Three Ways Beyond the Standard Model

Quantitative Unification, Axions, Portals

The standard model is astoundingly successful, but it has major esthetic flaws:

several moving parts, tenuously connected

many continuously adjustable parameters

Some of these shortcomings may reflect pure "environmental accidents", others may reflect selection bias ("anthropic principle").

In those cases it may be difficult to maintain traditional standards of theoretical physics. We might be reduced to *accommodation*, as opposed to constructive *explanation*.

We can identify a few outstanding empirical facts, however, that seem unlikely to be explained away along those lines:

gauge group and multiplet structure suggestive of unification

approximate unification of gauge couplings

small but non-zero neutrino masses

smallness of the QCD θ parameter

These facts have inspired truth-worthy theoretical proposals with wide-ranging implications.

With the coming of the LHC, and expected advances in observational astronomy, the trial date for those ideas is approaching.

Also, the structure of the SM suggests some particular kinds of "new physics" that are both plausible and accessible .

Also, the structure of the (*extended*) SM suggests some particular forms of "new physics" that are both ~~plausible~~ *not implausible* and ~~accessible~~ *not inaccessible*.

Many of the central ideas I'll discuss go back a long way -- some even to the days of my youth -- but there's been continuing ferment.

Crucial aspects remain vague and sketchy; there's a big challenge to do better!

Quantitative Unification

First, qualitative unification:

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

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

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

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

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

$$\nu^{R}$$

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

mixed, not unified

three fundamental "forces"

(plus gravity)

six fundamental "materials"

(plus 2 repeats)

One "material"

	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	-	-	-	-	-

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

SO(10)

One "force"

We should aspire to embed this striking regularity within a consistent dynamical framework, and to draw further consequences from it.

(Philosophical prejudices: Simplicity and testability are virtues.)

Some simple ideas take us rather far, and lead to testable consequences.

The standard theories of superconductivity and of electroweak symmetry breaking show us how gauged spontaneous symmetry breaking can give reduced symmetry, and lift the masses of the unobserved vector bosons nonabelian symmetry requires.

The renormalization group shows us how observed (low-energy) couplings might diverge from the (high-energy) equality nonabelian symmetry requires.

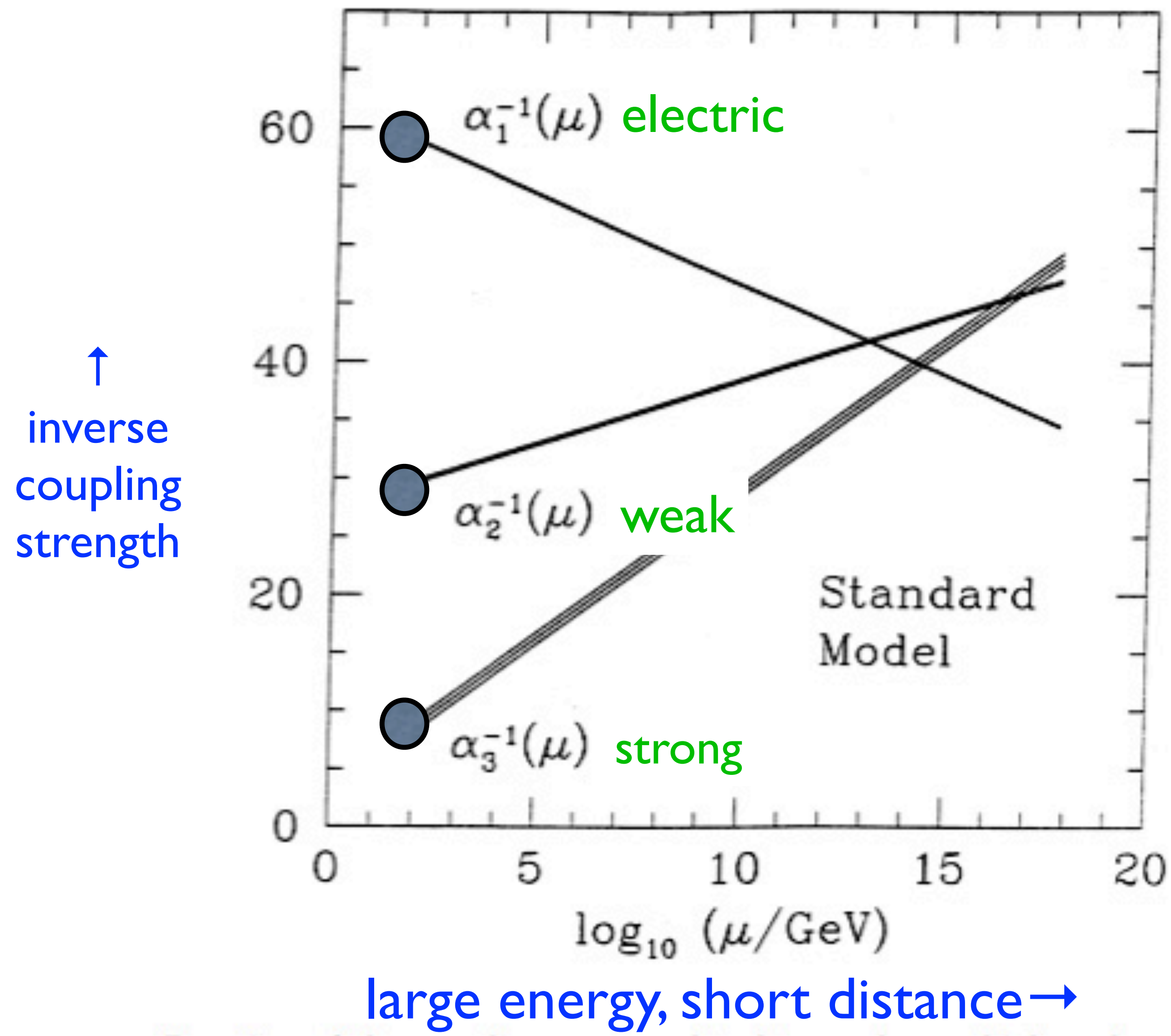
We’re invited to apply those two great dynamical lessons of the standard model to achieve unification.

The big questions are whether this scenario:

survives more detailed and quantitative scrutiny

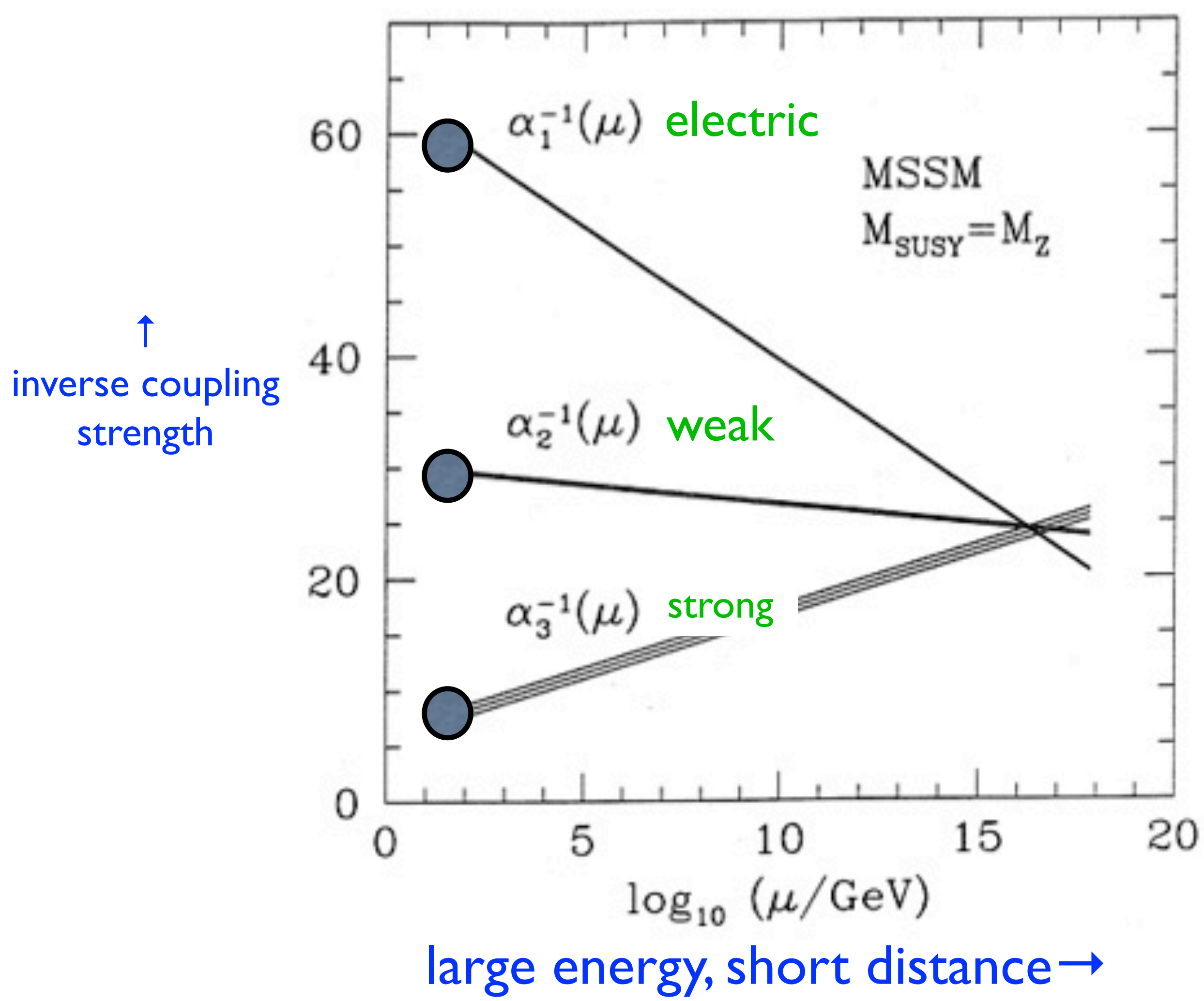
bears additional fruit

Famously, if we construct our unified theory using only the degrees of freedom in the standard model, it doesn’t quite work:


60
40
20
0
0
5
10
15
20
$\alpha_1^{-1}(\mu)$ electric
$\alpha_2^{-1}(\mu)$ weak
$\alpha_3^{-1}(\mu)$ strong
Standard Model
$\log_{10}(\mu/\mathrm{GeV})$
↑ inverse coupling strength
large energy, short distance→

while if we extend the theory to include the degrees of freedom required for approximate supersymmetry, at masses ~10^2-10^3 GeV, it works much better:

Why I ♥ SUSY



↑
inverse coupling
strength
$\alpha_1^{-1}(\mu)$ electric
$\alpha_2^{-1}(\mu)$ weak
$\alpha_3^{-1}(\mu)$ strong
MSSM
$M_{SUSY}=M_Z$
60
40
20
0
0
5
10
15
20
$\log_{10}(\mu/\mathrm{GeV})$
large energy, short distance→

How good is it? To get an objective idea, consider the statement relating observables to theory:

$$\frac{1}{g_j^2(M)} - \frac{1}{g_j^2(\mu)} \;=\; -\,b_j \log\frac{M}{\mu}$$

$$b_1(\Delta_2 - \Delta_3) + b_2(\Delta_3 - \Delta_1) + b_3(\Delta_1 - \Delta_2) \;=\; 0$$

$$\Delta_j - \Delta_k \;\equiv\; \left(\frac{1}{g_j^2(M)} - \frac{1}{g_j^2(\mu)}\right) - \left(\frac{1}{g_k^2(M)} - \frac{1}{g_k^2(\mu)}\right) \overset{?}{=} \frac{1}{g_k^2(\mu)} - \frac{1}{g_j^2(\mu)}$$

$$-0.04 + 4\delta_1 - 9.6\delta_2 + 5.6\delta_3 = 0$$

$\delta_j \equiv$ fractional deviation from unified coupling

$$\alpha_U \sim \frac{1}{25}$$

$$M_U \sim 2 \times 10^{16}\,\mathrm{GeV}$$

These results have several good features:

coupling not terribly strong

coupling not terribly weak

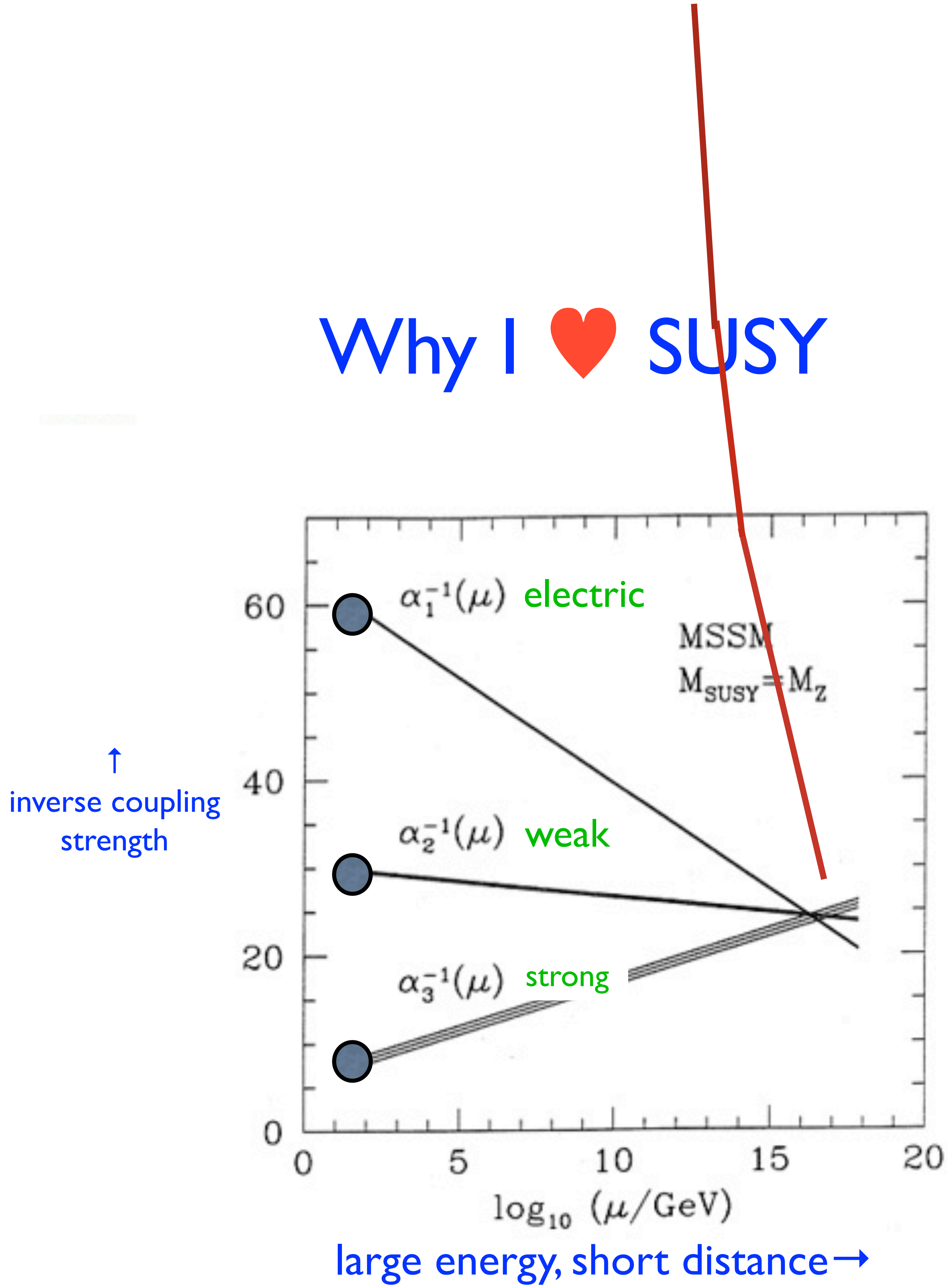
scale not too large (quantum gravity)

scale not too small (proton decay)

reasonable input to neutrino seesaw

remarkably good - but not perfect - unification with gravity:

Why I ♥ SUSY



Gravity fits too! (roughly)

To leading order, neither the accuracy of unification nor the scale of unification are affected by the addition of complete SU(5) multiplets (nor of course SU(3)xSU(2)xU(1) singlets). This is because only the differences (b_j - b_k) figure in the relevant calculations.

Extensions

If the symmetry-breaking terms are of a simple kind we get additional unification predictions, for fermion masses. The cleanest application is to the heaviest family.

5 dominance in SU(5) gives $y_b (M_U) = y_\tau (M_U)$

10 dominance in SO(10) gives $y_b (M_U) = y_\tau (M_U) = y_t (M_U)$

Of course, these Yukawa couplings get renormalized and processed before becoming masses.

The mass predictions are considerably more sensitive to low-energy corrections than are the gauge coupling predictions.

b- τ unification works reasonably well, and may suggest $m_{gluino} << m_{sbottom}$ and $\tan\beta >> 1$.

b- τ -t unification requires a large ratio between Higgs vacuum expectation values, $\tan\beta \approx 50$, and strongly suggests $m_{gluino} << m_{sbottom}$.

With precise information about the low-energy parameters, precise comparisons will become possible.

Axions

The theory of the strong interaction (QCD) admits a parameter, θ, that is observed to be unnaturally small: $|\theta| < 10^{-9}$.

This "coincidence" can be understood by promoting translation of θ to an asymptotic or classical quasi-symmetry, Peccei-Quinn (PQ) symmetry, that is spontaneously broken.

The axion field is established at the PQ transition, $<\phi> = F\ e^{i\theta} = F\ e^{ia/F}$.

At the transition, the energy associated with varying θ is negligible, and differences from the minimum $\theta \cong 0$ can be imprinted.

They store field energy that eventually materializes, with density roughly proportional to $F \sin^2\theta_0$ today.

ρ_0 in play

dilution by expansion

adiabatic damping

$$\rho_{\mathrm{Today}} = \sin^2\theta_0\,\Lambda_{\mathrm{QCD}}^4 \;\left(\frac{T}{\Lambda_{\mathrm{QCD}}}\right)^3 \;\frac{H}{m_a}$$

$$= \sin^2\theta_0\;\Lambda_{\mathrm{QCD}}\;T^3\;\left(\frac{\Lambda_{\mathrm{QCD}}^2}{M_{\mathrm{Planck}}}\right)/\left(\frac{\Lambda_{\mathrm{QCD}}^2}{F}\right)$$

$$= T^3\sin^2\theta_0\,\frac{F\Lambda_{\mathrm{QCD}}}{M_{\mathrm{Planck}}}$$

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.

Since experimental constraints require F $\geq$ 10^{10} GeV, axions are almost forced to be an important component of the astronomical dark matter, if they exist at all.

So it seems interesting to entertain the hypothesis that axions provide the bulk of the dark matter, and F $\cong$ 10^{12} GeV.

This has traditionally been regarded as the default axion cosmology. A cosmic axion background with $F \cong 10^{12}$ GeV might be detectable, in difficult experiments.

Searches are ongoing. $(a \rightarrow \underset{= B_{ext.}}{\underset{\uparrow}{\gamma}}\ \gamma)$

Inflationary Axion Cosmology

If inflation occurs after the PQ transition, things are very different.

Then the correlated volume inflates to include the entire presently observed universe, so we shouldn't average.

$F > 10^{12}$ GeV can be accommodated, by allowing "atypically" small $\sin^2\theta_0$.

In this scenario, most of the multiverse is overwhelmingly axion-dominated, and inhospitable for the emergence of complex structure, let alone observers.

Selection effects must be considered. (Linde, 1988).

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, $\sin^2\theta_0\, d\theta_0$ for ρ_{DM}/ρ_b.)

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

... nor, for that matter: unification, supersymmetry, landscape artistry, ...

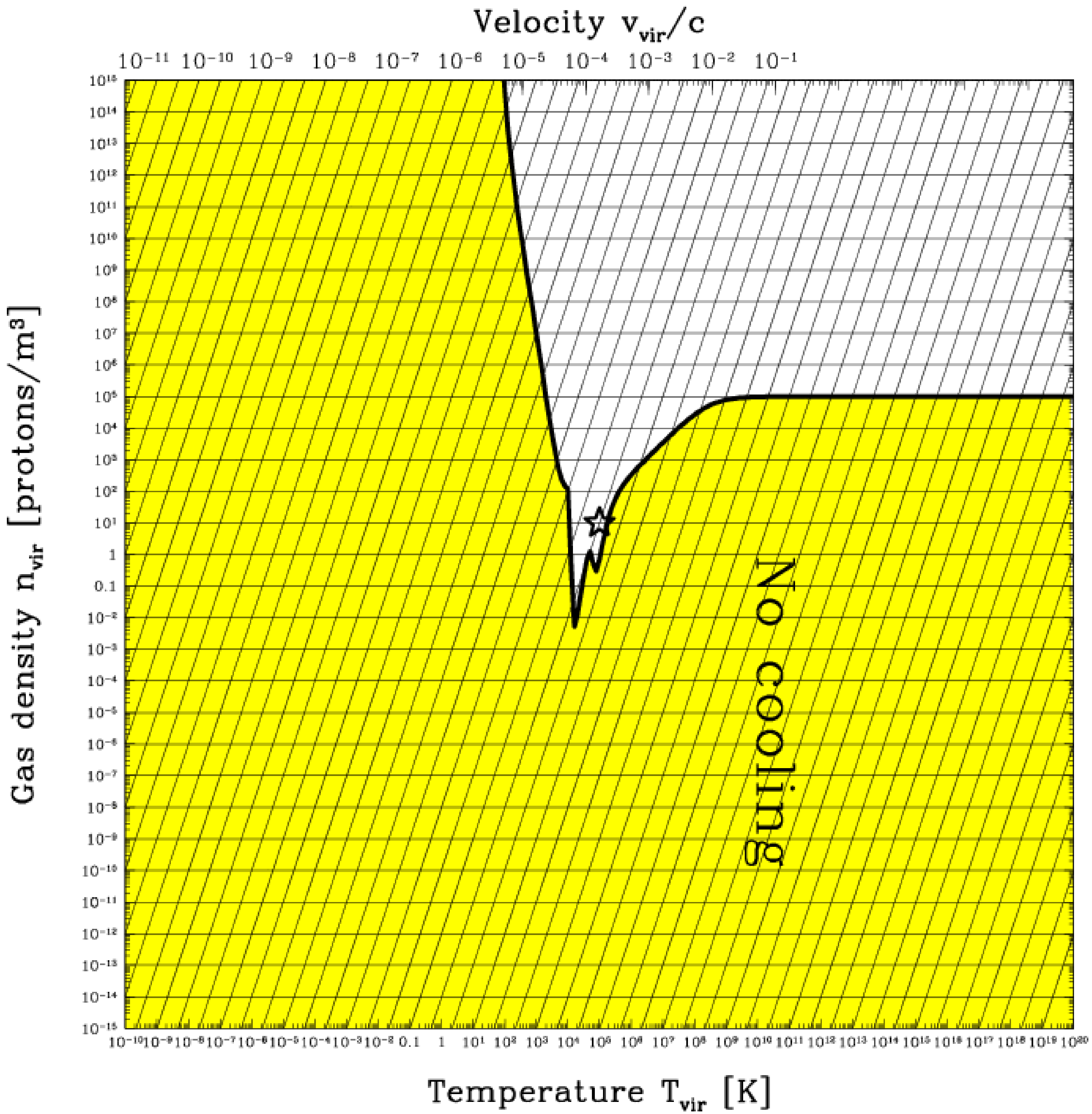
The underlying theory may be right, or it may be wrong, but it is hard to imagine a clearer, cleaner case for applying anthropic reasoning.

Making User-Friendly Structures from Gas Clouds

or: The Fragility of Life

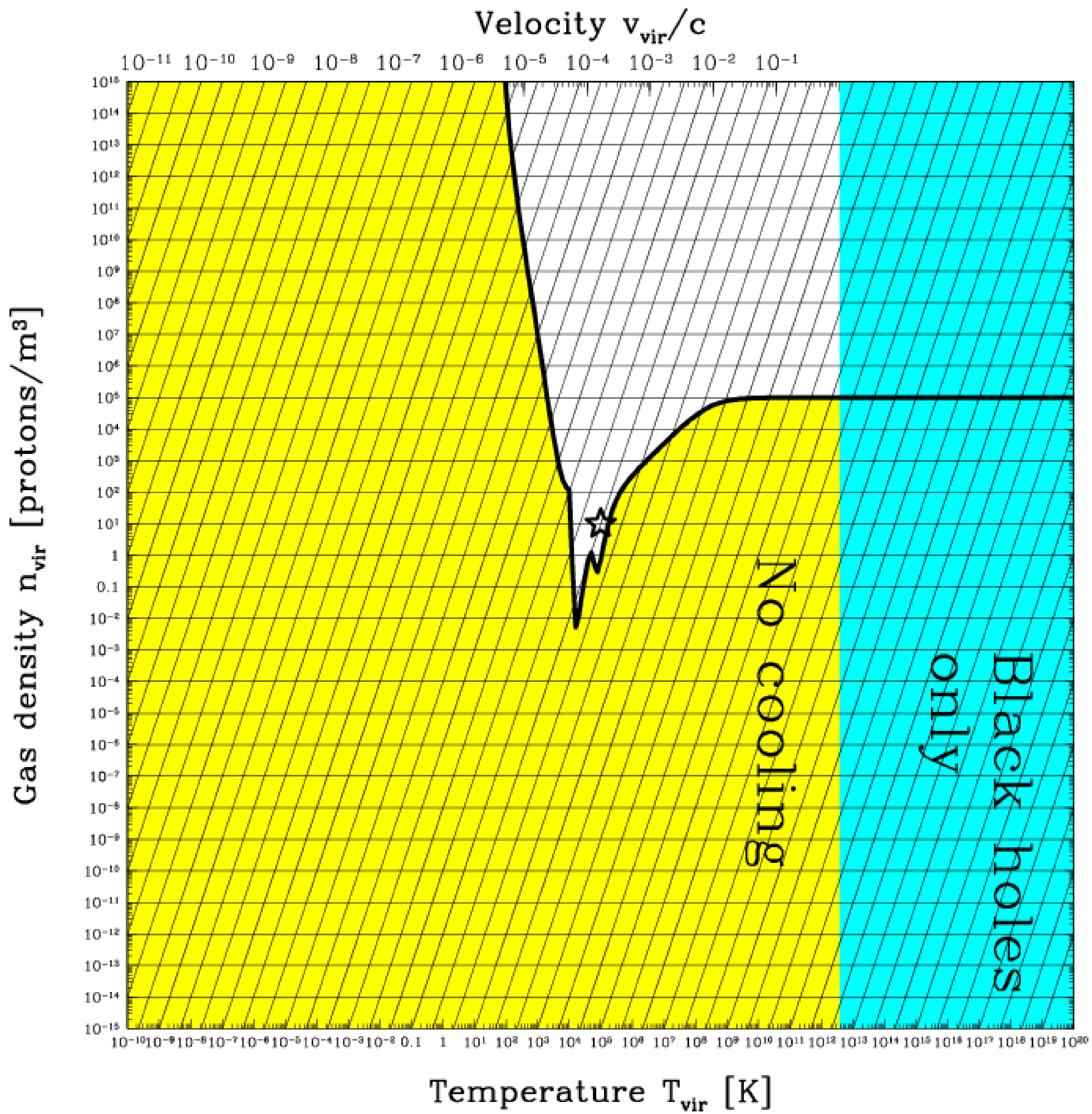
Lots of things can go wrong when you try to make user-friendly solar systems, starting from small seed fluctuations.

The (normal) matter might fail to cool, so it sloshes around and remains diffuse, like the observed dark matter:



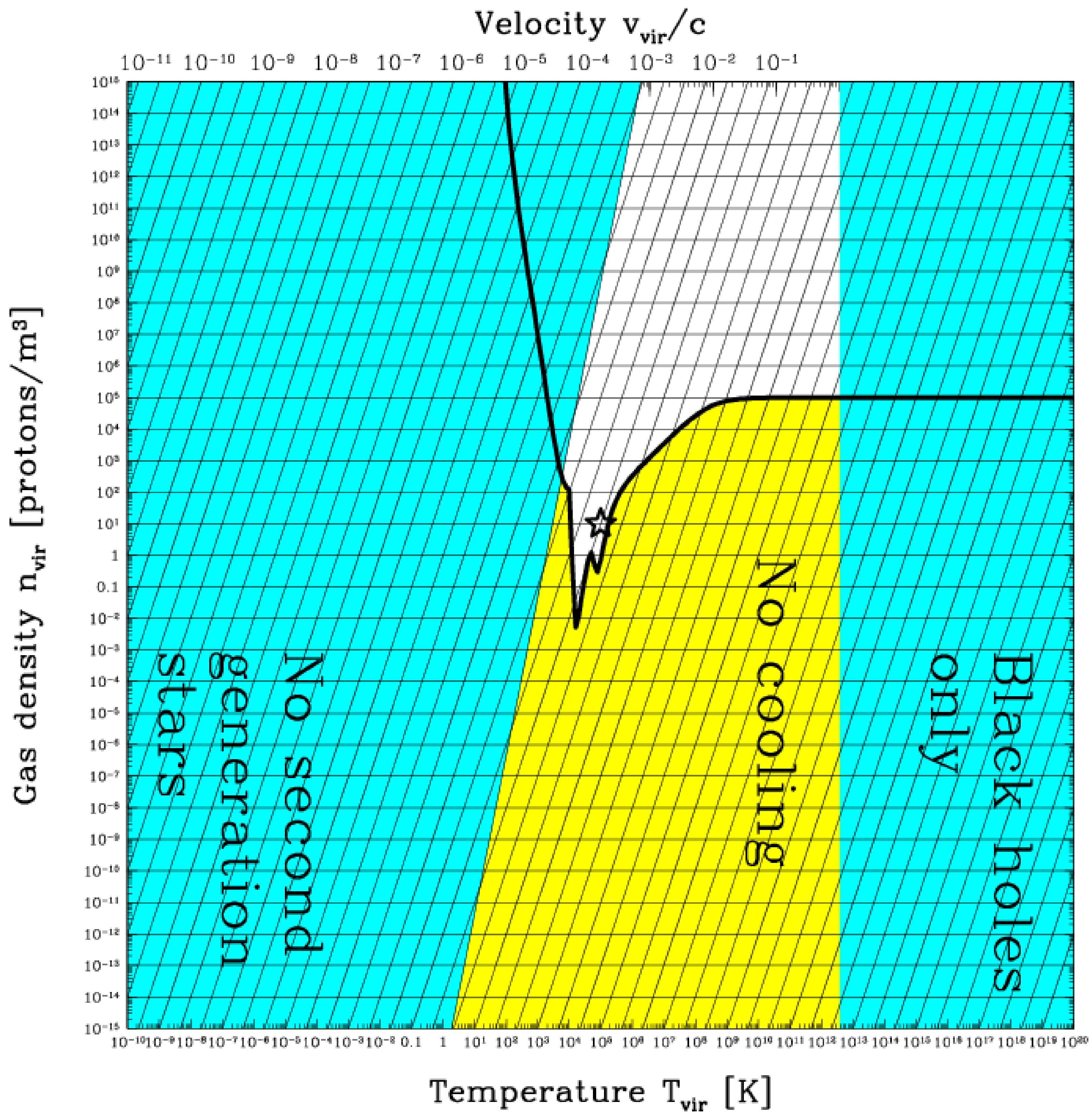
Velocity v_{vir}/c
Gas density n_{vir} [protons/m^3]
Temperature T_{vir} [K]
No cooling

Your fluctuations might collapse into black holes:



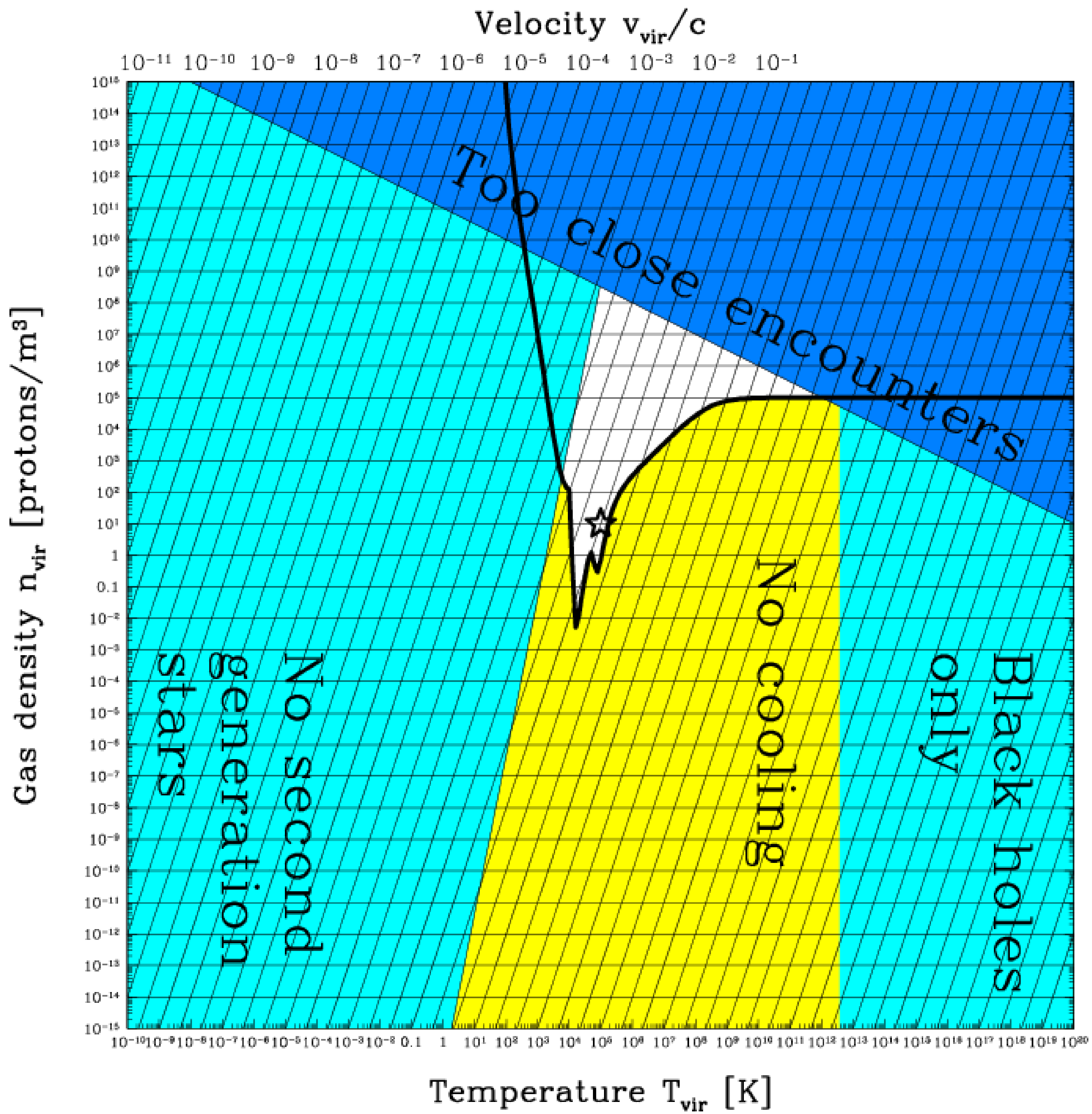
Velocity v_{vir}/c
Gas density n_{vir} [protons/m³]
Temperature T_{vir} [K]
No cooling
Black holes only

The matter might get swept out by the first supernovae:

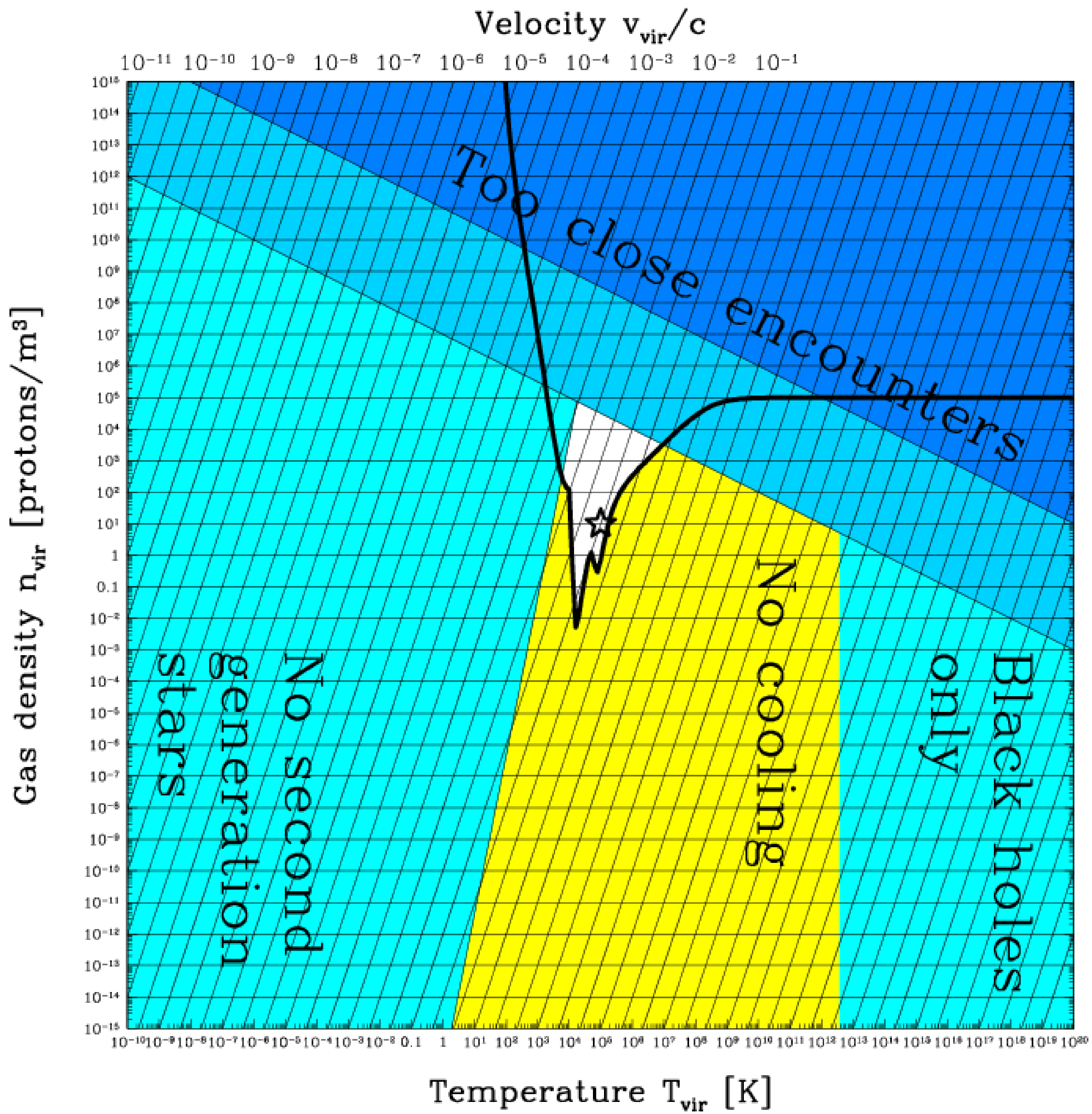


Velocity v_{vir}/c
Gas density n_{vir} [protons/m^3]
Temperature T_{vir} [K]
No second generation stars
No cooling
Black holes only

There might be no safe haven from disruptive encounters:



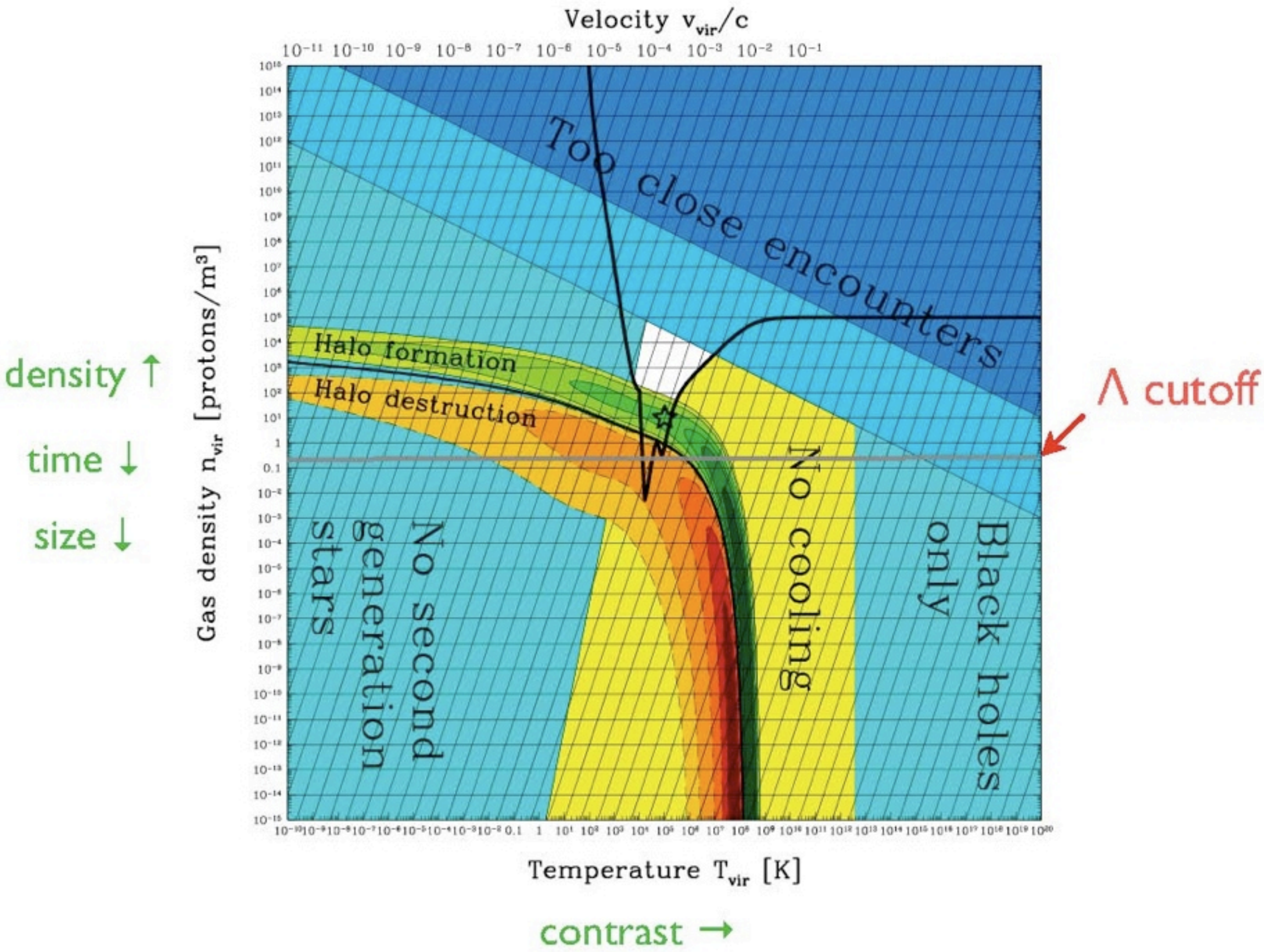
Velocity v_{vir}/c
Gas density n_{vir} [protons/m^3]
Temperature T_{vir} [K]
Too close encounters
No second generation stars
No cooling
Black holes only


Velocity v_{vir}/c
Gas density n_{vir} [protons/m^3]
Temperature T_{vir} [K]
Too close encounters
No second generation stars
No cooling
Black holes only

Making Structures From Primordial Fluctuations

We can overlay the fate map of such seeds with the spectrum of seeds we get from cosmological models of primordial fluctuations, to derive the predicted galaxy (or failed galaxy) spectrum.

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



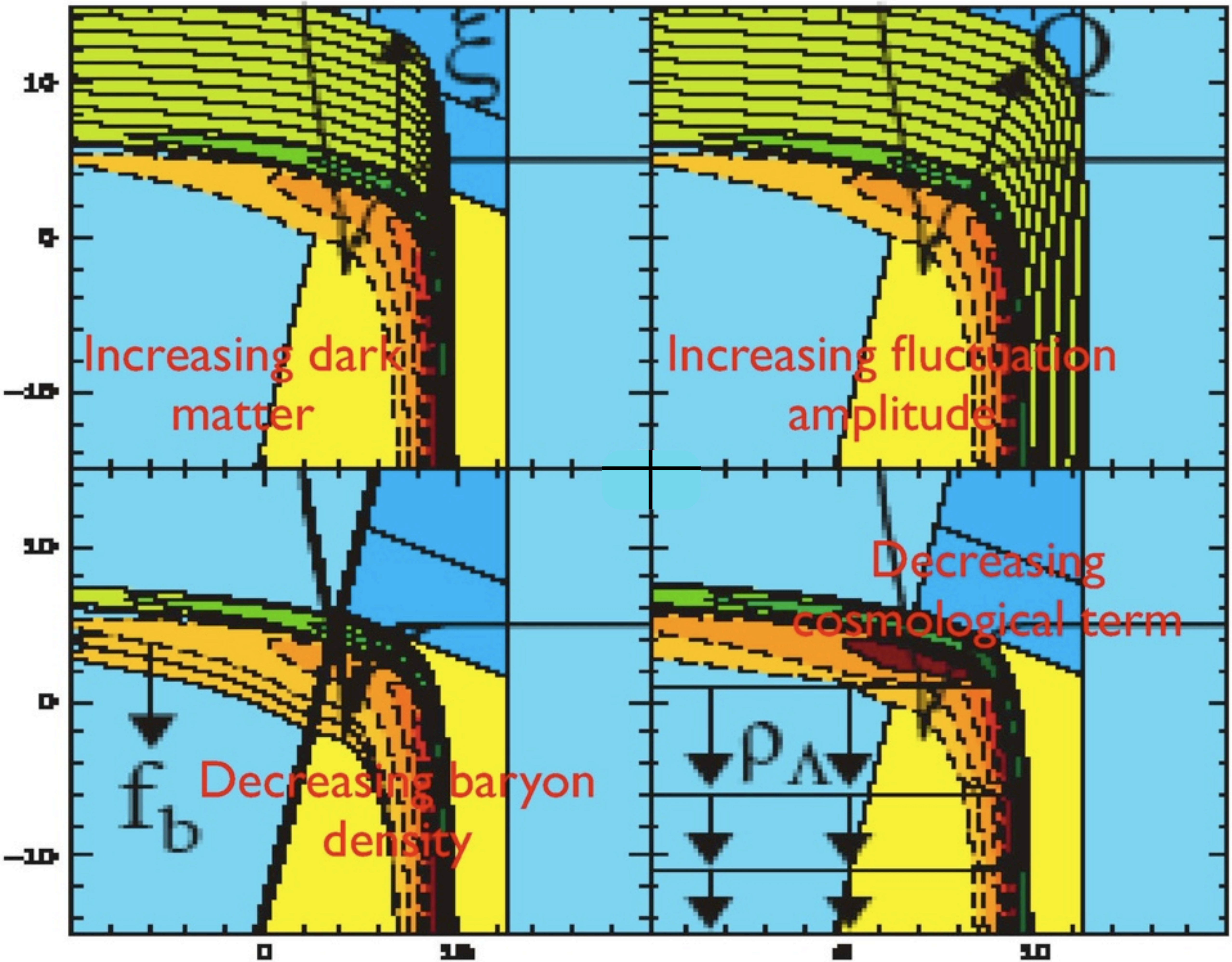
Velocity v_{vir}/c
Temperature T_{vir} [K]
Gas density n_{vir} [protons/m^3]
Too close encounters
Halo formation
Halo destruction
No second generation stars
No cooling
Black holes only
density ↑
time ↓
size ↓
Λ cutoff
contrast →

(When dark energy starts to dominate, and exponential expansion kicks in, growth of new structure is inhibited. That provides the Λ cutoff.)

These calculations give a semi-quantitative explanation of the characteristic size of galaxies.

So far what what we've done is entirely conventional astrophysics and cosmology.

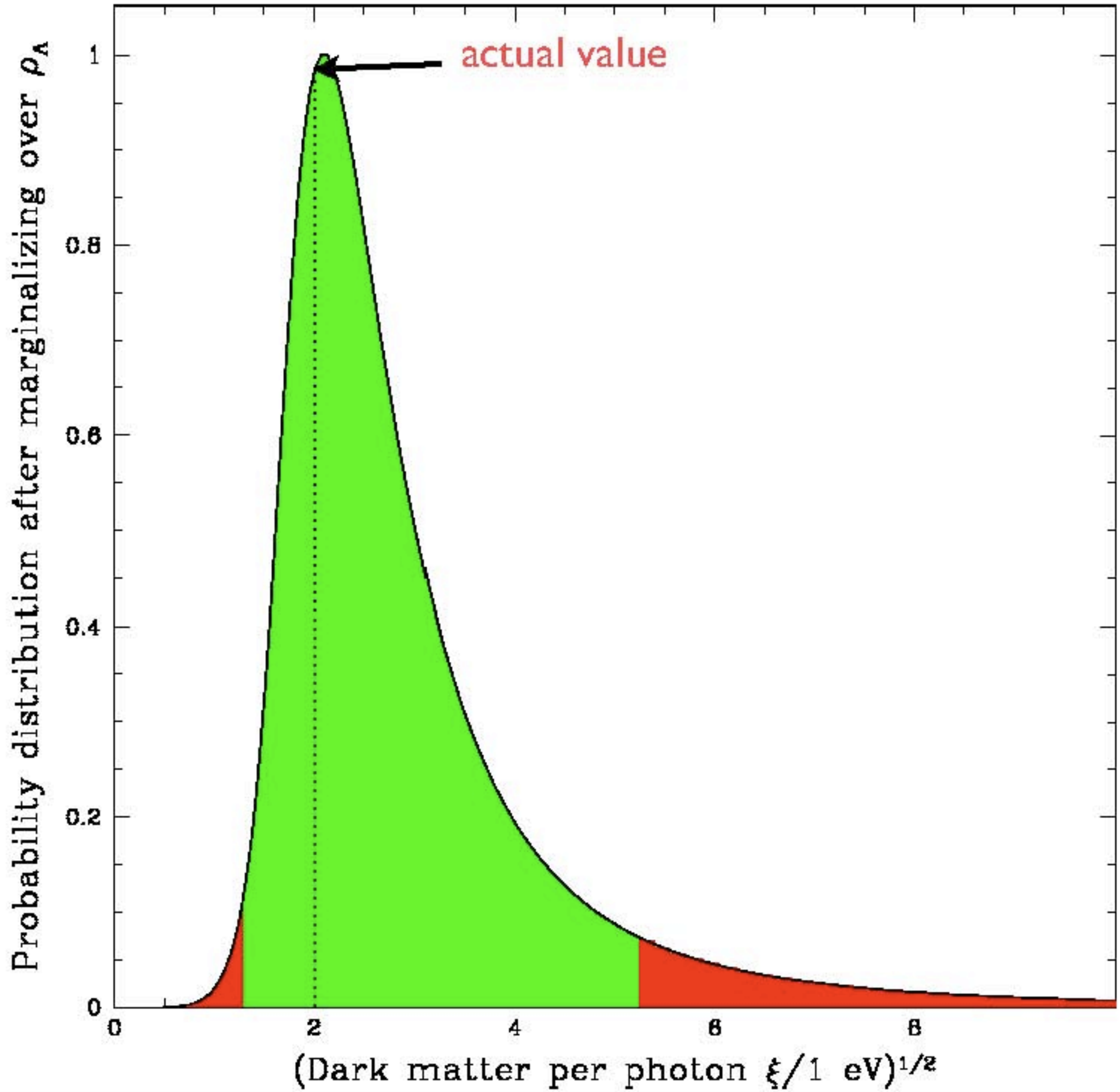
With our confidence soaring, we can proceed to consider the effect of varying the parameters that govern the primordial fluctuations, in particular the ratio (dark matter)/(baryonic matter), which is in turn governed by F $\sin^2 \theta_0$.


Increasing dark matter
Increasing fluctuation amplitude
Decreasing cosmological term
Decreasing baryon density
ξ
Q
f_b
ρ_Λ
10
0
−10
0
10

We can implement selection bias, very crudely, by calculating probability distributions *per baryon in the user-friendly region*, <u>not</u> per unit volume.

(An additional subtle and not uncontroversial factor, which disfavors regions of large dark matter density, comes in if we compare universes at equal comoving time.)

Here is the θ_0 probability distribution, translated into dark matter density per baryon in the user-friendly region:


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

That is a striking result, I think.

The scenario with inflation after the PQ transition also removes some annoying difficulties of the traditional alternative. Specifically:

there is no need for the a separate intermediate mass scale; F can be $\sim M_{\text{Unification}}$

axion strings and domain walls are diluted away

Testability: Fluctuations and Black Hole Atmospheres

A canonically normalized boson field - graviton or axion - acquires fluctuations of amplitude $T_{GH} \sim \Lambda_{infl.}^2/M_{Pl}$.

For axions, this translates into jitter in θ_0, and thus ultimately into isocurvature density fluctuations.

Constraints on isocurvature fluctuations thereby translate into constraints on $\Lambda_{infl.}$, and thus on the gravity wave background.

So inflationary axion cosmology would be falsified, were we to see a significant gravitational wave background without a larger isocurvature background.

It could be “truthified” if we still have a dark matter problem after LHC + WIMP searches; or especially if we discover isocurvature fluctuations.

Very recently Arvanitaki and Dubovsky (elaborating A+D+Dimpoulos, Kaloper, March-Russell) have argued that axions whose Compton wavelength is a small multiple of the horizon size of a spinning black hole will form an atmosphere around that hole, populated by super-radiance.

This effect will alter the gravitational wave and x-ray signals from such holes, possibly in spectacular ways (bose-nova).

Since $(m_a)^{-1} \approx 2$ cm. (F / 10^{12} GeV) and $R_{Schwarzschild} \approx 2$ km. (M / M_{Sun}), this provides a promising window through which to view F $\geq 10^{15}$ GeV axions.

One might resolve the strong P, T and dark matter problems, give powerful support to inflation, and exhibit strong-field quantum gravity at work, at one stroke!

Portals

A very real possibility is that there is a "hidden sector" of SU(3)xSU(2)xU(1) singlet fields.

This does not upset the success of quantitative unification, nor axion physics.

(Examples: ν_R, axion, NMSSM, modes on distant branes, ...)

The Higgs field is an especially promising portal into such hidden sectors, because it supports low mass dimension interactions with SM singlets:

$$\mathcal{L}_{\text{Higgs portal}} \;\propto\; \phi^\dagger \phi\, \eta^2$$

This soon-opening portal might reveal dramatic surprises.
Here is a simple example of what's possible:

Question: Might the LHC observe *nothing* beyond the standard model?

Conventional Answer: A Higgs particle must show up, at least.

But in fact there are quite simple, phenomenologically unobjectionable models in which the Higgs particle becomes effectively invisible, or at least much harder to access.

To the standard model, add an SU(3)xSU(2)xU(1) singlet real scalar field 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:

$$V(\phi,\eta) = -\mu_1^2\,\phi^\dagger\phi + \lambda_1(\phi^\dagger\phi)^2$$
$$-\mu_2^2\,\eta^2 + \lambda_2\,\eta^4 \quad -\kappa\,\phi^\dagger\phi\,\eta^2$$

The upshot is that two mass eigenstates (=particles) emerge, mixtures of the conventional Higgs field and the η field.

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

The same overall production rate of Higgs particles gets divided between two lines.

Rather than one channel with S/N = 2, for the same exposure you might have two channels with S/N=1.

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

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

$5 \times 1\ \sigma \cong 0$

New singlets could themselves be the "Higgs fields" of an entire new sector, that also has its own gauge fields and matter (all SM singlets).

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

So not only might production be divided, but also visible decay might be diluted.

Fortunately:

In more complex and better-motivated models, as for instance arise in SUSY, we can access hidden sectors indirectly, e.g. through missing energy in decay chains.

We can analyze available portals into different spins systematically:

Low-Dimension Portals

vector V_μ	$\times\ \bar{f}\gamma_\mu f$	(through $\bar{f}\not{V} f$)	"extra Zs"
	$\times\ \overleftarrow{\partial}_\nu B_{\mu\nu}$		kinetic mixing
	$\times\ \overleftarrow{\partial}_\nu \tilde{B}_{\mu\nu}$		θ-mixing (useless)
	$\times\ \varphi^+ \nabla_\mu \varphi$	(through $\lvert\nabla\varphi\rvert^2$)	charge "dequantization"
fermion N	$\times\ \varphi^+ L$		
		Weyl	ν_R, "sterile"
		Majorana	see-saw

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

An especially noteworthy possibility:

The LOSP - Lightest Ordinary SuperPartner - might decay into a gravitino, goldstino, or axino.

Such slow decays might yield unusual collider signatures. The quasi-stable LOSP might decay far from the interaction vertex, and might even be charged.

The LOSP gets lost, cosmologically. (It has been a little embarrassing to have *two* excellent dark matter candidates, ...)

Summary

What I Hope, and Expect, the Future Will Bring

First tier expectations:

Some version of low-energy supersymmetry, to consummate unification.

Some version of axions, to consummate the story of T.

Second tier expectations:

b/τ unification (suggests m_{gluino} << $m_{sfermion}$ and large $\tan\beta$)

$b/\tau/t$ unification (requires large $\tan\beta$)

Large F (requires isocurvature fluctuations >> cosmic gravity waves; suggests black hole atmospheres)

The LOSP gets lost (suggests gauge mediated SUSY breaking)

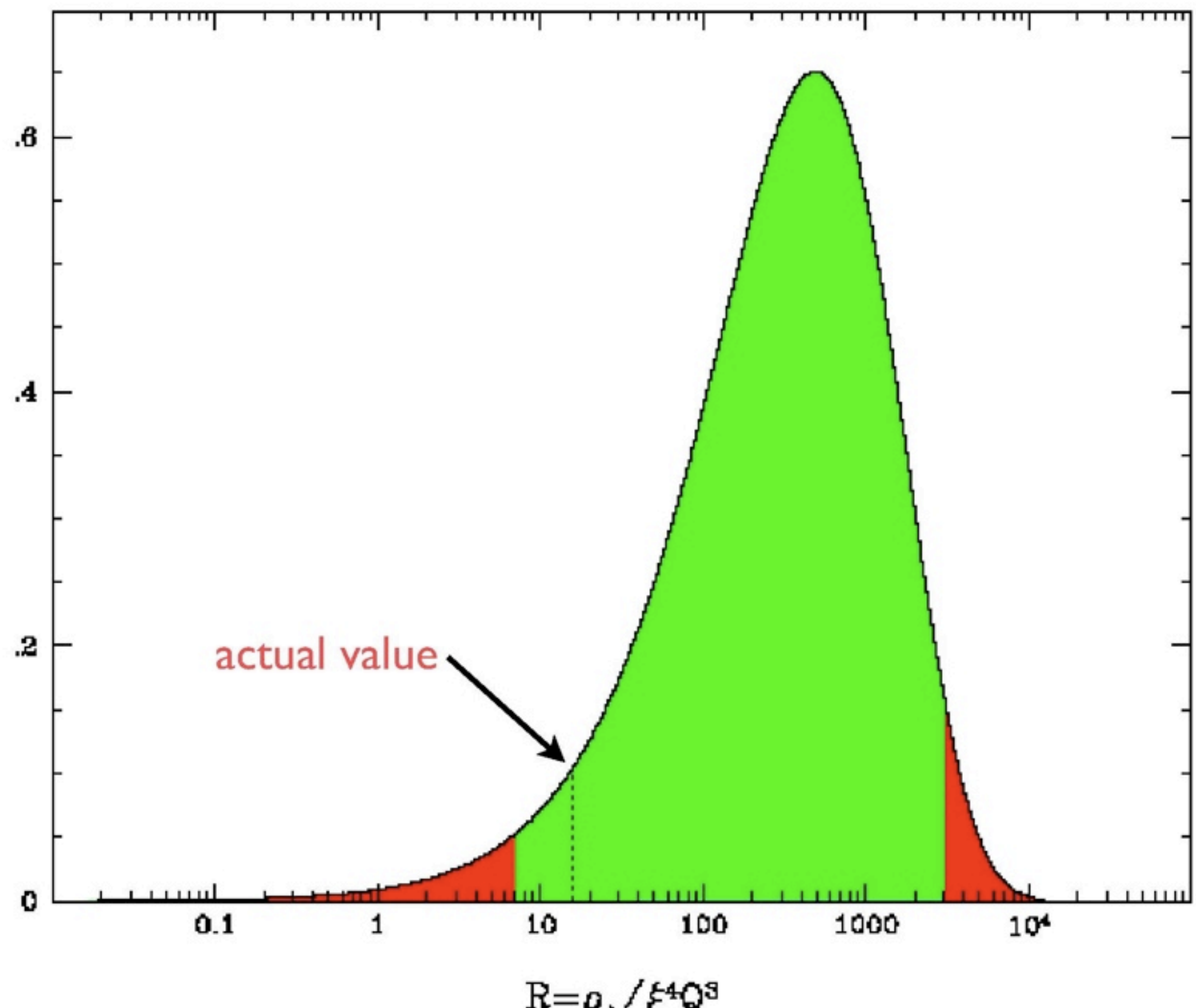
More broadly, I expect and hope for:

A triumph of the human mind, building worthily upon the Standard Model

A well-stocked base camp for further ascents

For orientation, here is the ρ_Λ distribution, given a flat prior, and **"holding everything else fixed"***.

*(This prescription is seriously ill-defined: E.g., do we hold Q fixed ... or $Q\Lambda$ ... or $Q\Lambda^p$?)



.6
.4
.2
0
actual value
0.1
1
10
100
1000
10^4
$R = \rho_\Lambda / \xi^4 Q^3$

The result is suggestive, but its foundation is somewhat insecure.