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).

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

Höcker+Ligeti, hep-ph/0605217

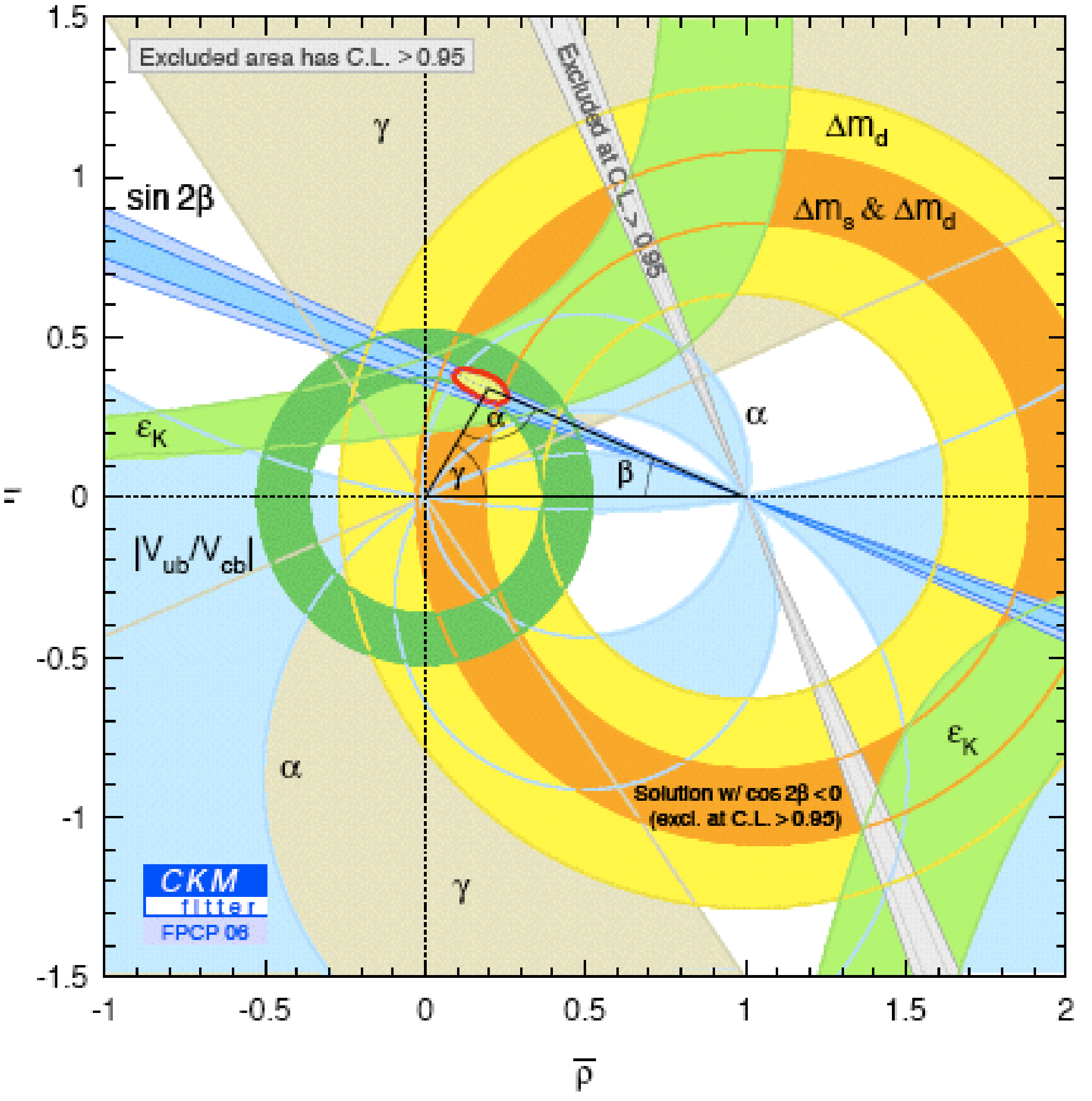


Figure 8: Confidence levels in the (ρ, η) plane for the global CKM fit. The shaded areas indicate 95% C.L. allowed regions [51].

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?

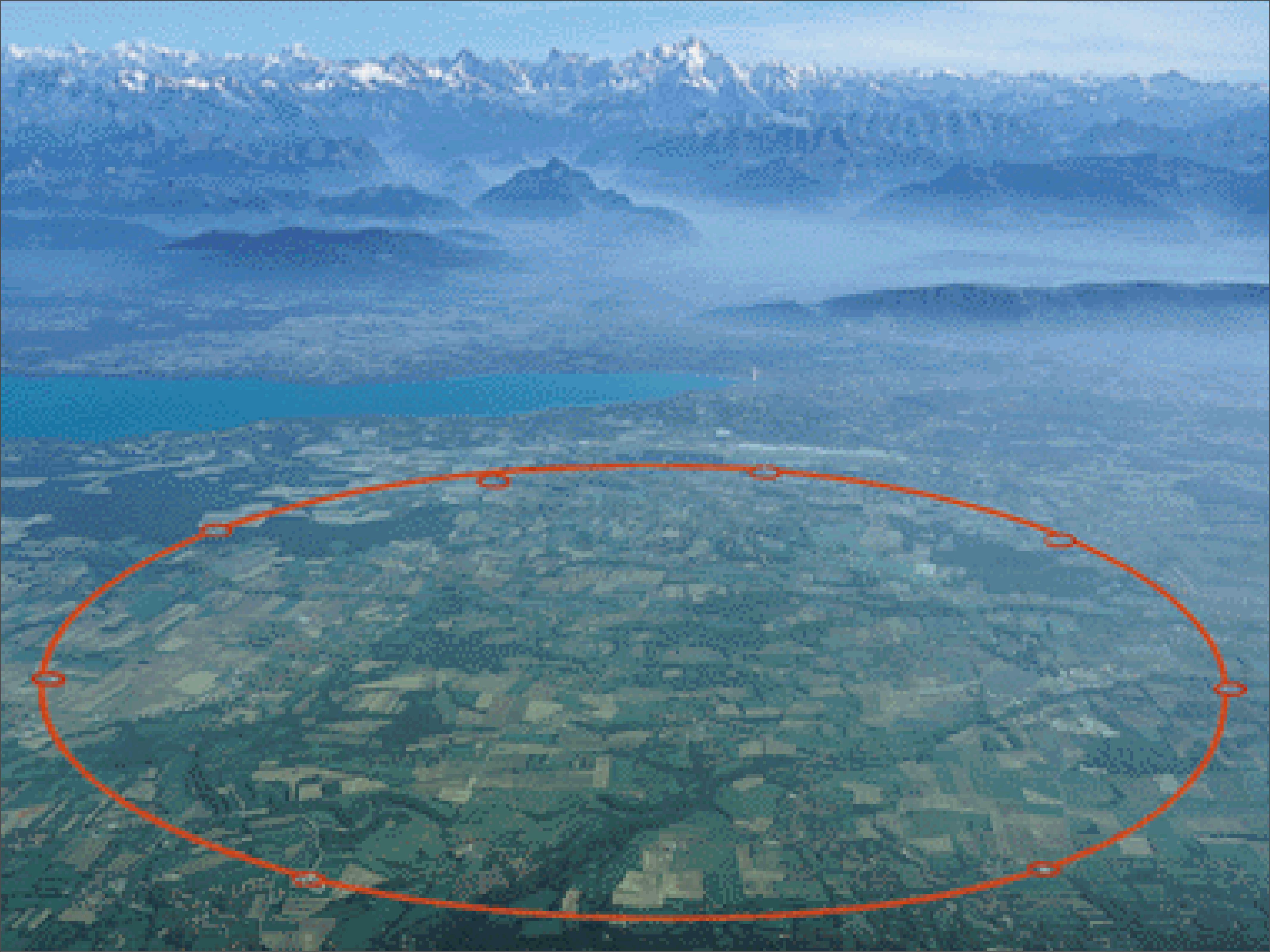
What's the dark matter?

What's the dark energy?

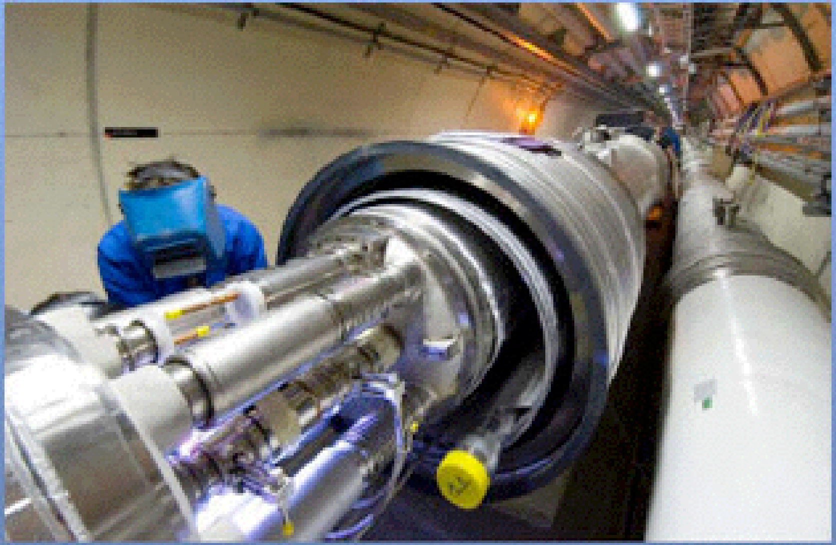
Can we clean up the messy bits?

What else is left out?

Some answers should be forthcoming soon:



Underground



The SM leaves an unfinished agenda, however:

What drives electroweak symmetry breaking?

Do the gauge interactions unify nicely?

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?

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?

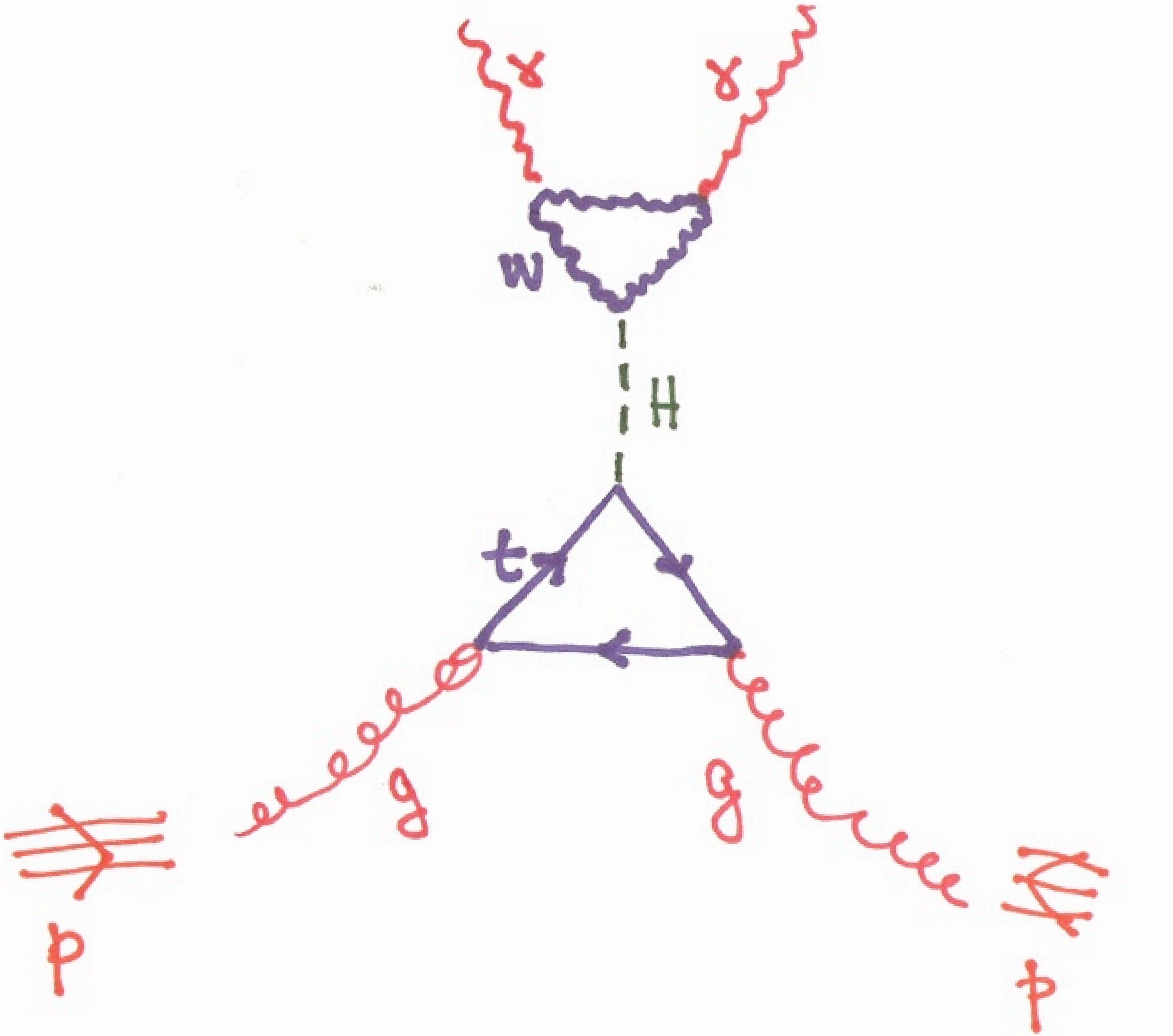
The Minimal Model

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.


γ
γ
W
H
t
g
g
p
p

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

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

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

$$(\,u \quad u \quad u\,)^{R}_{2/3}$$

$$(\,d \quad d \quad d\,)^{R}_{-1/3}$$

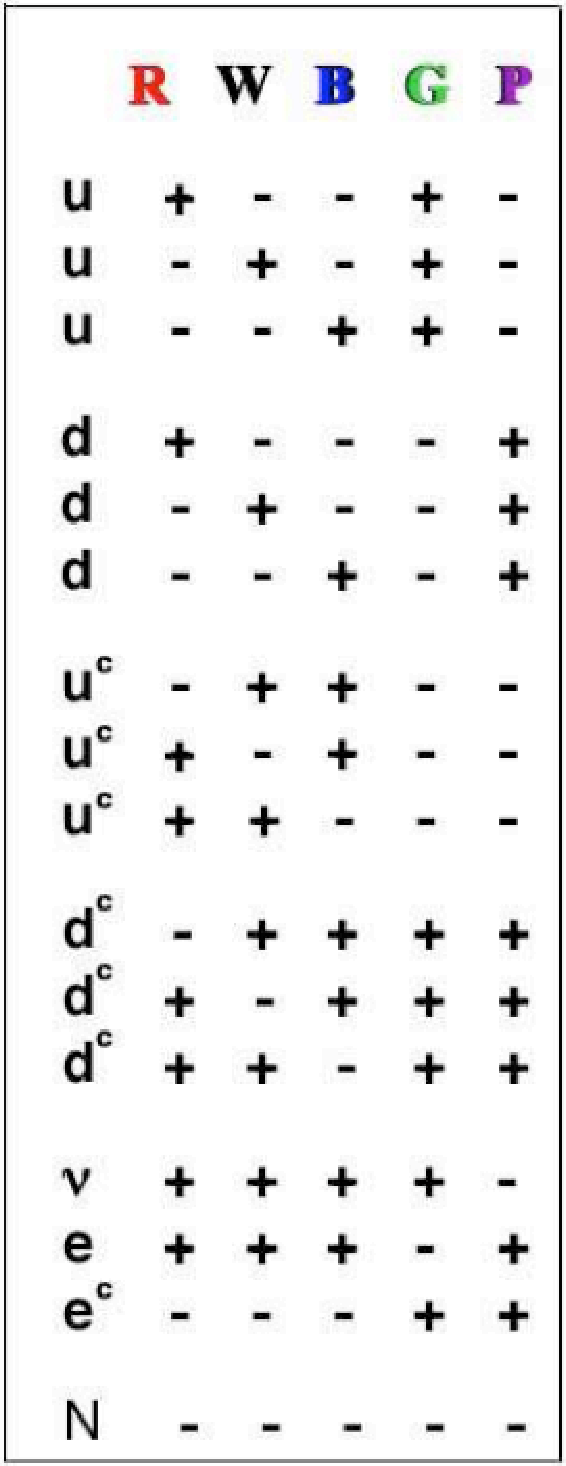
$$(\,e\,)^{R}_{-1}$$

No ν^{R}

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

mixed, not unified

SO(10)

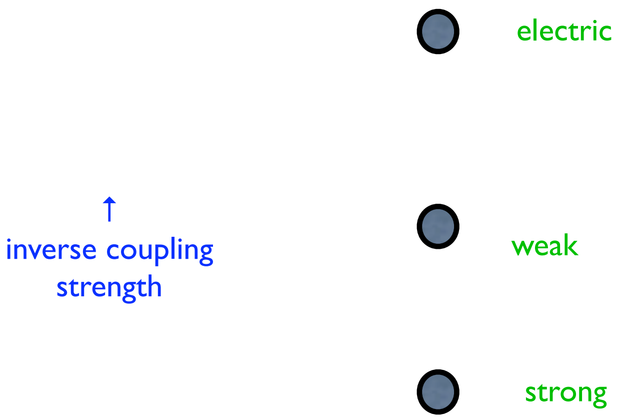


	R	W	B	G	P
u	+	-	-	+	-
u	-	+	-	+	-
u	-	-	+	+	-
d	+	-	-	-	+
d	-	+	-	-	+
d	-	-	+	-	+
u^c	-	+	+	-	-
u^c	+	-	+	-	-
u^c	+	+	-	-	-
d^c	-	+	+	+	+
d^c	+	-	+	+	+
d^c	+	+	-	+	+
ν	+	+	+	+	-
e	+	+	+	-	+
e^c	-	-	-	+	+
N	-	-	-	-	-

N.B.: One hand rules them all!

Hypercharge Y = -1/6 (R+W+B) + 1/4 (G+P) electron ↔ quarks

photon ↔ gluons



↑

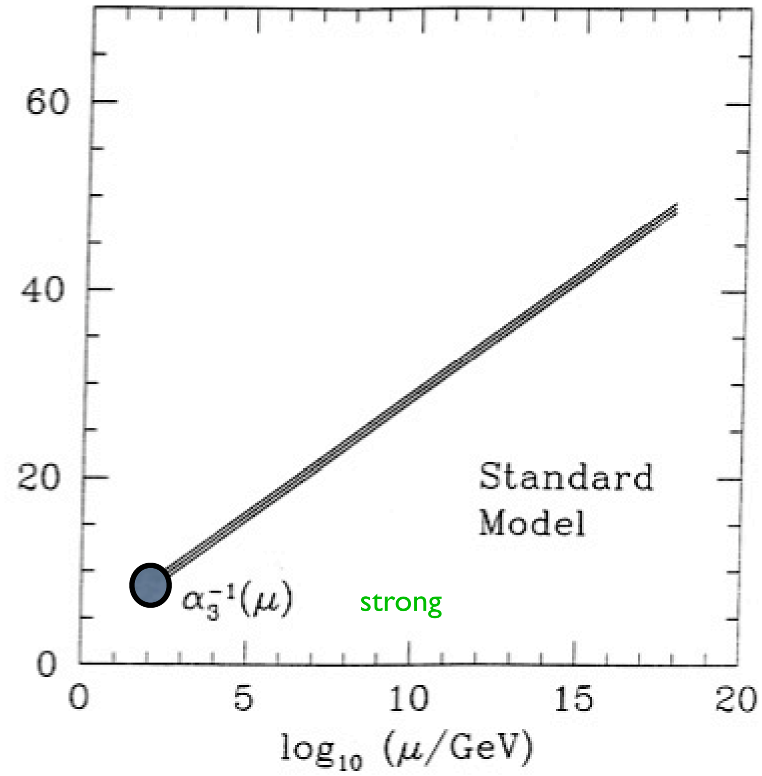
inverse coupling strength

electric

weak

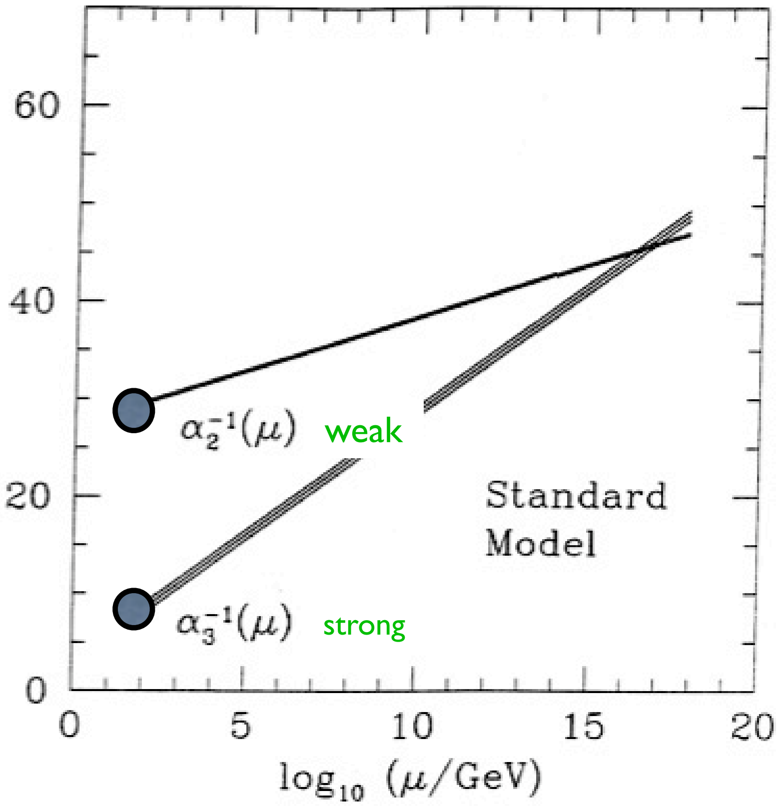
strong

↑
inverse coupling
strength

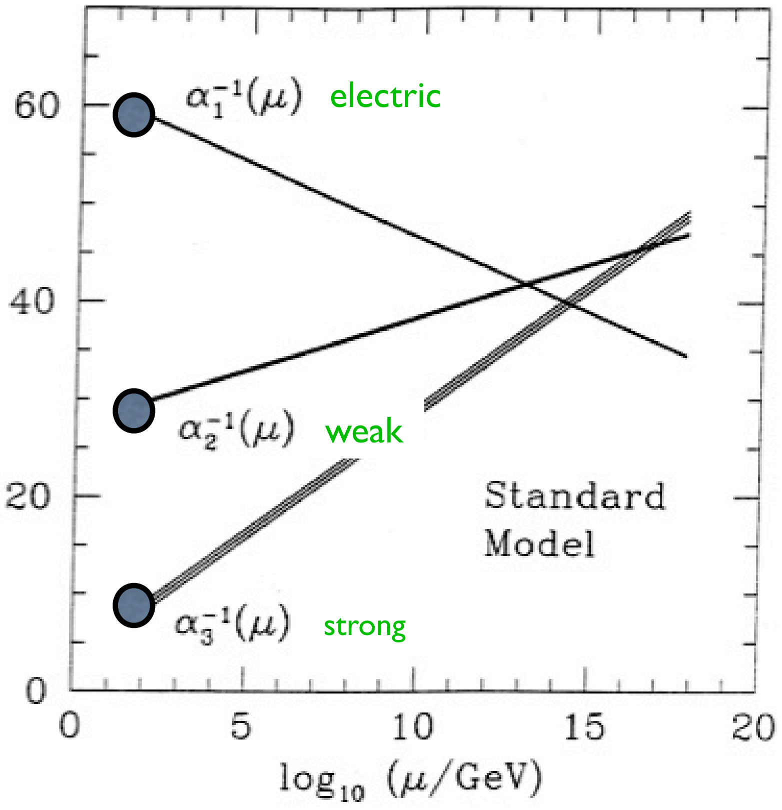


large energy, short distance→

↑
inverse coupling
strength



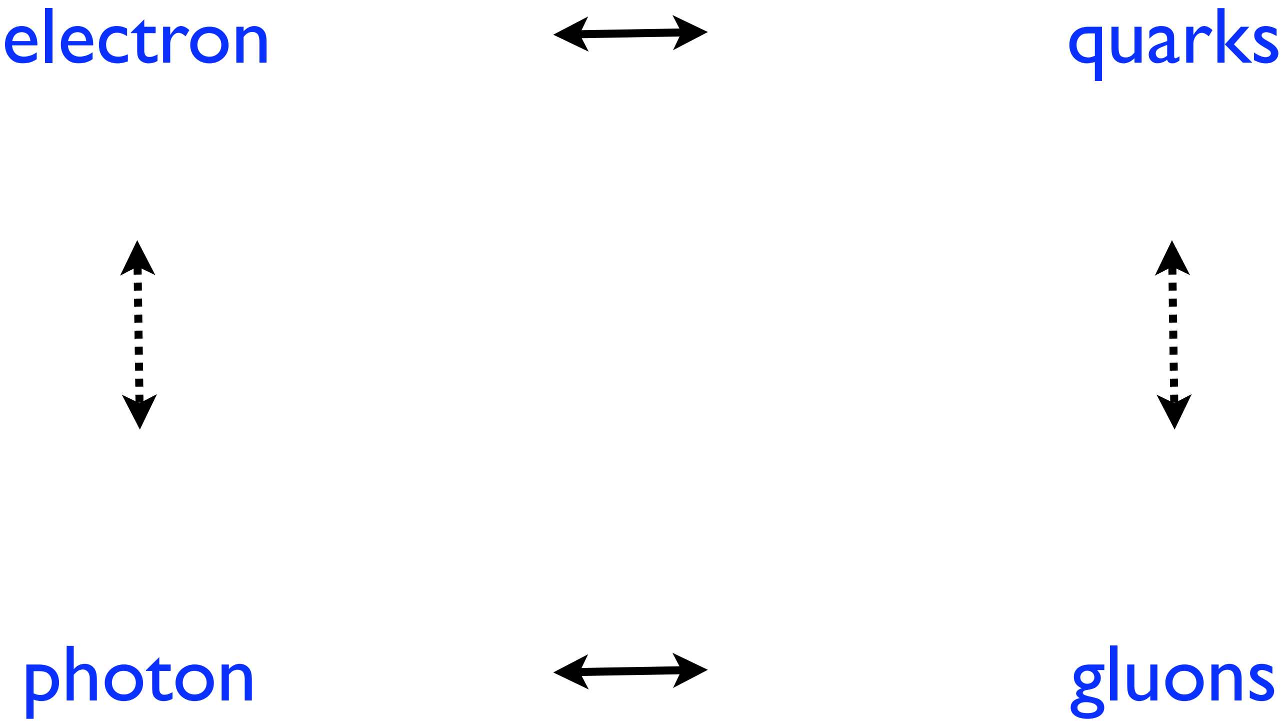
large energy, short distance→



↑
inverse coupling
strength

large energy, short distance→

Now Add SUSY



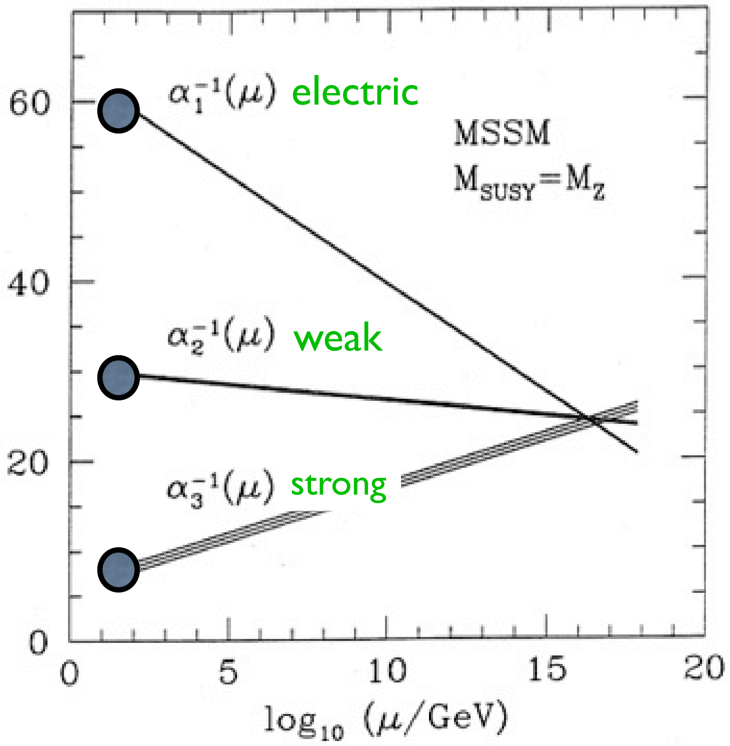
electron

quarks

photon

gluons

Unification ♥ SUSY

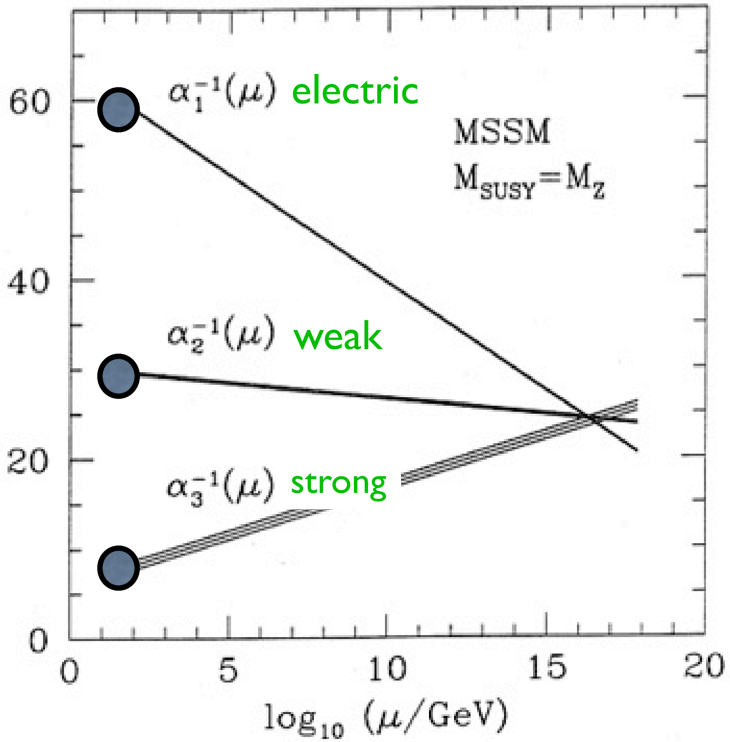


↑
inverse
coupling
strength

large energy, short distance→

Unification ♥ SUSY

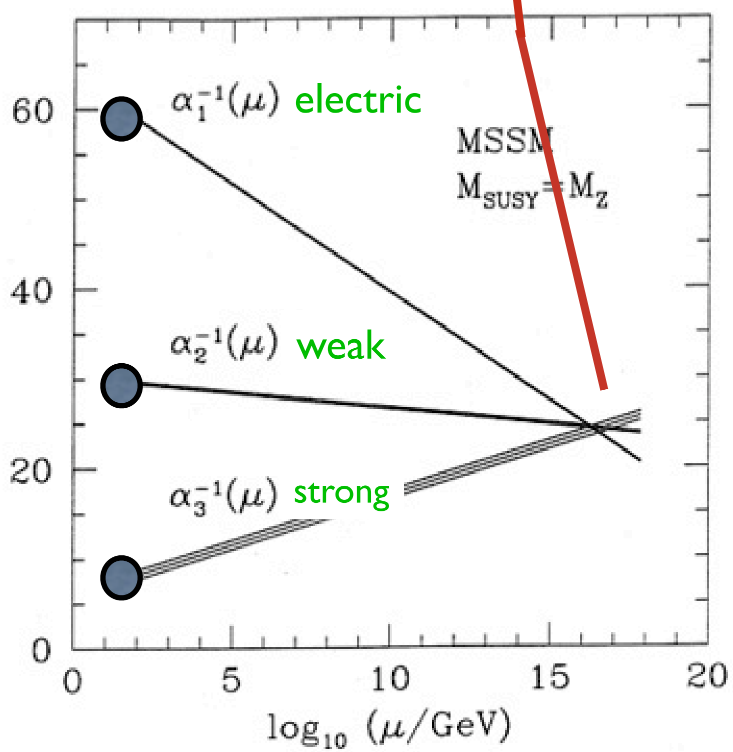
↑
inverse
coupling
strength



large energy, short distance→

Gravity fits too!
(roughly)

Unification ♥ SUSY

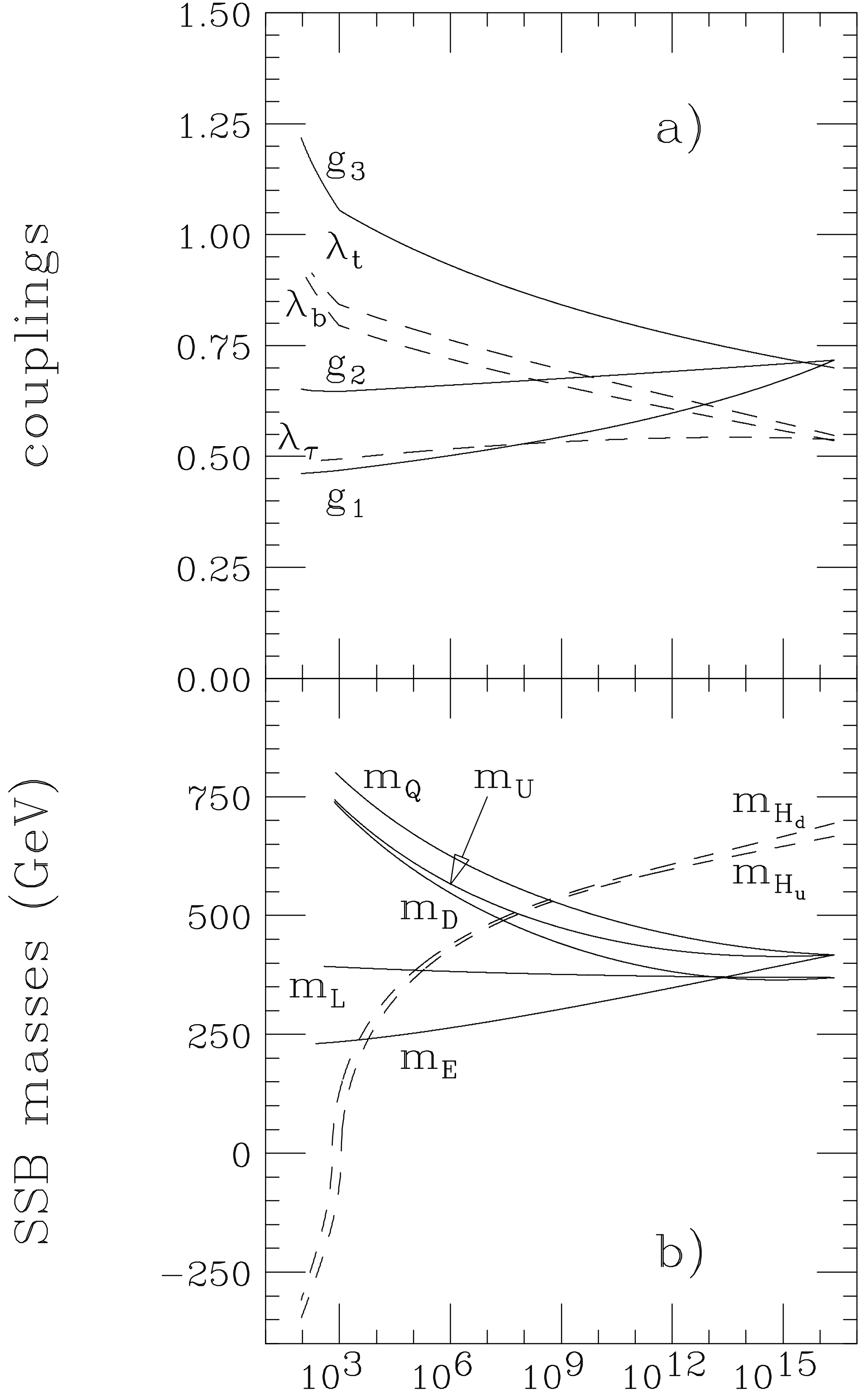


↑
inverse
coupling
strength

large energy, short distance→

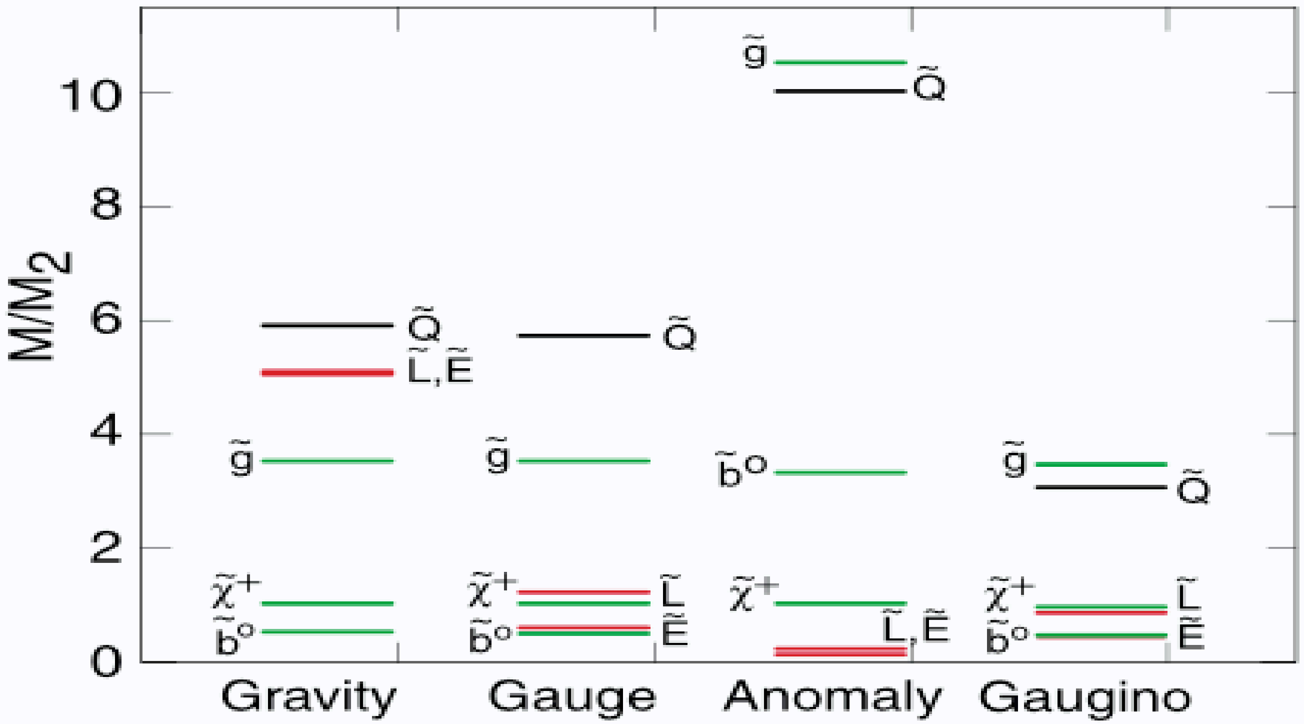
Gravity fits too!
(roughly)

There could be additional manifestations of unification:


couplings
1.50
1.25
1.00
0.75
0.50
0.25
0.00
a)
g_3
λ_t
λ_b
g_2
λ_τ
g_1
SSB masses (GeV)
750
500
250
0
−250
b)
m_Q
m_U
m_D
m_L
m_E
m_{H_d}
m_{H_u}
10^3
10^6
10^9
10^{12}
10^{15}

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!

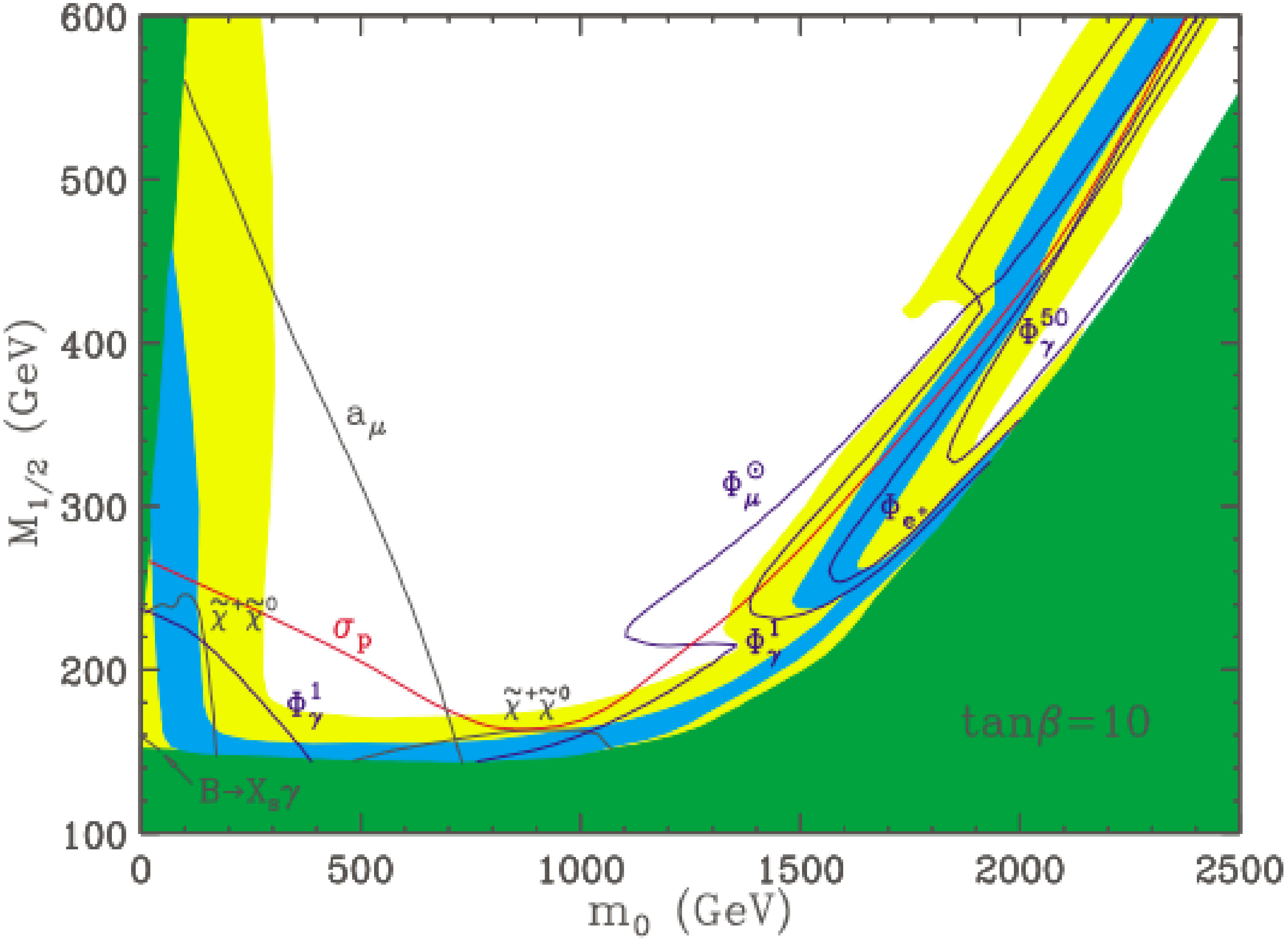
Sparticle spectra for various mediation mechanisms.

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.


600
500
400
300
200
100
$M_{1/2}$ (GeV)
0
500
1000
1500
2000
2500
m_0 (GeV)
a_μ
σ_p
$\tilde{\chi}^+\tilde{\chi}^0$
$\tilde{\chi}^+\tilde{\chi}^0$
Φ_γ^1
Φ_γ^1
$\Phi_\mu^\odot$
Φ_{e*}
Φ_γ^{50}
$B \to X_s\gamma$
$\tan\beta=10$

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]

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 $T \geq 1$ GeV, θ stays frozen at θ_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.

θ_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 θ_0, $d \sin^2\theta_0$ for ρ_{DM}/ρ_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.

Tegmark, Aguirre, Rees, FW astro-ph/0511774

The Fragility of Life

Making User-Friendly Structures

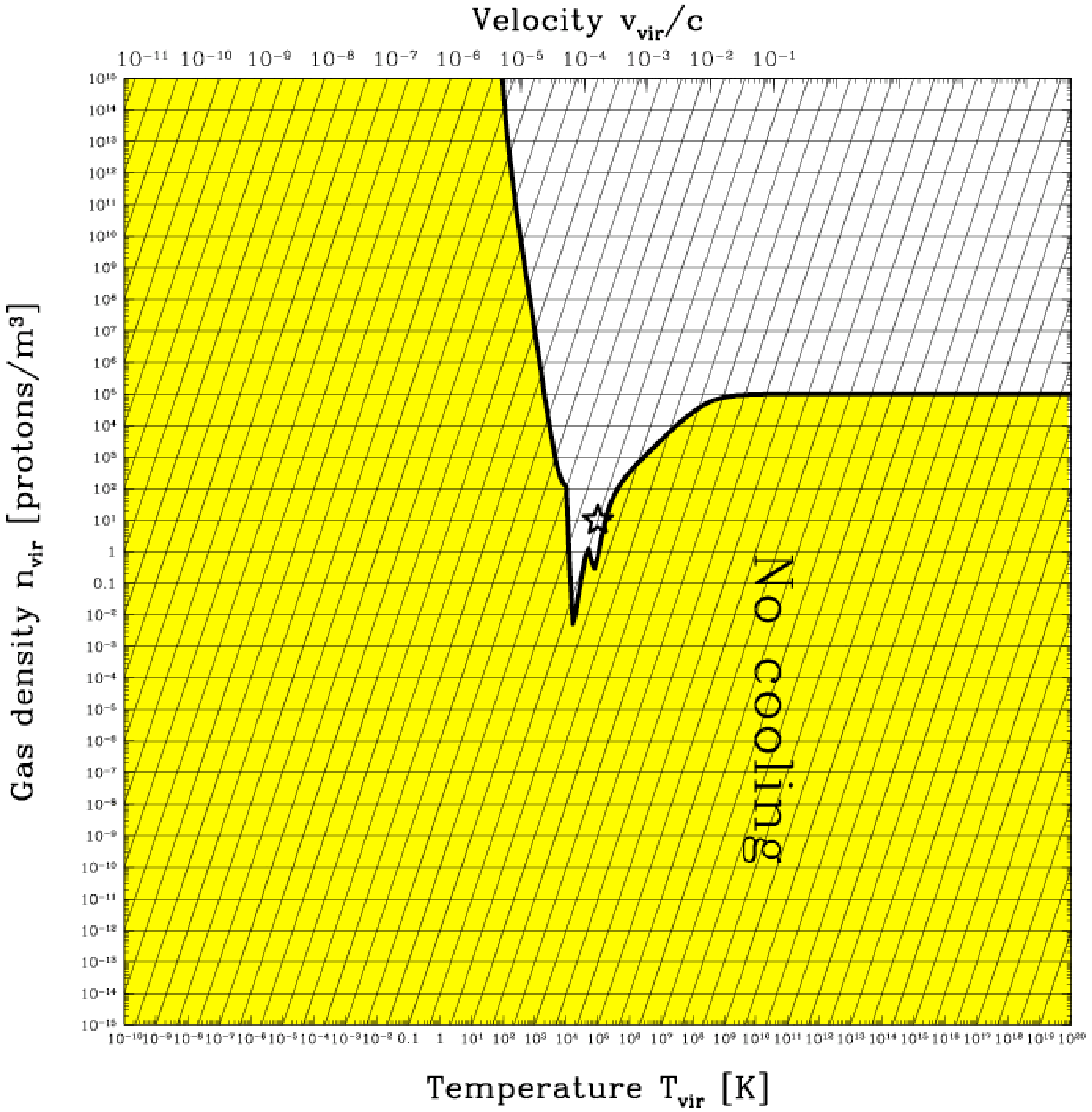
Lots of things can go wrong when you try to make nice solar systems, starting with small seed fluctuations:

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

density ↑

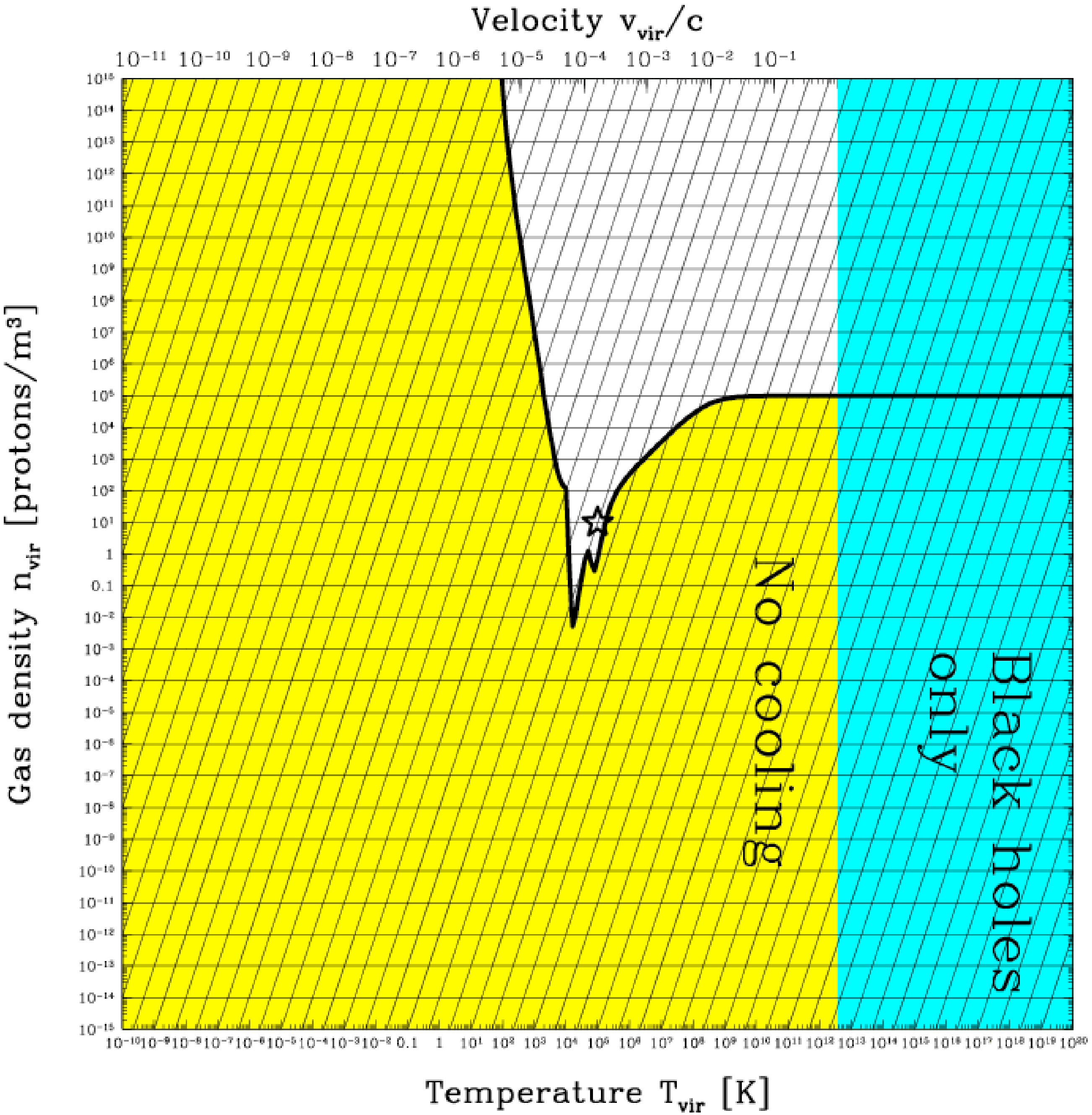
time ↓

size ↓



contrast →

Your fluctuations might collapse into black holes:



density ↑

time ↓

size ↓

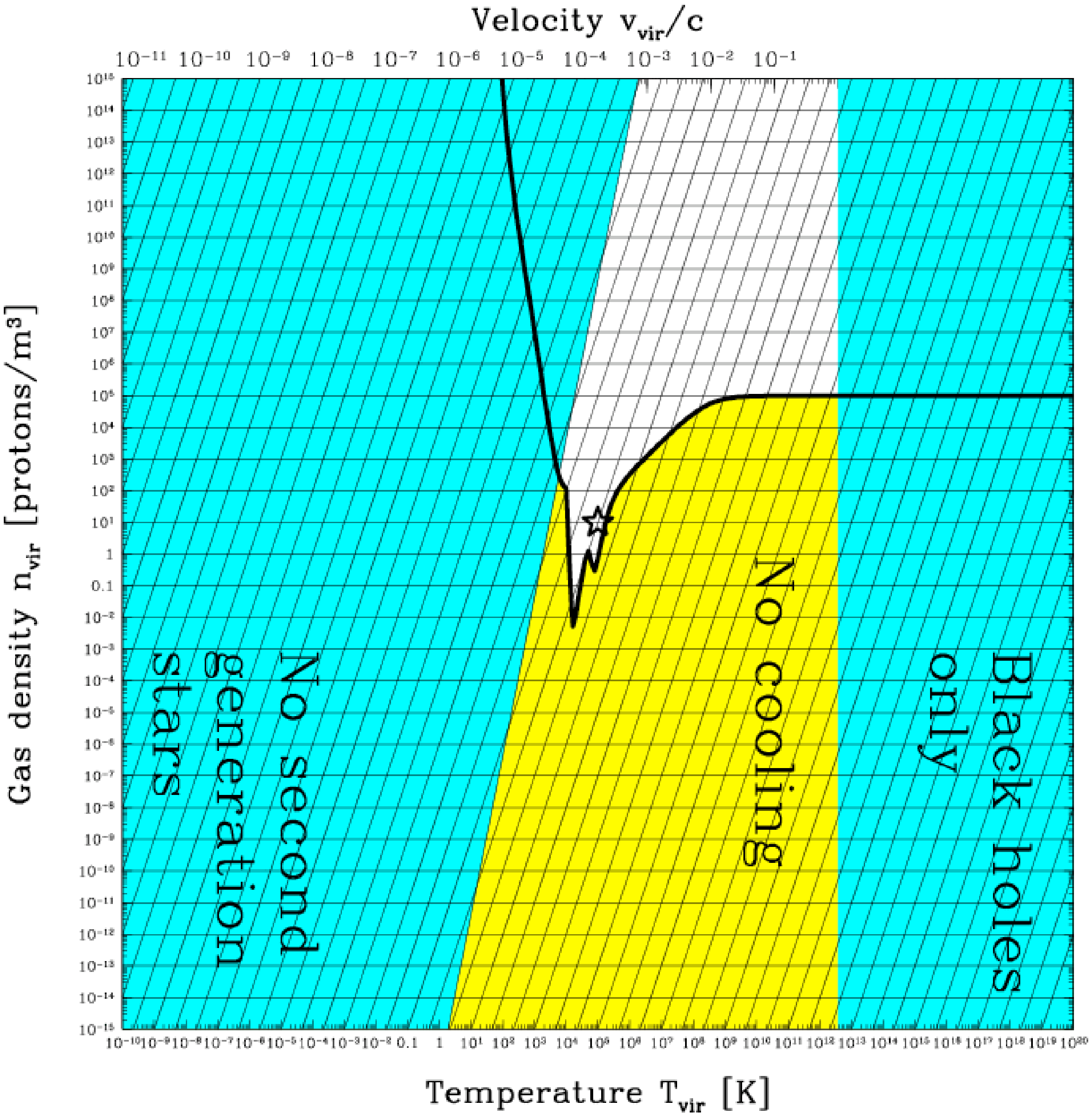
contrast →

The matter might get swept out by the first supernovae:

density ↑

time ↓

size ↓



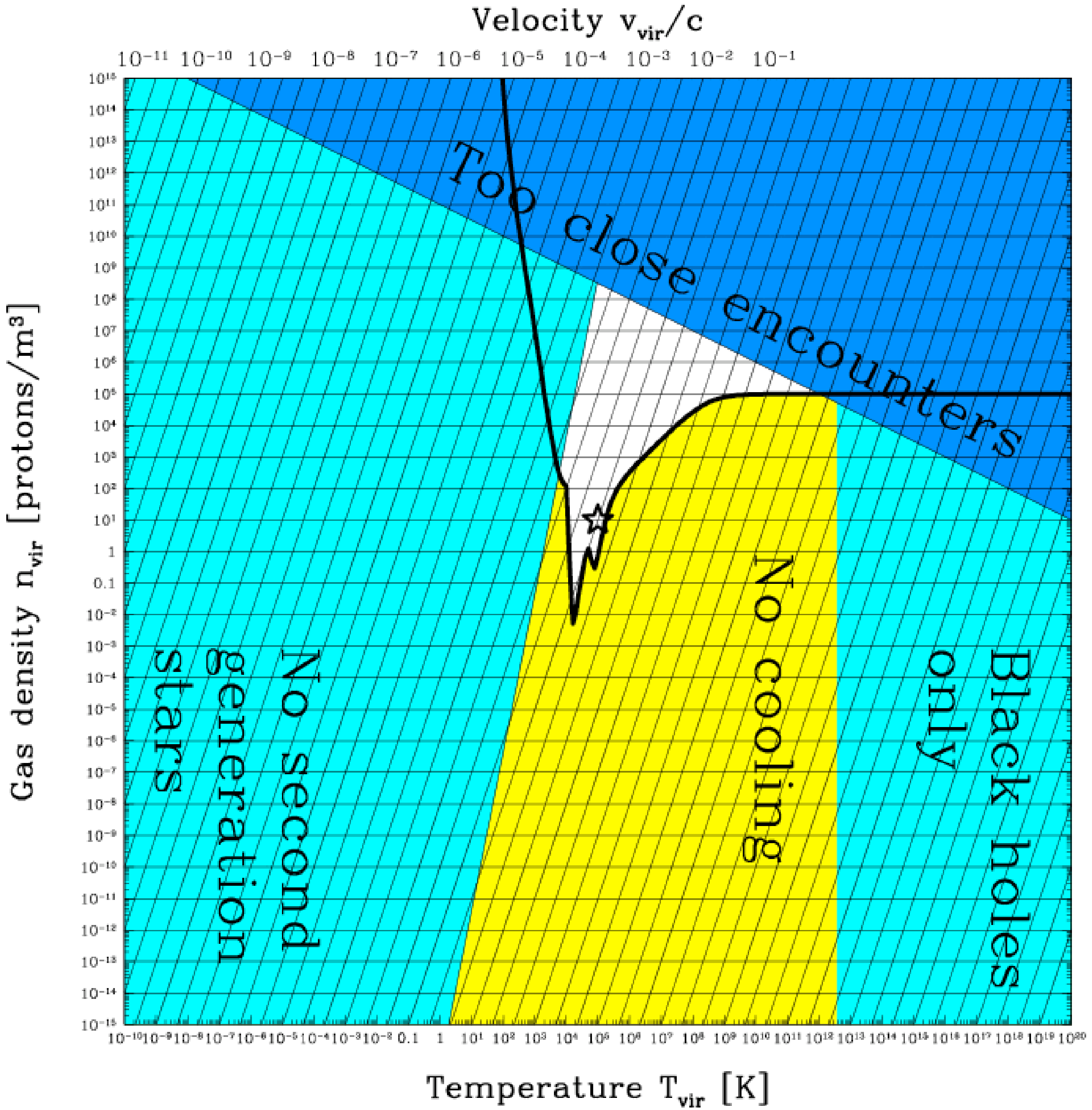
contrast →

There might be no safe haven from disruptive encounters:

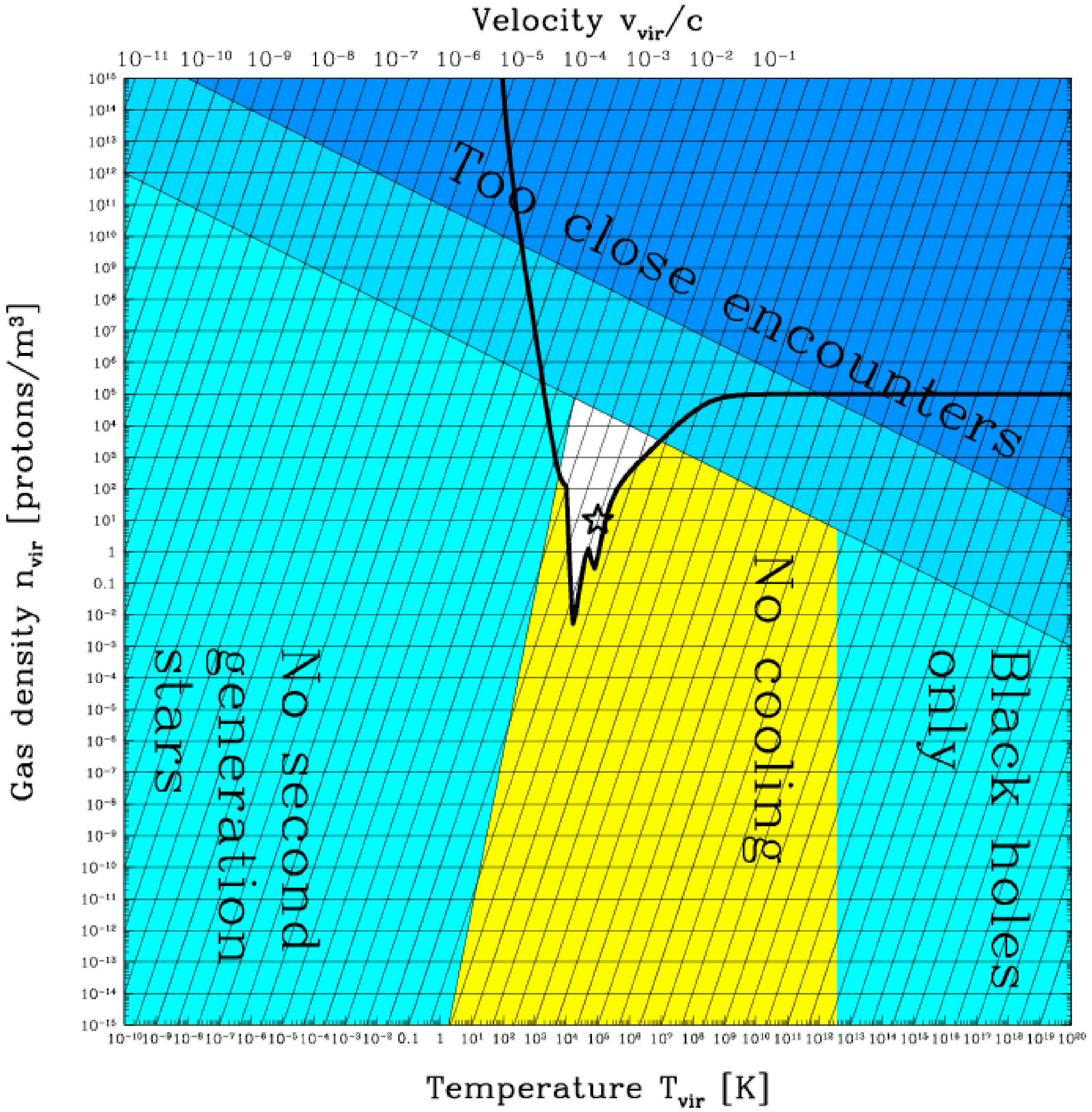
density ↑

time ↓

size ↓



contrast →



density ↑

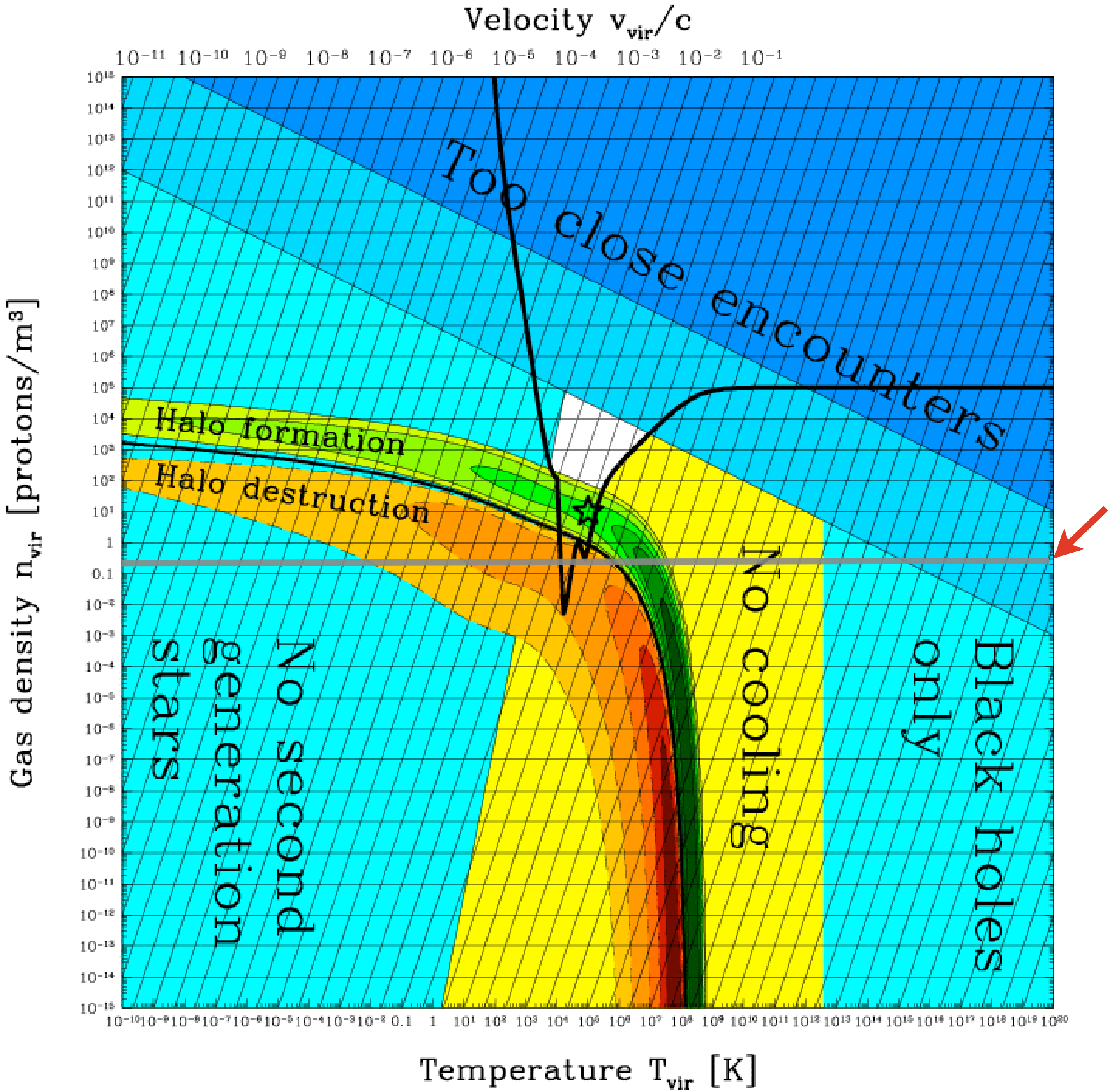
time ↓

size ↓

contrast →

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 ↑

time ↓

size ↓

Λ cutoff

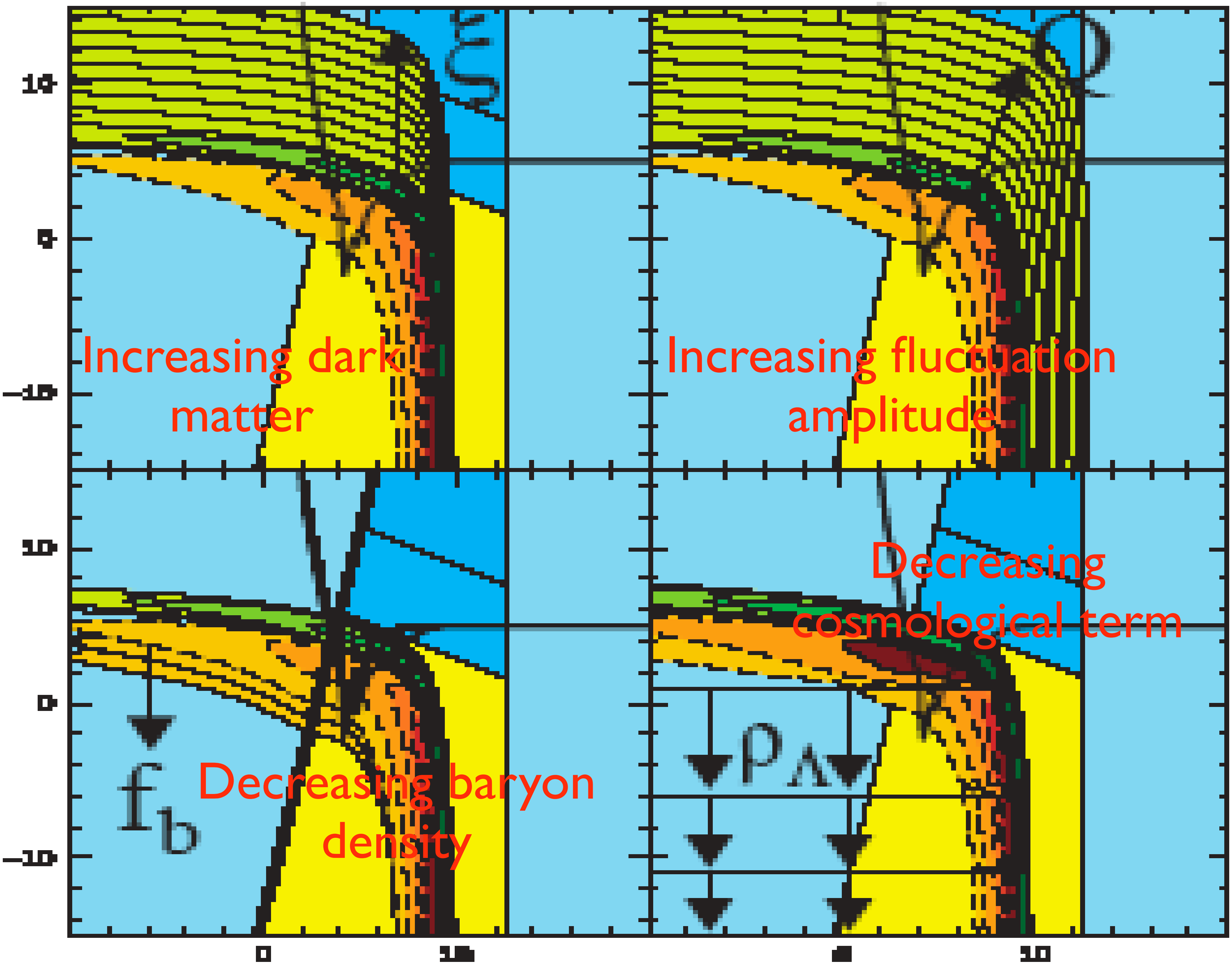
contrast →

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:



Increasing dark matter

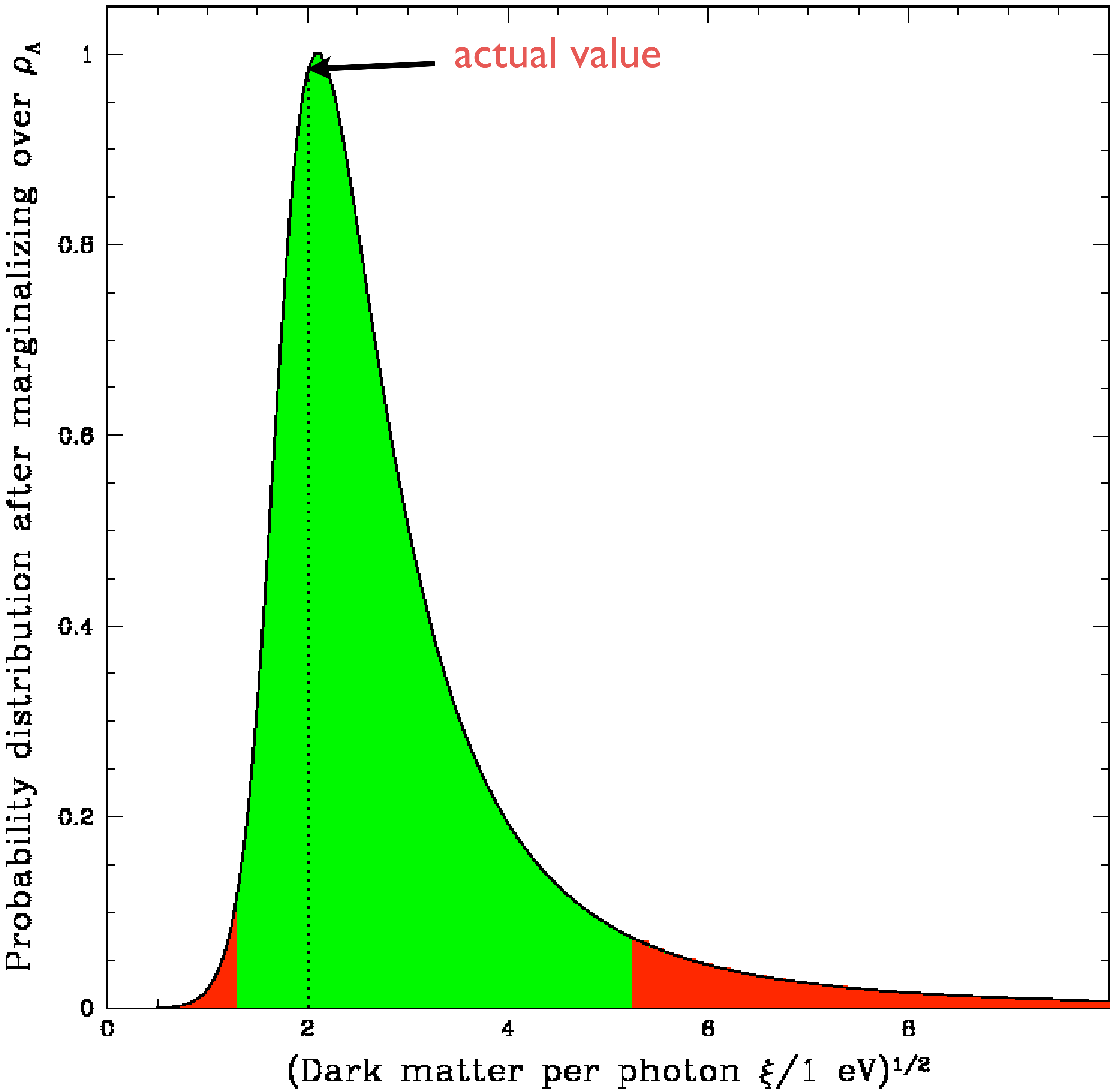
Increasing fluctuation amplitude

Decreasing baryon density

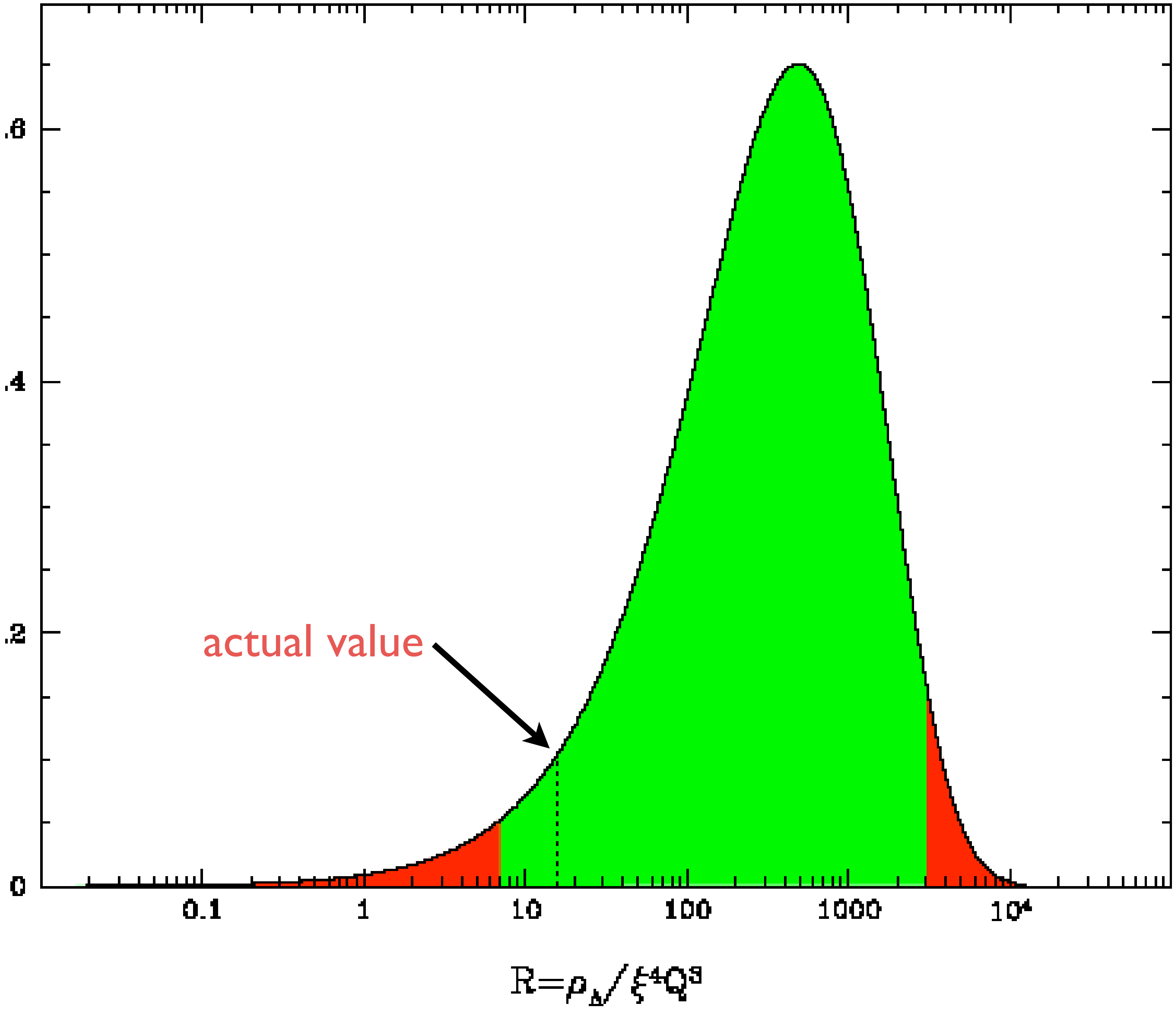
Decreasing cosmological term

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

Here is the θ_0 distribution near 0, translated into dark matter density:


actual value
Probability distribution after marginalizing over ρ_Λ
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
(Dark matter per photon ξ/1 eV)$^{1/2}$

For comparison, here is the ρ_λ (dark energy) distribution, given a flat prior:



actual value

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~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.

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.

Hidden Sectors

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)xSU(2)xU(1) singlet real scalar field *phantom* field η.

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:

$$V(\phi,\eta) = -\mu_1^2\,\phi^\dagger\phi + \lambda_1(\phi^\dagger\phi)^2$$

$$-\mu_2^2\,\eta^2 + \lambda_2\,\eta^4 \;\boxed{-\kappa\,\phi^\dagger\phi\,\eta^2}$$

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: Quantum Scale Model

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

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

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

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

The σ_0 can decay into its massless "pions". So we get dilution.

Motivations for Hidden Sectors

Hippocratic oath

Stacks and throats

Plays well with SUSY

Flavor and axions

Hippocratic Oath

First, do no harm.

Mixing in singlets does not upset the unification of couplings, nor does it introduce any flavor 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 $E_8 x E_8$ heterotic string was an early incarnation of a hidden sector.

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 "naturality" problems.

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)xSU(2)xU(1), at a high scale.)

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

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.

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

We can analyze “portals” of different spin systematically:

Low-Dimension Portals

vector V_μ	$\times\ \bar{f}\gamma_\mu f$	(through $\bar{f}\not{\nabla}f$)	"extra Zs"
	$\times\ \overleftarrow{\partial}_\nu B_{\mu\nu}$		kinetic mixing
	$\times\ \overleftarrow{\partial}_\nu \tilde{B}_{\mu\nu}$		Θ-mixing (useless)
	$\times\ \varphi^\dagger \nabla_\mu \varphi$	(through $\lvert\nabla\varphi\rvert^2$)	charge "dequantization"
fermion N	$\times\ \varphi^\dagger L$		
		Weyl	ν_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.

Summary and Conclusions

With the LHC, we will move firmly beyond the standard model.

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 prove or disprove that explanation**.

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.