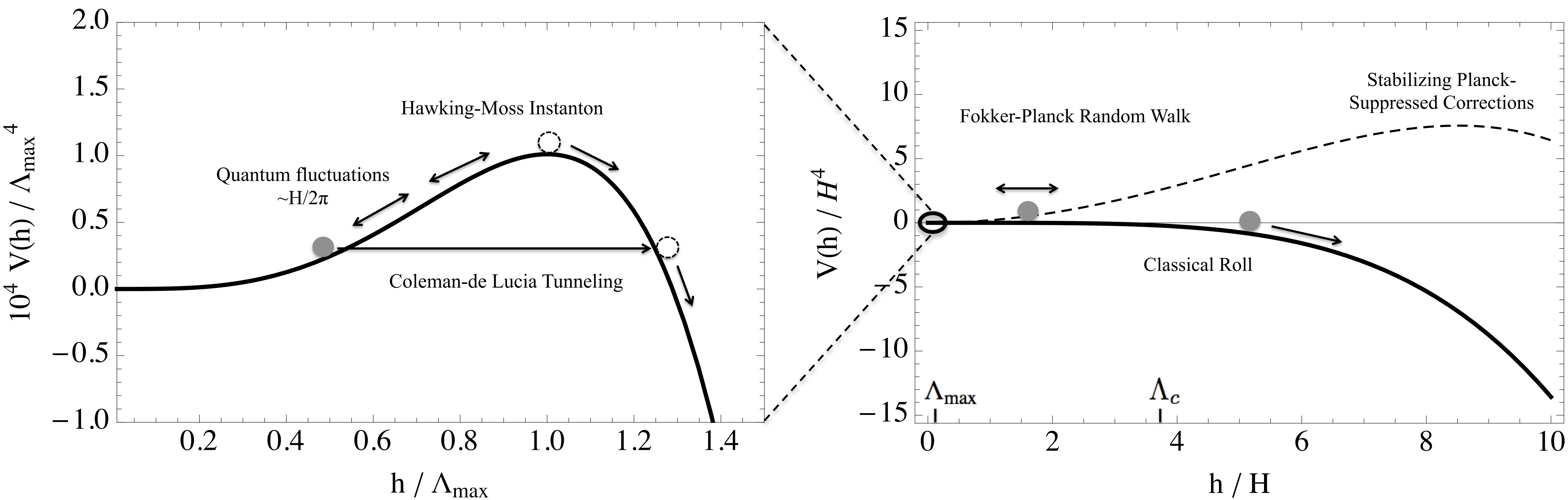
Scale of new physics: $\mathcal{O}_6 \equiv \frac{1}{\Lambda_{\rm NP}^2} h^6$



New result from Anders Andreassen, Will Frost, and Matt Schwartz (1408.tonight): careful treatment of gauge dependence in effective potential calculation. Rules out absolute stability ***unless*** new physics below $\sim 10^{12}$ GeV. (Exp. sensitive to top mass!)

Higgs Potential Instabilities

During inflation: fields lighter than ~ Hubble have quantum fluctuations of order Hubble. If Hubble >> scale of Higgs instability, Higgs can fluctuate over the hill! But: order-one Planck-suppressed operators remove the problem.



Hook, Kearney, Shakya, Zurek 1404.5953

Higgs Potential Instabilities: Lesson?

If we extrapolate the Standard Model to very high scales, it looks like it's **consistent** cosmologically: we can safely live in our vacuum for a long time.

But it's surprisingly close to the absolute stability boundary. Is this telling us anything deep? I haven't yet seen any suggestions of what it could mean that appear compelling to me, but it's something to keep an eye on.

Electroweak Phase Transition

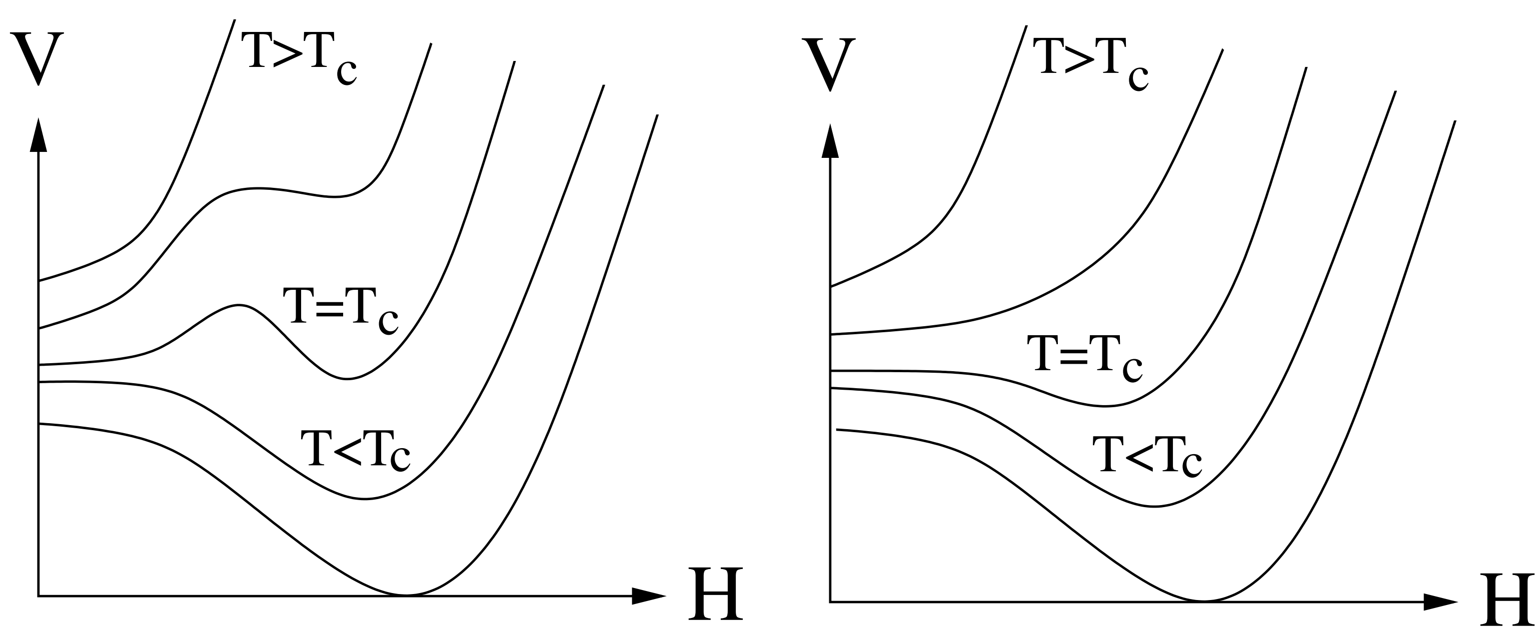
At finite temperature, the Higgs potential changes. Particles in the environment whose masses depend on the Higgs VEV will influence the Higgs field.

Qualitatively: becomes thermodynamically preferred to put the VEV at zero, because exciting all the massive particles at nonzero VEV is expensive.

Calculable (Dolan, Jackiw; Weinberg; 1974).

Electroweak Phase Transition

One major question: was the transition first-order, or not?



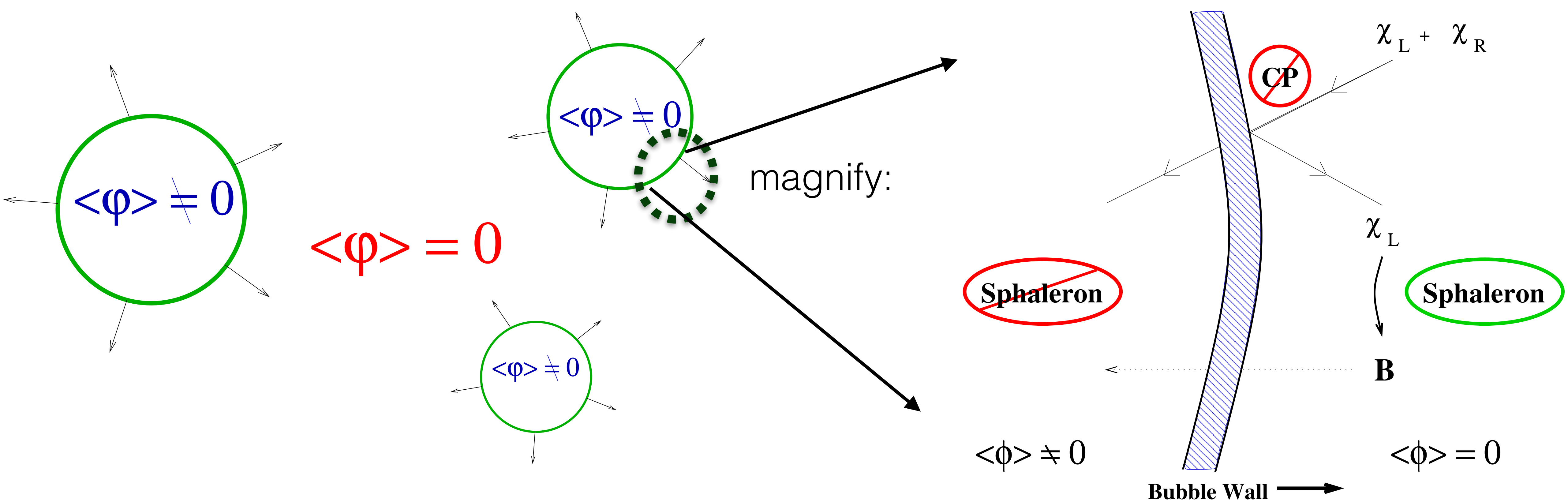
first order **second order**

Figure from Cline, hep-ph/0609145

For strongly first-order transition, need a cubic term $\sim TH^3$ to dominate over terms $\sim T^2H^2$. Turns out in SM this only happens for very light Higgs bosons.

Electroweak Baryogenesis

Physics happens at the walls of bubbles of EWK-breaking vacuum percolating within the EWK-preserving surroundings:

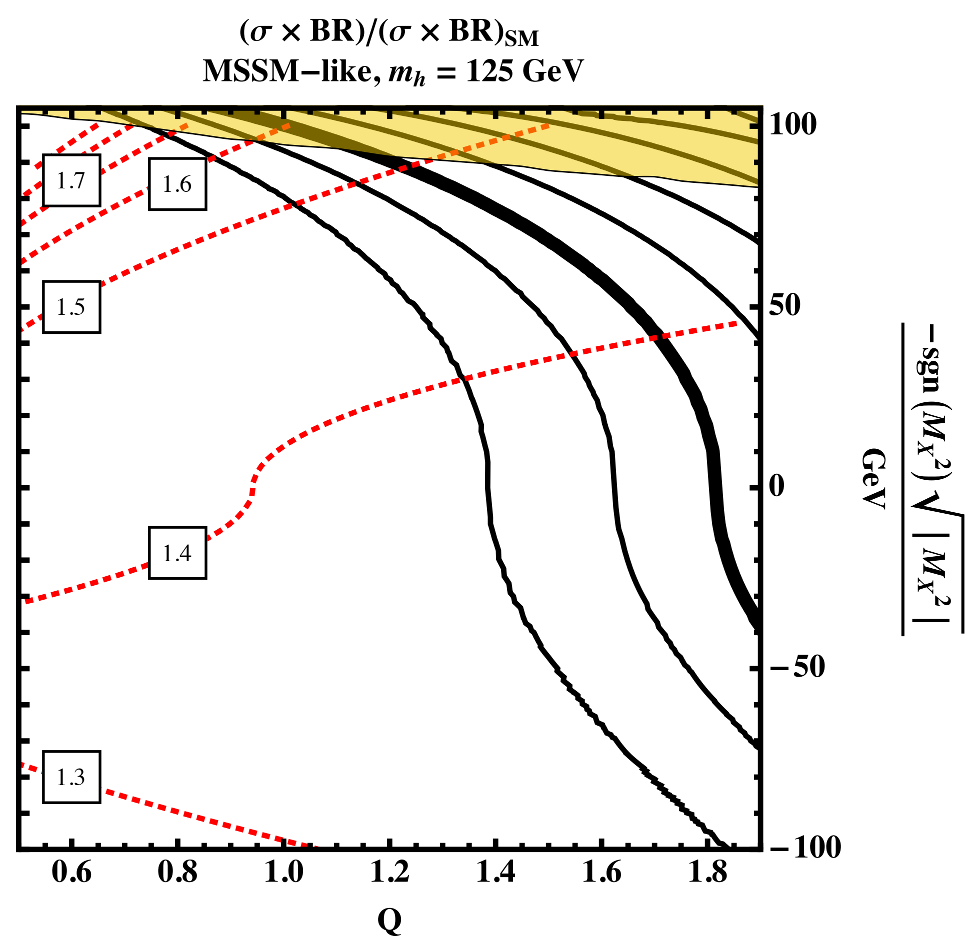


Figures from review by David Morrissey and Michael Ramsey-Musolf, arxiv: 1206.2924. Proposed by Kuzmin, Rubakov, Shaposhnikov in 1985. See e.g. work by Cohen, Kaplan, Nelson 1990/1; MSSM: recent reviews Carena, Nardini, Quiros, Wagner 0809.3760; 1207.6330

Electroweak Phase Transition

A strongly first-order phase transition requires **new physics that substantially alters the finite-temperature Higgs potential**. Either Higgs couples differently to SM particles or couples to beyond-SM particles. Either way, precision Higgs tests should see effects!

Cohen, Morrissey, Pierce 1203.2924
Effect of color triplet on Higgs potential.
Thick black line: strongly first-order transition.
Red contours: enhanced gluon fusion to diphoton rate.
Q: quartic $|H|^2|stop|^2$ coupling.



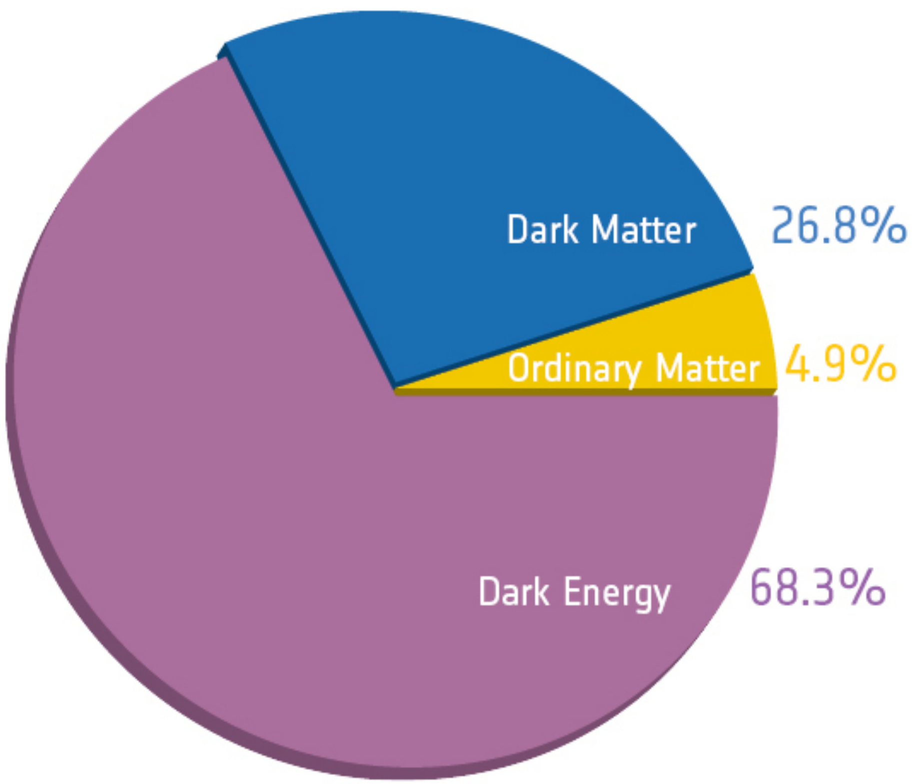
Electroweak Phase Transition

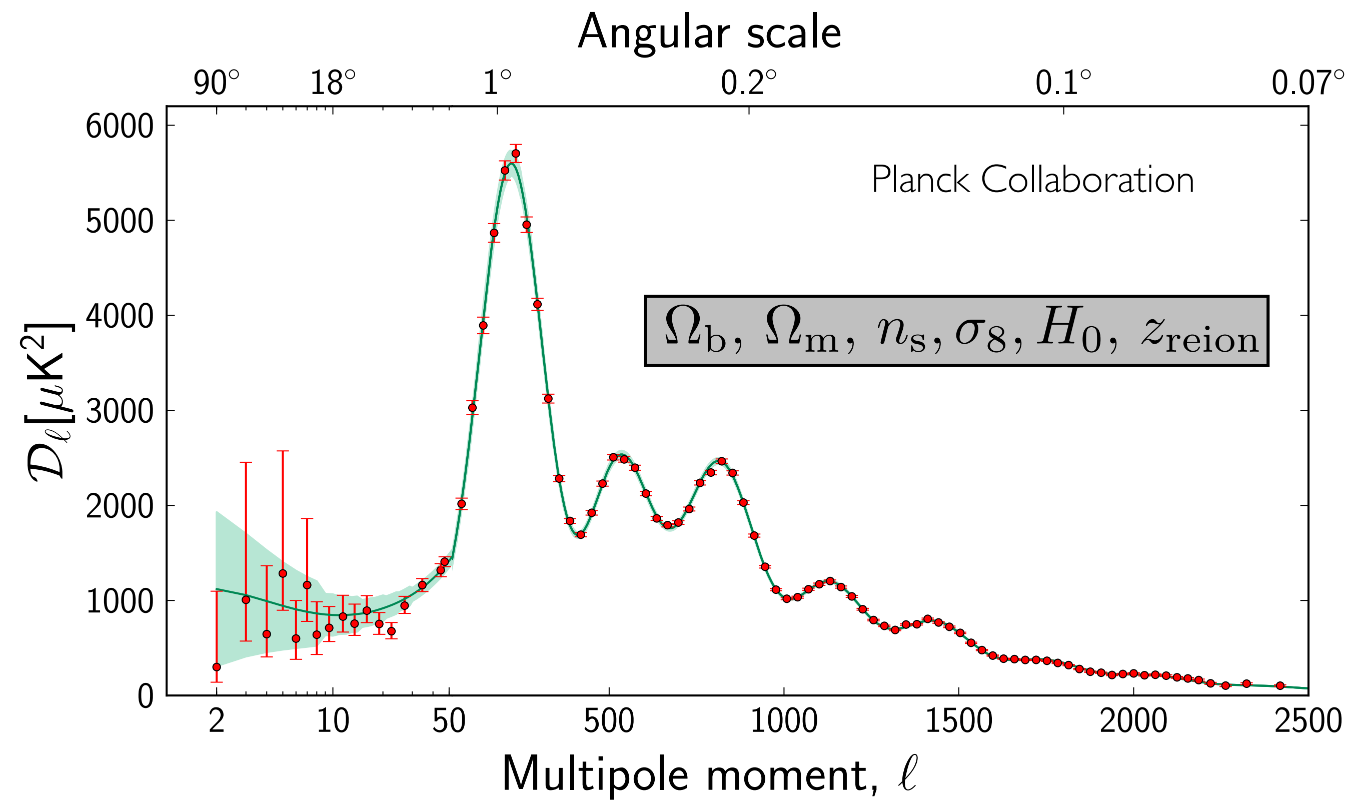
Given that naturalness is inherently fuzzy (do we worry with factor of 100 tuning? 1000? 10,000?), it's interesting to think about questions we can get a **sharp** answer to with future colliders.

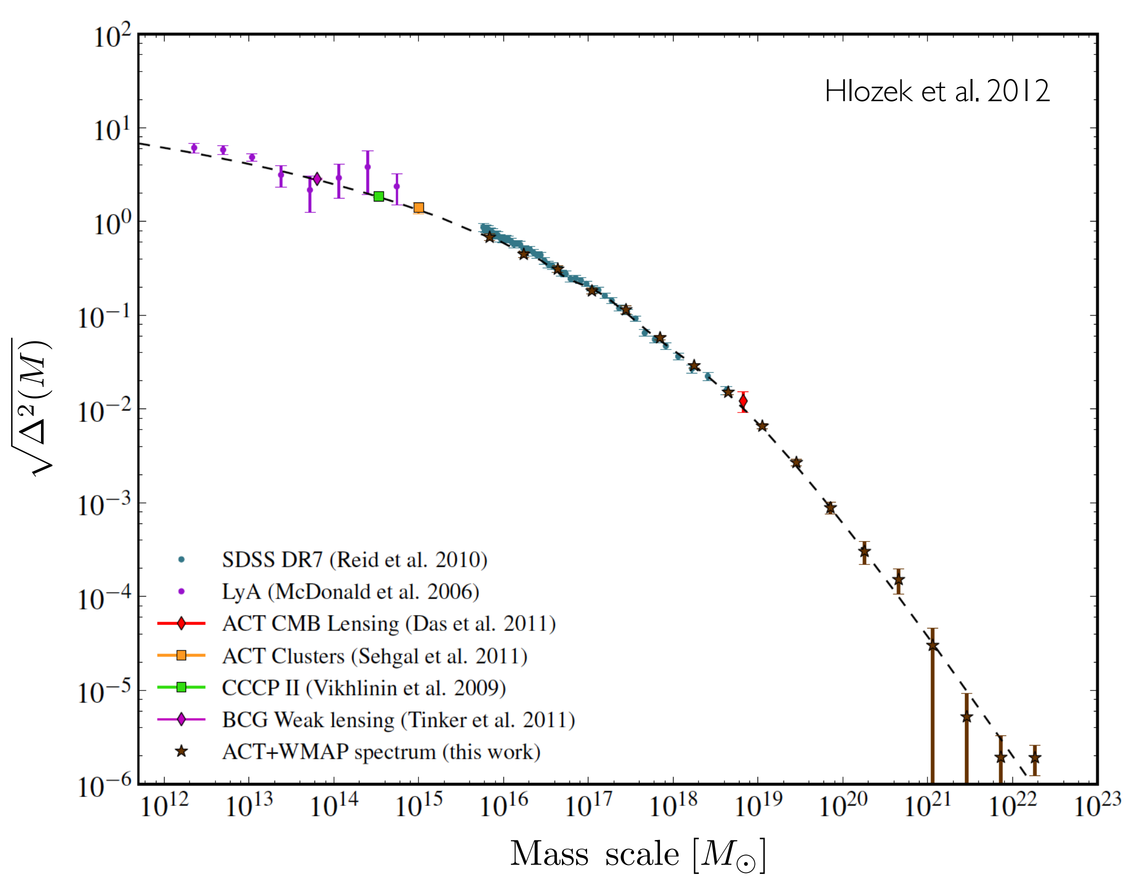
"Is the electroweak phase transition first-order?" seems like a question that the LHC can *almost* settle (looks like "no" so far), and conceivable future colliders probably can definitively settle.

Dark Matter and the LHC

What is Dark Matter?







It's most of the mass in the universe, gives precise fits to structure formation and the CMB.... But what *is* it?

Why Dark Matter and LHC?

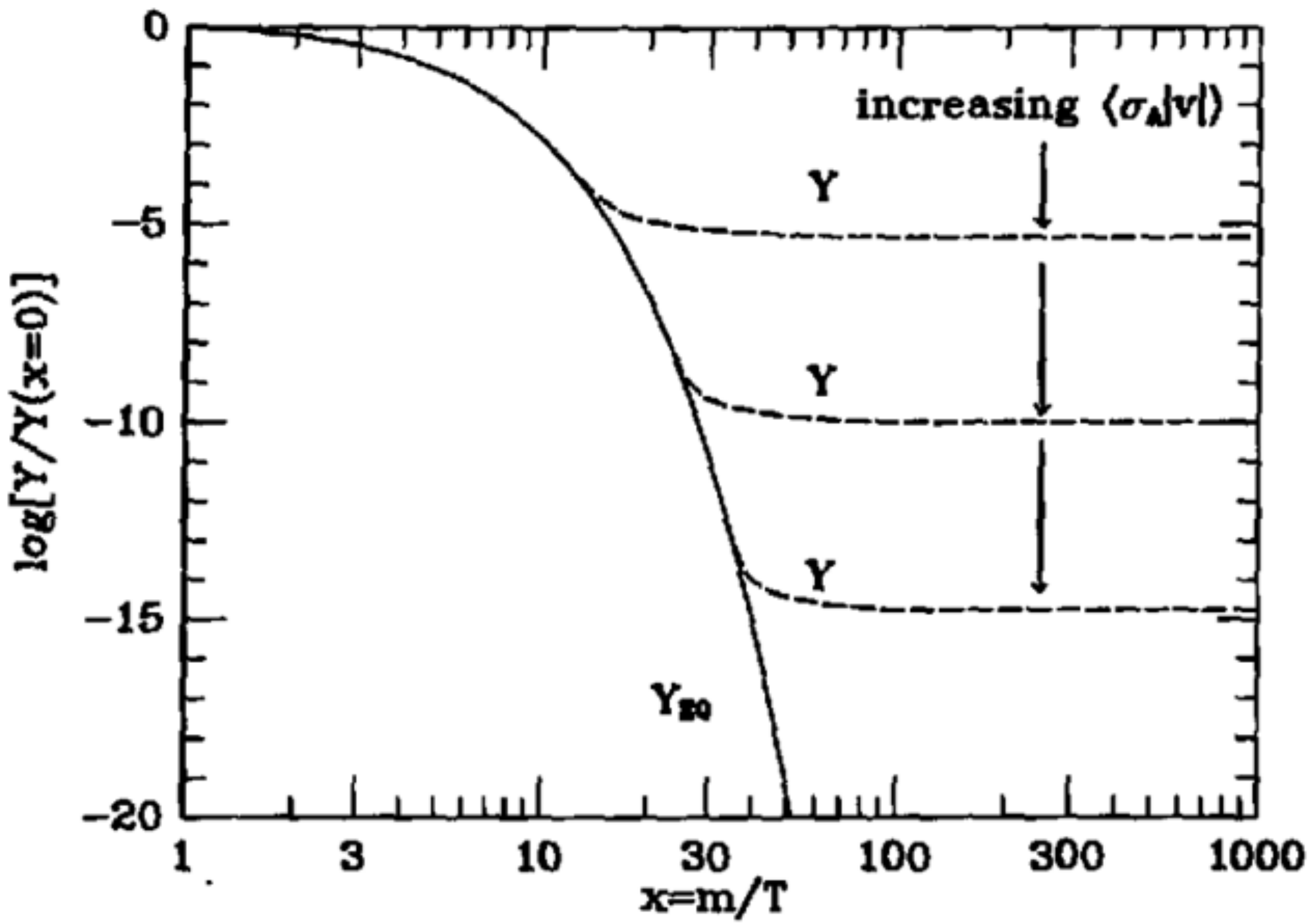
It's entirely possible that DM interacts with us only gravitationally, or otherwise through very weak forces (e.g. axions). Why should we think it might have anything to do with the LHC?

Three (not necessarily mutually consistent) semi-empirical motivations for DM being in reach colliders:

1. "WIMP miracle"
2. Coincidence of DM and baryon abundances
3. Self-interacting DM hints

Thermal Freezeout

Dark matter in equilibrium with the SM tracks thermal abundance until the Hubble expansion is faster than the interactions

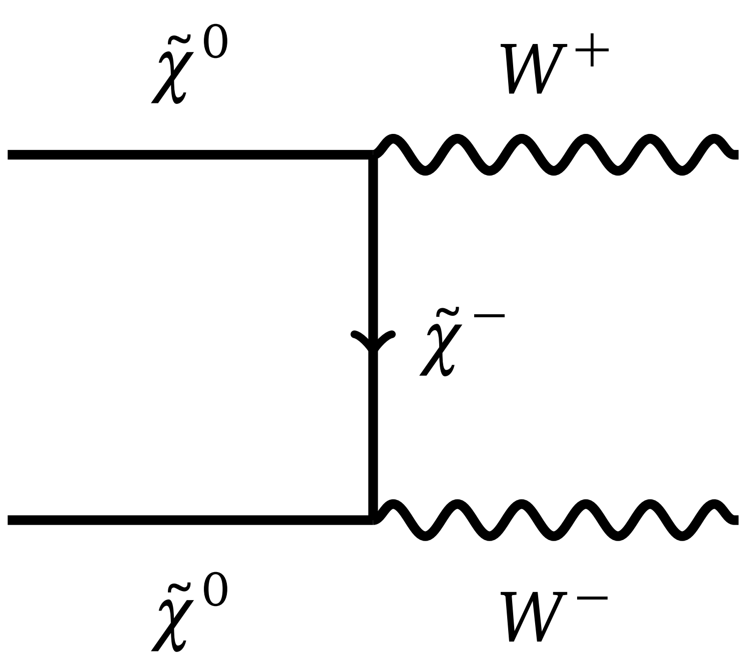


$$\Omega_{\rm DM}h^2 \approx 0.1 \left(\frac{3\times10^{-26}\ {\rm cm}^3/{\rm s}}{\langle\sigma v\rangle}\right).$$

"WIMP miracle"

MSSM Dark Matter

Neutralinos: superpartners of photon, Z, and Higgs.



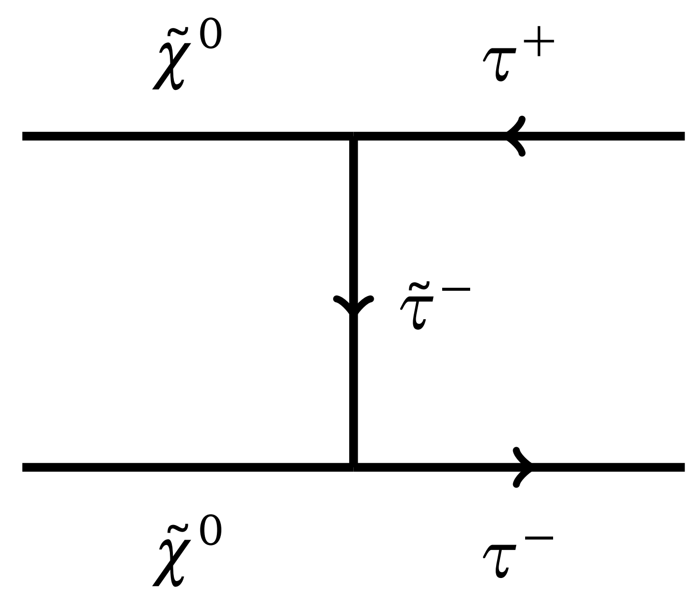
Wino and higgsino: in SU(2) multiplets; can annihilate a lot.

Thermal relic abundance is underpopulated unless they're heavy (about 1 TeV for higgsinos or 3 TeV for winos), e.g.:

$$\langle \sigma v(\chi\chi \to W^+W^-) \rangle \approx 3 \times 10^{-24} \frac{\mathrm{cm}^3}{\mathrm{s}} \text{ for } m_\chi \approx 140 \text{ GeV}$$

MSSM Dark Matter

Bino: overpopulates, unless slepton is very light or degenerate within 5% for coannihilation.



Viable MSSM dark matter:

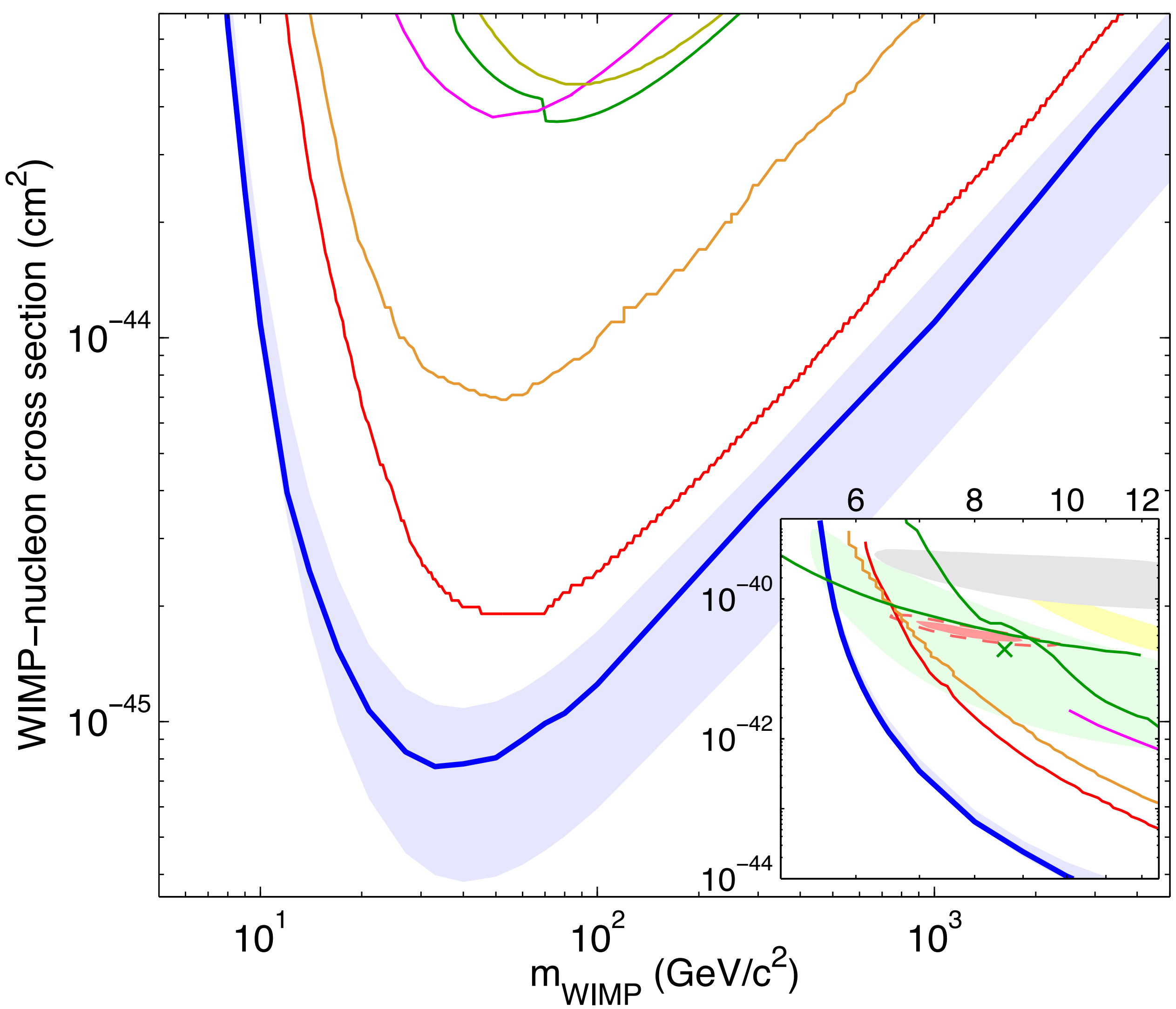
- **heavy** (bottom of spectrum at 1 or 3 TeV)
- **coannihilation** to boost relic abundance of a mostly-bino state
- delicate **mixing** of wino/higgsino and bino to get thermal abundance (“well-tempered”)
- **non-thermal relic abundance**

Begins to look like less of a miracle after all.

DM Complementarity

LUX bounds are ruling out WIMP-nucleon cross sections of around 10^{-45} cm^2. What does this mean?

1310.8214

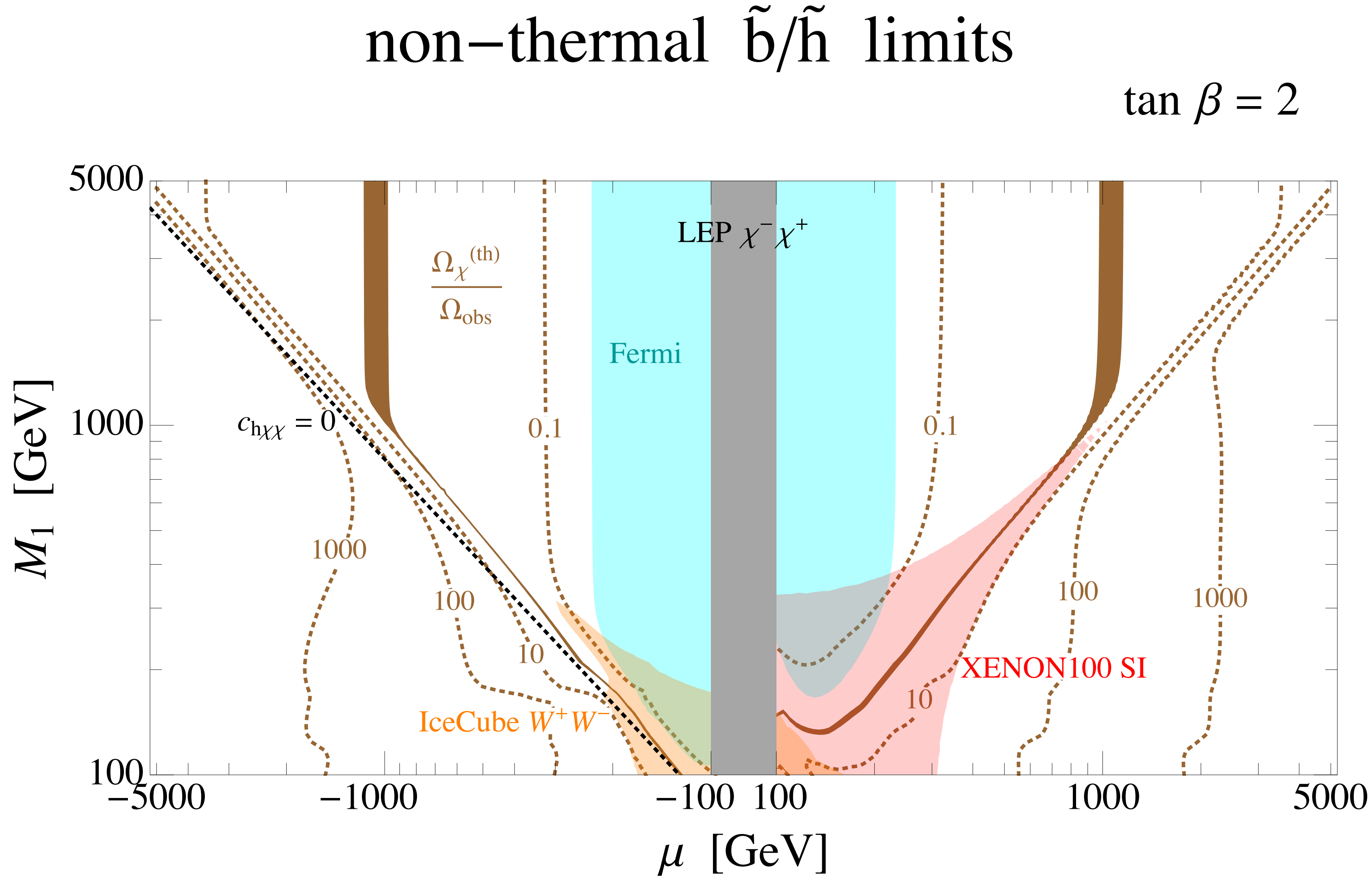


E.g. a scalar with quartic coupling $\lambda|S|^2|H|^2$:

$$\sigma \approx \lambda^2 \times \left(\frac{100\ \mathrm{GeV}}{M_{\mathrm{DM}}}\right)^2 \times 3 \times 10^{-44}\ \mathrm{cm}^2$$

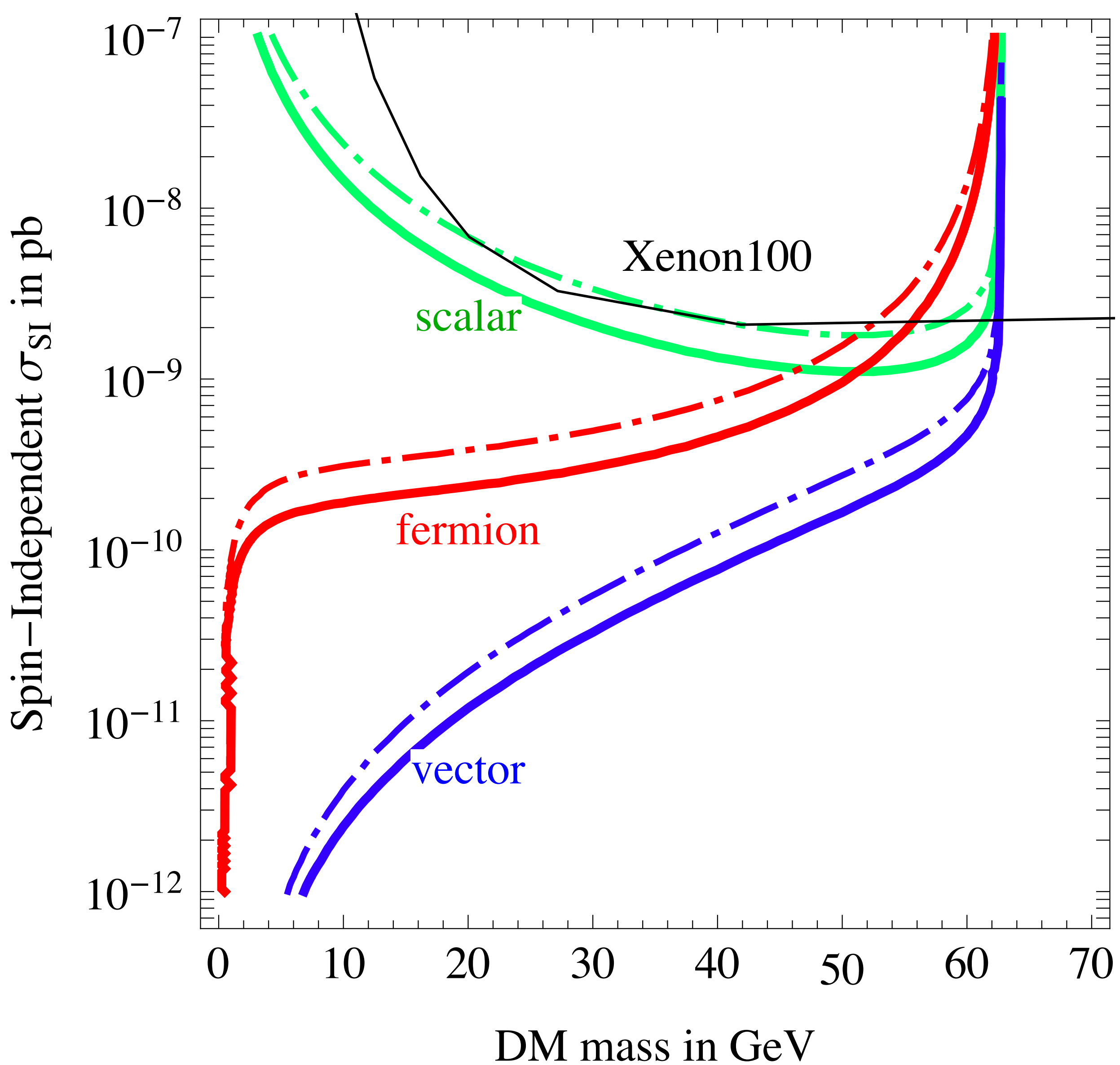
Higgs exchange is what direct detection experiments are probing now.

Direct Detection



Cheung/Hall/Pinner/Ruderman 1211.4873: much of mixed bino-higgsino thermal relic space is ruled out, but blind spots for direct detection exist.

DM Complementarity



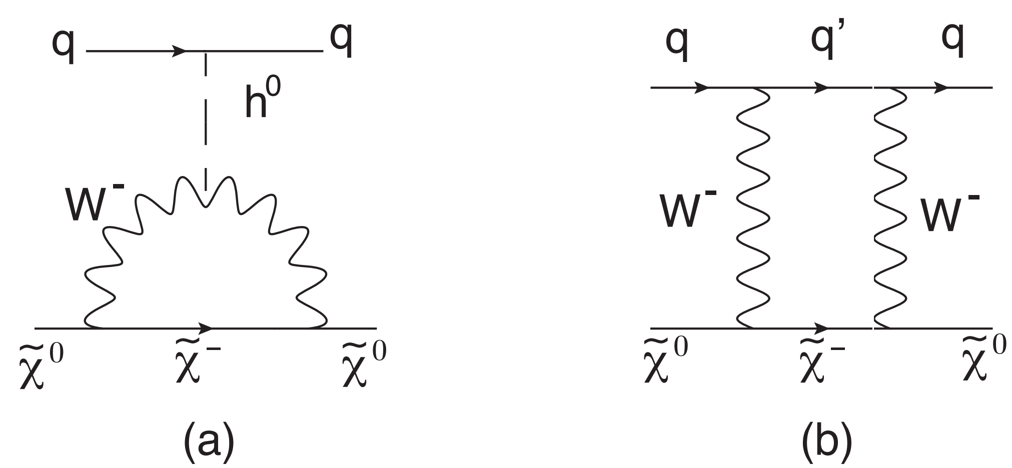
XENON/LUX don't work well for sufficiently light DM; it doesn't have enough kinetic energy to give the nucleus a detectable kick.

But colliders are ideal in this regime: the Higgs would decay to these light DM particles!

Giardino, Kannike, Masina, Raidal, Strumia 1303.3570

Direct Detection Rates

There can be weakly-interacting particles with neither Z- nor Higgs-mediated interactions, but with ***W* loops**.
E.g. supersymmetric "winos":



Hisano et al. 1004.4090 $\sigma \lesssim 10^{-47}\ \mathrm{cm}^2$

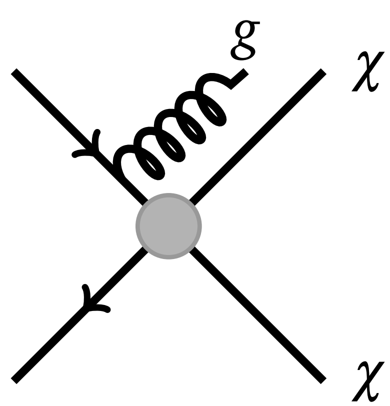
(beware sign mistakes leading to false optimism in earlier refs)

Down in the neutrino background. Even "WIMPs" may not show up at XENON/LUX!

Colliders, indirect detection needed: complementarity

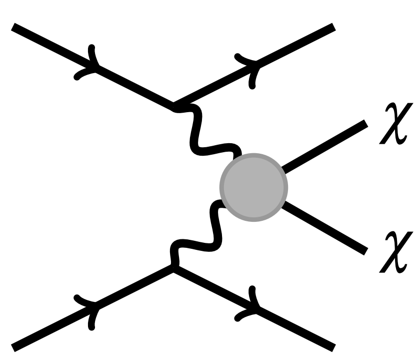
WIMPS at Colliders

Lots of recent excitement about minimal **signatures**



Mono-jet (generally: mono-X)

or



VBF

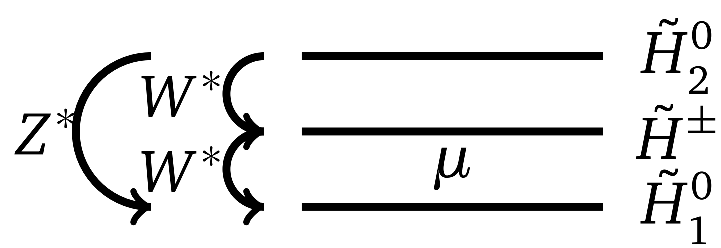
Real models generally have *non*-minimal signatures.

For instance, in MSSM we either had coannihilation or an SU(2) multiplet. Either way, **more particles around. Dark matter + “Friends of dark matter”**

SU(2)$_L$ multiplets by definition involve **multiple** states, some charged

$\}\delta m \sim \frac{\alpha}{\pi} m_W$ (tree-level dim 7)

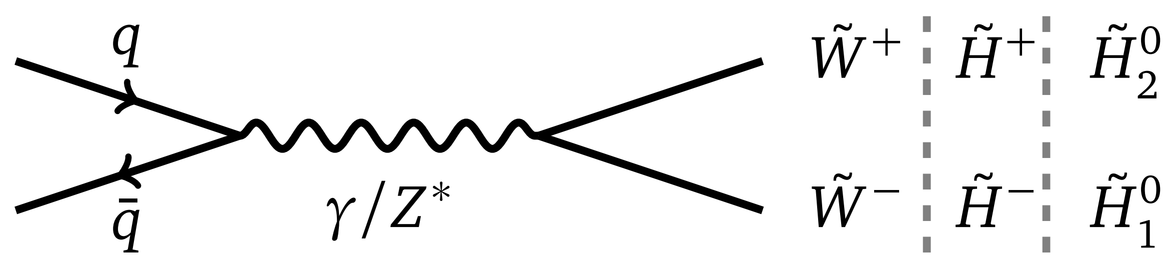
Wino charged -> neutral: **disappearing track**

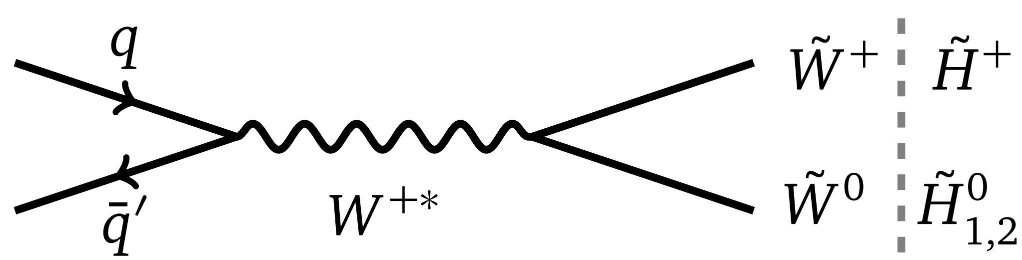


$\}\delta m \sim \frac{m_Z^2}{M_2}$

Higgsino charged -> neutral, neutral -> neutral: **soft leptons or jets**

SU(2) multiplet (**WIMP**) production channels

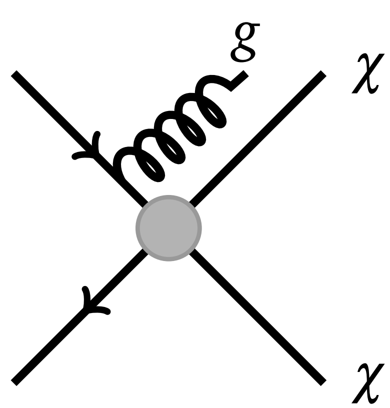




Almost never DM—DM. Always DM—“DM-friend” or “DM friend”—“DM friend”

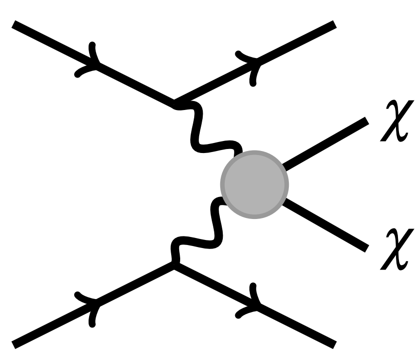
Not mono-jet, but “mono-jet + Y”: Y = disappearing track or soft lepton

Minimal signatures for non-minimal DM?



Mono-jet (generally: mono-X)

or

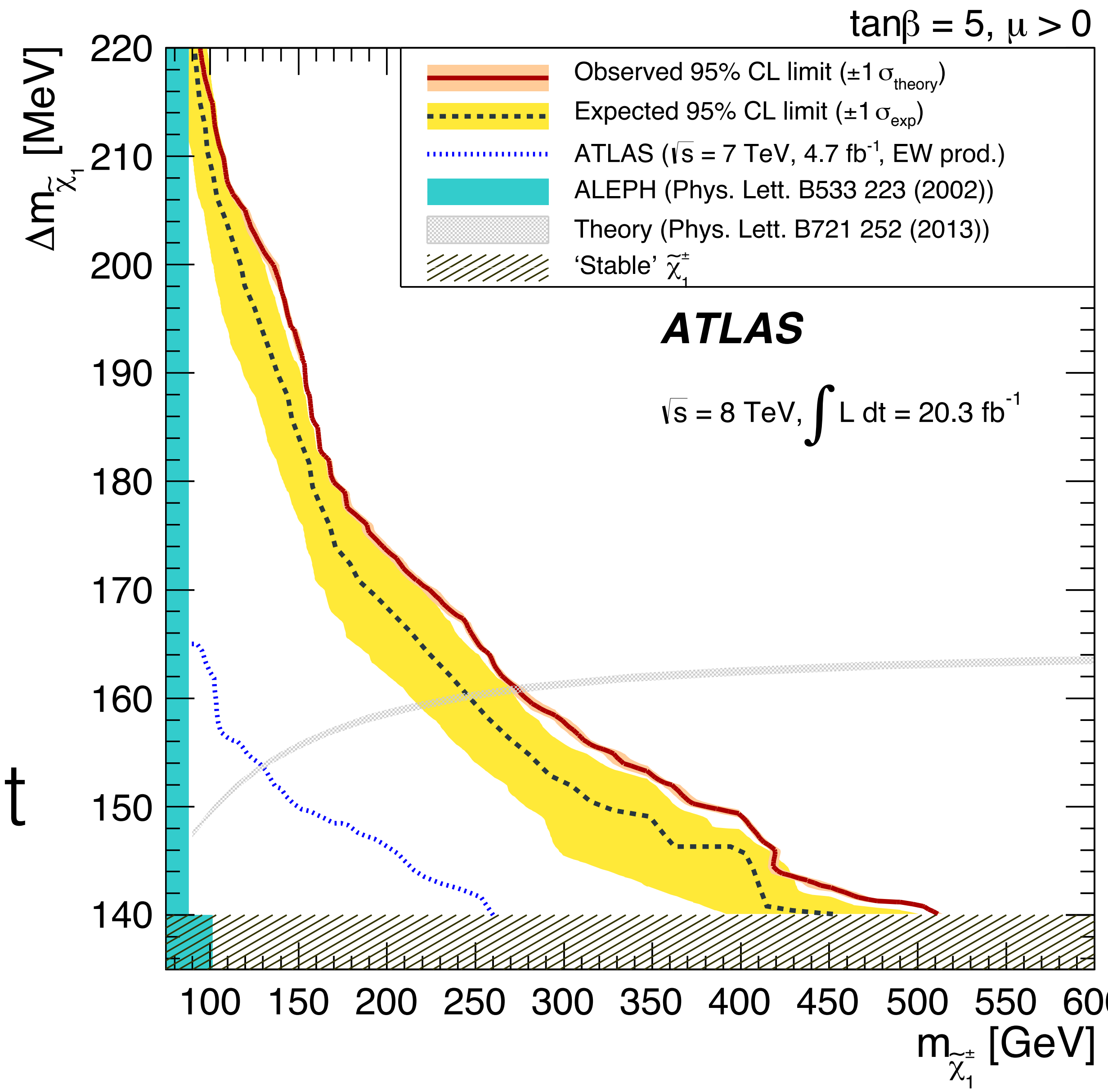


VBF

If DM is not an $SU(2)_L$ multiplet, these interactions are usually high-dim. operators. **We integrated something out.** Often can look for that thing: **additional nonminimal signatures.**

ATLAS 1310.3675: **wino** search. **Mono-jet + disappearing track.** Rules out wino up to 270 GeV.

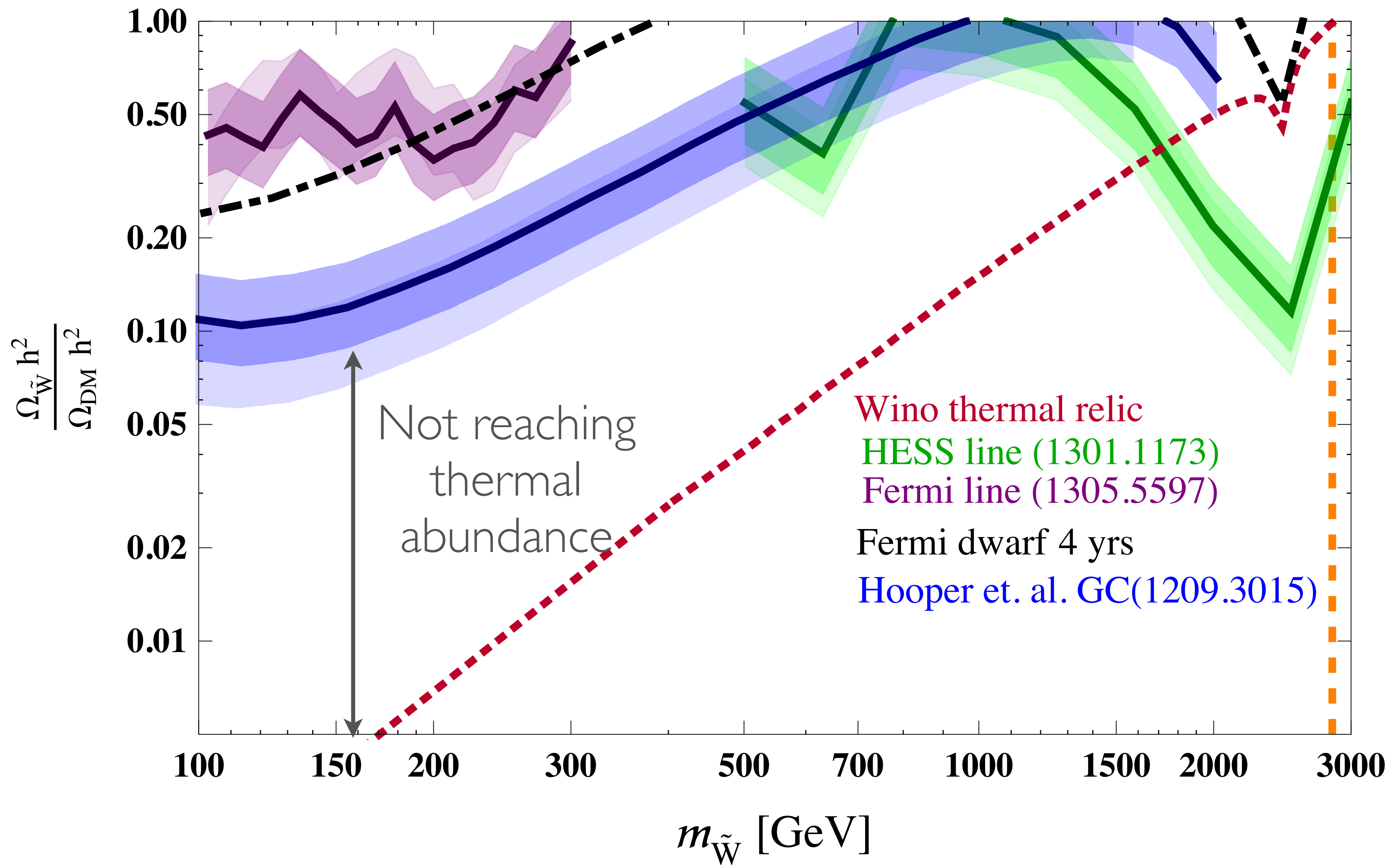
Search gets a lot of extra mileage out of **nonminimal signature.**



(Higgsinos are tougher because the soft stuff doesn't help a lot. LHC still no better than LEP for higgsinos.)

Indirect Detection of Wino Dark Matter: Gamma Rays

Covers a broader mass range than colliders, but only if **large fraction of DM.**



J. Fan, MR 1307.4400; see also T. Cohen, M. Lisanti, A. Pierce, T. Slatyer 1307.4082

What To Do With The Bounds?

A lot of well-motivated swaths of SUSY dark matter parameter space are already ruled out by direct or indirect detection.

SUSY is motivated by naturalness (now swallowing mild tuning) and gauge coupling unification. **Models that look good except for DM can be patched up**: it could be that the would-be-problematic DM decays, either through R-parity violation or through an R-parity conserving hidden valley.

Lifetimes that are long on collider scales can be short relative to BBN, so keep looking for both prompt decays, displaced decays, and no decay at all.

When it comes to empirically-motivated models that put dark matter masses in a range that might be probed at colliders, WIMPs aren’t the only game in town.

I’ll briefly mention two other possibilities.

Asymmetric Dark Matter

In recent years many model-builders have considered that dark matter may also have an *asymmetry*-- more dark matter than anti-dark matter.

$$\Delta n_\chi = n_\chi - n_{\bar{\chi}} \neq 0$$

Some physics in the early universe establishes

$$n_\chi, n_{\bar{\chi}}, n_B, n_{\bar{B}}$$

In general, asymmetries $\Delta n_\chi, \Delta n_B$ convert into each other.

Often assumed symmetric component **annihilates completely**; today have χ but no $\bar{\chi}$.

Asymmetric Dark Matter

The idea has a long history, with an essentially modern version proposed by David B Kaplan in 1992 and recent activity kicked off by David E Kaplan, Markus Luty, and Kathryn Zurek in 0901.4117.

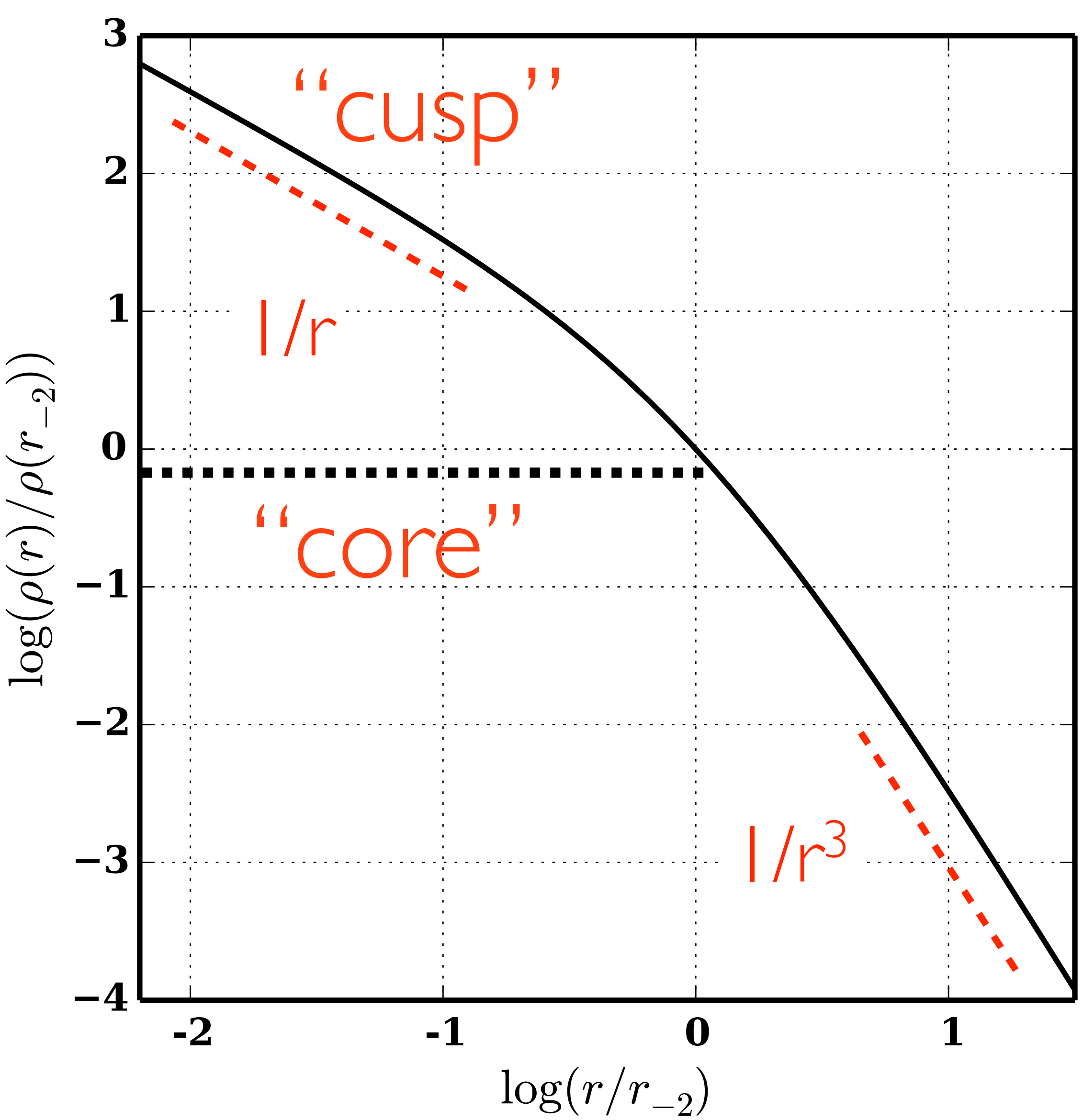
Models of this type often have the feature:

- **DM asymmetry** and **baryon asymmetry** are equal up to a calculable order-one factor
- Then $n_{\rm DM} \sim n_{\rm baryon}$ and $\rho_{\rm DM} \approx 5\rho_{\rm baryon}$
- As a result, we expect dark matter masses $m_{\rm DM} \sim m_{\rm baryon}$

So, frequently (not always!) predict dark matter masses in the ~1 to 10 GeV range.

Self-Interacting Dark Matter

There are ***possible*** hints of dark matter self-interactions, e.g. from presence of cores in DM distribution in dwarf galaxies.



NFW profile (Navarro, Frenk, White 1993) with **cusp**: robust outcome of N-body simulations of dark matter only.

Data in dwarf satellites favors a **core**. *SIDM, or baryonic effects?*

Self-Interacting Dark Matter

The cross sections required, if SIDM is the right explanation for the hints in data, are large by particle physics standards:

$\sigma \sim 0.1$ barn (m_{DM} / GeV).

Model-dependent translation into mass and couplings, but e.g. for glueball (strong, point-like interaction):

$\sigma \sim 4\pi/m_{DM}^2$, so $m_{DM} \sim 100$ MeV. (Other cases may have, e.g., Rutherford $1/v^4$ enhancement, so larger masses.)

But: **generally not too far above weak scale**, if SIDM is to explain data. (Caveat: coupling to SM not guaranteed.)

Outlook

There are about as many possible LHC/cosmology connections as there are models of new physics.

It's hard to forecast where we're going, but there is a lot of potential for excitement given the very different complementary probes we can bring to bear if new physics exists near the weak scale.

Let's keep digging for signals!