

# Anticipating a New Golden Age

Our current Standard Model of fundamental interactions was in place by the mid-70s. It has survived scrutiny at energies and levels of precision orders of magnitude beyond its origins.

Neutrino masses require a modest, and welcome, *expansion* of the SM. (More below.)

Even the “ugly” parts work amazingly well (CKM matrix).

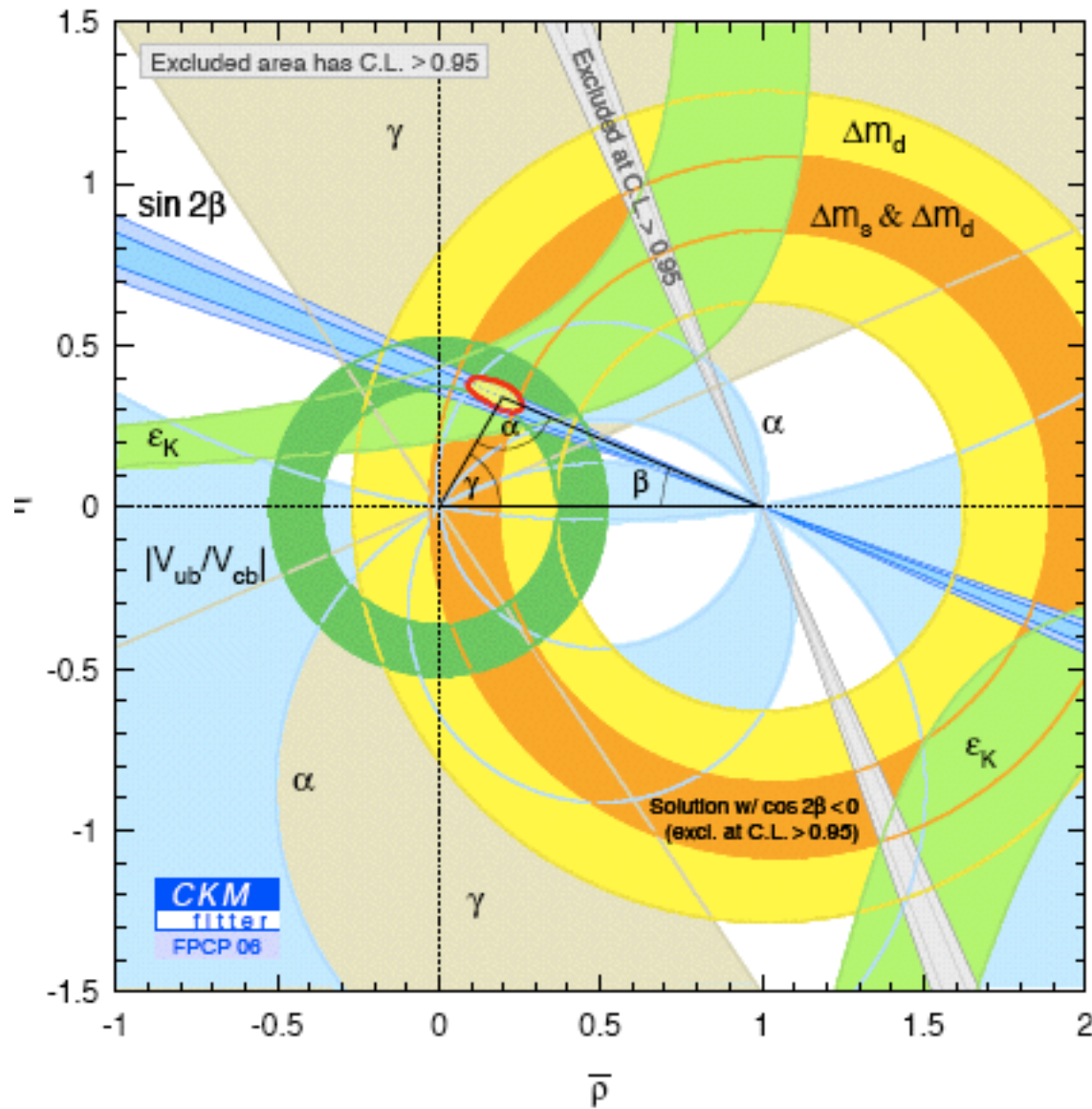


Figure 8: Confidence levels in the  $(\rho, \eta)$  plane for the global CKM fit. The shaded areas indicate 95% C.L. allowed regions [51].

**We should be very proud of ourselves!**

The SM leaves an unfinished agenda, however:

What drives electroweak symmetry breaking?

Do the gauge interactions unify?

What about gravity?

What's the dark matter?

What's the dark energy?

Can we clean up the messy bits?

What else is left out?

Some answers should be forthcoming soon:



The SM leaves an unfinished agenda, however:

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What about gravity?

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What else is left out?



# Electroweak Symmetry Breaking

The universe, i.e. “empty” space, is an exotic superconductor.

We don't know what causes the superconductivity. What is it that plays the role of the Cooper pairs?

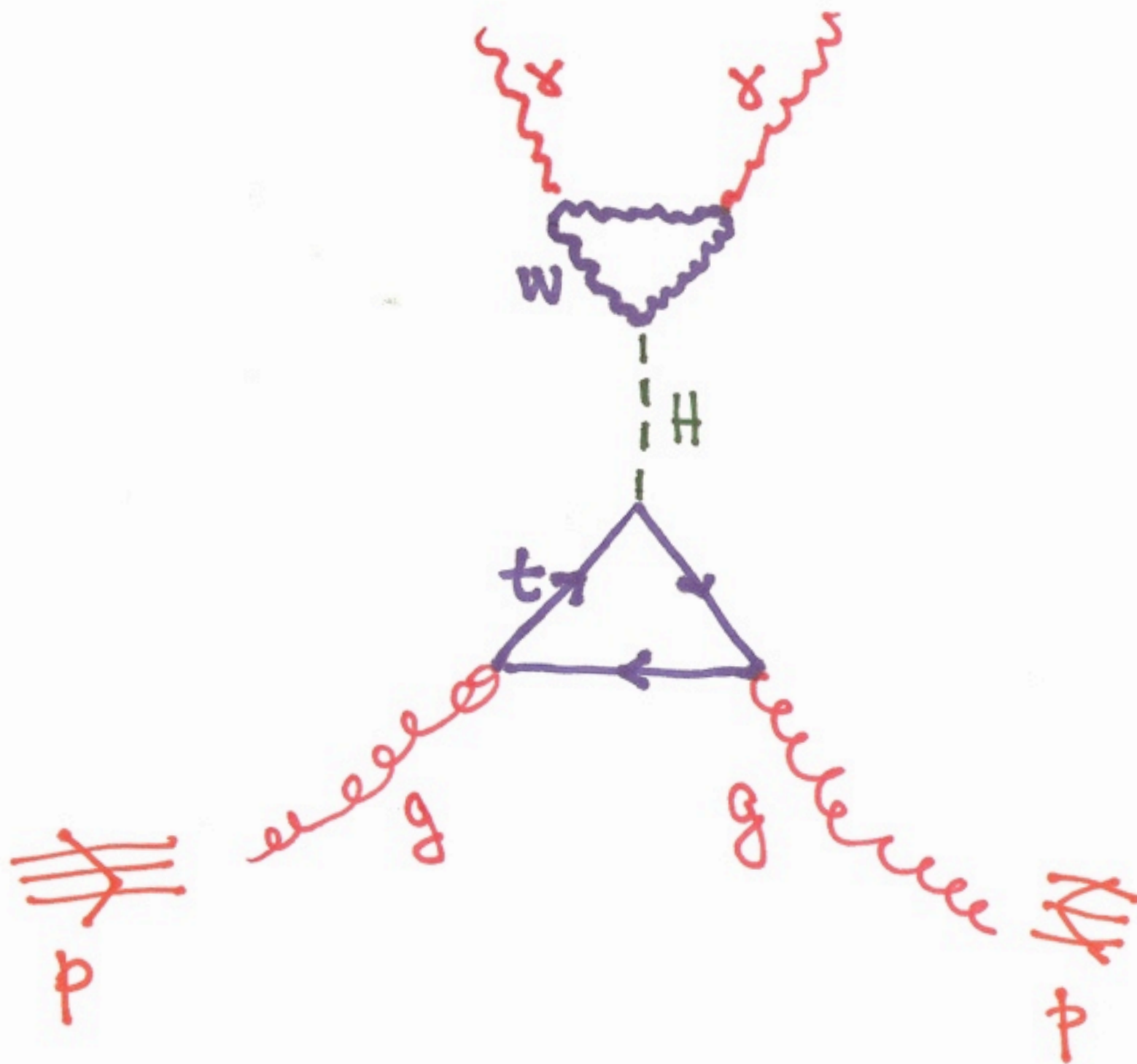
# The Minimal Model

The minimal model introduces a single scalar (“Higgs”) doublet for that job.

This introduces four degrees of freedom, three of which have been observed.

The other is the so-called Higgs particle.

There is only one unknown parameter in this minimal model, namely the Higgs particle mass.



It's logically possible that the minimal model is all that will be found at LHC.

That would be disappointing, because it would leave the (other) major questions hanging.

As will appear, I don't think it's likely ...

In non-minimal models, there's more structure, and more particles to discover.

# Unification and Supersymmetry

$$\begin{pmatrix} u & u & u \\ d & d & d \end{pmatrix}^L_{1/6}$$

$$\begin{pmatrix} \nu \\ e \end{pmatrix}^L_{-1/2}$$

$$\begin{pmatrix} u & u & u \end{pmatrix}^R_{2/3}$$

$$\begin{pmatrix} d & d & d \end{pmatrix}^R_{-1/3}$$

$$\begin{pmatrix} e \end{pmatrix}^R_{-1}$$

No  $\nu^R$

**SU(3) x SU(2) x U(1)**

↑      ↑  
mixed, not unified

	<b>R</b>	<b>W</b>	<b>B</b>	<b>G</b>	<b>P</b>
u	+	-	-	+	-
u	-	+	-	+	-
u	-	-	+	+	-
d	+	-	-	-	+
d	-	+	-	-	+
d	-	-	+	-	+
u <sup>c</sup>	-	+	+	-	-
u <sup>c</sup>	+	-	+	-	-
u <sup>c</sup>	+	+	-	-	-
d <sup>c</sup>	-	+	+	+	+
d <sup>c</sup>	+	-	+	+	+
d <sup>c</sup>	+	+	-	+	+
ν	+	+	+	+	-
e	+	+	+	-	+
e <sup>c</sup>	-	-	-	+	+
N	-	-	-	-	-

SO(10)

N.B.: One hand rules them all!

$$\text{Hypercharge } Y = -1/6 (\mathbf{R} + \mathbf{W} + \mathbf{B}) + 1/4 (\mathbf{G} + \mathbf{P})$$



electron



quarks

photon



gluons

↑  
inverse coupling  
strength



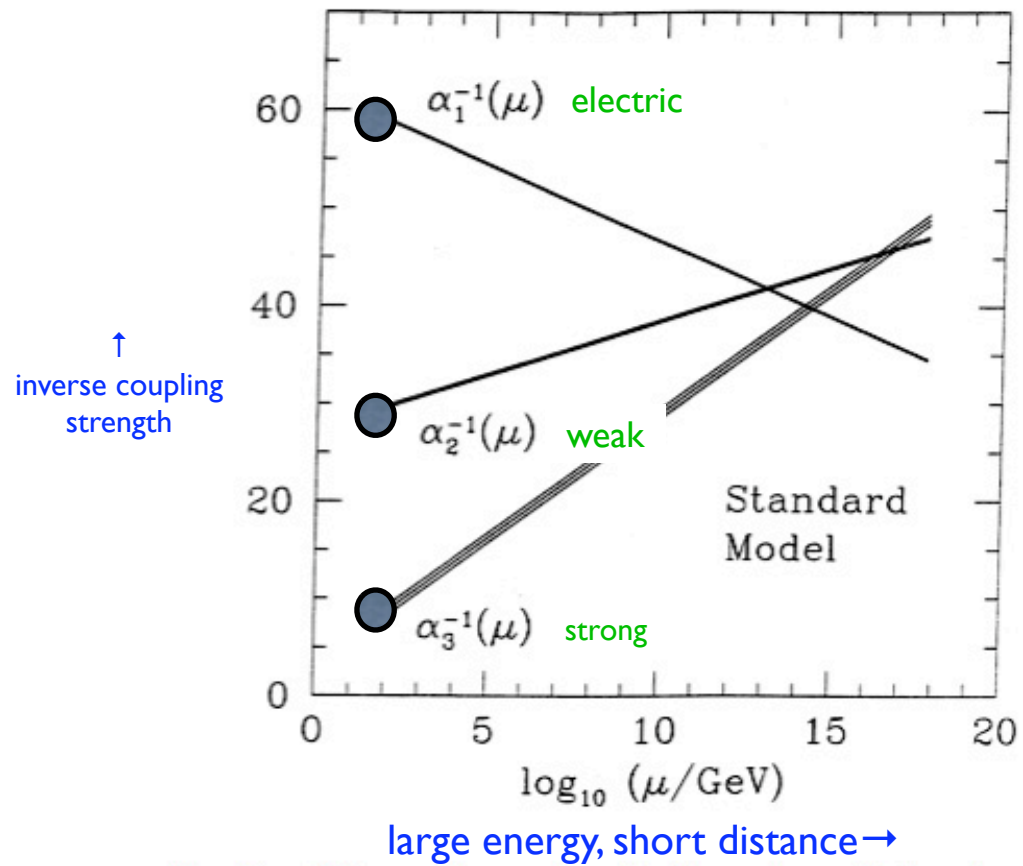
electric



weak



strong



Now Add SUSY

electron



quarks

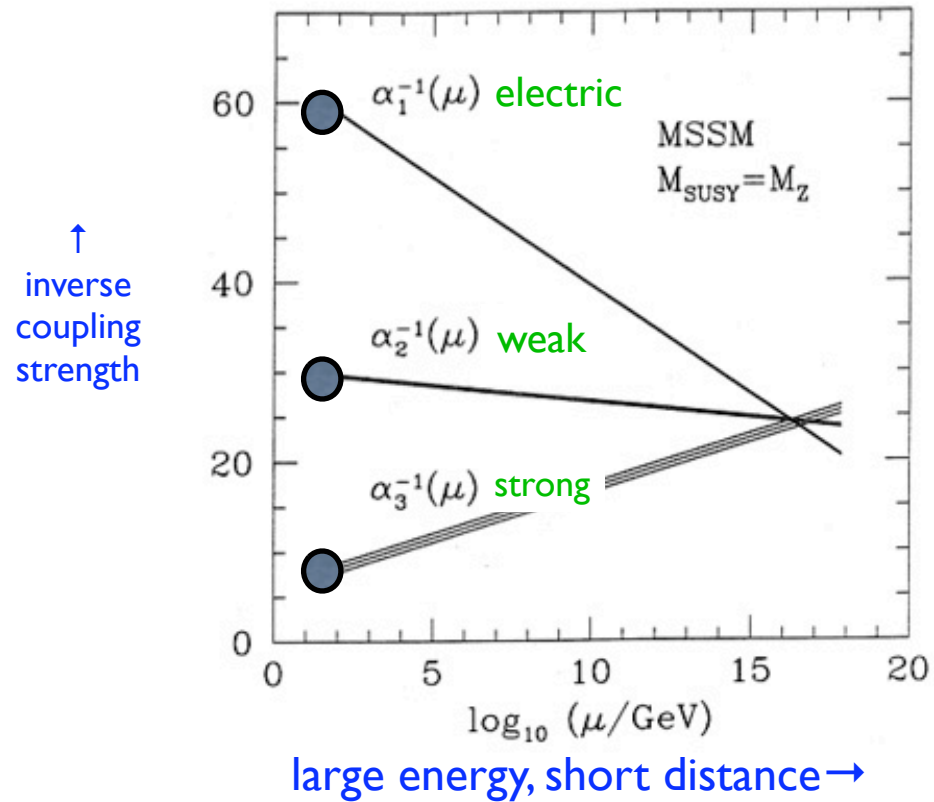


photon

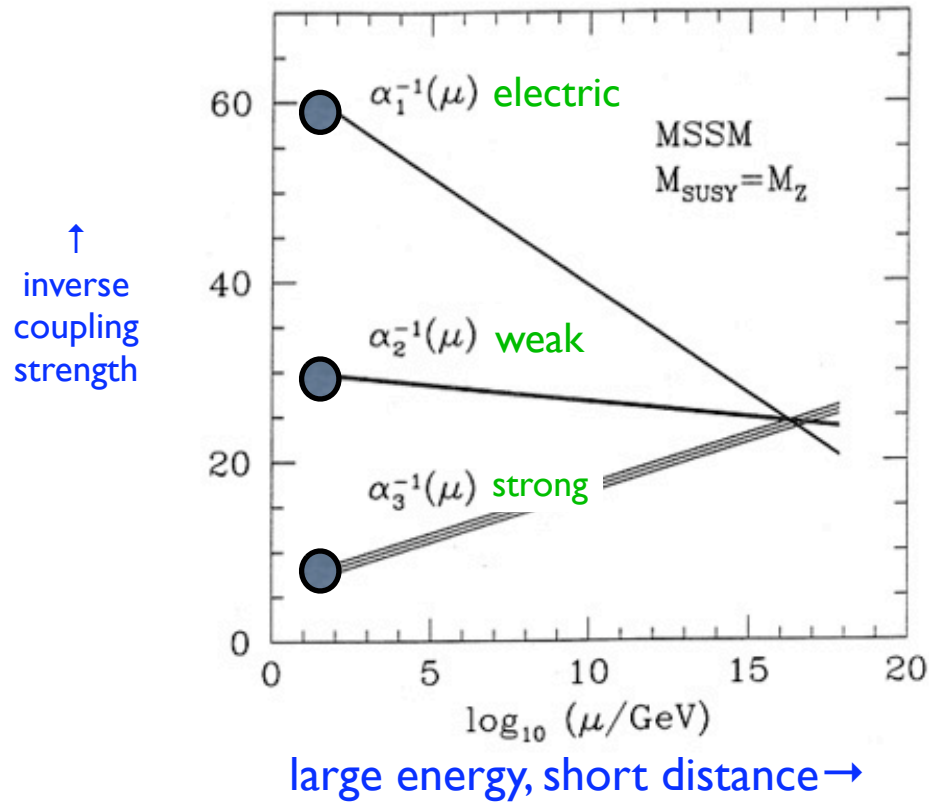


gluons

# Unification ♥ SUSY



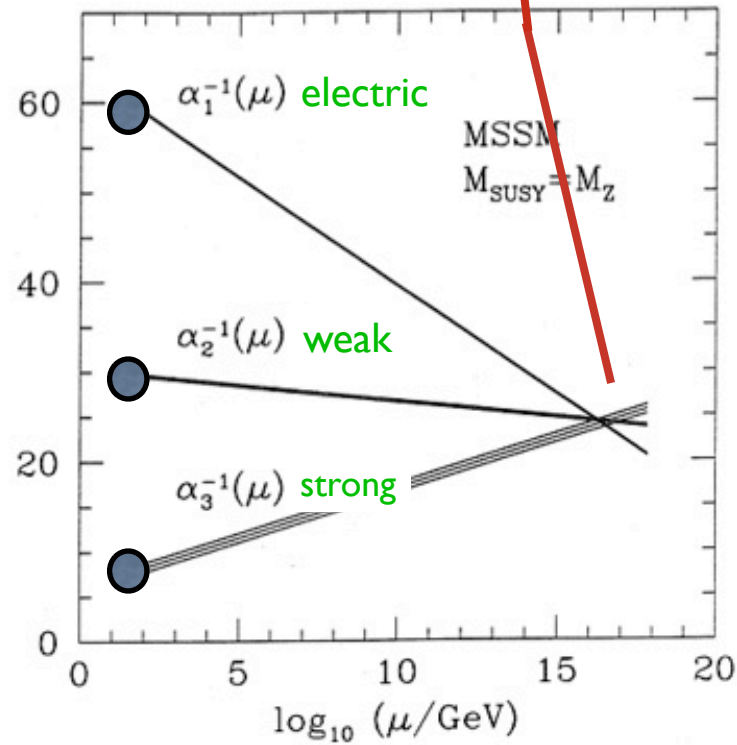
# Unification ♥ SUSY



Gravity fits too!  
(roughly)

# Unification ♥ SUSY

↑  
inverse  
coupling  
strength



large energy, short distance →

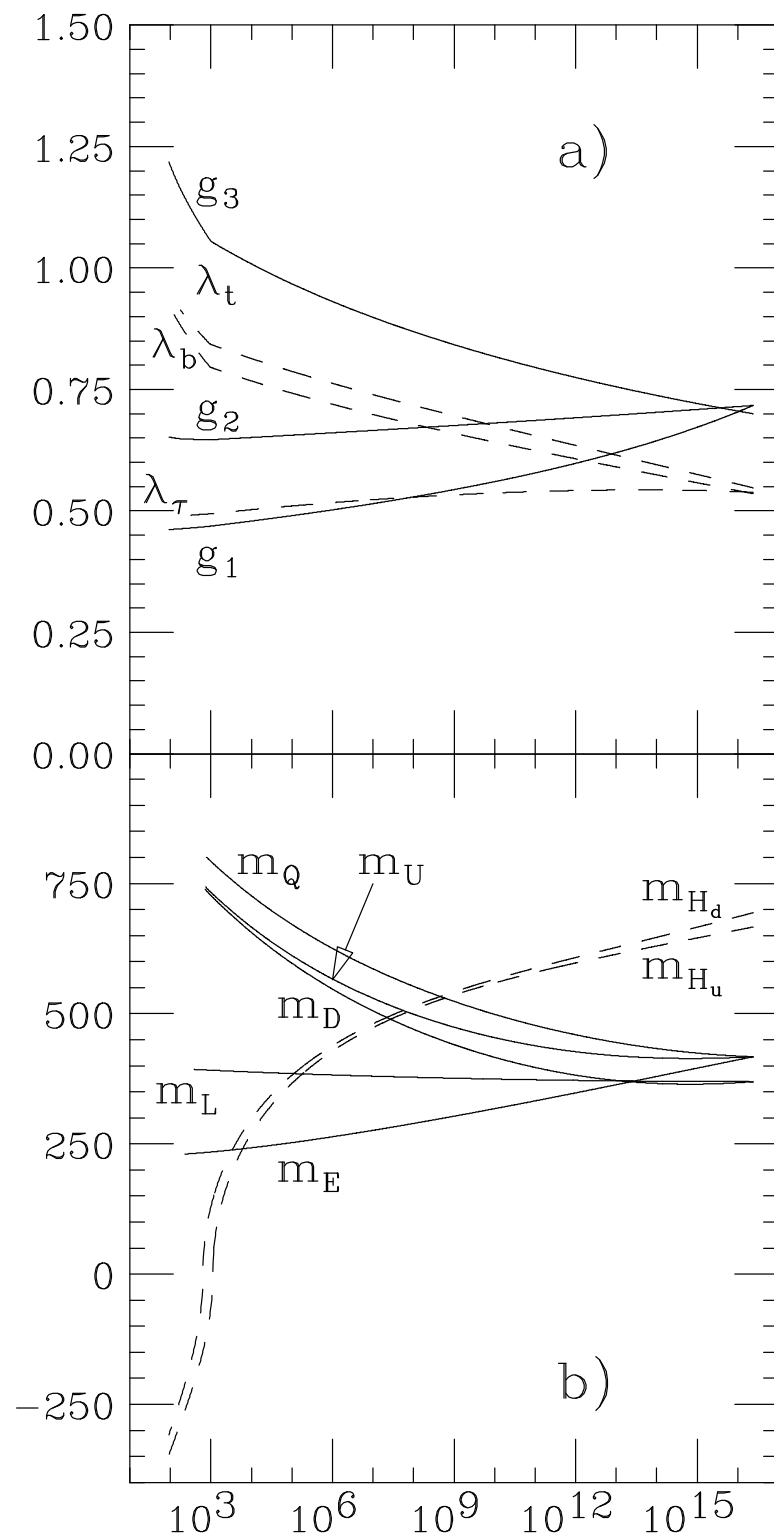
Gravity fits too!  
(roughly)

There could be additional manifestations of unification:



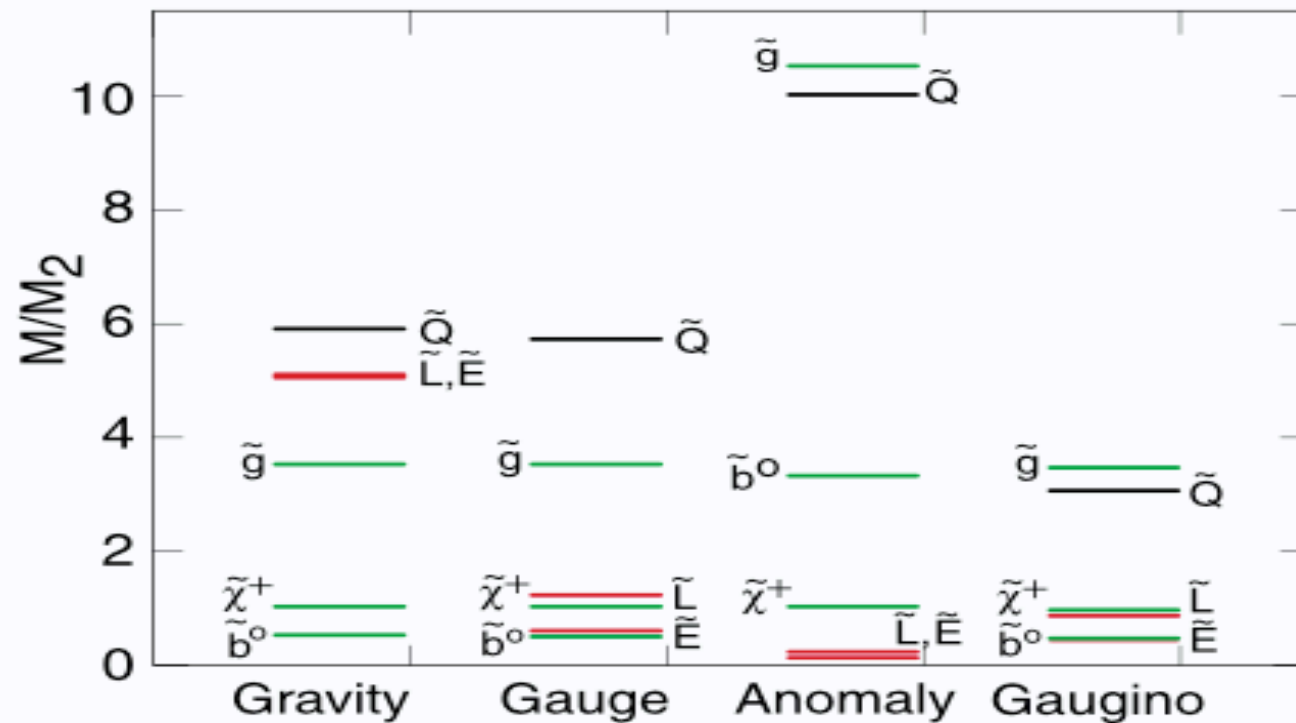
couplings

SSB masses (GeV)



The mechanism of supersymmetry *breaking* is up for grabs. The leading candidates are all pretty glamorous.

# Sparticle Spectra



non-minimal gravity! quantum effects!  
new interactions! new interactions!

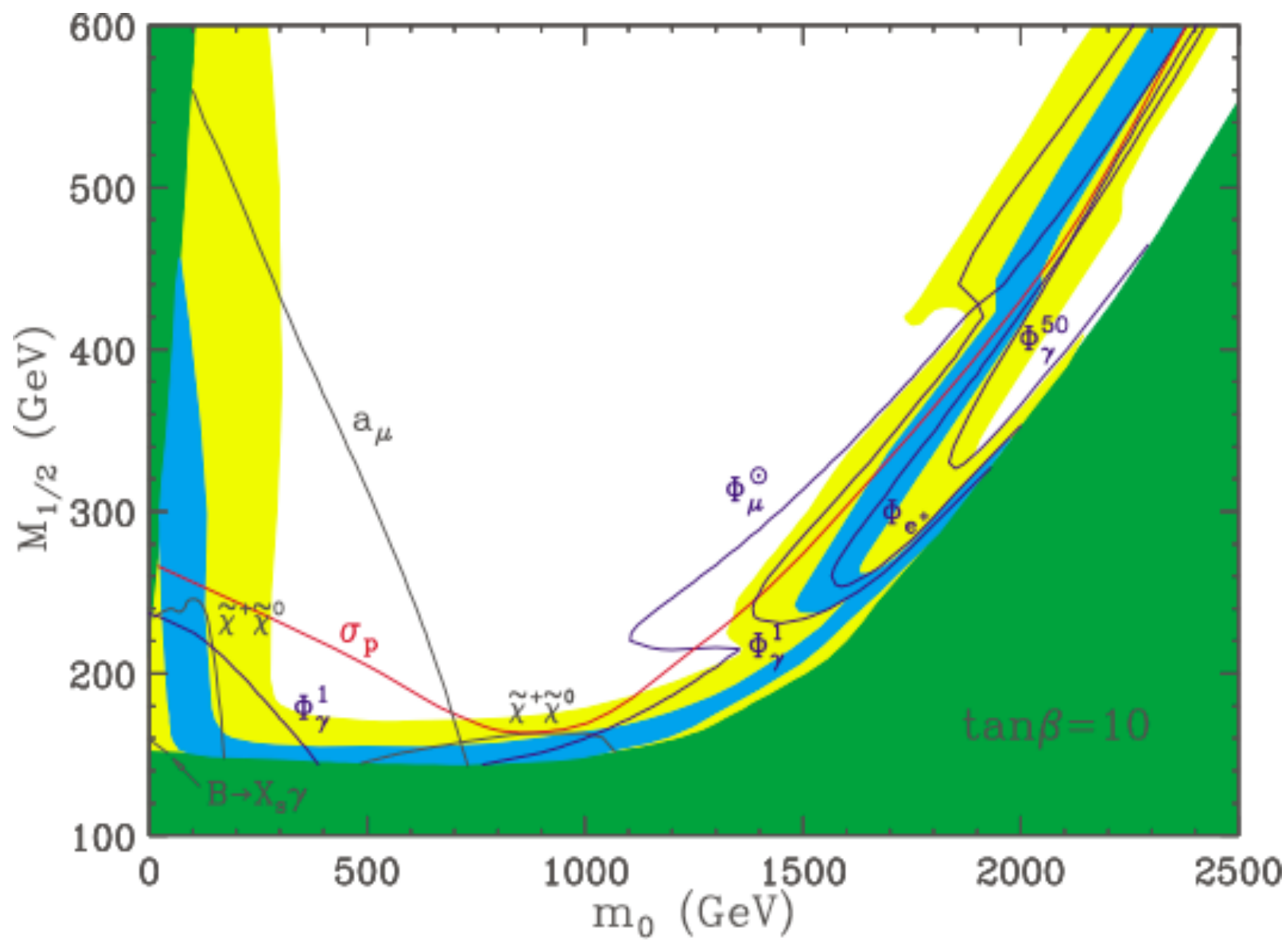
Sparticle spectra for various mediation mechanisms.

# Dark Matter

All particles in the standard model have positive R-parity, where  $R \equiv (-1)^{3B+L+2S}$ . Their supersymmetry partners have negative R-parity.

The lightest particle with R-parity -1 will probably be very stable.

In many models, this “lightest supersymmetric particle”, or LSP, has roughly the right properties to provide the astronomical dark matter.



It will be a great enterprise to check whether the properties of an observed particle, processed through the big bang, lead to the observed dark matter.

This is far from being a formality. There are live, attractive alternatives:

The “apparent” LSP might decay slowly into a lighter, very weakly coupled true LSP, such as a gravitino or axino.

Most of the dark matter could be something else entirely, e.g. my favorite, axions. [skip ahead]

# Might the LHC See Nothing?

The usual answer is:

A Higgs particle must show up, at least.

But that is not guaranteed. In fact, there are quite simple, phenomenologically unobjectionable models in which the Higgs particle becomes effectively invisible.



# How to Hide Higgs

Take the standard model, and add an  $SU(3) \times SU(2) \times U(1)$  singlet real scalar field *phantom* field  $\eta$ .

All the couplings of gauge fields to fermions, and of both to the Higgs field doublet remain as they were in the original standard model.

The Higgs potential is modified, however:

$$\begin{aligned}
 V(\phi, \eta) = & -\mu_1^2 \phi^\dagger \phi + \lambda_1 (\phi^\dagger \phi)^2 \\
 & -\mu_2^2 \eta^2 + \lambda_2 \eta^4 - K \phi^\dagger \phi \eta^2
 \end{aligned}$$

The upshot is that the two mass eigenstates (=particles) are created by mixtures of the conventional Higgs field and the phantom field.

The phantom component contributes nothing to the amplitude for production from conventional particle sources, i.e. quarks and gluons.

Thus the same overall production rate of Higgs particles is now divided between two lines.

Rather than one channel with  $S/N = 2$ , for the same exposure you'll get two channels with  $S/N=1$ .

Of course, it's easy to generalize this model. With more phantom fields, one has more division.

$$5 \times 1 \sigma \neq 5 \sigma.$$

It gets worse. The phantoms might actually be the “Higgs fields” of an entire new sector, that has its own gauge fields and matter.

Then the Higgs-phantom mixtures can also decay into particles of the new sector, which are effectively invisible.

So not only is production divided, but also decay is diluted.

**Example: All Mass from  
Quantum Effects**

$$G = SU(4) \times SU(3) \times SU(2) \times U(1)$$

$SU(4)$  is a new strong interaction that supports spontaneous chiral symmetry breaking and thus a  $\sigma$ -model.

$$V(\phi, \vec{\sigma}) = -\mu_1^2 \phi^\dagger \phi + \lambda_1 (\phi^\dagger \phi)^2 - \mu_2^2 \vec{\sigma}^2 + \lambda_2 (\vec{\sigma}^2)^2 - K \phi^\dagger \phi \vec{\sigma}^2$$

We can imagine  $\mu_1^2 = 0$ , and no classical masses in the theory anywhere



The  $\sigma_0$  can decay into its  
massless "pions", so we get  
dilution.

# Broader Motivations for Hidden Sectors

Flavor and axions

Stacks and throats

Plays well with SUSY

Hippocratic oath

# Flavor and Axions

Flavor symmetries, if they exist, are plausibly associated with hidden sectors. (We'd need to break such symmetries, but not  $SU(3) \times SU(2) \times U(1)$ , at a high scale.)

Axion physics is the best-motivated and most developed example.

# Plays Well With SUSY

Hidden sectors are introduced in several mechanisms of SUSY breaking (gravity-mediated, gauge-mediated).

The NMSSM, which introduces a singlet field, has been advocated on phenomenological grounds. It eases “naturalness” problems.

# Stacks and Throats

In string theory, hidden sectors easily arise from far-away (in the extra dimensions) stacks of D-branes or orbifold points.

The original  $E_8 \times E_8$  heterotic string was an early incarnation of a hidden sector.

# Hippocratic Oath

**First, do no harm.**

Mixing in singlets does not upset the unification of couplings, nor does it introduce any flavor problems.

# The Good News

In an absolutely minimal, “purely neutral” Higgs sector, the portal will be challenging to exploit. But in more complex Higgs sectors, as in SUSY, we can access it indirectly, e.g. through missing energy in decays of charged Higgs particles.

# Summary and Conclusions

With the LHC, we will expand the frontiers of fundamental physics.

We will learn, through a *tour de force* of physics, what makes empty space a cosmic superconductor.

We will learn whether existing indications for unification and supersymmetry have been Nature teaching us or Nature teasing us.



If the superworld opens up, it will probably supply a good candidate for the dark matter.

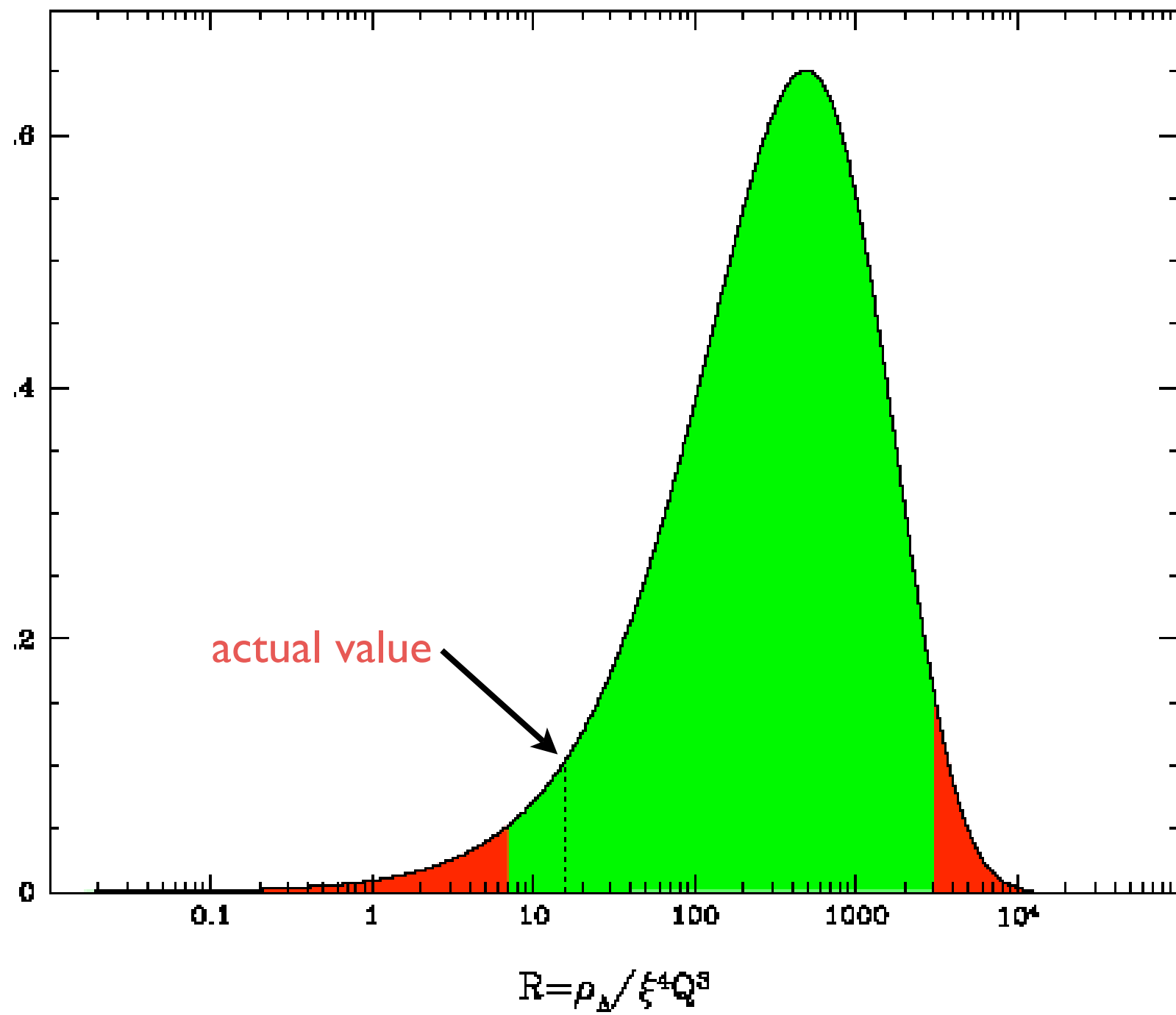
**It will be a great enterprise to establish or disprove that candidate.**

Hidden sectors are entirely possible. They could complicate things in the short run, but teach us even more in the long run.

I've had to be very selective and sketchy, but I hope I've given you a sense of some of the ambitious issues and ideas that we can expect to advance dramatically in the next few years.



For comparison, here is the  $\rho_\lambda$  (dark energy) distribution, given a flat prior:



# Scholium

( = Comments)

The scenario with inflation after the PQ transition removes some annoying difficulties of the traditional alternative (axion strings, domain walls).

The new scenario would be falsified by observing cosmological gravity waves of significant amplitude ...

... or by direct axion detection ( $F \sim 10^{12}$  GeV)!

It could be “truthified” if we still have a dark matter problem after LHC (+ ILC), through details of the dark matter distribution, or by seeing isocurvature fluctuations.



# Old and New Axion Cosmology

The axion field is established at the Peccei-Quinn (PQ) transition,  $\Phi = F e^{i\theta}$ .

It stores energy, due to its initial misalignment, roughly proportional to  $F \sin^2\theta_0$ .

For  $T \geq 1 \text{ GeV}$ ,  $\theta$  stays frozen at  $\theta_0$ . Then it relaxes to 0, liberating the stored energy.

If no inflation occurs after the PQ transition then the correlation length, which is no larger than the horizon at the transition, corresponds to a very small length in the present universe.

We therefore average over  $\sin^2\theta_0$ .

$F \sim 10^{12}$  GeV corresponds to the observed dark matter density.

If inflation occurs after the PQ transition, then the correlated volume inflates to include the entire presently observed universe.

Therefore we shouldn't average.

$F > 10^{12}$  GeV can be accommodated, using “atypically” small  $\sin^2\theta_0$ .

In this scenario, most of the multiverse is overwhelmingly axion-dominated. That's bad news for the emergence of complex structure, let alone observers.

Selection effects must be considered.

$\theta_0$  controls the dark matter density, but it has little or no effect on anything else. So we know what the prior measure is. (Namely  $d\theta_0$  for  $\theta_0$ ,  $d \sin^2\theta_0$  for  $\rho_{\text{DM}}/\rho_{\text{b.}}$ )

We do not have to get embroiled in questions of baby universe nucleation ...

... nor, for that matter, unification, supersymmetry, string theory ...

The theory may be right, or it may be wrong, but it is hard to imagine a clearer case for applying anthropic reasoning.

Linde, 1988

Tegmark, Aguirre, Rees, FW [astro-ph/0511774](#)

# The Fragility of Life

Making User-Friendly Structures



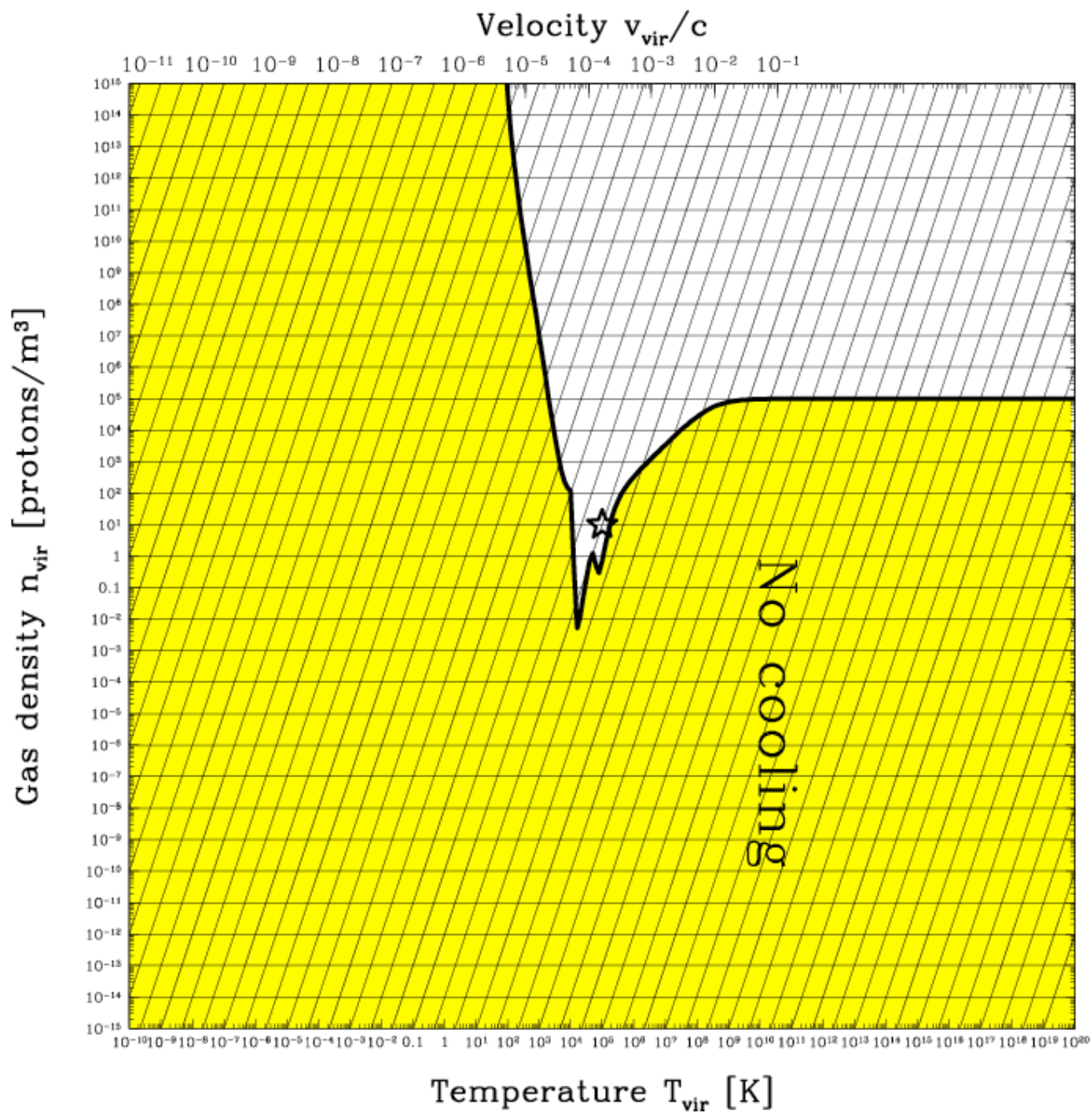
Lots of things can go wrong when you try to make nice solar systems, starting with small seed fluctuations:

The (ordinary, baryonic) matter might fail to cool, so it sloshes around and remains diffuse:

density  $\uparrow$

time  $\downarrow$

size  $\downarrow$



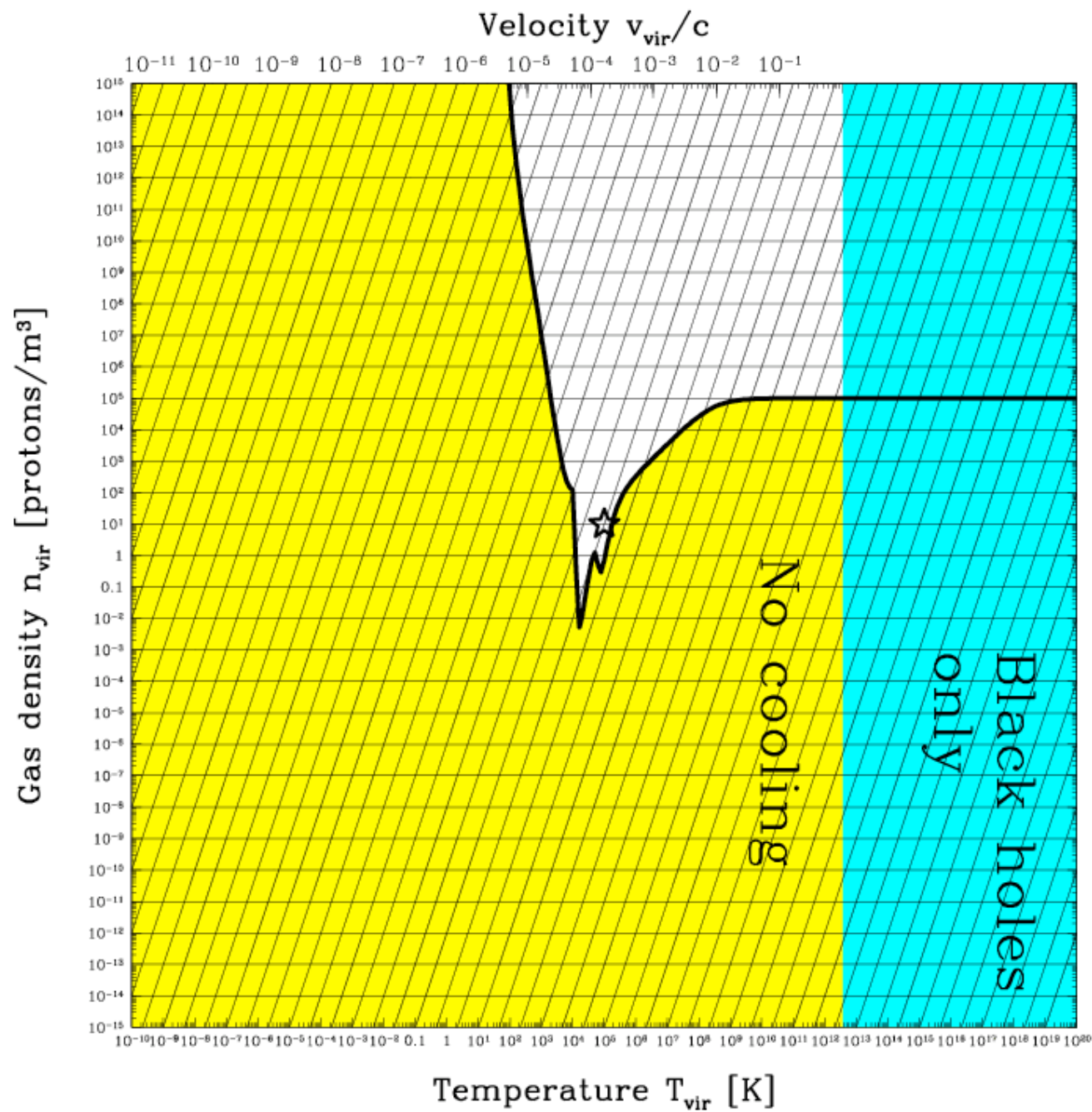
contrast  $\rightarrow$

Your fluctuations might collapse into  
black holes:

density  $\uparrow$

time  $\downarrow$

size  $\downarrow$



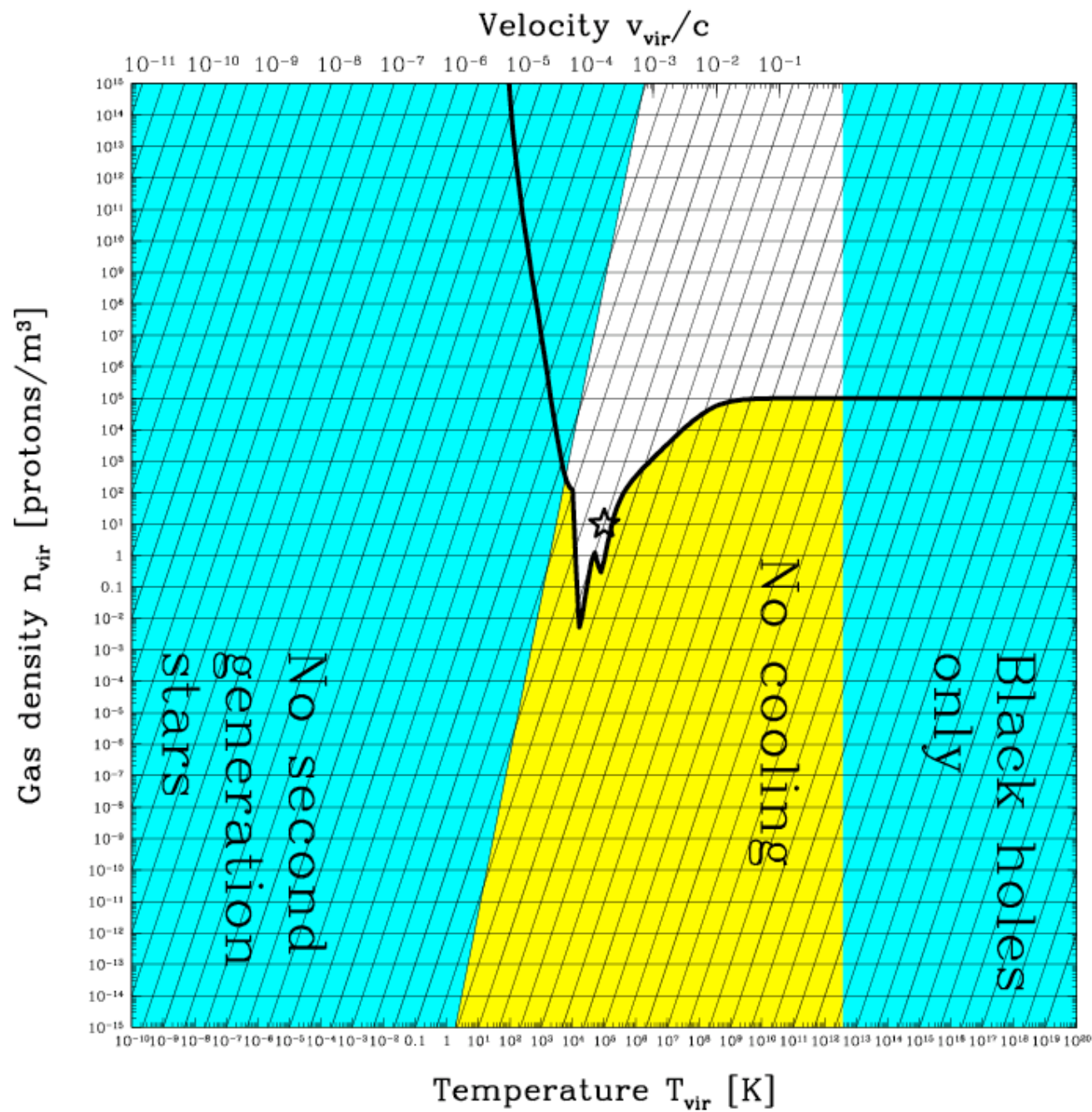
contrast  $\rightarrow$

The matter might get swept out by the first supernovae:

density  $\uparrow$

time  $\downarrow$

size  $\downarrow$



contrast  $\rightarrow$

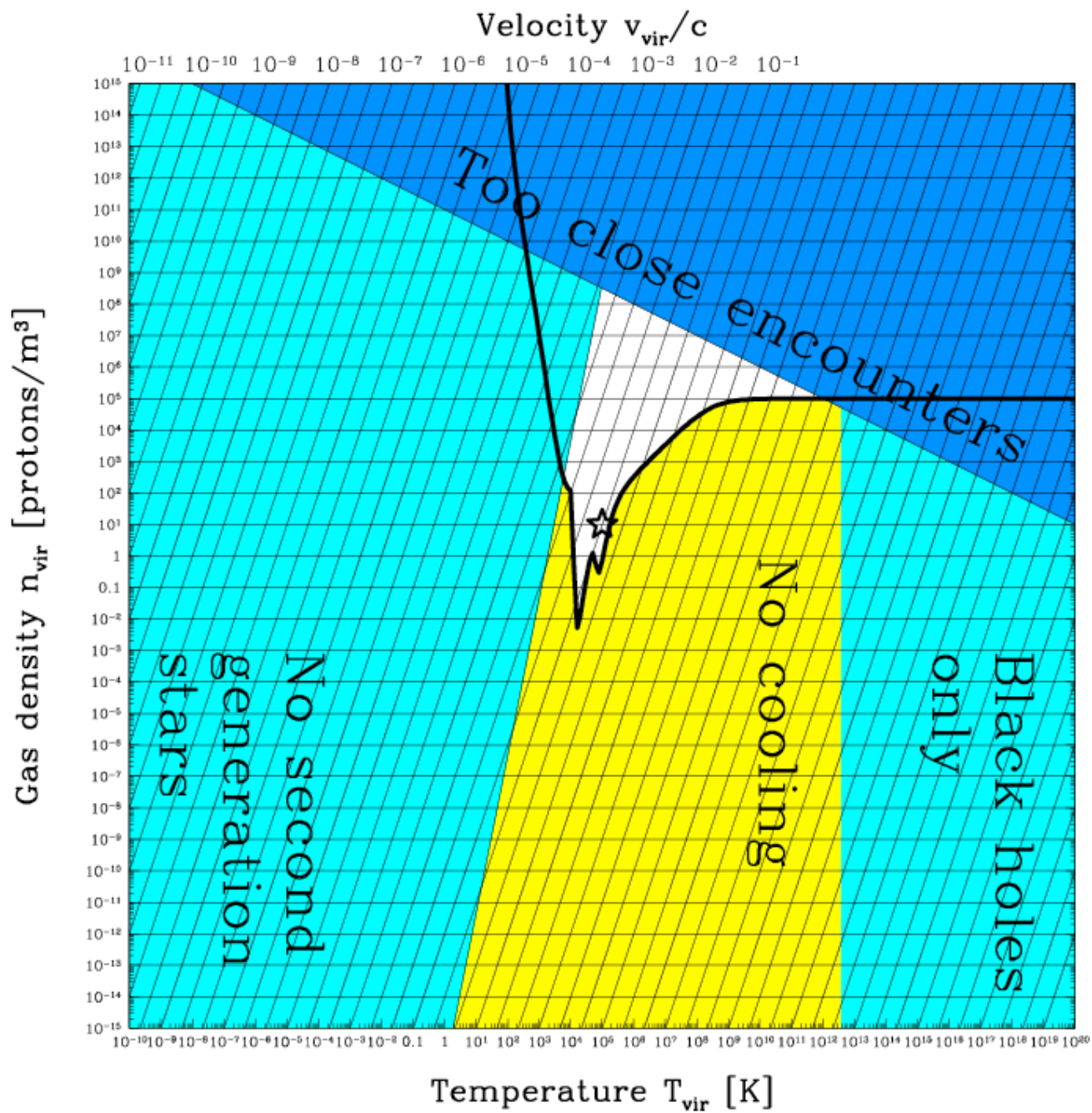
There might be no safe haven from  
disruptive encounters:



density  $\uparrow$

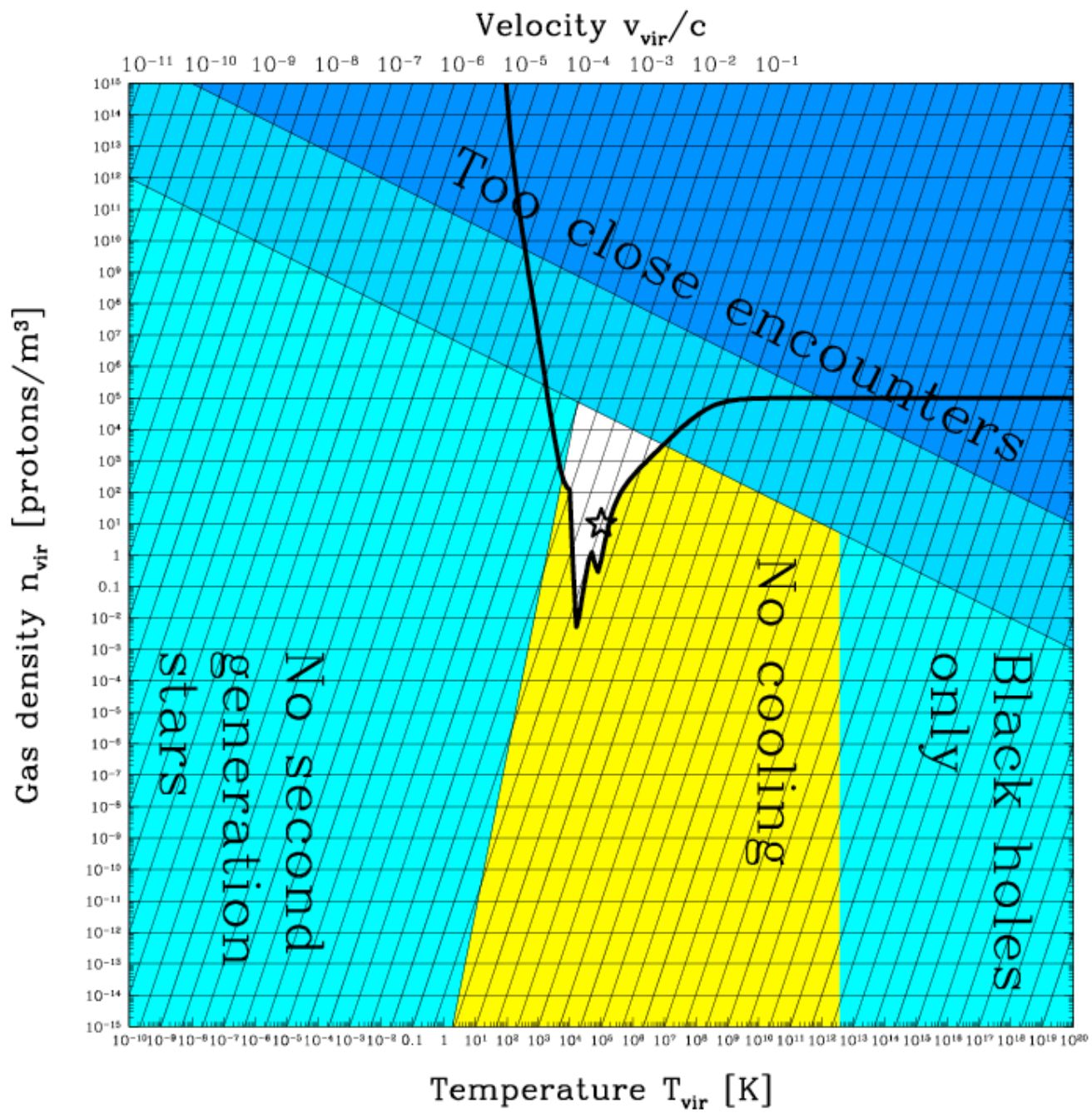
time  $\downarrow$

size  $\downarrow$



contrast  $\rightarrow$

density  $\uparrow$   
time  $\downarrow$   
size  $\downarrow$

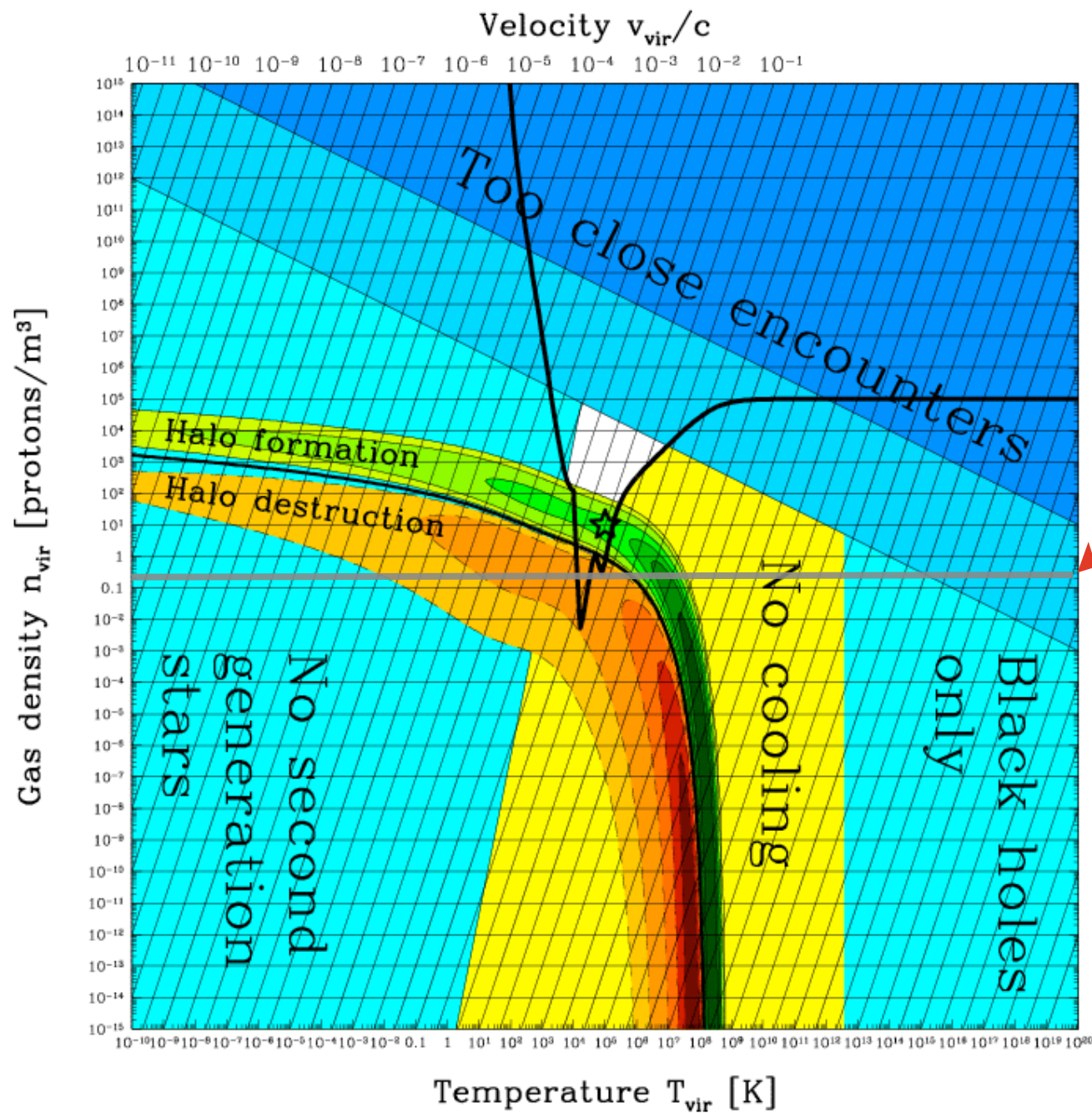


contrast  $\rightarrow$

We can compare the potentially user-friendly seeds with what we get from primordial fluctuations.

Here is what we get with the observed fluctuation spectrum and dark matter density:

density  $\uparrow$   
time  $\downarrow$   
size  $\downarrow$



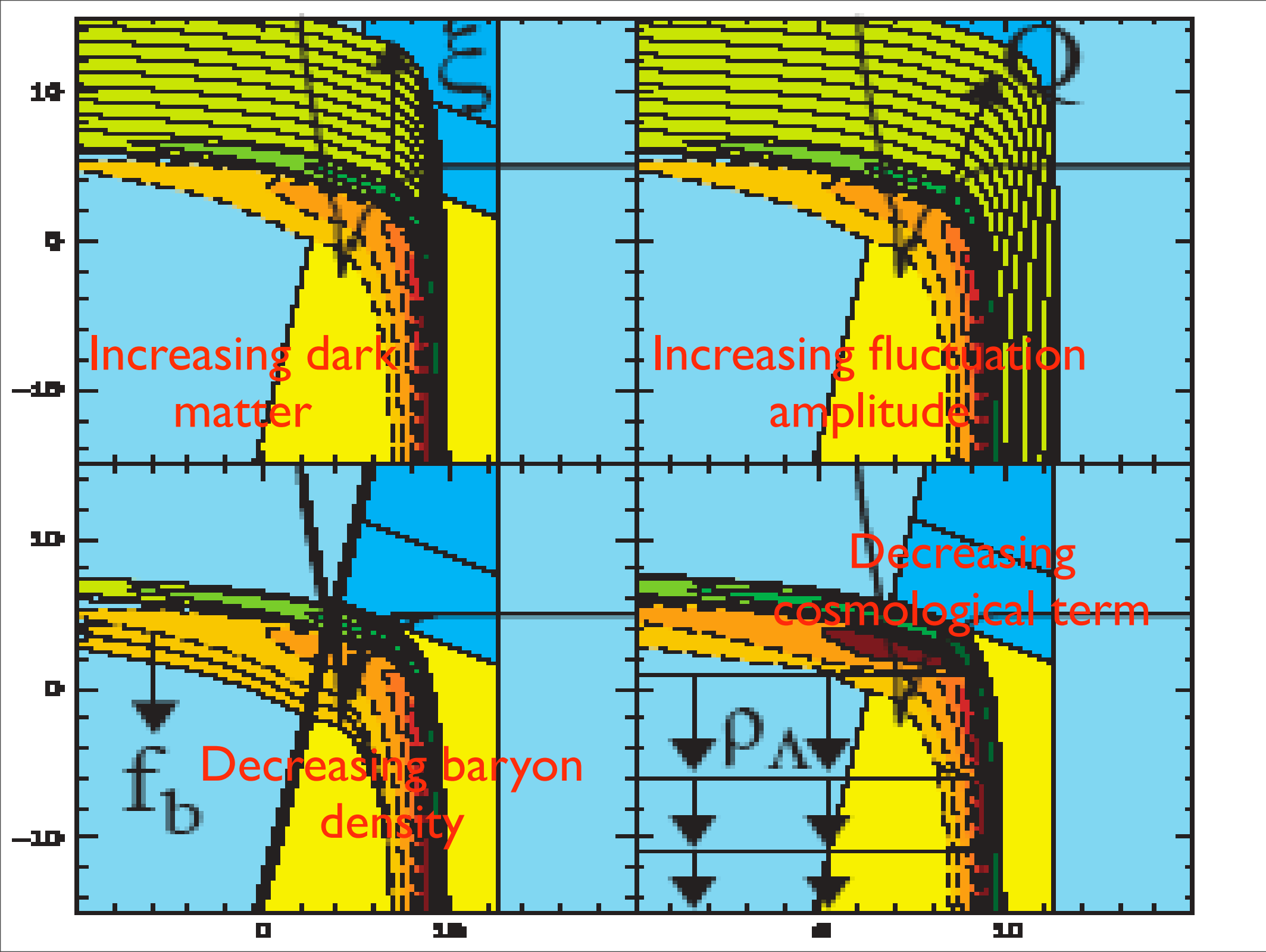
contrast  $\rightarrow$

The cosmological term cuts off growth.

This calculation gives a semi-quantitative explanation of the characteristic size of galaxies!

Note: So far, what we've done is conventional astrophysics.

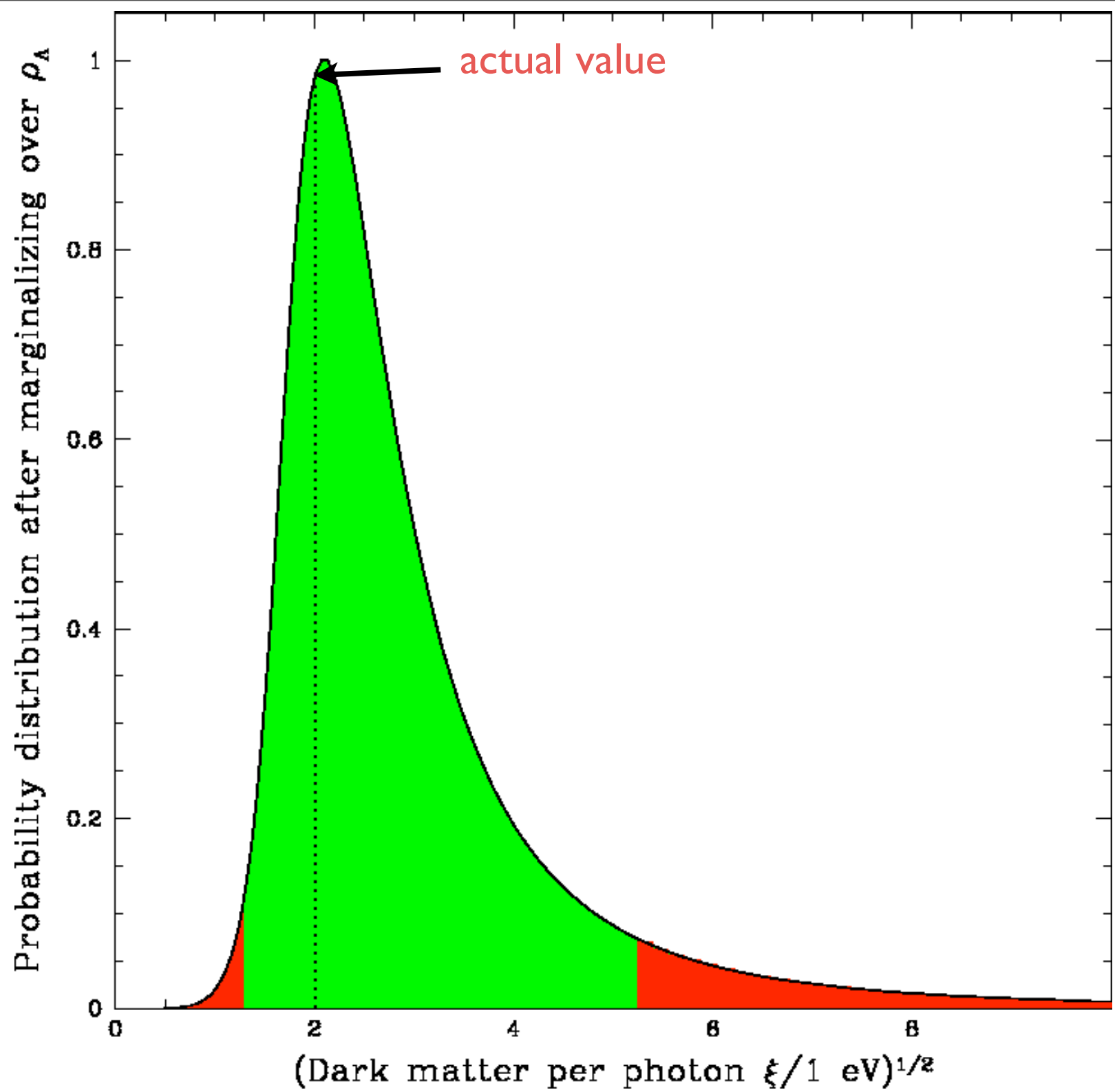
Now we can consider the effect of changing parameters governing the primordial fluctuations:



We can calculate probability distributions  
*per baryon in the user-friendly region.*

Here is the  $\theta_0$  distribution near 0, translated into dark matter density:





The theoretical success of axion cosmology emphasizes that if SUSY, and a dark matter candidate, are found at LHC, it will be important to pin its properties down and calculate its cosmological production.

Because if it's not enough, axions will happily  
- and naturally - supply the deficit.

Of course, particles in the hidden sector need not be scalars.

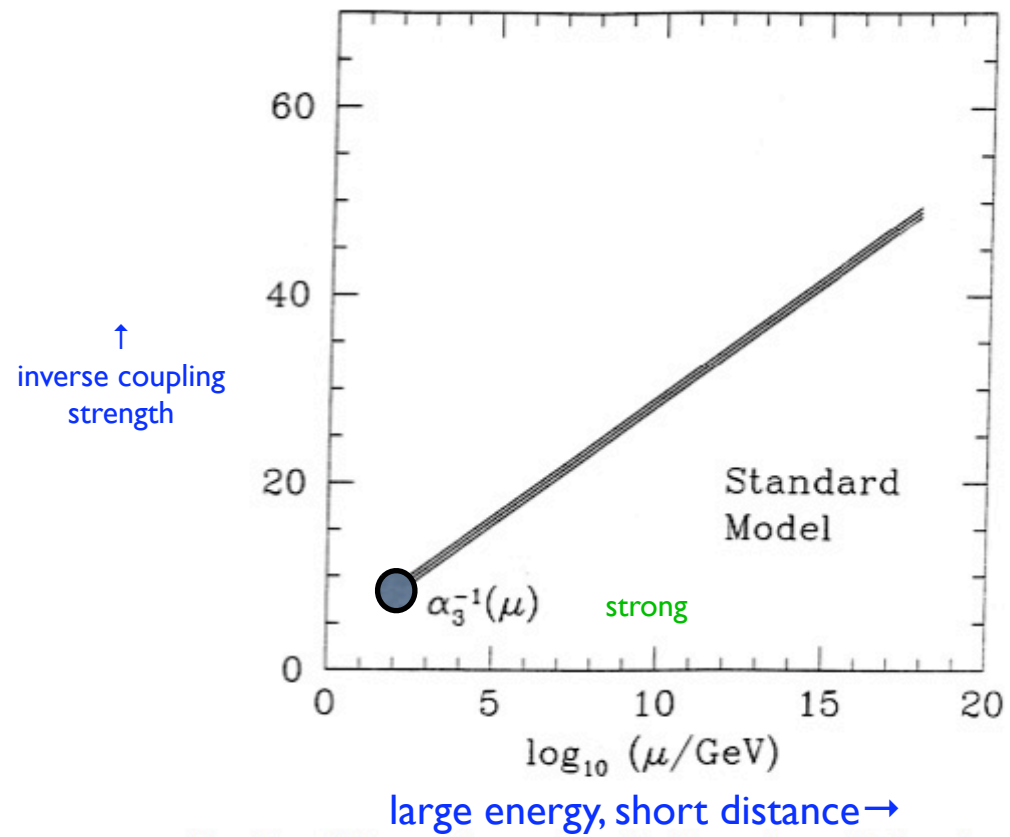
We can analyze “portals” of different spin systematically:

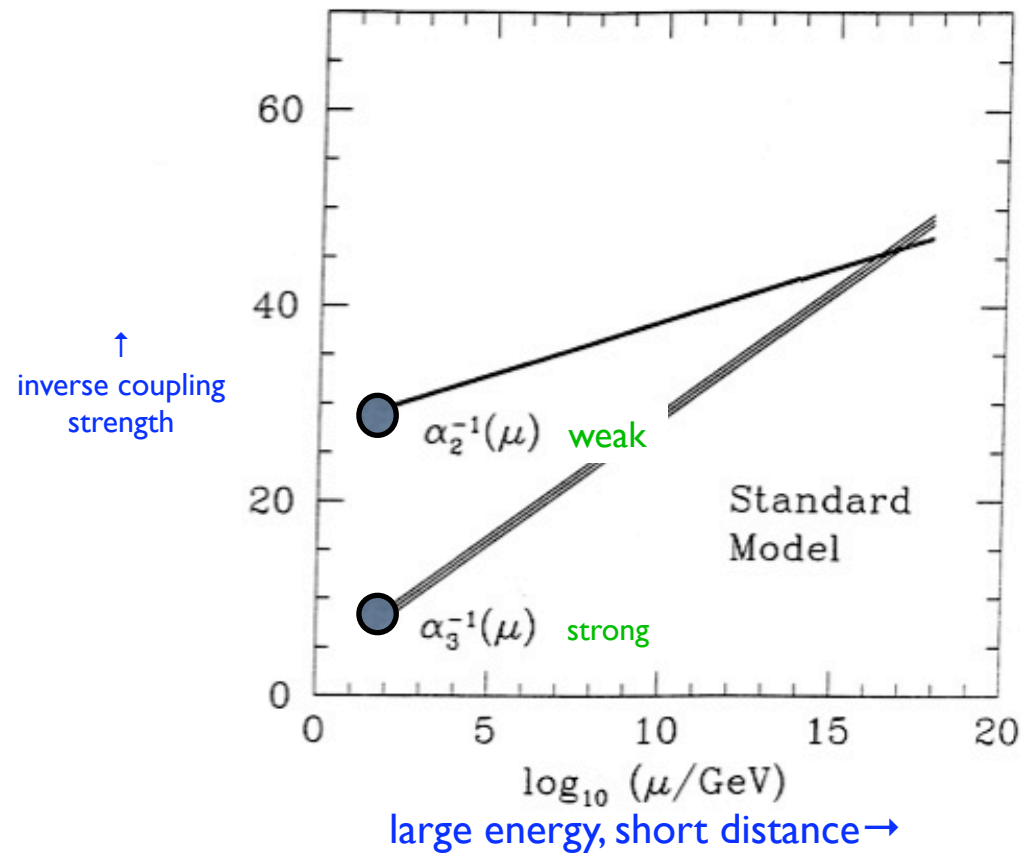
## Low-Dimension Portals

vector $V_\mu$	$\times \bar{f} \gamma_\mu f$ (through $\bar{f} \not{V} f$ )	"extra $Z$ s"
	$\times \overleftarrow{\partial}_\mu B_{\mu\nu}$	kinetic mixing
	$\times \overleftarrow{\partial}_\nu \tilde{B}_{\mu\nu}$	$\theta$ -mixing (weless)
	$\times \varphi^\dagger \nabla_\mu \varphi$ (through $ \nabla \varphi ^2$ )	charge "dequantization"
fermion $N$	$\times \varphi^\dagger L$	
	Weyl	$\nu_R$ , "sterile"
	Majorana	see-saw

Including supersymmetric particles, or higher dimension operators, opens up many more possibilities.

Especially noteworthy: The lightest “conventional” superpartner might decay very slowly into a gravitino or axino. This affects the dark matter density.





Observable	central $\pm$ C.L. $\equiv 1\sigma$	$\pm$ C.L. $\equiv 2\sigma$	$\pm$ C.L. $\equiv 3\sigma$
$ V_{ud} $	$0.97383^{+0.00024}_{-0.00023}$	$+0.00047$ $-0.00047$	$+0.00071$ $-0.00071$
$ V_{us} $	$0.2272^{+0.0010}_{-0.0010}$	$+0.0020$ $-0.0020$	$+0.0030$ $-0.0030$
$ V_{ub} $ [ $10^{-3}$ ]	$3.82^{+0.15}_{-0.15}$	$+0.31$ $-0.29$	$+0.49$ $-0.44$
$ V_{ub} $ [ $10^{-3}$ ] (meas. not in fit)	$3.64^{+0.19}_{-0.18}$	$+0.39$ $-0.36$	$+0.60$ $-0.55$
$ V_{cd} $	$0.22712^{+0.00099}_{-0.00103}$	$+0.00199$ $-0.00205$	$+0.00300$ $-0.00307$
$ V_{cs} $	$0.97297^{+0.00024}_{-0.00023}$	$+0.00048$ $-0.00047$	$+0.00071$ $-0.00071$
$ V_{cb} $ [ $10^{-3}$ ]	$41.79^{+0.63}_{-0.63}$	$+1.26$ $-1.27$	$+1.89$ $-1.90$
$ V_{cb} $ [ $10^{-3}$ ] (meas. not in fit)	$44.9^{+1.2}_{-2.8}$	$+2.4$ $-5.7$	$+3.8$ $-7.7$
$ V_{td} $ [ $10^{-3}$ ]	$8.28^{+0.33}_{-0.29}$	$+0.92$ $-0.57$	$+1.38$ $-0.86$
$ V_{ts} $ [ $10^{-3}$ ]	$41.13^{+0.63}_{-0.62}$	$+1.25$ $-1.24$	$+1.87$ $-1.86$
$ V_{tb} $	$0.999119^{+0.000026}_{-0.000027}$	$+0.000052$ $-0.000054$	$+0.000078$ $-0.000082$
$ V_{td}/V_{ts} $	$0.2011^{+0.0081}_{-0.0065}$	$+0.0230$ $-0.0127$	$+0.0345$ $-0.0195$
$ V_{ud}V_{ub}^* $ [ $10^{-3}$ ]	$3.72^{+0.15}_{-0.14}$	$+0.30$ $-0.29$	$+0.48$ $-0.43$
$\arg[V_{ud}V_{ub}^*]$ (deg)	$59.8^{+4.9}_{-4.0}$	$+13.9$ $-7.8$	$+20.9$ $-12.1$
$\arg[-V_{ts}V_{tb}^*]$ (deg)	$1.043^{+0.061}_{-0.057}$	$+0.151$ $-0.114$	$+0.238$ $-0.176$
$ V_{cd}V_{cb}^* $ [ $10^{-3}$ ]	$9.49^{+0.15}_{-0.15}$	$+0.30$ $-0.30$	$+0.45$ $-0.45$
$\arg[-V_{cd}V_{cb}^*]$ (deg)	$0.0339^{+0.0021}_{-0.0020}$	$+0.0050$ $-0.0040$	$+0.0077$ $-0.0060$
$ V_{td}V_{tb}^* $ [ $10^{-3}$ ]	$8.27^{+0.33}_{-0.29}$	$+0.93$ $-0.57$	$+1.38$ $-0.85$
$\arg[V_{td}V_{tb}^*]$ (deg)	$-22.84^{+1.00}_{-0.99}$	$+1.98$ $-2.02$	$+2.93$ $-3.21$
$\sin\theta_{12}$	$0.2272^{+0.0010}_{-0.0010}$	$+0.0020$ $-0.0020$	$+0.0030$ $-0.0030$
$\sin\theta_{13}$ [ $10^{-3}$ ]	$3.82^{+0.15}_{-0.15}$	$+0.31$ $-0.30$	$+0.49$ $-0.44$
$\sin\theta_{23}$ [ $10^{-3}$ ]	$41.78^{+0.63}_{-0.63}$	$+1.26$ $-1.26$	$+1.90$ $-1.89$

Table 3: Numerical results of the global CKM fit (II) [51]. The errors correspond to one, two and three standard deviations, respectively.



# Hidden Sectors

# Underground

