



# Constraints on New Physics from Stellar Cooling

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**In collaboration with**  
**V.Cirigliano, A.Friedland, A. Heger, L. Duffy**

# Outline

- Introduction:
  - \* Stars and the standard model
  - \* Stars and physics beyond the standard model
- Some Examples:
  - \* Axion
  - \* Stars and Extra-Dimensions (with [A.Friedland](#) )
- **Massive stars and physics beyond the standard model**  
(with [V.Cirigliano](#), [A.Friedland](#), [A.Heger](#), [L.Duffy](#))
- Massive stars and neutrino magnetic moment
  - \* 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?
  - \* What are the observational effects?
- Conclusions and perspectives

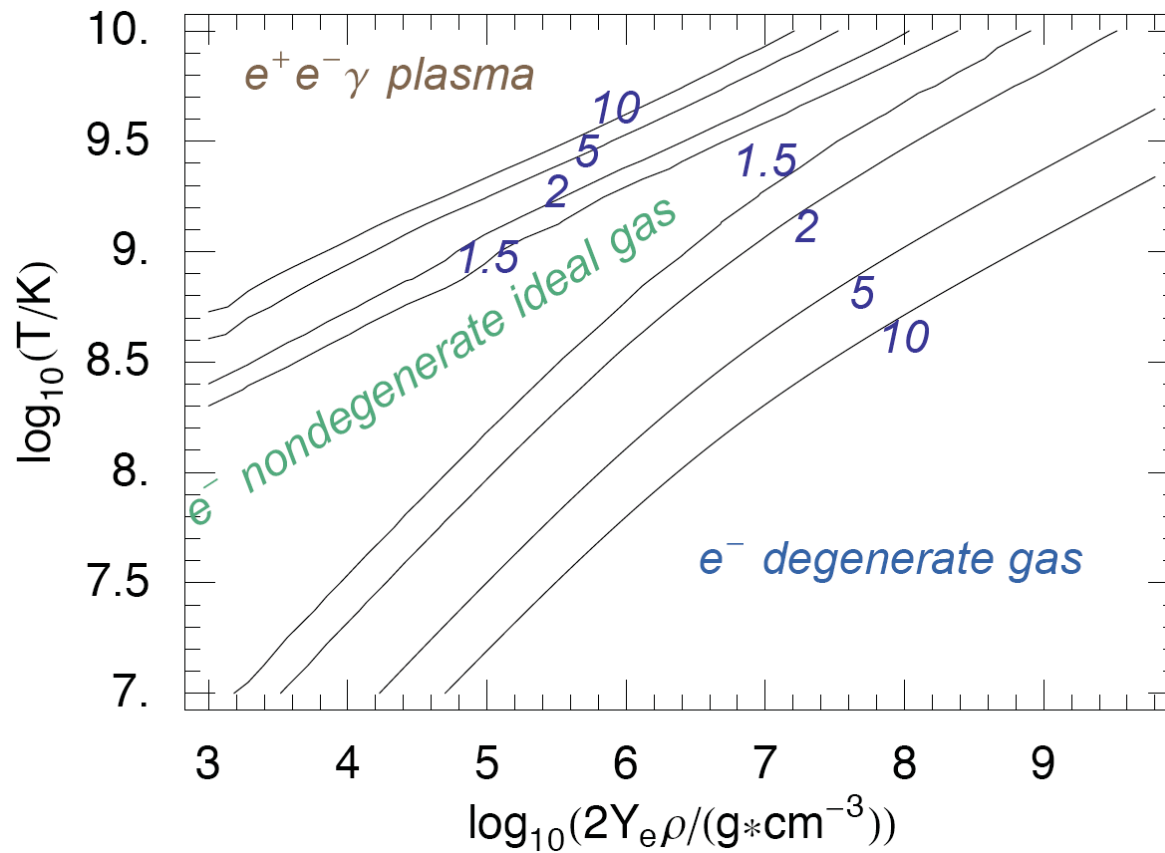
# Weak Interactions and Star Cooling

Role of weak interactions in stellar cooling.

Year	Reference	Results	Comments
1957	Feynman, Gell-Mann	V-A theory of weak interactions	
1964	W. Fowler, F. Hoyle	Neutrino pair production	$\frac{e^+ + e^- \rightarrow \nu \bar{\nu}}{e^+ + e^- \rightarrow \gamma \gamma} \simeq 10^{-19}$ Impossible to detect in terrestrial experiments
1964	Inman, Ruderman	Plasmon decay	$\gamma \rightarrow \nu \bar{\nu}$ Possible only in a sufficiently dense plasma
1967	Petrosian, Beaudet, Salpeter	Photoneutrino process	$\gamma + e \rightarrow e + \nu \bar{\nu}$
1967	Petrosian, Beaudet, Salpeter	Thorough discussion of neutrino role in stellar cooling.	Discussed all the main neutrino production mechanism and also Bremsstrahlung $e^-(Ze) \rightarrow (Ze)e^- \nu \bar{\nu}$
1972	Dicus	Weinberg-Salam model and star cooling	

Already in 1963 **Bernstein, Ruderman and Feinberg** studied the effects of electromagnetic properties of neutrinos for the cooling of the sun. Their bound on the neutrino magnetic moment was better than the experimental bound at that time.

# The Plasma inside a Star

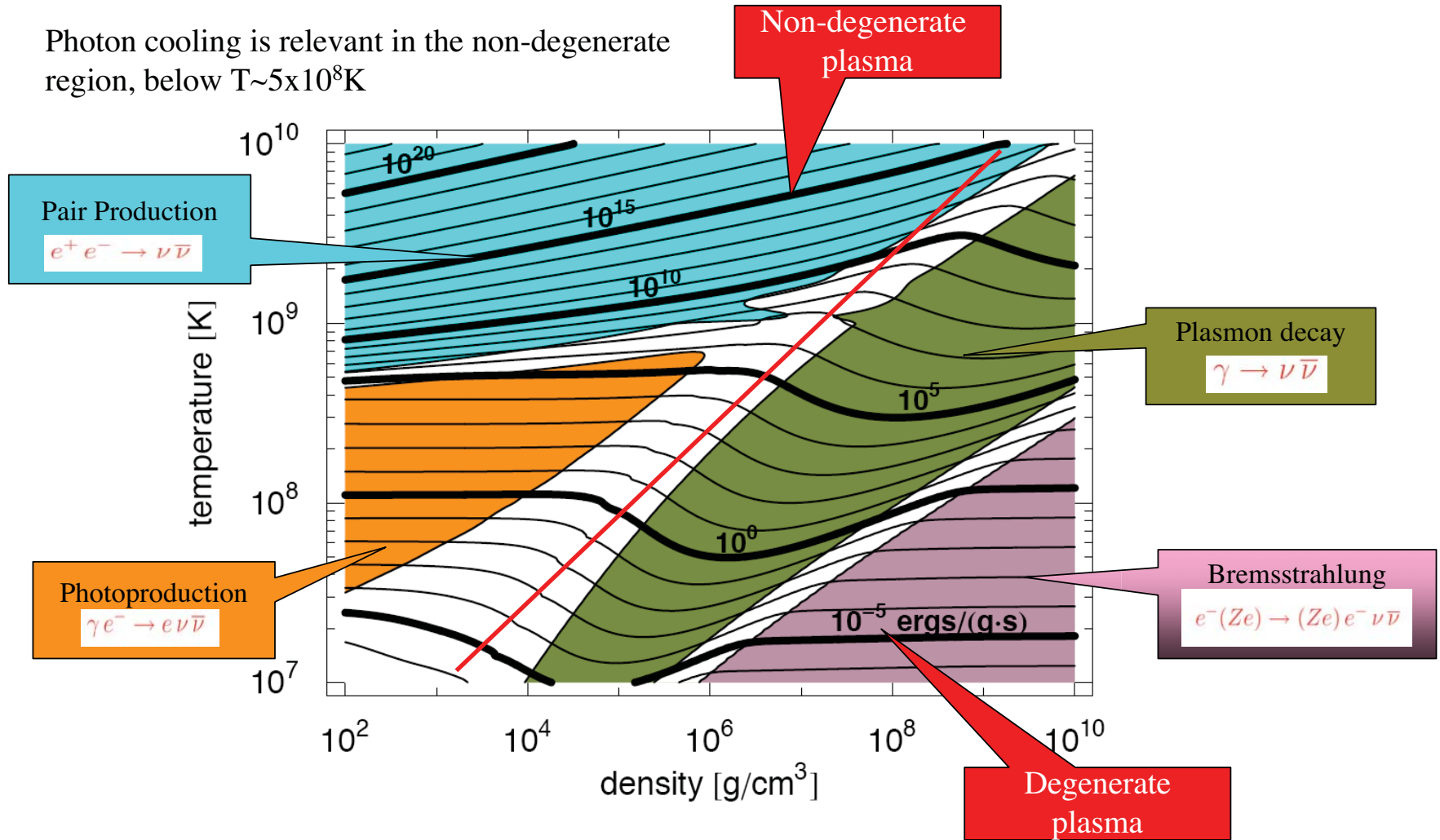


From A.Heger, A.Friedland, M.G., V.Cirigliano APJ:696 (2009)

# Neutrino Cooling in Stars

**Standard Cooling:** photons and neutrinos

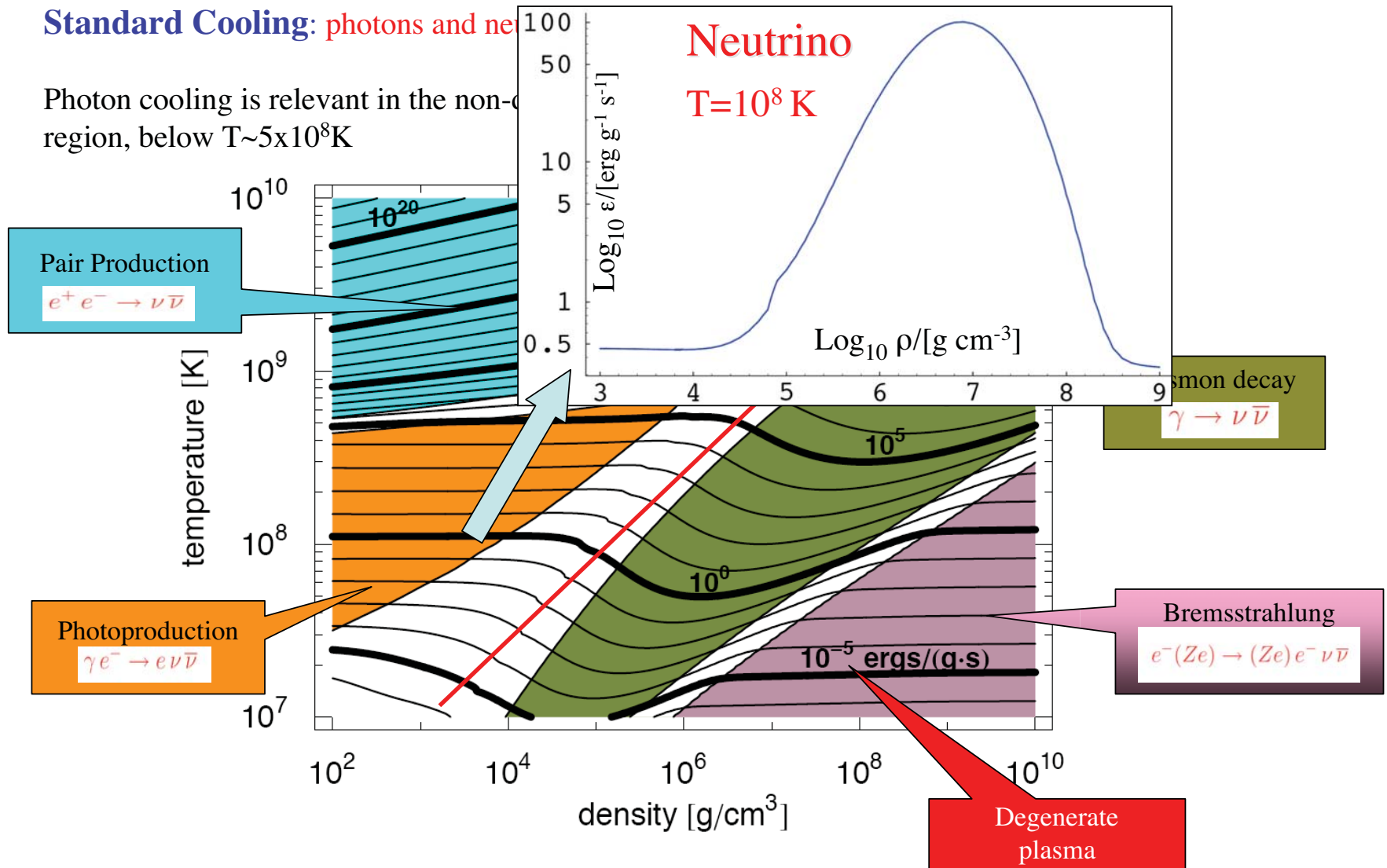
Photon cooling is relevant in the non-degenerate region, below  $T \sim 5 \times 10^8 \text{K}$



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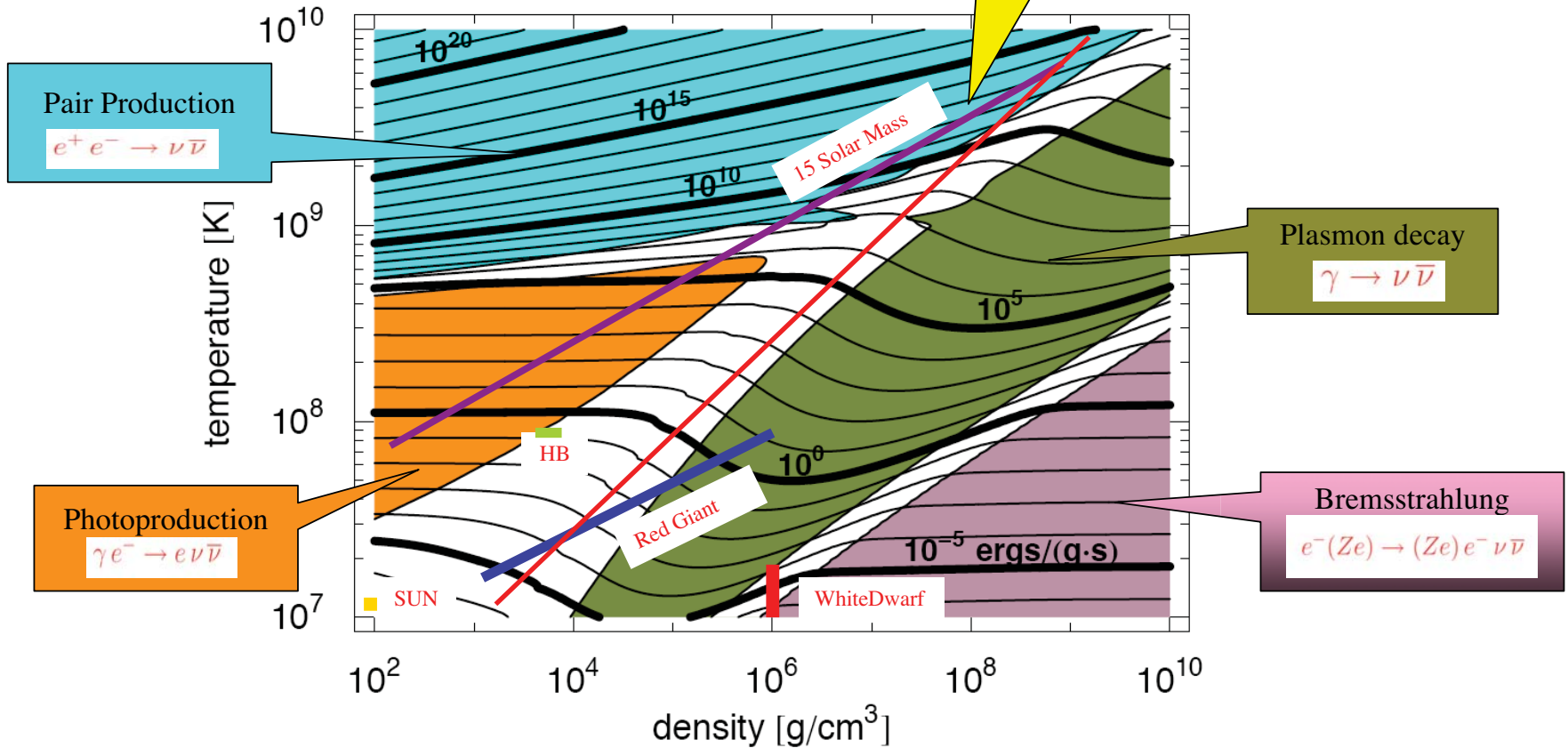


# Neutrino Cooling in Stars

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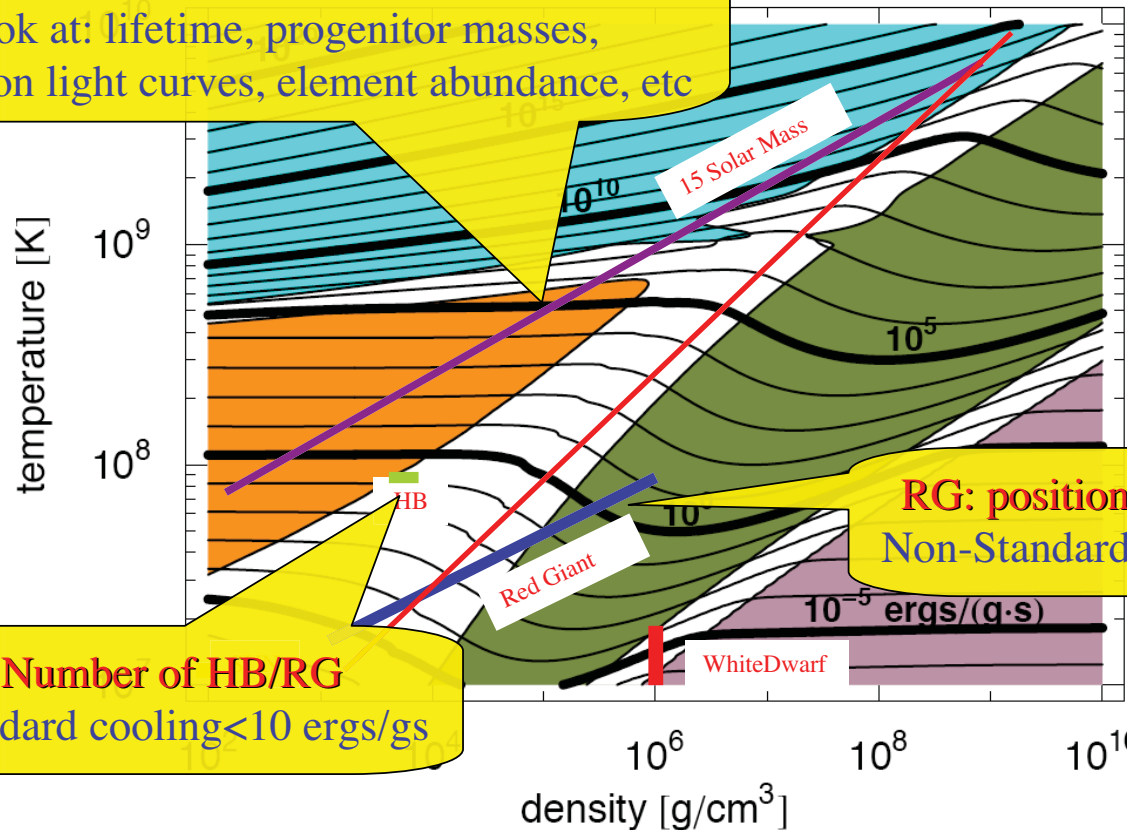
**Massive Stars**  
 $T \sim M^{2/3} \rho^{1/3}$



# Neutrino Cooling in Stars

**Standard Cooling:** photons and neutrinos

**Massive Stars**  
 Difficult observations and no simple criteria  
 Look at: lifetime, progenitor masses,  
 explosion light curves, element abundance, etc



**RG:** position of the He-flash tip  
 Non-Standard cooling < 30 ergs/g

**HB:** Number of HB/RG  
 Non-Standard cooling < 10 ergs/g

# Examples: Why should we be interested in Stars

\* **Neutrino magnetic moment**

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

Stars give a better bound  
**~ 1 order of magnitude**

---

\* **Axion**

Couplings inverse  
prop to a mass scale

Stars give a better bound  
**~ 5 orders of magnitude**  
(Excluding CAST)

---

\* **RS2 Extended Models  
which predict photon  
disappearing**

Escape probability  
proportional to extradim  
length to some power

Stars give a better bound  
**~ 6 orders of magnitude**

A. Friedland, M. Giannotti  
**Phys.Rev.Lett.100 (2008).**

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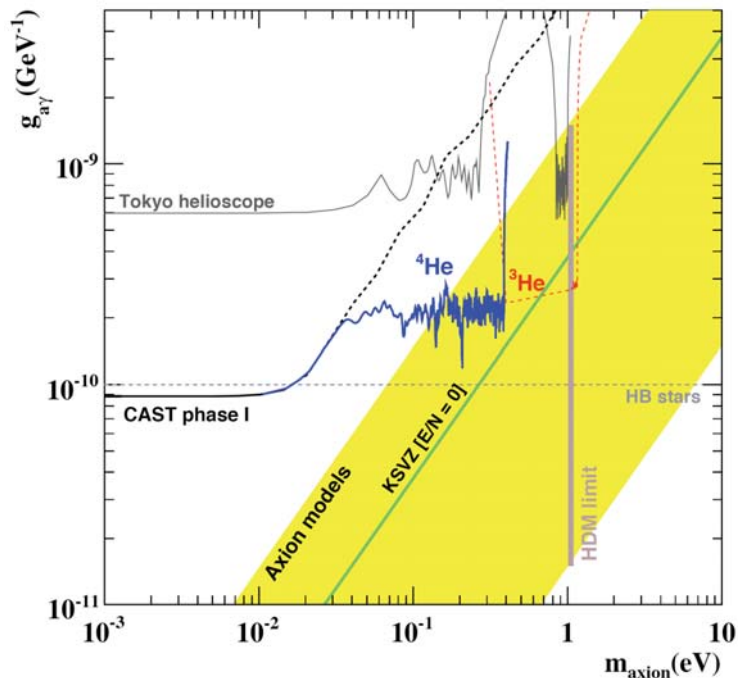
\* **Many other examples**

Mirror World scenario,  
Millicharged particles, etc.

# Some Clarifications about Axions

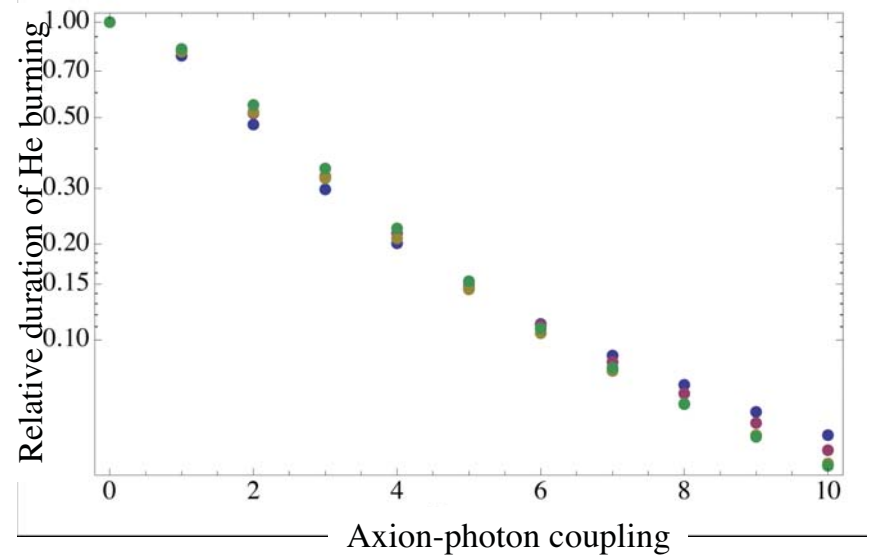
## Axion-Photon coupling: Terrestrial (CAST) versus Stars

CAST is reaching  
the stellar bound



CAST collaboration, *Journal of Cosmology and Astroparticle Physics*, 02, 008, 2009

Stars of different masses have the  
same sensitivity to  $a\text{-}\gamma$  coupling:  
Here, effect of axion cooling for stars  
with masses in the range  $6\text{-}40 M_{\odot}$



L.Duffy, A.Friedland, M.G., A.Heger  
In preparation

## Neutrino Magnetic Moment

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

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  $\mu_\nu < 10^{-10} \mu_B$  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 require changes in the weak sector of the SM

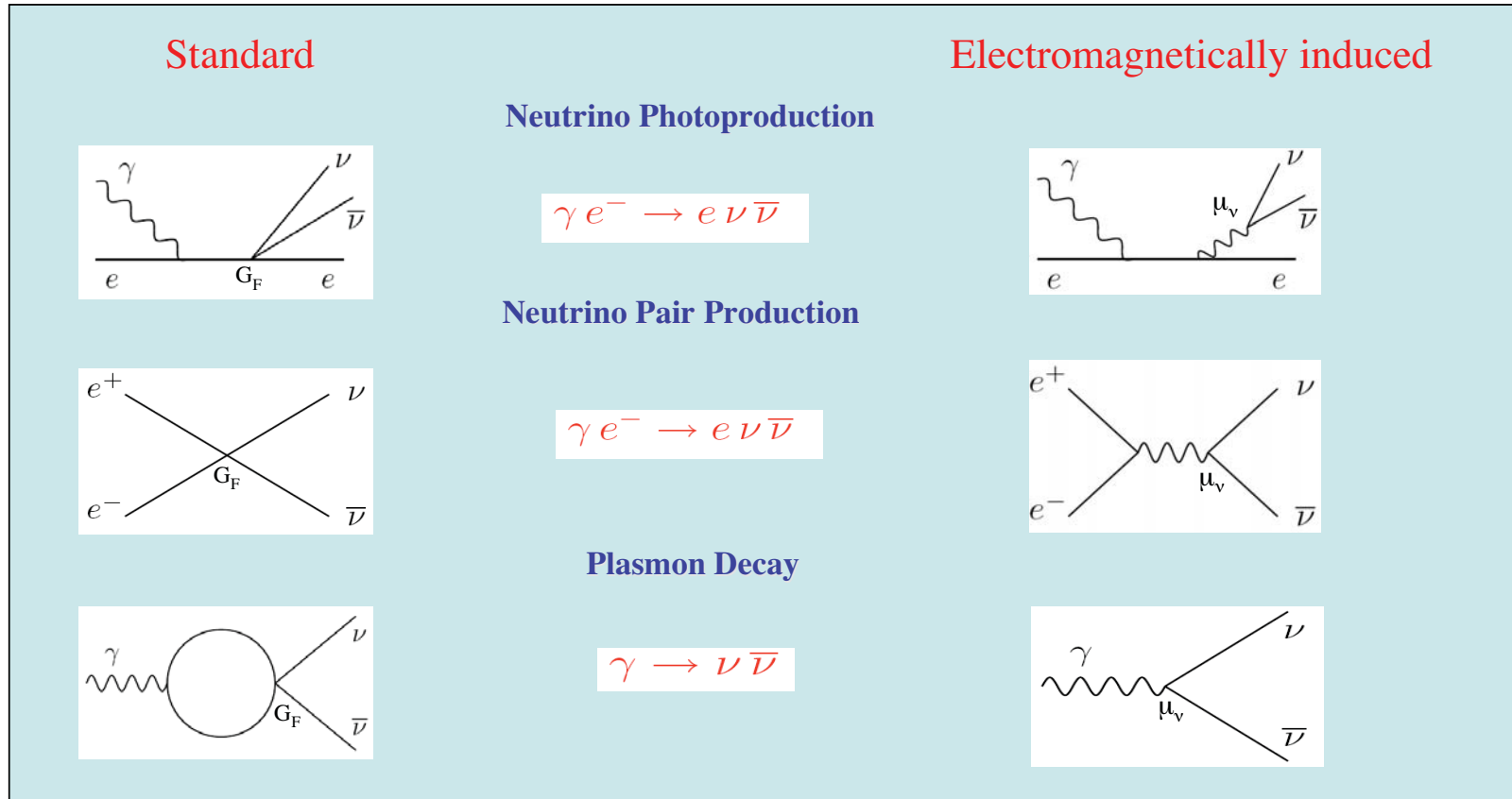
If  $10^{-15} \mu_B < \mu_\nu < 10^{-10} \mu_B$  is measured or inferred by astrophysical considerations, it would be a strong indication that neutrinos are Majorana fermions.

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 $\mu_\nu/\mu_B$	Comments	Reference
Experimental bound	$\sim 10^{-10}$	Electron neutrino scattering. A first experimental bound $\mu_\nu < 10^{-9}$ was deduced by <b>Cowan and Reines</b> (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) $< 0.58 \times 10^{-10}$  Similar bound from Borexino collaboration
Sun	$\sim 4 \times 10^{-10}$	Plasmon decay: Life time too short	J. Bernstein et al (1963)
Red Giants	$\sim 3 \times 10^{-12}$	Plasmon decay delay of the helium Flash. ( <b>White Dwarfs</b> 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)
Neutron Stars	$\sim 5 \times 10^{-7}$	$10^{-10}$ would lead to significant effects	Iwamoto et al (1995)
SN	$\sim 3 \times 10^{-12}$	From neutrino flip. Valid only for Dirac Neutrinos	R. Barbieri, R.N. Mohapatra (1988) A. Ayala et al (1998) A. Kuznetsov, N. Mikheev $< 10^{-12}$
SN and Magnetic field	$\sim 10^{-12}$	From neutrino double flip in the SN and in the galactic magnetic field. Valid for Dirac Neutrinos	R. Barbieri, R.N. Mohapatra (1988) D. Notzold (1988)
Cosmology	a few $\times 10^{-11}$	BBN	See, e.g., A. Dolgov Phys. Rep. 370 (2002)

# Neutrino Energy Loss: Testing Neutrinos magnetic moment

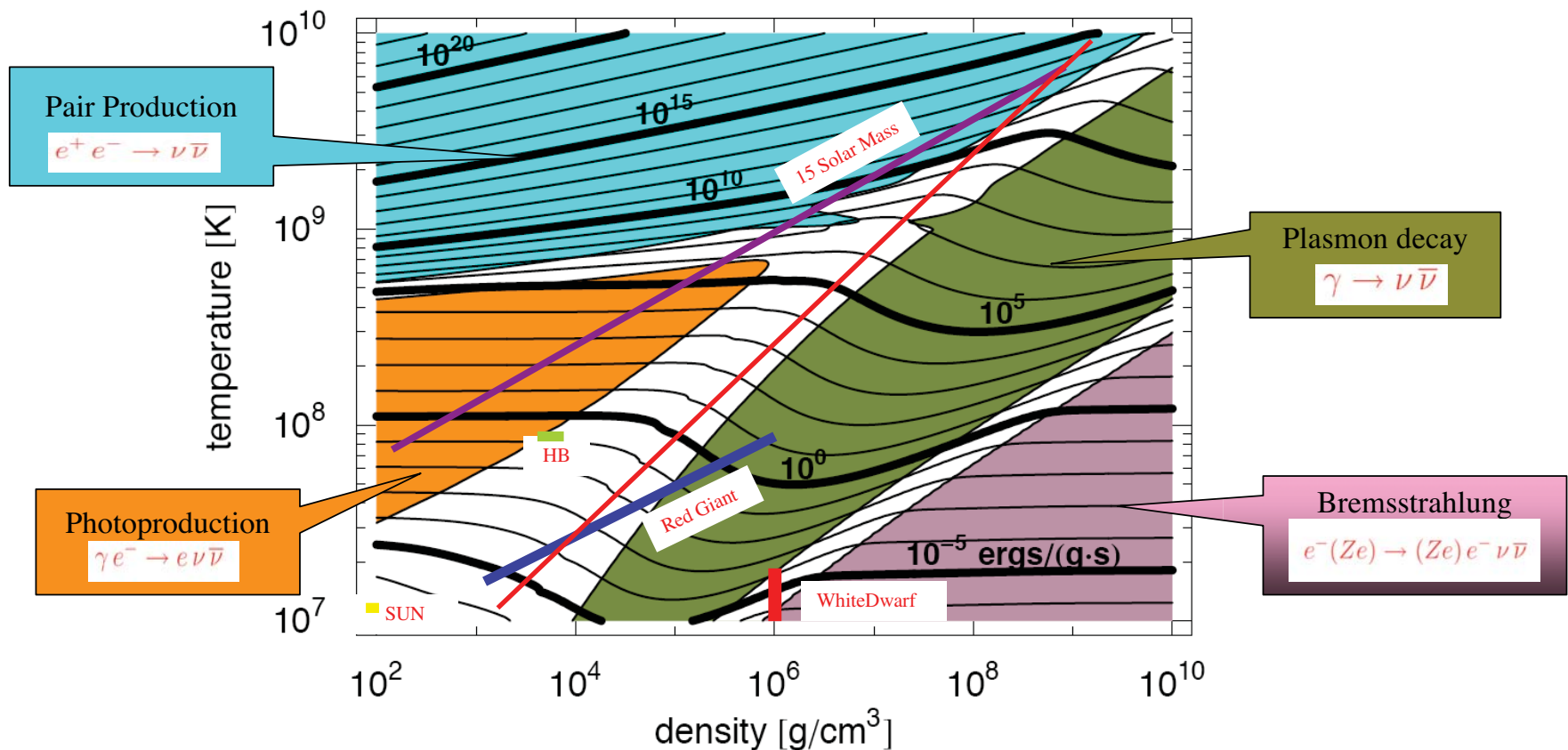


At low energies, for all the neutrino processes but the plasmon decay, the energy loss for the electromagnetic and weak induced processes are equal for  $\mu_\nu \sim 10^{-10} \mu_B$ , which is approximately the experimental bound.

In the case of plasmon decay there is a non-trivial dependence on the density

# Neutrino Magnetic Moment and Stars Cooling

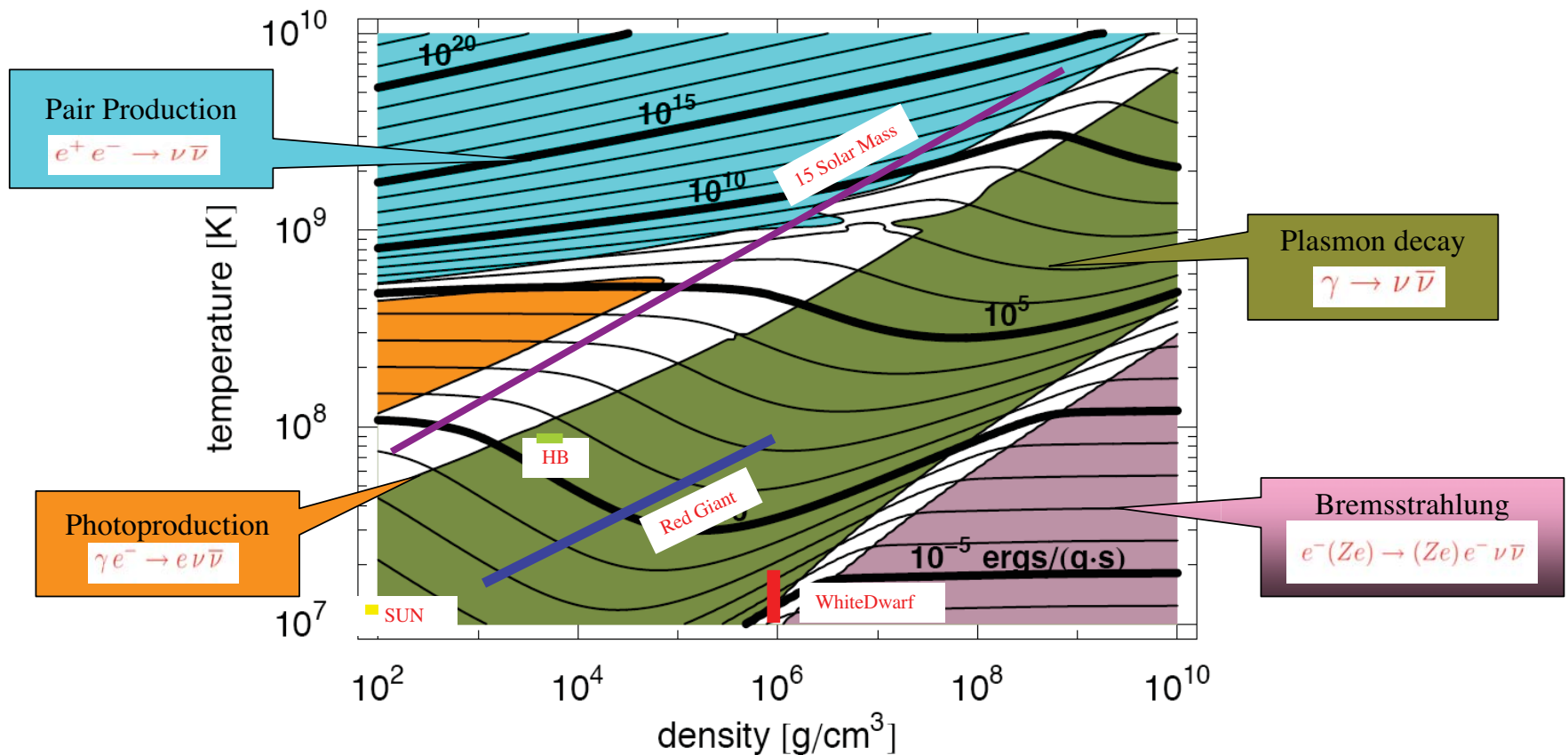
$$\mu_\nu = 0$$



From A.Heger, A.Friedland, M.G., V.Cirigliano APJ:696 (2009)

# Neutrino Magnetic Moment and Stars Cooling

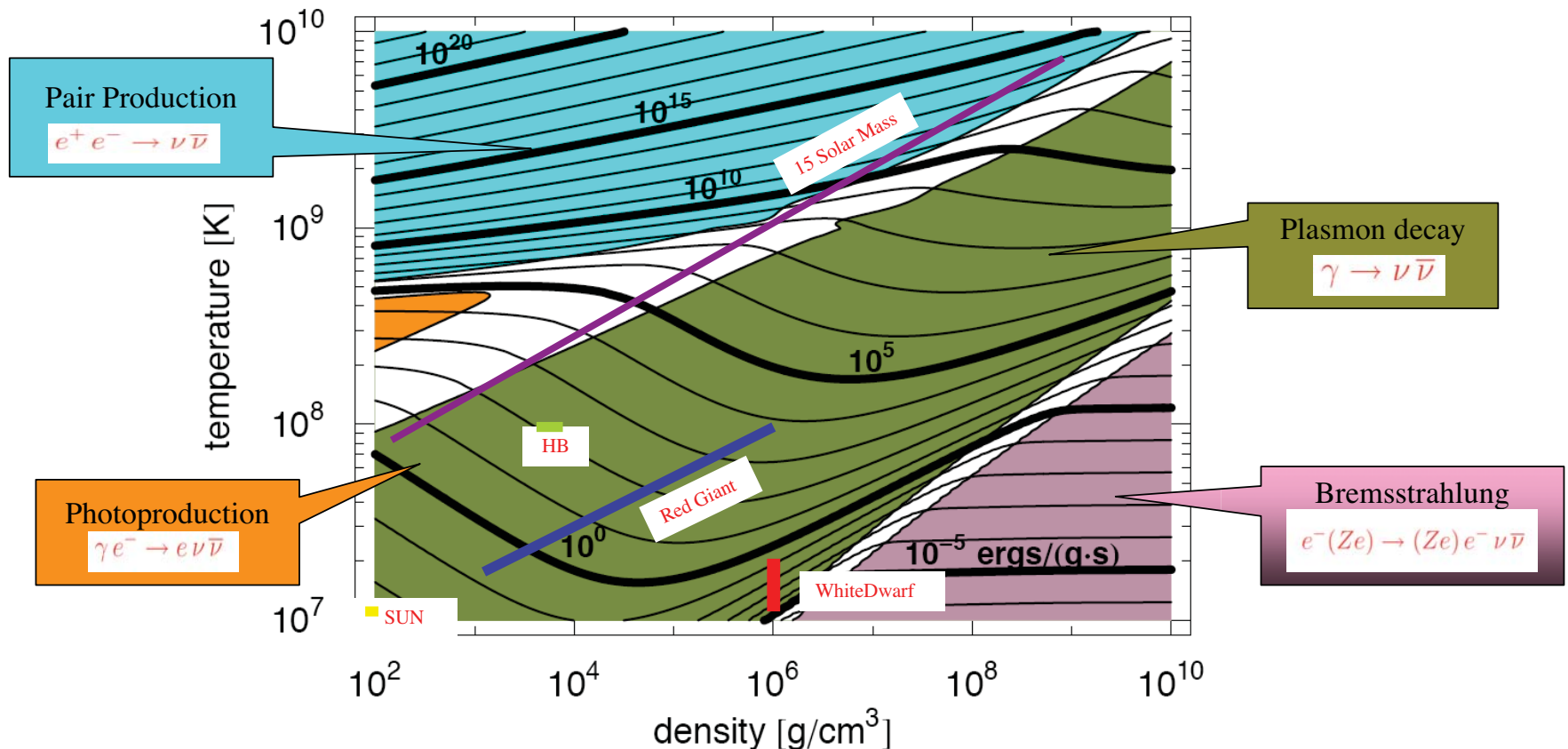
$$\mu_\nu = 10^{-11} \mu_B$$



From A.Heger, A.Friedland, M.G., V.Cirigliano APJ:696 (2009)

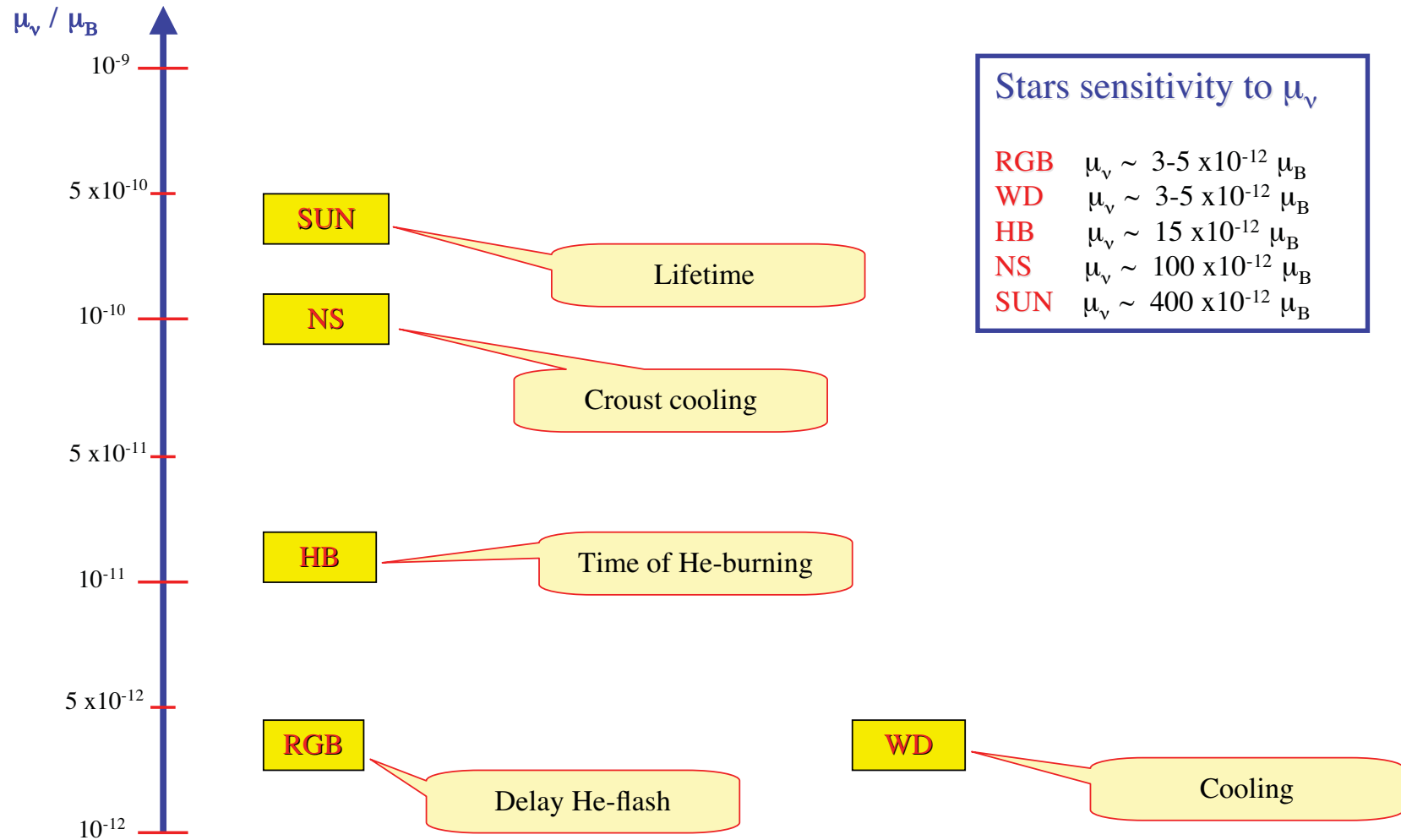
# Neutrino Magnetic Moment and Stars Cooling

$$\mu_\nu = 5 \times 10^{-11} \mu_B$$

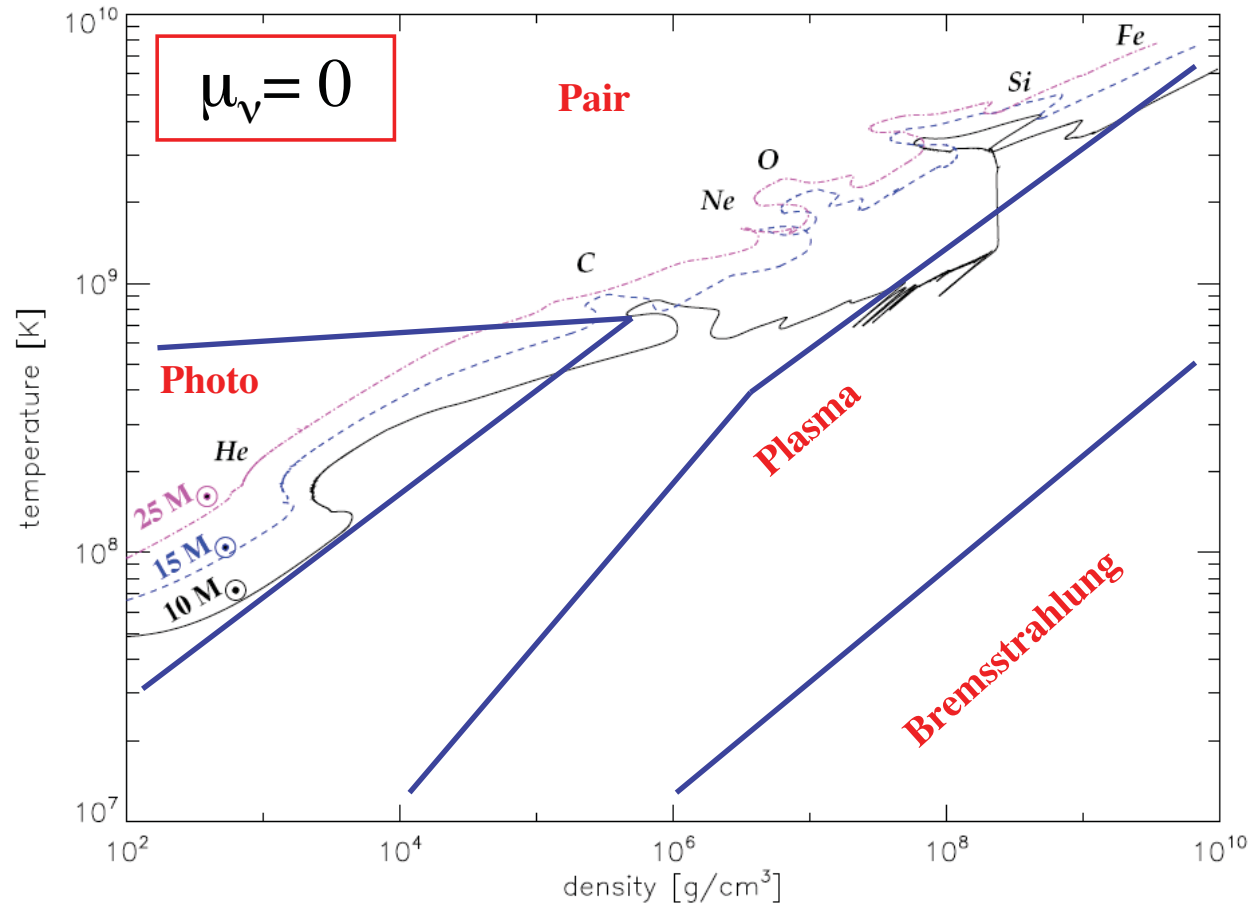


From A.Heger, A.Friedland, M.G., V.Cirigliano APJ:696 (2009)

# Stars Sensitivity to Neutrino Magnetic Moment

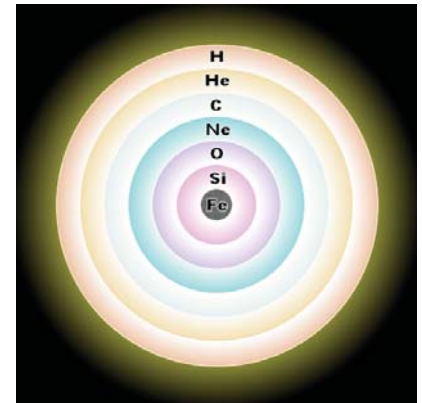


# Evolution of Massive Stars: No Neutrino Magnetic Moment

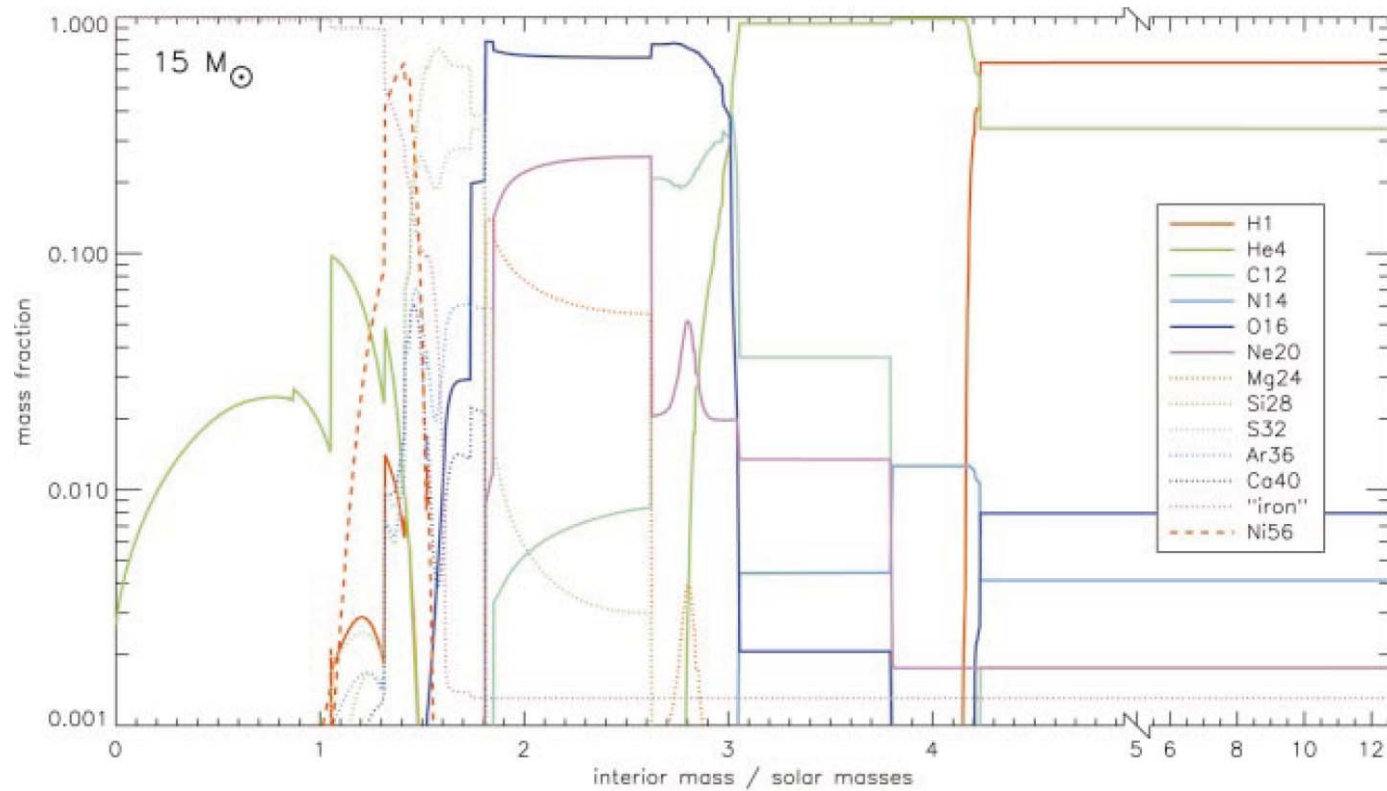


From A.Heger, A.Friedland, M.G., V.Cirigliano APJ:696 (2009)

# Massive Stars: Final Stage

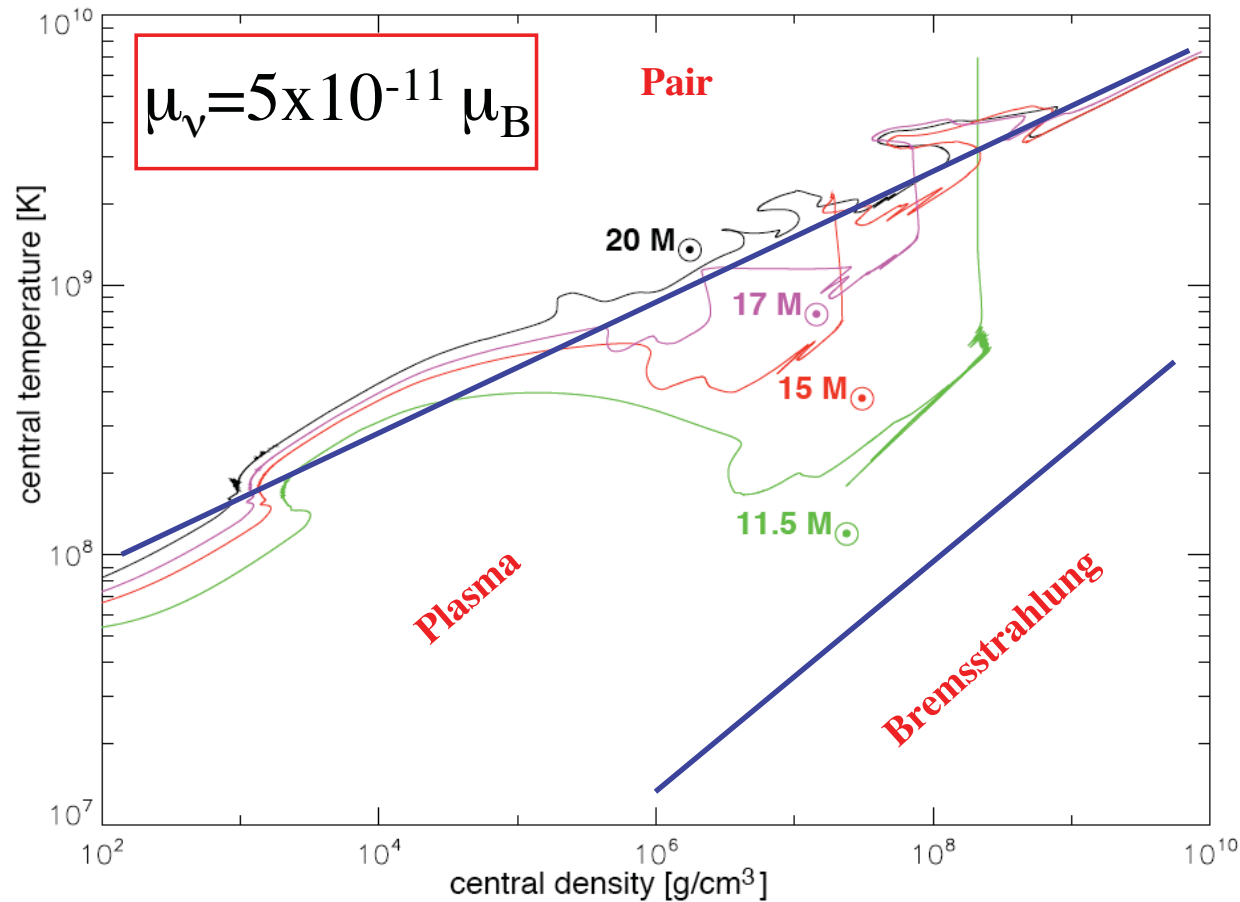


Final composition of a  $15 M_{\odot}$  star (Solar Metallicity)



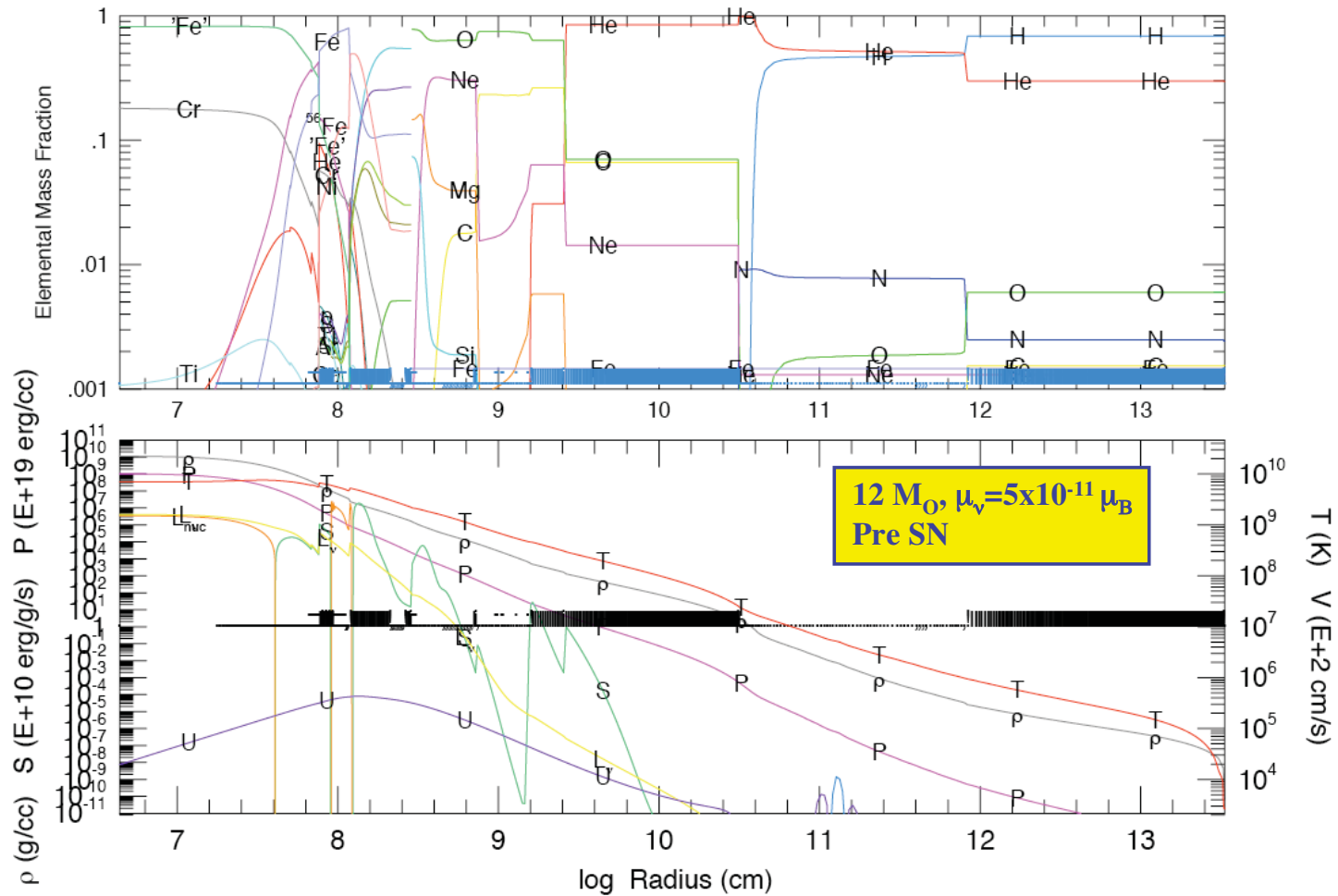
From Woosley, Heger, Weaver, Rev Mod Phys, 74, 1015 (2002)

# Evolution of Massive Stars: Standard + Neutrino Magnetic Moment

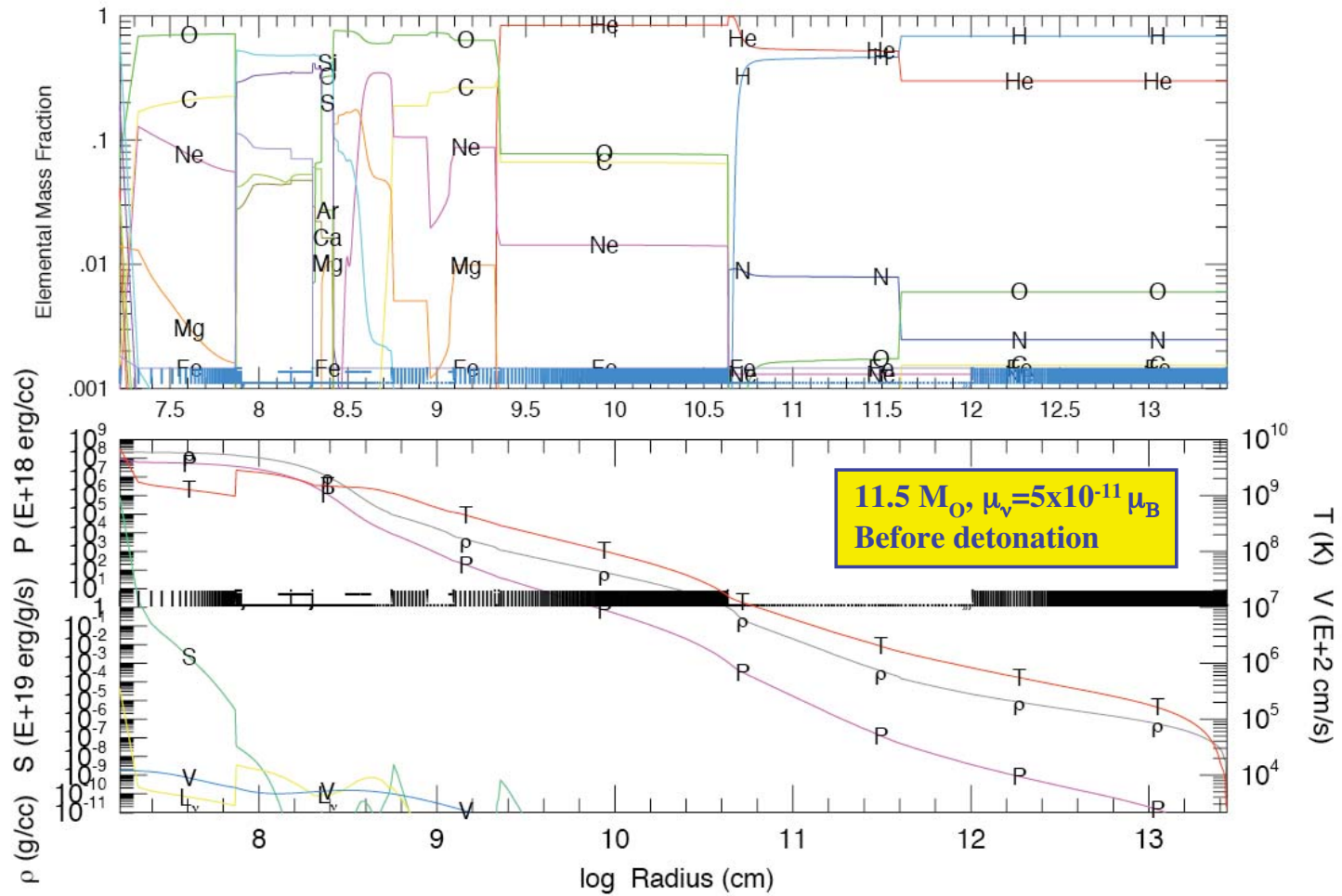


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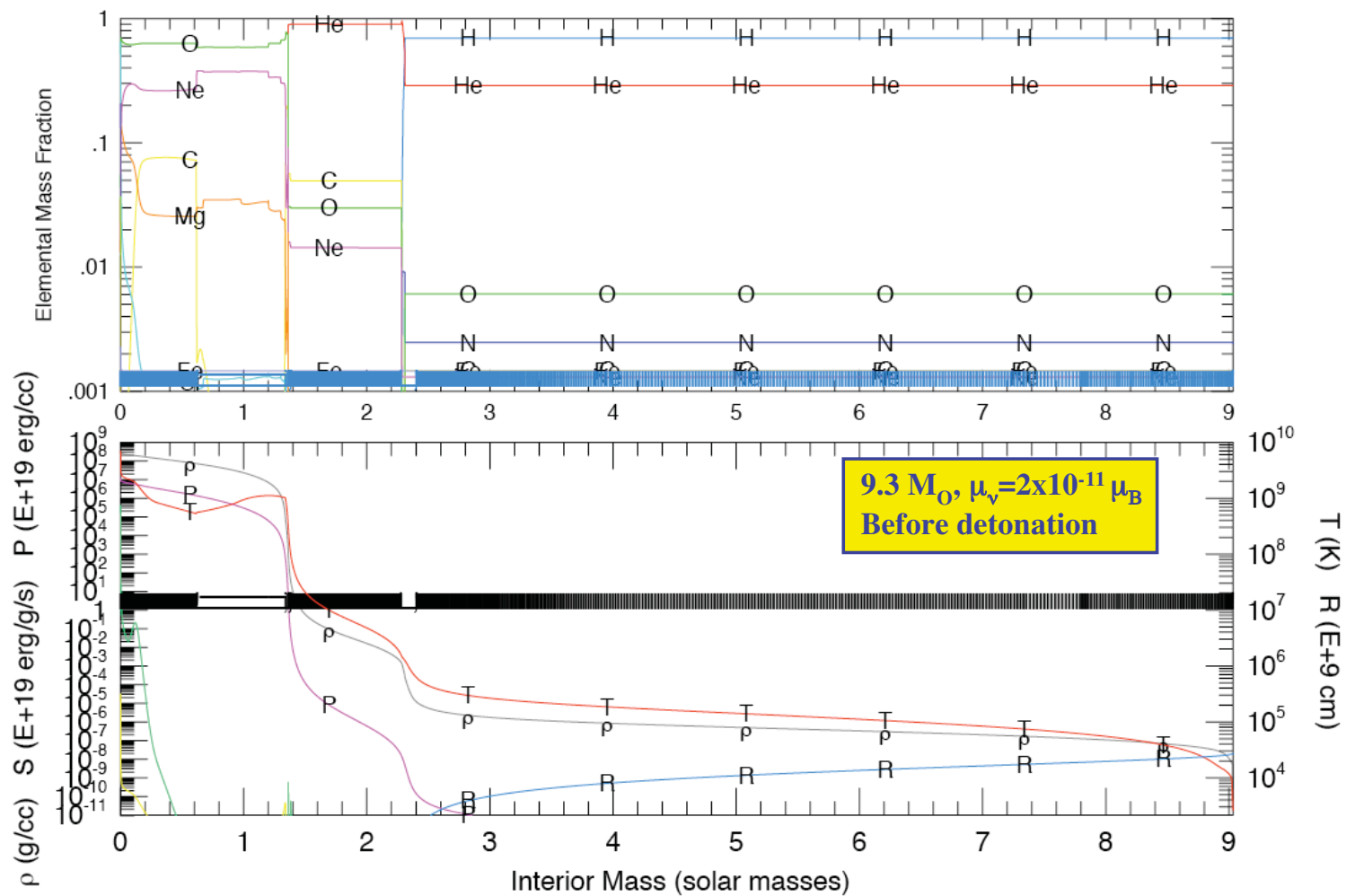
# Massive Stars and Magnetic dipole Moment



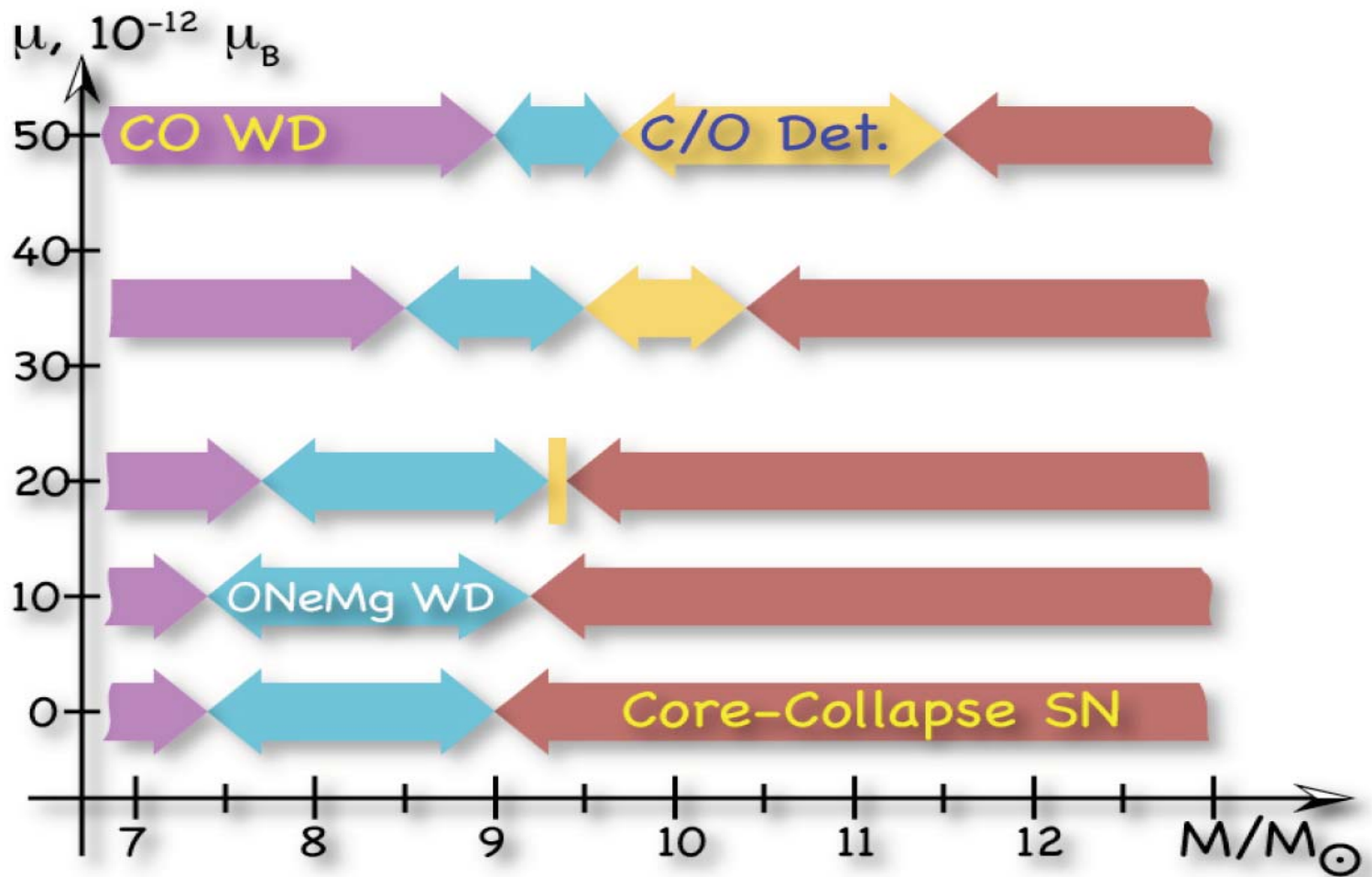
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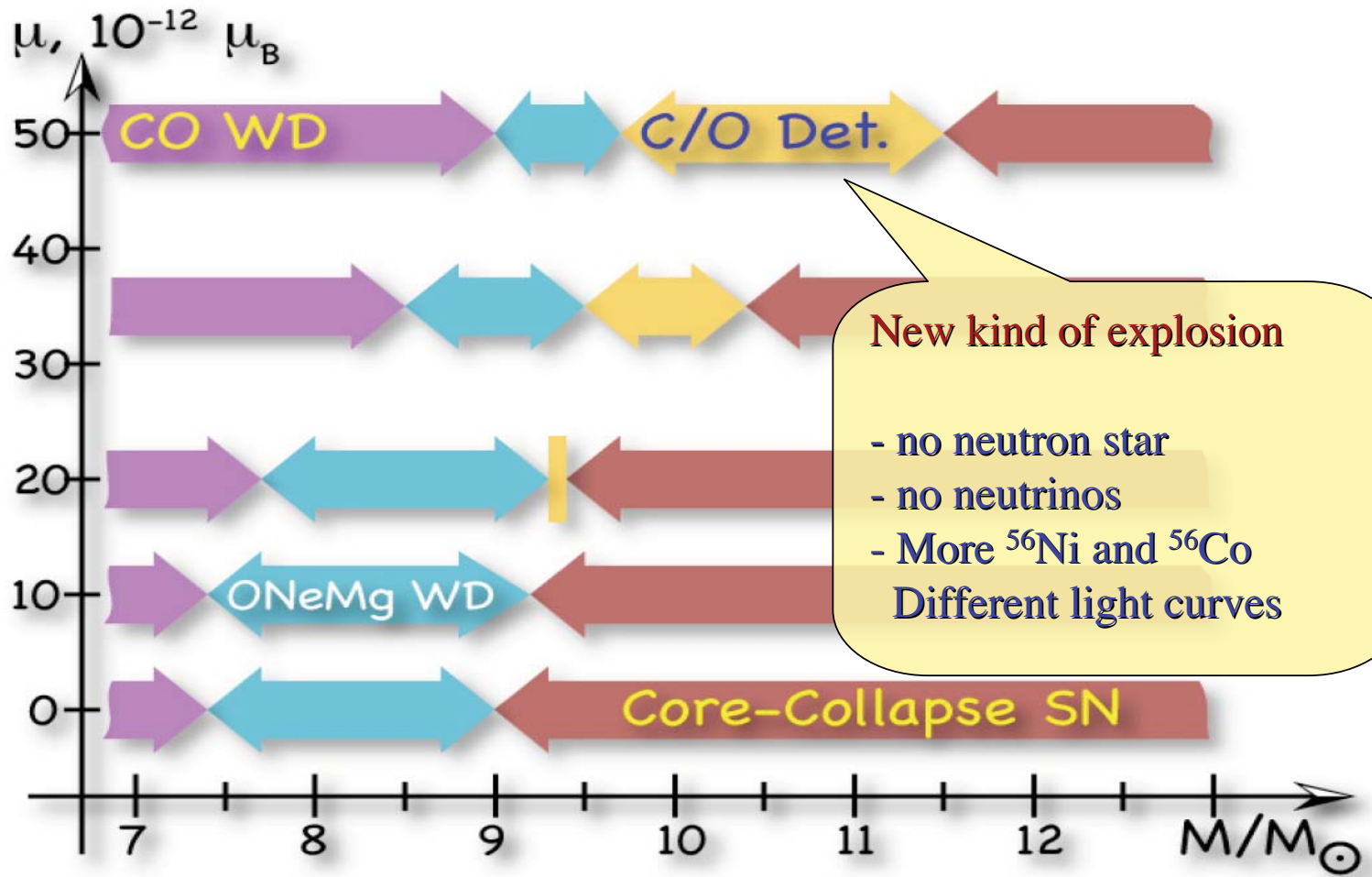
# Massive Stars and Magnetic dipole Moment



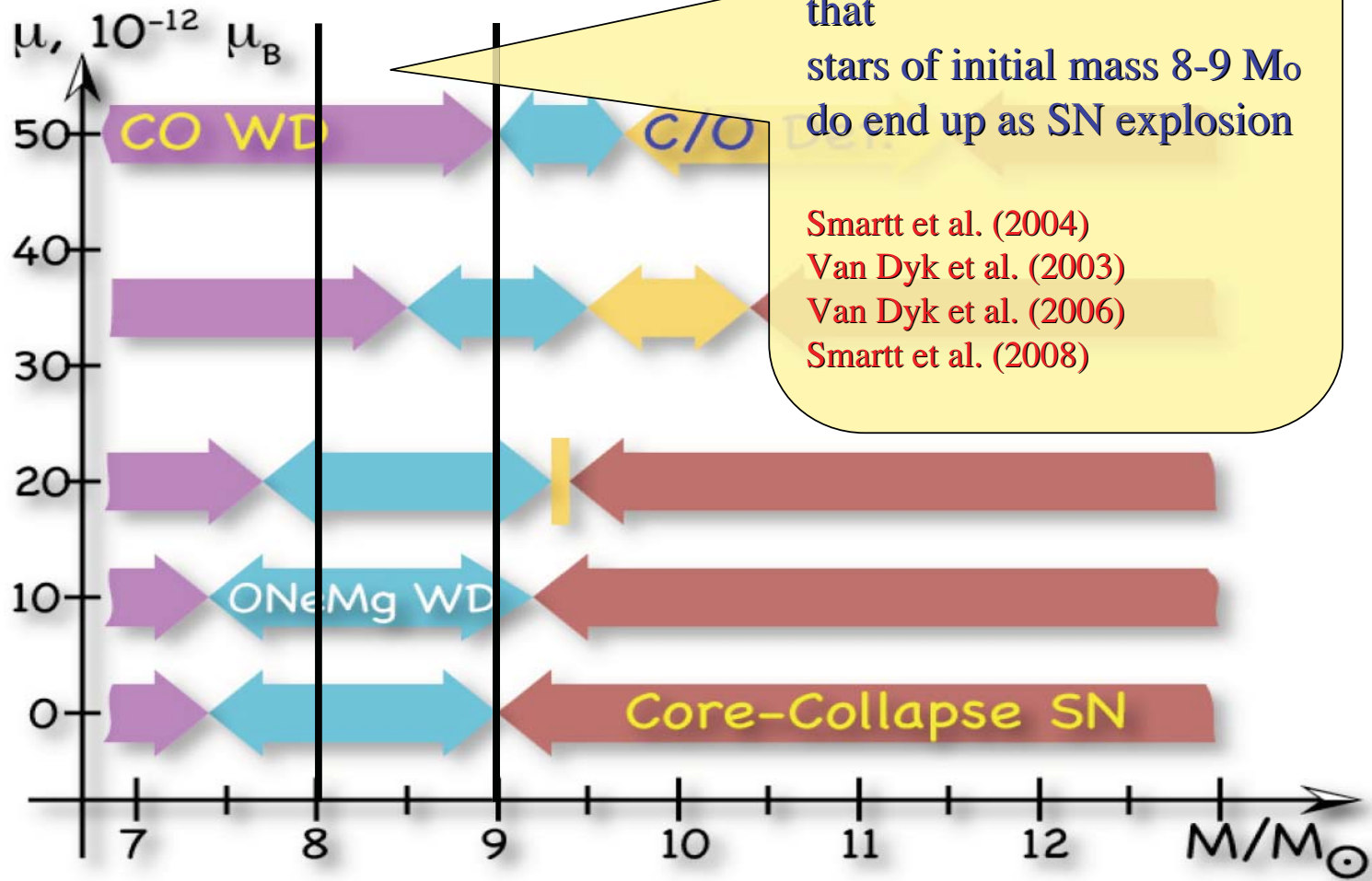
# Neutrino Magnetic Moment and the fate of Stars of different masses



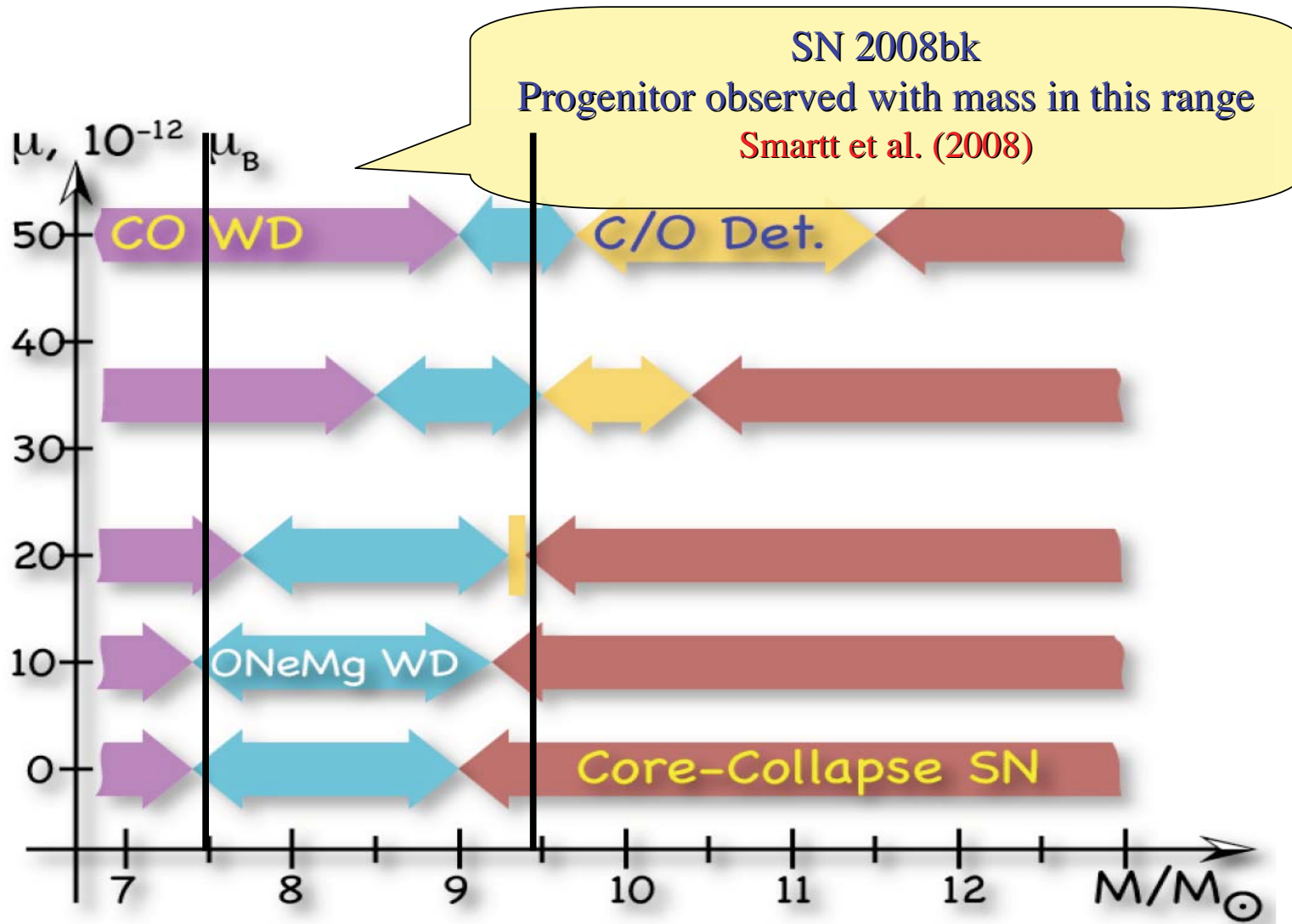
# Observations



# Observations



# Observations



# Conclusions

- Stars offer a variety of interesting environments to test physics beyond the standard model
- From astrophysics we can get invaluable insights on the physics beyond the SM:
  - \* The **invisible** axion is **invisible** because of astrophysics
  - \* There are examples in which stars provides bound several order of magnitude more restrictive than terrestrial experiments on new physics
- **Massive stars** seem to be more interesting for particle physics than we thought!
  - \* The sensitivity of massive stars to magnetic moment is comparable to the sensitivity of HB stars
  - \* Observations are improving at a fast pace
  - \* The response to new physics could be dramatic... new kind of explosions! Maybe they are a good place to find new physics rather than test it!
  - \* Axion-photon coupling effects in massive stars is in preparation