Massive Stars and Nonstandard Cooling Mechanisms

Implications of
Neutrino Flavor Oscillations

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OUTLINE

- Stars and the physics beyond the standard model

- Comparison of the sensitivity of different stars to neutrinos magnetic dipole moment

- Massive stars and physics beyond the standard model

  * Does a non-vanishing magnetic moment influence the behavior of a massive star?
  * For which range of masses?
  * What are the induced effects and what is the sensitivity?

- Conclusions and perspectives

Stars and New Physics

The idea of probing new physics in stars is old

The effects of electromagnetic properties of neutrinos for the sun were originally studied by Bernstain, Ruderman and Feinberg in 1963 .

Their bound on the neutrino magnetic moment was better than the experimental bound at that time.

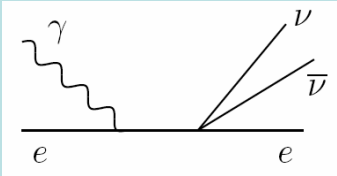
Presently, constraints coming from astrophysical considerations on particle physics beyond the standard model are frequently better than the terrestrial constraints

In stars, we can test new interactions until they become as strong as the weak interaction.

This does not mean that we can test physics only up to the weak interaction scale.
For example, we can test a class of extra dimensional models up to 10^6 TeV
(M.G. A. Friedland, in progress)

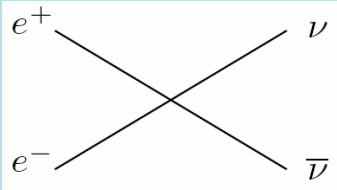
Neutrinos Energy Loss

Neutrino Photoproduction



$$\gamma\, e^- \longrightarrow e\, \nu\, \overline{\nu}$$

Neutrino Pair Production



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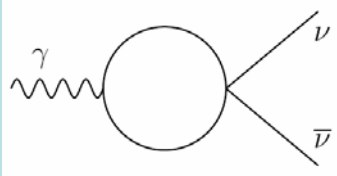
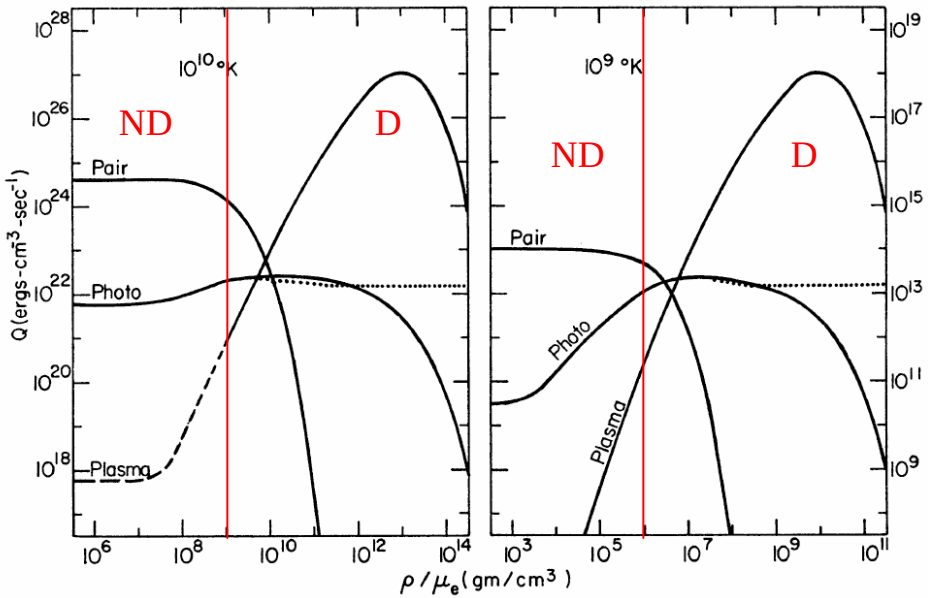
Plasmon Decay

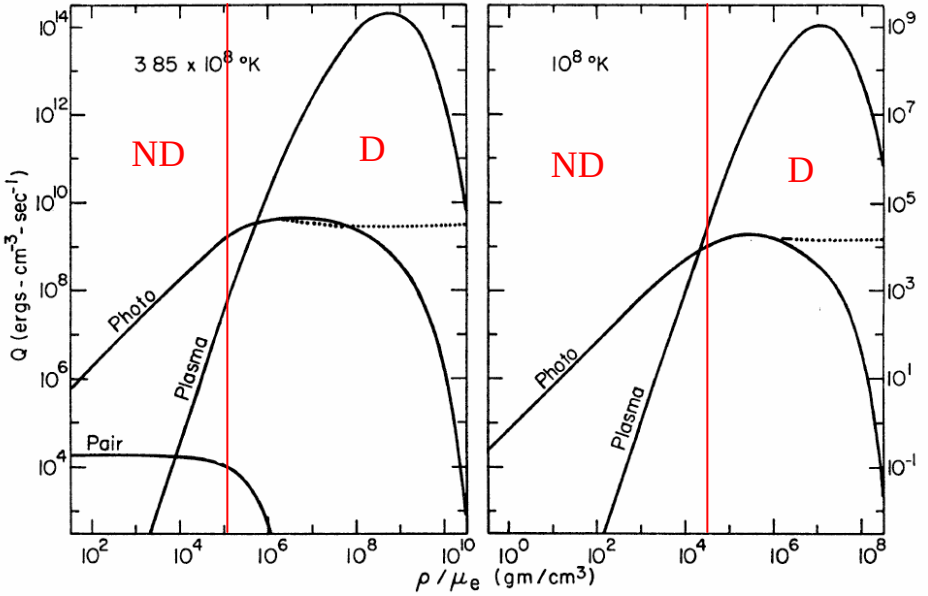


$$\gamma \longrightarrow \nu\, \overline{\nu}$$

D=Degenerate ND=Nondegenerate



(a)



From G Beaudet, V.Petrosian, E. Salpeter (1967)

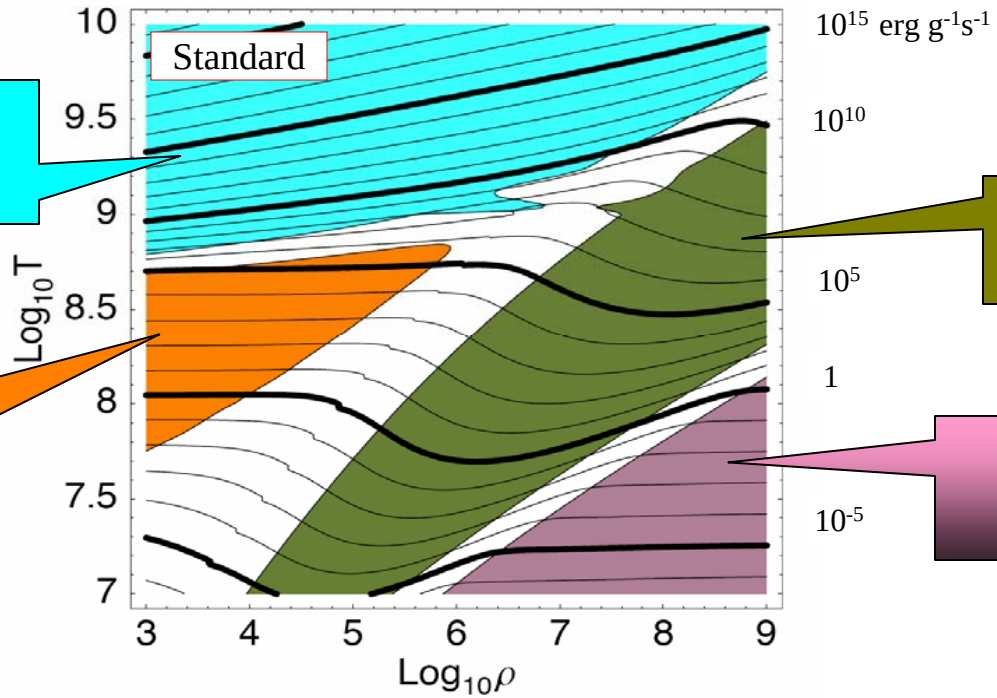
Neutrino Cooling in Stars

Neutrino pair production

$e^+ e^- \rightarrow \nu \overline{\nu}$

Neutrino photoproduction

$\gamma e^- \rightarrow e \nu \overline{\nu}$



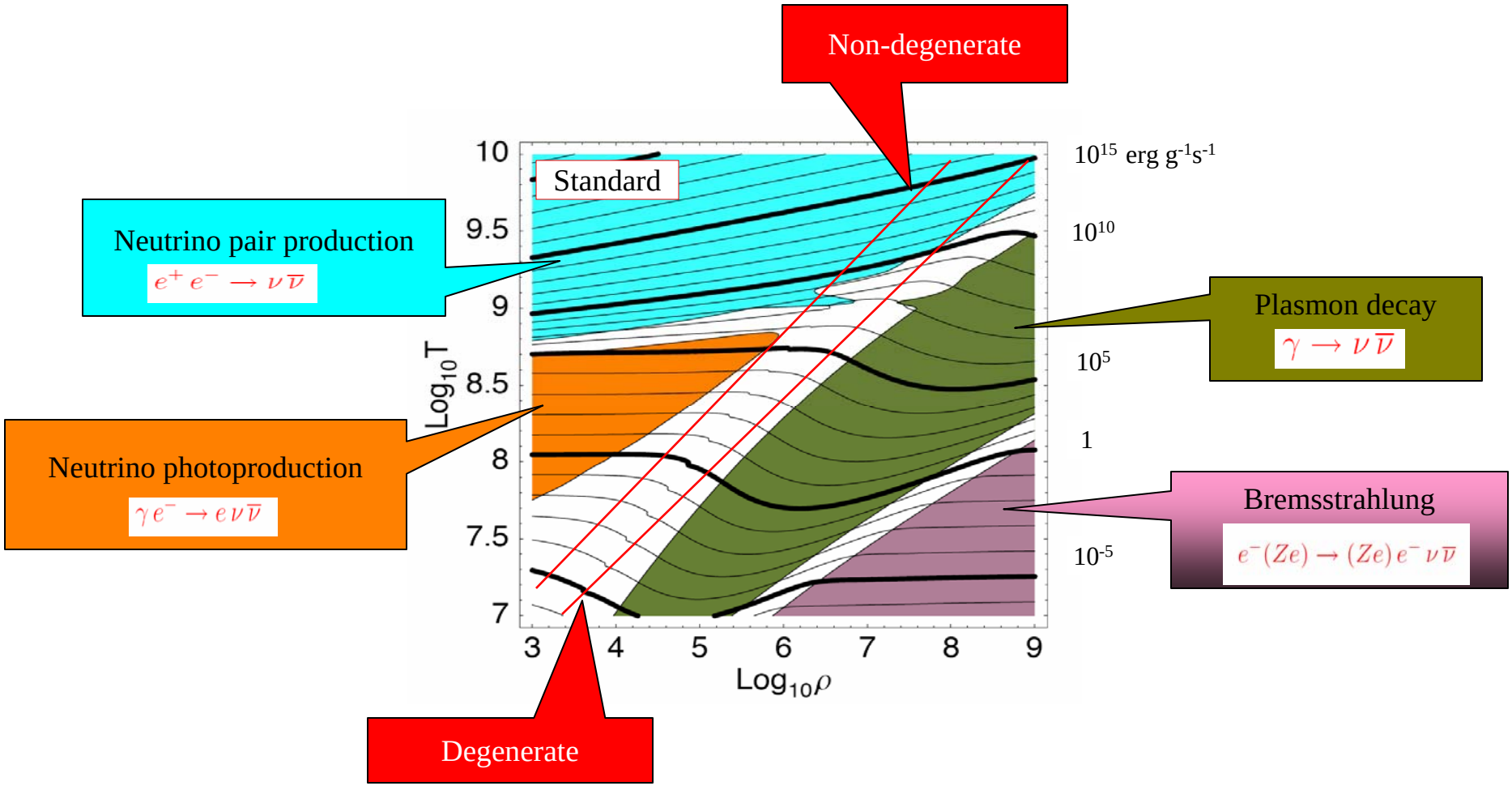
Plasmon decay

$\gamma \rightarrow \nu \overline{\nu}$

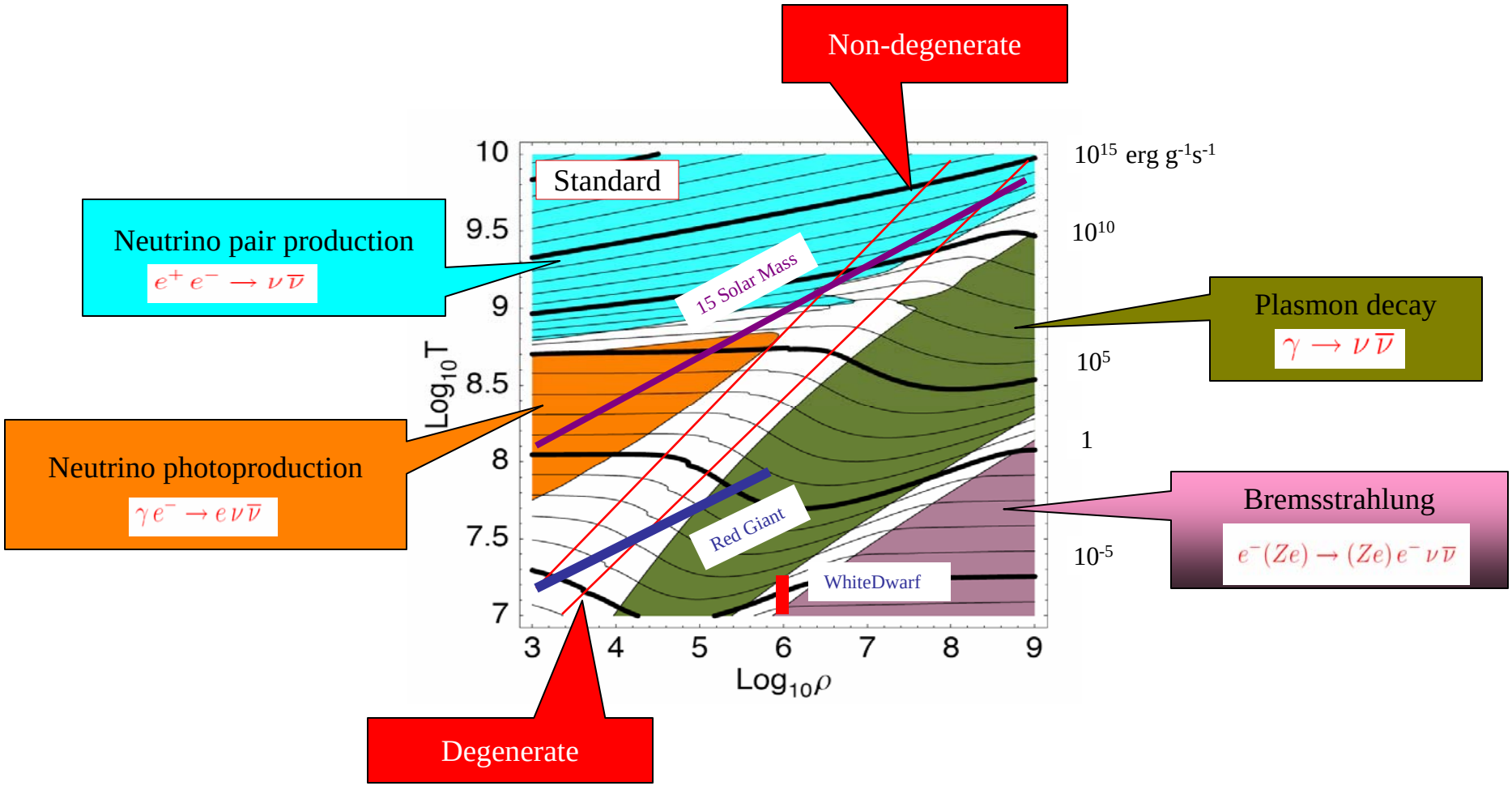
Bremsstrahlung

$e^-(Ze) \rightarrow (Ze) e^- \nu \overline{\nu}$

Neutrino Cooling in Stars



Neutrino Cooling in Stars



Light and Massive Stars

Light $M<8\text{-}9\ M_o$	Massive $M>8\text{-}9\ M_o$
1) Relatively simple, 1 or 2 burning stages	1) Complex evolution with several burning stages
2) More observational data	2) Less observational data (Salpeter IMF)
3) Stable configuration	3) Explosion
4) Production of some oxygen and carbon	4) Nucleosynthesis of heavy elements
5) Low density and low temperature (Sun) Low density and higher temperature (HB) High density and temperature ~ HB (RG,WD)	5) Wide range of densities and temperatures. Core degenerate only at the end of the evolution.

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5) Low density and low temperature (Sun) Low density and higher temperature (HB) High density and temperature ~ HB (RG,WD)	5) Wide range of densities and temperatures. Core mildly degenerate only at the end of the evolution.

Each star has it own properties and could be more or less sensitive to some process.
The sun is the star that we know best but it is not always the best laboratory for high energy physics.

Neutrino Magnetic Moment

$$L_{\text{int}} = \frac{1}{2}\mu_\nu \, \overline{\psi} \, \sigma_{\alpha\beta} \, \psi \, F^{\alpha\beta}$$

Massive neutrinos are expected to have a non-vanishing magnetic moment.

$$\frac{\mu_\nu}{\mu_B} \simeq 3 \times 10^{-19} \left[\frac{m_\nu}{1\text{eV}}\right]$$

$$\mu_B = e/(2m_e)$$

The experimental limit $\mu_\nu < 10^{-10}$ is very weak:
there are many orders of magnitude between this and the SM prediction.

Theories beyond the SM predict higher values for the neutrino magnetic moment

Evidence that $\mu_\nu/\mu_B > 10^{-19}$ would shed light on the dynamics of the lepton sector of any SM extension

If $10^{-15}\ \mu_B < \mu < 10^{-10}\ \mu_B$ is measured or inferred by astrophysical considerations, it would be a strong indication that neutrinos are Majorana fermions.

R.Barbieri, G.Fiorentini, 1988
N. F. Bell et al, 2005
S. Davidson et al 2005
N. F. Bell et al, 2006

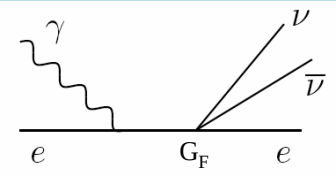
Neutrino Magnetic Moment: Bounds

Source	Bound on μ_ν/μ_B	Comments	Reference
Experimental bound	$\sim 10^{-10}$	Electron neutrino scattering. A first experimental bound $\mu_\nu < 10^{-9}$ was deduced by Cowan and Reines (1957) after a direct analysis of their famous experiment to detect neutrinos	Z. Daraktchieva et al (2005); A.G. Beda, V.B. Brudanin, E.V. Demidova, V.G. Egorov, M.G. Gavrilov, M.V. Shirchenko, A.S. Starostin,Ts. Vylov (2007) $< 0.58 \times 10^{-10}$
Sun	$\sim 4 \times 10^{-10}$	Plasmon decay: Life time too short	J. Bernstain et al (1963)
Red Giants	$\sim 3 \times 10^{-12}$	Plasmon decay delay of the helium Flash. (White Dwarfs give a comparable bound)	G. Raffelt (1990) G. Raffelt, A.Weiss (1992) V. Castellani, S. degli Innocenti (1993) M. Haft et al (1994) M. Catelan et al (1995)
SN	$\sim 3 \times 10^{-12}$	From neutrino flip. Valid only for Dirac Neutrnos	R. Barbieri, R.N. Mohapatra (1988) A. Ayala et al (1998)
SN and Magnetic field	$\sim 10^{-12}$	From neutrino double flip in the SN and in the galactic magnetic field. Valid for Dirac Neutrnos	R. Barbieri, R.N. Mohapatra (1988) D. Notzold (1988)
Neutron Stars	$\sim 5 \times 10^{-7}$	10^{-10} would lead to significant effects	Iwamoto et al (1995)
Cosmology	a few $\times 10^{-11}$	BBN	See, e.g., A. Dolgov Phys. Rep. 370 (2002)

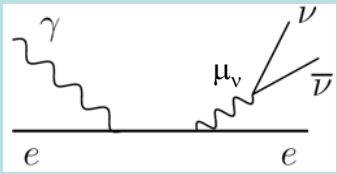
Neutrino Energy Loss: Testing Neutrinos magnetic moment

Standard | Electromagnetically induced

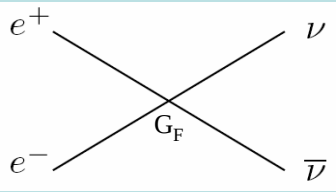
Neutrino Photoproduction



$$\gamma\, e^- \longrightarrow e\, \nu\, \overline{\nu}$$



Neutrino Pair Production



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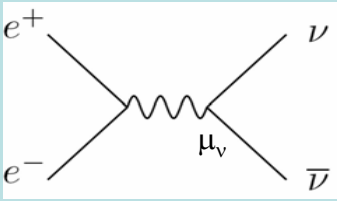
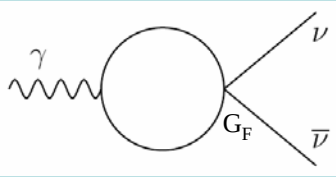
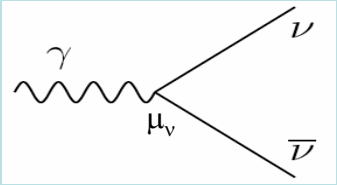


Plasmon Decay



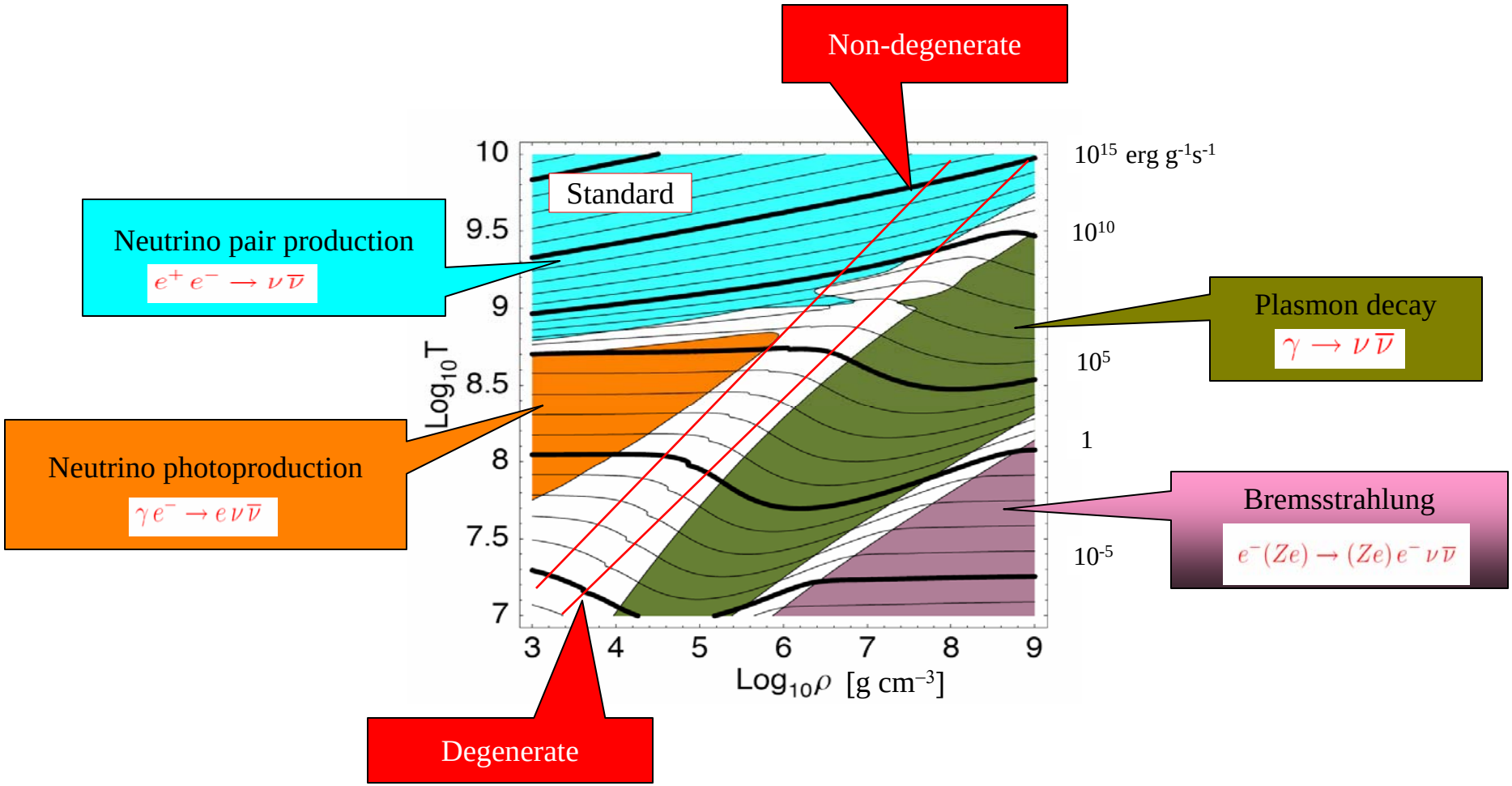
$$\gamma \longrightarrow \nu\, \overline{\nu}$$



At low energies, for all the neutrino processes but the plasmon decay, the cross section of the electromagnetic and weak induced processes are equal for $\mu_\nu \sim 10^{-10}\ \mu_B$, which is approximately the experimental bound. For such a value of μ_ν the plasmon decay is strongly dominated by the electromagnetic contribution

So with plasmon decay we can probe higher scales.

Neutrino Cooling in Stars



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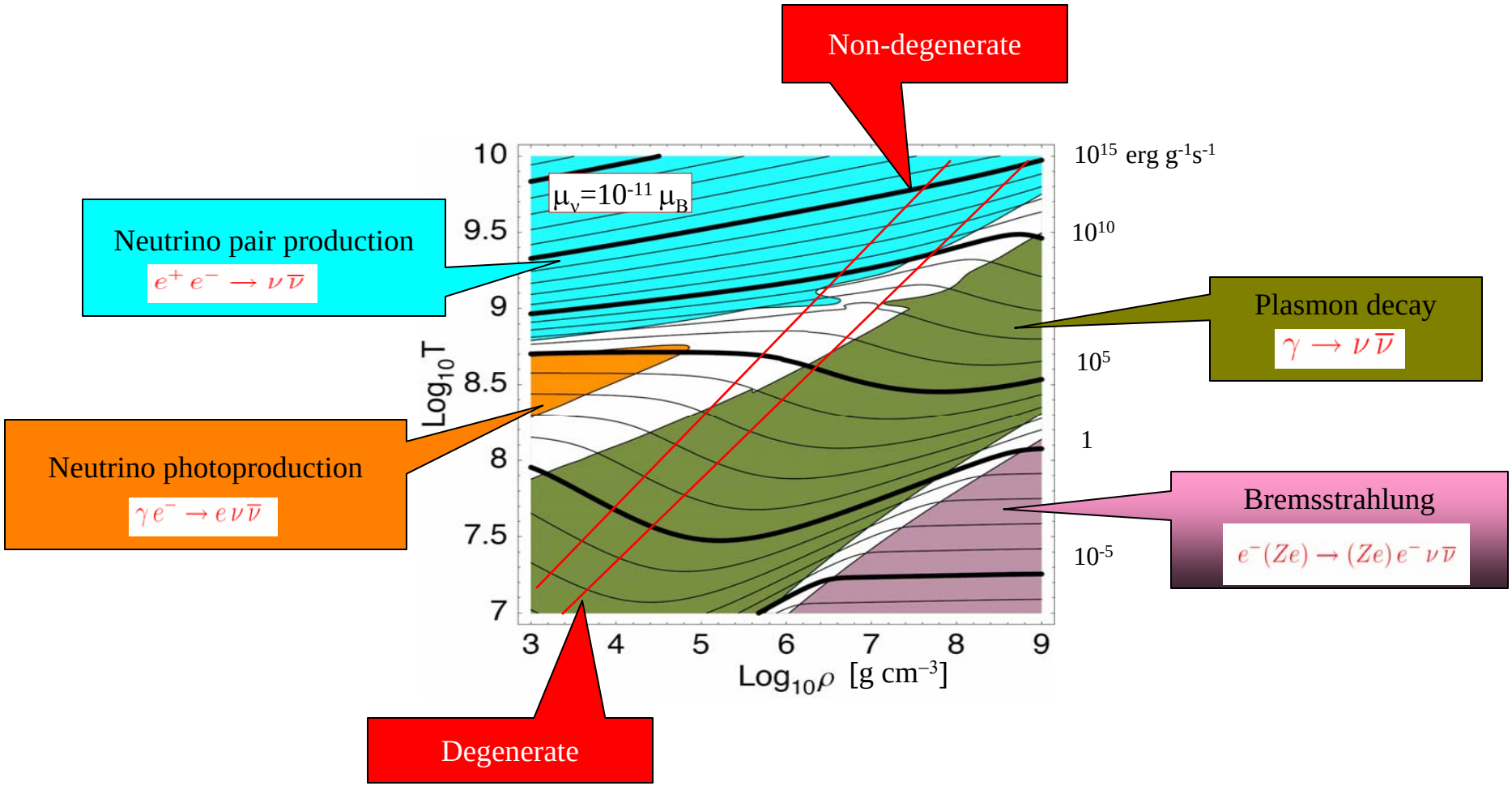

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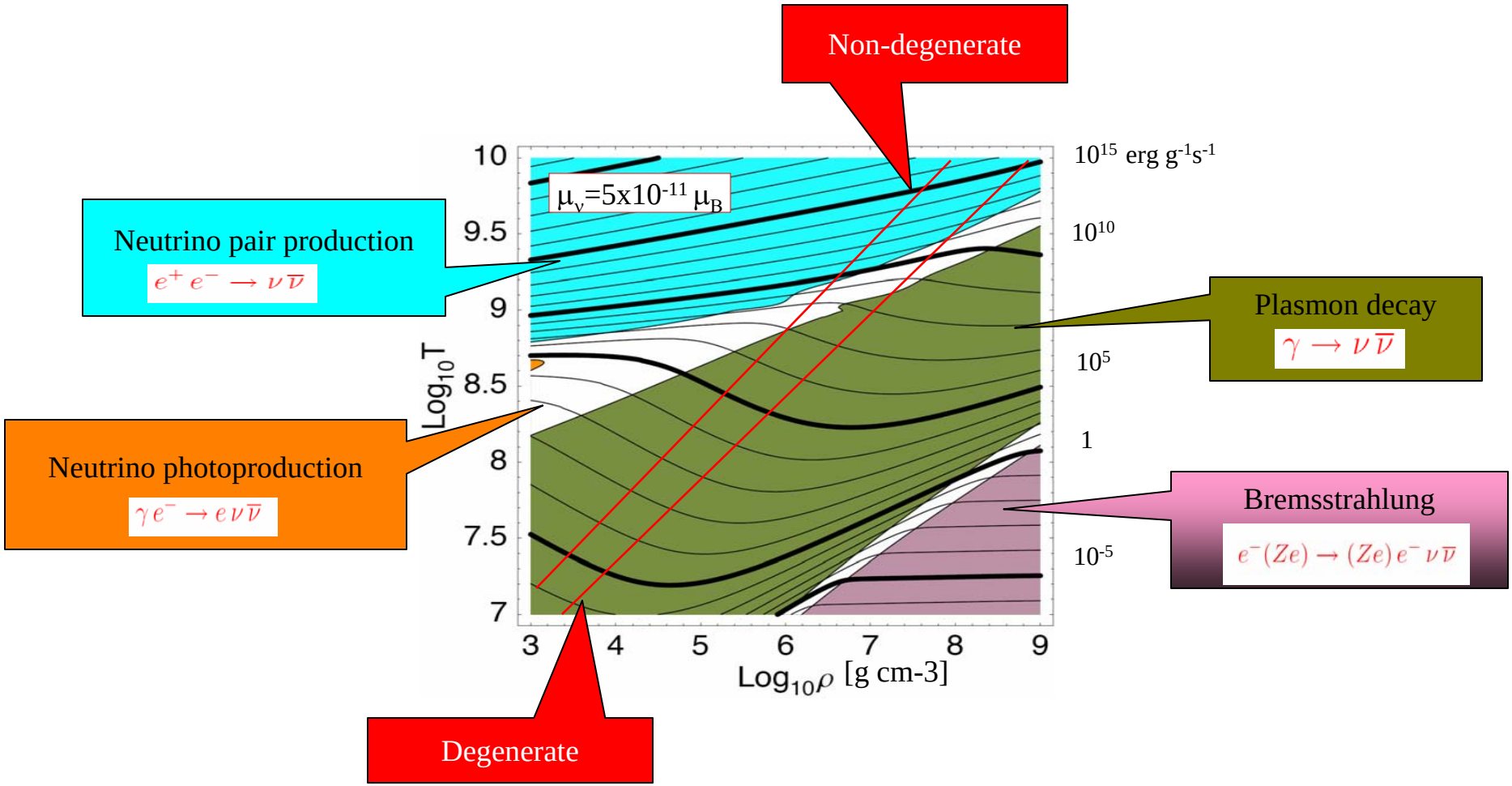

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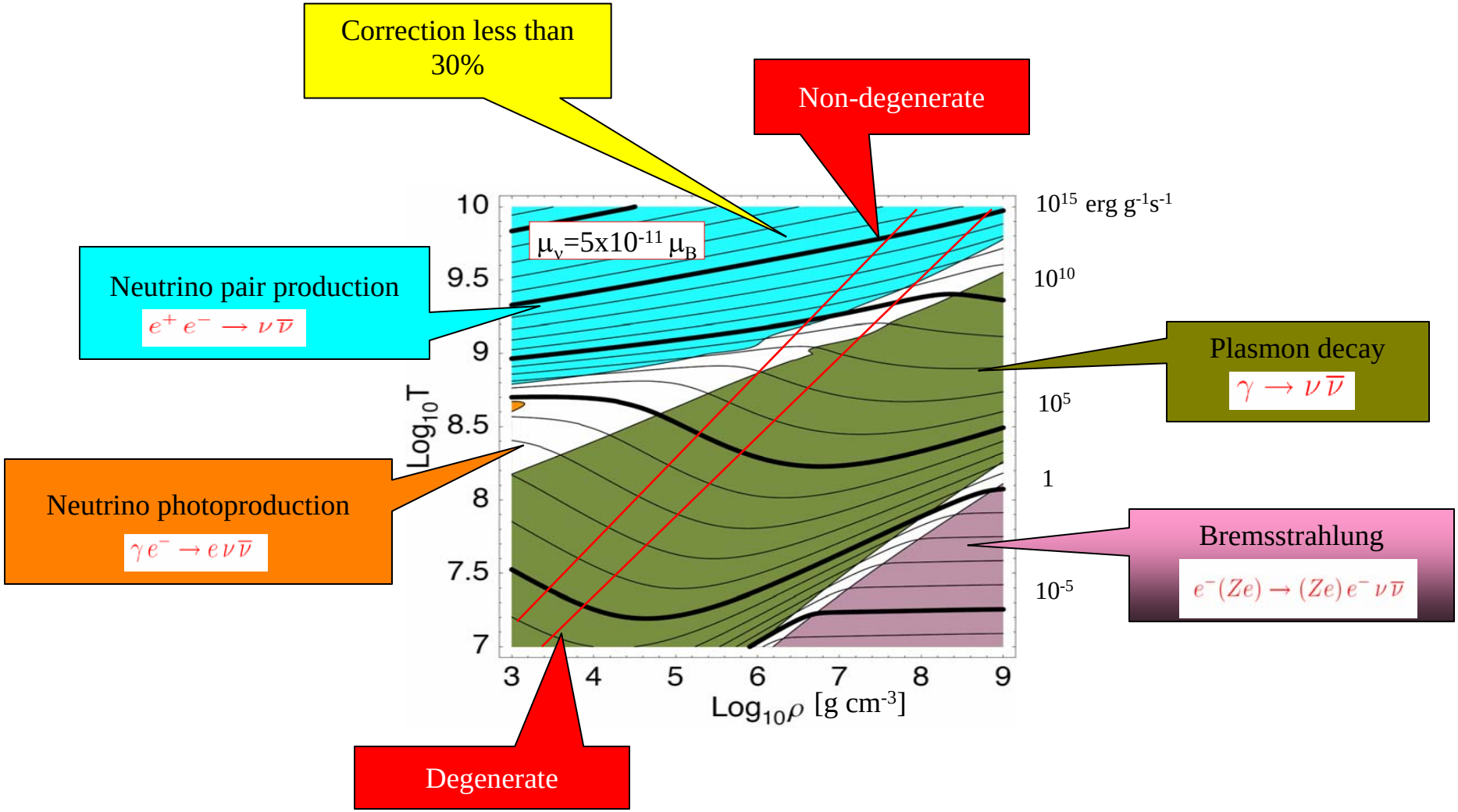
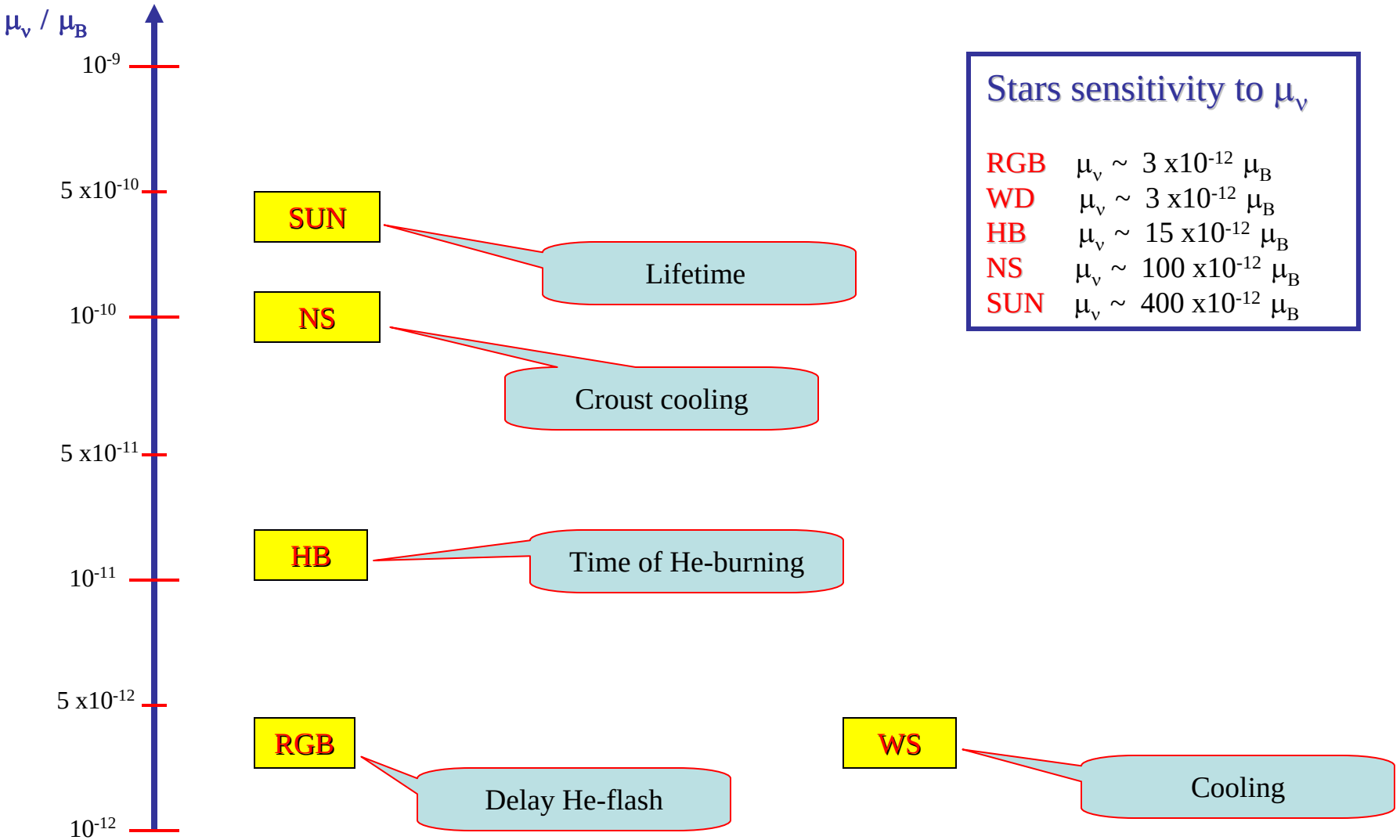


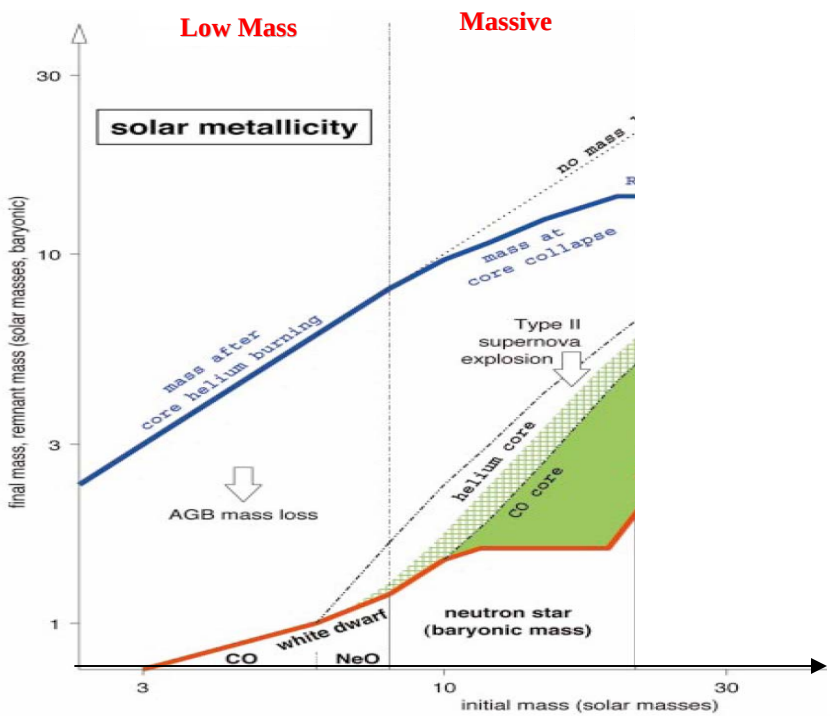
Star sensitivity to neutrino magnatic moment



Stars sensitivity to μ_ν

RGB	$\mu_\nu \sim 3 \times 10^{-12}\ \mu_B$
WD	$\mu_\nu \sim 3 \times 10^{-12}\ \mu_B$
HB	$\mu_\nu \sim 15 \times 10^{-12}\ \mu_B$
NS	$\mu_\nu \sim 100 \times 10^{-12}\ \mu_B$
SUN	$\mu_\nu \sim 400 \times 10^{-12}\ \mu_B$

Massive Stars



From Woosley, Heger, Weaver, ReV Mod Phys, 74, 1015 (2002)

Simple Facts

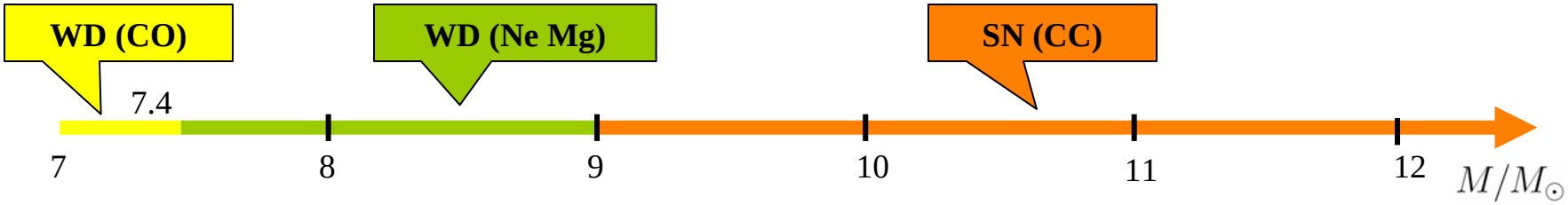
-Low mass stars do not ignite carbon and make a CO WD

-A little heavier ignite carbon and make a NeMg WD

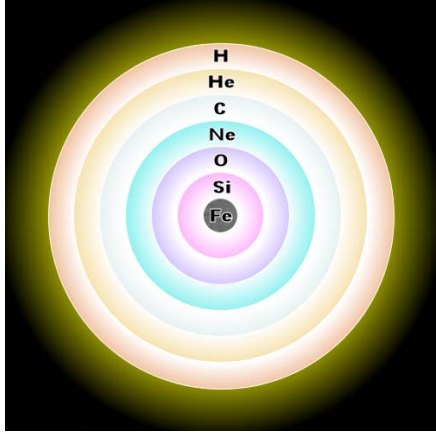
-Heavier stars ignite C, Ne, O, Si (onion) and make a SN (or BH)

-The core evolution is in the nondegenerate region except for the last stages

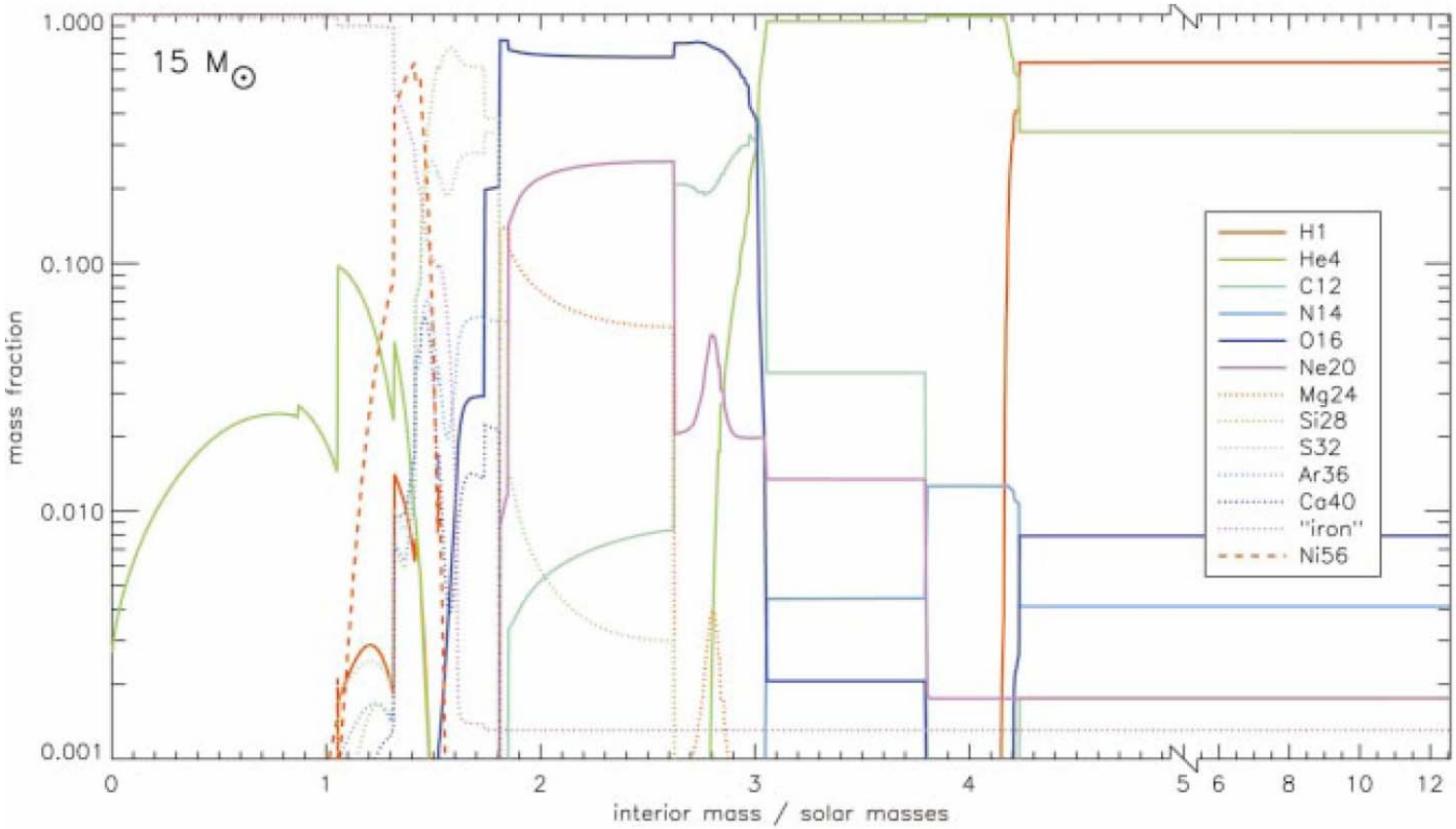
-After the SN explosion the material is ejected… if we exist is thanks to massive stars



The Onion



Final composition of a 15 M_o star (Solar Metallicity)



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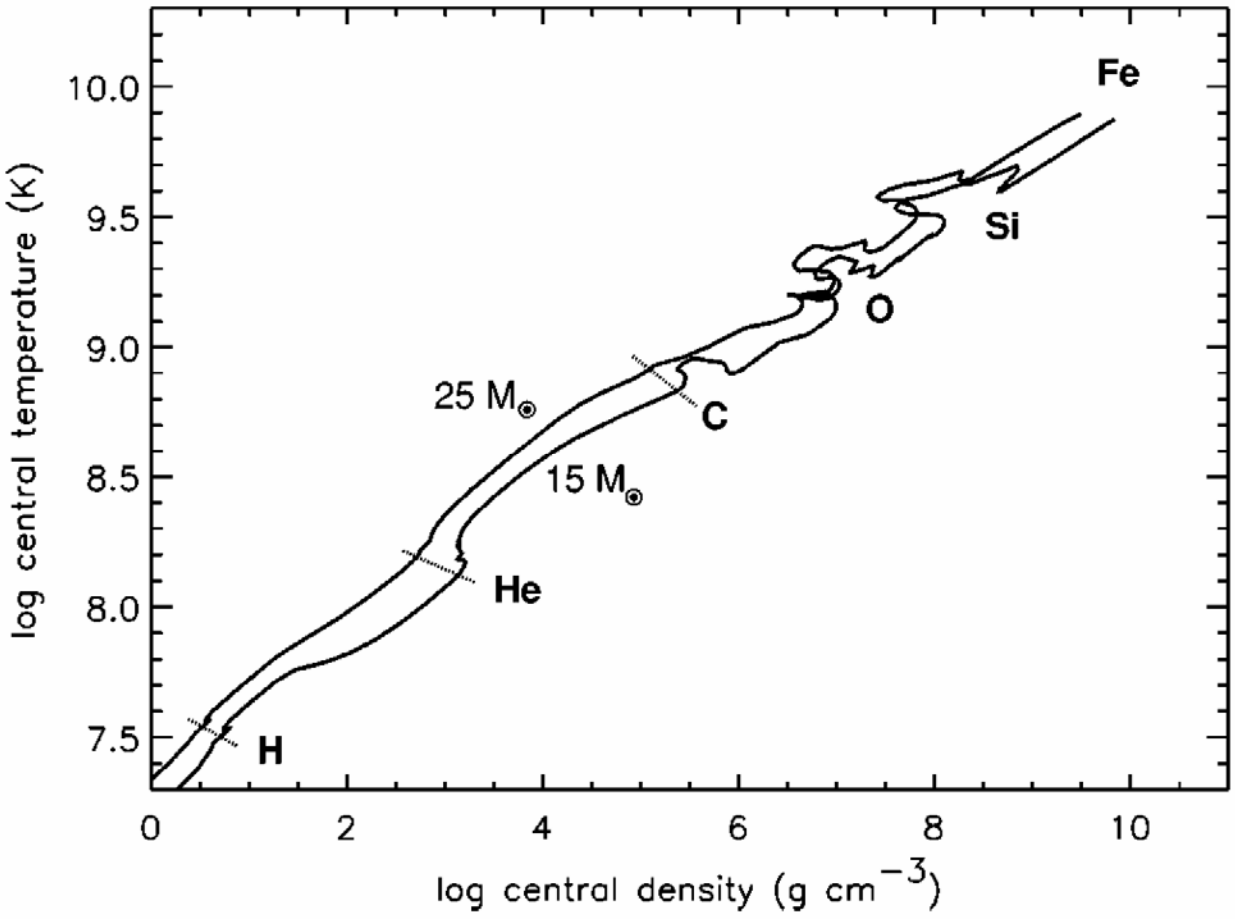
Core evolution of a Massive Star



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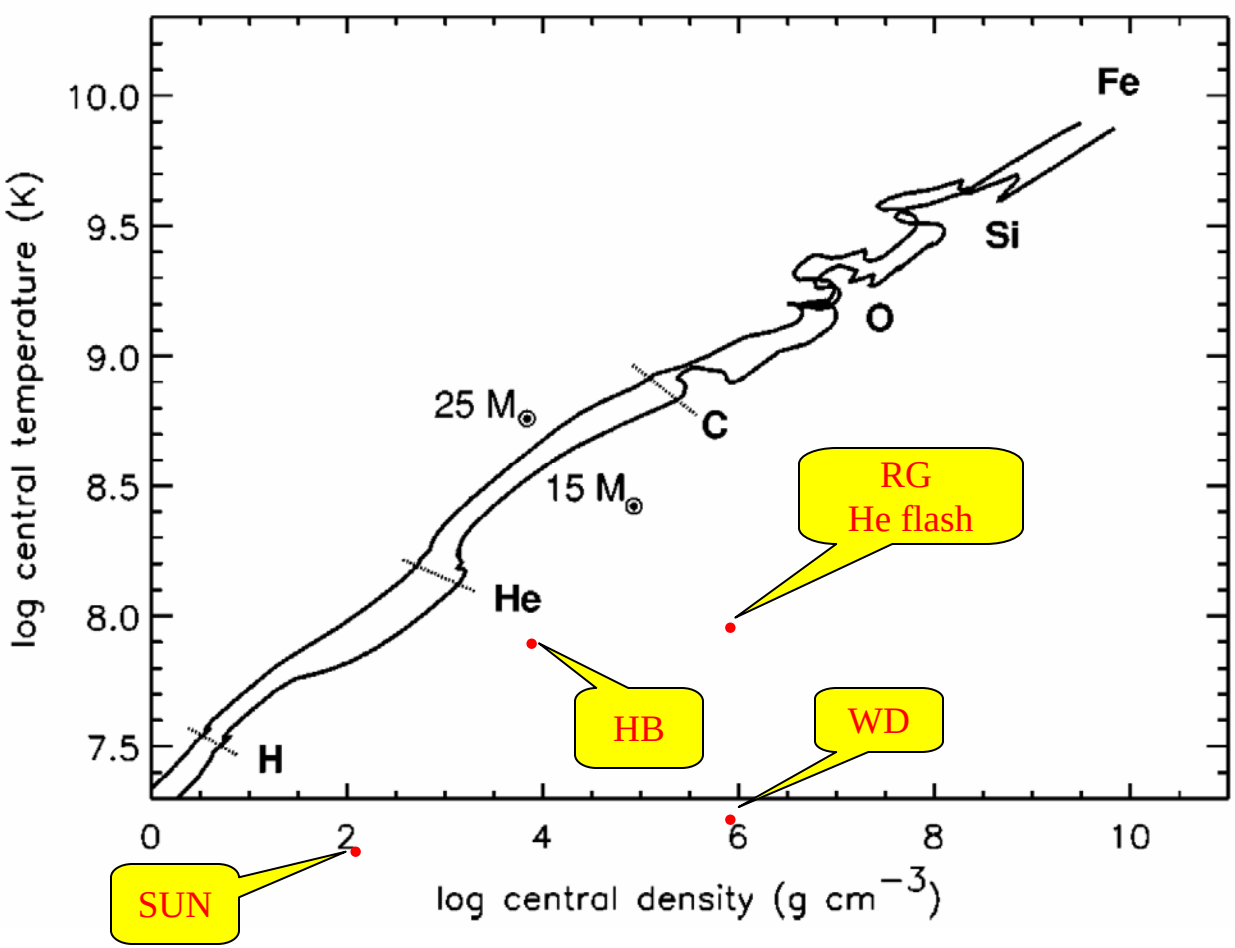

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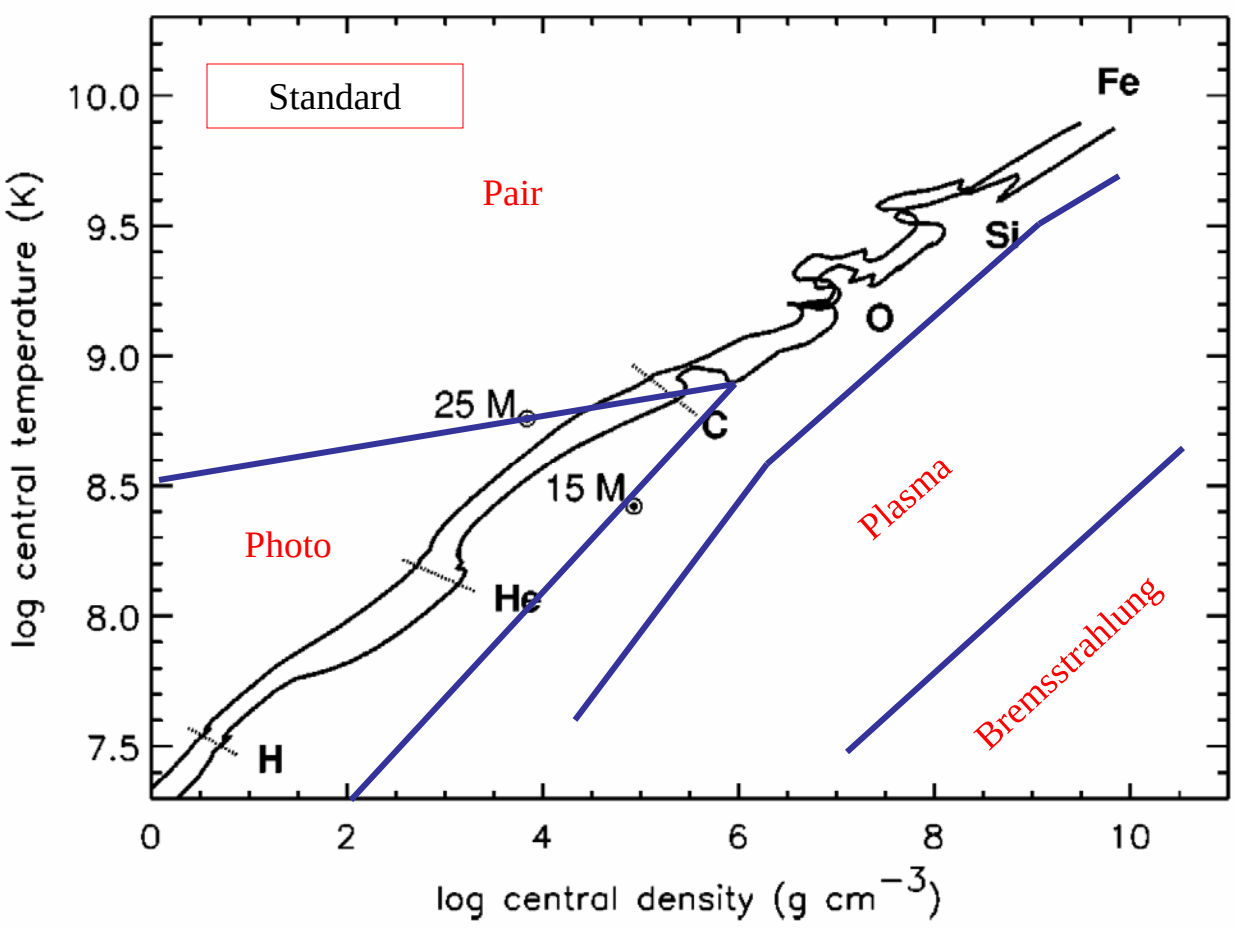
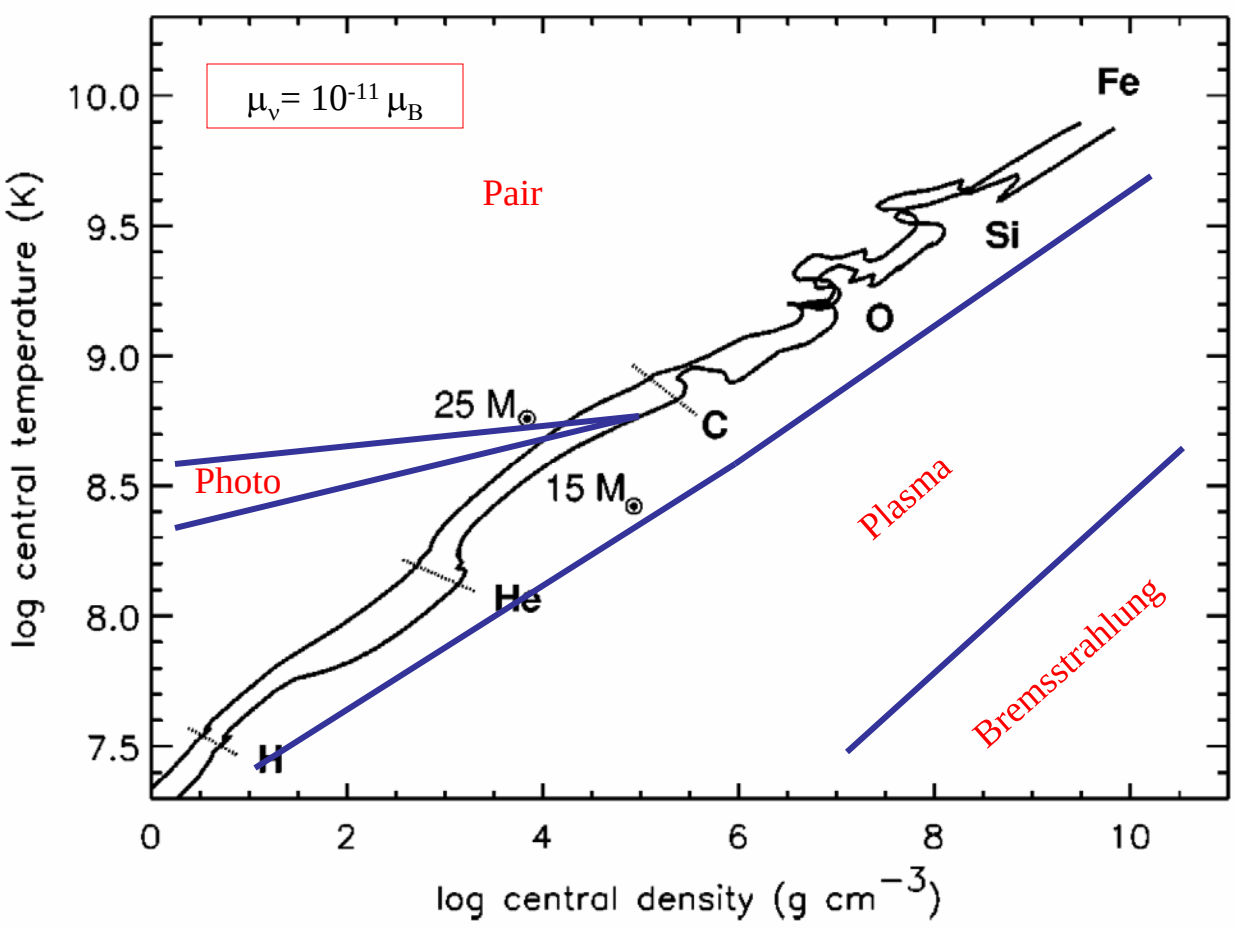


From Woosley, Heger, Weaver, ReV Mod Phys, 74, 1015 (2002)

Massive Stars sensitivity to magnetic dipole moment



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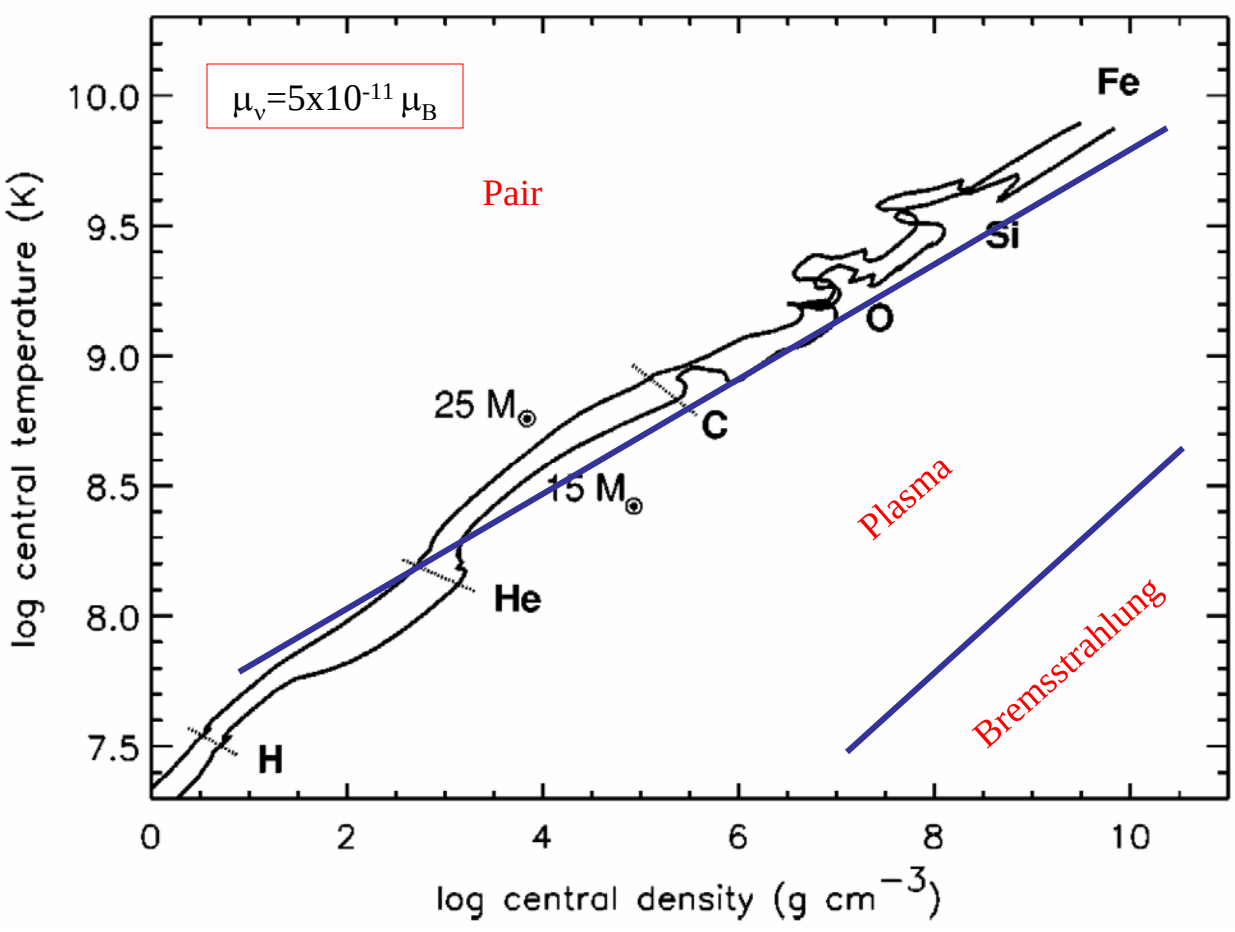

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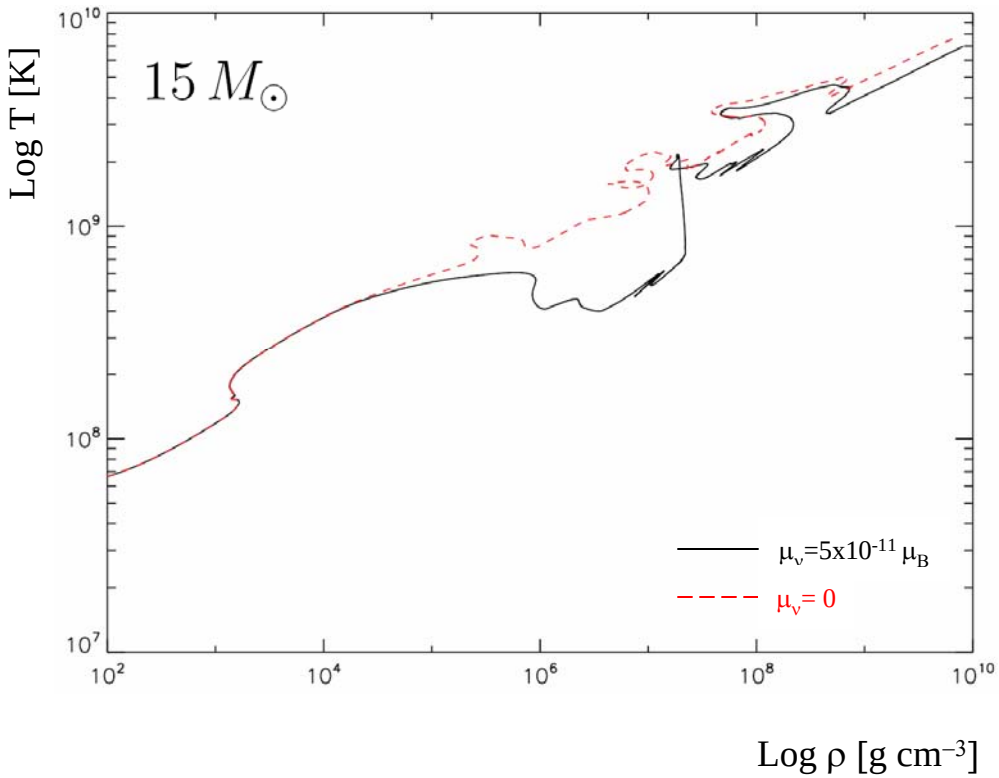
Massive Stars sensitivity to magnetic dipole moment

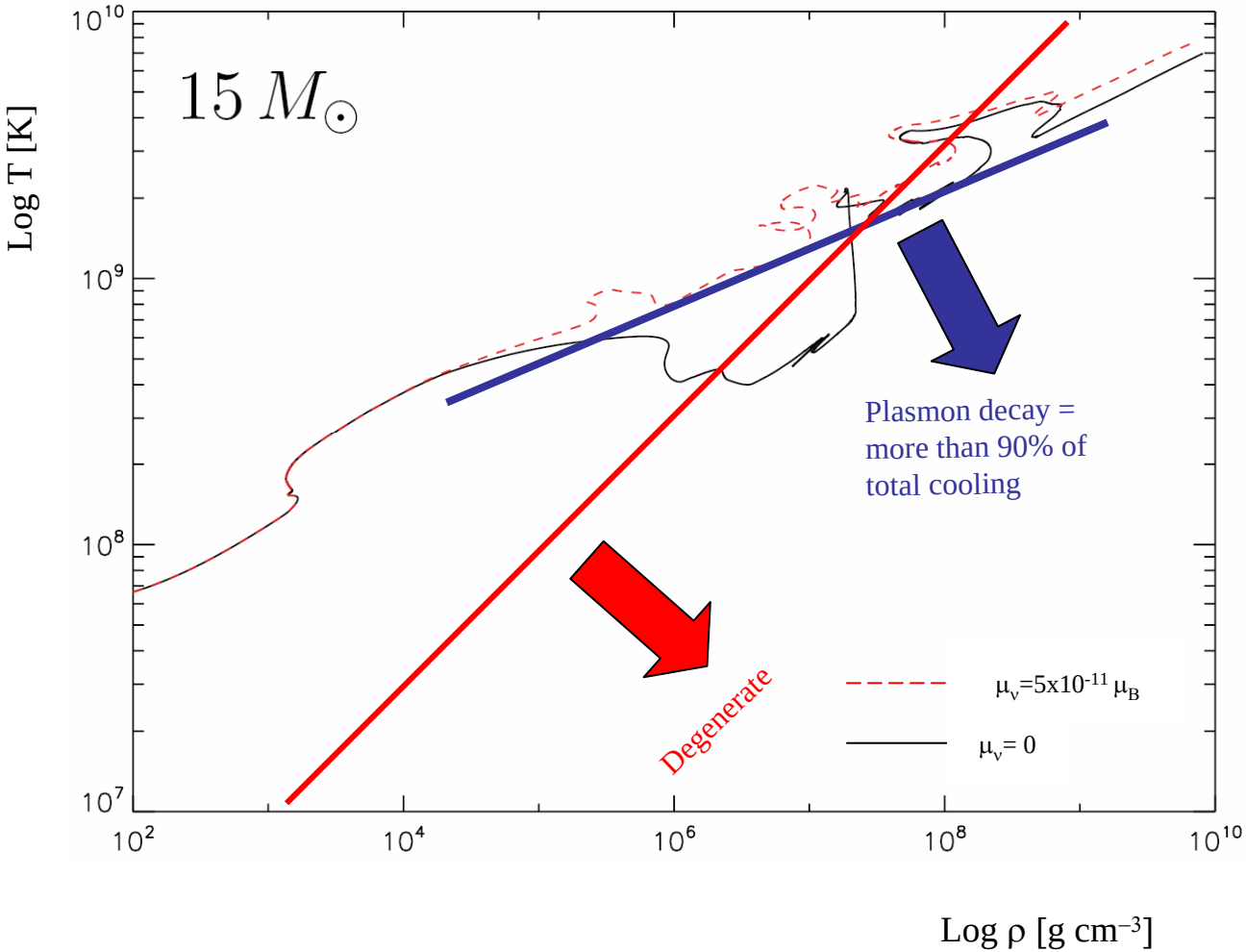
Evolution of central temperature and density



The 15 M_O star is sensitive to values of the magnetic moment below the experimental bound

Massive Stars sensitivity to magnetic dipole moment

Evolution of central temperature and density

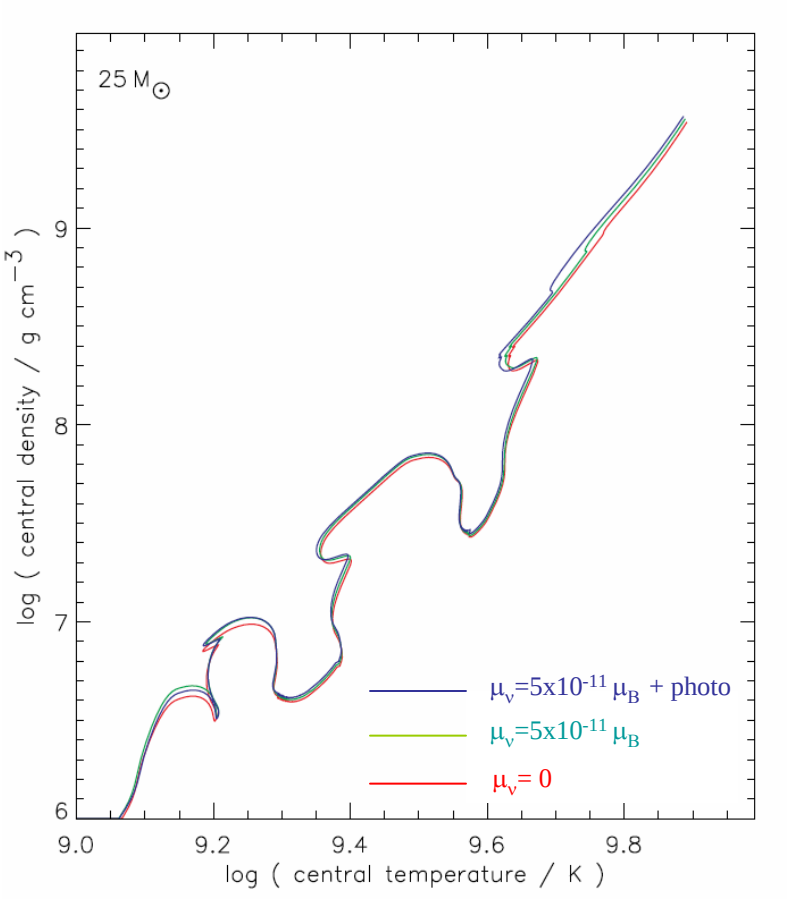


Plasmon becomes important after He burning. If μ_ν is big enough, the cooling becomes so strong that the star plasma becomes degenerate.

This phenomena is observed for stars of mass less than ~17 M_O when μ_ν=5x10^{-11} μ_B

In this case, the core is so "cold" that the ignition happens off-center. If the mass is above 12 M_O, the ignition moves to the center.
In the plot, we see this fact by a discontinuous change of temperature when the burning reaches the center.

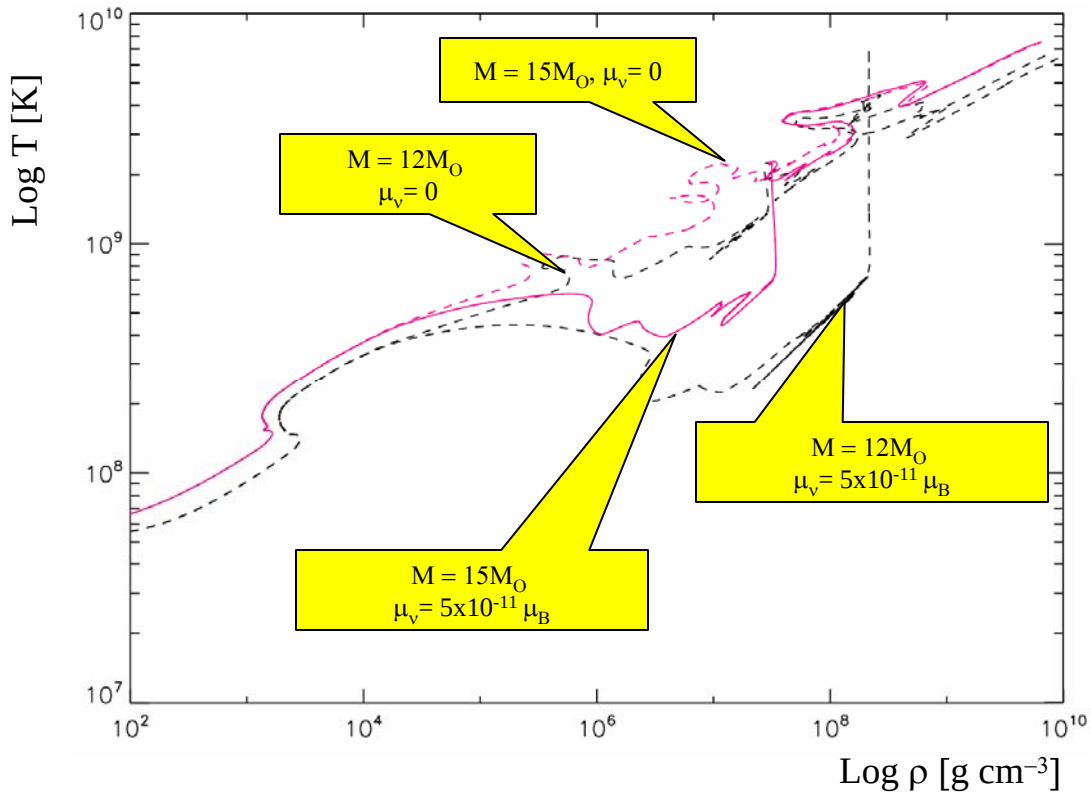
Massive Stars sensitivity to magnetic dipole moment



The 25 M_O star is not sensitive to values of the magnetic moment up to the experimental bound

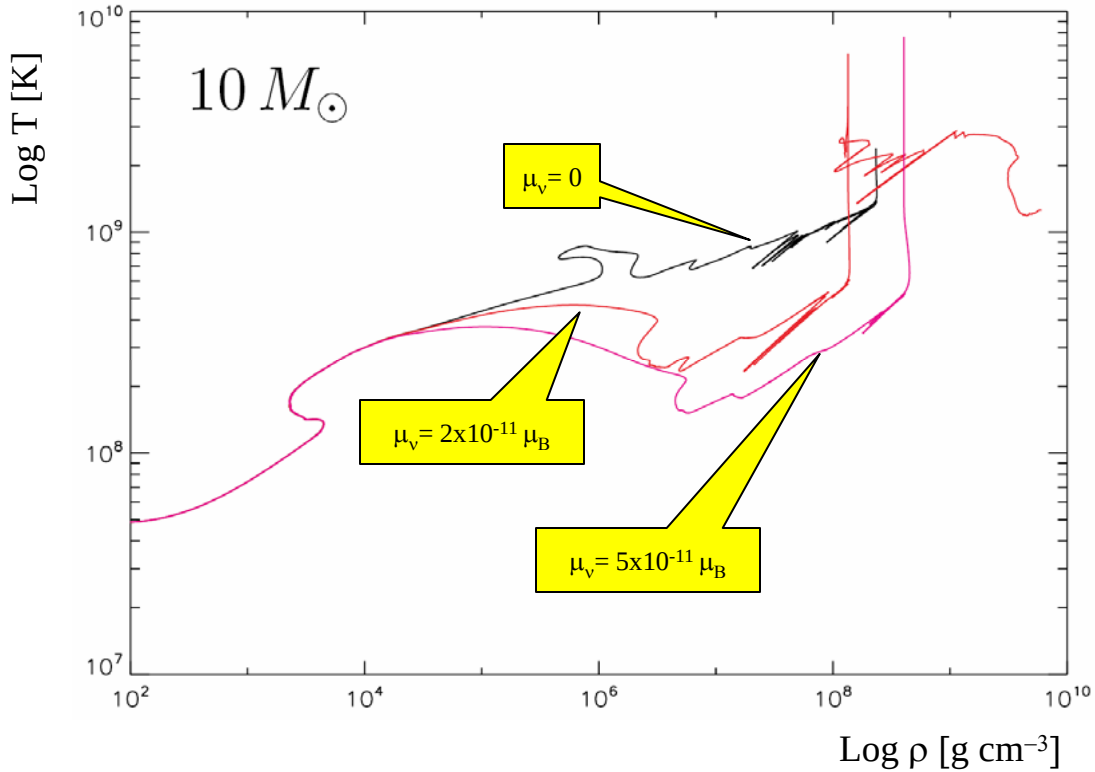
Massive Stars sensitivity to magnetic dipole moment

Evolution of central temperature and density

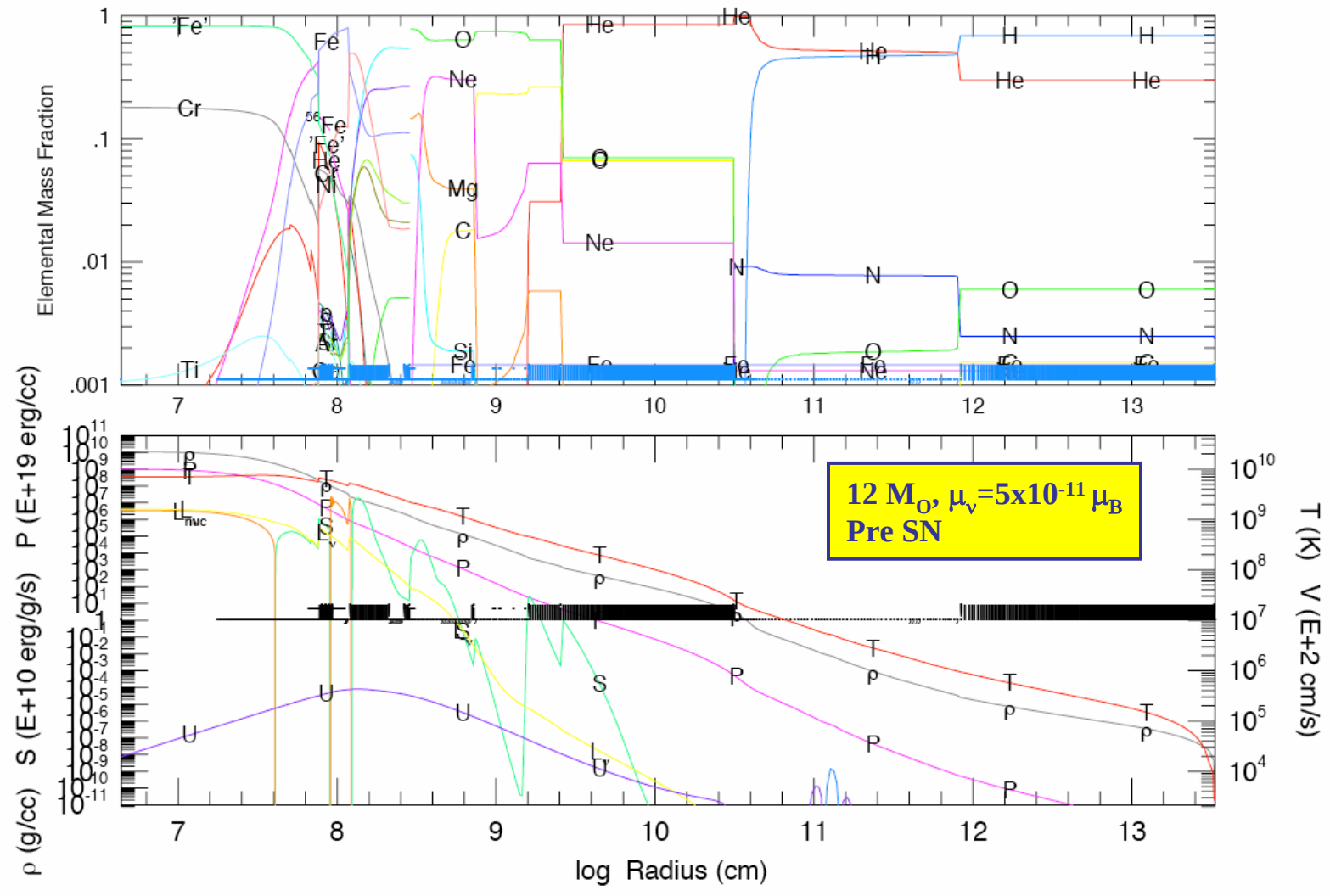


Massive Stars sensitivity to magnetic dipole moment

Evolution of central temperature and density



Massive Stars sensitivity to magnetic dipole moment



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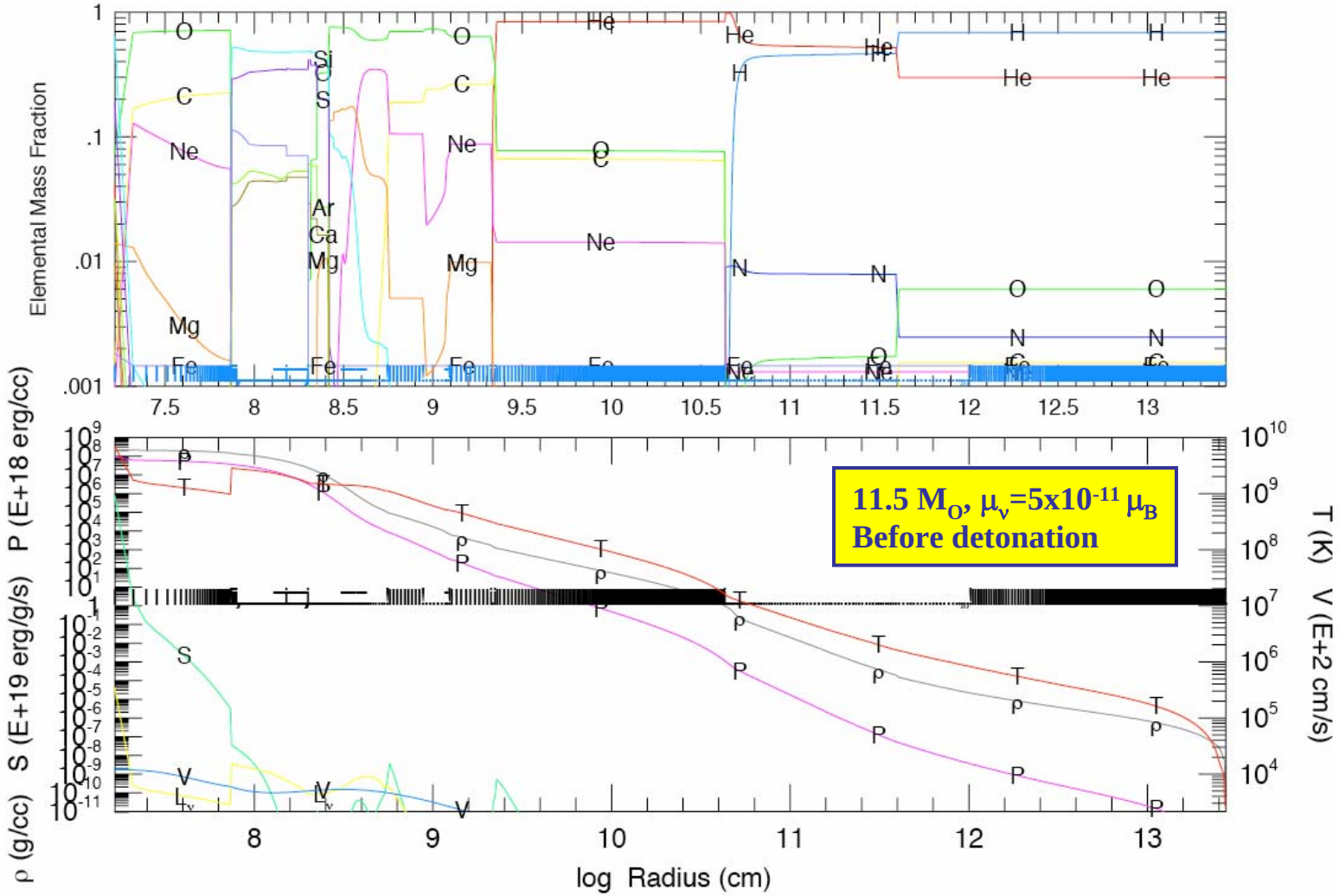

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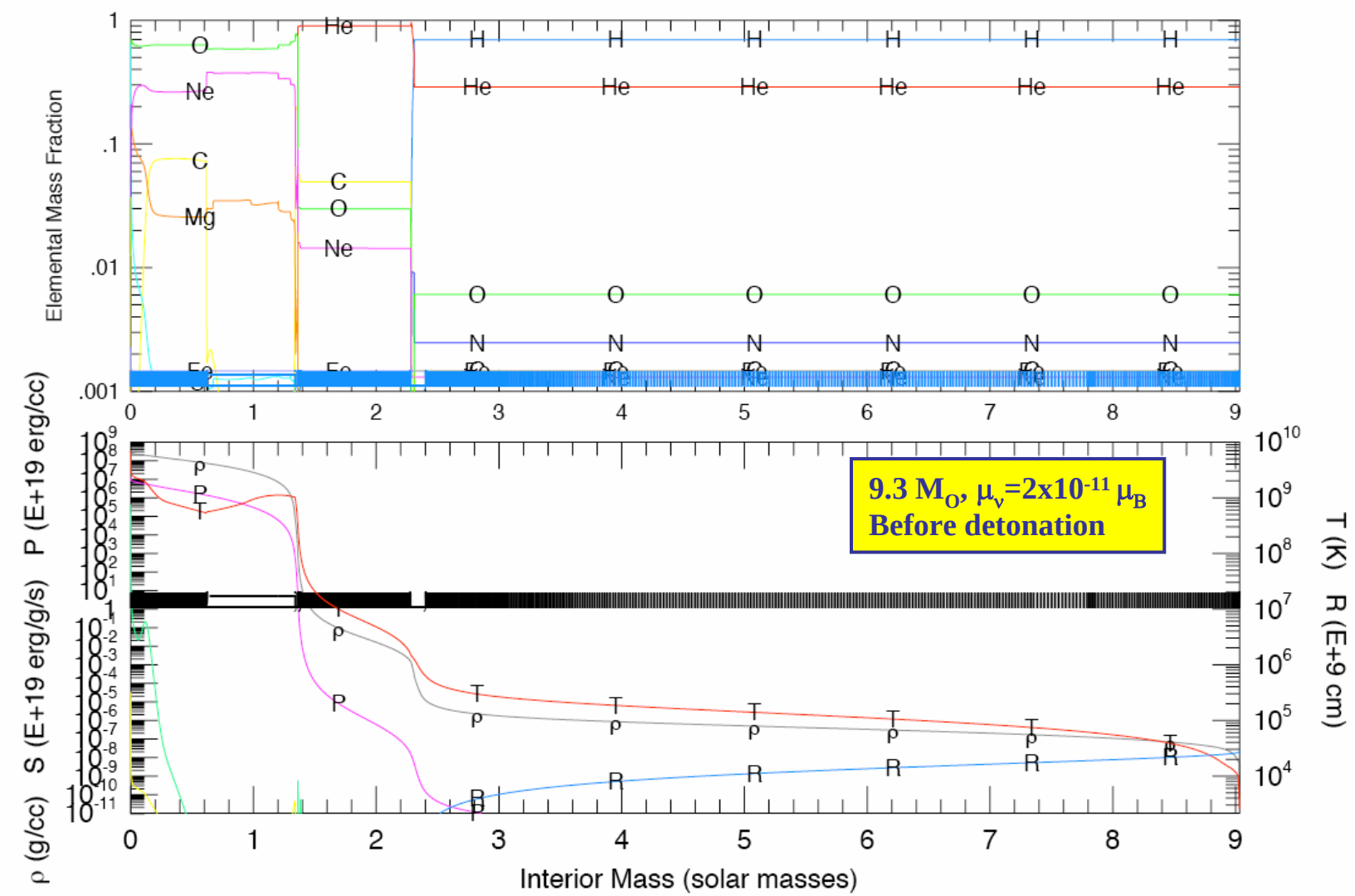

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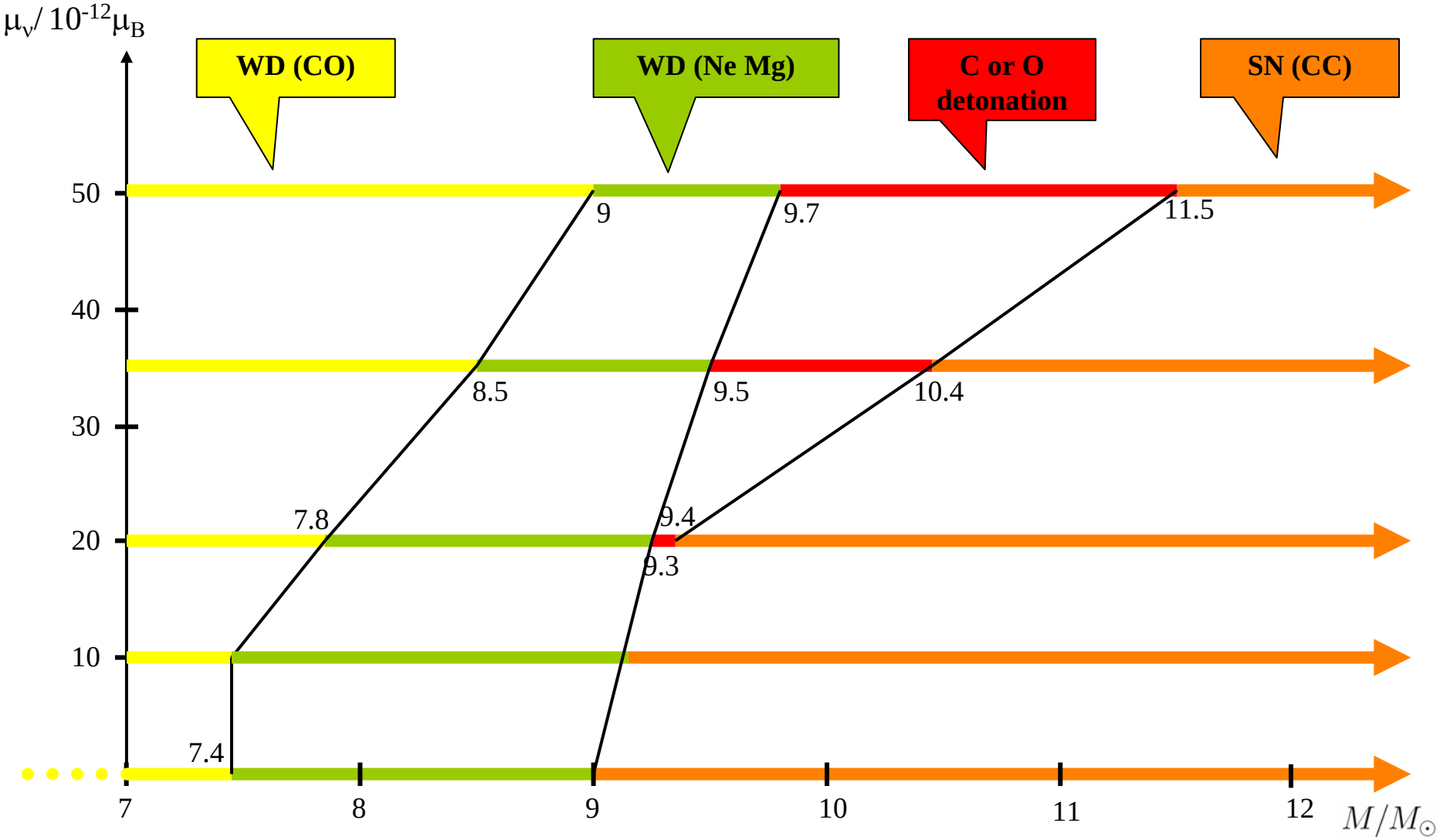
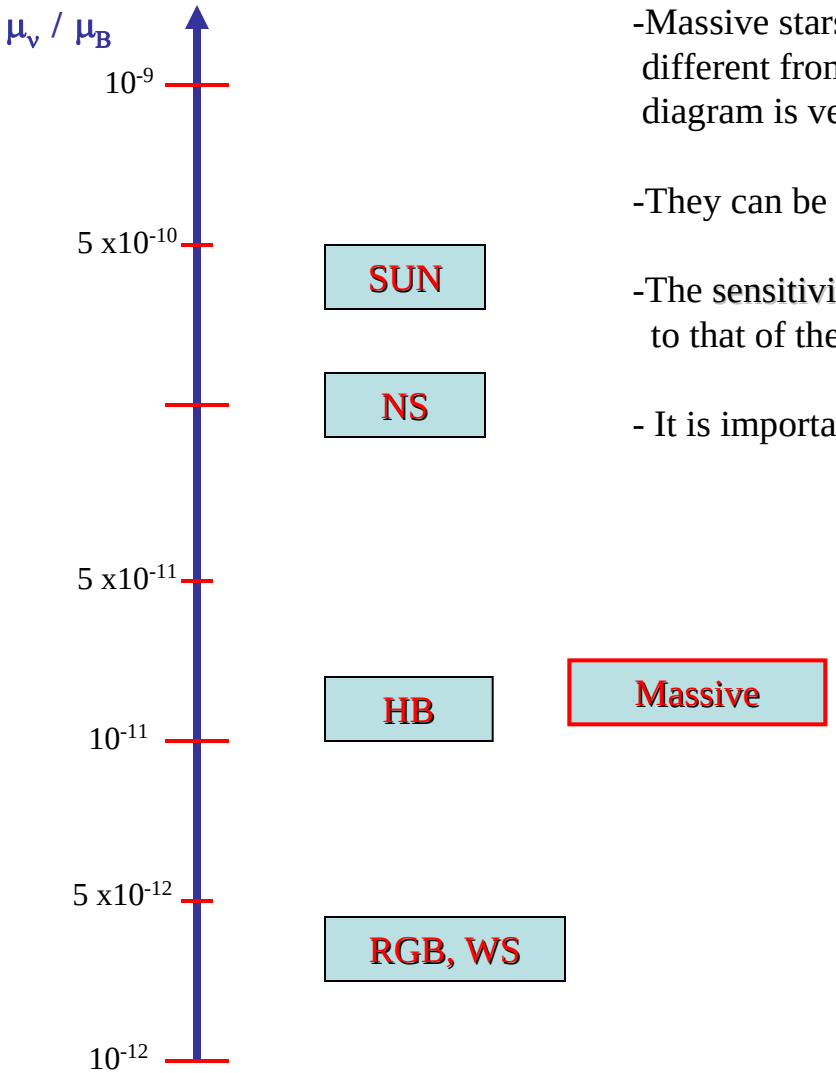


Summary and Conclusions



-Massive stars are "laboratories for fundamental physics" substantially different from the light stars. Their evolution in the density-temperature diagram is very peculiar

-They can be considerably sensitive to physics beyond the standard model.

-The sensitivity of massive stars to the neutrino dipole moment is comparable to that of the HB stars

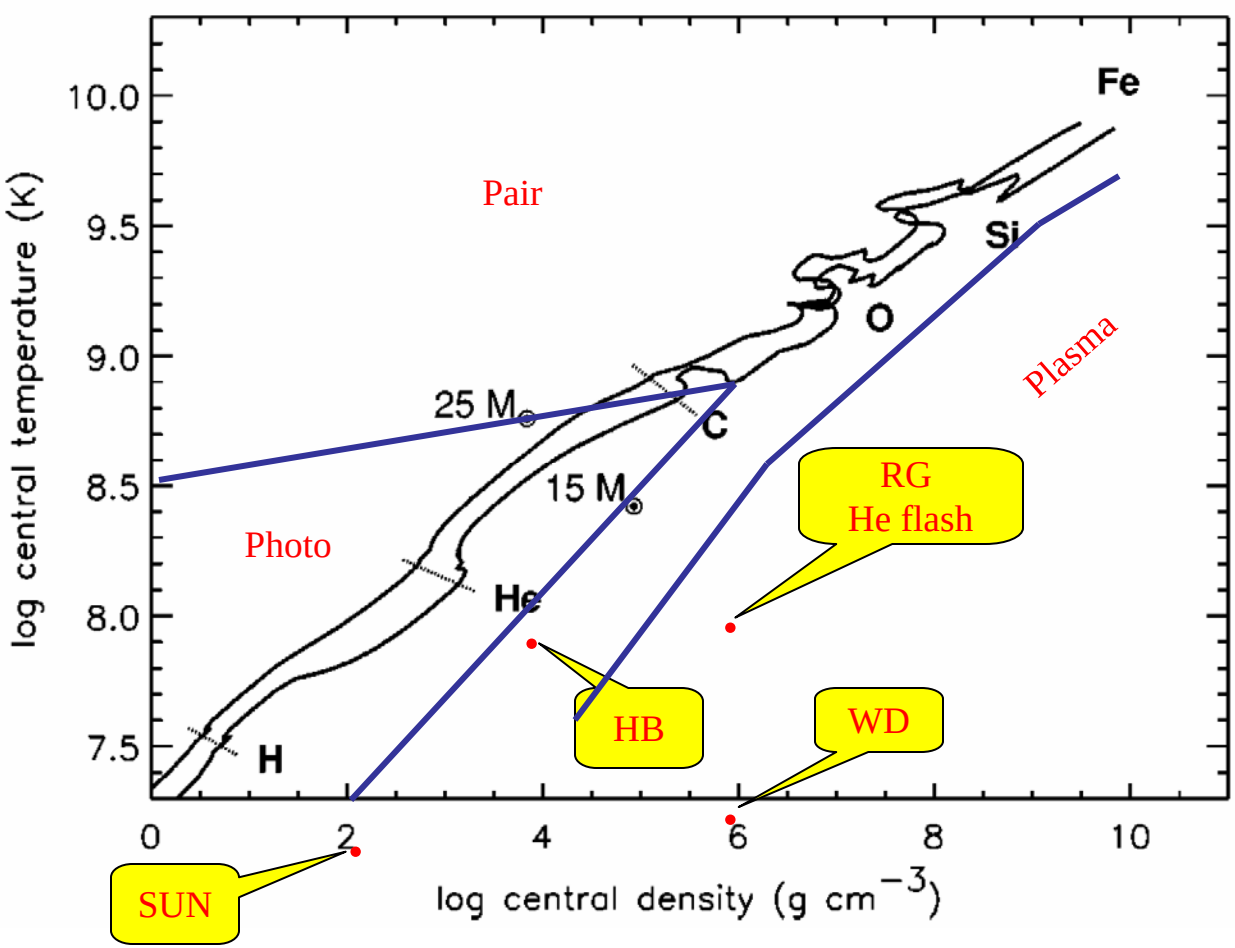
- It is important to understand the observations

Stars sensitivity to μ_ν

RGB	$\mu_\nu \sim 3 \times 10^{-12}\ \mu_B$
WD	$\mu_\nu \sim 3 \times 10^{-12}\ \mu_B$
HB	$\mu_\nu \sim 15 \times 10^{-12}\ \mu_B$
Massive	$\mu_\nu \sim 20 \times 10^{-12}\ \mu_B$
NS	$\mu_\nu \sim 100 \times 10^{-12}\ \mu_B$
SUN	$\mu_\nu \sim 400 \times 10^{-12}\ \mu_B$

Perspectives

Core evolution of a Massive Star



From Woosley, Heger, Weaver, ReV Mod Phys, 74, 1015 (2002)

Perspectives

- **Nucleosynthesis**

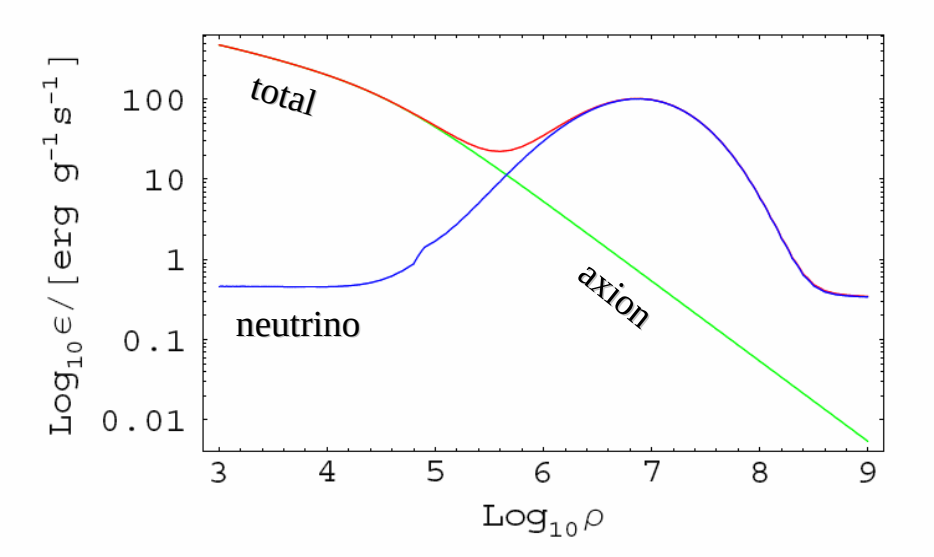
-Charged neutrinos

$Q/Q_{SM} \sim 1/\rho^4$ whereas for the magnetic moment $Q/Q_{SM} \sim 1/\rho^2$
=> The bound on neutrino charge is similar in RG, HB and SUN

-Extra dim

disappearing matter into extra dimension: **$e^+ e^- \rightarrow \gamma \rightarrow$ extradim** is very poorly constrained in low mass stars

- Axion



Energy loss due to
standard neutrino (blue),
axion emission for $g_{a\gamma}=10^{-10}$ GeV^{-1}(green),
and **total** (red), for $T=10^8$K.

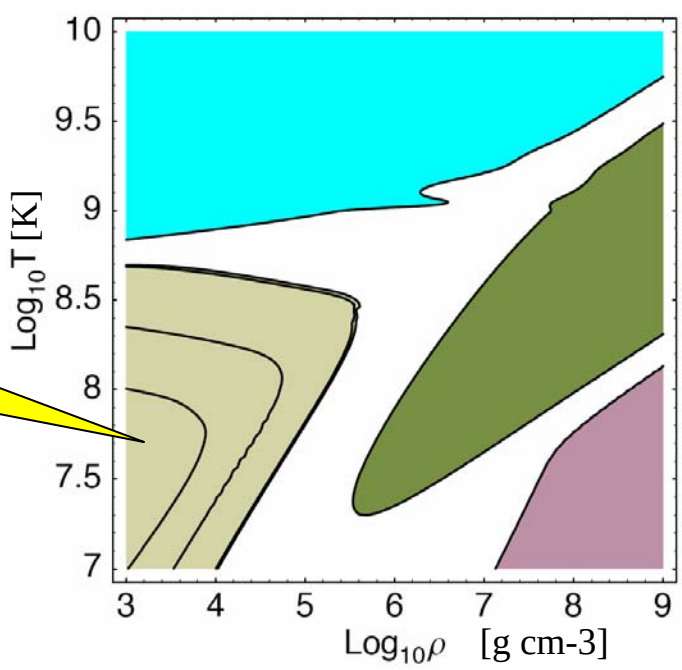
Production through Primakoff process
$\gamma \rightarrow a$

- The axion emission dominated at low densities.
- The axion emission is not strongly suppressed at high mass.

Perspectives

- Axion

Axion cooling
10, 100 1nd 1000
bigger than the
standard neutrino emission



Final Comment

Massive stars seem to be more interesting

for particle physics

than we thought!