New Physics and Stellar Evolution

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OUTLINE

- Weak interactions and stellar evolution.
- Temperature-Density diagram for stars.
- Stars and physics above the e.w. scale.
- Bounds from stellar evolution to extradimensions
- Conclusions

Weak interactions and star cooling

Starting from the late ‘50s it become clear the role of weak interactions in stellar cooling.
Thanks to those results today we can understand stellar evolution

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

Already in 1963 Bernstain, 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.

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

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IMPORTANT QUESTION

Can we use stars to test physics above the e.w. scale?

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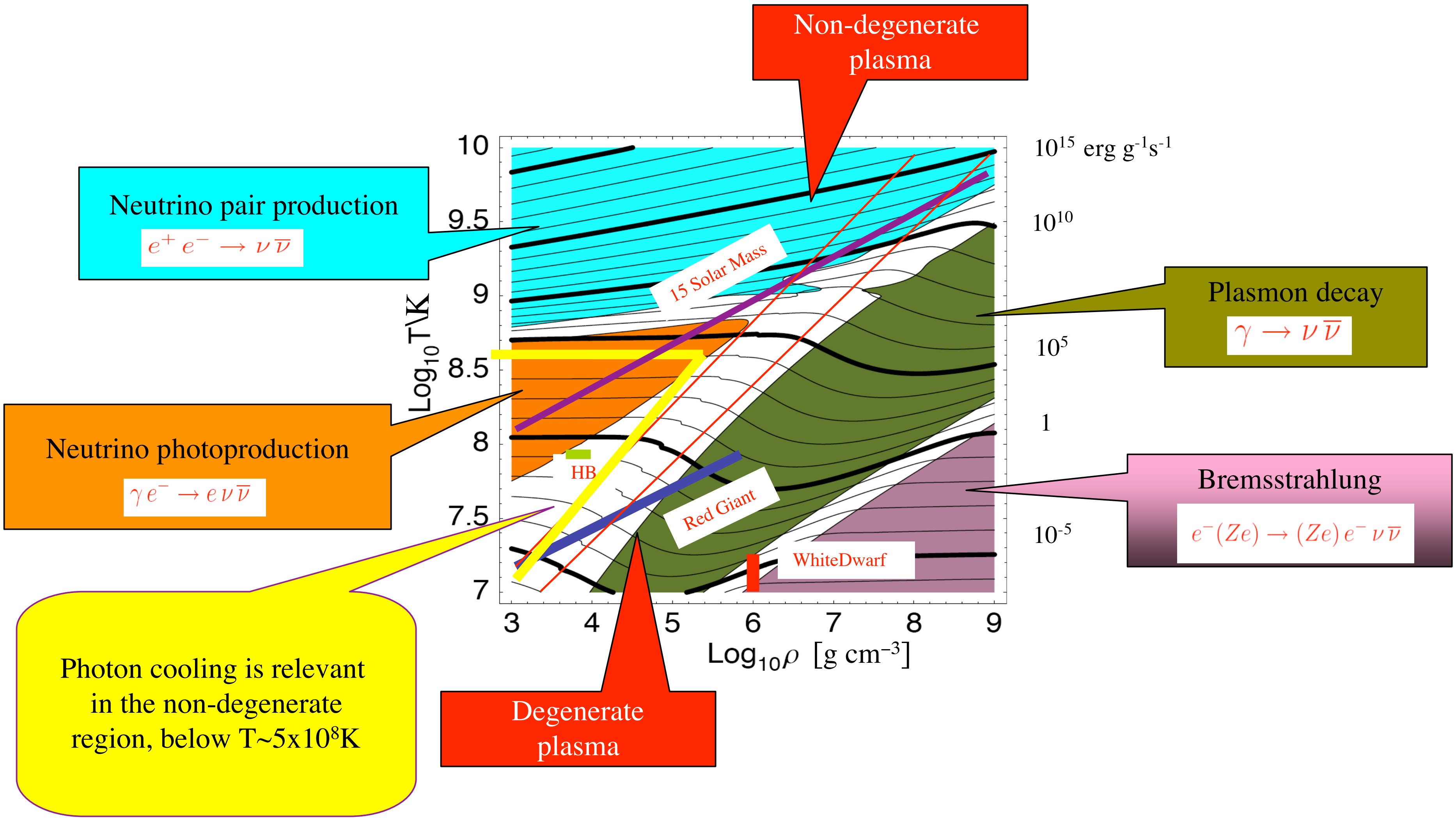
Neutrino Cooling in Stars

Standard Cooling: photons and neutrinos



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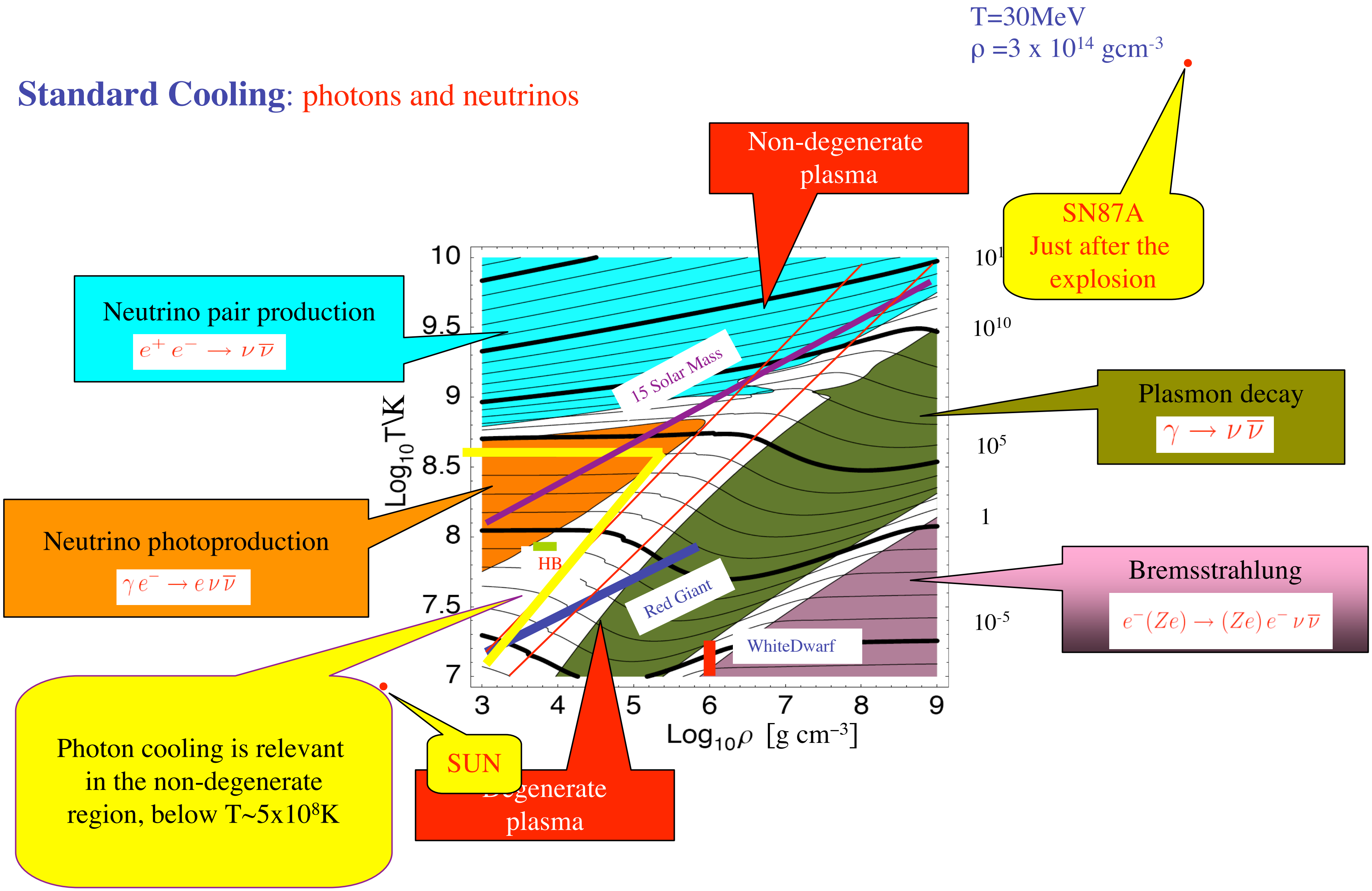

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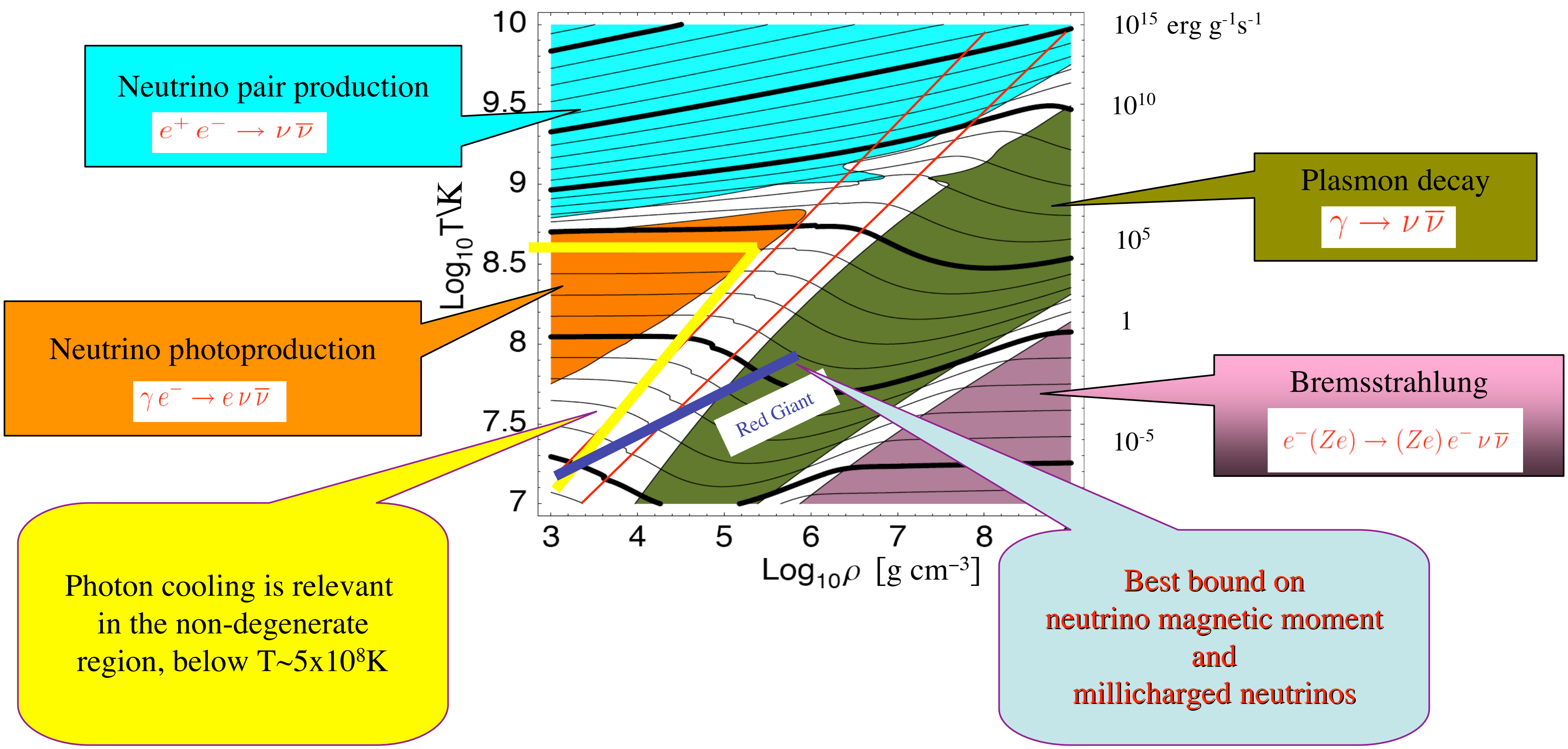


Neutrino Cooling in Stars

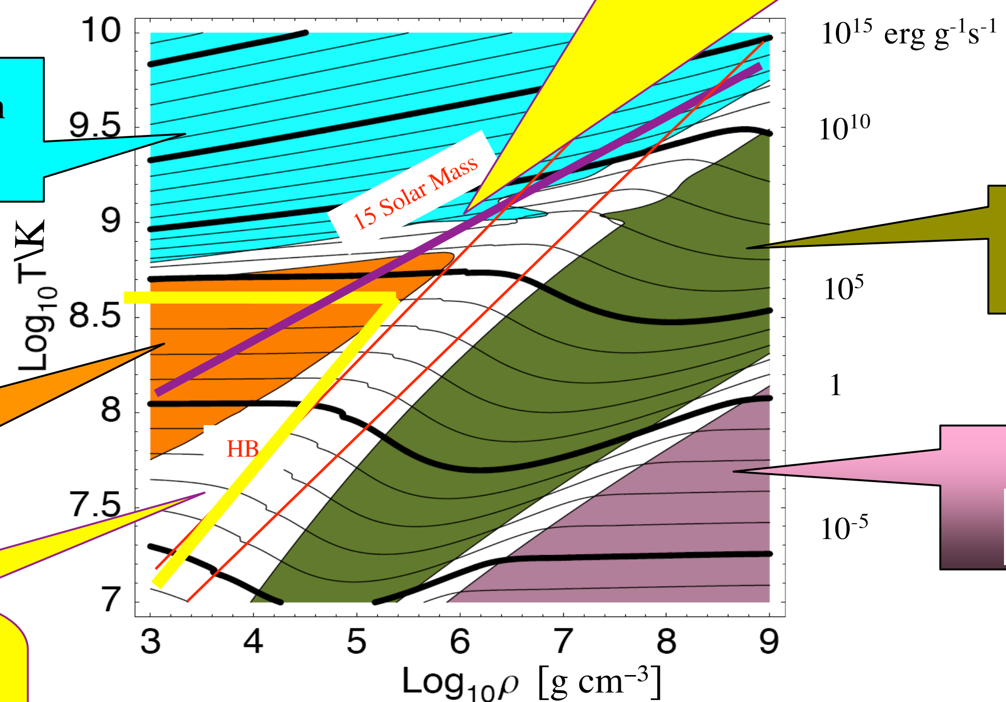
Standard Cooling: photons and neutrinos

Surprisingly Massive stars are sensitive to values of the neutrino magnetic moment below the experimental bound!

(Cirigliano,Friedland,MG,Heger 2008)

Neutrino pair production
$e^+ e^- \rightarrow \nu \overline{\nu}$

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



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

Photon cooling is relevant in the non-degenerate region, below T~5x10^8K

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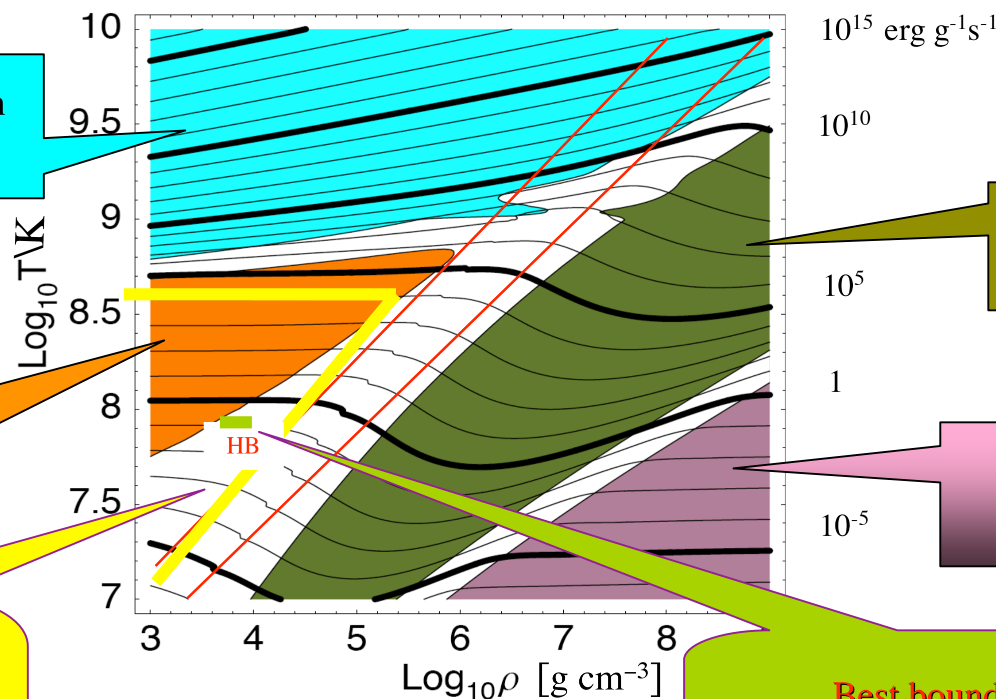

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Best bound on axion-photon coupling

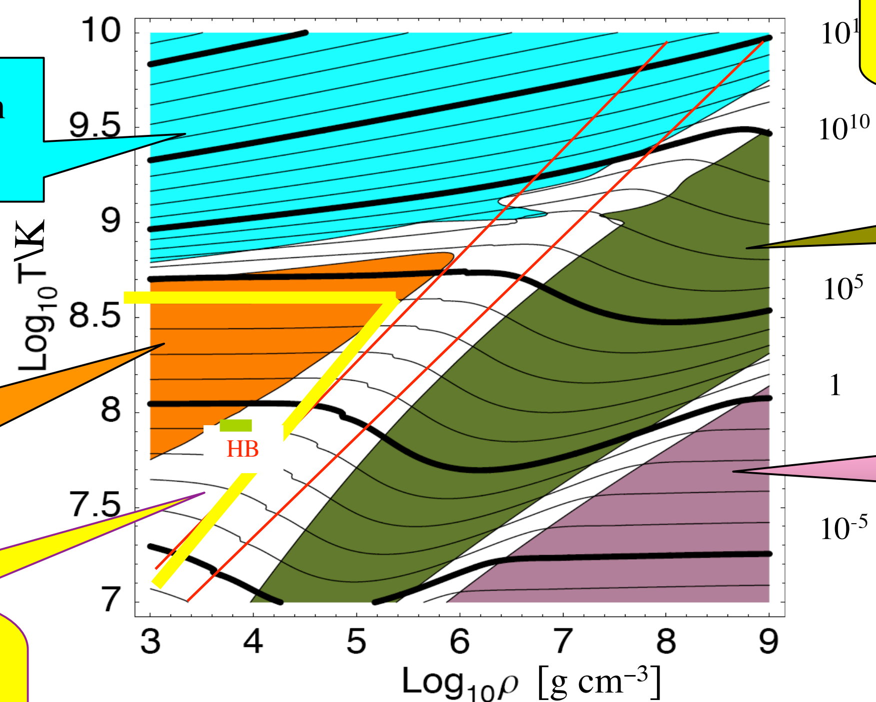
Neutrino Cooling in Stars

Standard Cooling: photons ar

T=30MeV
$\rho = 3 \times 10^{14}$ gcm^{-3}

Best bound on
axion-nucleon coupling
magnetic moment for Dirac neutrinos,
mirror world…

SN87A
Just after the
explosion



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Particles leaking in the extra dimensions

RS Metric (RS II, 1 brane)

L. Randall and R.~Sundrum
Phys. Rev. Lett. 83, 4690(1999)

$$ds^2 = a(z)^2 \eta_{\mu\nu} dx^\mu dx^\nu - dz^2$$

$$a(z) = \exp\left(-k|z|\right)$$

-- Massless scalar fields can be confined on the brane only through gravity

B.Bajc, G.Gabadadze
Phys.Lett. B474 (2000).

-- Massive scalar fields can decay into the extra dimensions
There is a mode peaked on the brane, but it is unstable.

S. Dubovsky, V. Rubakov and P.Tinyakov **Phys.Rev.D62 (2000)**

$$\boxed{\Gamma \propto m \left(\frac{m}{k}\right)^2}$$

Particles leaking in the extra dimensions

Extended RS Metric

$$ds^2 = a(z)^2 \left(\eta_{\mu\nu} dx^\mu dx^\nu - \sum^{n} \delta_{ij} d\theta_i d\theta_j \right) - dz^2$$

$$a(z) = \exp\left(-k|z|\right)$$

If n>0
Photon confinement on the brane

S. Dubovsky, V. Rubakov and P.Tinyakov,
JHEP **0008** 041 (2000);

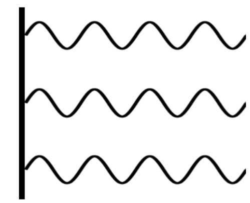
Virtual photons can decay into the extra dimensions

$$\boxed{\Gamma \propto \sqrt{p^2} \left(\frac{\sqrt{p^2}}{k} \right)^n}$$

Orthopositronium decay and new physics

Orthopositronium:

-- electron-positron bound state of spin=1
It cannot decay in 2 photons => main decay rate is in 3 photons =>
lifetime (~150 ns) longer than the corresponding spin 0 state (parapositronium)



-- It is a "clean" bound state of pure leptons => non strong interaction,
only electromagnetic

Standard decay:
oPs --> 3 γ

-- In fact, there is also a little of weak interactions

$$\boxed{\Gamma(o\mathrm{Ps} \rightarrow \nu\,\overline{\nu}) < 10^{-17}\Gamma_{3\gamma}}$$

This is so small than any measurable invisible decay mode would be an indication of new physics such as

-- Invisible decay into (infinite) extradimension

-- Other possibilities are:
Mirror World: Invisible decay through photon mirror-photon mixing,
Invisible decay into millicharged particles
……

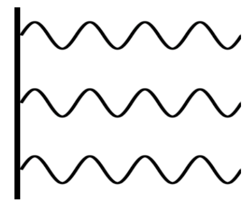
See, e.g.,
A. Badertscheret al.,
Phys. Rev. D75 (2007).

The goal is $$\boxed{\Gamma_{\mathrm{invisible}} = 10^{-8}\Gamma_{3\gamma}}$$

Orthopositronium decay in the extra dimensions

Orthopositronium decay into the extra dimensions (n=2)

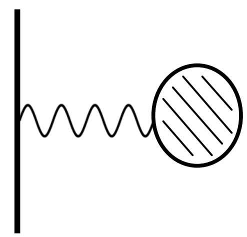
$$\frac{\Gamma(o\mathrm{Ps} \to \text{extra dim})}{\Gamma(o\mathrm{Ps} \to 3\gamma)} \simeq 1.2 \times 10^5 \left(\frac{m_{o\mathrm{Ps}}}{k}\right)^2 < 10^{-8}$$



Standard decay:
oPs --> 3 γ

This implies the bound
n=2 => k ~ 1 TeV
comparable to the bounds from Lep and Z decay width

For n>2 the bound is very weak (n=3 => k>20GeV).
From Z decay width: k> 100 GeV for any n



Non-standard decay:
oPs --> γ* –> extra dim

REFERENCES

Gninenko, Krasnikov, Rubbia, **Phys.Rev.D67 (2003);**

A. Badertscheret al., **Phys. Rev. D75 (2007);**

Proceedings of the 2005 APS April Meeting,
http://meetings.aps.org/link/BAPS.2005.APR.T12.7;

Proceedings of the2006Joint APS/JPSMeeting,
http://tabletop.icepp.s.u-tokyo.ac.jp/invisi/jps2006Hawaii.pdf;

Plasmon decay into the extra dimensions

The different photon polarizations in a plasma behave like massive particles with mass ~ ω_{pl}

They can decay into the extra dimensions.

We found

$$\boxed{\Gamma_{\mathrm{ED}} \simeq \omega_{\mathrm{pl}} \left(\frac{\omega_{\mathrm{pl}}}{k}\right)^n}$$

n = number of extra compact dimensions

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

We can now compute the energy loss and consider what that would imply for different stars.

The strongest impact would be for Red Giant stars:
The energy loss through photon decay into the extra-dimensions would delay the ignition of helium in the core of a RG. The new energy-loss rate must not exceed the standard loss through plasmon decay by more then a factor of 2-3.

Plasmon decay into the extra dimensions and stars

From RG stars
Delay of the He-flash

$$k \gtrsim 108\, M_W \left(\frac{M_W}{\omega_{\rm pl}}\right)^3 \simeq 10^{21}\,\mathrm{TeV} \qquad \text{n=1}$$

$$k \gtrsim 10\, M_W \left(\frac{M_W}{\omega_{\rm pl}}\right) \simeq 10^{6}\,\mathrm{TeV} \qquad \text{n=2}$$

$$k \gtrsim 5\, M_W \left(\frac{M_W}{\omega_{\rm pl}}\right)^{1/3} \simeq 10^{2}\,\mathrm{TeV} \qquad \text{n=3}$$

The goodness of our result depends on the huge ratio between the weak scale and the plasma frequency

Our bounds imply that to keep the scales in the model close to the electroweak scale one either needs a large (n=4 or more) number of extra dimensions, or to arrange for an additional binding mechanism for the photon

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From HB stars
(observed number ratio of HB/RG stars) we find comparable results

From SN87A
Neutrino signal from SN87A

$$k \gtrsim 10^{14}\,\mathrm{TeV} \qquad \text{n=1}$$

$$k \gtrsim 10^{4}\,\mathrm{TeV} \qquad \text{n=2}$$

$$k \gtrsim 30\,\mathrm{TeV} \qquad \text{n=3}$$

Comments on the oPs experiment

A terrestrial experiments sensitive to the invisible decay modes of the orthopositronium should have the following sensitivities in order to provide an analogous bound on k

$\mathrm{BR} < 2 \times 10^{-24+1.75\,n}$	for RG stars
$\mathrm{BR} < 2 \times 10^{-26+2.5\,n}$	for HB stars
$\mathrm{BR} < 2 \times 10^{-15-1.5\,n}$	for SN87A

-- Our analysis shows that, for n=2, the sensitivity for the BR in the o-Ps experiment should improve by about 13 orders of magnitude to be competitive with the astrophysical bounds. The SN bound requires at least 8 orders of magnitude better sensitivity for the BR than the present sensitivity of the oPs experiment, for any n

-- The experiment can sill be interesting to test other physics beyond the standard model such as mirror world, millicharged particles etc.

Conclusions

-- Stars offer a variety of interesting environments to test physics beyond the standard model

-- Bounds from astrophysics can be much better than the experimental bounds.

-- The models which try to confine the photon on the brane through gravity only are severely constrained by stellar evolution considerations. In this case, the sensitivity required in the oPs experiment to provide the same bound is beyond any possibility in the near future.
Our result is that the number of extra compact dimensions must be 4 or greater, in order to keep the scale of extradimensions close to the electroweak scale.

-- The sensitivity of the oPs experiment to standard-mirror photon coupling is getting close to the cosmological and astrophysical bounds