Electroweak stars

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ICHEP
PARIS 2010

July 22-28, 2010

University at Buffalo
The State University of New York

Based on:

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

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e-Print: **arXiv:0912.0520**

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Motivation

- **Stellar evolution** is one of the most interesting questions in modern astrophysics
- Despite tremendous progress in this field, it looks like it is far from being closed

Conventional evolution stops with neutron stars

New stages proposed: quark stars, preon stars, dark stars…

Electroweak stars!

Outline

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

Can Electroweak Stars powered by baryon number violating processes exist?

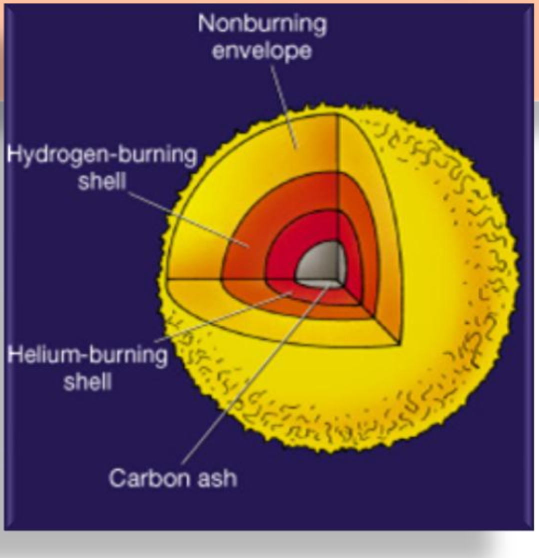
- Can a star's core be compressed to EW densities without being within its own R_S?
- Can this new phase last long enough to be called a star?

Perhaps YES!

The hierarchy in the central core density

- Protostar
- Main Sequence Star
- White Dwarf
- Neutron Star
- Quark Star ?
- ???

- Central core density grows

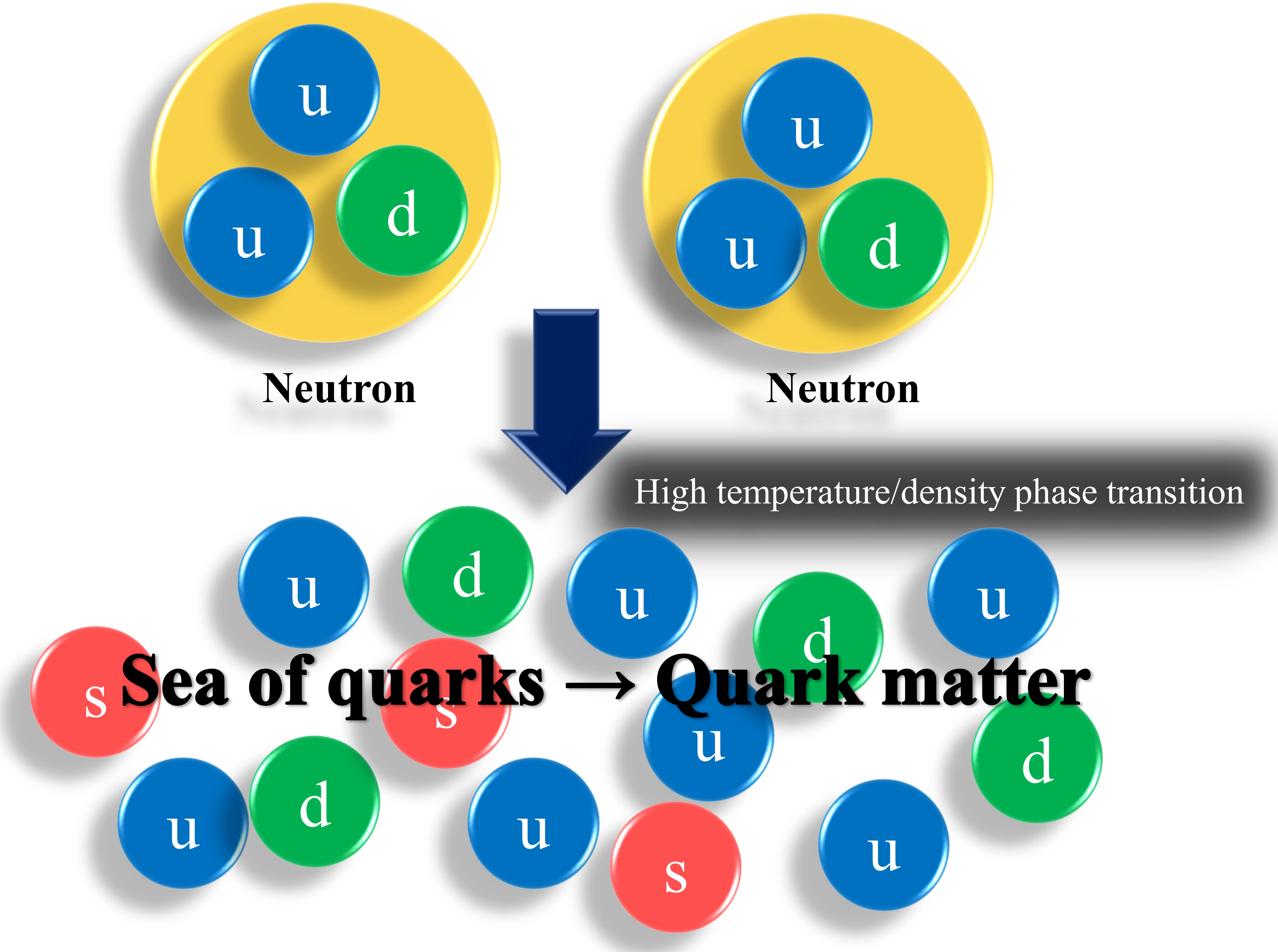


Quark Star

- 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



Neutron **Neutron**

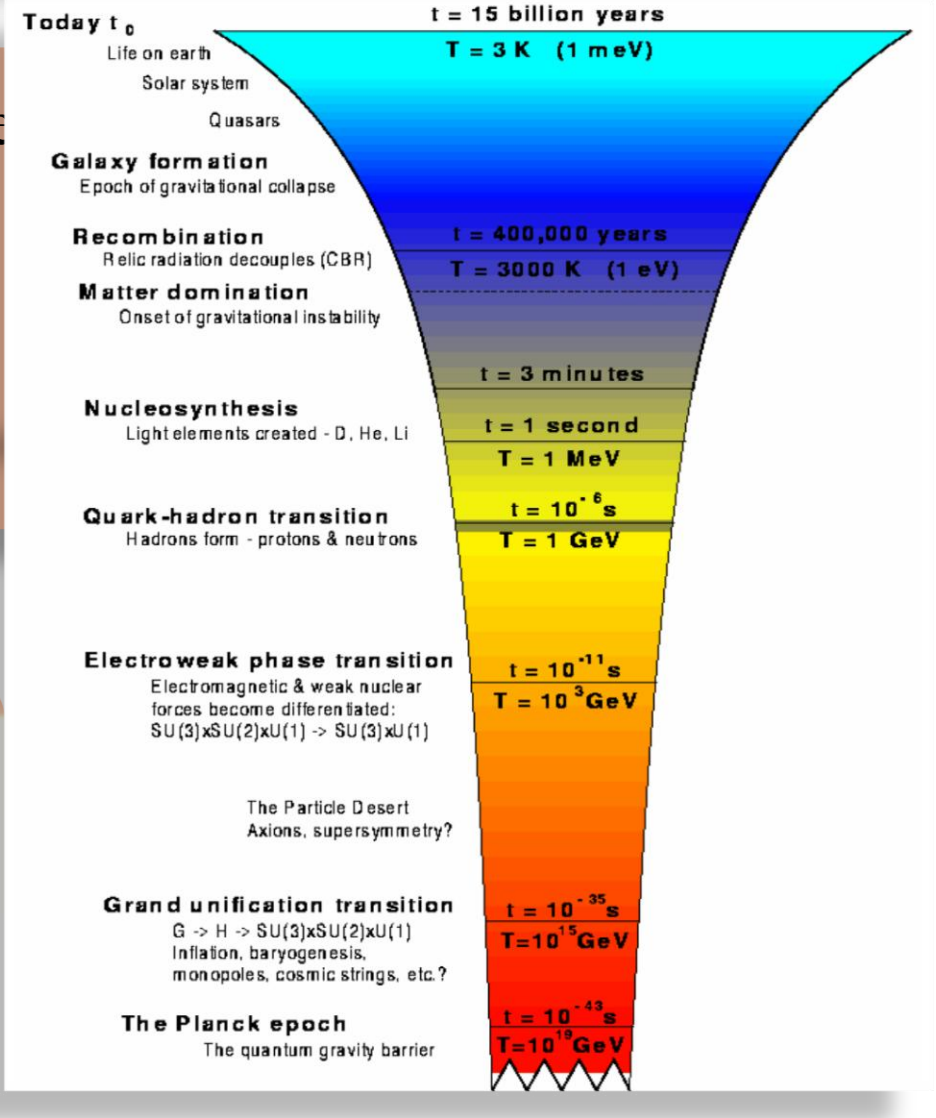
High temperature/density phase transition

Sea of quarks → Quark matter

"Og discovered fire, and Thorak invented the wheel. There's nothing left for us."

What happens next?

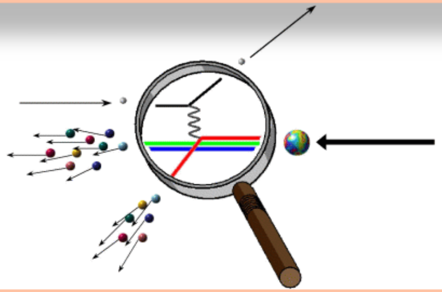
- Gravitational collapse continue
- Inverse Big Bang
- Densities reach $\sim (100\ \text{GeV})^4$



Electroweak phase transition happens!

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



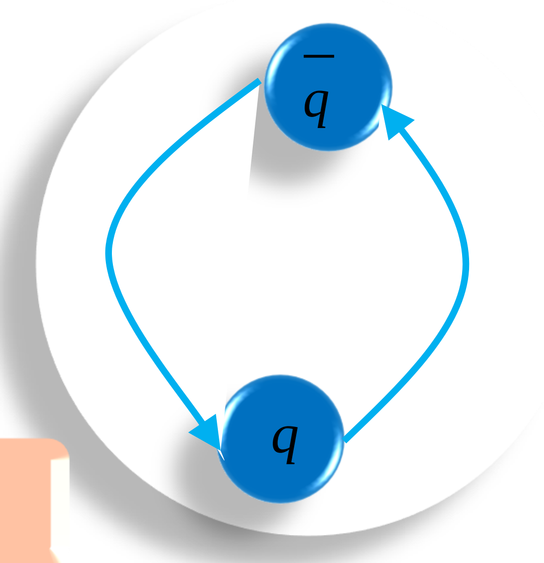
Non-perturbative baryon number violating electroweak processes

Conversion of quarks to leptons

Baryon Number

- Baryon number is a global symmetry of the SM Lagrangian

$$\partial_\mu J_B^\mu = \sum_i \partial_\mu \left(\bar{q}_i \gamma^\mu q_i \right) = 0$$



- Baryonic current is perturbatively conserved

- Quarks can appear and disappear only in pairs

Baryonic current anomaly

Quantum corrections destroy conservation of baryon number

$$\partial_\mu J_B^\mu = \frac{g^2 const}{16\pi^2} F_{\mu\nu}^a \tilde{F}^{a\,\mu\nu}$$

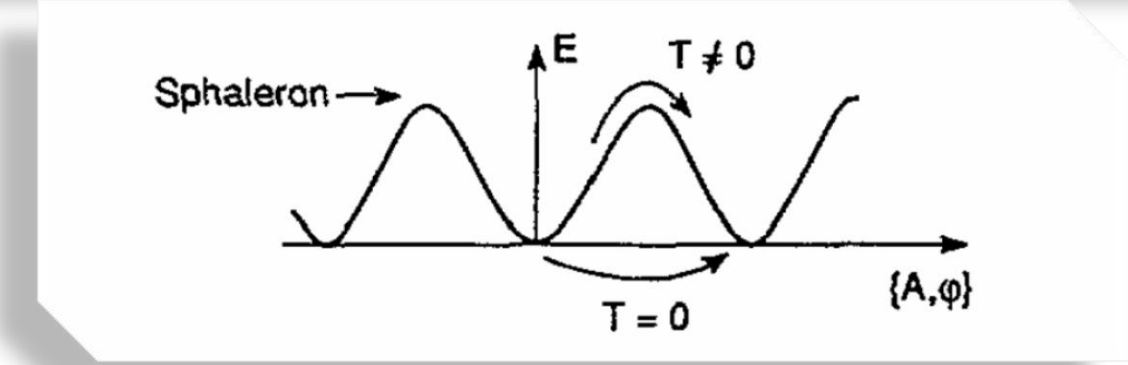
$$F_{\mu\nu}^a \rightarrow \text{gauge} \quad \text{field} \quad \text{strength}$$

Known as Adler-Bell-Jackiw anomaly

Baryon number violating processes are inherently quantum (instanton) processes

Sphaleron

At zero temperature such processes can occur only by quantum tunneling and are exponentially suppressed by $e^{-8\pi\alpha} \sim e^{-3000}$



At finite temperature one may classically pass over the barrier with the Boltzmann factor $e^{-E/T}$

Sphaleron - an unstable solution to the equations of motion

Sphaleron rate

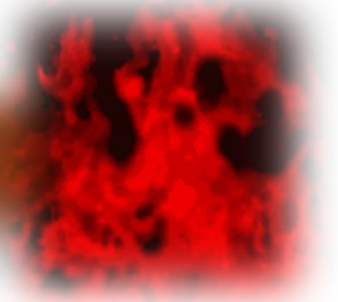
At finite temperature, the sphaleron rate is $\frac{\Gamma_{sph}}{V} \approx (\alpha_W T)^4 e^{-E_{sph}/T}$

$$E_{sph} \approx \frac{M_W}{\alpha_W} \approx 10 \text{ TeV} \qquad \text{for} \quad T < T_c$$

$$E_{sph} \approx T \qquad \text{for} \quad T > T_c$$

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.

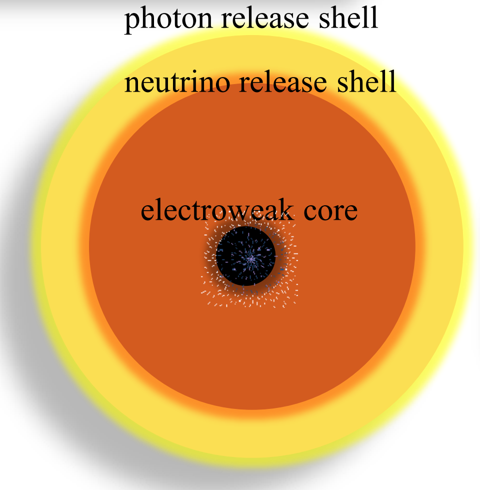
B-L preserving interaction can convert 9 quarks into 3 anti-leptons

$$\begin{array}{ccc} udd & & \\ css & \to & \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau \\ tbb & & \end{array}$$

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

The structure of the star

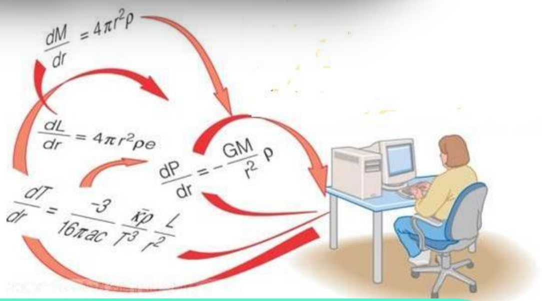
Electroweak core
- T above EW-breaking scale: T >100 GeV



Photon release shell
- Effective radius of the star

Neutrino release shell
- Inside the shell neutrinos are trapped
- Outside they can freely stream

Finding the solution



Tolman-Oppenheimer-Volkoff equations

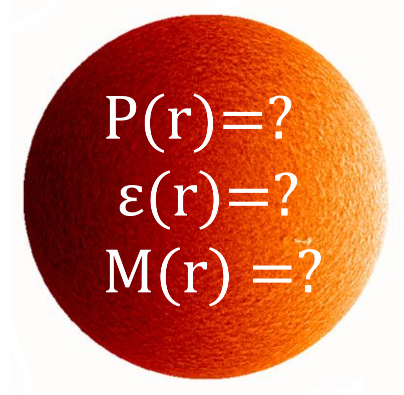
$$\frac{dP}{dr} = -\frac{(\varepsilon + P)(M + 4\pi p r^3)}{r^2(1 - 2M/r)}$$

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

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

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

ε = total energy density
P = total pressure



P(r)=?
ε(r)=?
M(r) =?

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

Variables and parameters

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

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

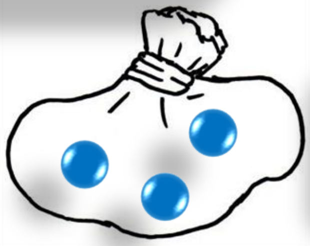
$$n_i = \frac{g_i}{2\pi^2}\int_{m_i}^{\infty} dE\,\left(E^2 - m_i^2\right)^{1/2} E\, f_i(E)$$

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

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

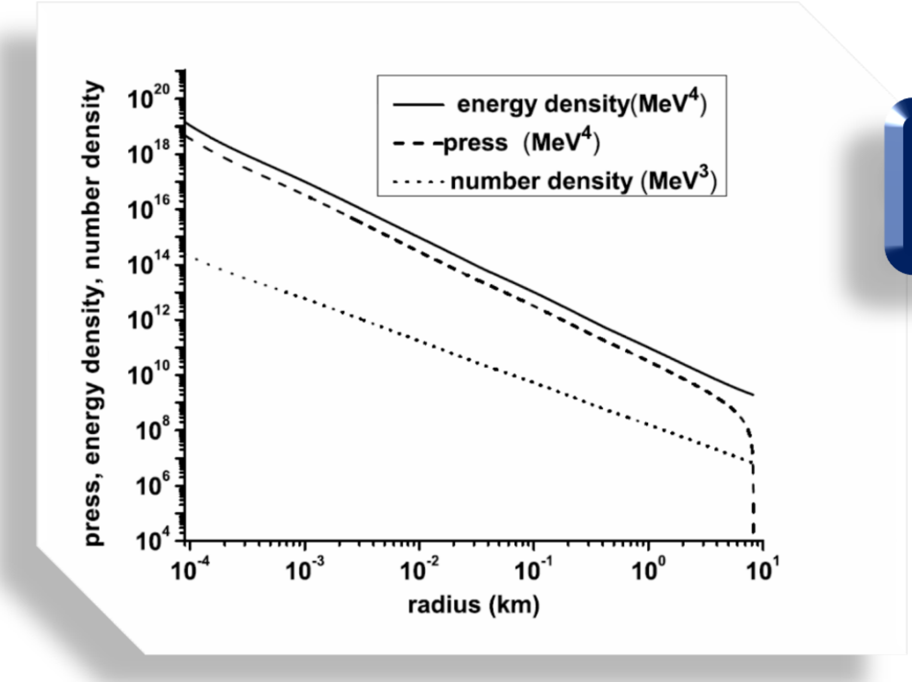
$$P = \sum_i p_i - B$$

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



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

Star Parameters



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

$M_{star} = 1.3\ M_{sun}$

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

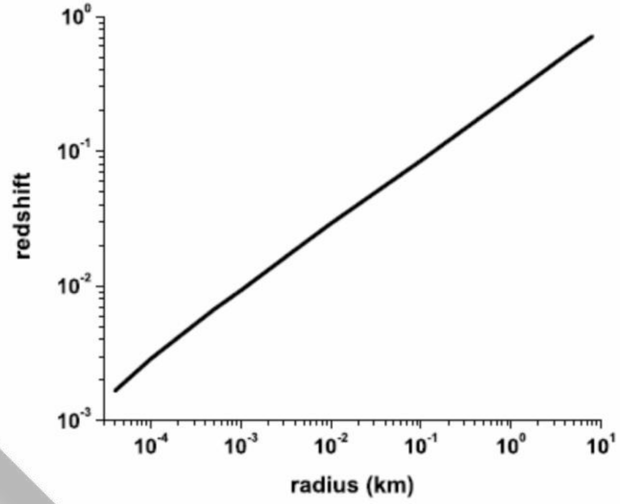
The solution is non-singular at the center – not a black hole

Neutrino energy redshift

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

- Energy changes as:

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

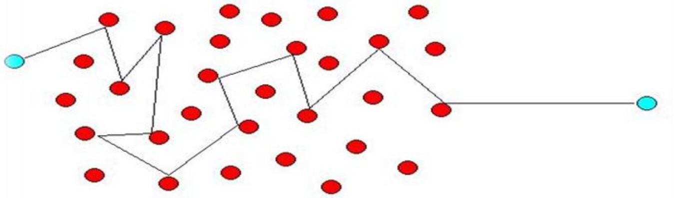


The redshift factor $\sqrt{g_{tt}}(r)$ inside the star. A particle with the original energy of 100GeV near the center carries away only 100MeV as it leaves the surface

Neutrino mean free path

The neutrino mean free path inside the star

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



with

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

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 →

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

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

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

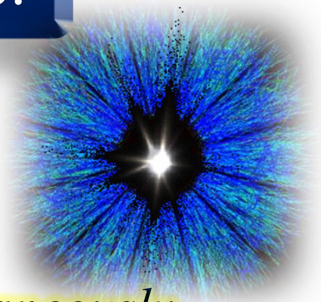
$$\left(\frac{dE}{dt}\right)_{\max} = 4\pi r_{ew}^2 \sqrt{\frac{2\lambda M(r_{ew})}{r_{ew}^2}}\,\varepsilon_\nu(r_{ew})\,g_{tt}(r_{ew})$$

$\approx 10^{27}\ \mathrm{MeV}^2$

Compare this with EW baryogenesis/baryodestruction rate:

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

$\approx 10^{34}\ \mathrm{MeV}^2$



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

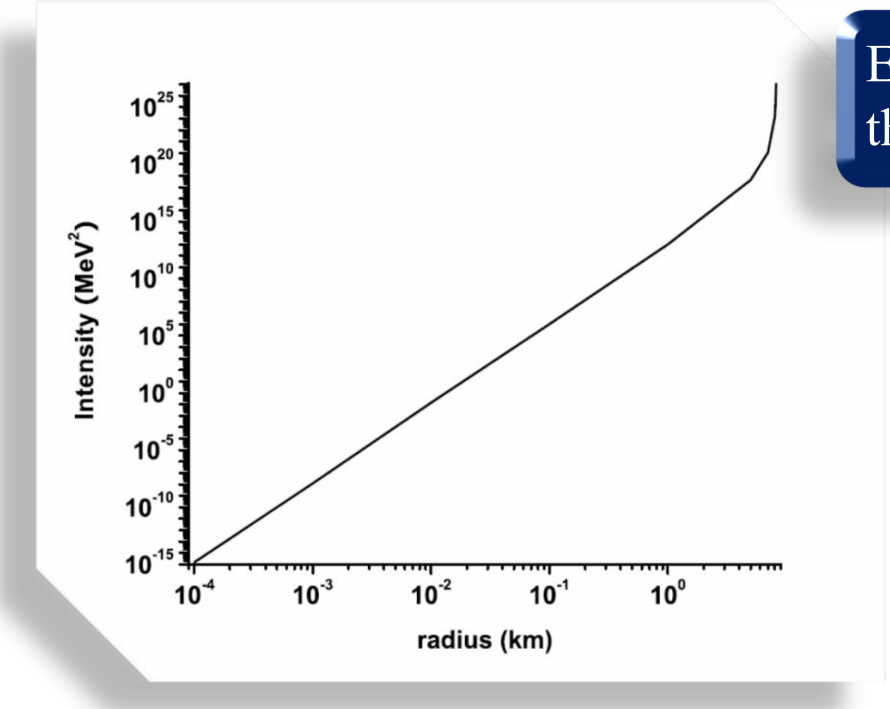
$$\frac{dE_\infty}{dt} = -4\pi r^2 \lambda \frac{d[S(r) g_{tt}(r)]}{\sqrt{-g_{rr}(r)}dr}$$

with

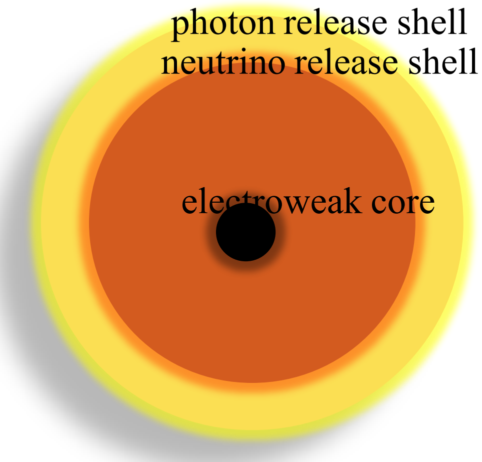
$$S(r) = \frac{dE(r)}{dtdA}$$

- 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:



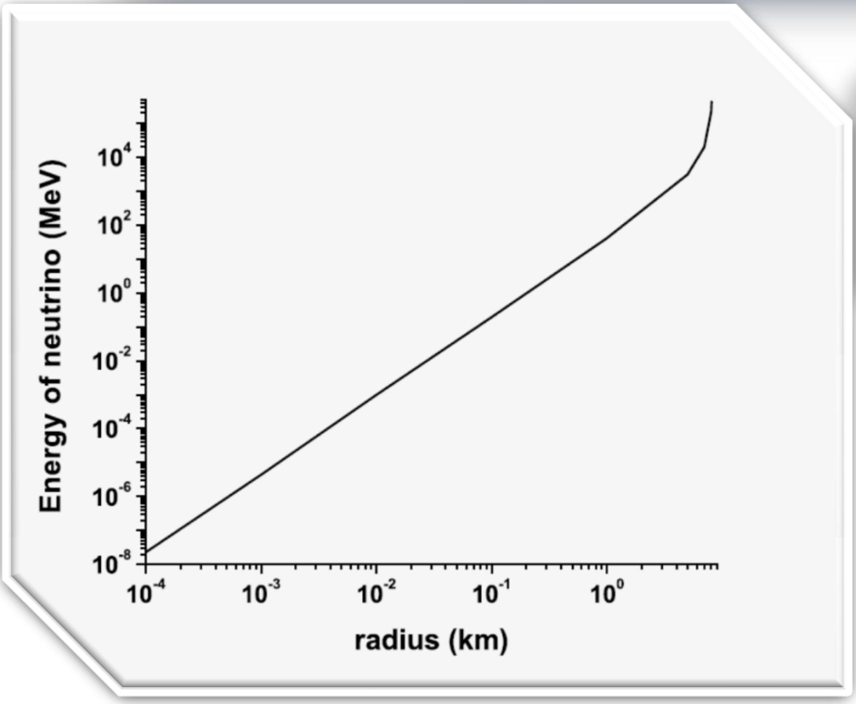
Energy release rate increases with the radius of the neutrino release shell



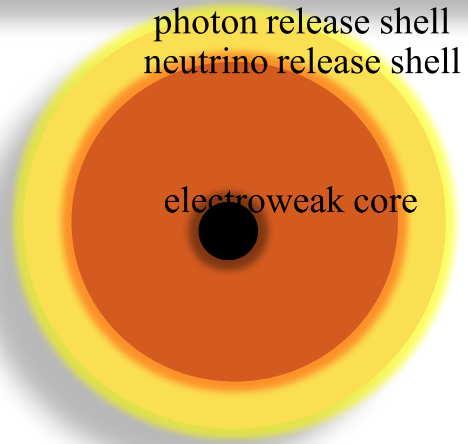
The maximum energy release rate is on the surface, but there it exceeds the limit from the quark shell free fall into the electroweak core **$\approx 10^{27}$ MeV^2**

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.



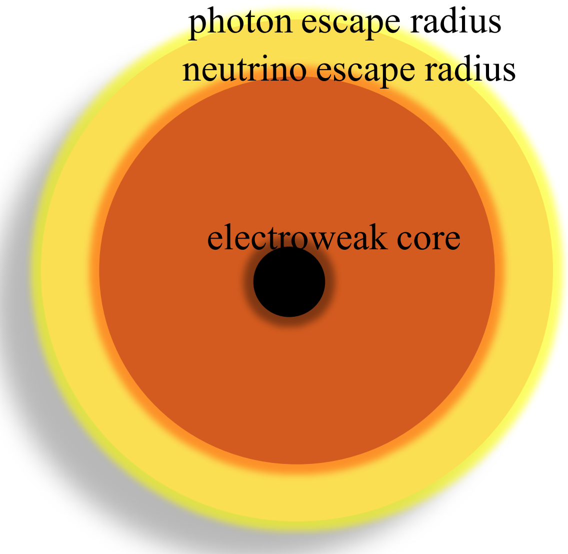
However, the energy is already larger than 300GeV at 8.1 km

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}

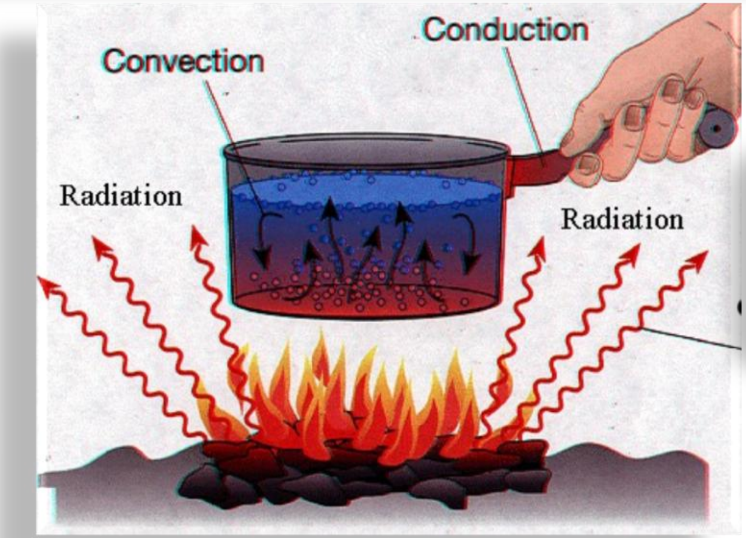


This is the minimal life-time of the electroweak star *(provided that all the available quark fuel burns)*

What did we neglect?

We neglected the fact that some fraction of energy is carried away by photons, since they have shorter mean free path

We also ignored the effects of energy transport due to convection



Order of magnitude estimate will not change

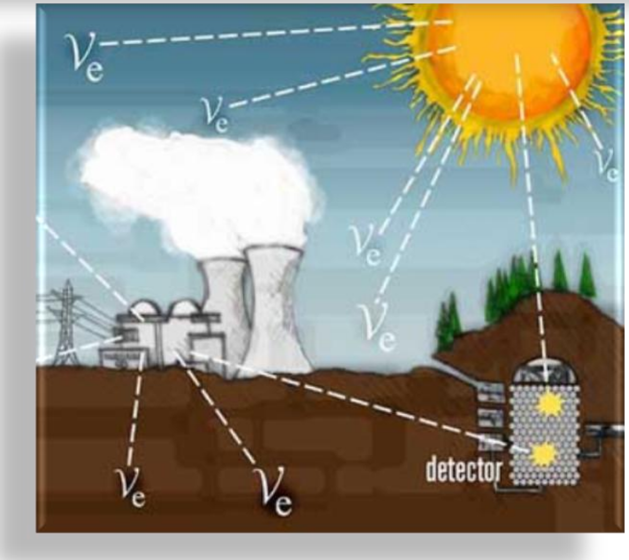
Observational signature?

Most of the energy is emitted in form of neutrinos

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

Most of the astrophysical object emit (electron) neutrinos

Antineutrino emitters (of all families) might be electroweak stars!



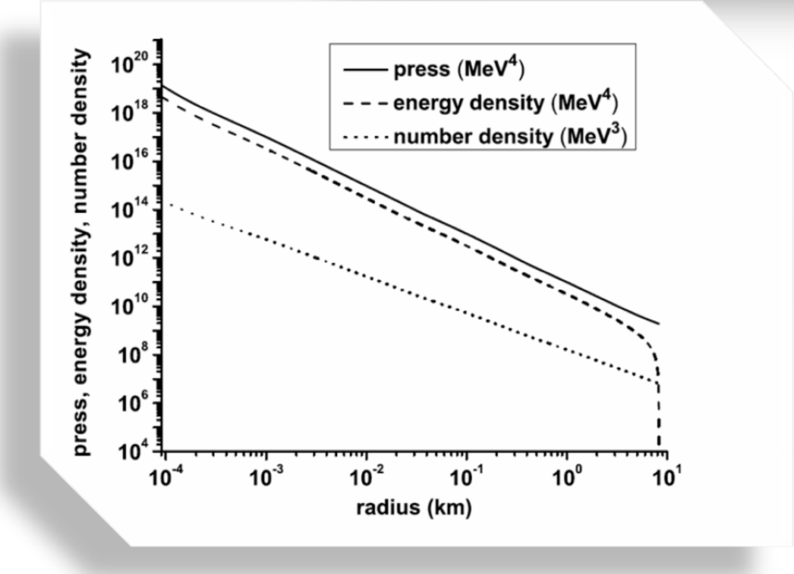
Observational signature?

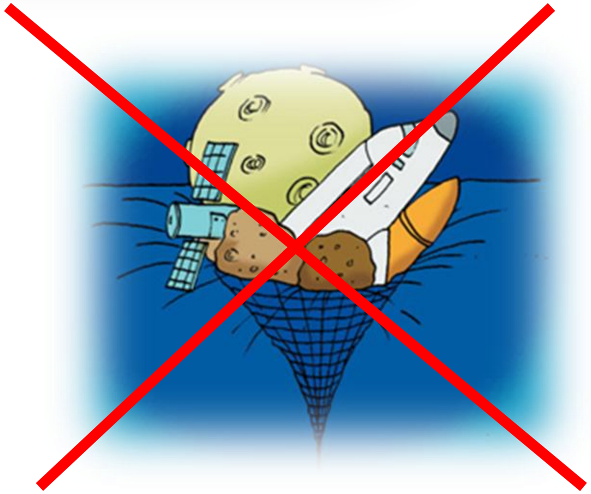
Energy released in photons very important for the signature

- Most of the energy emitted in neutrinos
- But significant percentage might be photons

Important to calculate photo-luminosity!

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

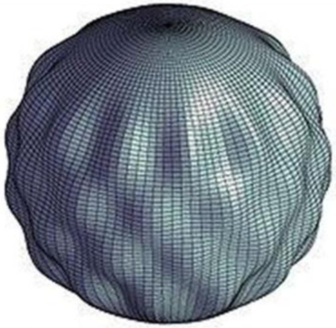
The core of the star:
Earth mass in a region of the size of an apple

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!

Full stability analysis



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

Gravity is balanced by the gas pressure and also radiation pressure

Dynamic rather than static equilibrium

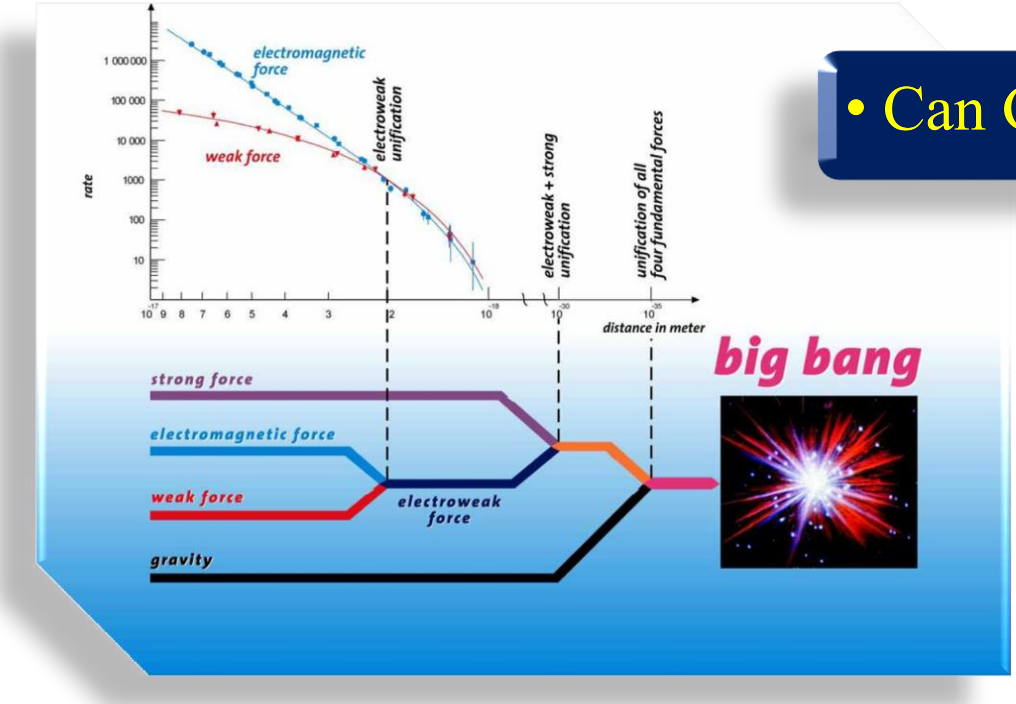
Stability is much more difficult to check!

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?
- Can electroweak burning spend all of the quark fuel (i.e. black hole never forms) ?

Requires much more detailed modeling of the star!

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 can be as long as 10 million years

Remains to be done:

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

THANK YOU