Title: Electroweak stars: Electroweak Matter Destruction as Exotic Stellar Engine

Date: Mar 23, 2010 02:00 PM

URL: http://pirsa.org/10030003

Abstract: Stellar evolution from a protostar to neutron star is of one of the best studied subjects in modern astrophysics. Yet, it appears that there is still a lot to learn about the extreme conditions where the fundamental particle physics meets strong gravity regime. After all of the thermonuclear fuel is spent, and after the supernova explosion, but before the remaining mass crosses its own Schwarzschild radius, the temperature of the central core of the star might become higher than the electroweak symmetry restoration temperature. The source of energy, which can at least temporarily balance gravity, are baryon number violating instanton processes which are basically unsuppressed at temperatures above the electroweak scale. We constructed a solution to the Oppenheimer-Volkoff equation which describes such a star. The energy release rate is enormous at the core, but gravitational redshift and the enhanced neutrino interaction cross section at these densities make the energy release rate moderate at the surface of the star. The lifetime of this new quasi-equilibrium can be more than ten million years, which is long enough to represent a new stage in the evolution of a star.

Electroweak stars

Dejan Stojkovic

SUNY at Buffalo

Perimeter Institute

Waterloo, March 23, 2010

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

University at Buffalo

Based on:

Electroweak stars: how nature may capitalize on the standard model's ultimate fuel.

D. Dai[1], A. Lue[2], G. Starkman[3], D. Stojkovic[1]

e-Print: **arXiv:0912.0520**

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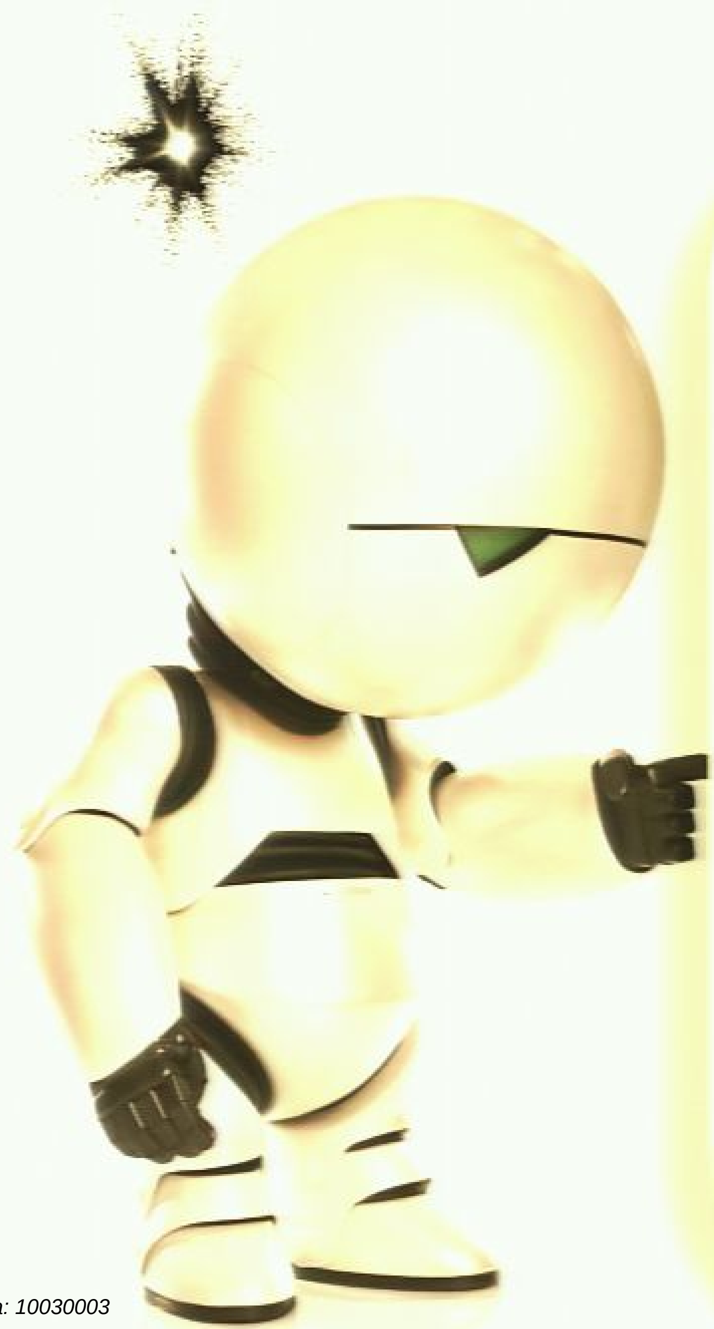
Electroweak stars!



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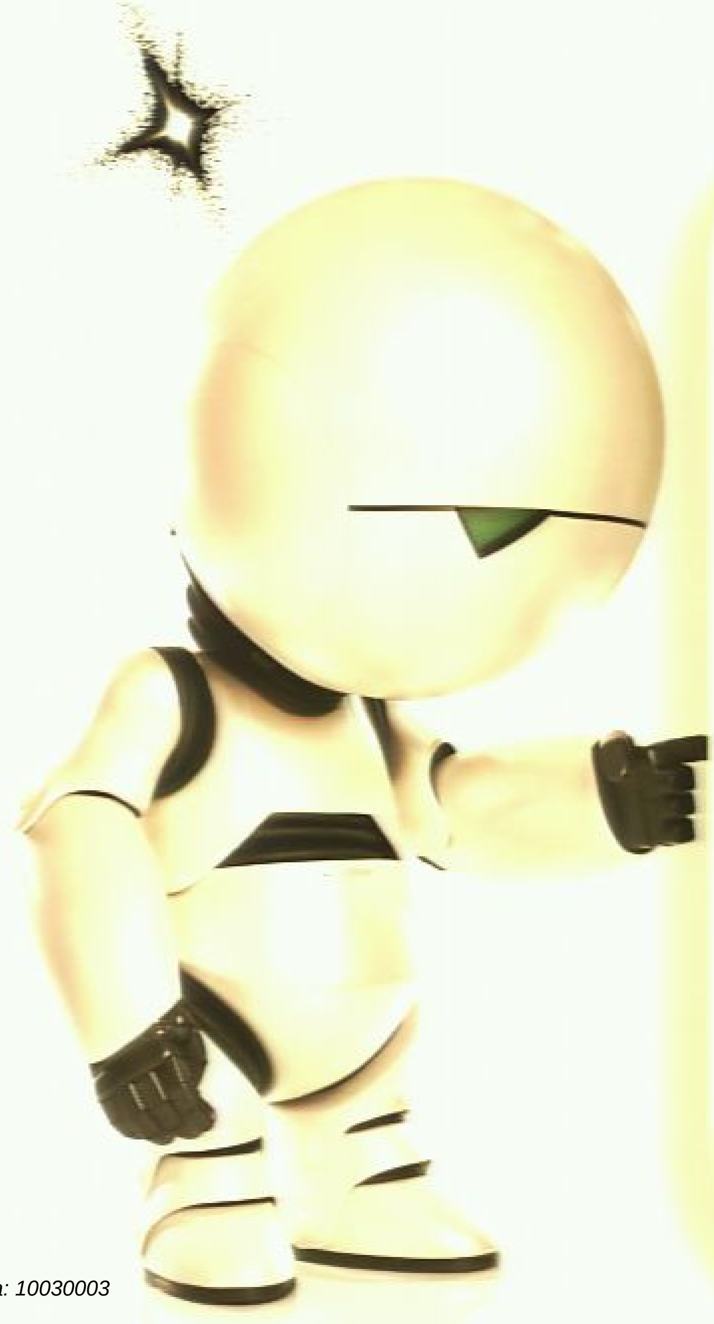
- **Brief overview**
  - Stellar evolution: protostar – neutron star
  - Quark star
- **Question:**

Can Electroweak Stars powered by baryon number violating processes exist?



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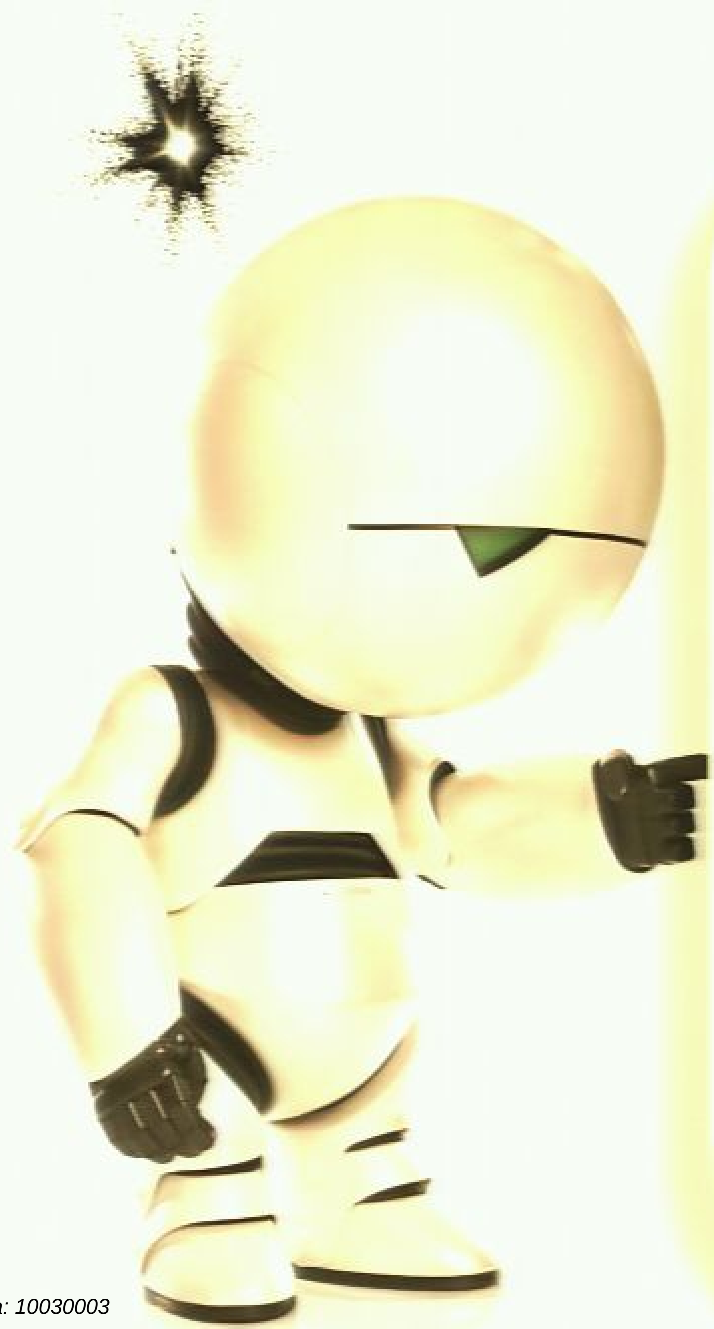

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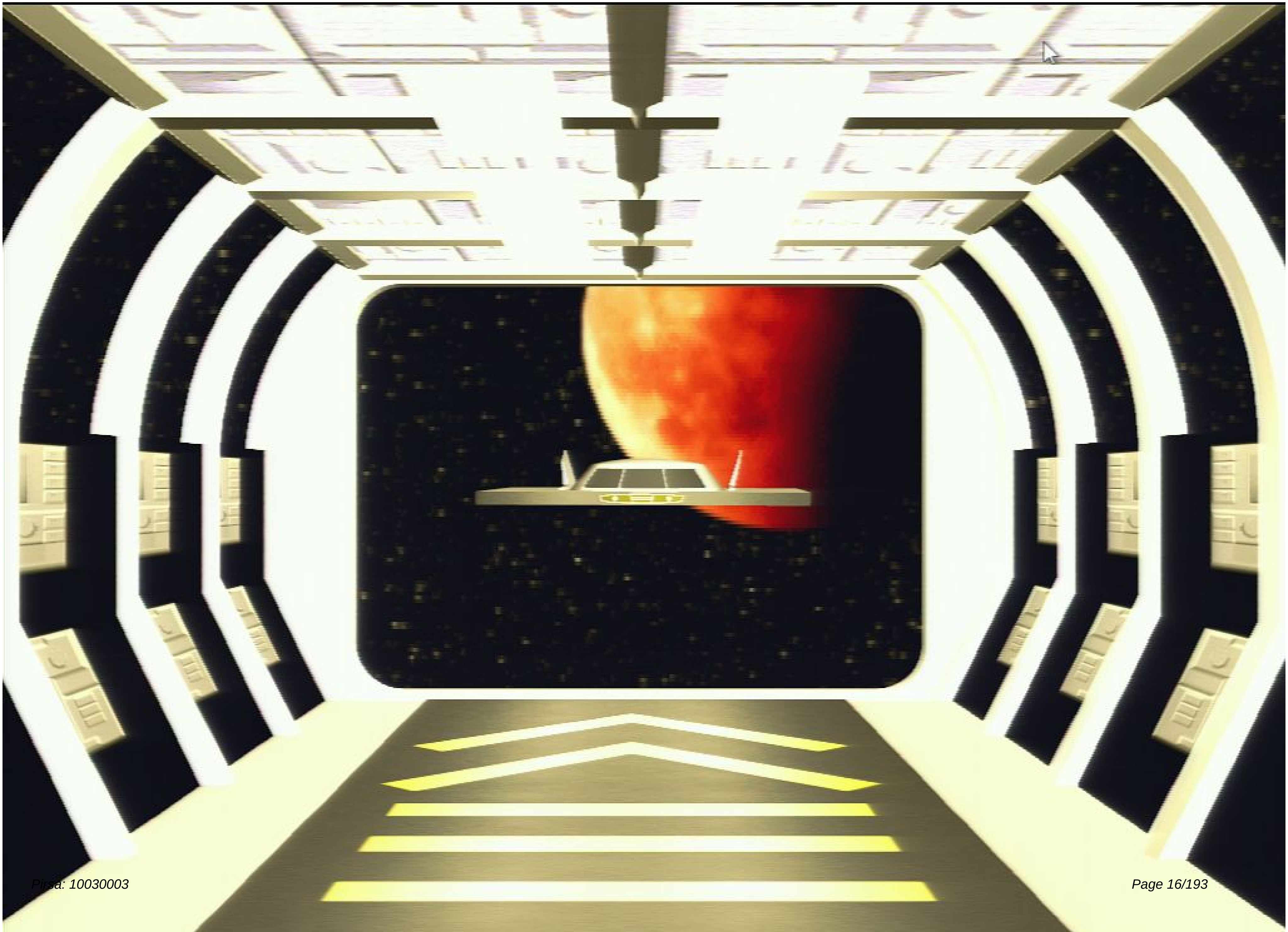
Perhaps YES!



Dark Matter

- Our universe is filled with clouds of dust and gas. (71% hydrogen, 27% helium, 2% everything else)

- In some places these **nebulae** are dense enough that gravity pulls them together more strongly than their natural expansion tries to move them apart.

- These will collapse to become stars.

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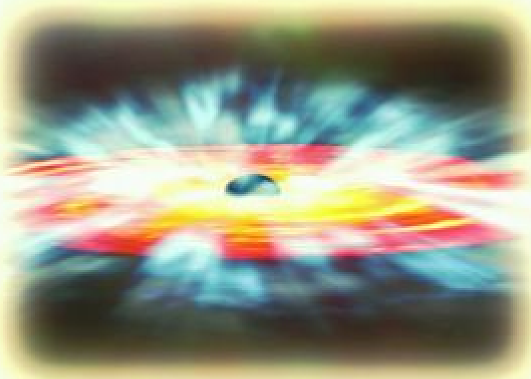
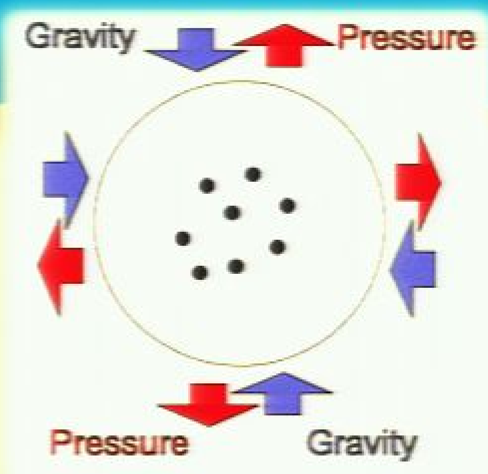
Protostar Stage

- Gases being pulled together by gravity accelerate as they fall inward.
- Then they crash into the other gases that have accumulated at the center.
- This causes the central, "baby star" (called a **protostar**) to be very hot.



Main Sequence Star

- The core of a protostar gets hot enough for nuclear fusion to commence
- A protostar is so long as gases are still falling inwards onto it
- Protostar stage lasts a few million years
- A **main sequence star** is powered only by nuclear fusion in an equilibrium with gravity



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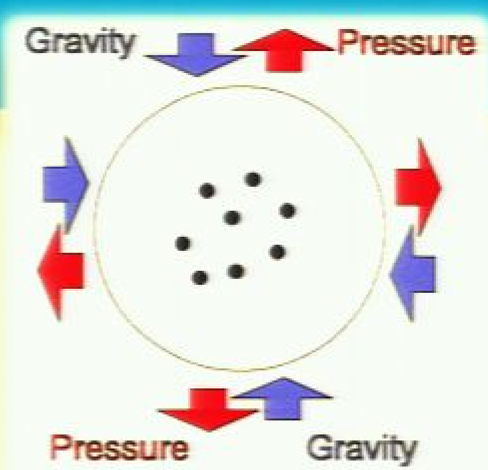

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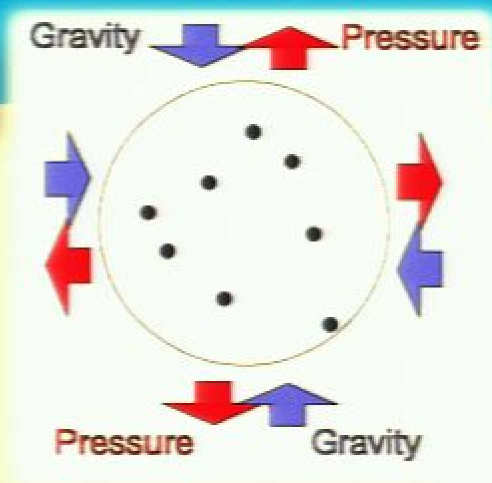

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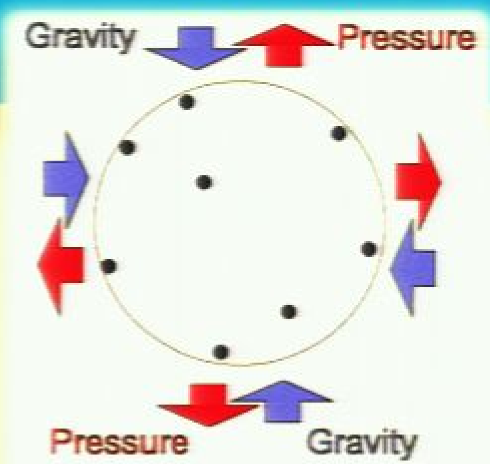

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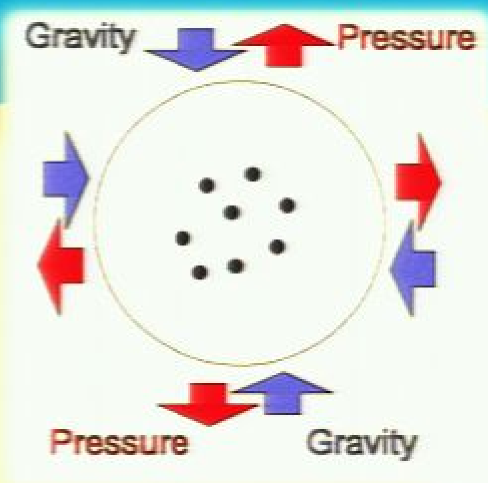

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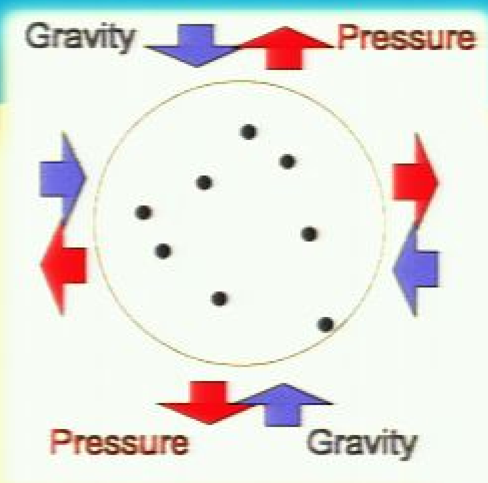

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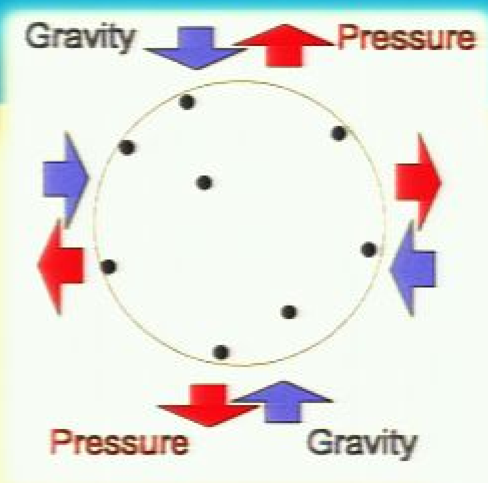

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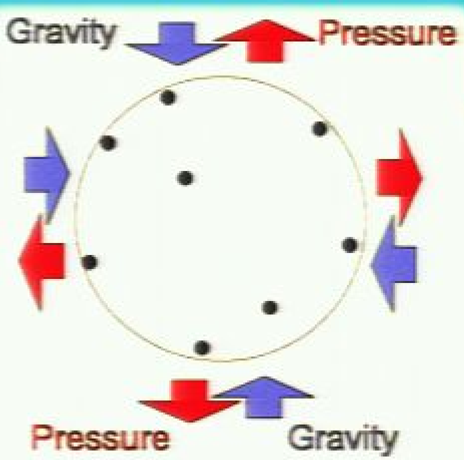

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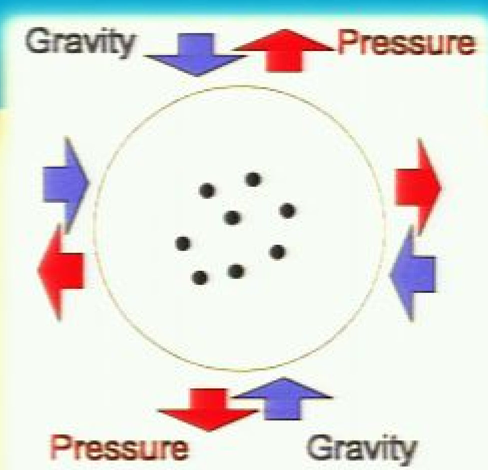

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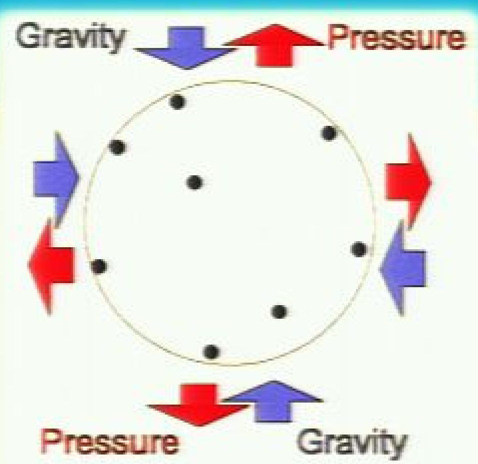

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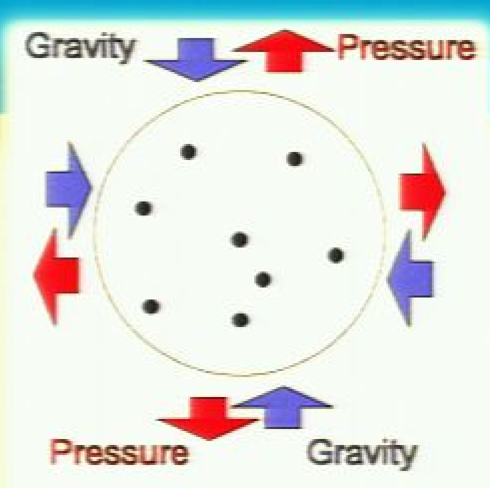

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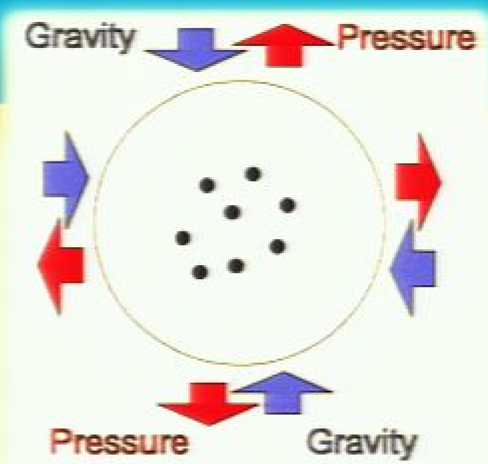

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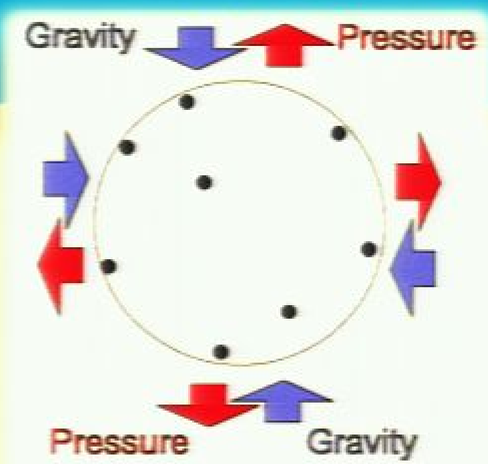

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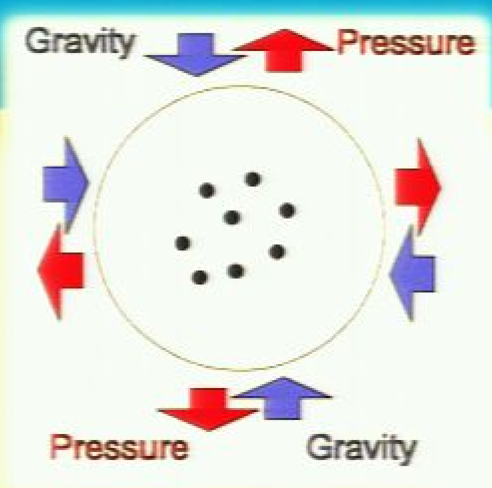

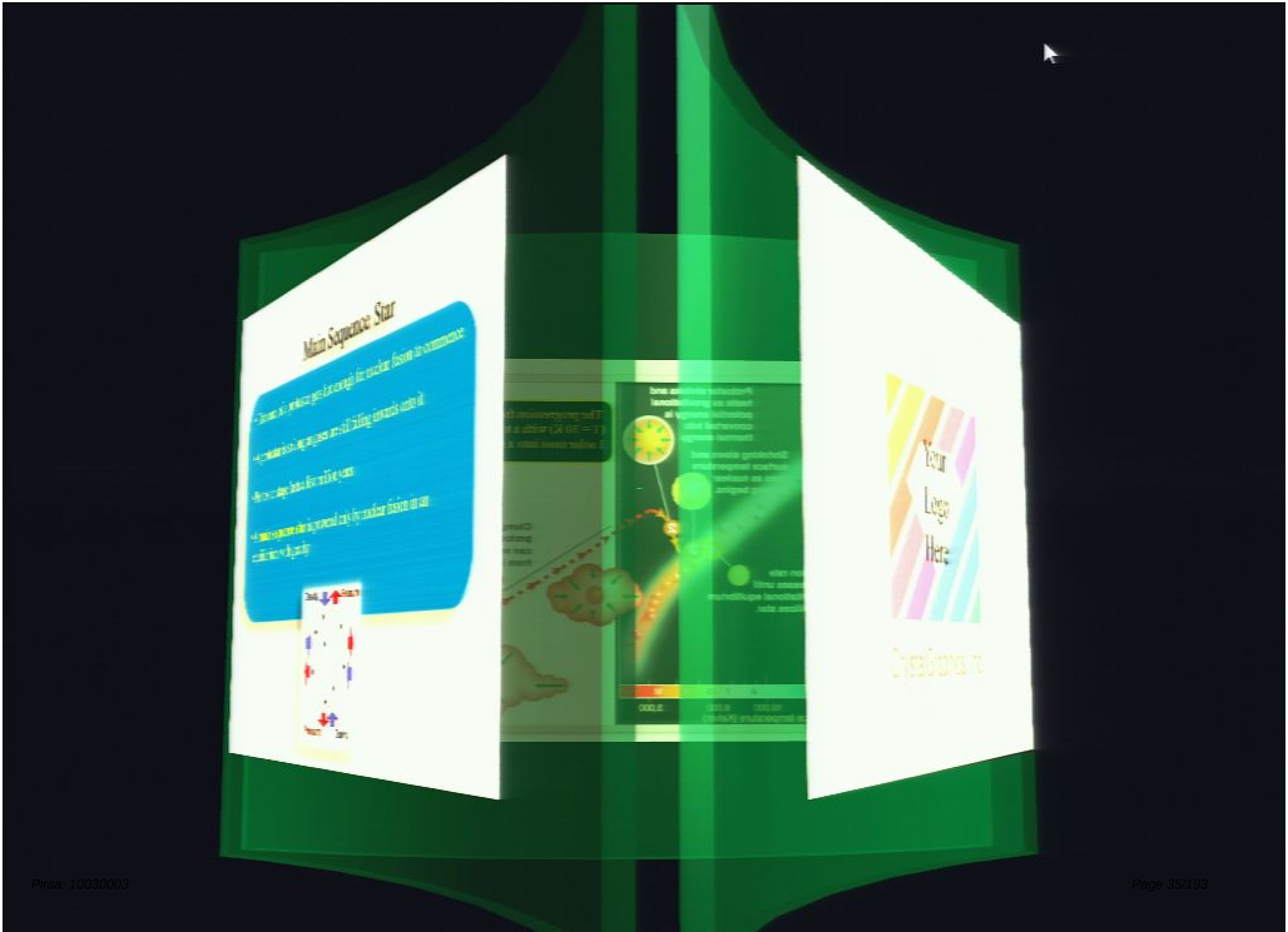
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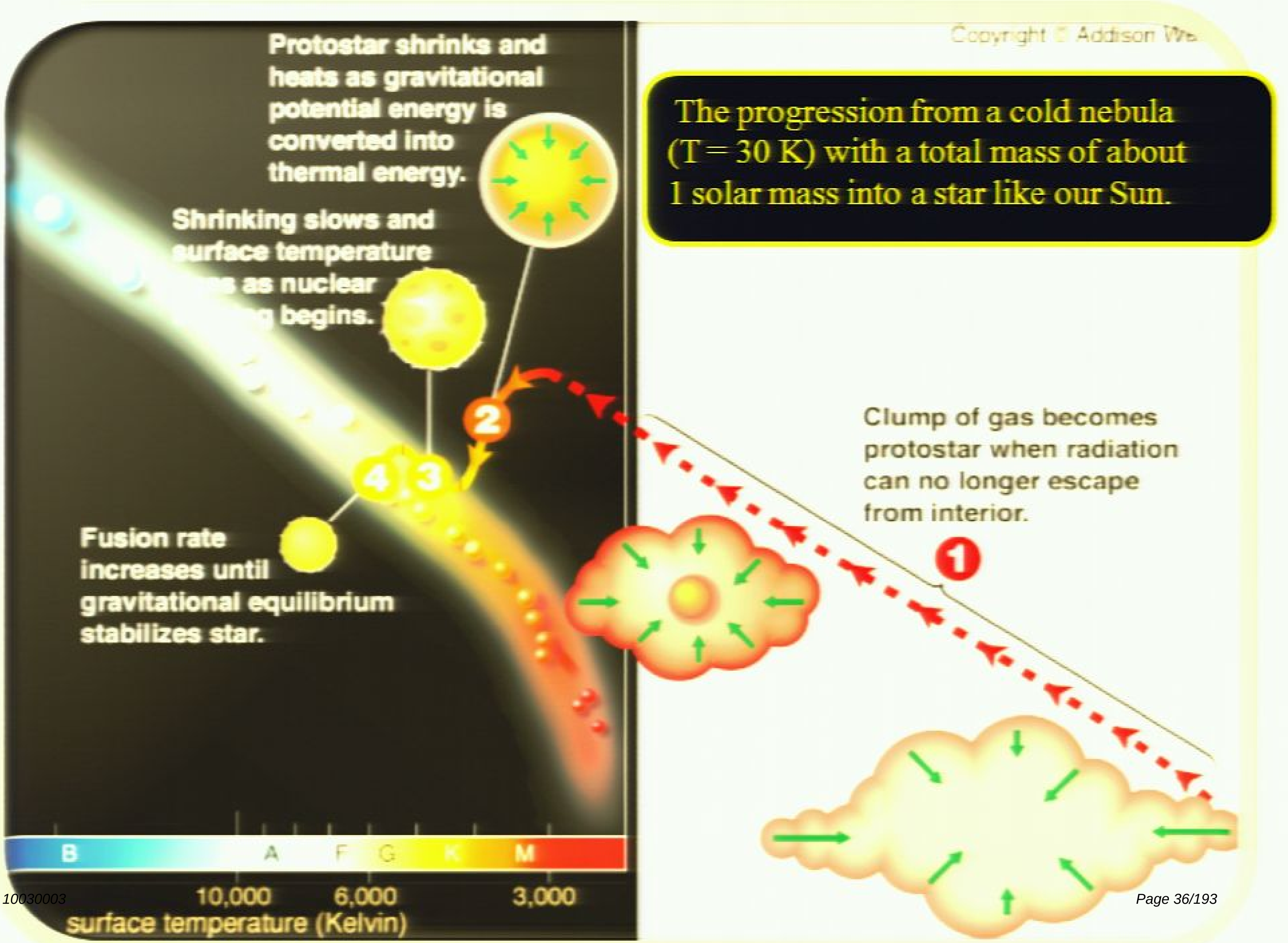
Your
Logo
Here



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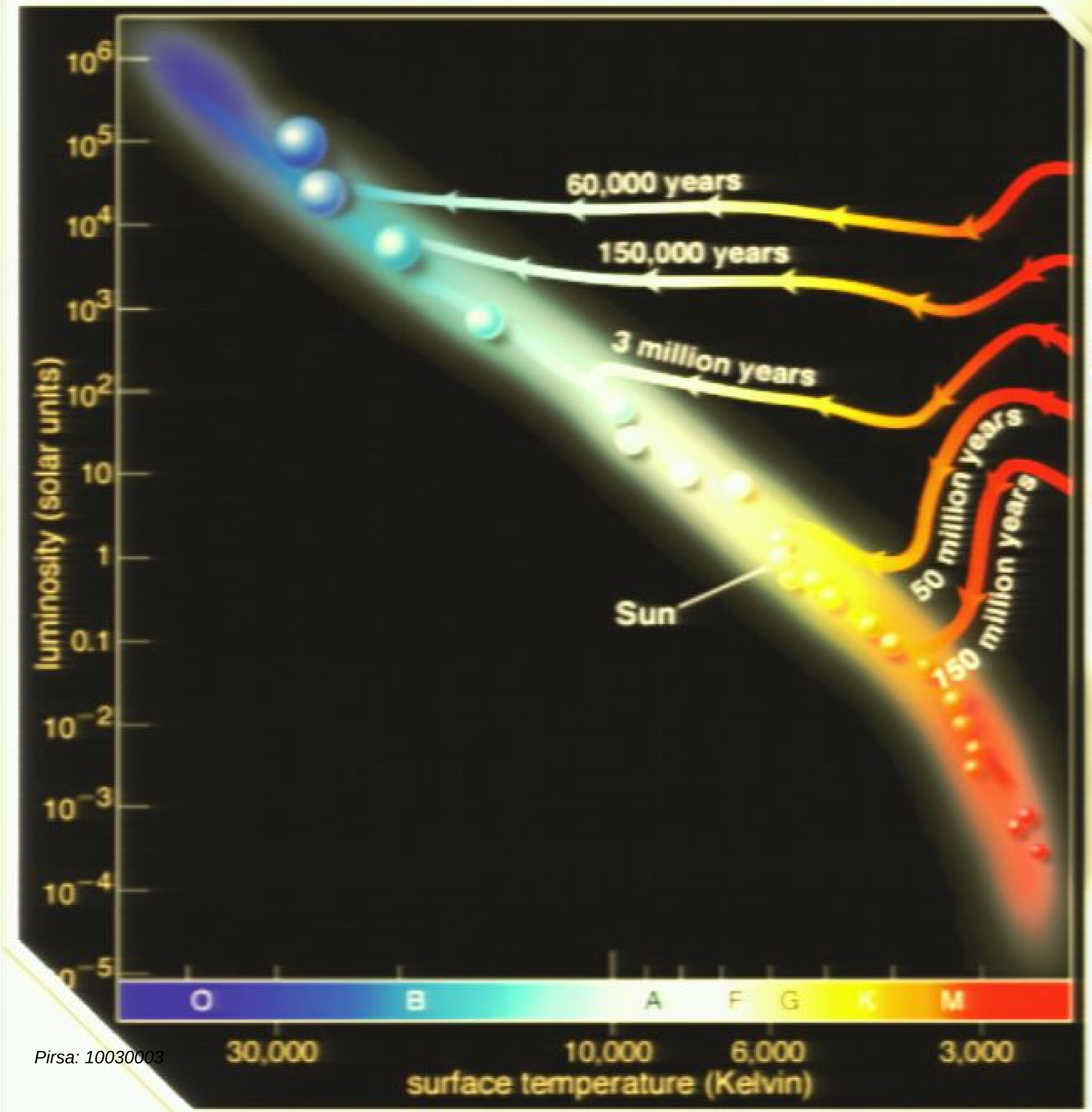
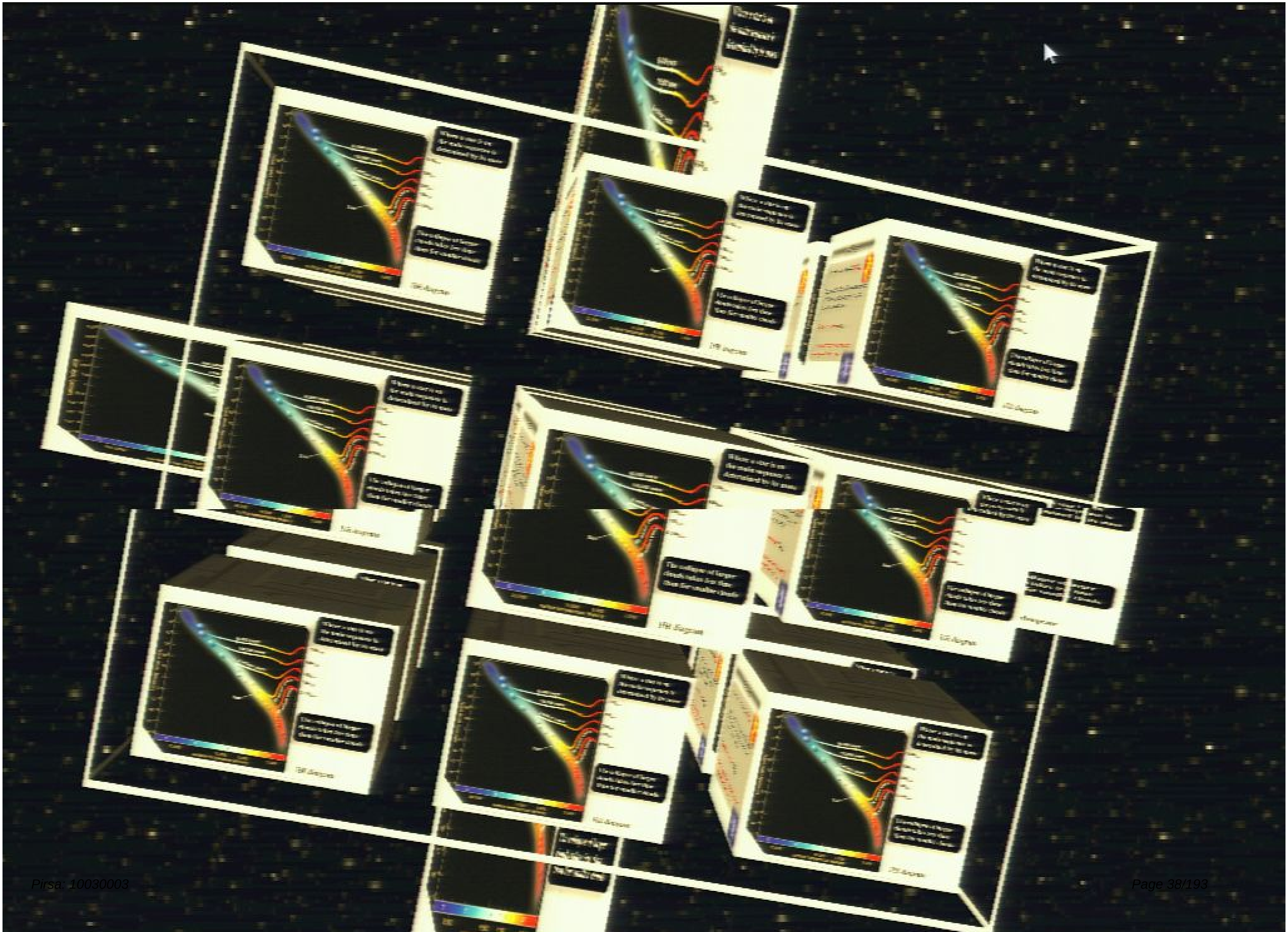
The progression from a cold nebula (T = 30 K) with a total mass of about 1 solar mass into a star like our Sun.
Protostar shrinks and heats as gravitational potential energy is converted into thermal energy.
begins.
Fusion rate increases until gravitational equilibrium stabilizes star.
Clump of gas becomes protostar when radiation can no longer escape from interior.
1
2
3
4
B
A
F
G
K
M
10,000
6,000
3,000
surface temperature (Kelvin)



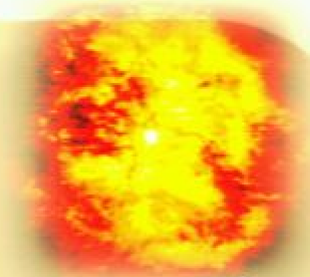
Where a star is on the main sequence is determined by its mass

The collapse of larger clouds takes *less* time than for smaller clouds

HR diagram



Mass Range



- The most massive stars are around **100 M_{Sun}**
- Larger stars can't form because the "solar wind" generated by the first 100 M_{Sun} will push away other gases rather than allowing them to join the star
- The smallest stars are around **0.1 M_{Sun}**
- Any smaller than this and the core never gets hot and dense enough for nuclear fusion to occur

Evolution of the Main Sequence Stars

A star's life time Δt ~ energy reservoir / luminosity

TABLE 12-2
Main-Sequence Stars

Spectral Type	Mass (sun = 1)	Luminosity (sun = 1)	Approximate Years on Main Sequence
O5	40	405,000	1×10^6
B0	15	13,000	11×10^6
A0	3.5	80	440×10^6
F0	1.7	6.4	3×10^9
G0	1.1	1.4	8×10^9
K0	0.8	0.46	17×10^9
M0	0.5	0.08	56×10^9

Energy reservoir ~ M

Luminosity L ~ $M^{3.5}$

$\Delta t \sim M/L \sim 1/M^{2.5}$

Massive stars live shorter!

Evolution of stars

- Stellar models show how stars change
- Star moves on the HR diagram

  e.g. evolution onto the main sequence (MS) (birth)
  e.g. evolution on the MS (life)
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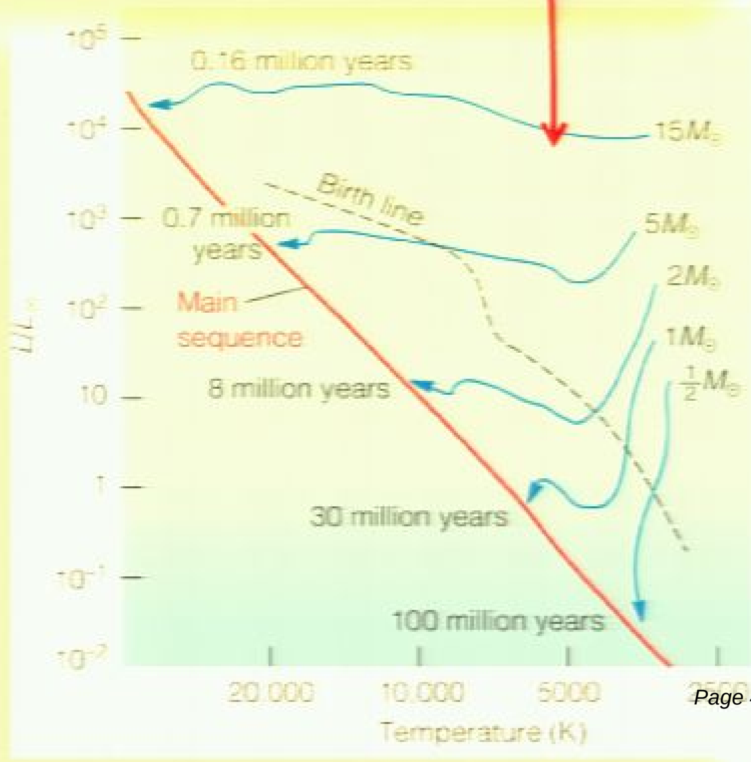

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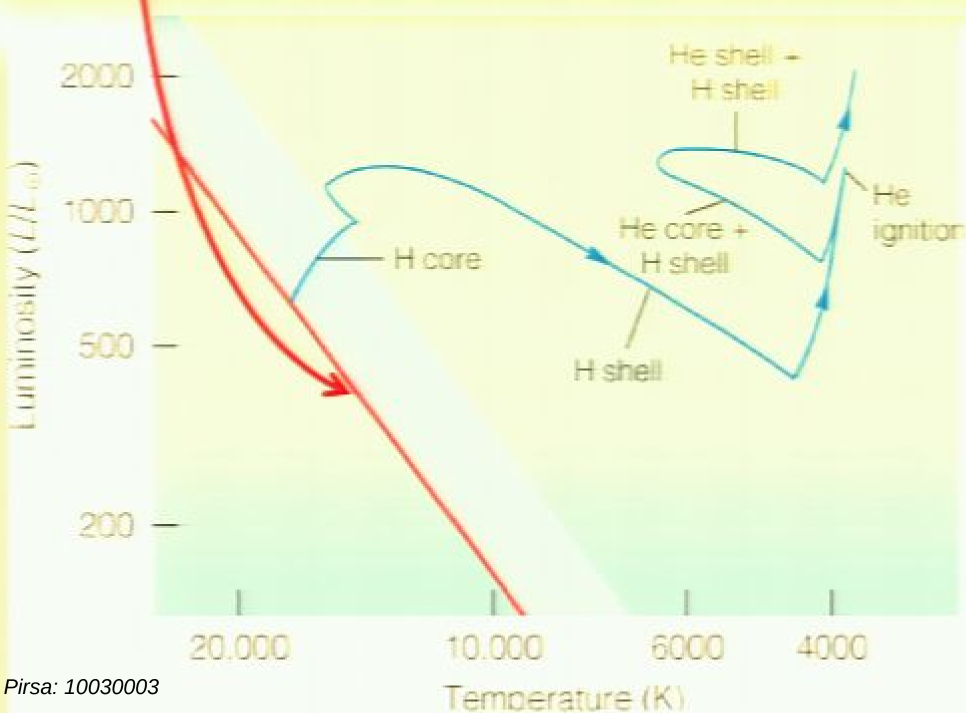
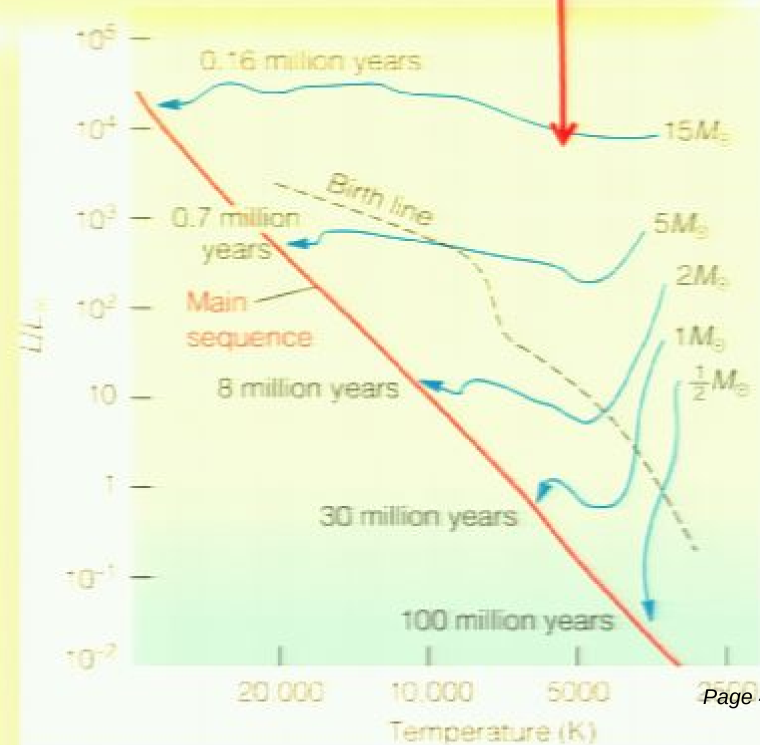
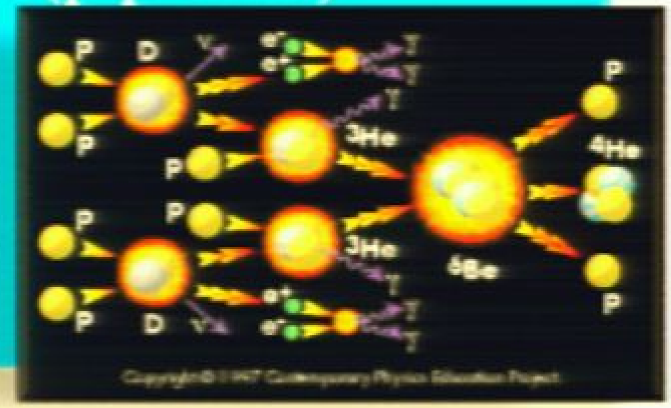




- For 90% of the star's life: H → He in core (p-p chain)
- Doesn't move (much) on HR diagram
- Small change during lifetime



Good news, main sequence stars are boring!

Why is that good news?

Because we live on a planet orbiting a main sequence star.

We want that star to do exactly the same thing
every day without anything new and exciting.

Ancient Chinese curse:
"may you live in interesting times."

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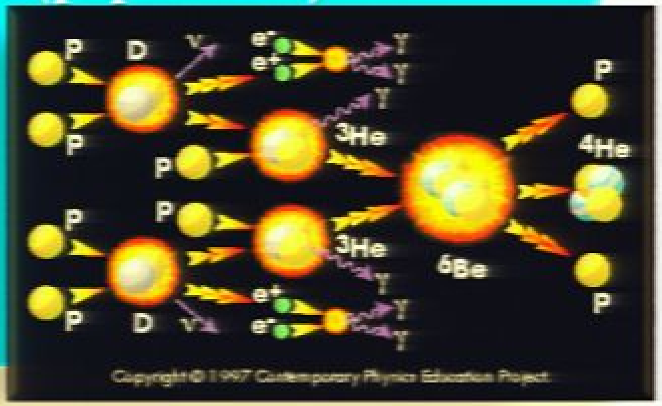

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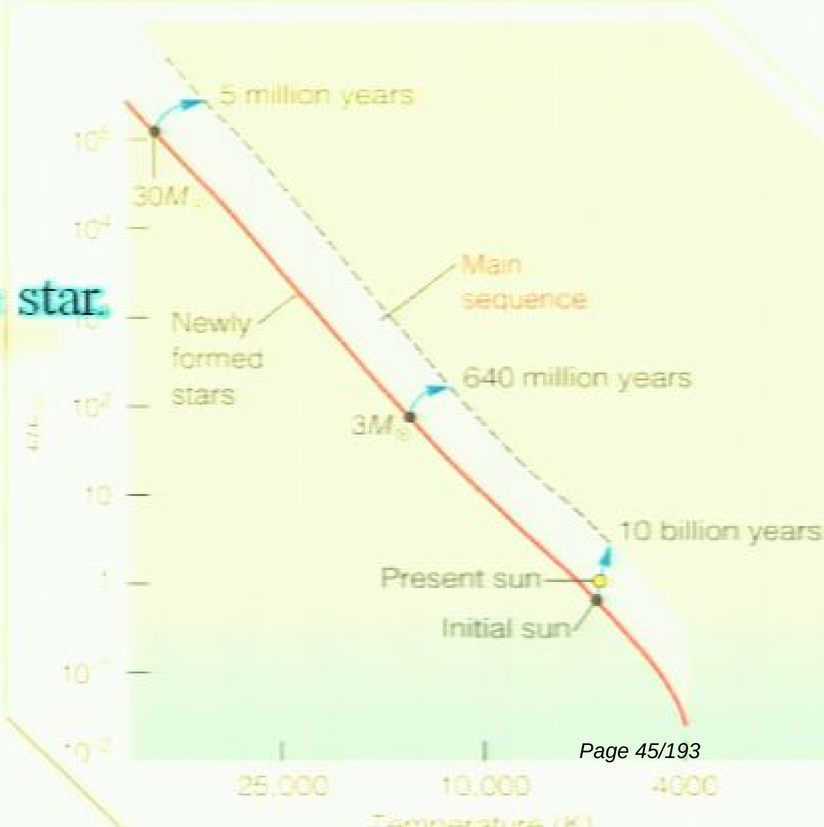

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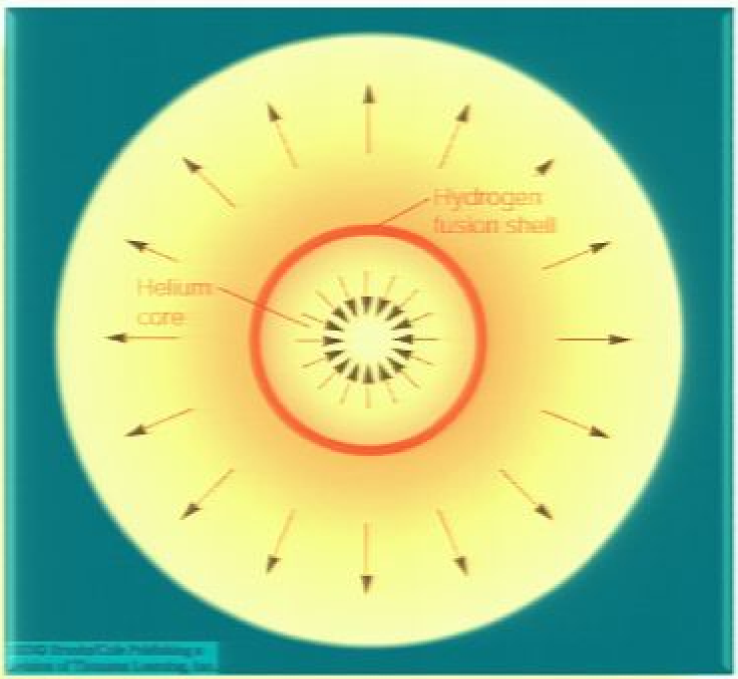
Interesting times: leaving the main sequence (Red Giant)



He Core + H-burning shell produce more

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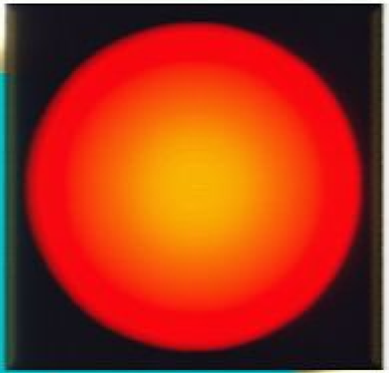
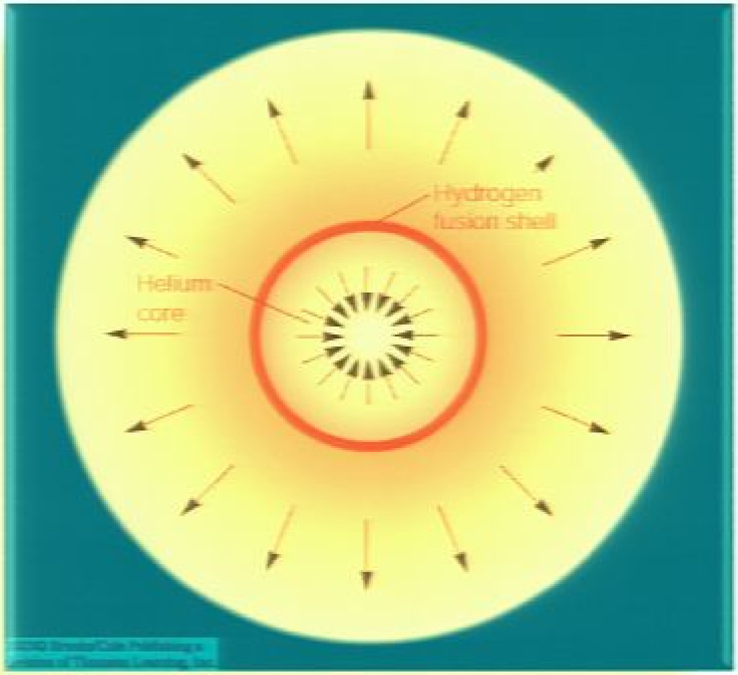


- Hydrogen in core gradually gets used up
  - He "ash" accumulates
  - Helium core contracts, pulls down fresh hydrogen
  - Hydrogen burns vigorously in a shell, outside the core
  - high L → envelope swells → red giant (tiny core, huge envelope)



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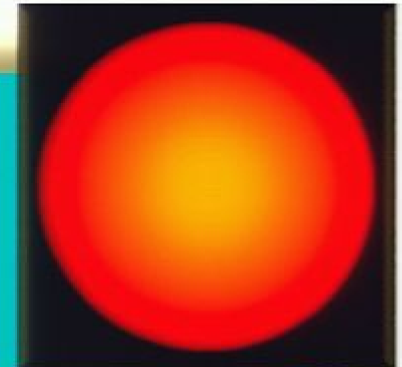

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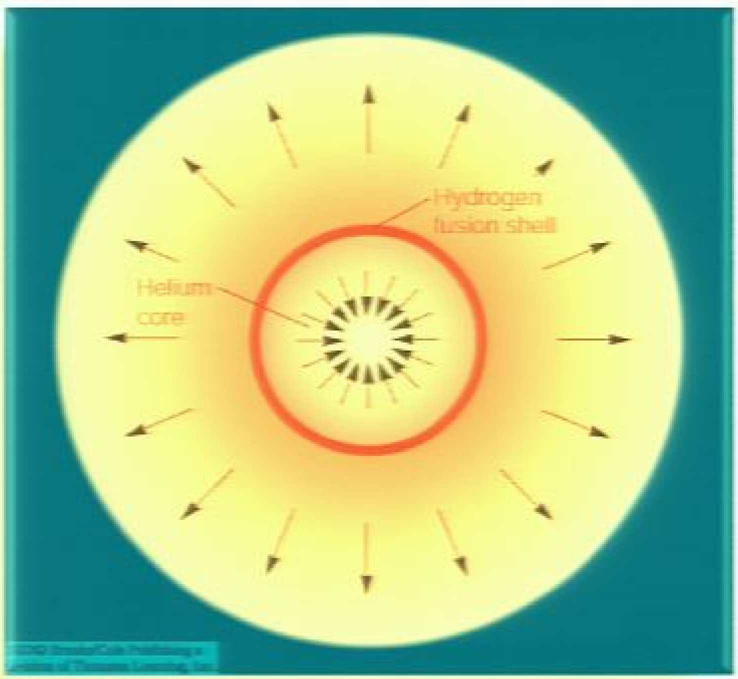

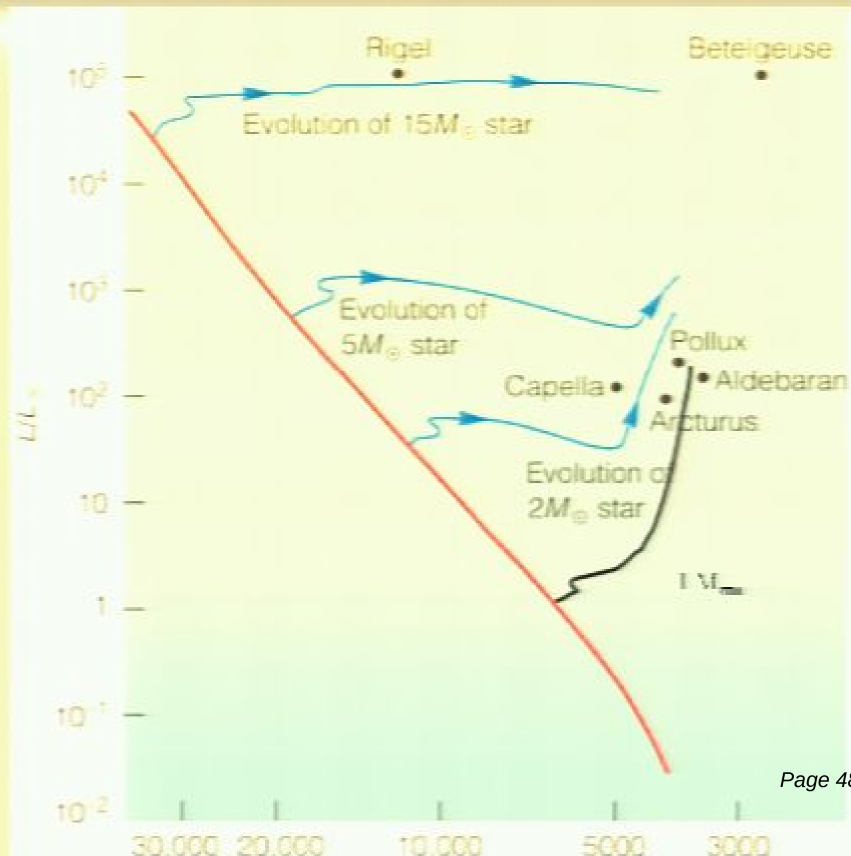

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The end of life on Earth…

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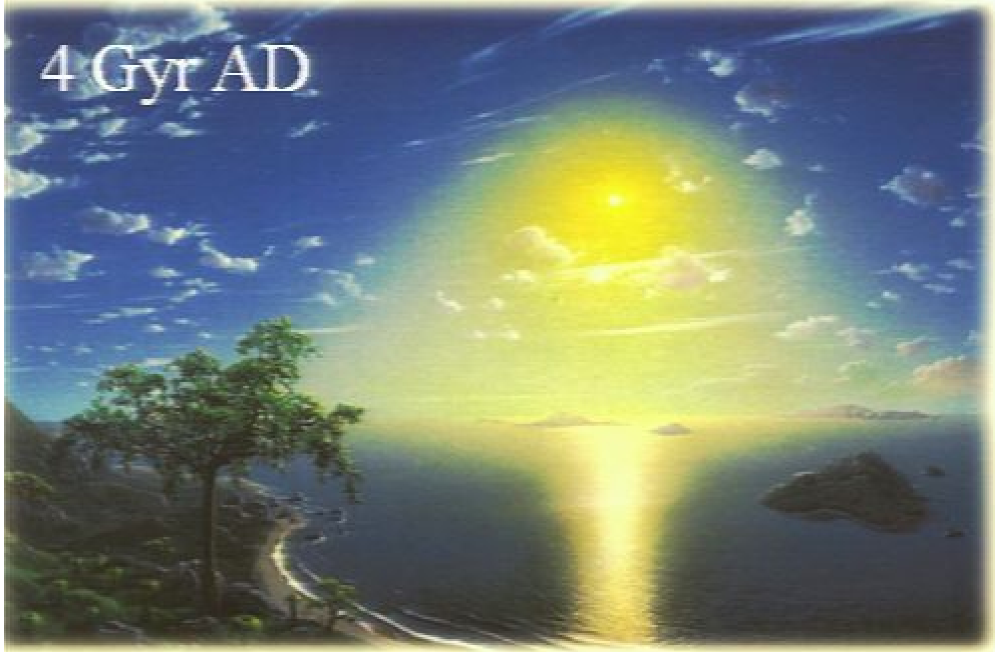

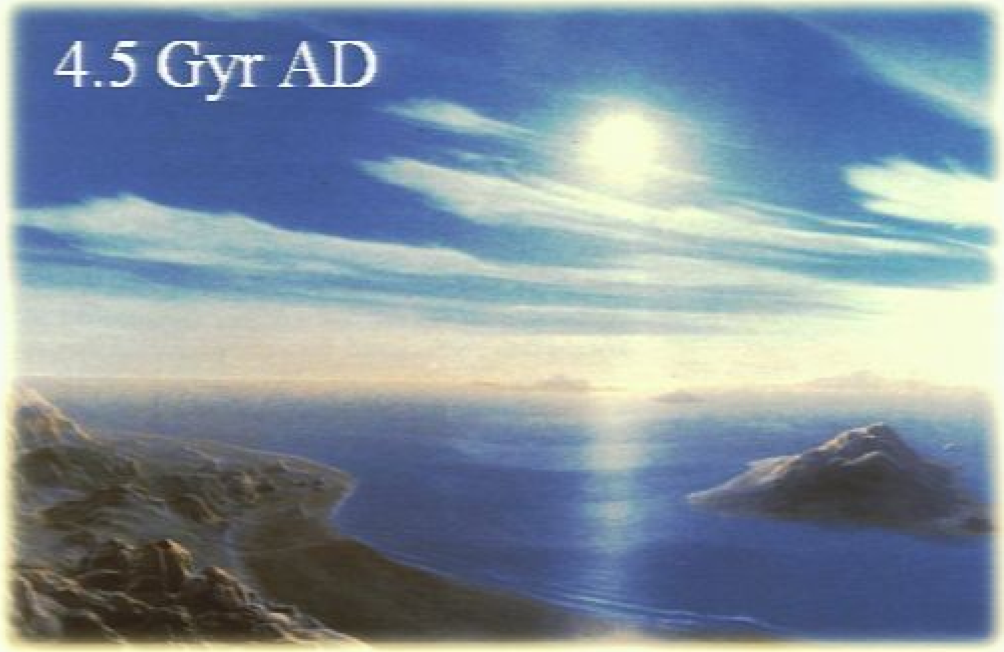

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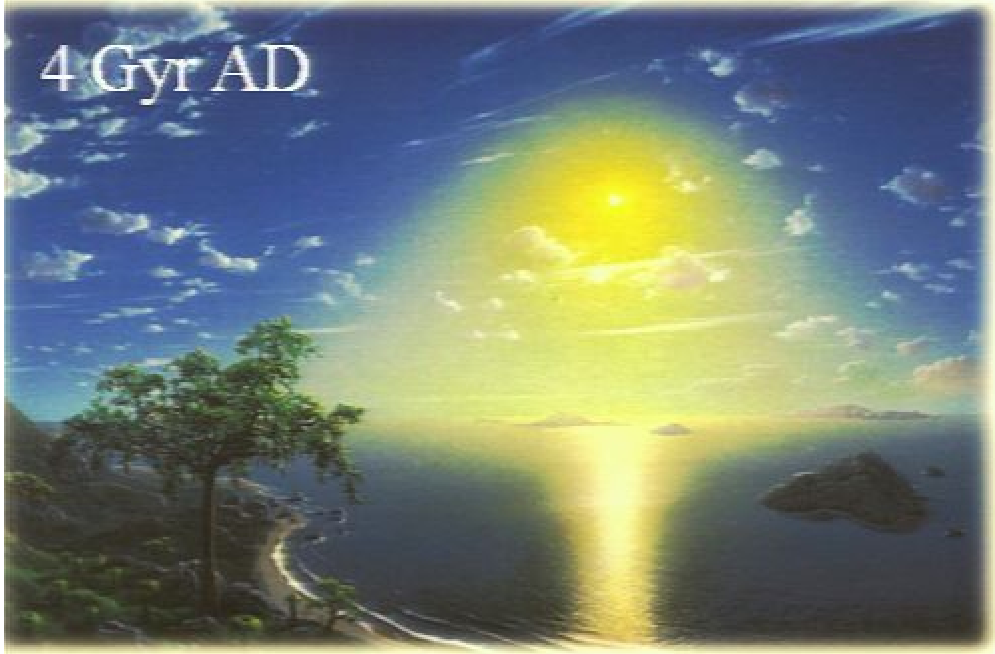

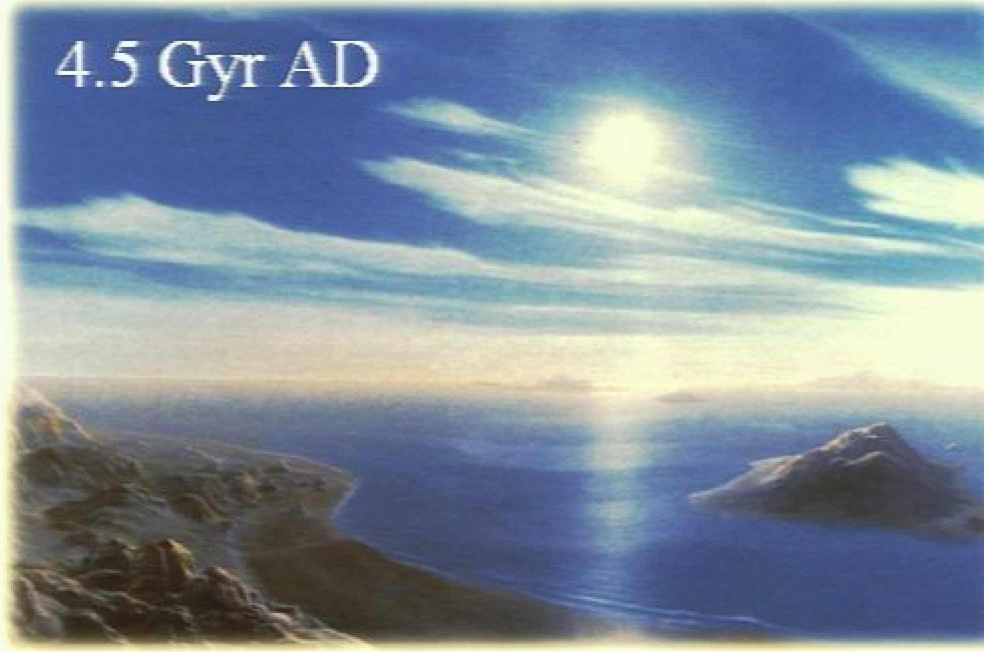

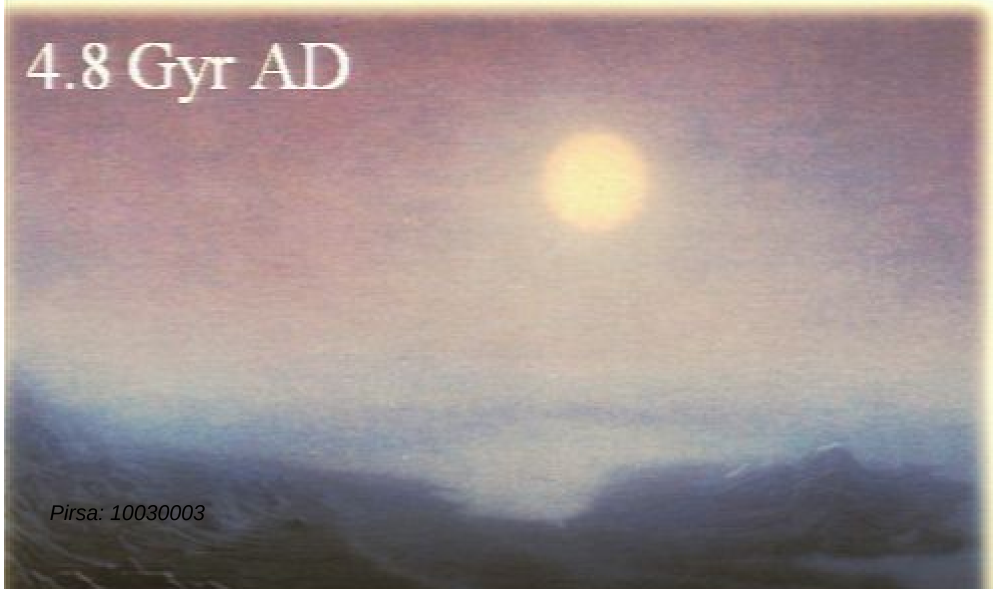

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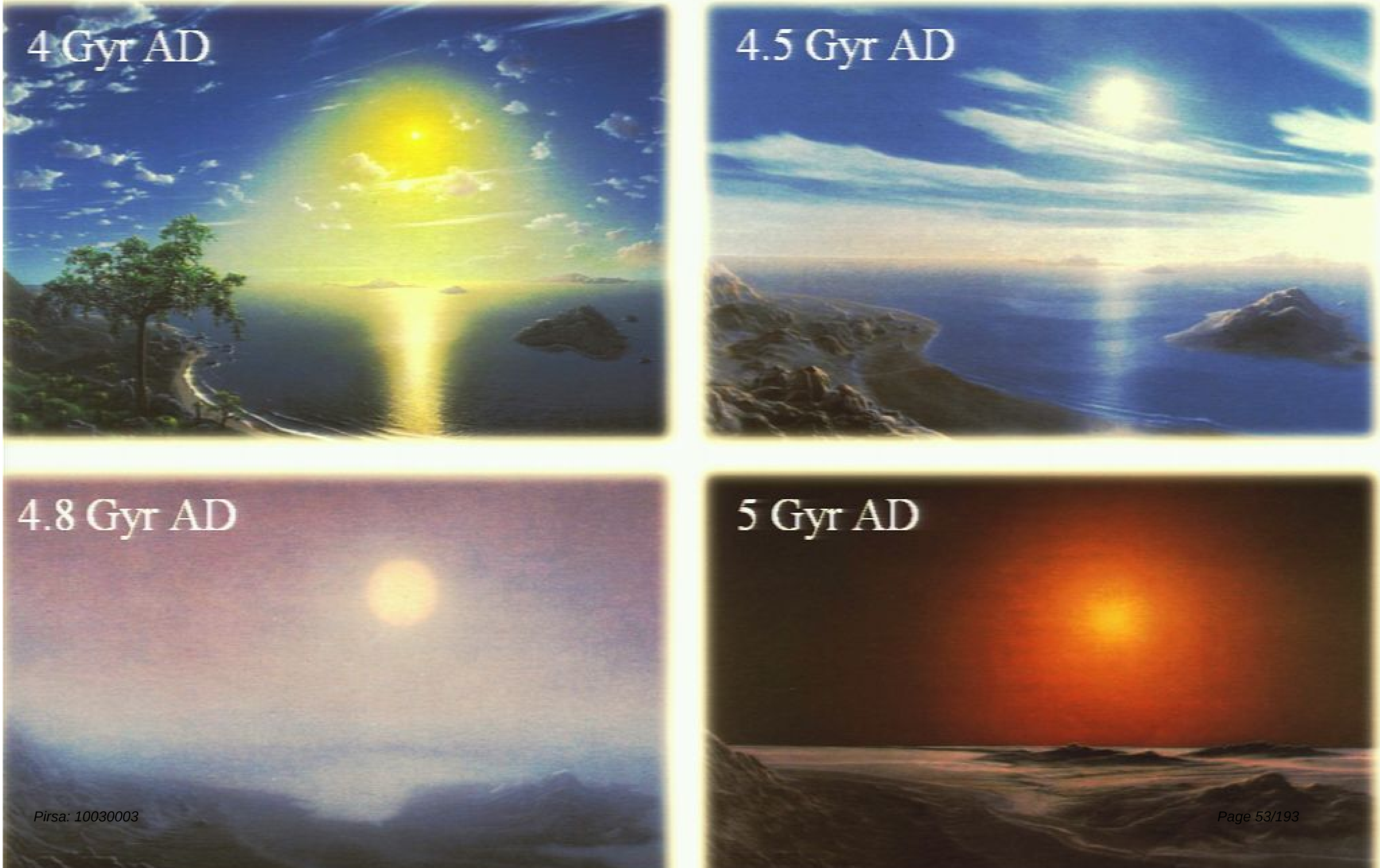
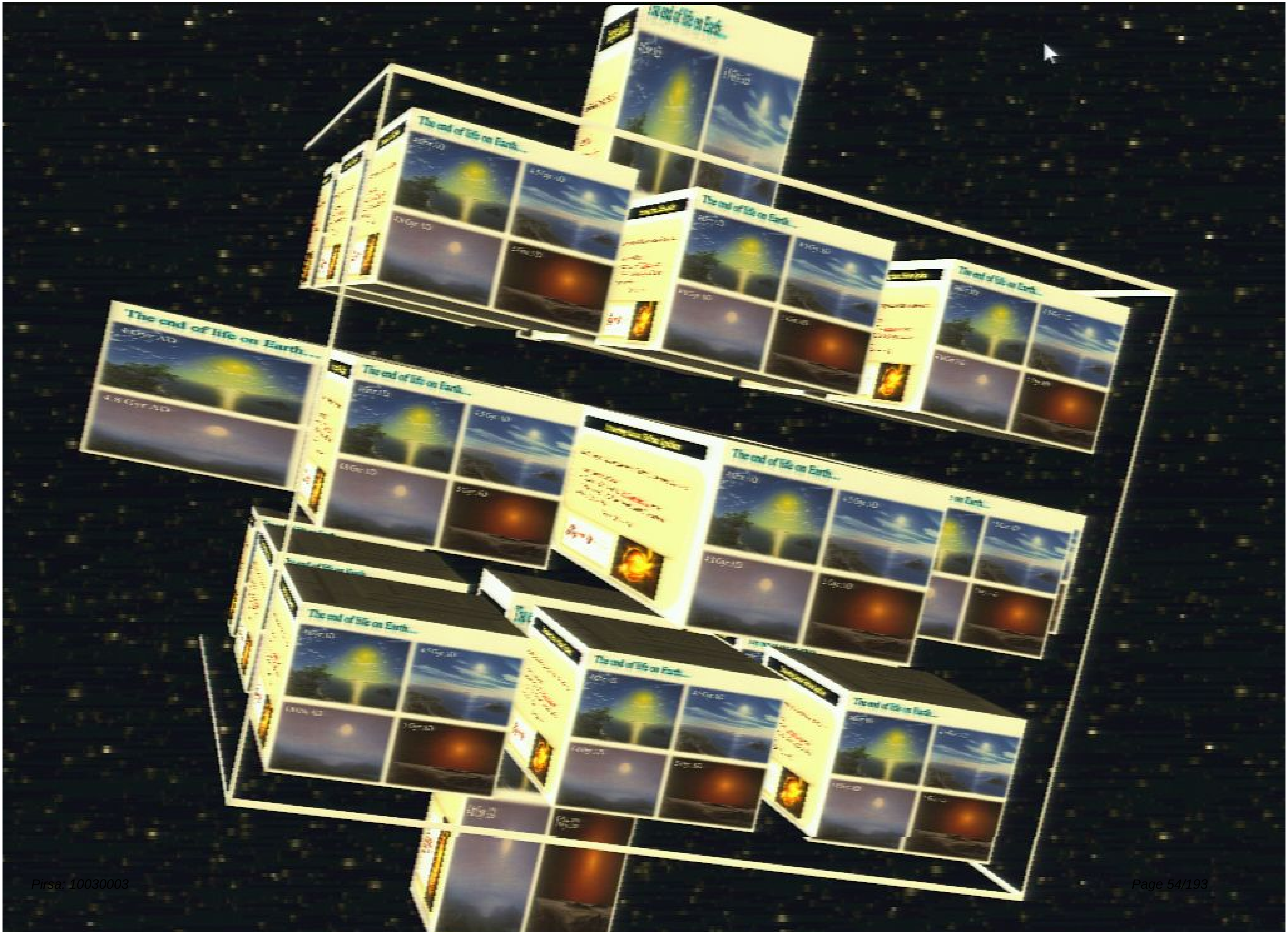
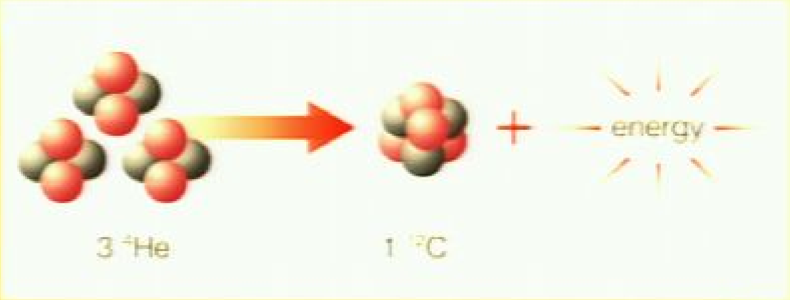



The end of life on Earth...

Interesting times: Helium Ignition

- The hydrogen shell dumps more Helium ash onto the core
  - core grows and heats
  - when $T > 120 \times 10^6$ K Helium fusion starts
  - $3\ {}^4He \rightarrow {}^{12}C$ called the "triple alpha" reaction
  - ${}^4He + {}^4He \rightarrow {}^8Be$

$${}^8Be + {}^4He \rightarrow {}^{12}C$$



2^{nd} Red Giant

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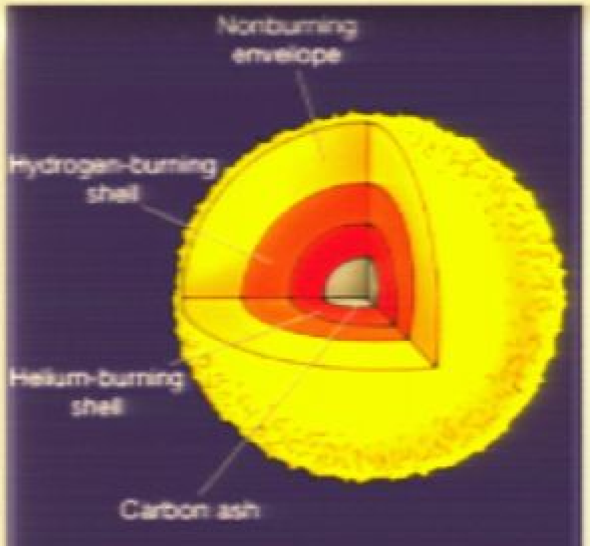
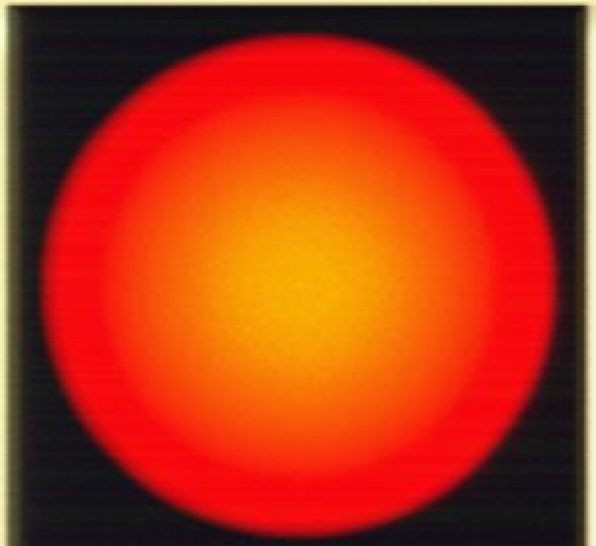
He exhausted → C/O ash in core → contracts

He burns in shell L ↑

H burns in shell envelope expands again

- 2^{nd} Red Giant (Red Super-Giant)
- even larger star & even more luminous (e.g. Betelgeuse)





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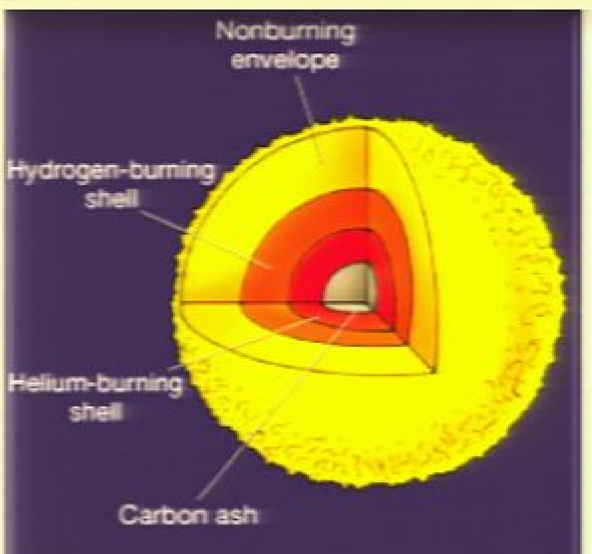

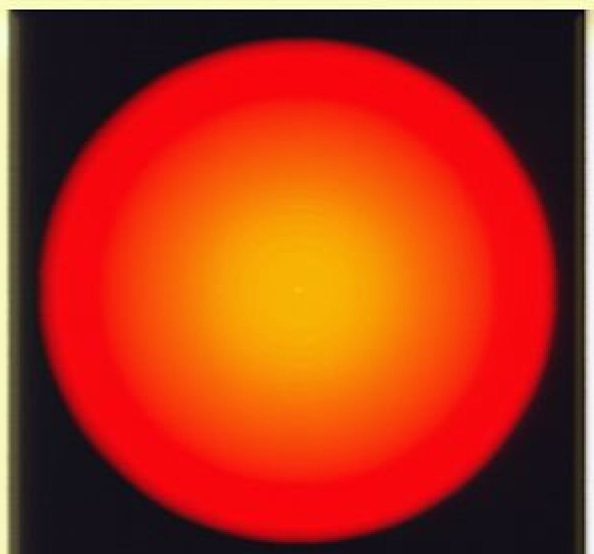

Carbon Ignition

- Carbon ignition needs 600×10^6 K (C^{6+} nuclear repulsion)
- Not all stars can achieve this high core temperature:

  $M < 4\ M_{sun}$ C/O cannot burn → star dies

  $M > 4\ M_{sun}$ C & O ignite

Heavier reactions need higher temps & go faster

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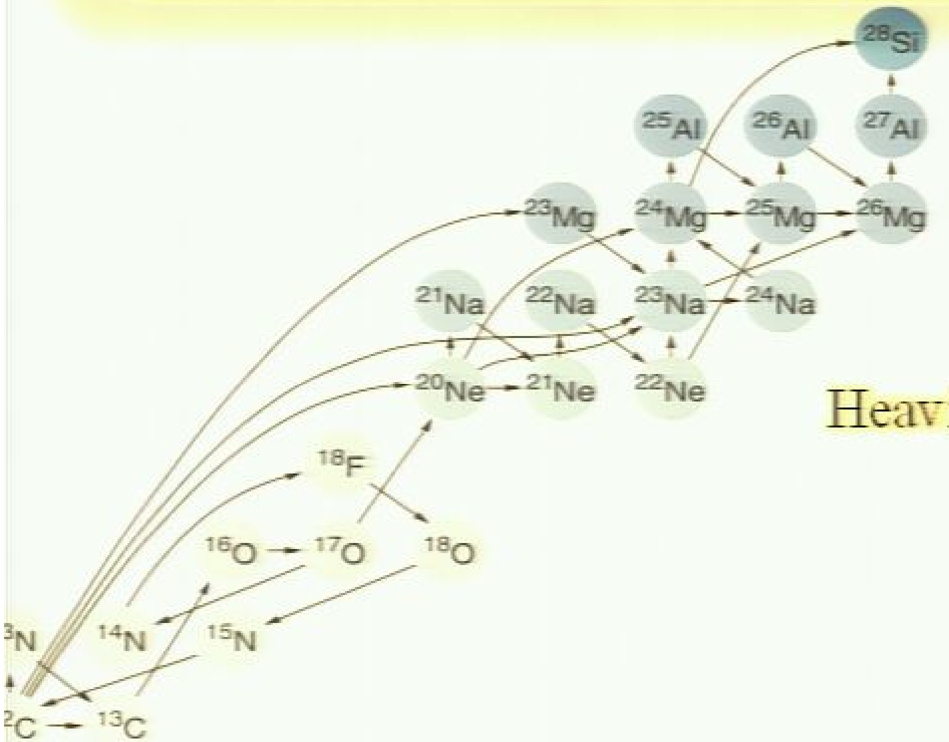

Complex reaction network

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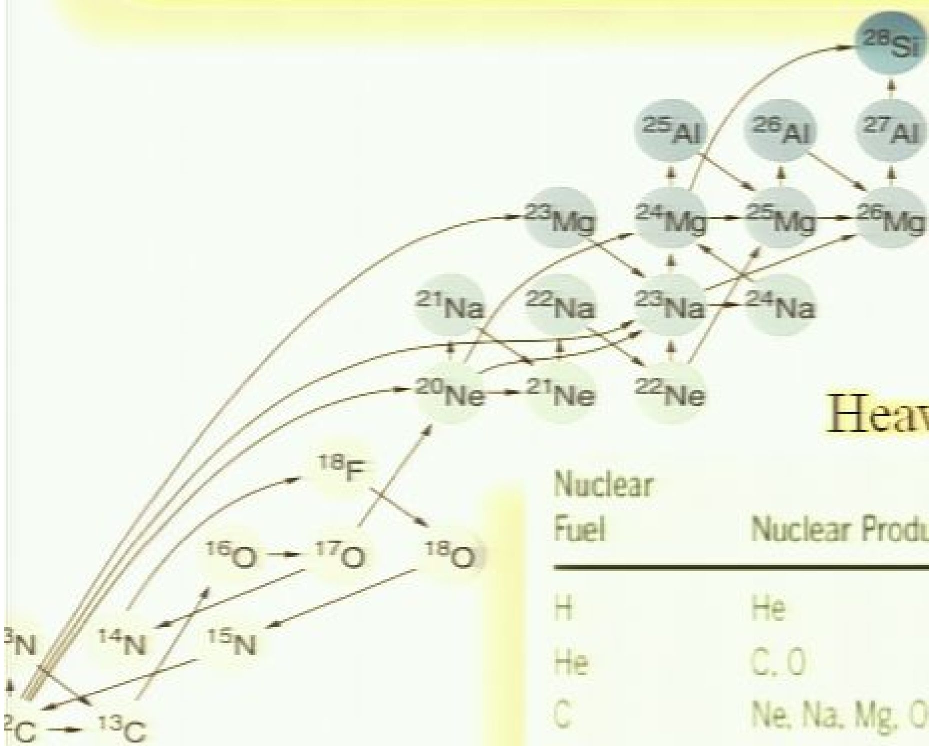


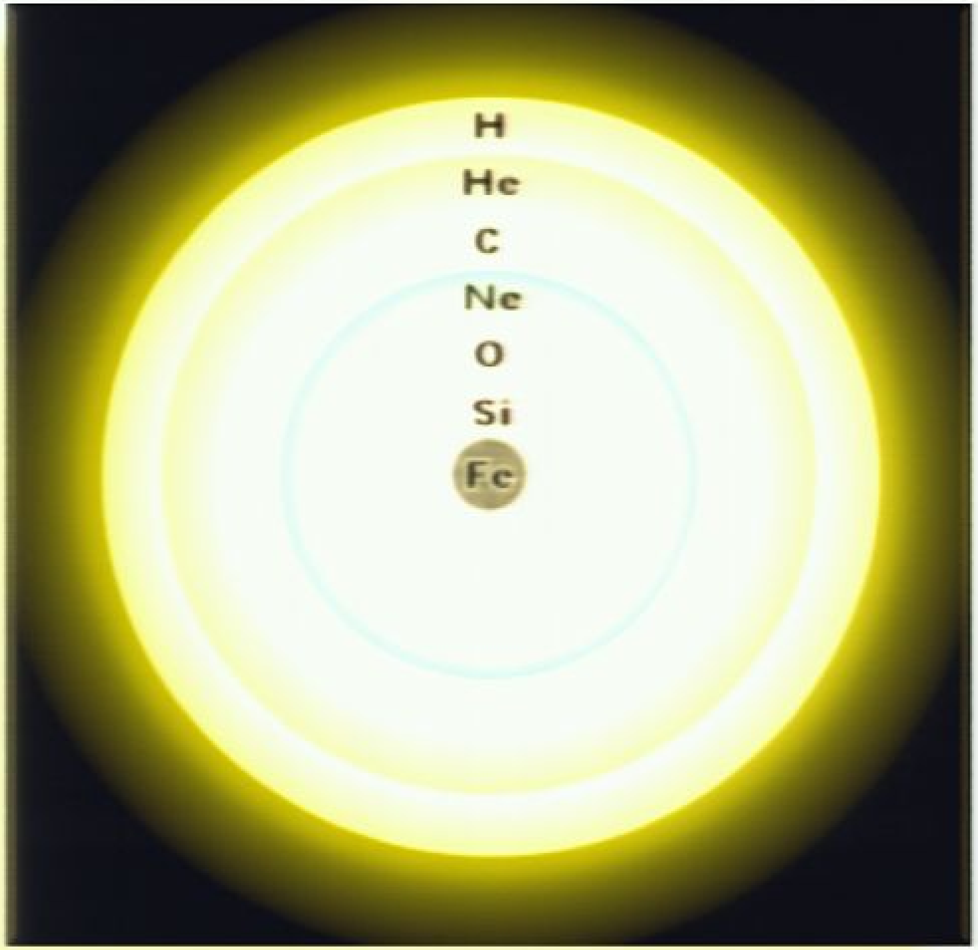
Complex reaction network

Heavier reactions need higher temps & go faster

Nuclear Fuel	Nuclear Products	Minimum Ignition Temperature	Main-Sequence Mass Needed to Ignite Fusion	Duration of Fusion in a 25-$M_\odot$ Star
H	He	4×10^6 K	$0.1\ M_\odot$	7×10^6 yr
He	C, O	120×10^6 K	$0.4\ M_\odot$	0.5×10^6 yr
C	Ne, Na, Mg, O	600×10^6 K	$4\ M_\odot$	600 yr
Ne	O, Mg	1.2×10^9 K	$\sim 8\ M_\odot$	1 yr
O	Si, S, P	1.5×10^9 K	$\sim 8\ M_\odot$	~ 0.5 yr
Si	Ni to Fe	2.7×10^9 K	$\sim 8\ M_\odot$	~ 1 day

The hierarchy in the core of the star

- Fusion builds up heavier and heavier nuclei (up to iron)
- **Nucleosynthesis**
- Gravitational collapse is an inverse Big Bang



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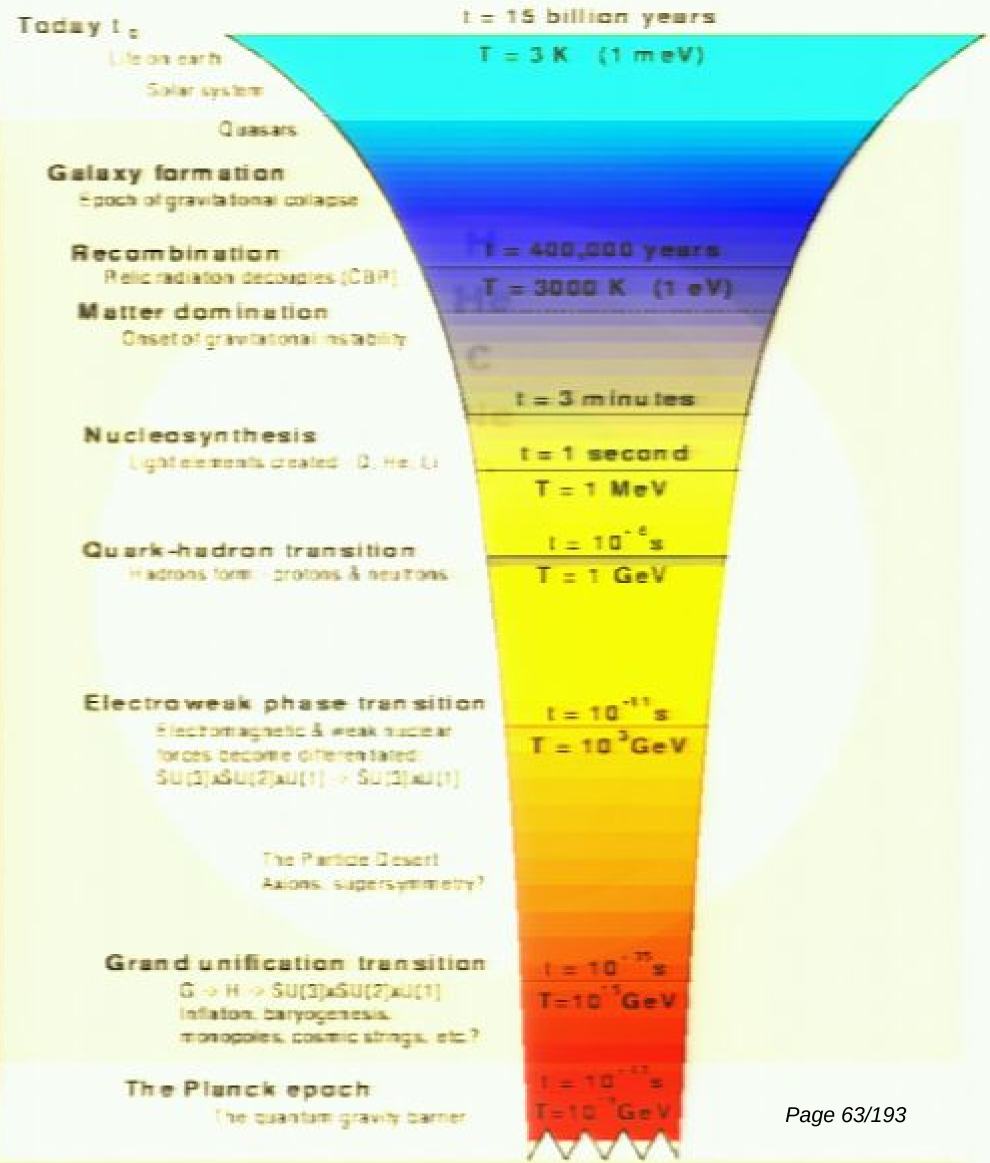

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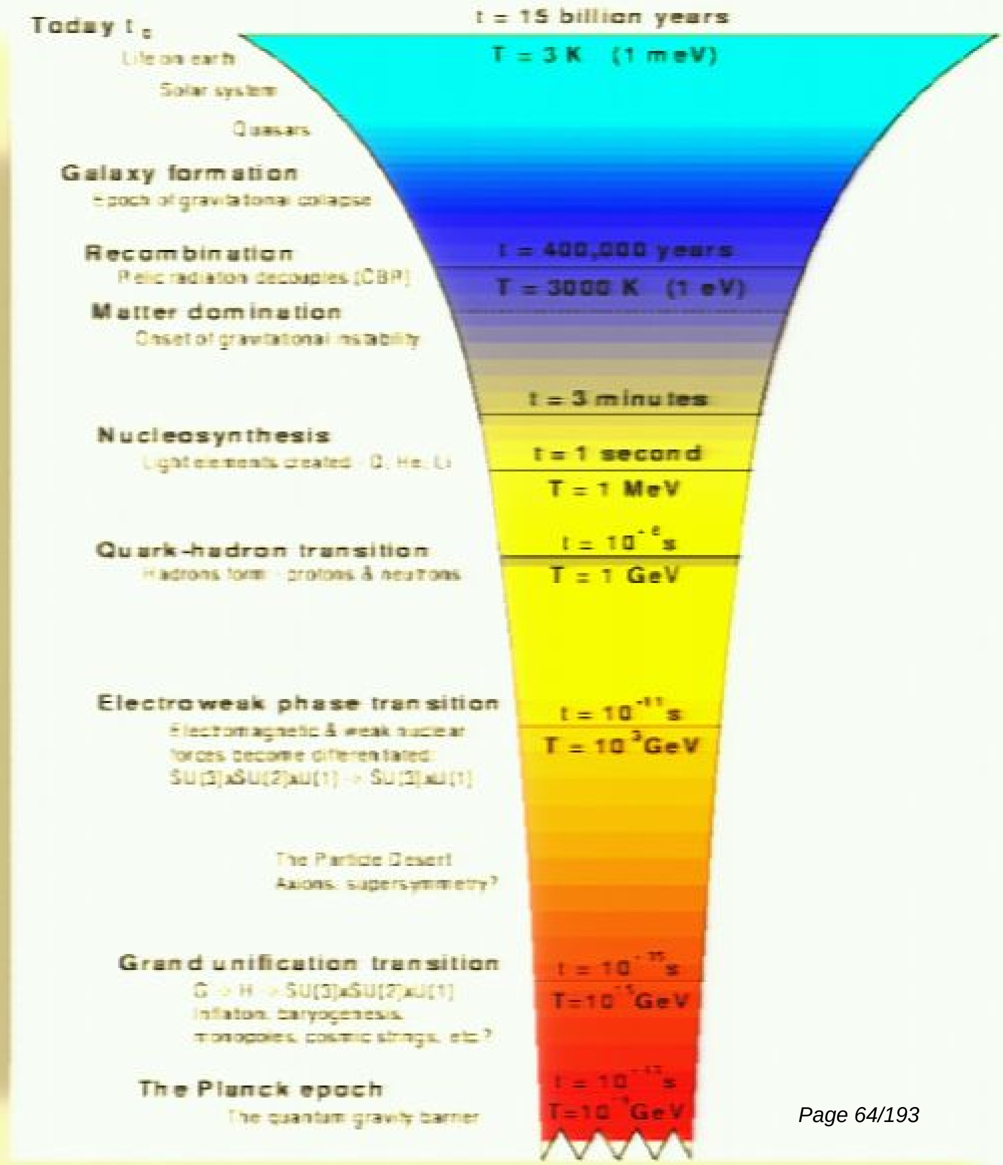

Type II Supernova

- The core is full of iron nuclei, undergoing some fusion and fission, but not generating the new energy needed to maintain the pressure
- The star suffers a sudden decrease in core pressure which had been balancing gravity.
- The star material basically goes into free fall, accelerating over an AU or more of distance, pulled towards the core by gravity.
- That material crashes onto the core and mostly rebounds back into space.
- This is a (**Type II**) **Supernova explosion**

Core Collapse

- Gravity causes the core to shrink.
- Inverse beta decay reactions occur:

$$p + e^- \rightarrow n + \nu$$

- All the protons and electrons are "merged" leaving a core of almost entirely neutrons
- In most cases, the collapse will continue until stopped by **neutron degeneracy**, the packing limit of neutrons

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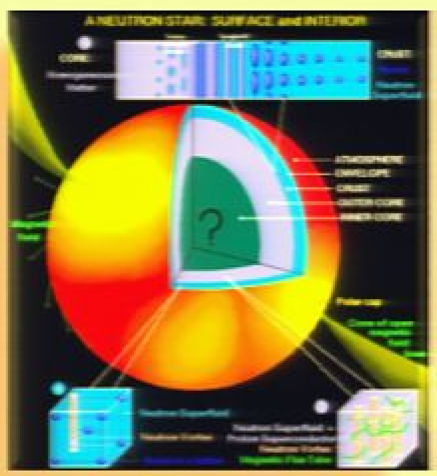
Neutron Star

The core will end up a tightly packed ball of neutrons.

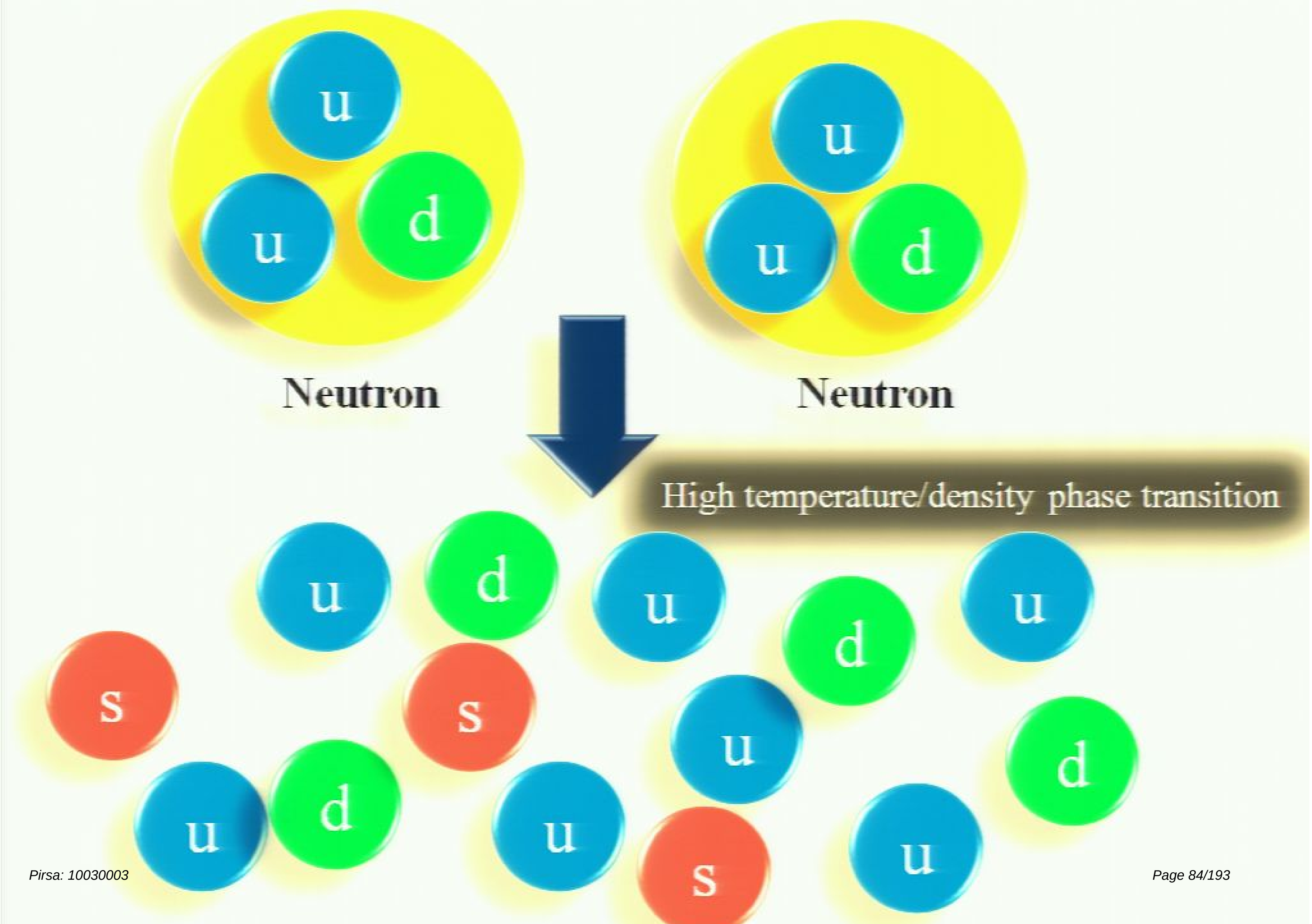
In less than a second of time, two solar masses worth of iron is mashed into a ball of neutrons about 10 km across

This surviving object has been named a **neutron star**



Quark Star

- Fermi pressure can support only neutron stars lighter than about 2.1 M_{sun} → **Tolman-Oppenheimer-Volkoff** limit
- Cores of stars heavier than this have densities comparable with QCD phase transition densities ~ $(100\ \mathrm{MeV})^4$
- This may lead to a **quark star**:
  state where one can not distinguish between the nucleons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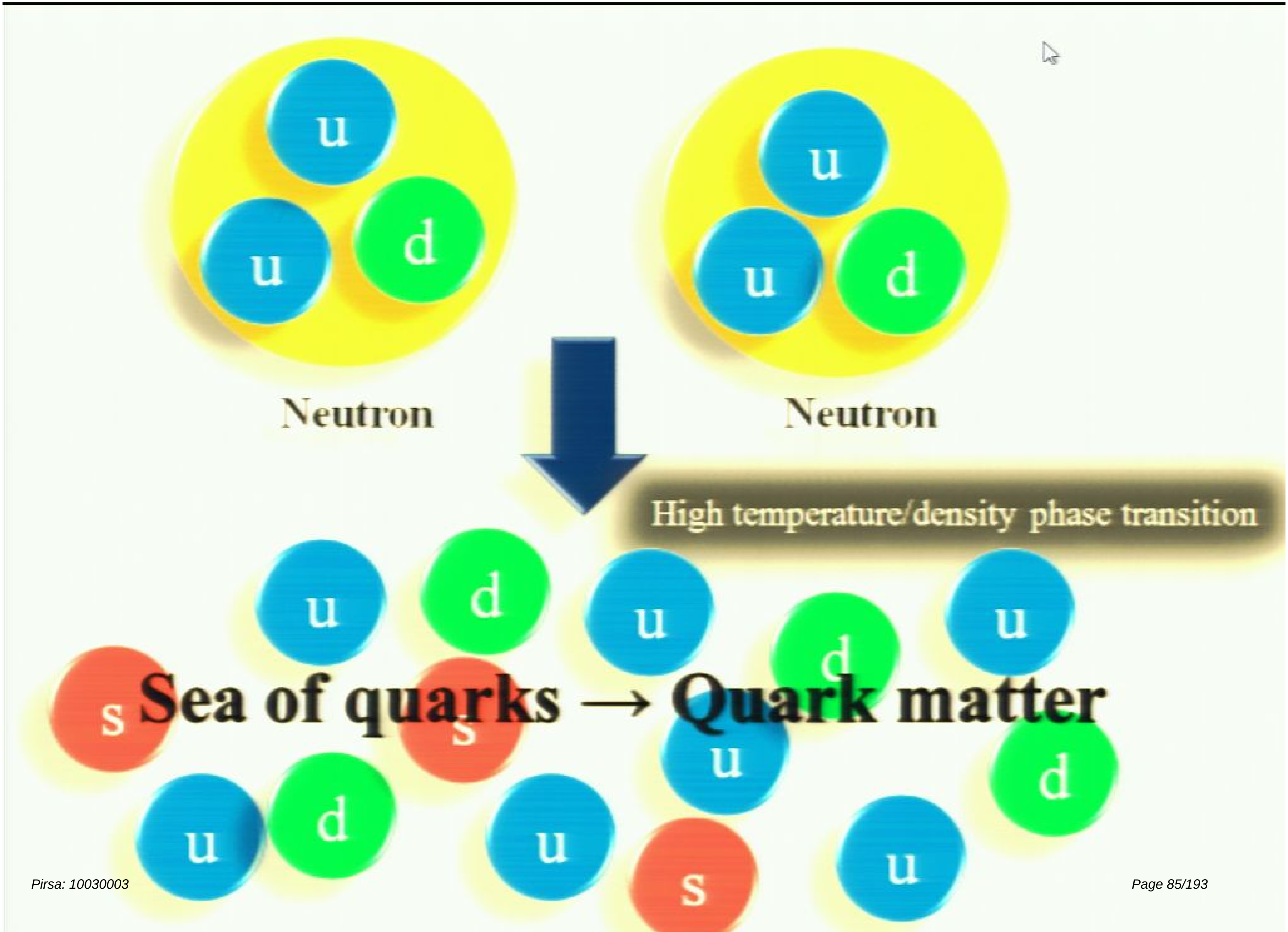
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High temperature/density phase transition
Sea of quarks → Quark matter
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Quark Star

- The transition to a quark state of matter can typically release 10^{53} erg in about 10^{-2} sec
- After this energy burst, a star containing effectively only three quark flavors (u,d,s) can exist in a stable equilibrium
- At higher densities where four or more quarks are present, quark matter can not stop the gravitational collapse…

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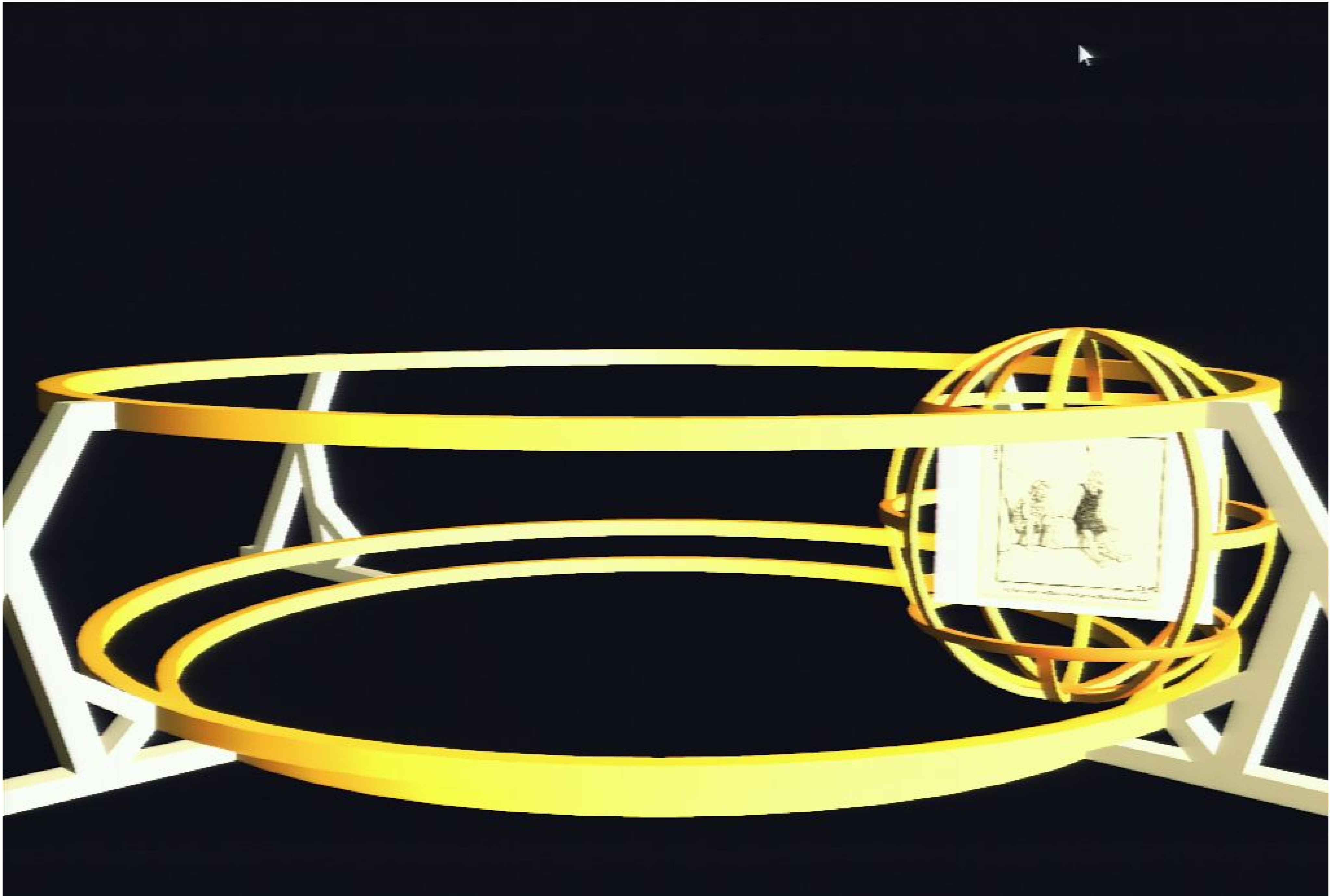
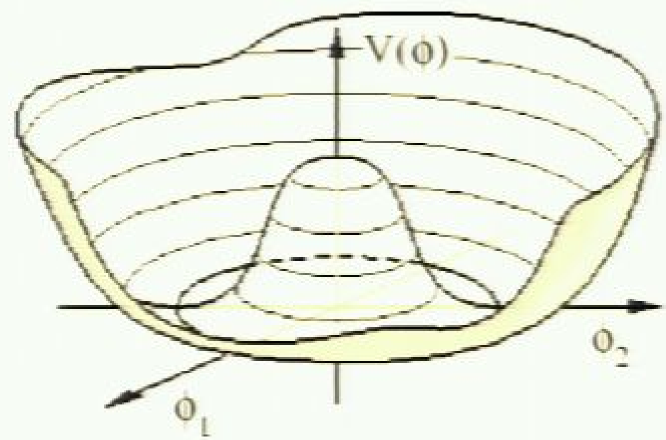


What happens next?

- Gravitational collapse continues…
- Inverse Big Bang
- Densities reach $\sim (100\ \text{GeV})^4$ ➡ **Electroweak densities**

Electroweak phase transition happens!



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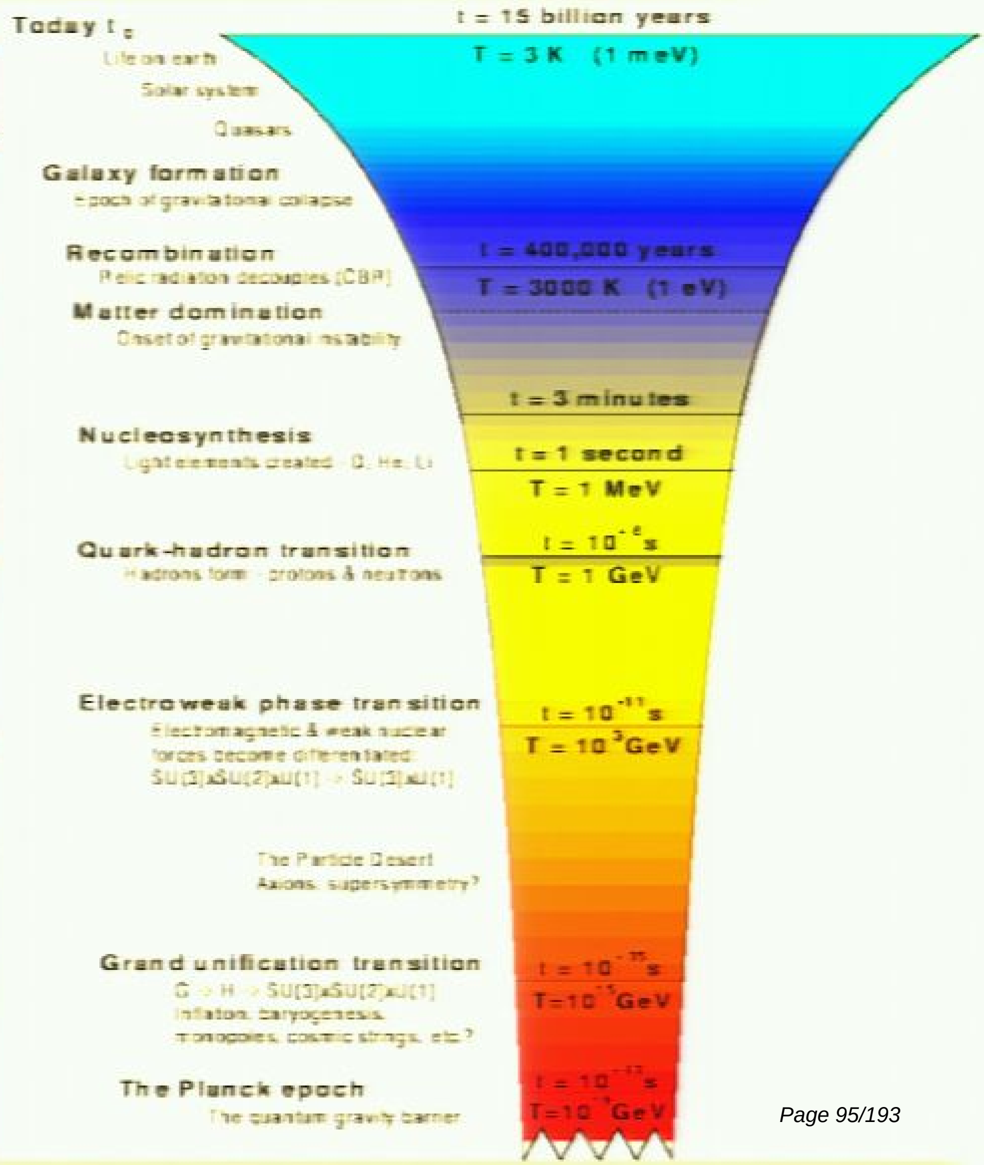

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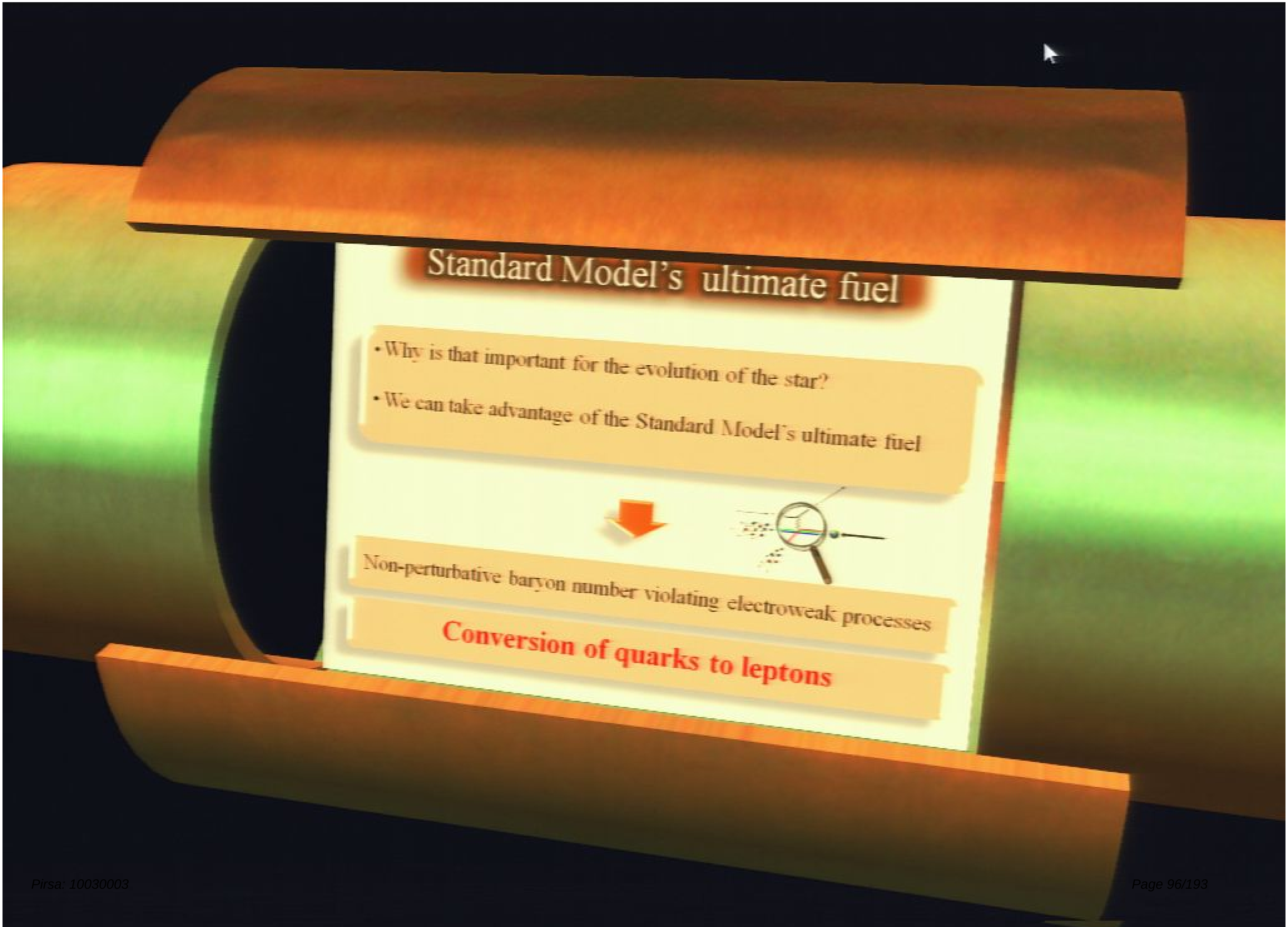
Standard Model's ultimate fuel
• Why is that important for the evolution of the star?
• We can take advantage of the Standard Model's ultimate fuel
Non-perturbative baryon number violating electroweak processes
Conversion of quarks to leptons

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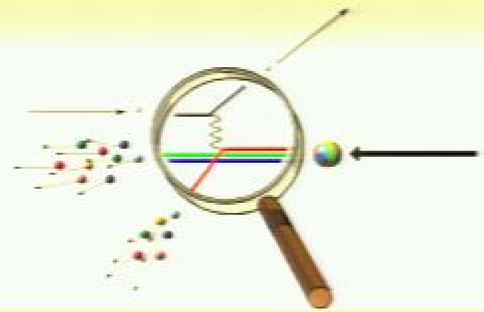

Non-perturbative baryon number violating electroweak processes

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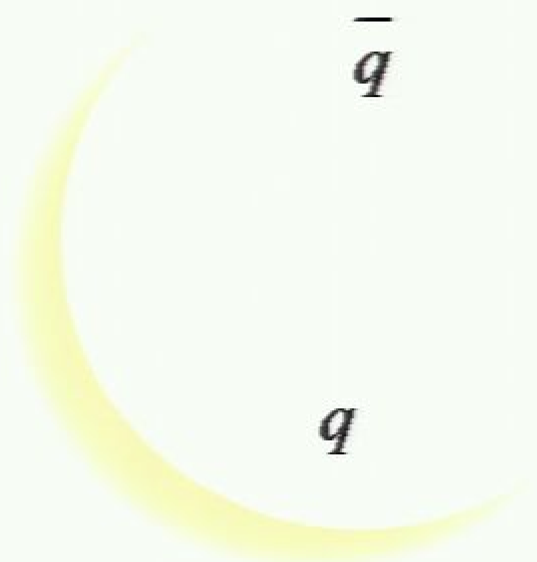
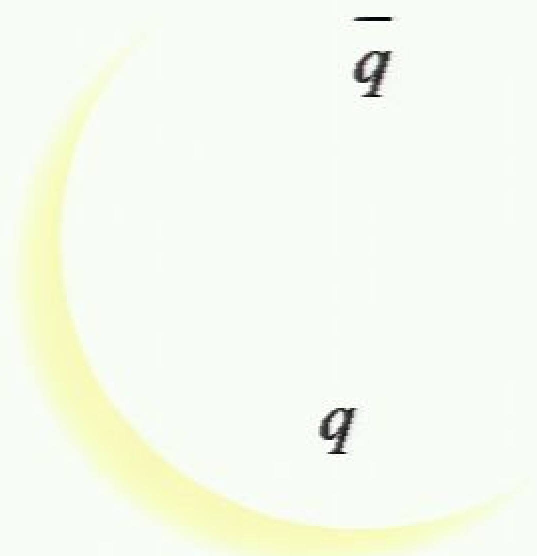
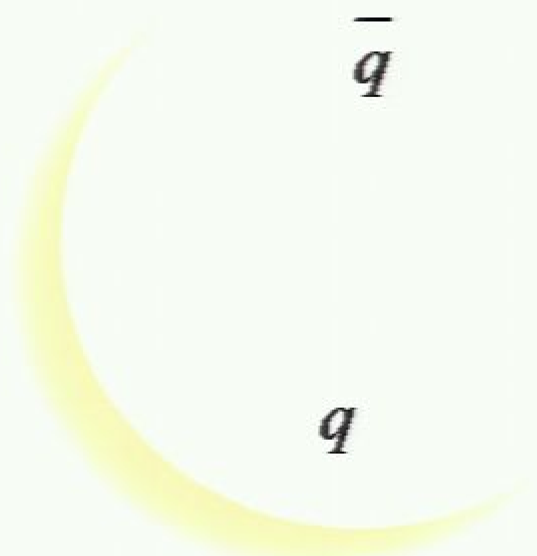

$\bar{q}$
q

Baryon Number



Baryon Number

- Baryon number is a global symmetry of the SM Lagrangian



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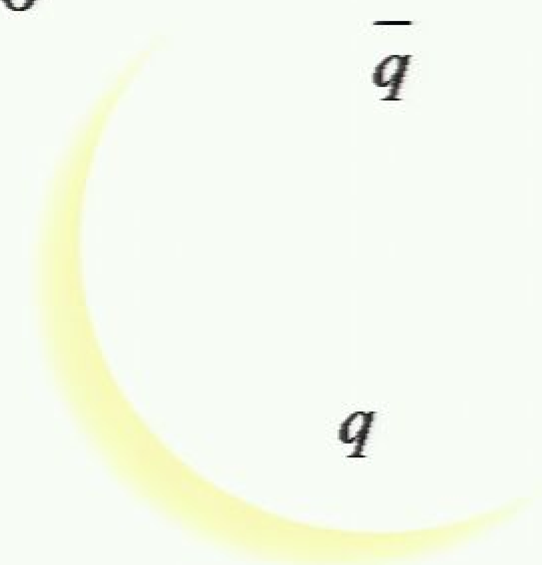

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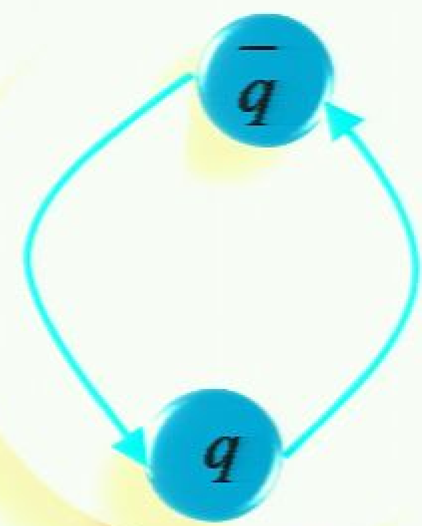

- Quarks can appear and disappear only in pairs

Baryonic current anomaly

Quantum corrections destroy conservation of baryon number

$$\text{—}\; F^a_{\mu\nu}\tilde{F}^{a\,\mu\nu}$$

ield strength

Baryonic current anomaly

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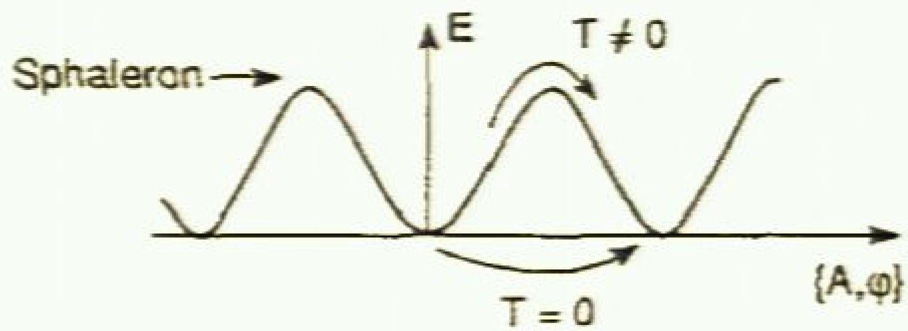

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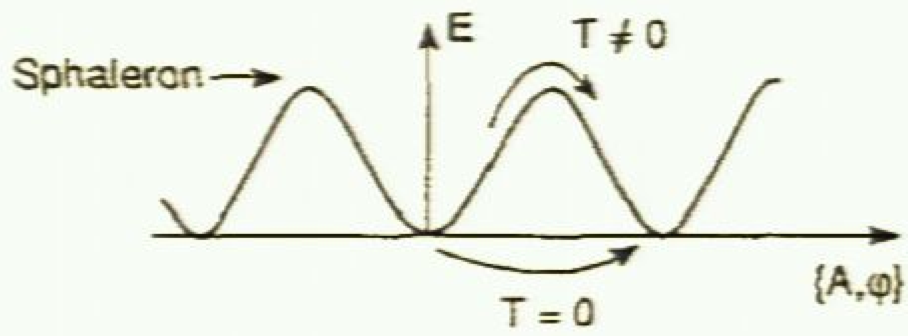

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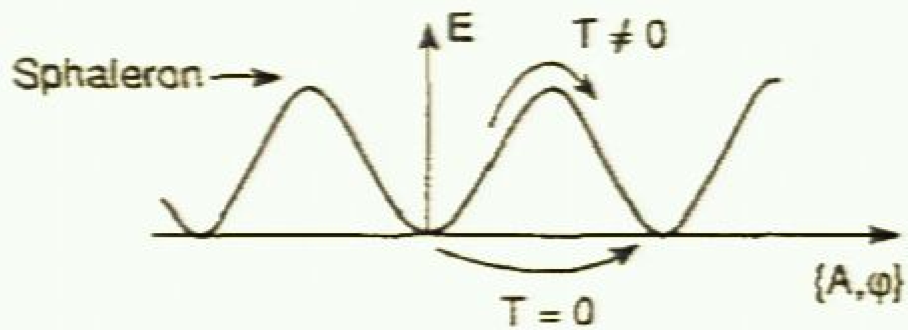

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Sphaleron - an unstable solution to the equations of motion

Sphaleron rate

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So, above EW symmetry-breaking scale ($T_c \approx 100$ GeV), baryon number violating processes are essentially unsuppressed

Electroweak Burning

Quarks can then be effectively converted into leptons. In this **electroweak burning** huge amounts of energy can be released.

B-L preserving interaction can convert 9 quarks into 3 anti-leptons

$$\begin{matrix} udd \\ css \\ tbb \end{matrix} \quad \rightarrow \quad \overline{\nu}_e, \overline{\nu}_\mu, \overline{\nu}_\tau$$

At these temperatures each particle carries about 100 GeV of energy, so this process can release about 300 GeV per neutrino

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•Inside the shell neutrinos are trapped

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The structure of the star

Electroweak core

• T above EW-breaking scale: T >100 GeV

Photon release shell

• Effective radius of the star

Neutrino release shell

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Einstein's equations describing the structure of the star

Tolman-Oppenheimer-Volkoff equations

Einstein's equations describing the structure of the star

Tolman-Oppenheimer-Volkoff equations

$R/R_\odot$	T (10^6 K)	Density (g/cm^3)	$M/M_\odot$	$L/L_\odot$
1.00	0.006	0.00	1.00	1.00
0.90	0.60	0.009	0.999	1.00
0.80	1.2	0.035	0.996	1.00
0.70	2.3	0.12	0.990	1.00
0.60	3.1	0.40	0.97	1.00
0.50	4.9	1.3	0.92	1.00
0.40	5.1	4.1	0.82	1.00
0.30	6.9	13	0.63	0.99
0.20	9.3	36	0.34	0.91
0.10	13.1	89	0.073	0.40
0.00	15.7	150	0.000	0.00

Finding the solution

Tolman-Oppenheimer-Volkoff equations

$$\frac{dP}{dr} = -\frac{(\varepsilon + P)(M + 4\pi p r^3)}{r^2(1 - 2M/r)}$$

$$\frac{dM}{dr} = 4\pi\varepsilon r^2$$

$$g_{tt} = \left(1 - \frac{2M_{star}}{R_{surface}}\right)\exp\left(-2\int_0^{P(r)} \frac{dP}{P + \varepsilon}\right)$$

$$g_{rr} = \frac{1}{1 - \frac{2M(r)}{r}}$$

ε = total energy density
P = total pressure

Metric coefficients g_{tt} and g_{rr} very important!

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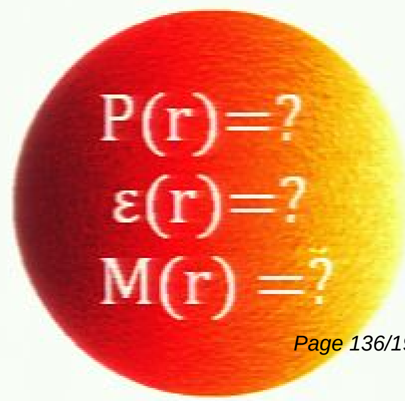

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Variables and parameters

The pressure, energy density, and number density of particles can be well approximated from an ideal gas distribution

$$p_i = \frac{g_i}{6\pi^2}\int_{m_i}^{\infty} dE\left(E^2 - m_i^2\right)^{3/2} f_i(E)$$

$$n_i = \frac{g_i}{2\pi^2}\int_{m_i}^{\infty} dE\left(E^2 - m_i^2\right)^{1/2} E f_i(E)$$

$$\varepsilon_i = \frac{g_i}{2\pi^2}\int_{m_i}^{\infty} dE\left(E^2 - m_i^2\right)^{1/2} E^2 f_i(E)$$

$$f_i(E) = \frac{1}{1 \pm e^{(E-\mu_i)/T}}$$

$$P = \sum_i p_i - B$$

$$\varepsilon = \sum_i \varepsilon_i + B$$

B = “bag” energy = 145 MeV from the “bag” model of nucleons

The equation of state

Numerically integrate TOV equations to get P(r), M(r), ε(r) and P(ε)

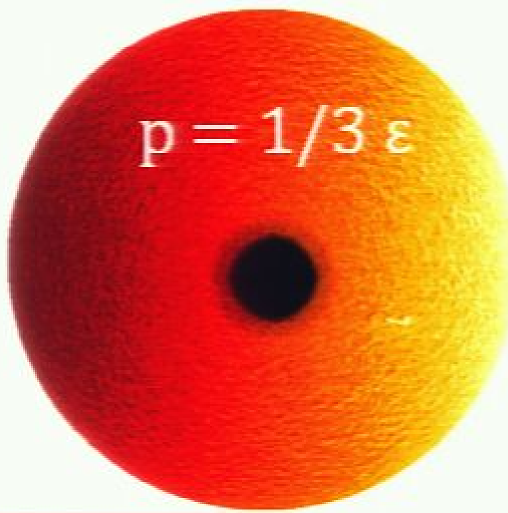
Throughout the star:

$p = 1/3\ \varepsilon$

(ultrarelativistic particles)

The equation of state

Numerically integrate TOV equations to get $P(r)$, $M(r)$, $\varepsilon(r)$ and $P(\varepsilon)$



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The equation of state

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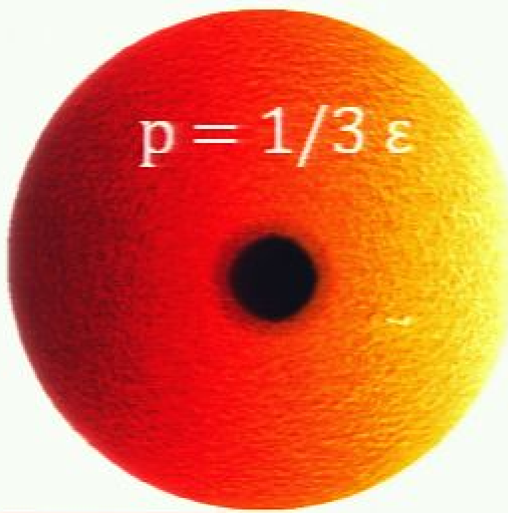
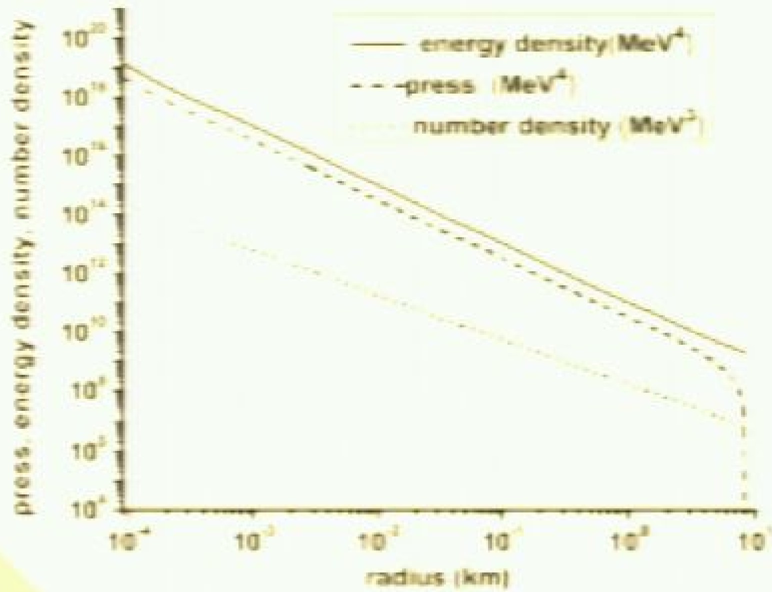


Throughout the star:

$p = 1/3\ \varepsilon$

(ultrarelativistic particles)

Star Parameters



The pressure, energy density and particle number density dependence of the radius of the star

$R_{star} = 8.2$ km
$M_{star} = 1.3\ M_{sun}$

- Core ends where ε drops below $(100\mathrm{GeV})^4$
- Several cm in size

The solution is non-singular at the center – not a black hole

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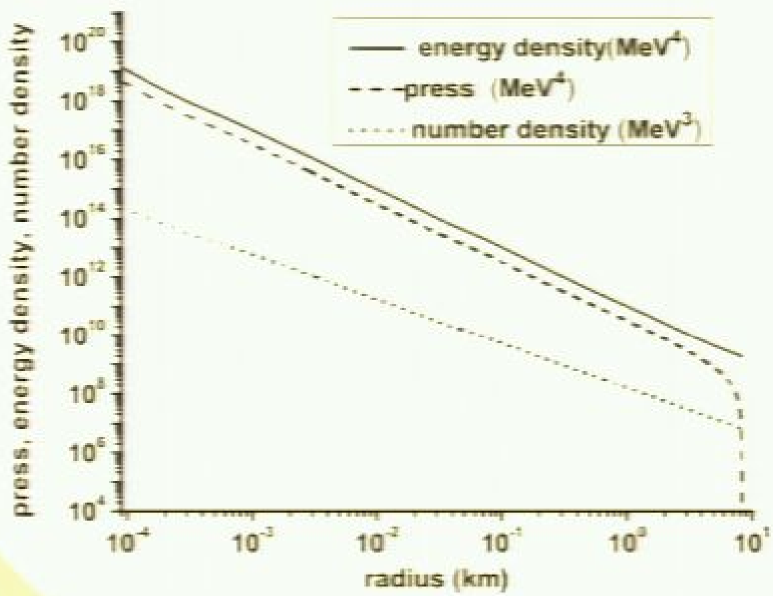

The pressure, energy density and particle number density dependence of the radius of the star

Radius of the star is where P and ε drop to zero

$R_{star} = 8.2$ km
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- Core ends where ε drops below $(100 GeV)^4$
- Several cm in size

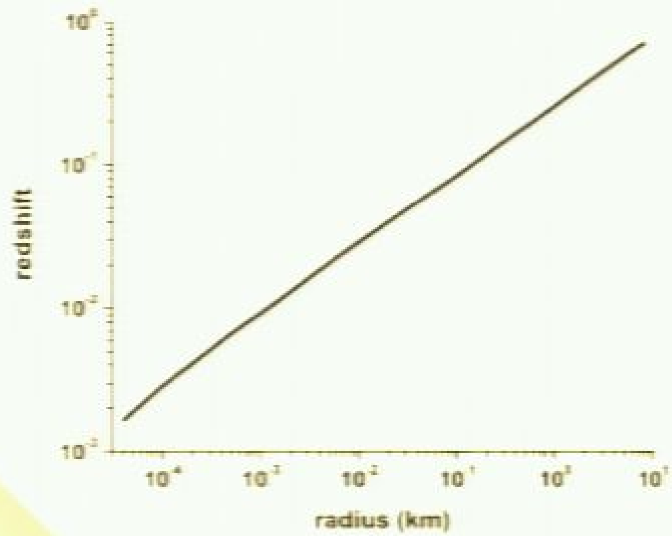
The solution is non-singular at the center – not a black hole

Neutrino energy redshift

- Unlike ordinary stars, particles propagating through the electroweak stars suffer large gravitational redshift

- Energy changes as:

$$E_{\nu}(r) = \frac{\sqrt{g_{tt}(r_0)}}{\sqrt{g_{tt}(r)}} E_{\nu}(r_0)$$



The redshift factor $\sqrt{g_{tt}}(r)$ inside the star. A particle with the original energy of 100GeV near the center carries away only 100MeV as it leaves the surface

Neutrino mean free path

The neutrino mean free path inside the star

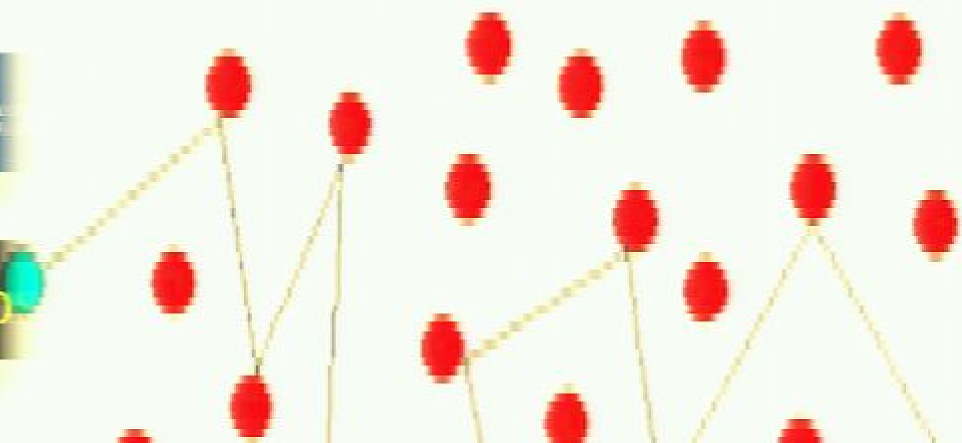
$$\frac{1}{\lambda} = \sum_i \sigma_i n_i$$

with

$$\frac{E_\nu E_i}{\pi}$$

Near the

Neutrino



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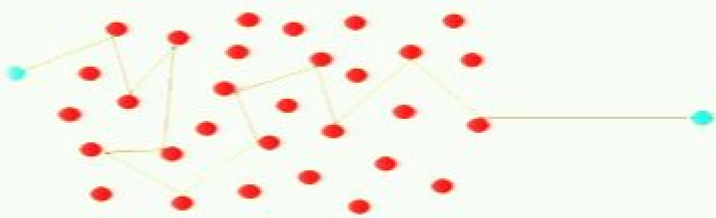
The neutrino mean free path inside the star

$$\frac{1}{\lambda} = \sum_i \sigma_i n_i$$

with

$$\sigma_i \approx \frac{G_F^2 E_\nu E_i}{\pi}$$



Near the core, the mean free path is $\lambda \sim 10^{-14}$m

Neutrinos interact many times before they leave the star

Estimated luminosity

Neutrino luminosity → $L_\nu \approx \sigma T_{core}^4 \, 4\pi r_{\rm core}^2$

$\approx 10^{41}$ MeV^2 $\approx 10^{53}$ erg /sec

At this rate it would take less than a second to release M_{sun}

However, this is a severe over-estimate!

Not taken into account:

- GR effects
- Luminosity depends not just on the T and ε but also on their gradients: *the net outward flux of energy*

Maximal energy release rate

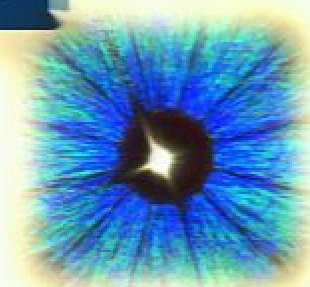
Free fall time of the quark shell into the EW-burning core

→ upper bound on dE/dt

$$\left(\frac{dE}{dt}\right)_{max} = 4\pi r_{ew}^2 \sqrt{\frac{2\lambda M(r_{ew})}{r_{ew}^2}}\,\varepsilon_V(r_{ew})\,g_{tt}(r_{ew}) \approx 10^{27}\ \mathbf{MeV^2}$$

Compare this with EW baryogenesis/baryodestruction rate:

$$\left(\frac{dE}{dt}\right)_{EWbd} = 0.1\cdot 4\pi r_{ew}^2\,\alpha_{ew}^4\,T^4 \approx 10^{34}\ \mathbf{MeV^2}$$



As quarks reach the EW core, they are converted into neutrinos instantaneously. Otherwise, the infalling matter would pile up and form a black hole.

Modeling the energy transport through the star

Relativistic transport of energy can be described by

$$\frac{dE_\infty}{dt} = -4\pi r^2 \lambda \frac{d[S(r)\, g_{tt}(r)]}{\sqrt{-g_{rr}(r)}\, dr}$$

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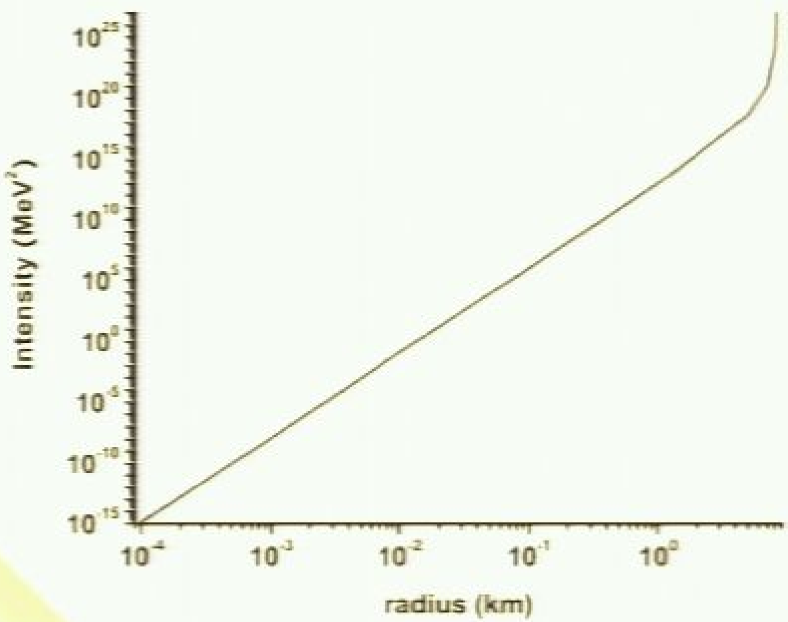
$$S(r) = \frac{dE(r)}{dt\, dA}$$

- Metric coeff. $g_{tt}(r)$ describes both the redshift and time delay
- Energy flux $S(r)$ can be modeled by the energy density ε knowing the energy (i.e. chemical potential) of neutrinos

The energy release rate vs. neutrino release radius:

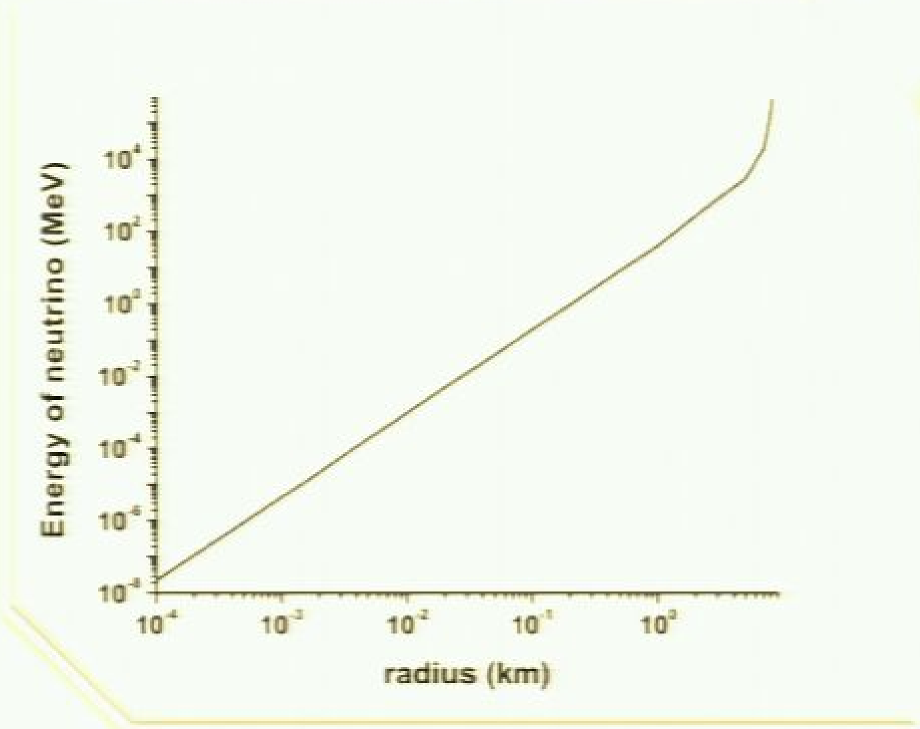


Energy release rate increases with the radius of the neutrino release shell

The maximum energy release rate is on the surface, but there it exceeds the limit from the quark shell free fall into the electroweak core **$\approx 10^{27}$ MeV^2**

This implies that the neutrino release shell must be inside the star.

Neutrino energy at the surface of the core vs. neutrino release radius:



Higher energy release rate needs the source of higher energy. Energy of neutrinos therefore increases with the radius of release shell.

However, the energy is already larger than 300GeV at 8.1 km

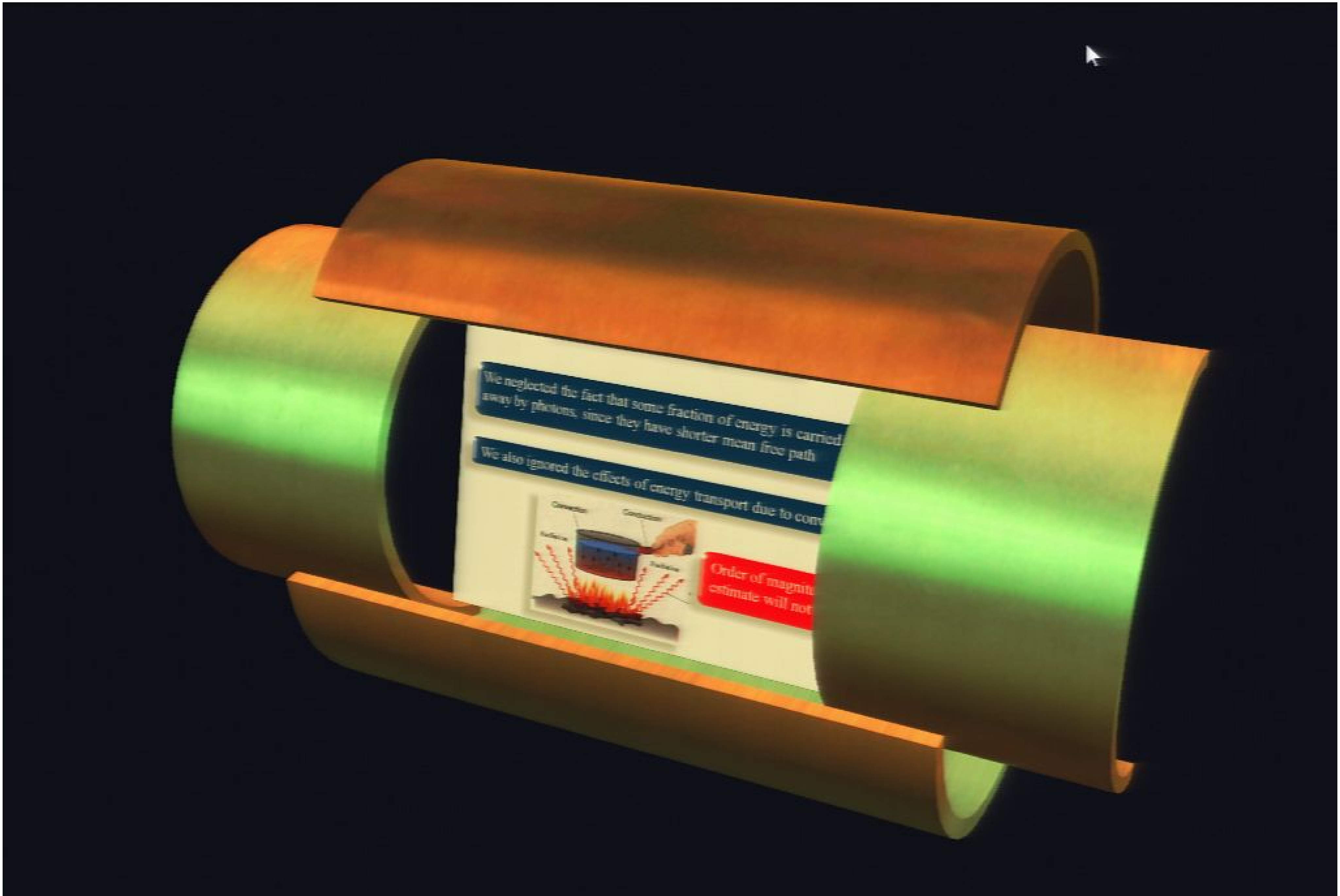
The star cannot support this amount of energy implying that the radius of the neutrino-sphere must be smaller 8.1km

The life-time of the electroweak star

If the neutrino escape radius is 8.1 km, the energy release rate is 10^{24} MeV^2

This implies that it takes about 10 million years to release 1 M_{Sun}

This is the minimal life-time of the electroweak star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Order of
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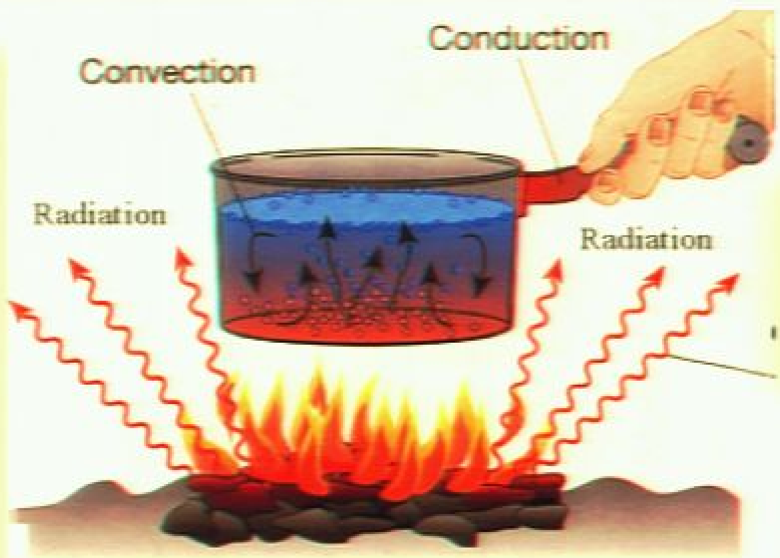
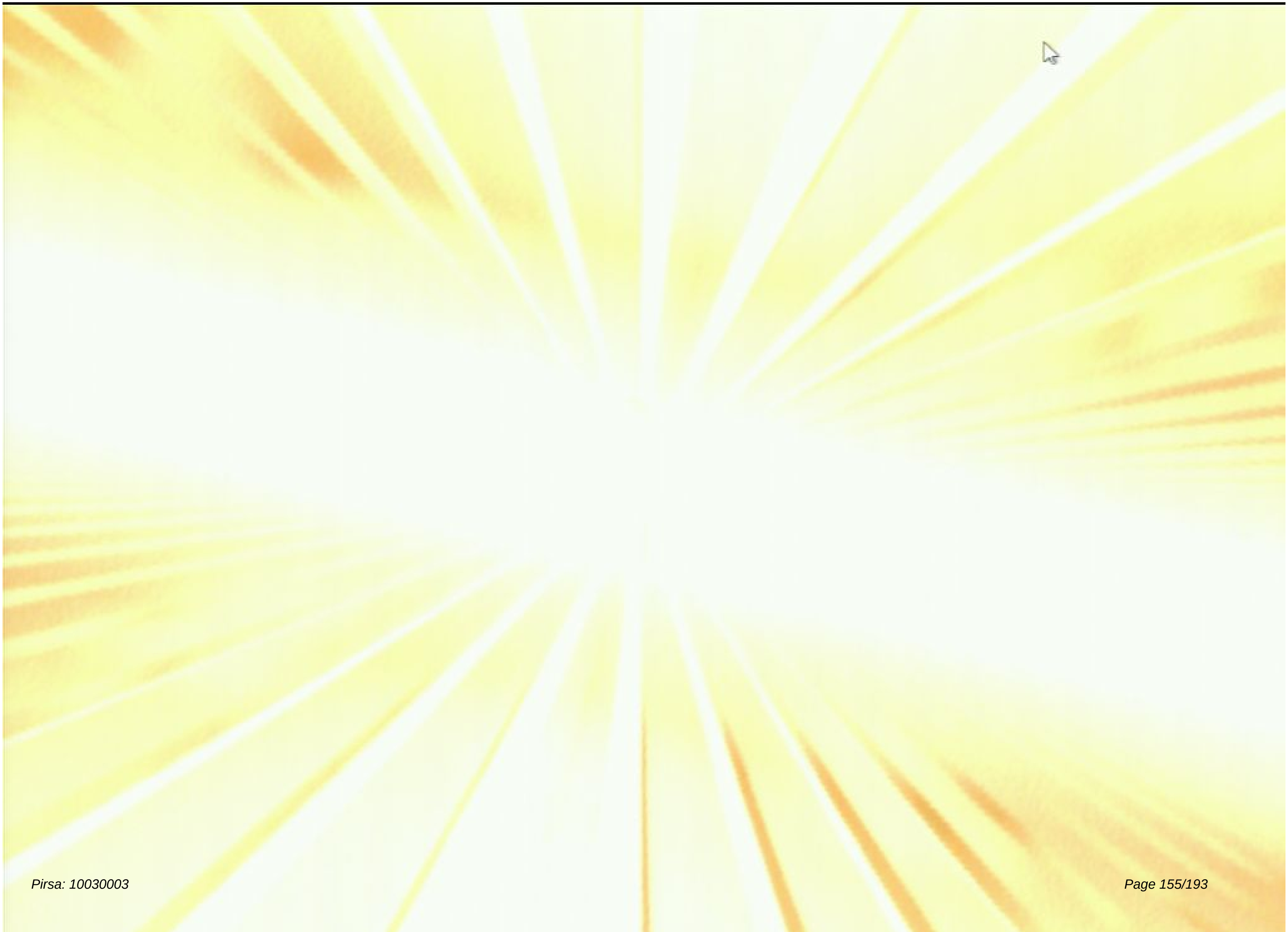
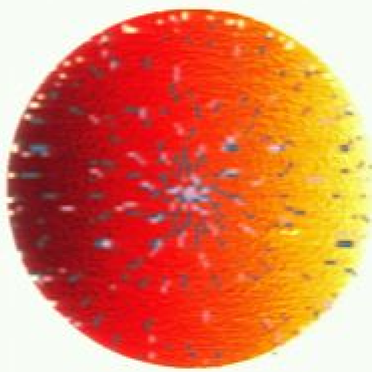


Order of magnitude estimate will not change



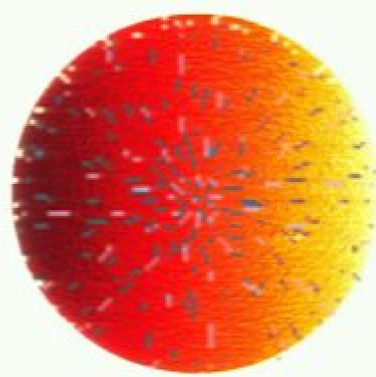
Observational signature?



Observational signature?

Most of the energy is emitted in form of neutrinos

When quarks are transformed into leptons, we get mostly *antineutrinos*



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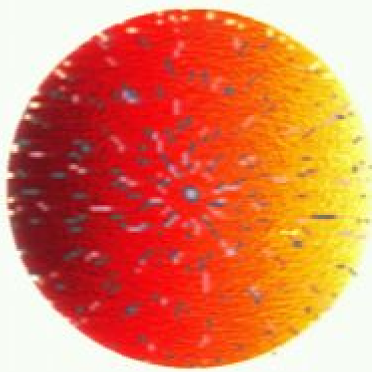

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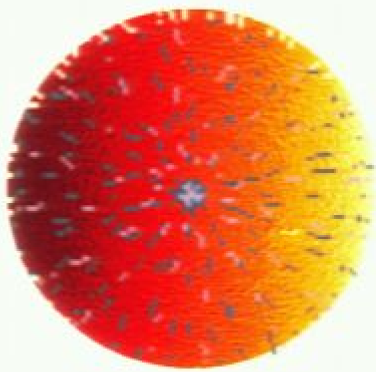

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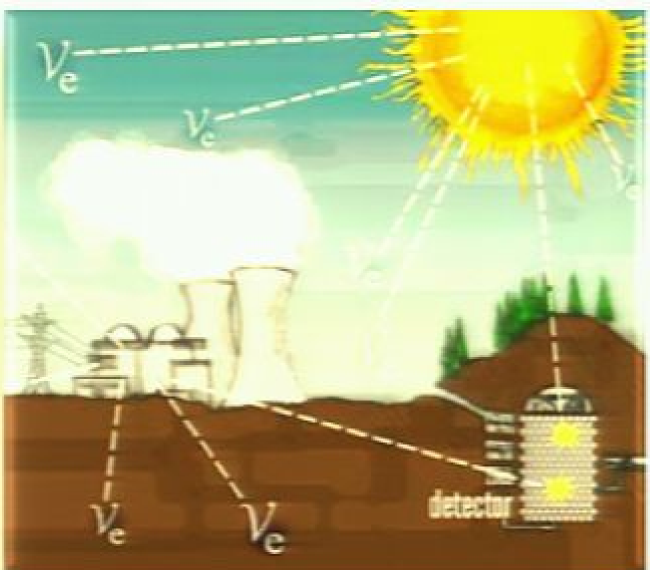

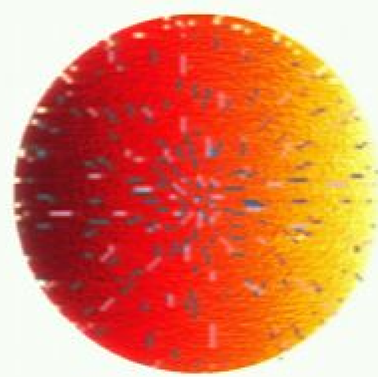

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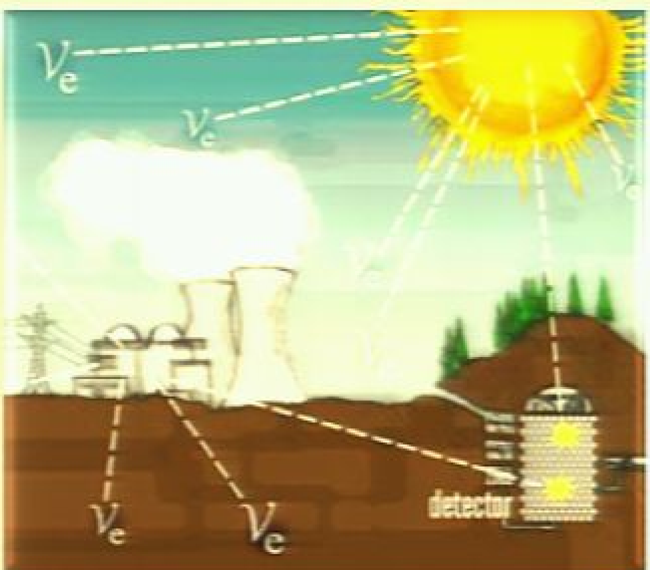
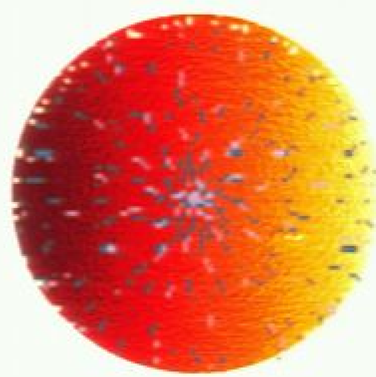
Antineutrino emitters might be electroweak stars!





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Important to calculate photo-luminosity!

Electroweak Star

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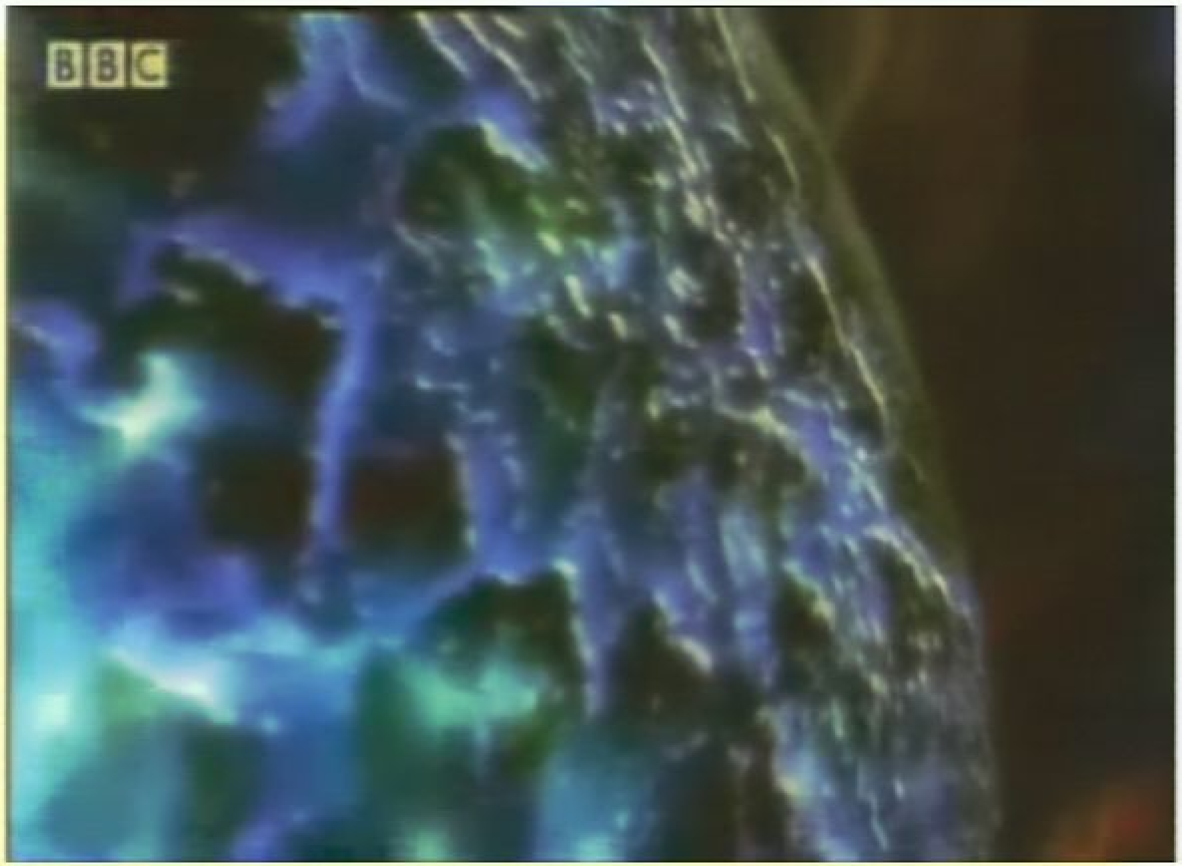
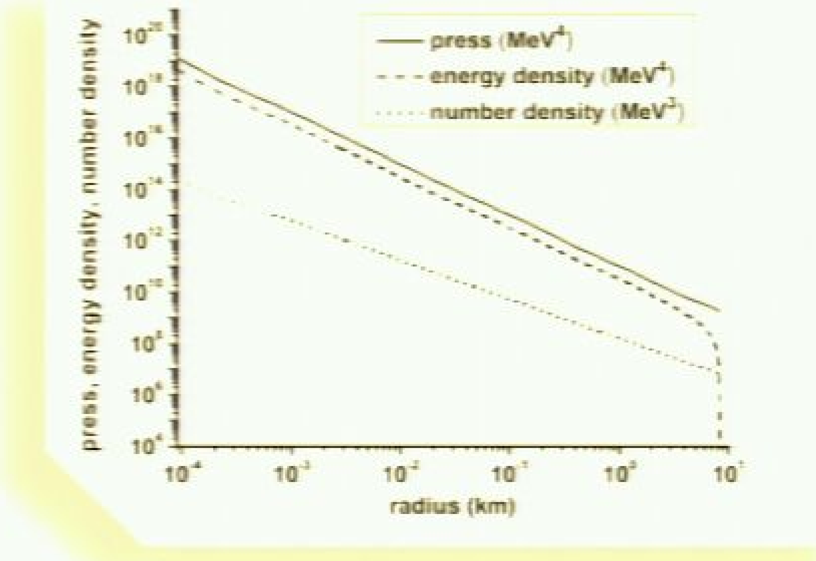


Potential problems



- We found a non-singular solution to TOVE → not a black hole
- However, TOVE assume quasi-equilibrium
- We have not solved a full time-dependent evolution of the system
- Will EW density be reached before the object crosses its own Schwarzschild radius?

Full time-dependent analysis

The core of the star:
Earth mass in a region of the size of an apple

It is almost a black hole!

In this regime most of the approximations (e.g. homologous collapse, PPN) fail

Must use full GR with back reaction included
Very challenging task!

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The electroweak star can't be in a static equilibrium like a neutron star or a black hole

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Important questions:

- Should a star spend at least 10^7 years in the EW stage before it becomes a black hole?
- When does electroweak burning stop?
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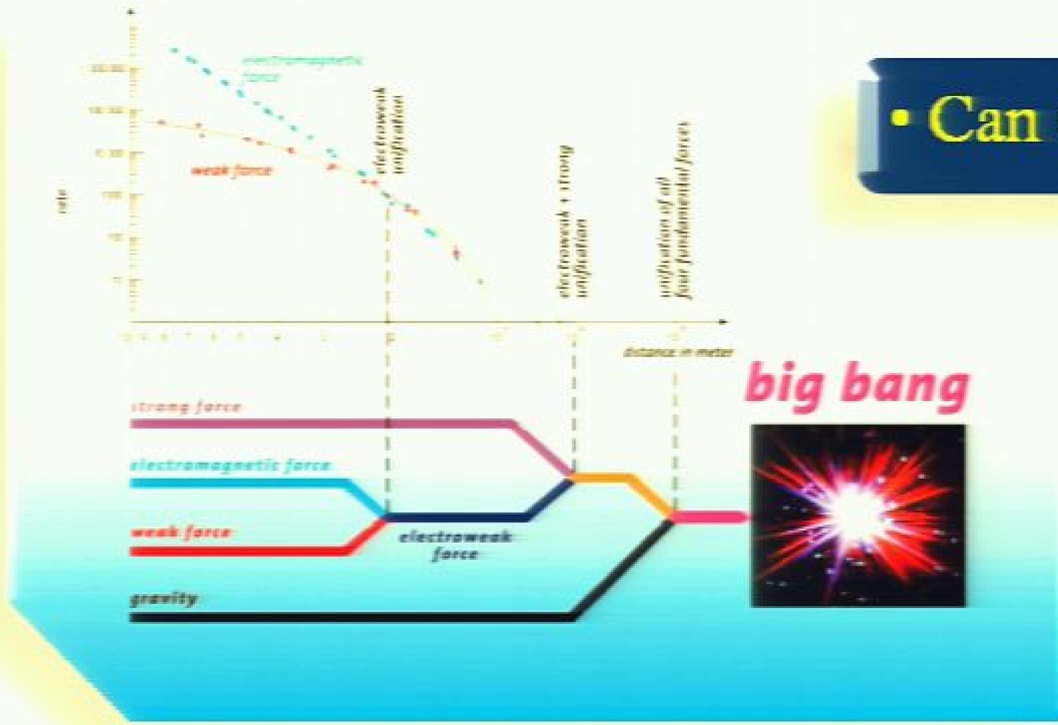
Next? GUT phase transition?



- Can GUT stars exist?

- Core of the GUT star must be microscopic

- Unlike to support the whole star
- Unlike to happen before the star crosses its own R_S

Conclusions

Electroweak star is an interesting new phase in stellar evolution

We found the solution and basic properties:

- Enormous energy is released at the core
- Energy release rate is moderate at the surface
- Life-time is at least 10 million years

Remains to be done:

- Photo-luminosity and other observational signature
- Full time-dependent analysis

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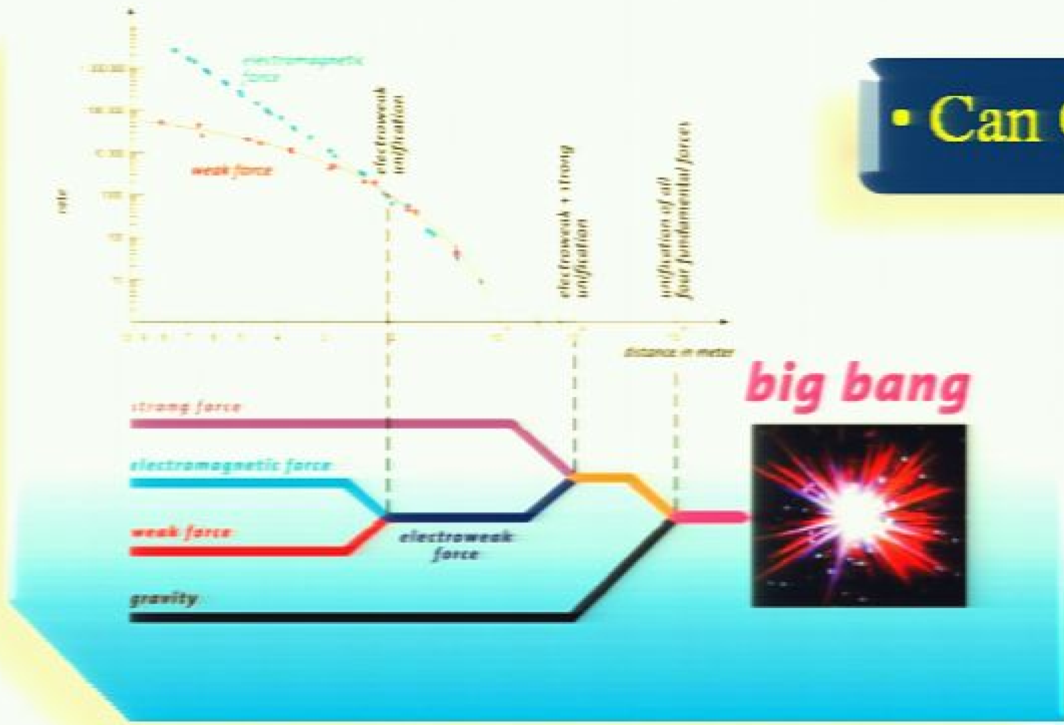

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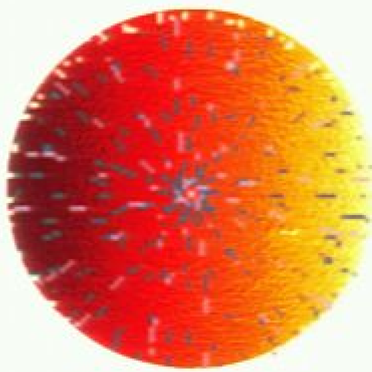

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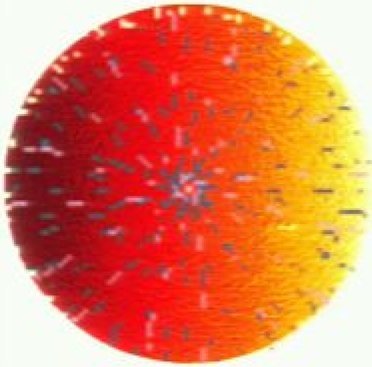

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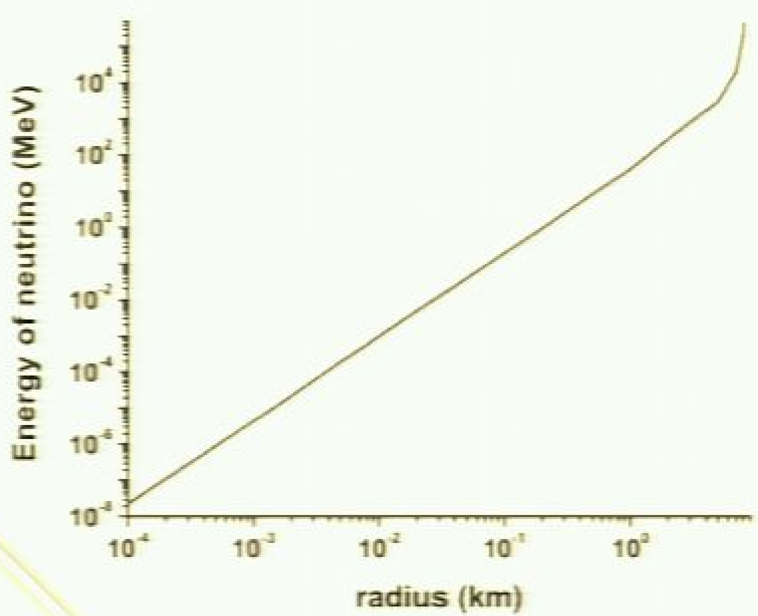

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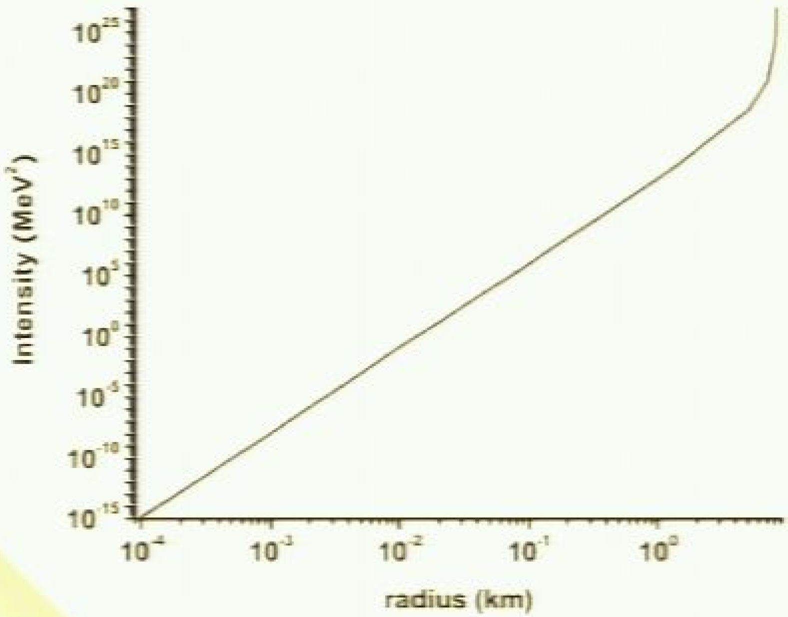

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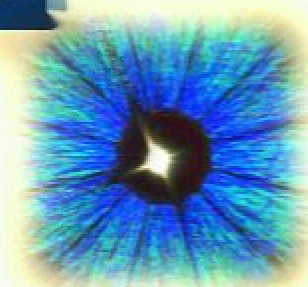

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