Stars and Fundamental Physics*

Georg G. Raffelt

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany

Abstract. Stars are powerful sources for weakly interacting particles that are produced by nuclear or plasma processes in their hot interior. These fluxes can be used for direct measurements (e.g. solar or supernova neutrinos) or the back-reaction on the star can be used to derive limits on new particles. We discuss two examples of current interest, the search for solar axions by the CAST experiment at CERN and stellar-evolution limits on the size of putative large extra dimensions.

1 Introduction

Astrophysics and cosmology provide a natural testing ground for virtually any new idea in the area of elementary particle physics. Usually one may first think of the early universe or perhaps high-energy cosmic rays when searching for astrophysical arguments in favor or against a new particle-physics model. However, there are a number of interesting cases where the low energies available in stars are quite sufficient for rather useful and restrictive tests of high-energy physics phenomena.

The basic idea is very simple. Stars are powerful sources for weakly interacting particles such as neutrinos, gravitons, hypothetical axions, and other new particles that can be produced by nuclear reactions or by thermal processes in the hot stellar interior. The solar neutrino flux is now routinely measured with such precision that compelling evidence for neutrino oscillations has accumulated. The measured neutrino burst from supernova (SN) 1987A has been used to derive many useful limits. Even when the particle flux can not be measured directly, the absence of visible decay products, notably x- or γ-rays, can provide important information. The properties of stars themselves would change if they lost too much energy into a new channel. This "energy-loss argument" has been widely used to constrain a long list of particles and particle properties. All of this has been extensively reviewed [1,2] and is now widely appreciated among particle physicists [3].

Therefore, instead of reviewing once more the general ideas I will rather focus on two topical examples of current interest that nicely illustrate the overall methods. One is the search for solar axions by the CAST experiment at CERN (Sec. 2). The other is the possibility that space-time has large extra dimensions. This hypothesis predicts a "tower" of graviton modes that can be produced in

* Prepared for the Proceedings of the ESO-CERN-ESA Symposium on Astronomy, Cosmology and Fundamental Physics (4–7 March 2002, Garching, Germany).

stars, notably in SN cores or neutron stars. The most restrictive limits on the size of the extra dimensions arises from the astrophysical arguments presented in Sec. 3. A brief summary and outlook is given in Sec. 4.

2 Axion-Like Particles

Axions are hypothetical particles that are predicted in the context of a theoretical scheme to solve the CP problem of strong interactions [4,5]. This is the problem that quantum chromodynamics (QCD) ought to violate the CP symmetry in that the neutron should have a large electric dipole moment, contrary to experimental evidence. This observation can be explained by a new symmetry, the Peccei-Quinn symmetry, that is spontaneously broken at some large energy scale f_a, the Peccei-Quinn scale or axion decay constant. Axions are the "almost" Nambu-Goldstone bosons of this new symmetry and as such nearly massless.

Phenomenologically one should think of axions as the neutral pion's little brother. Model-dependent details aside, the axion's mass and couplings are given by those of the π^0, scaled with f_π/f_a where $f_\pi = 93$ MeV is the pion decay constant. The axion decay constant f_a is a free parameter and thus can be very large. Therefore, axions can be very light and very weakly interacting even though they are fundamentally a QCD phenomenon.

There are other plausible solutions of the strong CP problem. However, the Peccei-Quinn approach is particularly elegant and predicts something new—in the guise of axions it provides a handle for a possible experimental verification. Moreover, axions can play the role of the cosmic cold dark matter [6]. Therefore, two fundamental problems would be solved by the existence of one new particle.

The experimental search for axions has focused on their predicted interaction with the electromagnetic field that would be of the form

$$\mathcal{L}_{a\gamma\gamma} = \tfrac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \widetilde{F}^{\mu\nu}\, a = -g_{a\gamma\gamma} \mathbf{E}\cdot\mathbf{B}\, a\,, \tag{1}$$

where F is the electromagnetic field-strength tensor, $\widetilde{F}$ its dual, and $\mathbf{E}$ and $\mathbf{B}$ the electric and magnetic fields, respectively. The coupling strength is

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a} C_\gamma, \qquad C_\gamma = \frac{E}{N} - 1.92 \pm 0.08\,, \tag{2}$$

where E/N is the ratio of the electromagnetic and color anomalies, a model-dependent ratio of small integers. One popular case is the DFSZ model where $E/N = 8/3$, another the KSVS model where $E/N = 0$, but there are more general examples [7].

Assuming $m_a = 0.60\ \text{eV} \times 10^7\ \text{GeV}/f_a$ for the axion mass, Fig. 1 shows $g_{a\gamma\gamma}$ as a function of m_a. The diagonal band marked "Axion Models" is somewhat arbitrarily delimited by the DFSZ and KSVZ models. The role of axions or axion-like particles is frequently assessed in the full two-dimensional $g_{a\gamma\gamma}$-m_a-space rather than the narrow band defined by conventional axion models, although this band remains the best-motivated location in this parameter space.

The electromagnetic interaction allows for the two-photon decay $a \to \gamma\gamma$ with a rate $\Gamma_{\rm decay} = g_{a\gamma\gamma}^2 m_a^3/64\pi$. This process is very slow if the axion mass is small and the coupling strength is weak. Therefore, it is more promising to consider the analogous process where one of the photons is virtual, i.e. an external electric or magnetic field. The $a \leftrightarrow \gamma$ conversion in the presence of an external E or B field is known as the Primakoff process; it was first considered for neutral pions half a century ago [8].

If axions are the galactic dark matter, they can be detected in the laboratory by the "haloscope" technique [9]. One places a tunable high-Q microwave cavity in a strong magnetic field and measures the power output. If the resonance frequency matches m_a, the Primakoff-conversion can produce a measurable signal. Two pilot experiments [10,11] and a first full-scale search [12,13] exclude a range of coupling strength shown in Fig. 1 that is marked "Haloscope." The new generation of experiments in Livermore [13] and Kyoto [14] should cover the dashed area in Fig. 1, perhaps leading to the discovery of axion dark matter.

In a different region of masses and couplings axions are detectable with a related technique called the "helioscope" [9,16]. Thermal photons in the solar

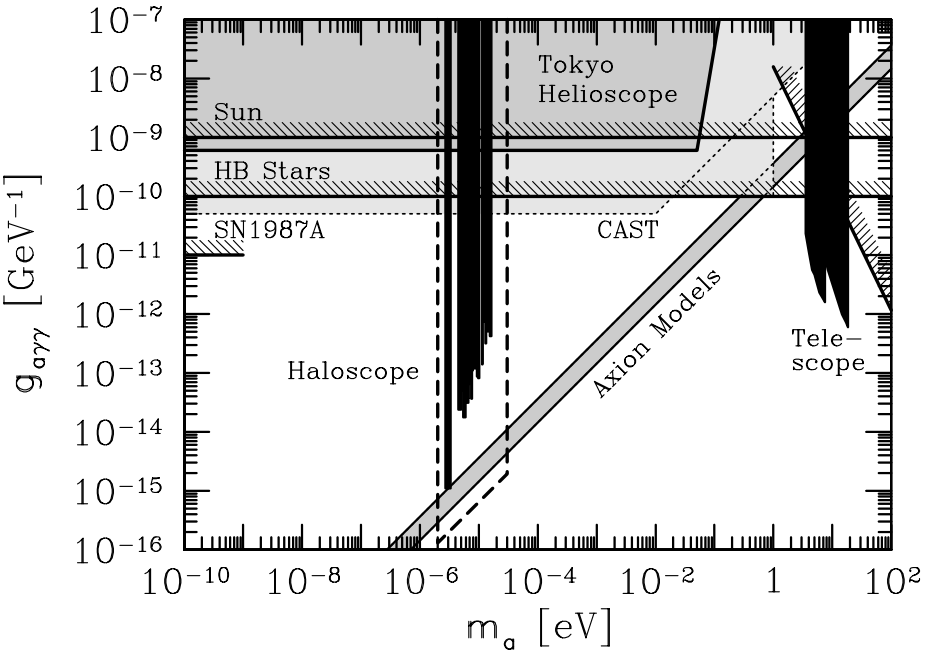

Fig. 1. Limits on the axion-photon coupling $g_{a\gamma\gamma}$ as a function of axion mass m_a. The limits apply to any axion-like particle except for the "haloscope" search which assumes that axions are the galactic dark matter; the dotted region marks the projected sensitivity range of the ongoing full-scale searches. Limits for higher masses than shown here are reviewed in Ref. [15]. The light-grey region marks the foreseen CAST sensitivity.

interior convert to axions by the Primakoff process in the microscopic electric fields of charged particles, producing a solar axion flux which peaks at energies of a few keV. If one views the Sun through a long dipole magnet, the axions partially back-convert into photons and become visible as x-rays at the far end of the magnet. A dedicated search for this effect by the Tokyo Axion Helioscope [17] excludes the dark-grey region in Fig. 1.

The conversion rate in the helioscope scales quadratically with the length L and field-strength B of the conversion region. Therefore, one can do much better in the new CAST project at CERN where a de-commissioned LHC test magnet is used as a "magnetic telescope" to search for solar axions [18,19]. Mounted on a movable platform (Fig. 2) allowing $\pm 40^\circ$ horizontal and $\pm 5^\circ$ vertical tracking, this instrument can achieve about 33 full days of alignment with the Sun per year. If we express the coupling strength as $g_{a\gamma\gamma} = g_{10}\,10^{-10}$ GeV^{-1}, the solar axion flux at Earth is $g_{10}^2\,3.5\times10^{11}$ cm^{-2} s^{-1}. The conversion probability in the magnet is $g_{10}^2\,1.8\times10^{-17}(B/8.4\,\mathrm{T})^2(L/10\,\mathrm{m})^2$. For the two magnet bores with a cross section of 2×14 cm^2 we thus expect an x-ray event rate of $15\,g_{10}^4$ per day of exposure time.

In order to reach the sensitivity shown as a light-grey area in Fig. 1 one needs to make great efforts to suppress background counts. One way is to focus the x-rays to a small detector region. Specifically, an engineering model for the seven x-ray telescopes of the Abrixas satellite has become available for this purpose and has been tested to be in good working condition. CAST should be able to take first data shortly, i.e. in the summer or fall of 2002.

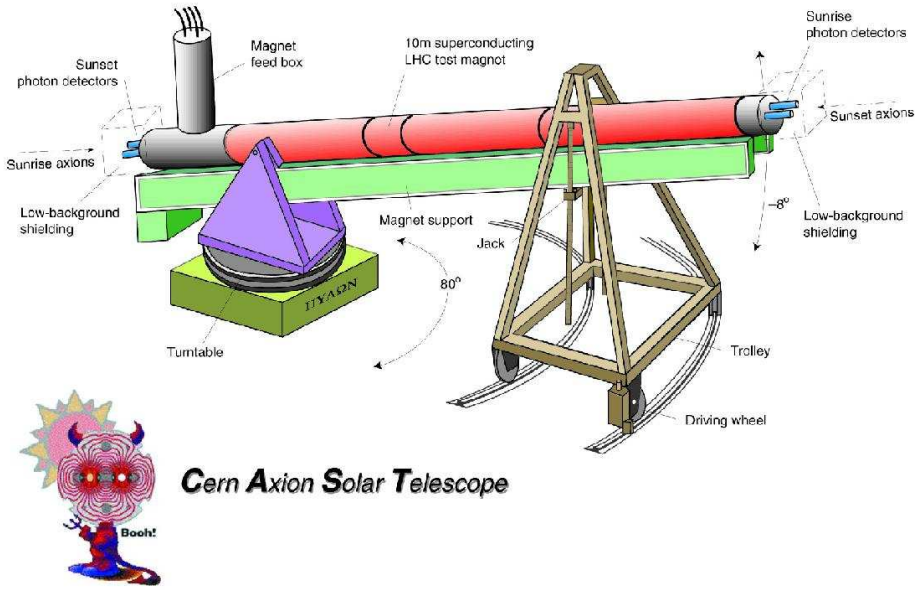

Fig. 2. Schematic view of the CAST experiment at CERN.

Figure 1 shows a loss of sensitivity for about $m_a > 10$ meV. The axion-photon conversion should be pictured as a phenomenon similar to neutrino oscillations [20]. For larger m_a the oscillation length becomes shorter than the magnet and the effective mixing angle is suppressed. This "momentum mismatch" between axions and photons can be overcome by giving the photons a refractive mass by virtue of a low-Z gas such as helium. This approach was successfully employed in the Tokyo Helioscope [17] and will be used in CAST as well. We may extend the sensitivity range to larger masses as shown in Fig. 1 and in the neighborhood of $m_a \sim 1$ eV actually bite into the parameter range of conventional axion models.

At somewhat larger masses axions are already ruled out by a telescope search for spectral lines from $a \to \gamma\gamma$ decay in galaxy clusters [21]. In the few-eV mass range axions would have been in thermal equilibrium in the early universe and contribute a small hot-dark matter component.

If we use the Sun as an axion source we must be sure that our sensitivity range is not excluded by an excessive modification of stellar properties by the axionic energy loss. An observable modification of the solar p-mode frequencies excludes $g_{a\gamma\gamma}$ values above the horizontal line in Fig. 1 marked "Sun" [22]. Significantly smaller couplings are excluded because the energy-loss of horizontal-branch (HB) stars would shorten their helium-burning lifetime, reducing the relative number of HB stars observed in globular clusters [1,2]; see the horizontal line in Fig. 1 marked "HB Stars." The CAST experiment advances into uncharted territory.

For very small axion masses, however, the CAST sensitivity range is already excluded by an argument involving SN 1987A. Axions would have been produced in the hot SN core by the Primakoff effect, and then would have back-converted into γ-rays in the galactic magnetic field. The non-observation of a γ-ray burst in the SMM instrument in coincidence with the observed SN 1987A neutrinos excludes $g_{a\gamma\gamma}$ values above the line marked SN 1987A [23,24]. This limit applies only for about $m_a < 10^{-9}$ eV; for larger masses the conversion is suppressed by the mass difference relative to photons.

The magnetically induced transition from photons to axion-like particles in intergalactic space has been proposed as a mechanism that would make distant photon sources look dimmer, with important consequences for the interpretation of the SN Ia Hubble diagram [25,26,27,28,29]. The relevant masses are very small, again to avoid suppressing the transition by a large axion-photon mass difference. Therefore, the relevant $g_{a\gamma\gamma}$ range is limited by the SN 1987A argument and thus falls outside the CAST sensitivity range.

3 Large Extra Dimensions

The Planck scale of about 10^{19} GeV, relevant for gravitation, is very much larger than the electroweak scale of about 1 TeV of the particle-physics standard model. A radical new approach to solving this notorious hierarchy problem holds that there could be large extra dimensions, the main idea being that the standard-model fields are confined to a 3+1 dimensional brane embedded in a higher

dimensional bulk where only gravity is allowed to propagate [30,31,32,33,34]. This concept immediately puts stringent constraints on the size of the extra dimensions because Newton's law holds at any scale which has thus far been observed, i.e. down to about 1 mm. Extra dimensions can only appear at a smaller scale.

Following common practice the new dimensions are taken to form an n-torus of the same radius R in each direction. The Planck scale of the full higher dimensional space, $M_{\mathrm{P},n+4}$, can be related to the normal Planck scale,[1] $M_{\mathrm{P},4} = 1.22 \times 10^{19}$ GeV, by Gauss' law [30]

$$M_{\mathrm{P},4}^2 = R^n M_{\mathrm{P},n+4}^{n+2}. \tag{3}$$

Therefore, if R is large then $M_{\mathrm{P},n+4}$ can be much smaller than $M_{\mathrm{P},4}$. If this scenario is to solve the hierarchy problem then $M_{\mathrm{P},n+4}$ must be close to the electroweak scale, i.e. $M_{\mathrm{P},n+4} < 10$–100 TeV. This requirement already excludes $n = 1$ because $M_{\mathrm{P},n+4} \simeq 100$ TeV corresponds to $R \simeq 10^8$ cm. However, $n \geq 2$ remains possible, and particularly for $n = 2$ there is the intriguing perspective that the extra dimensions could be accessible to experiments probing gravity at scales below 1 mm.

The most restrictive limits on $M \equiv M_{\mathrm{P},n+4}$ obtain from supernovae and neutron stars. The first example is the SN 1987A energy-loss argument. If large extra dimensions exist, the usual 4D graviton is complemented by a tower of Kaluza-Klein (KK) states, corresponding to new phase space in the bulk. These KK gravitons would be emitted from the SN core after collapse by nucleon bremsstrahlung $N + N \to N + N + \mathrm{KK}$. The KK gravitons interact with the strength of ordinary gravitons and thus are not trapped in the SN core. However, this energy-loss channel can compete with neutrino cooling because of the large multiplicity of KK modes and shorten the observable signal [36,37,38,39]. This argument has led to the tight bound $R < 0.66$ μm ($M > 31$ TeV) for $n = 2$ and $R < 0.8$ nm ($M > 2.75$ TeV) for $n = 3$ [39].

The KK gravitons emitted by all core-collapse SNe over the age of the universe produce a cosmological background of these particles. Later they decay into all standard-model particles which are kinematically allowed; for the relatively low-mass modes produced by a SN the only channels are $\mathrm{KK} \to 2\gamma$, e^+e^- and $\nu\bar{\nu}$. The relevant decay rates are $\tau_{2\gamma} = \frac{1}{2}\tau_{e^+e^-} = \tau_{\nu\bar{\nu}} \simeq 6 \times 10^9 \ \mathrm{yr}\,(m/100\ \mathrm{MeV})^{-3}$ [33]. Therefore, over the age of the universe a significant fraction of the produced KK modes has decayed into photons, contributing to the diffuse cosmic γ-ray background observed by EGRET. This argument implies that if the number of extra dimensions $n = 2$ or 3, their radius R must be about a factor of 10 smaller than implied by the SN 1987A cooling limit, i.e. for $n = 2$ one finds $R < 0.9 \times 10^{-4}$ mm or $M \geq 84$ TeV. For $n = 3$ the new limit is $R < 0.19 \times 10^{-6}$ mm or $M > 7$ TeV [40].

This, however, is not the end of the story. We later realized that the KK gravitons emitted by the SN core will stay gravitationally trapped because most

[1] Some authors define the Planck mass as $M_{\mathrm{P},4} = 1.22 \times 10^{19}\ \mathrm{GeV}/(8\pi)^{1/2} = 2.4 \times 10^{18}$ GeV. Limits on $M_{\mathrm{P},n+4}$ in this system of units have been reviewed in Ref. [35].

of them are produced near their kinematical threshold, i.e. with barely relativistic velocities [41]. Therefore, every neutron star is surrounded by a halo of KK gravitons which is dark except for the decays into $\simeq 100$ MeV neutrinos, e^+e^- pairs and γ-rays. In principle, this radiation can be directly observed. Conversely, the non-observation allows one to set stringent limits. In addition, the radiation impinges on the neutron star, keeping it hot, above the observed temperature in some cases such as the pulsar PSR J0953+0755. One obtains the limit $M > 1680$ TeV for $n = 2$ and $M > 60$ TeV for $n = 3$. In view of these limits one expects that if large extra dimensions solve the hierarchy problem, their number n should probably exceed 4.

Similar arguments can be applied to other particles than gravitons that may exist and may be able to propagate in the bulk of the larger-dimensional space. The hypothetical majorons are one case in point [42].

Of course, there are loop holes to such limits. The size of the extra dimensions need not be equal, or there can be other than toroidal compactifications. The KK gravitons may be able to decay fast into invisible channels, and so forth. However, our main point is that straightforward astrophysical arguments lead to non-trivial and restrictive limits on the structure of this new theory.

4 Summary and Outlook

Stars continue to provide some of the most restrictive limits on new particle-physics ideas. The much-discussed hypothesis that our space-time has extra dimensions that are compactified on the sub-millimeter scale is a recent case in point. In addition to deriving limits, there are opportunities for new discoveries. The CAST experiment at CERN searching for solar axions will have a sensitivity range that for the first time pushes beyond stellar-evolution limits and thus has a realistic chance of actually finding axion-like particles emitted by the Sun.

In future the observation of solar neutrinos will continue to provide valuable information. The ongoing efforts in neutrino physics virtually guarantee that large detectors will operate for many years to come; even a megatonne detector may be built to search for proton decay and to perform precision measurements at laboratory neutrino beams. Therefore, chances are that one will measure the neutrino burst from a galactic supernova, providing high-statistics information both on the SN event and a host of information of particle physics interest.

The recent excitement about the possible discovery of strange-matter stars [43], even though not conclusive, illustrates that compact stars offer one of the few opportunities to discover the true ground state of nuclear matter.

Astroparticle physics is now an established research activity at the interface between inner space and outer space. The physics and observationd of stellar objects continue to offer a number of intriguing opportunities in this multi-faceted and interdisciplinary field.

Acknowledgements

This work was partly supported by the Deutsche Forschungsgemeinschaft under grant No. SFB 375 and the ESF network Neutrino Astrophysics.

References

1. G.G. Raffelt: *Stars as Laboratories for Fundamental Physics* (Chicago University Press, Chicago, 1996)
2. G.G. Raffelt: "Particle physics from stars," Ann. Rev. Nucl. Part. Sci. **49**, 163 (1999).
3. D.E. Groom et al. (Particle Data Group): "Review of particle physics," Eur. Phys. J. C **15**, 1 (2000).
4. J.E. Kim: "Light pseudoscalars, particle physics and cosmology," Phys. Rept. **150**, 1 (1987).
5. H.Y. Cheng: "The strong CP problem revisited," Phys. Rept. **158**, 1 (1988).
6. E.W. Kolb and M.S. Turner: *The Early Universe* (Addison-Wesley, Redwood City, 1990).
7. J.E. Kim: "Constraints on very light axions from cavity experiments," Phys. Rev. D **58**, 055006 (1998).
8. H. Primakoff: "Photo-production of neutral mesons in nuclear electric fields and the mean life of the neutral meson," Phys. Rev. **81**, 899 (1951).
9. P. Sikivie: "Experimental tests of the 'invisible' axion," Phys. Rev. Lett. **51**, 1415 (1983), Erratum ibid. **52**, 695 (1984).
10. W.U. Wuensch et al.: "Results of a laboratory search for cosmic axions and other weakly coupled light particles," Phys. Rev. D **40**, 3153 (1989).
11. C. Hagmann, P. Sikivie, N.S. Sullivan and D.B. Tanner: "Results from a search for cosmic axions," Phys. Rev. D **42**, 1297 (1990).
12. S.J. Asztalos et al.: "Experimental constraints on the axion dark matter halo density," Astrophys. J. **571**, L27 (2002).
13. S. Asztalos et al.: "Large-scale microwave cavity search for dark-matter axions," Phys. Rev. D **64**, 092003 (2001).
14. K. Yamamoto et al.: "The Rydberg-atom-cavity axion search," hep-ph/0101200.
15. E. Masso and R. Toldra: "New constraints on a light spinless particle coupled to photons," Phys. Rev. D **55**, 7967 (1997).
16. K. van Bibber, P.M. McIntyre, D.E. Morris and G.G. Raffelt: "A practical laboratory detector for solar axions," Phys. Rev. D **39**, 2089 (1989).
17. Y. Inoue et al.: "Search for sub-electronvolt solar axions using coherent conversion of axions into photons in magnetic field and gas helium," Phys. Lett. B **536**, 18 (2002).
18. K. Zioutas et al.: "A decommissioned LHC model magnet as an axion telescope," Nucl. Instrum. Meth. A **425**, 482 (1999).
19. CERN Axion Solar Telescope homepage at http://axnd02.cern.ch/CAST/
20. G. Raffelt and L. Stodolsky: "Mixing of the photon with low mass particles," Phys. Rev. D **37**, 1237 (1988).
21. M.A. Bershady, M.T. Ressell and M.S. Turner: "Telescope search for multi-eV axions," Phys. Rev. Lett. **66**, 1398 (1991).
22. H. Schlattl, A. Weiss and G. Raffelt: "Helioseismological constraint on solar axion emission," Astropart. Phys. **10**, 353 (1999).

23. J.W. Brockway, E.D. Carlson and G.G. Raffelt: "SN 1987A gamma-ray limits on the conversion of pseudoscalars," Phys. Lett. B **383**, 439 (1996).
24. J.A. Grifols, E. Masso and R. Toldra: "Gamma rays from SN 1987A due to pseudoscalar conversion," Phys. Rev. Lett. **77**, 2372 (1996).
25. C. Csaki, N. Kaloper and J. Terning: "Dimming supernovae without cosmic acceleration," Phys. Rev. Lett. **88**, 161302 (2002).
26. C. Csaki, N. Kaloper and J. Terning: "Effects of the intergalactic plasma on supernova dimming via photon axion oscillations," Phys. Lett. B **535**, 33 (2002).
27. J. Erlich and C. Grojean, "Supernovae as a probe of particle physics and cosmology," Phys. Rev. D **65** (2002) 123510.
28. C. Deffayet, D. Harari, J.P. Uzan and M. Zaldarriaga: "Dimming of supernovae by photon—pseudoscalar conversion and the intergalactic plasma," hep-ph/0112118.
29. E. Mörtsell, L. Bergström and A. Goobar: "Photon axion oscillations and type Ia supernovae," astro-ph/0202153.
30. N. Arkani-Hamed, S. Dimopoulos and G. Dvali: "The hierarchy problem and new dimensions at a millimeter," Phys. Lett. B **429**, 263 (1998).
31. I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali: "New dimensions at a millimeter to a Fermi and superstrings at a TeV," Phys. Lett. B **436**, 257 (1998).
32. N. Arkani-Hamed, S. Dimopoulos and G. Dvali: "Phenomenology, astrophysics and cosmology of theories with sub-millimeter dimensions and TeV scale quantum gravity," Phys. Rev. D **59**, 086004 (1999).
33. T. Han, J.D. Lykken and R. Zhang: Phys. Rev. D **59**, 105006 (1999).
34. G.F. Giudice, R. Rattazzi and J.D. Wells: "Quantum gravity and extra dimensions at high-energy colliders," Nucl. Phys. B **544**, 3 (1999).
35. Y. Uehara: "A mini-review of constraints on extra dimensions," hep-ph/0203244.
36. S. Cullen and M. Perelstein: "SN 1987A constraints on large compact dimensions," Phys. Rev. Lett. **83**, 268 (1999).
37. V. Barger, T. Han, C. Kao and R.J. Zhang: "Astrophysical constraints on large extra dimensions," Phys. Lett. B **461**, 34 (1999).
38. C. Hanhart, D.R. Phillips, S. Reddy and M.J. Savage: "Extra dimensions, SN 1987A, and nucleon nucleon scattering data," Nucl. Phys. B **595**, 335 (2001).
39. C. Hanhart, J.A. Pons, D.R. Phillips and S. Reddy: "The likelihood of GODs' existence: Improving the SN 1987A constraint on the size of large compact dimensions," Phys. Lett. B **509**, 1 (2001).
40. S. Hannestad and G.G. Raffelt: "New supernova limit on large extra dimensions: Bounds on Kaluza-Klein graviton production," Phys. Rev. Lett. **87**, 051301 (2001).
41. S. Hannestad and G.G. Raffelt: "Stringent neutron-star limits on large extra dimensions," Phys. Rev. Lett. **88**, 071301 (2002).
42. S. Hannestad, P. Keranen and F. Sannino: "A supernova constraint on bulk majorons," hep-ph/0204231.
43. C. Seife: "If it quarks like a star, it must be ... strange?," Science **296**, 238 (2002).