

Title: How to test multiverse theories

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Abstract:

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Lee Smolin

Perimeter Institute

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Why have multiverse theories been proposed?

The problem of the parameters of physics and cosmology

There is a standard model for all physics except gravity

It has passed all experimental tests since 1973, except that neutrino masses and mixings have been added.

It has, with the neutrinos, about 27 parameters

There is a standard model for cosmology

It has about 15 parameters

What sets the values of all these parameters?

What sets the values of all these parameters?

What chooses the gauge groups?

What chooses the fermion content?

But its worse than just this: *the parameters have improbable values*

The hierarchy problem: there are large ratios in the observed values

$$m_{\text{proton}}/m_{\text{Planck}} = 10^{-19}$$

$$hG\Lambda = 10^{-120}$$

$$m_{\text{top}}/m_e = 340,000$$

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$$hG\Lambda \sim 10^{-120}$$

$$m_{\text{top}}/m_e \sim 340,000$$

The special tuning problem: The observed parameters allow the existence of stable structures over a vast range of scales:

Long lived stars

~100 stable nuclei

complex chemistry

It turns out that there is only a small region of the parameter space

which allows these structures.

The existence of stable nuclei, up to at least carbon, requires

$$\Delta m = m_{\text{neutron}} - m_{\text{proton}} < 18 \text{ MeV}$$

$$\alpha < .1$$

$$\alpha_{\text{Strong}} > \text{present value}/2$$

Nuclear fusion requires:

$$\Delta m \approx 2m_{\text{electron}}$$

$$\alpha \approx \frac{\Delta m}{m_{\pi}}$$

$$\alpha > \frac{m_{\text{electron}}}{m_{\text{proton}}}$$

Changes that destabilize nuclei:

A reversal of the sign of $\Delta m = m_{\text{neutron}} - m_{\text{proton}}$.

A small increase in Δm (compared to m_{neutron}) will destabilize helium and carbon.

An increase in m_{electron} of order m_{electron} itself, will destabilize helium and carbon.

An increase in m_{neutrino} of order m_{electron} itself, will destabilize helium and carbon.

A small increase in α will destabilize all nuclei.

A small decrease in α_{strong} , the strong coupling constant, will destabilize all nuclei.

LONG LIVED STARS IMPOSE REQUIREMENTS:

Hydrogen burning stars are stable, photon pressure \sim gravity

$$\frac{m_{electron}}{m_{proton}} > \alpha^2 50^{-4/3}$$

$$G_{Newton} m_{proton}^2 < \alpha^{12}$$

Convective stars require:

$$G_{Newton} m_{proton}^2 \approx \left(\frac{m_{electron}}{m_{proton}} \right)^4 \alpha^{12}$$

The existence of supernova constrains the weak interaction:

$$G_{Fermi} m_{electron}^2 \approx \left(G_{Newton} m_{electron}^2 \right)^{\frac{1}{4}} \left(\frac{m_{electron}}{m_{proton}} \right)^{\frac{1}{2}}$$

Up till recently the question physics sought to answer was:

What are the laws of nature?

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Now we have a new question:

Why these laws?

Four explanations have been proposed

First approach: uniqueness of unification

- We hypothesize that there is a unique theory that unifies the known four forces within quantum theory.
- That theory will imply unique values for all the standard model parameters.
- That theory will give unique predictions for future experiments by which it can be confirmed.

For the last two decades several approaches to unification and quantum gravity have been studied. What do they have to say about this?

String theory

Loop quantum gravity

Spin foam models

Causal dynamical triangulations

Quantum information theory approaches

Causal sets...

String theory: conjectured to be a unique unification:

- 1984 5 theories in 10 dimensions
- 1985 ~100,000 theories with 3+1 large dimensions
“Calabi Yau manifolds”
- 1986 Torsion, a *vast number* of theories

String theory appears to make no predictions for gauge group, fermion content, Higgs content or parameters of the standard model, even once we impose 3+1 large dimensions and weak scale SUSY breaking.

- 1995 Conjecture that all string theories are unified, still open.
(Principles and laws of the conjectured theory remain unknown)
- 1998 Discovery of positive vacuum energy-inconsistent with supersymmetry
- 2003 Evidence for $< 10^{500}$ non-SUSY string theories w positive vacuum energy
- 2006 Evidence for discrete infinities of string theories

Strominger, 1986 concluded:

*'The class of supersymmetric superstring compactifications has been enormously enlarged. . . . It does not seem likely that [these] solutions . . . can be classified in the foreseeable future. As the constraints on [these] solutions are relatively weak, it does seem likely that a number of phenomenologically acceptable . . . ones can be found. . . . While this is quite reassuring, in some sense life has been made too easy. **All predictive power seems to have been lost.***

All of this points to the overwhelming need to find a dynamical principle for determining [which theory describes nature].

Loop quantum gravity and other proposed unifications, appear to make few constraints on particle content and other gauge fields.

New possibility: *elementary particles arise as topological excitations in LQG (Markopoulou),*

Possible connection to preon models (Bilson-Thompson) suggested, but needs to be better understood.

Second approach: the strong anthropic principle

“There is an all powerful God who made the universe so that, not only would there come to evolve intelligent life, they would study the universe and realize their existence was due to some remarkable coincidences in the parameters of the laws. They would then be led by reason to know and love God.”

Second approach: the strong anthropic principle

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Not part of science: ie doesn't lead to falsifiable tests.

Given the failure of the first two approaches, multiverse theories were invented as an act of desperation in the search of a scientific approach to the problem of the parameters.

There are two kinds of multiverse theories:

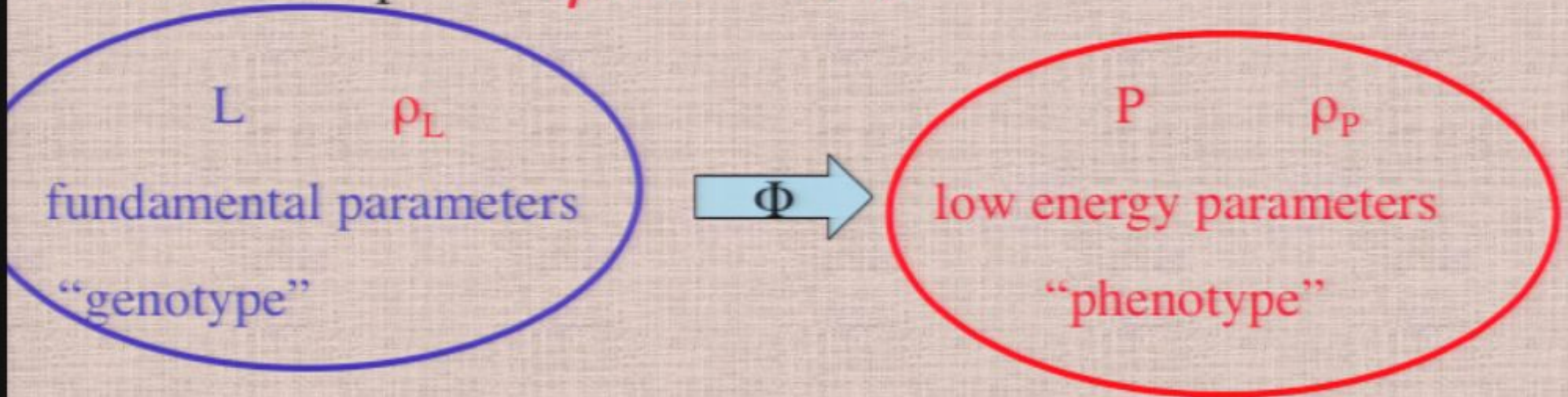
Static and dynamic.

These are represented by

- Eternal inflation (eternal = static)
- Cosmological natural selection (CNS)

Third approach: the weak anthropic principle (AP).

- There is a parameter space of fundamental unified theories, L
- There is a parameter space of the standard models, P
- There is a map $\phi: L \longrightarrow P$

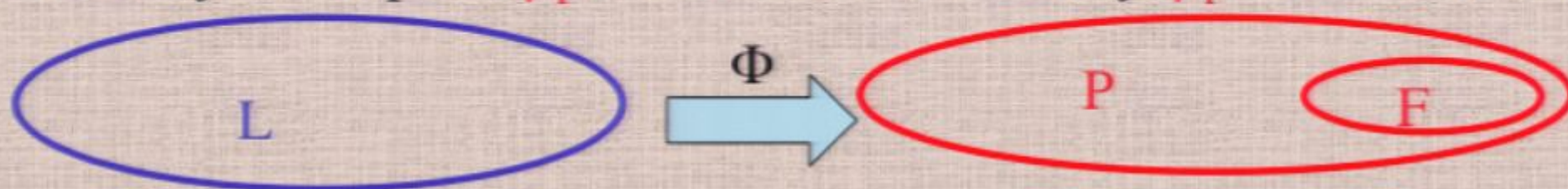


- There is a vast population of “universes”-the multiverse, with laws “randomly chosen” from L
--> a static probability distribution ρ_L on L
- This gives a probability distribution $\phi: \rho_L \longrightarrow \rho_P$ on P

But life cannot exist for most laws in P . So there is an extremely tiny subspace F of P which is friendly for life.

By restriction we get a probability distribution ρ_F on F .

Since by assumption ρ_P is random, and F is tiny, ρ_F is constant on F .



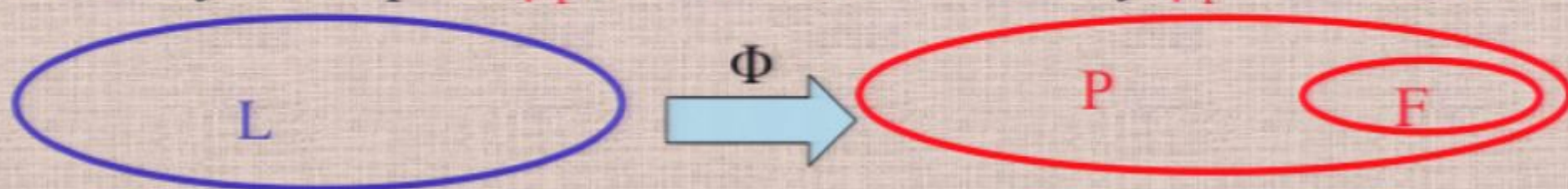
Hence, we can only make predictions that are consequences of our existence.

So we can make no falsifiable predictions because, whatever the LHC sees, it will be within L and hence as probable as any other observation within L .

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So we can make no falsifiable predictions because, whatever the LHC sees, it will be within L and hence as probable as any other observation within L .

CONCLUSION: *To make falsifiable predictions from this setup, the mechanism that creates the ensemble must result in a highly non-random ρ_P so we get a highly random ρ_L .*

There are claims for successful predictions from the AP:

If the preceding argument is right these must be fallacious.

Hoyle's argument:

1. Carbon is necessary for life to exist.
2. In fact carbon is abundant in our universe.
3. Using the laws of physics, we can deduce that for carbon to exist there must be a resonances at a certain energy in the beryllium nuclei.
4. Hence we predict that resonance to exist.

The experiment was done and the resonance was found.

What is the fallacy?

The correct argument:

- ~~1. Carbon is necessary for life to exist.~~
2. In fact carbon is abundant in our universe.
3. Using the laws of physics, we can deduce that for carbon to exist there must be a resonances at a certain energy in the beryllium nuclei.
4. Hence we predict that resonance to exist.

The experiment was done and the resonance was found.

The fallacy is that the first line does no work: life is irrelevant.

How to tell? Suppose that the resonance had not been found. We would not have questioned the existence of life, we would have looked for a mistake in the nuclear physics in 3.

Multiverse version of Hoyle's argument:

0. We live in a multiverse with random laws distributed over a vast ensemble of universes.
1. Carbon is necessary for life to exist. Hence we must live in one of those universe that have carbon.
2. In fact carbon is abundant in our universe.
3. Using the laws of physics, we can deduce that for carbon to exist there must be a resonances at a certain energy in the beryllium nuclei.
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The experiment was done and the resonance was found.

What is the fallacy now?

The multiverse plays no role in the argument:

- ~~0. We live in a multiverse with random laws distributed over a vast ensemble of universes.~~
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Had the experiment not found the resonance we could not and would not have questioned the existence of the multiverse. We would have checked the nuclear physics.

CONCLUSION: *The AP does not work and hence its existence is not falsifiable. As long as ρ_p is random it cannot be part of a falsifiable theory.*

Here is a similar argument about the cosmological constant:

0. We live in a multiverse with random laws distributed over a vast ensemble of universes.
1. Galaxies necessary for life to exist. Hence we must live in one of those universe that galaxies.
2. In fact galaxies are abundant in our universe.
3. Using the laws of physics, we can deduce that for galaxies to have formed the cosmological constant Λ must be less than some Λ_0 .
4. Hence we predict that $\Lambda < \Lambda_0$

The cosmological constant was found with $\Lambda < \Lambda_0$

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The *same fallacy* is present:

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The logic of the argument has nothing to do with multiverses or life.

Here is a different argument about the cosmological constant:

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3. Since the probability distribution is random on the sub-ensemble that involves life and our universe is a typical member of that ensemble we predict $\Lambda \sim \Lambda_0$

(Weinberg 1987)

Is this successful?

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Is this successful? *It depends on the ensemble studied.*

If the ensemble allows just Λ to vary:

Probability for $\Lambda < \Lambda_{\text{observed}}$ is about 10 %

If Λ and the size of the fluctuations is allowed to vary,

Probability for $\Lambda < \Lambda_{\text{observed}}$ goes down to 10^{-4}

CONCLUSION: *The weak anthropic principle makes no falsifiable predictions.*

Because the probability distributions on P, L and F are random, any outcome of an experiment consistent with life is as probable as any other outcome.

Claims for successful predictions fail because either the multiverse plays no role or the notion of typicality or random is loose enough that the predictions depend on what ensemble of multiverses our universe is assumed to be typical within. But since the distribution of multiverses cannot be observed there can be no independent check on choices made.

For the fourth approach, we turn to Charles Sanders Peirce (1893):

To suppose universal laws of nature capable of being apprehended by the mind and yet having no reason for their special forms, but standing inexplicable and irrational, is hardly a justifiable position. Uniformities are precisely the sort of facts that need to be accounted for. Law is par excellence the thing that wants a reason. Now the only possible way of accounting for the laws of nature, and for uniformity in general, is to suppose them results of evolution.

To apply natural selection to a system it must have:

- A space of parameters for each entity, such as the genes.
- A mechanism of reproduction.
- A mechanism for those parameters to change, but slightly, from parent to child.
- Reproductive success depends strongly on the parameters.

This agrees with our conclusion that a multiverse theory must depend on a mechanism that generates a highly non-random ensemble.

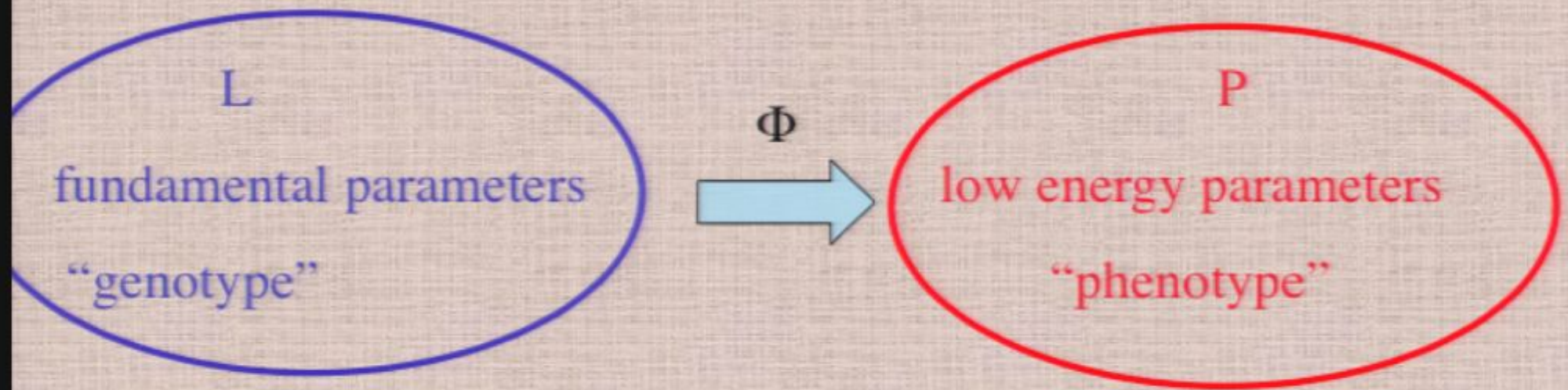
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Moreover, the method of reproduction should involve atomic physics and chemistry so that fitness can be sensitive to the special tunings of the observed parameters.

As in biology there are two parameter spaces:



We need a mechanism of reproduction of universes:

In each classical black hole there is a singularity inside the horizon where the curvature becomes infinite.

Cosmological solutions to Einstein's equations have initial singularities.

Quantum gravity effects are conjectured to eliminate these singularities. There is strong evidence for this in recent work.

When a black hole singularity is eliminated a new region of spacetime evolves which is to the future of the universe in which the black hole lived. This can be considered the creation of a new universe.

Hence, we hypothesize that each black hole in a universe gives rise to a new universe.

We need there to be variation on the landscape of theories at each universe creation.

This is natural but not demonstrated. If the transition between string theory “vacua” is a phase transition, it can take place when the energies, densities and temperatures approach Planck scales in the bounce of a black hole singularity.

We need this variation to be on average small:

There is as yet no theoretical evidence for or against this, so we assume it.

We need the fitness to depend strongly on the parameter space.

Fitness (p) = average number of black holes created to the future of the bounce for a universe with parameters p .

It is easy to show that the fitness does depend strongly on the parameters in the neighborhood of the present low energy parameters.

Then it likely depends strongly on the fundamental parameters on L .

We can then apply standard arguments from population biology.

The standard arguments of population biology lead to the following conclusions for a high dimensional parameter space:

After a sufficient time, the population evolves to one where ρ_P is peaked around local extrema of the fitness function.

This implies:

*Almost no local changes in the low energy parameters lead to increases in fitness
= expected number of black holes produced.*

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$T = \# \text{ of sources}$

$\cap(T)$

$\times 2)$

$3)$

$T = \# \text{ of sources}$
 $\beta(T)$

$\frac{C}{N}$
07
CIRN

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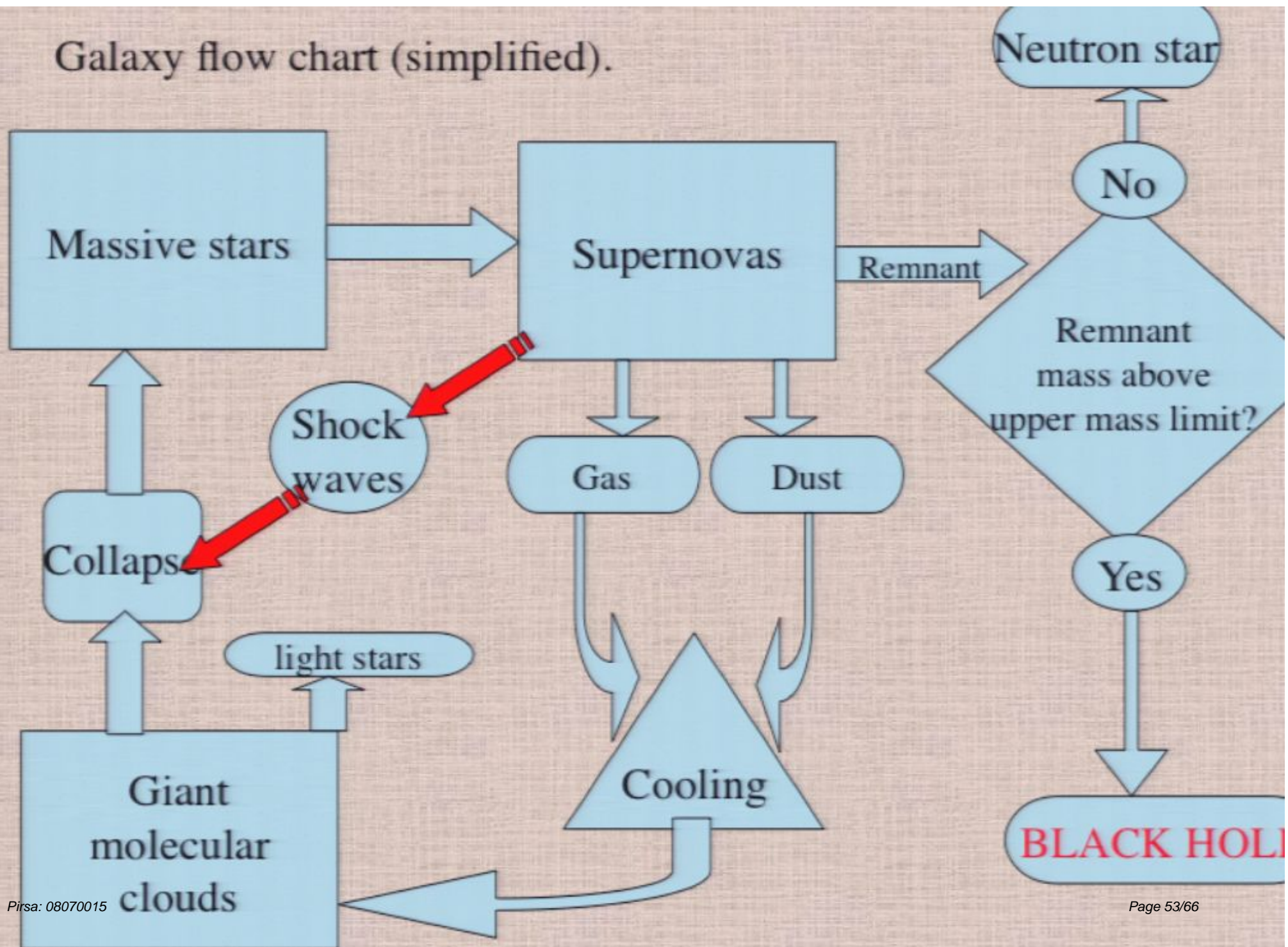
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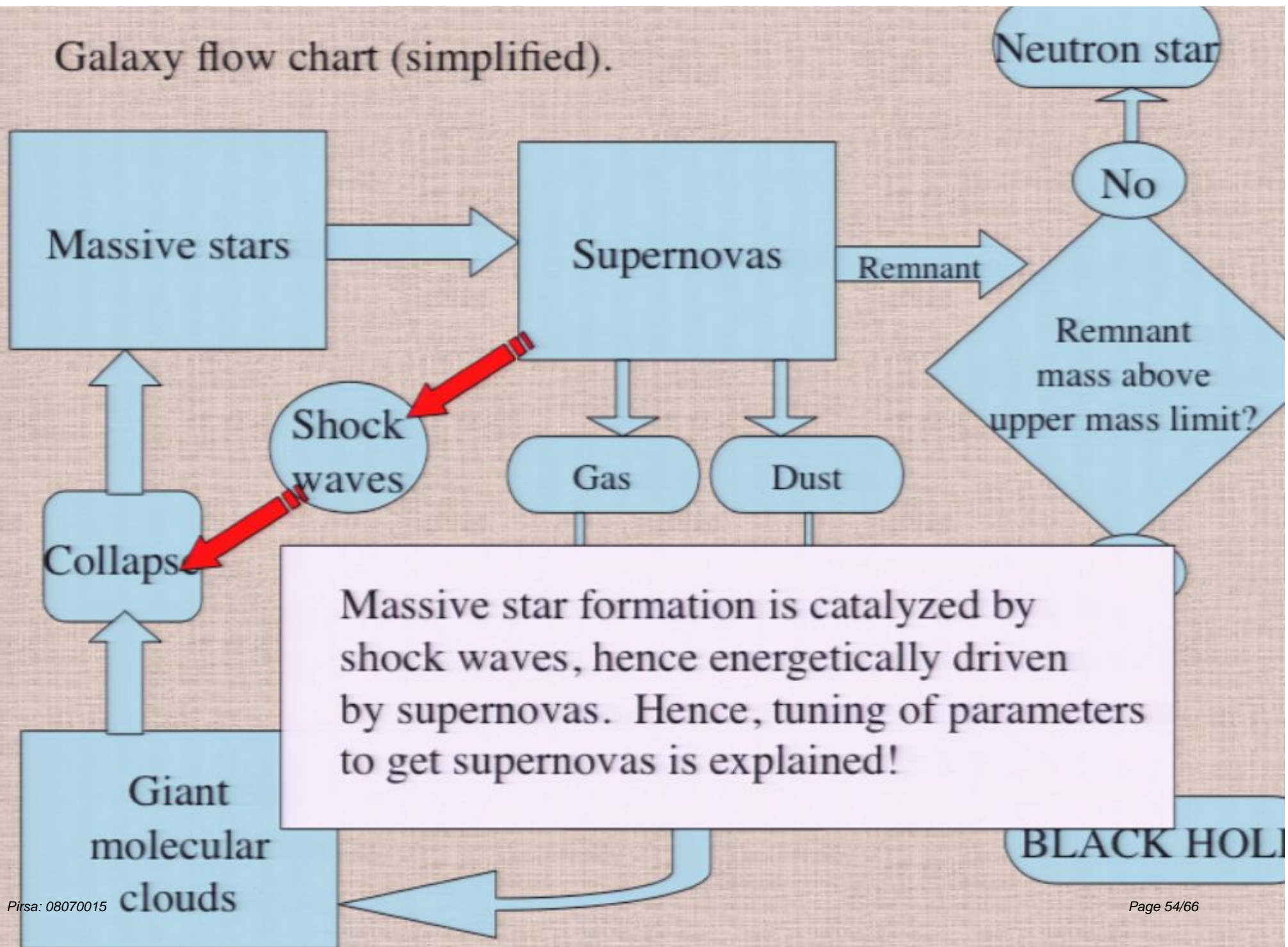
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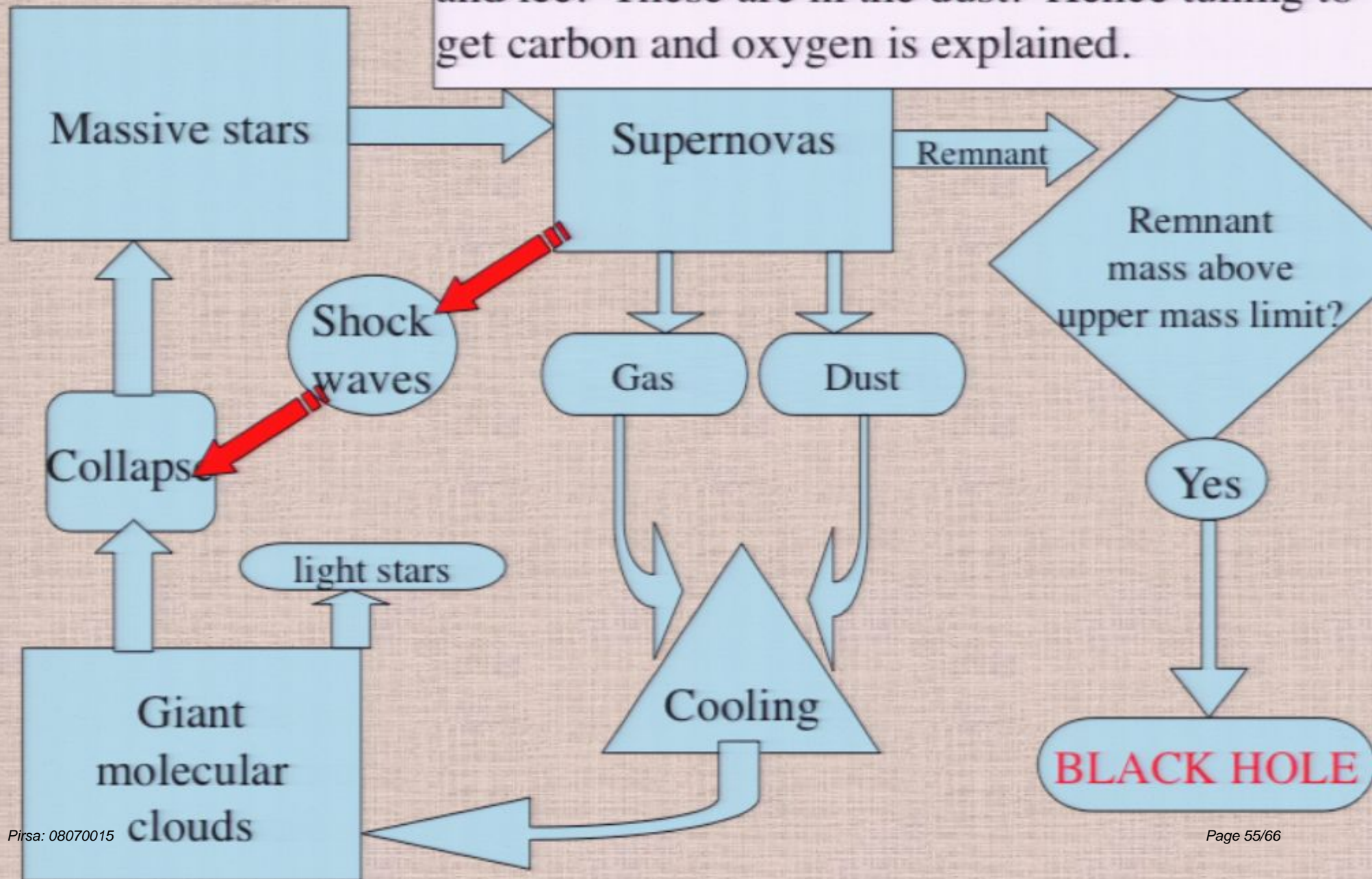
Galaxy flow chart (simplified).

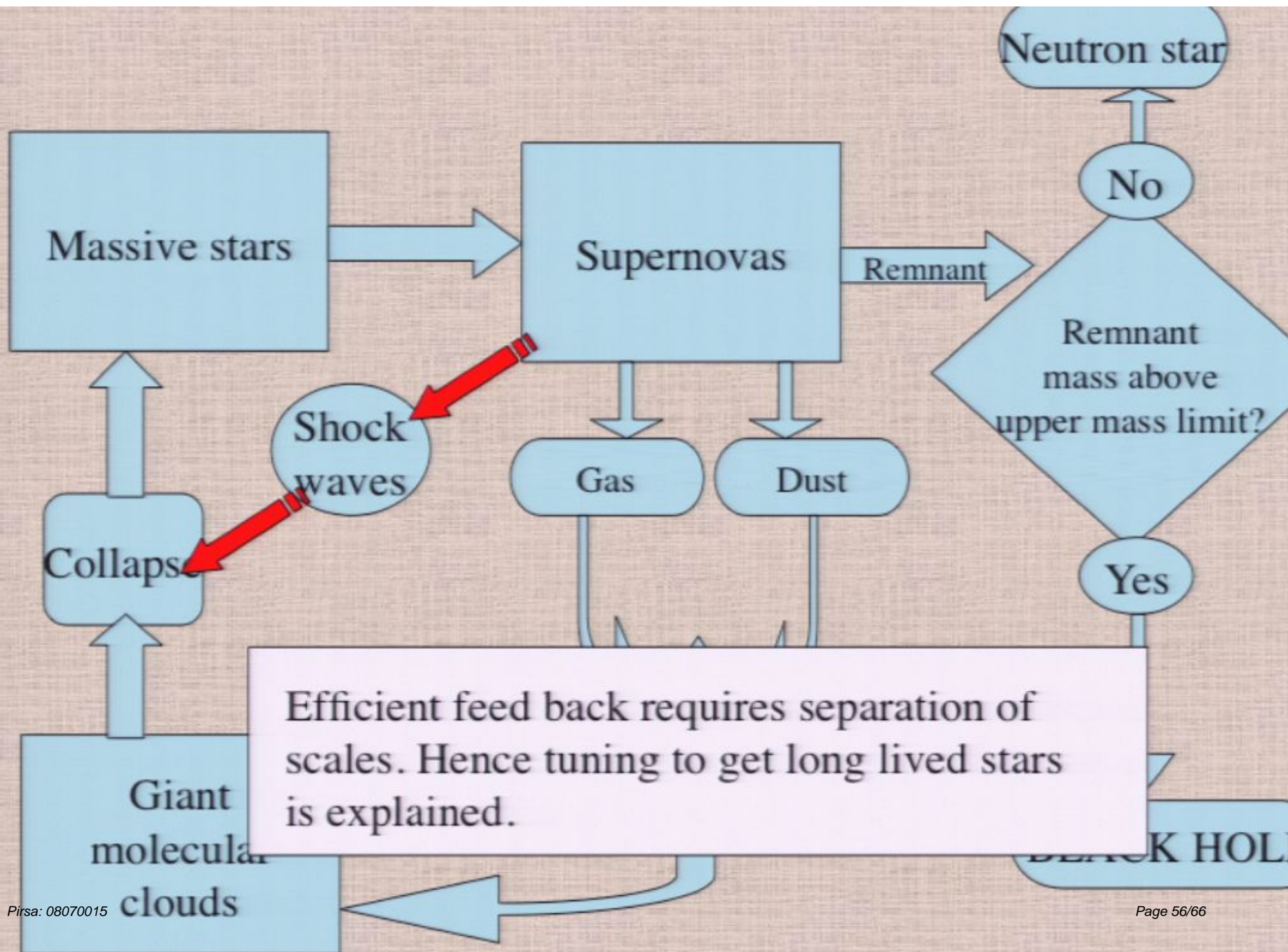


Galaxy flow chart (simplified).



Cooling requires CO, shielding requires carbon and ice. These are in the dust. Hence tuning to get carbon and oxygen is explained.





So the hypothesis that black hole production is locally extremized *explains* fine tuning for:

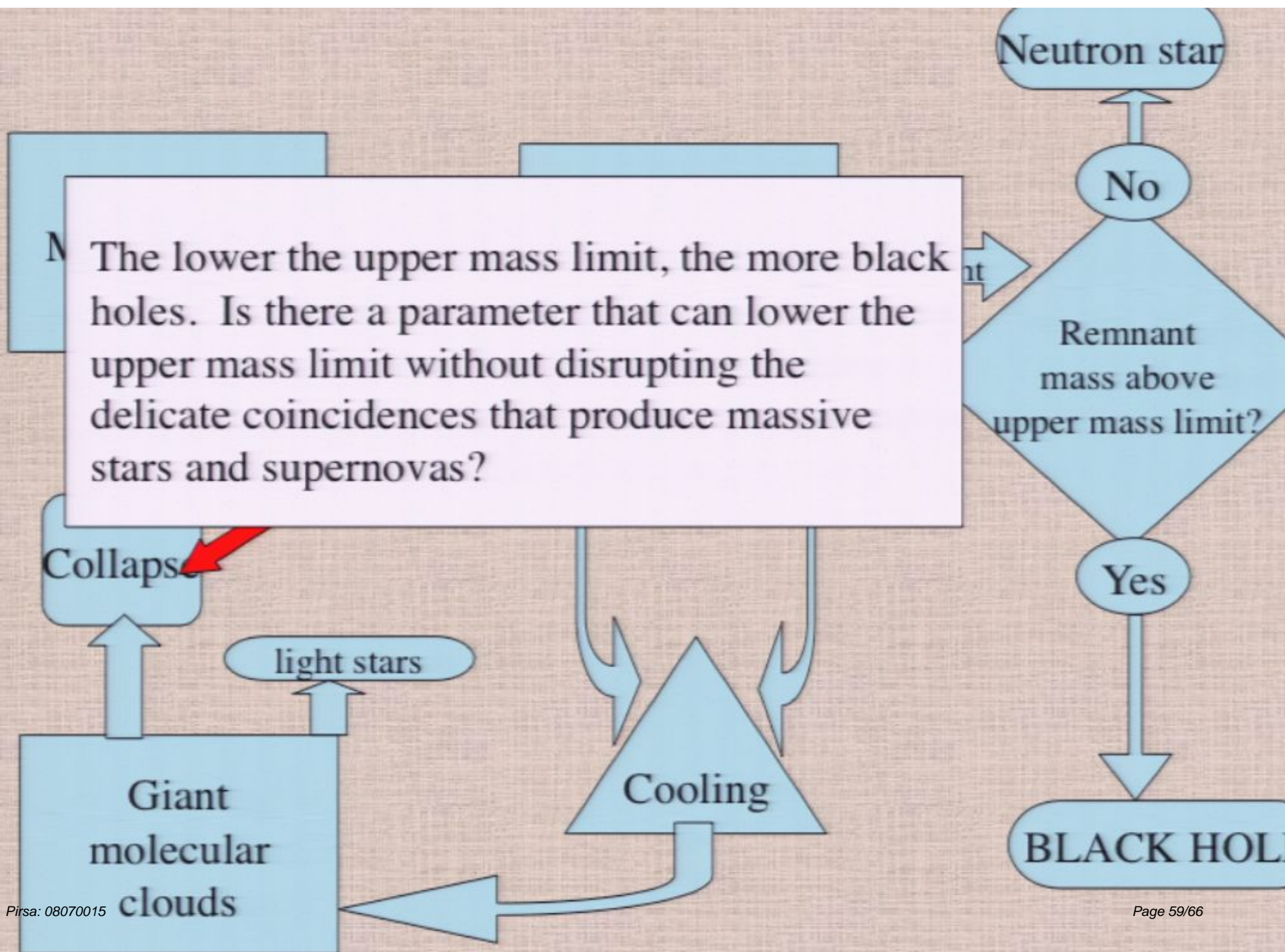
- Chemistry, particularly carbon and Oxygen
- Supernovas
- Long lived stars.

Hence, these explain all the coincidences noted above.

There is then a genuine, non-circular, explanation of why the universe is hospitable to our type of life. We can be here as a side effect of tuning the parameters to maximize reproduction of the Universe as a whole!

But to be taken seriously. A theory must make falsifiable predictions for doable experiments.

Three predictions, published in 1992:



Is there a parameter that can lower the upper mass limit without disrupting the delicate coincidences that produce massive stars?

YES: *the strange quark mass.*

Bethe and Brown hypothesize that neutron stars are actually K condensate stars, as they collapse electrons convert to K^- , so the stars are made of protons, neutrons and kaons.

They show that this, if true, lowers the upper mass limit to 1.6 solar masses.

They argue that there is a value m_c such that if $m_s < m_c$ neutron stars are kaon condensate stars, otherwise they are normal neutron stars.

HENCE, CNS predicts m_s must be less than m_c

HENCE, all neutron stars must have less than 1.6 solar masses!

Kaon Condensation, Black Holes and Cosmological Natural Selection

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Abstract

It is argued that a well measured double neutron star binary in which the two neutron stars are more than 4% different from each other in mass or a massive neutron star with mass $M \gtrsim 2M_{\odot}$ would put in serious doubt or simply falsify the following chain of predictions: (1) nearly vanishing vector meson mass at chiral restoration, (2) kaon condensation at a density $n \sim 3n_0$, (3) the Brown-Bethe maximum neutron star mass $M_{max} \approx 1.5M_{\odot}$ and (4) Smolin's 'Cosmological Natural Selection' hypothesis.

Although most well-measured binary pulsars satisfy the bound of $M_{max}^{BB} = 1.5M_{\odot}$, there are reported cases of compact-star masses that exceed the BB maximum mass. Up until recently, the most serious case against the BB scenario was PSRJ0751+1807, a neutron star in a binary with white dwarf, with mass $2.1_{-0.20}^{+0.20}M_{\odot}$ [17] which had spurred a large number of works purporting to rule out the kaon condensation at as low a density as $n \sim 3n_0$ as well as to provide support for quark stars with or without color superconductivity. This would have been a clean falsification of the BB theory as well as the CNS idea. However a recent analysis by the same group lowered the mass to $1.26_{-0.12}^{+0.14}M_{\odot}$ (see D. Nice, talk in *40 Years of Pulsars*, Aug. 12-17, McGill University, <http://www.ns2007.org>). There are other cases of higher mass neutron stars but there are reasons to believe that as they stand, they cannot be taken as a serious negative evidence. This matter is discussed in depth in [4]. At present, it seems fair to conclude that there is no “smoking-gun” evidence against the BB scenario.

“I know a way to make many more black holes. Just turn up $\delta = \delta\rho/\rho$ and lots of primordial black holes will be made.”

Why not?

In single field inflation $\delta \sim \lambda$ the inflaton coupling.

But the universe expands like e^N where $N = \lambda^{-1/2}$.

So the volume of the universe produced is exponentially smaller.

Details show that the most black holes are produced when δ is at the critical value below which galaxies don't form.

But this is not true for more complex inflation models.

*Hence, CNS predicts that in our universe single field inflation holds.
Hence predictions of single field inflation are predictions of CNS*

The third prediction is a test of the assumption that goes into the galaxy flow chart that carbon and oxygen are necessary for production of massive stars and hence black holes. This implies there should be few supernovas at high z when the interstellar media are less enriched.

Three predictions of cosmological natural selection, falsifiable and so far not falsified:

1. The upper mass limit of neutron stars is 1.6 solar masses
2. If inflation is right it should be single field, slow role inflation.
3. Few supernovas when the universe was less enriched.

Two kinds of landscape theories:

Time dependent

Cosmological natural selection

Population evolves on the landscape

Highly non-random population.

Our universe is typical

Creation mechanism implies typical universes have surprising features not implied by our existence.

Genuine falsifiable predictions.

Upper mass limit of neutron

Static

Eternal inflation

Static probability distribution

Random, equilibrium population

Our universe is very untypical

Anthropic principle must be invoked, all other parameters random.

No falsifiable predictions