Title: How to Make Testable Multiverse Theories

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Abstract:

How to make testable Multiverse theories

Lee Smolin
Perimeter Institute

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The Life of the Cosmos, 1997 Oxford University Press

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Why have multiverse theories been proposed?

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?

What sets the values of all the parameters?

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Why these laws?

What sets the values of all the parameters?

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What chooses the gauge groups?

What chooses the fermion representations?

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

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

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

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

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

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

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

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

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

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

vhich allows these structures.

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

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

$\alpha < .1$

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

Nuclear fusion requires:

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

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

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

Changes that destabilize nuclei:

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

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

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

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

A small increase in α will destabalize all nuclei.

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

LONG LIVED STARS IMPOSE REQUIREMENTS:

Hydrogen burning stars are stable, photon pressure ~ 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:

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

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

trominger, 1986 concluded:

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

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

What about alternatives to string theory?

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."

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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:

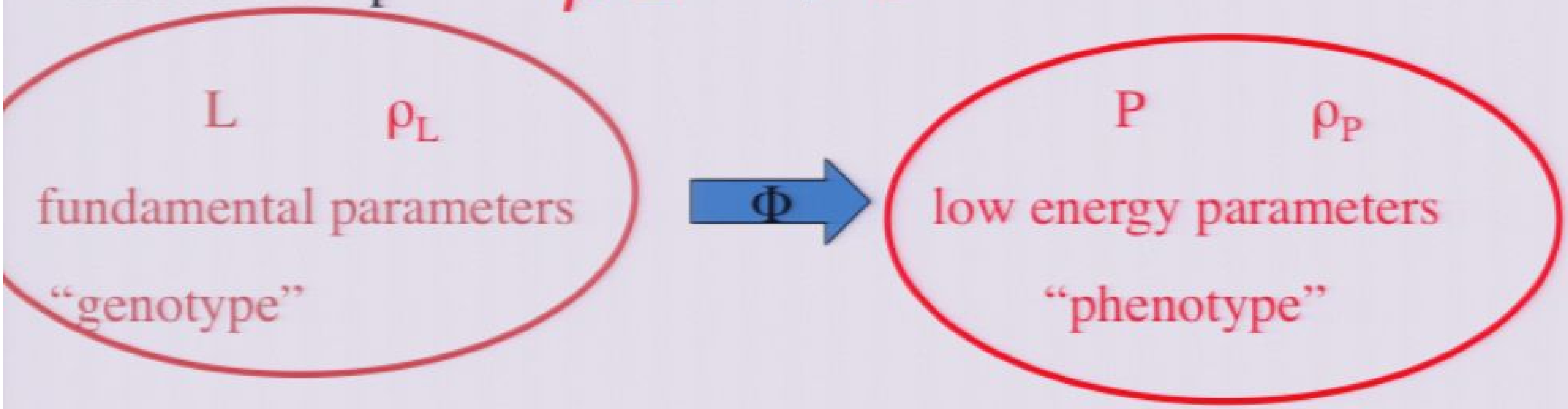
Static and dynamic.

These are represented by

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

Third approach: the weak anthropic principle (AP).

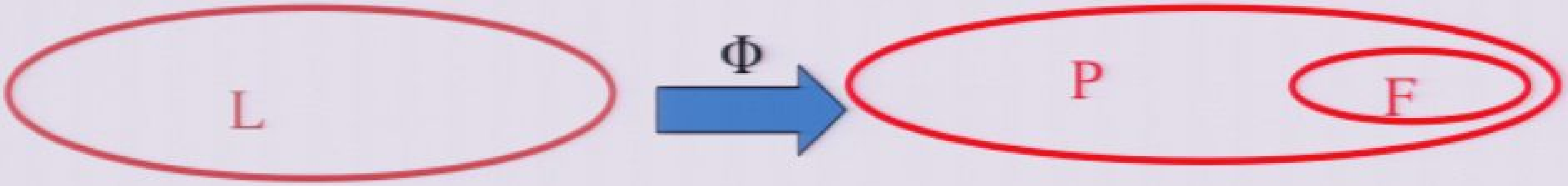
- There is a parameter space of fundamental unified theories, L
- There is a parameter space of the standard models, P
- There is a map $\phi: L \longrightarrow P$



- 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 $\phi: \rho_L \text{-->} \rho_P$ 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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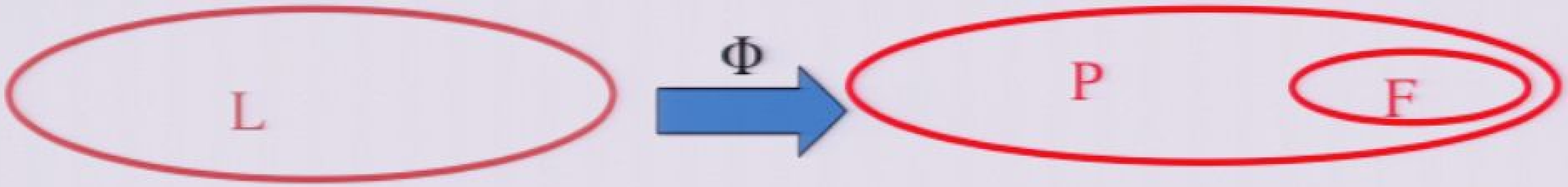

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So we can make no falsifiable predictions because, whatever the LHC sees, it will be within L and hence as probable as any other observation within L.

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 non-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.
4. Hence we predict that resonance to exist.

The experiment was done and the resonance was found.

What is the fallacy now?

'he multiverse plays no role in the argument:

). ~~We live in a multiverse with random laws distributed over a vast ensemble of universes.~~

. ~~Carbon is necessary for life to exist. Hence we must live in one of those universe that have carbon.~~

.. In fact carbon is abundant in our universe.

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. Hence we predict that resonance to exist.

Had the experiment not found the resonance we could not and would ot have questioned the existence of the multiverse. We would have hecked the nuclear physics.

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

Iere is a similar argument about the cosmological constant:

). We live in a multiverse with random laws distributed over a vast ensemble of universes.

. Galaxies necessary for life to exist. Hence we must live in one of those universe that galaxies.

. In fact galaxies are abundant in our universe.

. Using the laws of physics, we can deduce that for galaxies to have ormed the cosmological constant Λ must be less than some Λ_0.

. Hence we predict that $\Lambda < \Lambda_0$

'he cosmological constant was found with $\Lambda < \Lambda_0$

The *same fallacy* is present:

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

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

Here is a different 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. 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 $\Lambda < \Lambda_{observed}$ is about 10 %

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

Probability for $\Lambda < \Lambda_{observed}$ 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.

Wait: this is a bit too strong. There are extreme cases:

Suppose *every* member of the ensemble has a property, P, then that is a prediction:

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Suppose *every* member of the ensemble has a property, P, then that is a prediction:

Example:

Observational Consequences of a Landscape, hep-th/0505232
Freivogel, Kleban, Rodriguez Martinez, Susskind

"The most direct implication of a rich landscape is that our local universe was born in a tunnelling event from a neighboring vacuum. This would imply that we live in an open FRW universe with negative spatial curvature."

Wait : this is a bit too strong. There are extreme cases:

Suspose ***the ensemble is discretely infinite and all but a finite subset of member of the ensemble have a property, P,***
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Suppose ***the ensemble is discretely infinite and all but a finite subset of member of the ensemble have a property, P,***
then that is a prediction:

Example. Consider two anthropically allowed ranges of Λ:

$\Lambda^{+} = (0, \Lambda_{weinberg}),\quad \Lambda_{weinberg} > 0$

$\Lambda^{-} = (-\Lambda_{neg,}, 0\ ),\quad \Lambda_{neg} > 0$

Suppose there is a large but finite discretum of vacua in Λ^{+} and an infinite discretum of vacua in Λ^{-} . Then it follows that a universe with randomly selected laws from anthropically allowed domains will have $\Lambda < 0$ with probability unity.

(G Ellis)

Wait : this is a bit too strong. There are extreme cases:

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Acharya and Douglas, "A Finite Landscape?", arXiv: hep-th/0606212.
DeWolfe, Giryavets, Kachru and Taylor. "Type IIA Moduli Stabiliza- tion". arXiv: hep-th/0505160.

Shelton, Taylor, and Wecht, "Generalized Flux Vacua", arXiv: hep- th/0607015.

CONCLUSION: ***The weak anthropic principle makes almost 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.

The only exceptions are if every member of the ensemble has a property P, or if all but a finite subset of an infinite ensemble have a property, P, then P is predicted.

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

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

'o 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.

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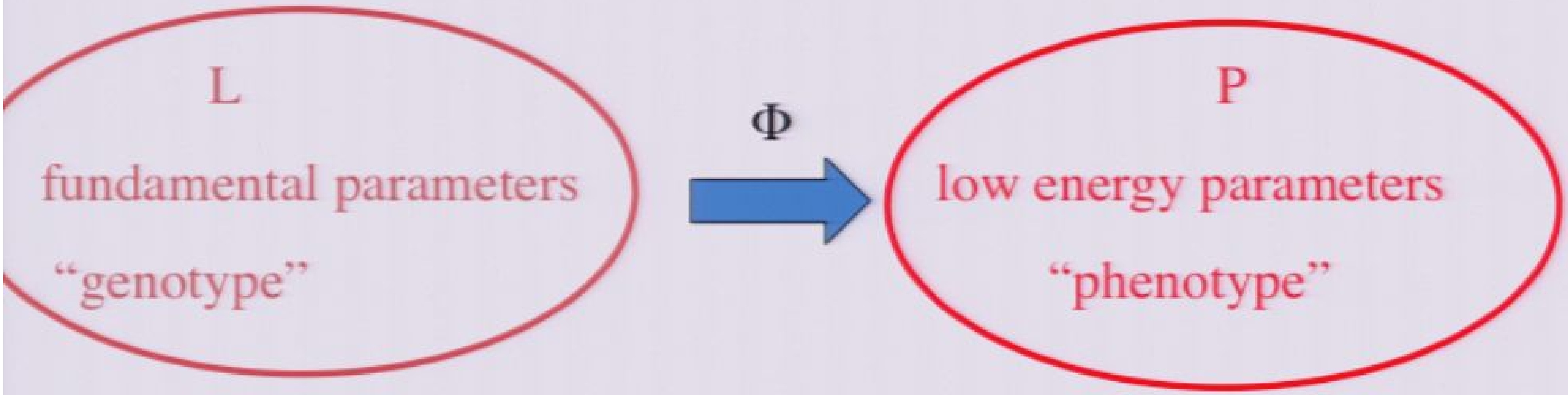
Ioreover, the method of reproduction should involve atomic physics nd chemistry so that fitness can be sensitive to the special tunings f the observed parameters.

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.

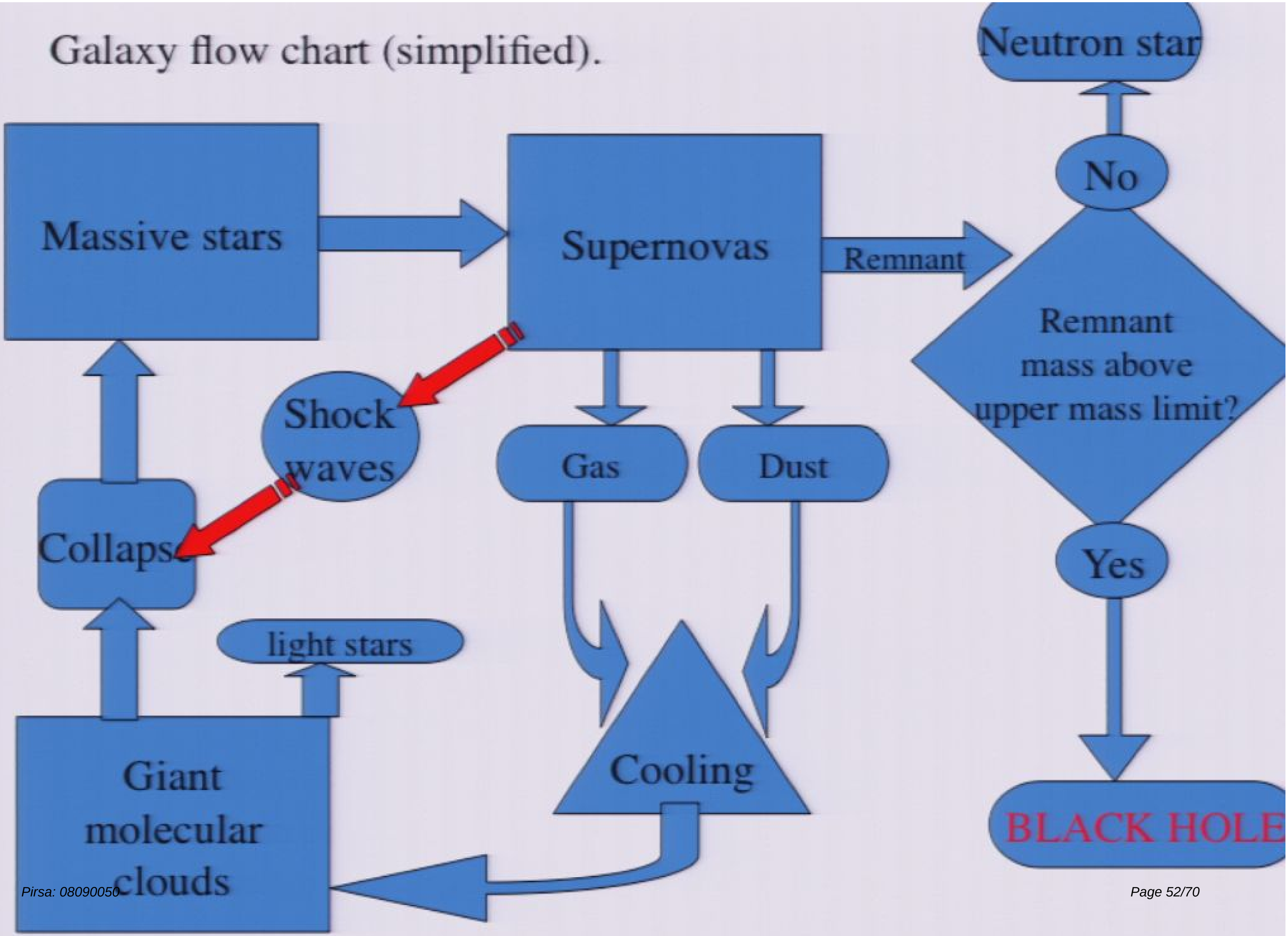
The standard arguments of population biology lead to the following conclusions for a high dimensional parameter space:

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.

Galaxy flow chart (simplified).



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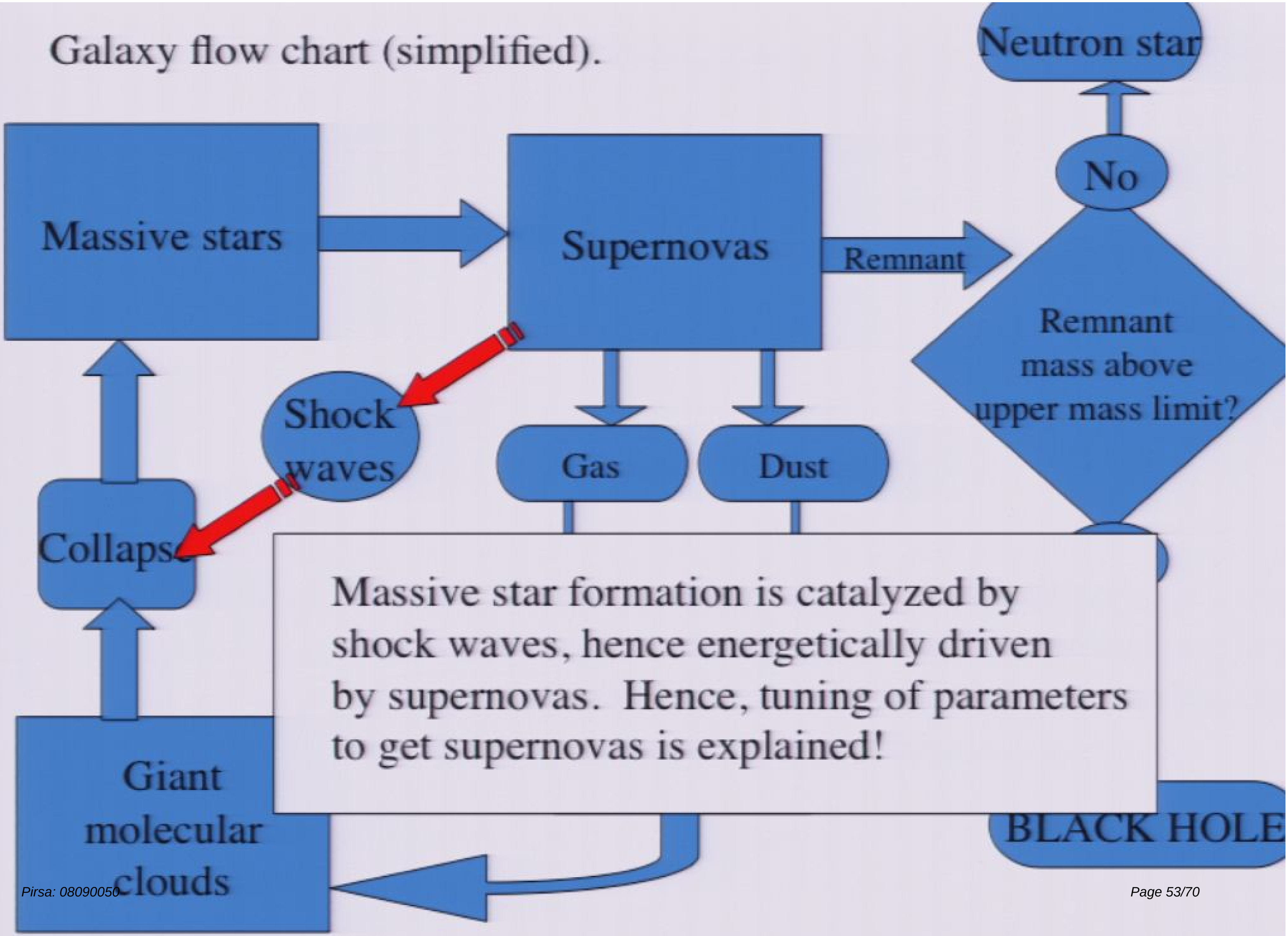
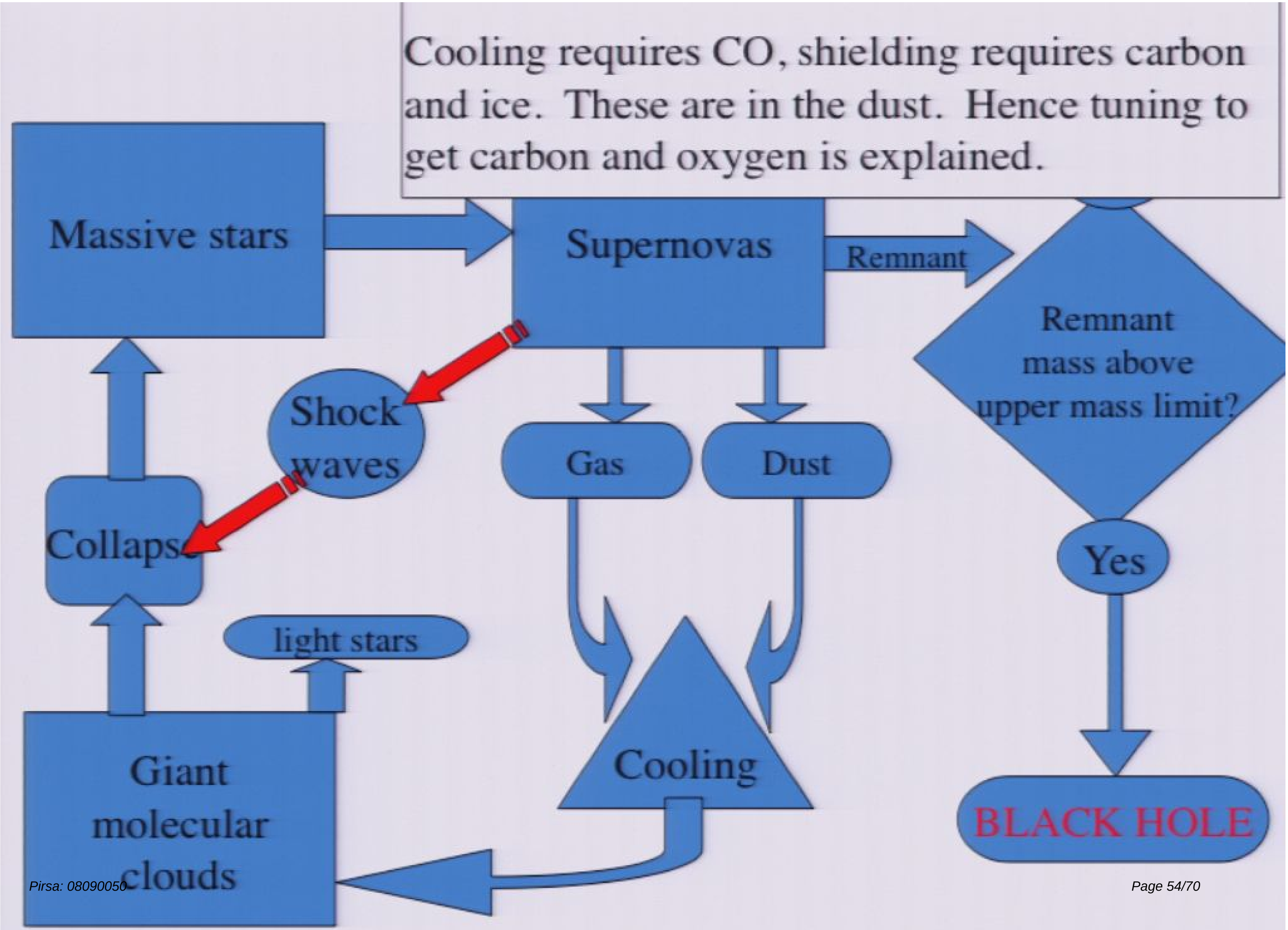
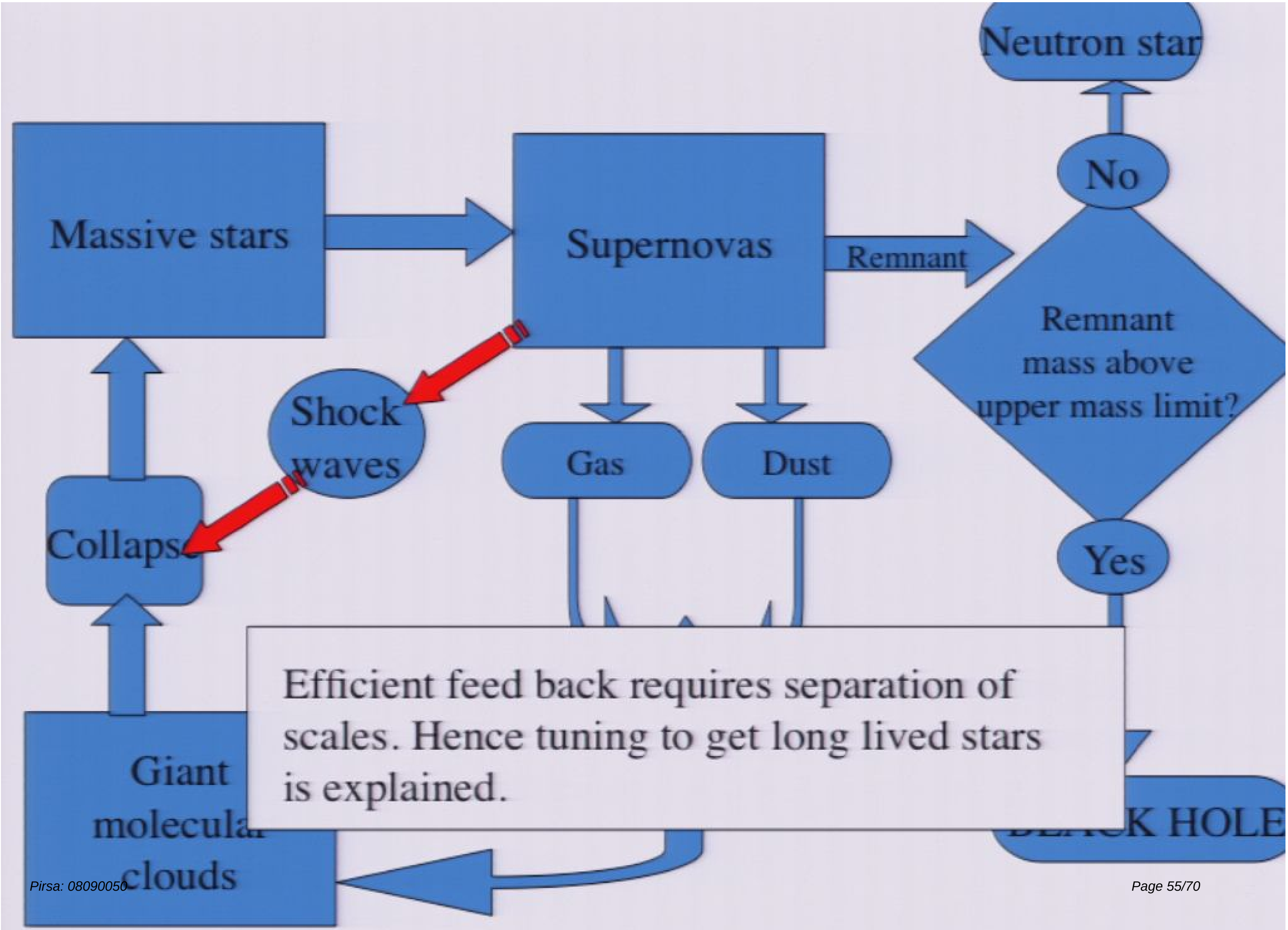


Massive star formation is catalyzed by shock waves, hence energetically driven by supernovas. Hence, tuning of parameters to get supernovas is explained!


Cooling requires CO, shielding requires carbon and ice. These are in the dust. Hence tuning to get carbon and oxygen is explained.
Massive stars
Supernovas
Remnant
Remnant mass above upper mass limit?
Shock waves
Gas
Dust
Collapse
Yes
light stars
Giant molecular clouds
Cooling
BLACK HOLE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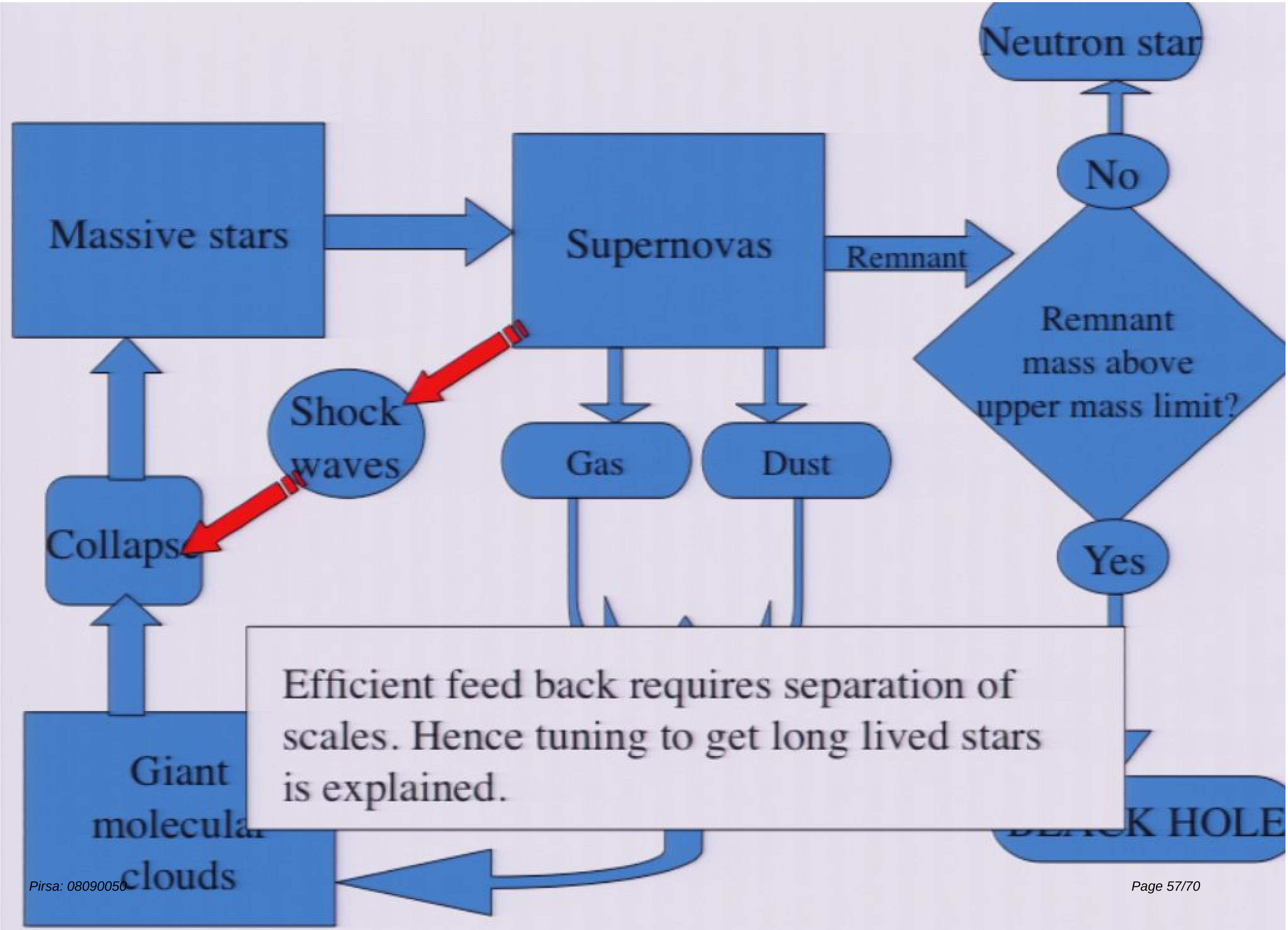
Yes
Efficient feed back requires separation of scales. Hence tuning to get long lived stars is explained.
Giant
molecular
clouds

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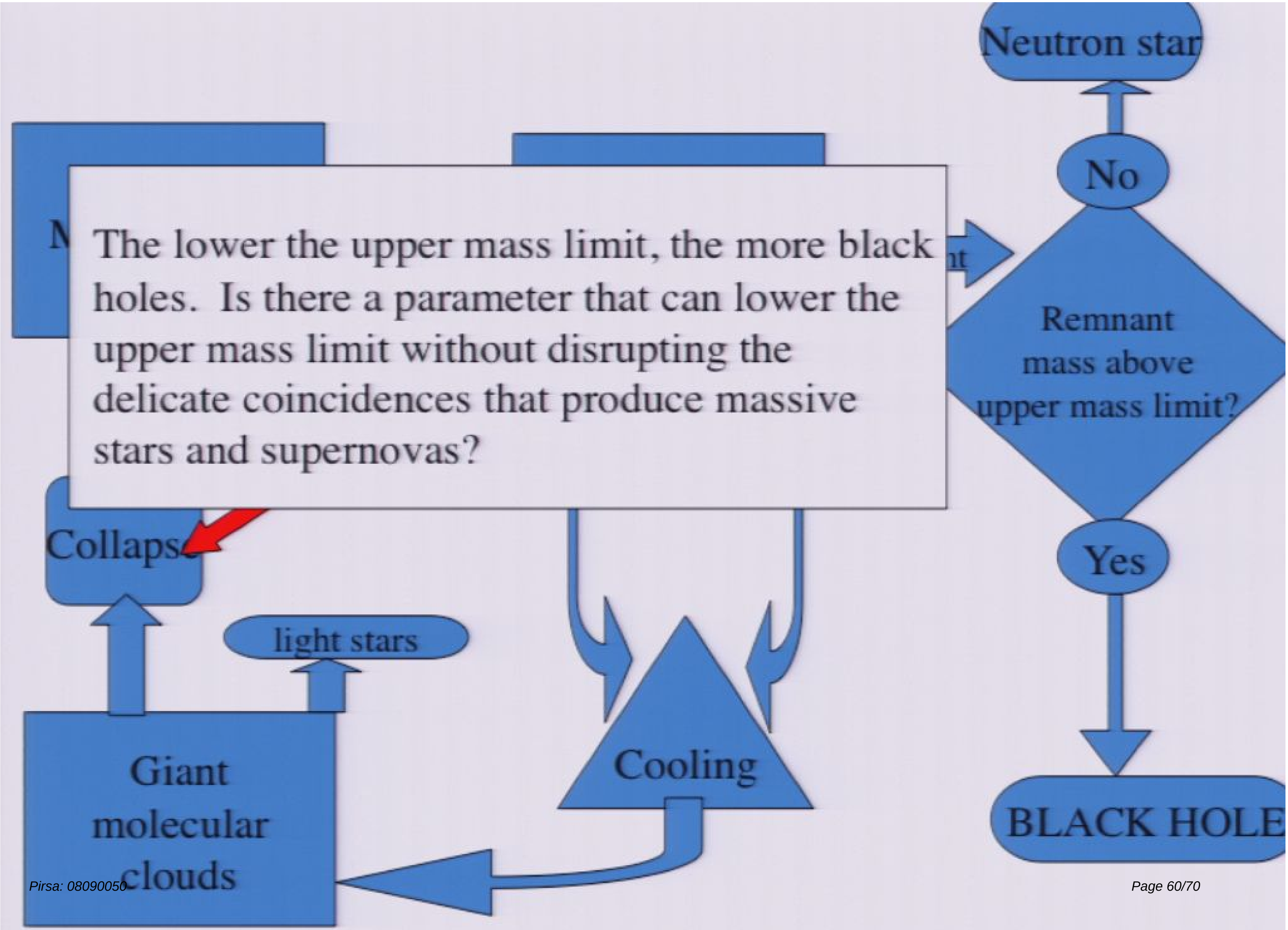
But to be taken seriously. A theory must make falsifiable predictions for doable experiments.

Three predictions, published in 1992:


The lower the upper mass limit, the more black holes. Is there a parameter that can lower the upper mass limit without disrupting the delicate coincidences that produce massive stars and supernovas?
Neutron star
No
Remnant mass above upper mass limit?
Yes
BLACK HOLE
light stars
Cooling
Giant molecular clouds

s there a parameter that can lower the upper mass limit without lisrupting 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.

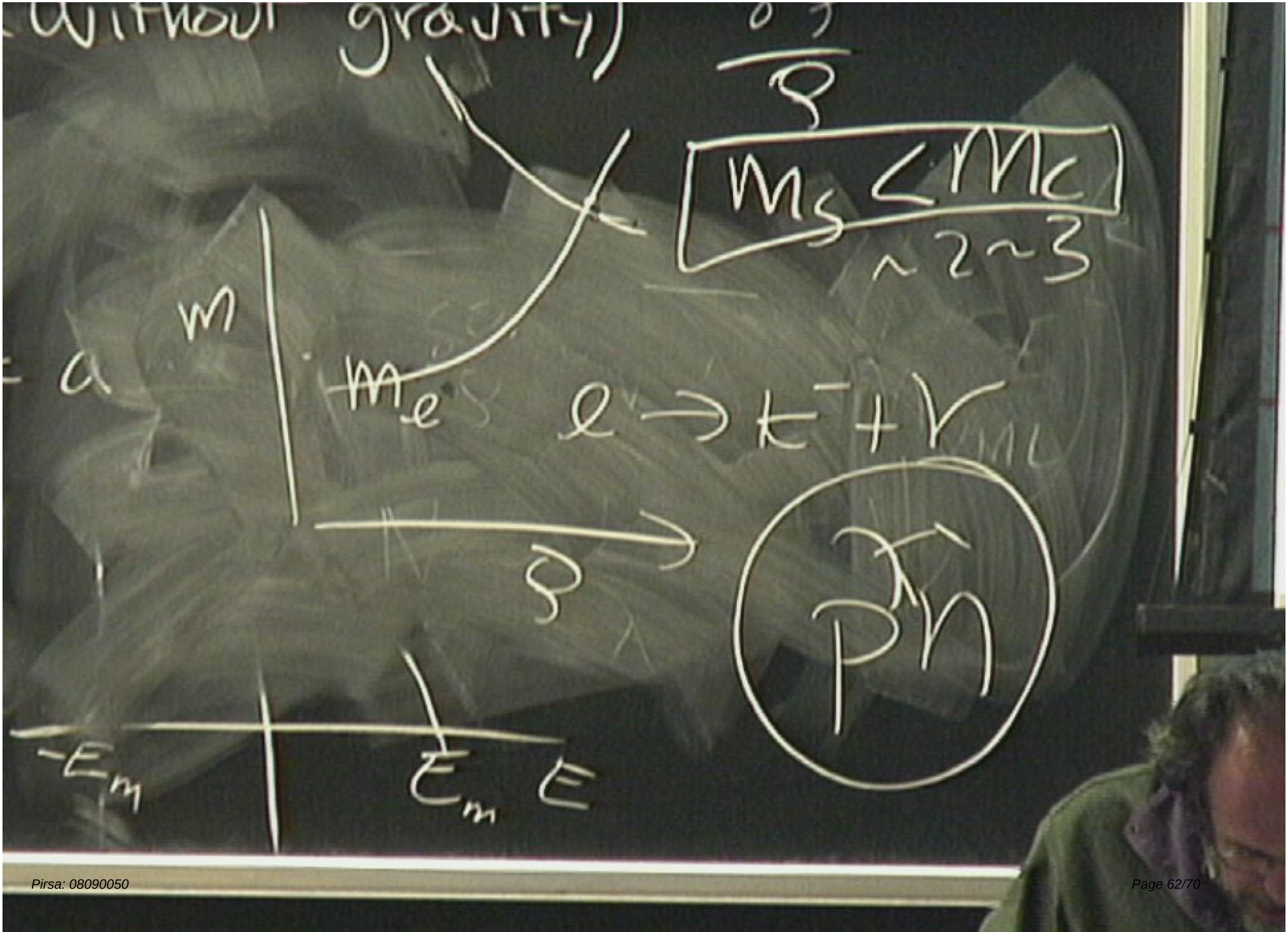
They show that this, if true, lowers the upper mass limit to 1.6 solar masses.

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!

So far all well measured neutron star masses are below 1.45 M_{solar}


(without gravity)
m_s < m_c
~2~3
m
m_e
e → t + ν
-E_m
E_m
E

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Kaon Condensation, Black Holes and Cosmological Natural Selection

G.E. Brown,[1] Chang-Hwan Lee,[2] and Mannque Rho[3]

[1] *Department of Physics and Astronomy, SUNY, Stony Btook, NY 11794, USA*
[2] *Department of Physics, Pusan National University, Busan 609-735, Korea*
[3] *Institut de Physique Théorique, CEA Saclay, 91191 Gif-sur-Yvette Cédex, France*

(Dated: February 21, 2008)

Find 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 $M \gtrsim 2M_\odot$. Then the following chain of predictions will be put in serious doubt or simply falsified: (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' theory.

I. A Web of Falsifiable Predictions:— Brushing aside a plethora of possible guerrilla effects and zeroing in on the most essential and most relevant nuclear and astrophysical mechanisms, Brown and Bethe (BB) [1] came up with a simple and unequivocal scenario on how black holes are formed in massive stellar collapse in the presence of kaon condensation in dense compact-star matter and deduced the maximum stable neutron star mass $M^{BB}_{max} \simeq 1.5M_\odot$ above which all massive stars will collapse to black holes. This scenario predicted about five times more light mass black holes than the standard scenario without kaon condensation [2, 3].

In this note we would like to point out an intricate web of relations between the critical density at which

density is increased beyond n_0. The predictio[n] is: "Find a well measured double neutron sta[r] nary in which the two neutron stars are more [t] 4% different from each other (modulo some s[] additional shift by He red giant) in mass. T[] the BB theory will be falsified." This predictio[n] quires that kaons condense at not too low a de[n] $< 3n_0$ and at not too high a density $> 3n_0$.

(c) Kaon condensation at $\sim 3n_0$ which gives an [] that when put in Tolman-Oppenheimer-Vo[] equation, leads to the maximum stable neutron mass of $\sim 1.5M_\odot$ has been predicted in several [dif]ferent ways, among which the most solid argu[ment] that we will rely on comes from low-energy [...]

Although most well-measured binary pulsars satisfy the bound of $M_{max}^{BB} = 1.5 M_\odot$, 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 $1.26^{+0.14}_{-0.12} M_\odot$ (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.

[4] G.E. Brown, C.-H. Lee, and M. Rho, Phys. Rept. (in press), arXiv:0708.3137 [astro-ph].

"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 predictinos 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

These are the only falsifiable predictions for doable observations so far generated by landscape theories.

Are there lessons?

"If I were to give an award for the single best idea anyone ever had, I'd give it to Darwin, ahead of even Newton or Einstein and everyone else. In a single stroke, the idea of evolution by natural selection unifies the realm of life, meaning and purpose with the realm of space and time, cause and effect, mechanism and physical law.

Darwin's idea had been born as an answer to questions in biology, but it threatened to leak out, offering answers -- welcome or not -- to question in cosmology"

Daniel Dennett, Darwin's Dangerous Idea (1995) p.21