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Internal magnetic fields of white dwarfs: a solution to the cooling anomaly?

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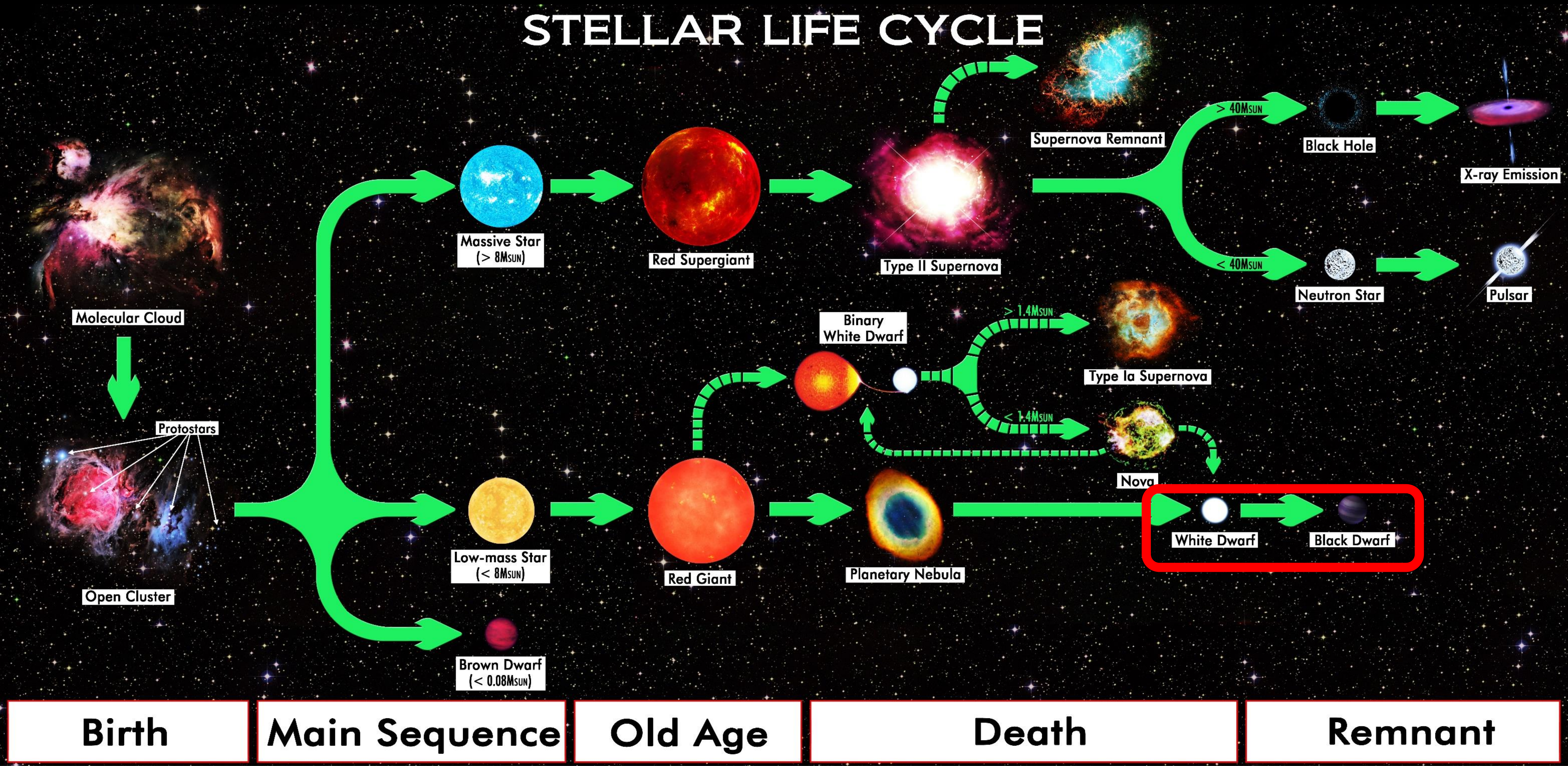
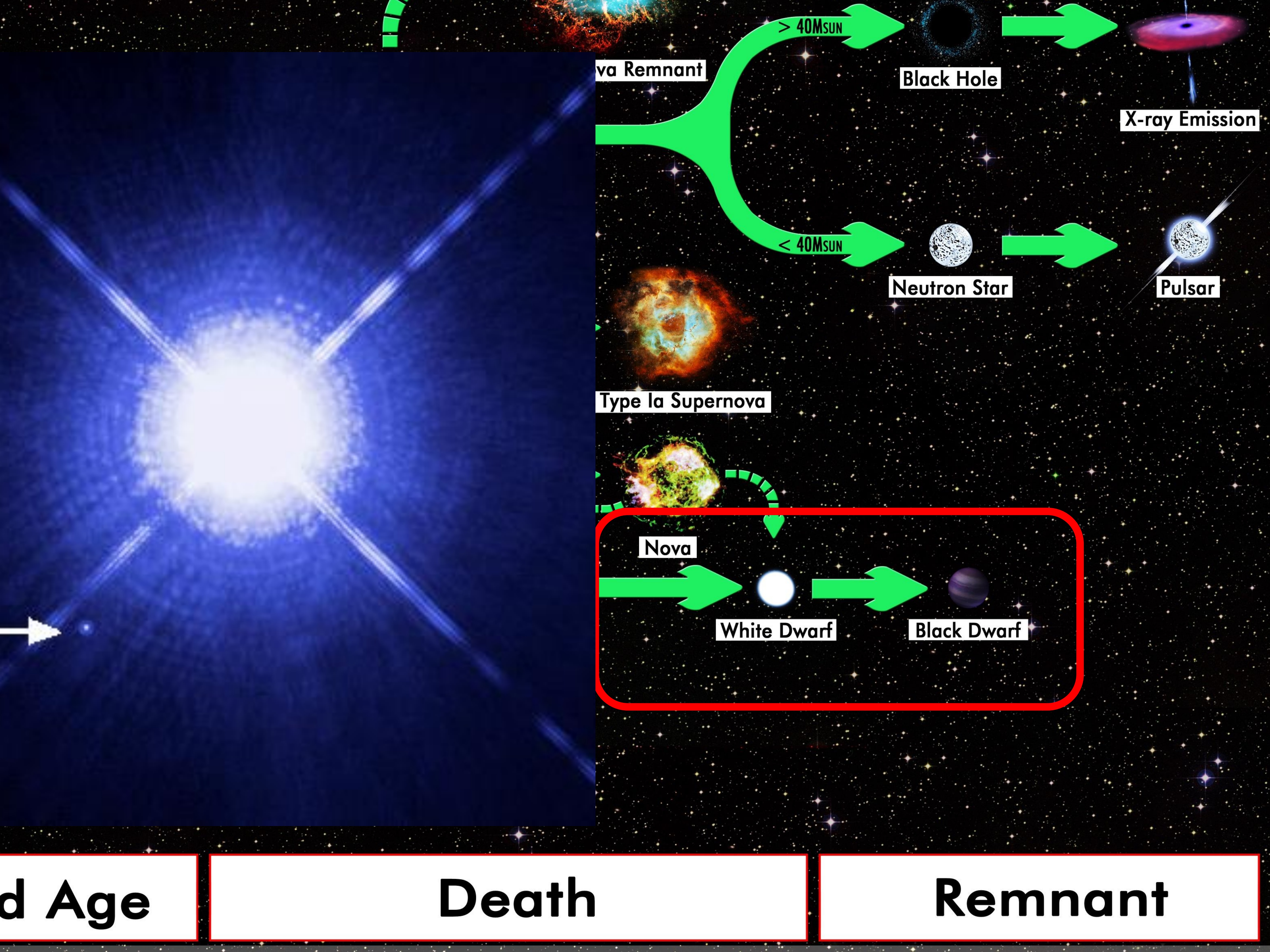
LLP11 Workshop

Based on arXiv:2109.06158 [astro-ph.SR]

A Star’s Life

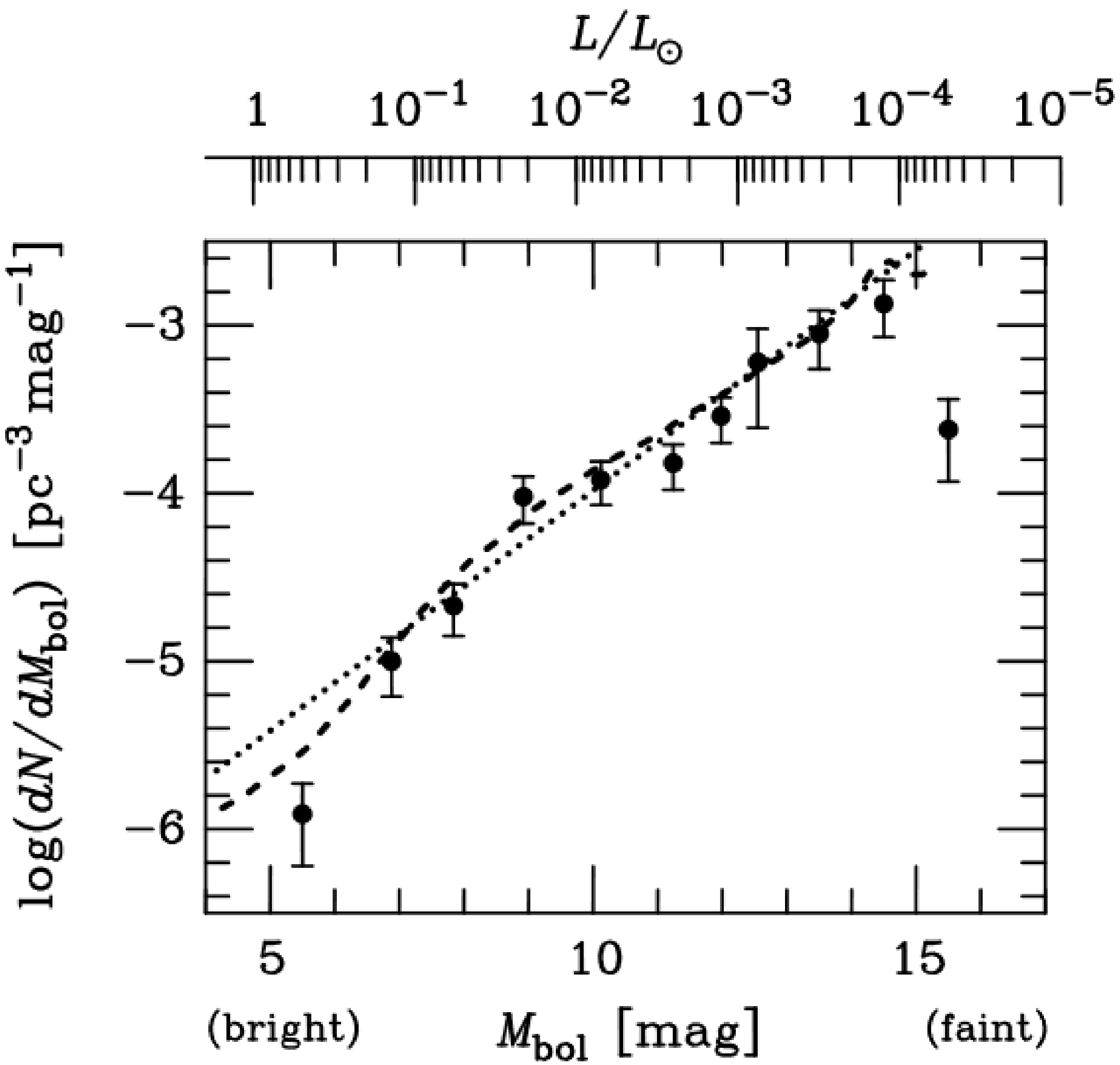


STELLAR LIFE CYCLE
Molecular Cloud
Protostars
Open Cluster
Massive Star (> 8MSUN)
Low-mass Star (< 8MSUN)
Brown Dwarf (< 0.08MSUN)
Red Supergiant
Red Giant
Type II Supernova
Supernova Remnant
> 40MSUN
< 40MSUN
Black Hole
X-ray Emission
Neutron Star
Pulsar
Binary White Dwarf
> 1.4MSUN
< 1.4MSUN
Type Ia Supernova
Nova
Planetary Nebula
White Dwarf
Black Dwarf
Birth
Main Sequence
Old Age
Death
Remnant

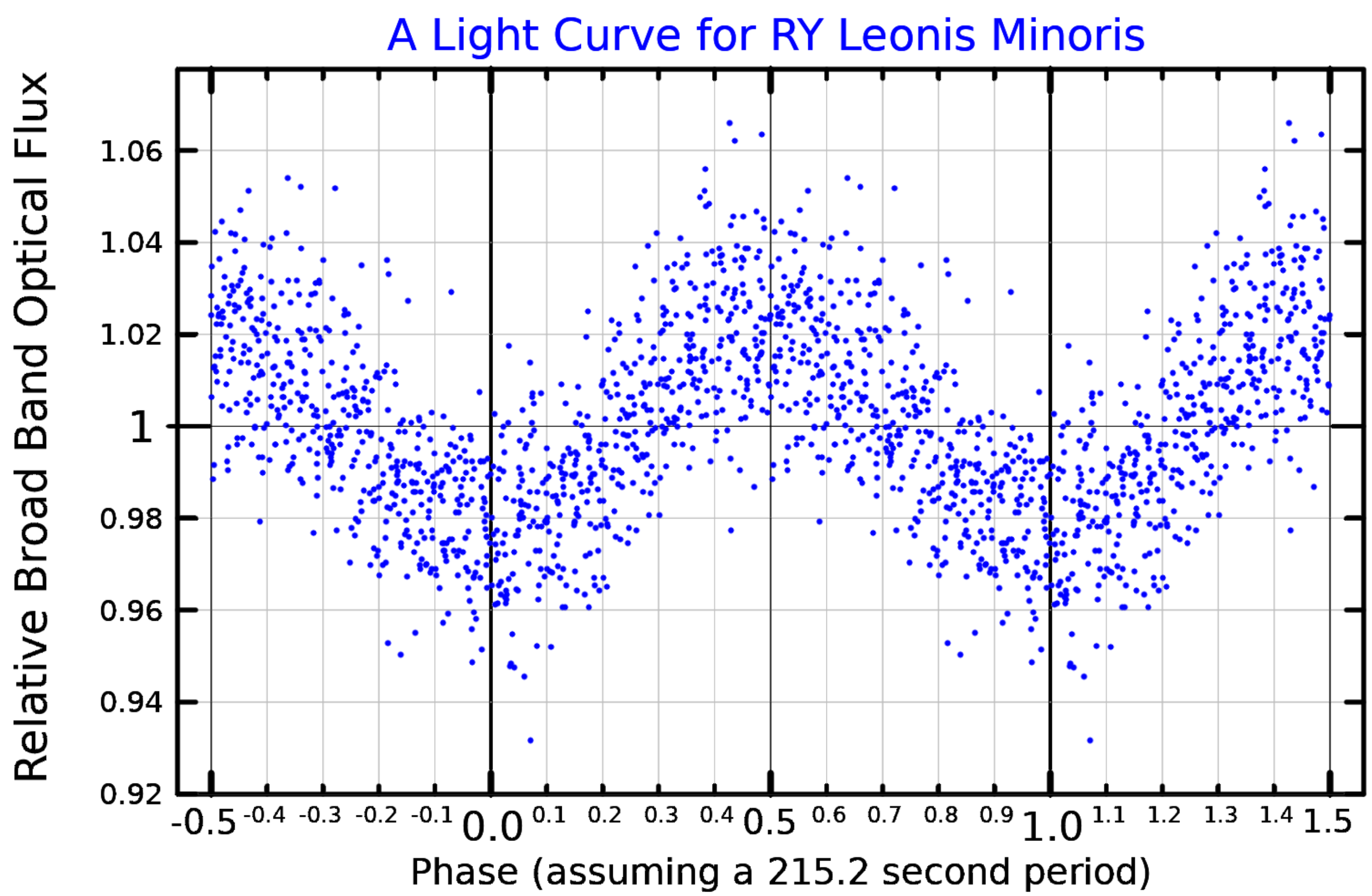

va Remnant
> 40MSUN
Black Hole
X-ray Emission
< 40MSUN
Neutron Star
Pulsar
Type Ia Supernova
Nova
White Dwarf
Black Dwarf
d Age
Death
Remnant

Observing WD Cooling

White Dwarf Luminosity Function (WDLF):
Population



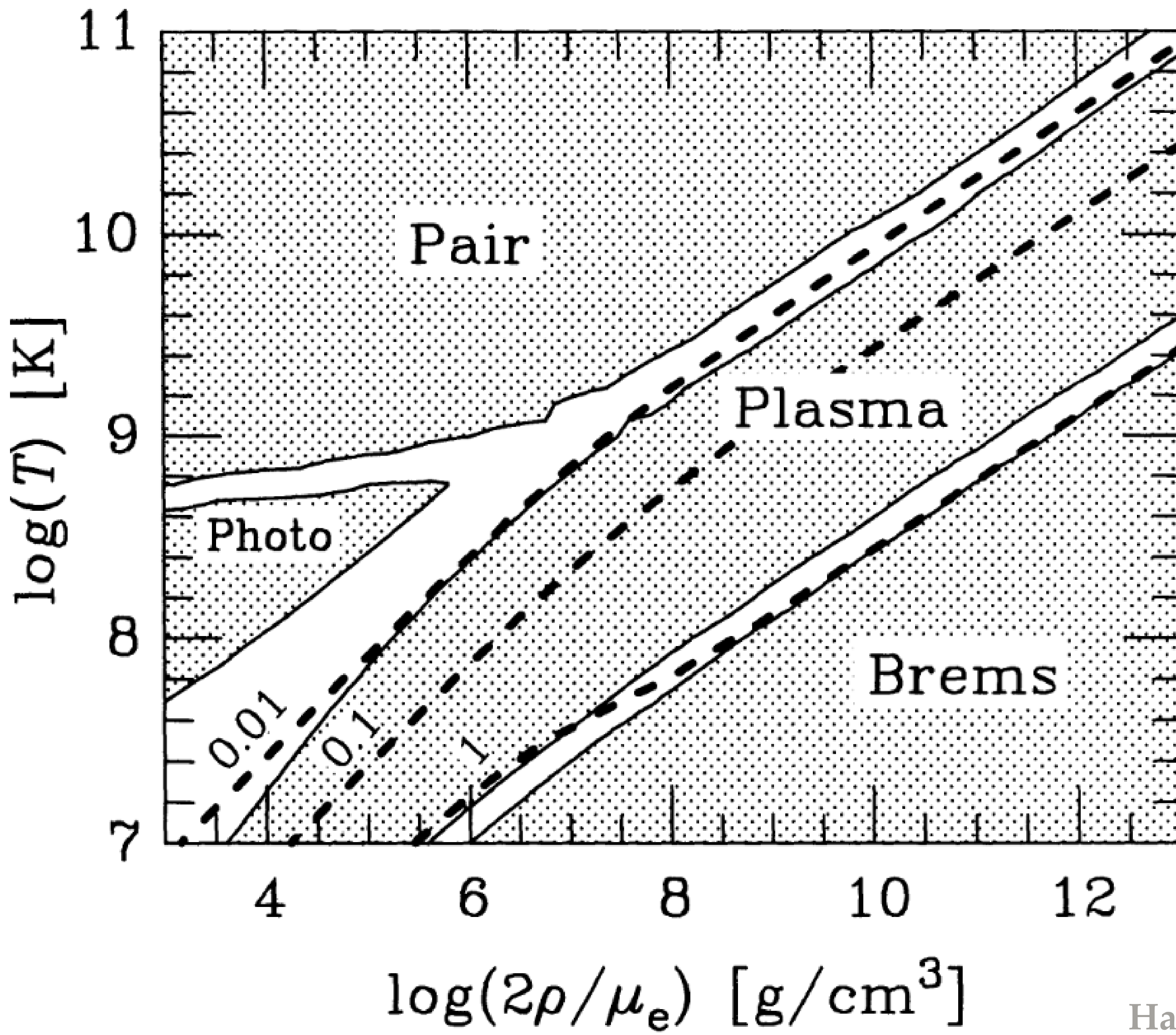
Pulsating WDs:
Individual stars



G117-B15A

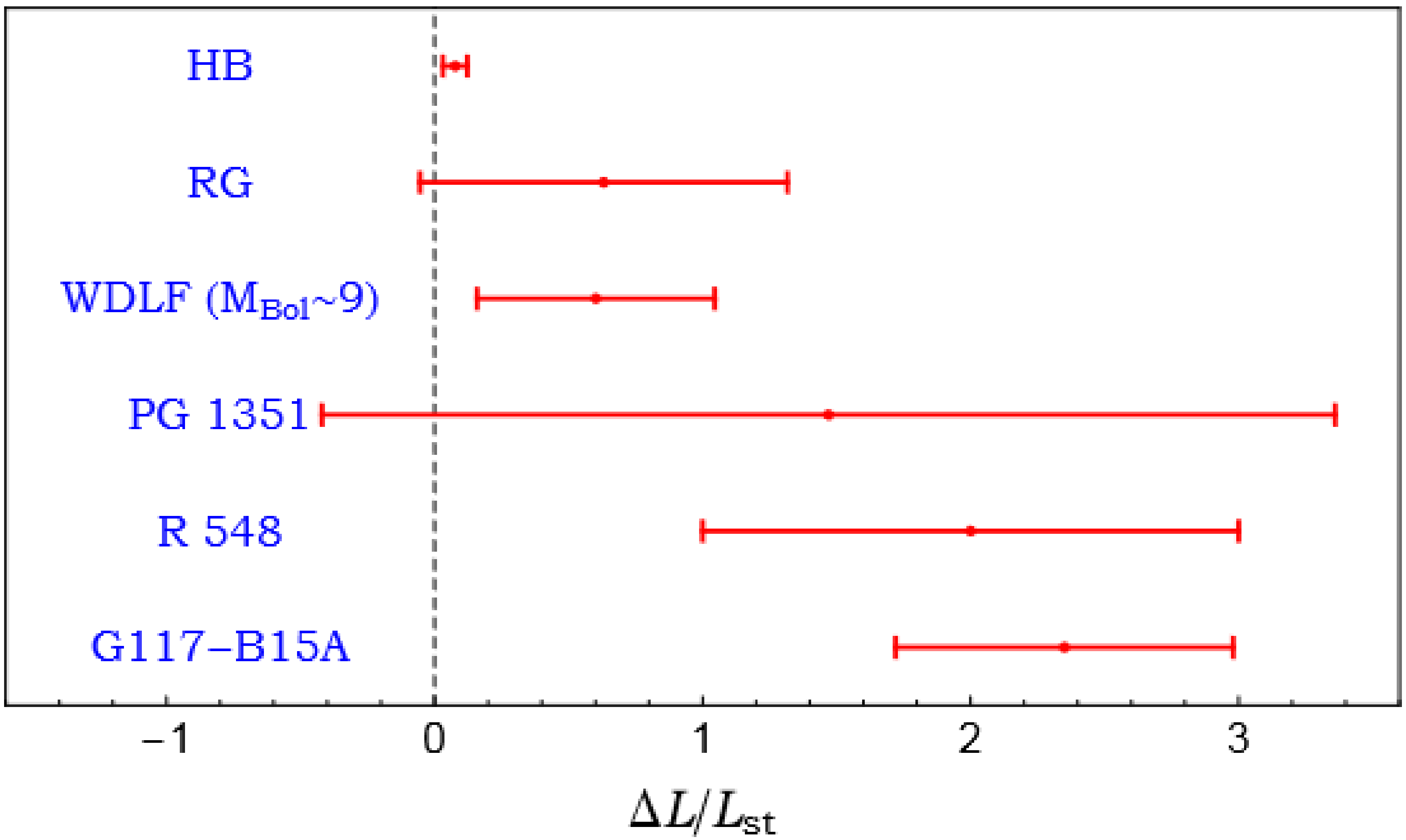
$$T = 1.2 \times 10^7\ \mathrm{K} \quad Y_e\rho \simeq 10^6\ \mathrm{g/cm^3}$$

Theory of WD Cooling



Haft/Raffelt/Weiss 1994

Cooling Anomaly



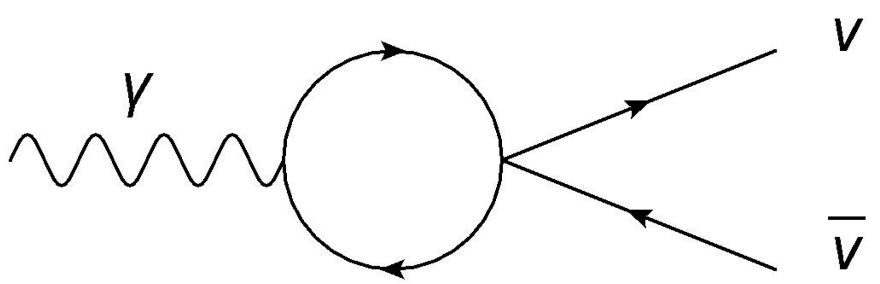
- Some WDs appear to be cooling too fast….
- Do they emit LLPs (axions, ALPs, …)?

Giannotti/Irastorza/Redondo/Ringwald 1512.08108

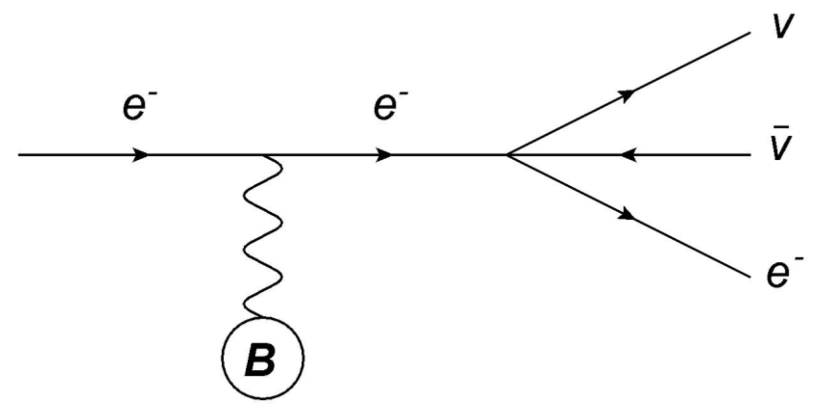
Impact of B-fields

Can internal magnetic fields explain this within the SM?

- Modify plasma processes $\gamma \to \nu\nu$



- Enable synchroton radiation $e \to e\nu\nu$



- Heating through Ohmic decay

Plasma Processes

- $\gamma \to \nu\nu$ possible in dense medium due to modified photon and plasmon dispersion relations, roughly characterised by the plasma frequency

cf. e.g. Braaten/Segel 9302213

$$\omega_p^2 = \frac{4\pi\alpha\, n_e}{m_e}\left[1 + \frac{1}{m_e^2}(3\pi^2 n_e)^{2/3}\right]^{-1/2} \simeq \left(20\,\mathrm{keV}\,\rho_6^{1/2}\right)^2$$

- Refractive index ("thermal mass") is determined by electron density, relevant scale is the frequency

cf. e.g. Kennet/Melrose astro-ph/9901156

$$\omega_B = \frac{eB}{m_e} = m_e \frac{B}{B_c} \simeq 11.5\, B_{12}\,\mathrm{keV} \qquad B_c = m_e^2/e = 4.41 \times 10^{13}\,\mathrm{G}$$

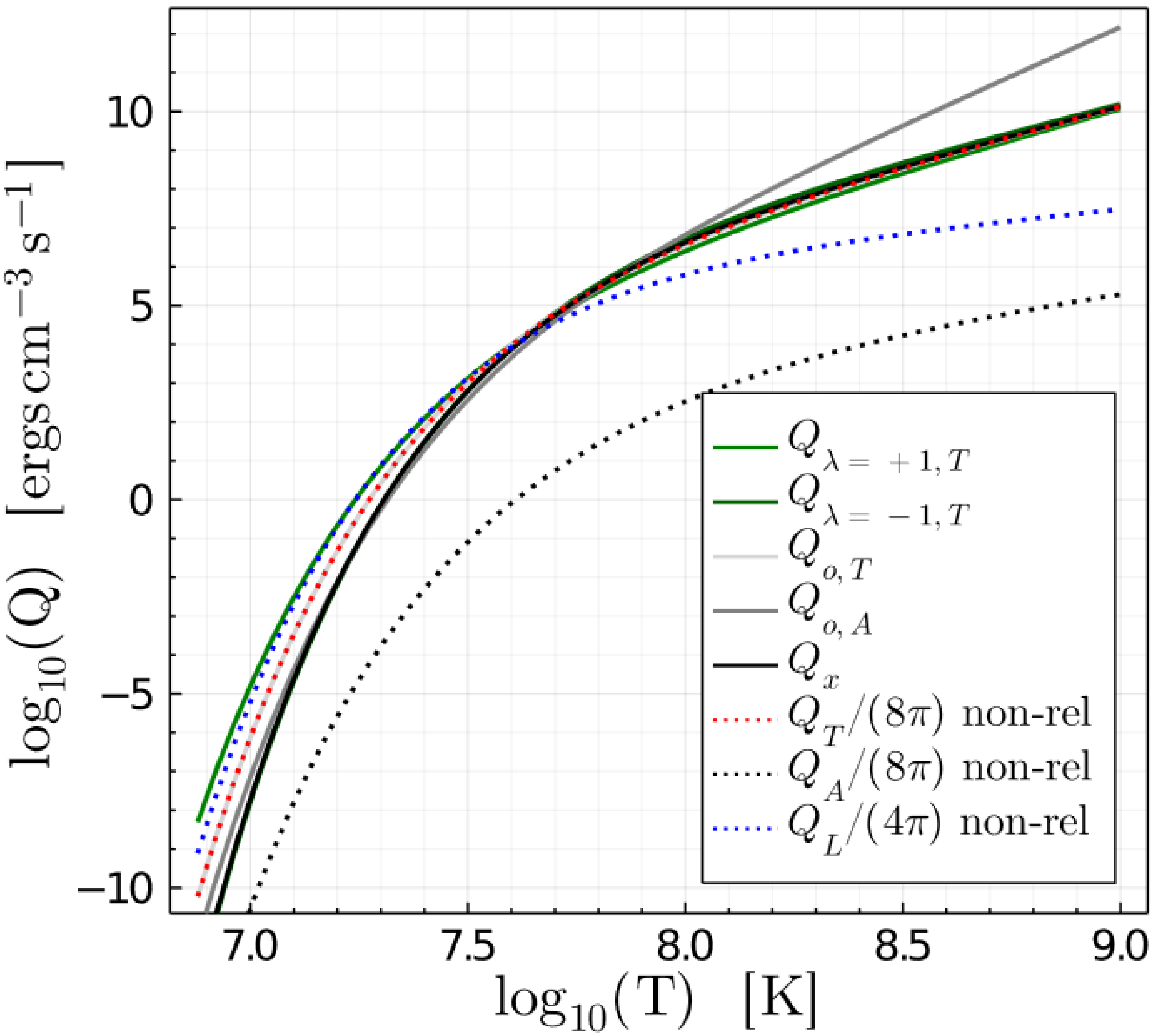
- Magnetic fields force electrons on Landau levels, modify refractive index

$$E_\nu = \sqrt{p_\parallel^2 + m_e^2\left(1 + 2\nu\frac{B}{B_c}\right)}$$

- Other effects (Schwinger-like pair creation, modification of wave function…) are negligible or sub-dominant

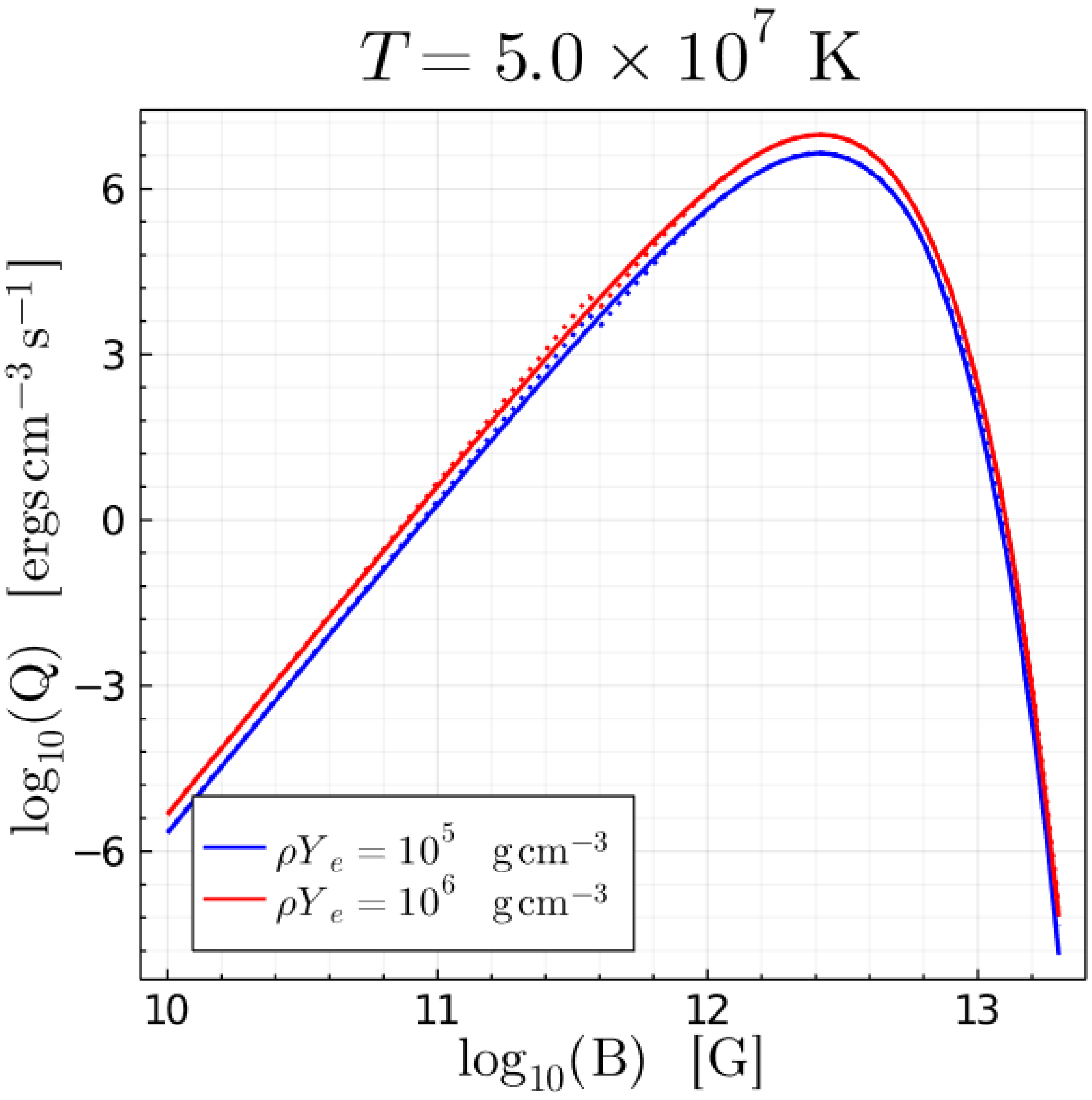
Plasma Processes

$$\rho Y_e = 10^6\,\mathrm{g\,cm^{-3}}$$



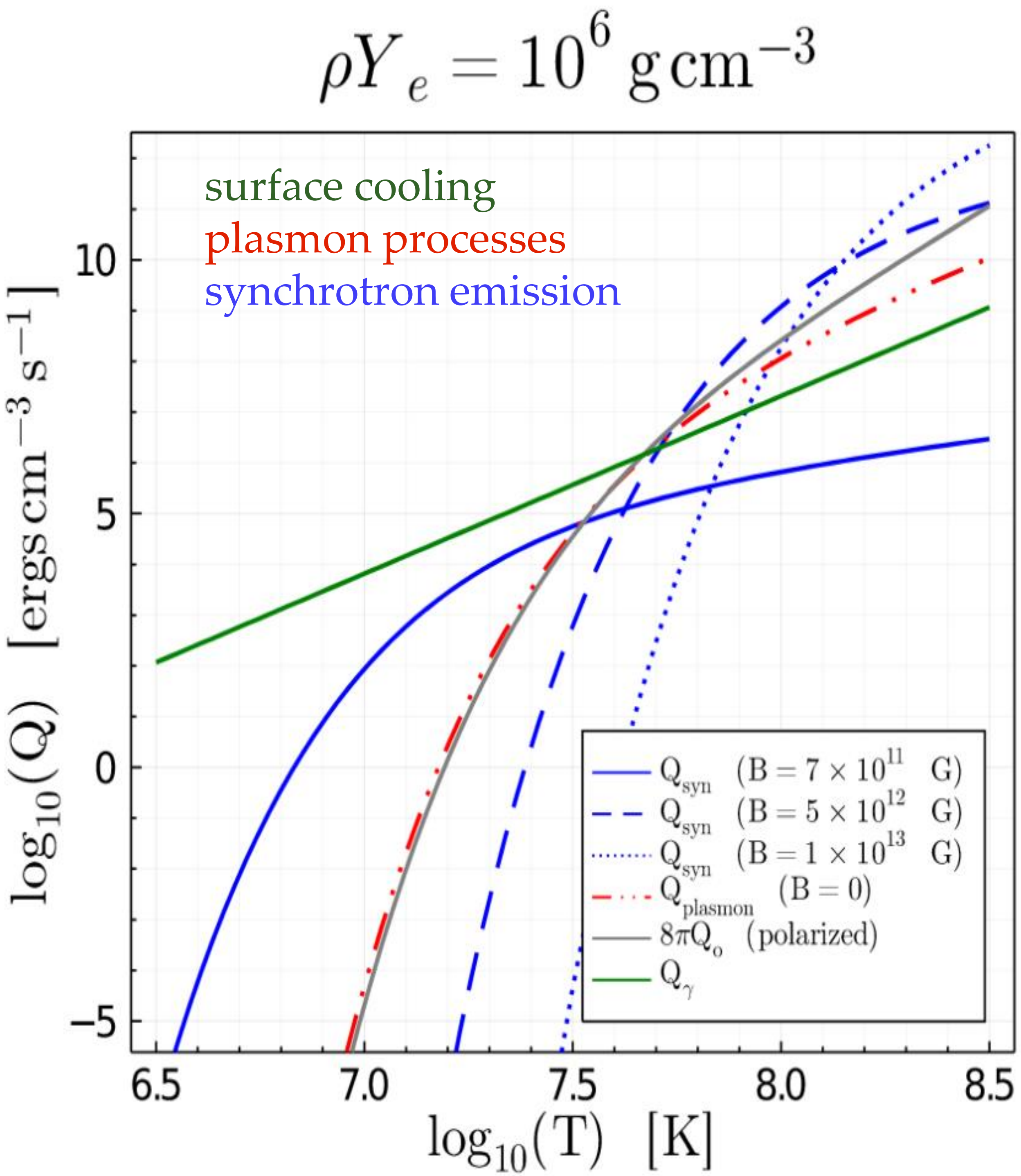
- For typical WD parameters, impact of B fields significant…
- …but only at temperature where other processes are more important

Synchrotron Radiation



- B-fields open up new cooling channel e → e$\nu\nu$
- In relevant regime the effect grows with B
- For very large B: suppression because next Landau level becomes inaccessible

Comparing Mechanisms



- Synchrotron emission can dominate for large temperatures
- Requires comparably large B fields
- Can potentially solve the anomaly for

$$B \sim 3 \times 10^{11}\ \mathrm{G}$$

- But how to generate these fields?
- Non-observation of stronger anomaly imposes upper bound

$$B < 6 \times 10^{11}\ \mathrm{G}$$

Final Remark: Ohmic Heating

- We so far assumed the B fields to be stable, but in reality they decay
- This decay releases energy into the plasma. Let's estimate

  B-field energy density $U_{\rm em} = B^2/2$

  Exponential decay $B = B_0 \exp(-t/t_{\rm Ohm})$

  Heating rate Q $dU_{\rm em}/dt \simeq B_0^2/t_{\rm Ohm} \simeq 750\,{\rm erg/cm^3/s}$

- For cooling time $t_{\rm Ohm} \simeq 3 \times 10^{11}$ this yields

  $|Q_{\rm Ohm}/Q_{\rm syn}| \simeq 7.6$ implying $B < 2.73 \times 10^{11}{\rm G}/\sqrt{Y_e}$

- Ohmic heating dominates over cooling! But depends on unknown cooling time…

Conclusions

- B-fields can in principle explain the WD cooling anomaly without the need for new LLPs…

- …but requires rather large magnetic fields

$$B \sim 3 \times 10^{11}\ \mathrm{G}$$

- Non-observation of larger anomalies allows to impose a new upper bound in internal magnetic fields of WDs,

$$B < 6 \times 10^{11}\ \mathrm{G}$$

Even if this is not the solution to the cooling anomaly, it demonstrates the use of neutrino emission as a diagnostic tool for the internal structure of WDs!