Particle-Physics Constraints from Stars

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Particle-Physics Constraints from Stars

Low-mass particles (neutrinos, axions and friends, hidden photons, low-mass carriers of new forces, ...) can be probed by stars.

- Particles from the Sun and their detection
- Impact of new energy-loss channels on low-mass stars
- Supernova 1987A
- Neutron-star cooling
- Axion conversion in pulsar magnetospheres
- Superradiance of ultra-light bosons from black holes

In this lecture focus on the astrophysics of these arguments (often not so clear to particle physicists) and not so much on the latest results for all types of particles.
Evolution of Stars

\[ M \lesssim 8 M_\odot \]
\[ 1 M_\odot = 2 \times 10^{30} \text{ kg} \]

\[ M \gtrsim 8 M_\odot \]

Small Star \rightarrow Red Giant

\[ \text{Planetary Nebula} \]
\[ M \sim 0.6 M_\odot \]
\[ R \sim 5000 \text{ km} \]

\[ R \sim 12 \text{ km} \]

White Dwarf

Compact Remnants

Large Star \rightarrow Red Supergiant

\[ \text{Neutron Star} \]
\[ \text{few–tens } M_\odot \]
\[ \text{few km} \]

Stellar Cloud with Protostars

\[ \text{Supernova} \]
Evolution of Stars

Surface $T \sim \text{eV} \ (\text{IR to UV})$
Inner $T \sim 1-100 \ \text{keV}$

Surface $T \sim \text{keV}$
Nuclear density

Inner $T \sim 30 \ \text{MeV}$

Stellar Cloud with Protostars

Black Hole
Very low energies by particle-physics standards
Mostly of interest at the “intensity frontier” for
feebly interacting particles
• Neutrino physics
• Axions and relatives
• Low-mass carriers of new forces, ...
Particles from the Sun:
- Direct search
- Back-reaction on Sun

- Lifetime of HB stars in globular clusters
- Brightness of tip of red-giant branch (TRGB)
- White dwarf luminosity function
- Period decrease of variable WDs

White Dwarf
DM axion conversion in pulsar magnetosphere
Neutrino signal from SN 1987A
Core-collapse supernova
Superradiance
Cooling speed
Black Hole
Particles from the Sun

2002 Solar Neutrinos (R. Davis, M. Koshiba)
2015 Solar Nu Oscillations (A. McDonald)

Search for solar axions with CAST and future IAXO

Excess events in XENON1T DM search.
Solar axions?
arXiv:2006.09721
The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

\[ H + H = D + e^+. \]  

The deuteron is then transformed into \( \text{He}^4 \) by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

\[
\begin{align*}
\text{C}^{12} + \text{H} &= \text{N}^{13} + \gamma, \\
\text{C}^{13} + \text{H} &= \text{N}^{14} + \gamma, \\
\text{N}^{14} + \text{H} &= \text{O}^{15} + \gamma, \\
\text{O}^{15} &= \text{N}^{15} + e^+, \\
\text{N}^{15} + \text{H} &= \text{C}^{12} + \text{He}^4.
\end{align*}
\]  

No neutrinos from nuclear reactions in 1938 ...
The Possible Role of Neutrinos in Stellar Evolution

It can be considered at present as definitely established that the energy production in stars is caused by various types of thermonuclear reactions taking place in their interior. Since these reaction chains usually contain the processes of β-disintegration accompanied by the emission of high speed neutrinos, and since the neutrinos can pass almost without difficulty through the body of the star, we must assume that a certain part of the total energy produced escapes into interstellar space without being noticed as the actual thermal radiation of the star. Thus, for example, in the case of the carbon-nitrogen cycle in the sun, about 7 percent of the energy produced is lost in the form of neutrino radiation. However, since, in such reaction chains, the energy taken away by neutrinos represents a definite fraction of the total energy liberation, these losses are of but secondary importance for the problem of stellar equilibrium and evolution.

More detailed calculations on this collapse process are now in progress.

G. Gamow

University of São Paulo,
São Paulo, Brazil,
November 23, 1940.

M. Schoenberg*

*Fellow of the Guggenheim Memorial Foundation. Now in Washington, D. C.

Phys. Rev. 58:1117 (1940)
Neutrinos from the Sun

Solar radiation: 98% light (photons) 2% neutrinos
At Earth 66 billion neutrinos/cm² sec

Thermonuclear reaction chains (1938)
Hydrogen Burning

PP-I Chain:

- $^1\text{H}$ + $^1\text{H}$ → $^2\text{H}$ + $^1\text{H}$
- $^1\text{H}$ → $^2\text{He}$ + $^1\text{H}$
- $^2\text{H}$ + $^1\text{H}$ → $^3\text{He}$ + $^1\text{H}$
- $^3\text{He}$ → $^4\text{He}$ + $^1\text{H}$

- $\nu$, $\gamma$

CNO Cycle:

- $^1\text{H}$ + $^15\text{N}$ → $^14\text{N}$ + $^4\text{He}$
- $^14\text{N}$ → $^15\text{O}$ + $^1\text{H}$
- $^15\text{O}$ → $^16\text{O}$ + $^1\text{H}$
- $^16\text{O}$ + $^1\text{H}$ → $^{12}\text{C}$ + $^4\text{He}$

- $\nu$, $\nu$, $\gamma$, $\gamma$
Solar Neutrinos from Nuclear Reactions

All components of pp chains (blue) have been measured

Very recently direct experimental evidence for CNO fluxes (orange) in Borexino
Solar Neutrino Spectroscopy with Borexino

Borexino Collaboration: *Comprehensive measurement of pp-chain solar neutrinos*  
Nature 562 (2018) 505
**Thermal Neutrinos: Production Processes**

**Figure 1.** Processes for thermal neutrino pair production in the Sun.

Vitagliano, Redondo & Raffelt, arXiv:1708.02248
Solar neutrino flux at keV energies

- Thermally produced neutrinos and antineutrinos dominate at keV energies
- Future detection opportunities?

Grand Unified Neutrino Spectrum (GUNS) at Earth


Why keV energies in the solar interior?
A gravitationally bound system of many particles obeys the virial theorem

\[ 2\langle E_{\text{kin}} \rangle = -\langle E_{\text{grav}} \rangle \]

\[ 2 \left( \frac{mv^2}{2} \right) = \left( \frac{G_NM_r m}{r} \right) \]

\[ \langle v^2 \rangle \approx G_NM_r \langle r^{-1} \rangle \]

Velocity dispersion from Doppler shifts and geometric size

Total Mass

Coma Cluster

Virial Theorem – Dark Matter in Galaxy Clusters
Virial Theorem Applied to the Sun

Virial Theorem \( \langle E_{\text{kin}} \rangle = -\frac{1}{2} \langle E_{\text{grav}} \rangle \)

Approximate Sun as a homogeneous sphere with
- Mass \( M_{\text{sun}} = 1.99 \times 10^{33} \text{g} \)
- Radius \( R_{\text{sun}} = 6.96 \times 10^{10} \text{cm} \)

Gravitational potential energy of a proton near center of the sphere
\[
\langle E_{\text{grav}} \rangle = - \frac{3}{2} \frac{G_N M_{\text{sun}} m_p}{R_{\text{sun}}} = -3.2 \text{ keV}
\]

Thermal velocity distribution
\[
\langle E_{\text{kin}} \rangle = \frac{3}{2} k_B T = -\frac{1}{2} \langle E_{\text{grav}} \rangle
\]

Estimated temperature
\( T = 1.1 \text{ keV} \)

Central temperature from standard solar models
\( T_c = 1.56 \times 10^7 \text{K} = 1.34 \text{ keV} \)
Standard Solar Model: Internal Structure

Temperature

Mass density

Hydrogen
Helium

Convection

Mass fraction

\[ T \text{ (K)} \]
\[ \rho \text{ (g cm}^{-3}\text{)} \]

\[ R/R_\odot \]

\[ R_{\text{CZ}} \]

\[ 14N \]
\[ 12C \]
\[ 13C \]
Experimental Tests of the "Invisible" Axion

P. Sikivie

Physics Department, University of Florida, Gainesville, Florida 32611
(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

Primakoff effect:

Axion-photon transition in external static E or B field
(Originally discussed for $\pi^0$ by Henri Primakoff 1951)

\[
\gamma \rightarrow \alpha
\]

Pierre Sikivie:

Macroscopic B-field can provide a large coherent transition rate over a big volume (low-mass axions)

- Axion helioscope:
  Look at the Sun through a dipole magnet
- Axion haloscope:
  Look for dark-matter axions with A microwave resonant cavity
Let's point a magnet at the sun...

...and look for X-Rays!

By CAST student Sebastian Baum
LHC Magnet Mounted as a Telescope to Follow the Sun

Cern Axion Solar Telescope

CAST Movie
Searching for Solar Axions with CAST

Next Generation Axion Helioscope (IAXO)

Need new magnet w/
- Much bigger aperture: \(~1 \text{ m}^2\) per bore
- Lighter (no iron yoke)
- Bores at \(T_{\text{room}}\)

- Armengaud et al.:
  Conceptual Design of the International Axion Observatory (IAXO), arXiv:1401.3233
Physics potential of the International Axion Observatory (IAXO)
Observation of Excess Electronic Recoil Events in XENON1T

~ 150 citations

Caused by solar axions or other particles from the Sun?
Some Quick Blog Links

17 June
- Resonannes, Particle Physics Blog: **Hail the XENON excess**
  [http://resonaances.blogspot.com/](http://resonaances.blogspot.com/)
- The Reference Frame: [https://motls.blogspot.com/2020/06/xenon1t-our-excess-is-due-to-tritium.html](https://motls.blogspot.com/2020/06/xenon1t-our-excess-is-due-to-tritium.html)
- **XENON1T: our excess is due to tritium junk, axions, or magnetic neutrinos**

18 June
- CosmoQuest: **Observation of Excess Events in the XENON1T Dark Matter Experiment**

19 June
- physicsworld, Particle and nuclear
- **XENON1T may have detected something very interesting, or maybe not**
  [https://physicsworld.com/a/xenon1t-may-have-detected-something-very-interesting-or-maybe-not/](https://physicsworld.com/a/xenon1t-may-have-detected-something-very-interesting-or-maybe-not/)

22 June
- Centrales Forschungsnetz Aussergewöhnlicher Himmels-Phänomene
- **Astronomie: Observation of Excess Events in the XENON1T Dark Matter Experiment**

30 June
- ParticleBites: The high energy physics reader's digest
- **The XENON1T Excess : The Newest Craze in Particle Physics**
- AlphaGalileo
- **Observation of Excess Events in the XENON1T Dark Matter Experiment**
  [https://www.alphagalileo.org/en-gb/Item-Display/ItemId/194613](https://www.alphagalileo.org/en-gb/Item-Display/ItemId/194613)
keV-Range Energy Depositions

Nuclear recoil

Electronic recoil (ER)

Dark-matter WIMPs

Solar neutrinos with large dipole moments

Coherent scattering of 10 MeV solar neutrinos

Solar axions (keV energies)

keV-mass bosonic DM particles (ALP-like, hidden photons, ...)

Georg Raffelt, MPI Physics, Munich
Observation of Excess Electronic Recoil Events in XENON1T

**arXiv:2006.09721 (17 June 2020), accepted in PRD**

**Graphs:**

(a) Tritium

(b) Solar axion

(c) Neutrino magnetic moment
Solar Axions/ALPs

\[ g_{\gamma\gamma} \]

\[ e, I \rightarrow \gamma \rightarrow a \rightarrow \gamma \]
Primakoff

\[ \gamma \rightarrow e \rightarrow a \rightarrow e \]
Compton

\[ e \rightarrow I \rightarrow I^* \rightarrow I \]
axio-deexcitation

\[ a \rightarrow e \rightarrow a \rightarrow e \]
axiorecombination

\[ e \rightarrow I \rightarrow e - I \; \text{bremsstrahlung} \]
e - I bremsstrahlung

\[ a \rightarrow e \rightarrow a \rightarrow e \]
e - e bremsstrahlung

\[ g_{\alpha\gamma} = 5 \cdot 10^{-10} \text{ GeV}^{-1}, \quad g_{\alpha e} = 5 \cdot 10^{-12}, \quad g_{\alpha\alpha}^{\text{off}} = 2 \cdot 10^{-6} \]

\[ \Phi_{\alpha} [\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}] \]

\[ Xe \rightarrow Xe^+ \]

\[ g_{\alpha e} \]

\[ a \rightarrow e \rightarrow a \rightarrow e \]

\[ \gamma \rightarrow a \rightarrow \gamma \]

\[ XENON \text{ Collab. 2006.09721} \]

\[ \text{Dent+ 2006.15118, Gao+ 2006.14598} \]
XENON1T Results for Solar Axions/ALPs

Gao+ 2006.14598
Including Primakoff detection

XENON Collab. 2006.09721
Only axio-electric detection

XENON1T excess cannot be due to solar axions/ALPs by a large margin
Physics potential of the International Axion Observatory (IAXO)  
Summary on XENON1T Excess

Electron-recoil excess events in XENON1T (3.5 $\sigma$) can be attributed to

- Statistical fluctuation
  ("extraordinary claims require extraordinary evidence")

- Tritium contamination (~3 atoms per kg xenon)
  - strong conflict with estimated purification
  - but not proven or disproven

- Dark matter signal (MANY scenarios, e.g. keV-range hidden photons)

- Solar neutrinos with non-standard interactions

Solar axion or neutrino MDM interpretation in strong conflict with CAST and/or stellar energy-loss limits

Solar hidden photons provide poor spectral fit
Solar Axions Cannot Explain the XENON1T Excess

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We argue that the interpretation in terms of solar axions of the recent XENON1T excess is not tenable when confronted with astrophysical observations of stellar evolution. We discuss the reasons why the emission of a flux of solar axions sufficiently intense to explain the anomalous data would radically alter the distribution of certain type of stars in the color-magnitude diagram in the first place and would also clash with a certain number of other astrophysical observables. Quantitatively, the significance of the discrepancy ranges from 3.3σ for the rate of period change of pulsating white dwarfs and exceeds 19σ for the $R$ parameter and for $M_{\text{TRGB}}$.

DOI: 10.1103/PhysRevLett.125.131804

Introduction.—The XENON1T collaboration [1] has reported an excess in low-energy electronic recoil data below 7 keV and peaking around 2–3 keV. The collaboration cautions that the excess could be due to an unaccounted background from β decays due to a trace amount of tritium, but they also explore the possibility that the signal could be due to solar axions. Because the axion energy spectrum for the ABC processes, the Primakoff and $^{57}$Fe components are both allowed to be absent as long as there is a nonzero ABC component. This selects $g_{ae}$ as the crucial coupling to attempt to explain the data in terms of the QCD

and because the location of the peak around 2–3 keV corresponds roughly to the maximum of the axion energy spectrum for the ABC processes, the Primakoff and $^{57}$Fe components are both allowed to be absent as long as there is a nonzero ABC component. This selects $g_{ae}$ as the crucial coupling to attempt to explain the data in terms of the QCD
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and because the location of the peak around 2–3 keV corresponds roughly to the maximum of the axion energy spectrum for the ABC processes, the Primakoff and $^{57}$Fe components are both allowed to be absent as long as there is a nonzero ABC component. This selects $g_{ae}$ as the crucial coupling to attempt to explain the data in terms of the QCD
Equations of Stellar Structure

Assume spherical symmetry and static structure (neglect kinetic energy) 
Excludes: Rotation, convection, magnetic fields, supernova-dynamics, ... 

Hydrostatic equilibrium 
\[ \frac{dP}{dr} = - \frac{G_N M_r \rho}{r^2} \]

Energy conservation 
\[ \frac{dL_r}{dr} = 4\pi r^2 \epsilon \rho \]

Energy transfer 
\[ L_r = \frac{4\pi r^2 d(aT^4)}{3\kappa \rho} \]

Literature
• Clayton: Principles of stellar evolution and nucleosynthesis (Univ. Chicago Press 1968)
• Kippenhahn & Weigert: Stellar structure and evolution (Springer 1990)

\[ r \quad \text{Radius from center} \]
\[ P \quad \text{Pressure} \]
\[ G_N \quad \text{Newton's constant} \]
\[ \rho \quad \text{Mass density} \]
\[ M_r \quad \text{Integrated mass up to } r \]
\[ L_r \quad \text{Luminosity (energy flux)} \]
\[ \epsilon \quad \text{Local rate of energy generation [erg g}^{-1}s}^{-1}] \]
\[ \epsilon = \epsilon_{\text{nuc}} + \epsilon_{\text{grav}} - \epsilon_{\nu} \]
\[ \kappa \quad \text{Opacity} \]
\[ \kappa^{-1} = \kappa_{\gamma}^{-1} + \kappa_{c}^{-1} \]
\[ \kappa_{\gamma} \quad \text{Radiative opacity} \]
\[ \kappa_{\gamma} \rho = \langle \lambda_{\gamma} \rangle_{\text{Rosseland}}^{-1} \]
\[ \kappa_{c} \quad \text{Electron conduction} \]
Fig. 22.7. The mass values $m$ from centre to surface are plotted against the stellar mass $M$ for the same zero-age main-sequence models as in Fig. 22.1. “Cloudy” areas indicate the extension of convective zones inside the models. Two solid lines give the $m$ values at which $r$ is 1/4 and 1/2 of the total radius $R$. The dashed lines show the mass elements inside which 50% and 90% of the total luminosity $L$ are produced.

Kippenhahn & Weigert, Stellar Structure and Evolution
Self-Regulated Nuclear Burning

Virial Theorem: \[ \langle E_{\text{kin}} \rangle = -\frac{1}{2} \langle E_{\text{grav}} \rangle \]

Small Contraction
\[ \rightarrow \text{ Heating} \]
\[ \rightarrow \text{ Increased nuclear burning} \]
\[ \rightarrow \text{ Increased pressure} \]
\[ \rightarrow \text{ Expansion} \]

Additional energy loss ("cooling")
\[ \rightarrow \text{ Loss of pressure} \]
\[ \rightarrow \text{ Contraction} \]
\[ \rightarrow \text{ Heating} \]
\[ \rightarrow \text{ Increased nuclear burning} \]

Hydrogen burning at nearly fixed T
\[ \rightarrow \text{ Gravitational potential nearly fixed:} \]
\[ G_N M / R \sim \text{ constant} \]
\[ \rightarrow R \propto M \text{ (More massive stars bigger)} \]
Nuclear Binding Energy

![Graph showing binding energy per nucleon for various mass numbers.](image)

- **Fusion** indicates the process where lighter nuclei combine to form heavier ones, releasing energy.
- **Fission** shows the opposite process, where a heavy nucleus splits into two or more smaller nuclei, also releasing energy.

The graph plots binding energy per nucleon against mass number, illustrating the energy released during nuclear reactions.

- **Note change of scale** is mentioned to indicate a significant change in the y-axis, which is crucial for understanding the energy variations over the mass number range.

The diagram includes a periodic table-like grid, highlighting different isotopes and their stability status:
- **Stable** isotopes are marked in red.
- **Unstable** isotopes are marked in green.

This representation helps in visualizing the distribution of binding energy and stability across different isotopes.
Coulomb repulsion prevents nuclear reactions, except for Gamow tunneling

Tunneling probability

\[ P \propto E^{-1/2} e^{-2\pi \eta} \]

where the Sommerfeld parameter is

\[ \eta = \left( \frac{m}{2E} \right)^{1/2} Z_1 Z_2 e^2 \]

Parameterize cross section with astrophysical S-factor

\[ S(E) = \sigma(E) E e^{2\pi \eta(E)} \]

LUNA Collaboration, nucl-ex/9902004

\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2\text{p} \]
Main Nuclear Burning Stages

Hydrogen burning  \[ 4p + 2e^- \rightarrow ^4\text{He} + 2\nu_e \]
- Each type of burning occurs at a very different T but a broad range of densities
- Never co-exist in the same location

- Proceeds by pp chains and CNO cycle
- No higher elements are formed because no stable isotope with mass number 8
- Neutrinos from p \(\rightarrow\) n conversion
- Typical temperatures: \(10^7\) K (\(\sim 1\) keV)

Helium burning

\[ ^4\text{He} + ^4\text{He} + ^4\text{He} \leftrightarrow ^8\text{Be} + ^4\text{He} \rightarrow ^{12}\text{C} \]

“Triple alpha reaction” because \(^8\text{Be}\) unstable, builds up with concentration \(\sim 10^{-9}\)

\[ ^{12}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O} \]

\[ ^{16}\text{O} + ^4\text{He} \rightarrow ^{20}\text{Ne} \]

Typical temperatures: \(10^8\) K (\(\sim 10\) keV)

Carbon burning

Many reactions, for example

\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + p \text{ or } ^{20}\text{Ne} + ^4\text{He} \text{ etc} \]

Typical temperatures: \(10^9\) K (\(\sim 100\) keV)
Hydrogen Exhaustion

Main-sequence star

Hydrogen Burning

Helium-burning star

Helium Burning

Hydrogen Burning
## Burning Phases of a 15 Solar-Mass Star

<table>
<thead>
<tr>
<th>Burning Phase</th>
<th>Dominant Process</th>
<th>$T_c$ [keV]</th>
<th>$\rho_c$ [g/cm$^3$]</th>
<th>$L_\nu/L_\gamma$</th>
<th>Duration [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>$H \rightarrow He$</td>
<td>3</td>
<td>5.9</td>
<td>2.1</td>
<td>$1.2 \times 10^7$</td>
</tr>
<tr>
<td>Helium</td>
<td>$He \rightarrow C, O$</td>
<td>14</td>
<td>$1.3 \times 10^3$</td>
<td>$6.0$</td>
<td>$1.3 \times 10^6$</td>
</tr>
<tr>
<td>Carbon</td>
<td>$C \rightarrow Ne, Mg$</td>
<td>53</td>
<td>$1.7 \times 10^5$</td>
<td>8.6</td>
<td>$6.3 \times 10^3$</td>
</tr>
<tr>
<td>Neon</td>
<td>$Ne \rightarrow O, Mg$</td>
<td>110</td>
<td>$1.6 \times 10^7$</td>
<td>9.6</td>
<td>7.0</td>
</tr>
<tr>
<td>Oxygen</td>
<td>$O \rightarrow Si$</td>
<td>160</td>
<td>$9.7 \times 10^7$</td>
<td>9.6</td>
<td>$2.1 \times 10^4$</td>
</tr>
<tr>
<td>Silicon</td>
<td>$Si \rightarrow Fe, Ni$</td>
<td>270</td>
<td>$2.3 \times 10^8$</td>
<td>9.6</td>
<td>$9.2 \times 10^5$</td>
</tr>
</tbody>
</table>

$L_\gamma [10^4 L_{\odot}]$
Degenerate Stars ("White Dwarfs")

Assume temperature very small
→ No thermal pressure
→ Electron degeneracy is pressure source

Pressure \sim \text{Momentum density } \times \text{Velocity}

• Electron density \( n_e = p_F^3 / (3\pi^3) \)
• Momentum \( p_F \) (Fermi momentum)
• Velocity \( v \propto p_F / m_e \)
• Pressure \( P \propto p_F^5 \propto \rho^{5/3} \propto M^{5/3} R^{-5} \)
• Density \( \rho \propto M R^{-3} \)

Hydrostatic equilibrium

\[ \frac{dP}{dr} = -\frac{G_N M \rho}{r^2} \]

With \( dP / dr \sim -P / R \) we have

\[ P \propto G_N M \rho R^{-1} \propto G_N M^2 R^{-4} \]

Inverse mass radius relationship

\[ R \propto M^{-1/3} \]

\[ R = 10,500 \text{ km} \left( \frac{0.6 M_\odot}{M} \right)^{1/3} (2Y_e)^{5/3} \]

\( (Y_e \text{ electrons per nucleon}) \)

For sufficiently large stellar mass \( M \), electrons become relativistic

• Velocity = speed of light
• Pressure

\[ P \propto p_F^4 \propto \rho^{4/3} \propto M^{4/3} R^{-4} \]

No stable configuration

Chandrasekhar mass limit

\[ M_{Ch} = 1.457 \ M_\odot \ (2Y_e)^2 \]
Galactic Globular Cluster M55

![Image of M55 globular cluster]

![H-R diagram for M55]

M55
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)
Color-Magnitude Diagram for Globular Clusters

Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)
Color-Magnitude Diagram for Globular Clusters

- Stars with M so large that they have burnt out in a Hubble time
- No new star formation in globular clusters

Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)
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Planetary Nebulae

Hour Glass Nebula

Planetary Nebula IC 418

Helix Nebula

Eskimo Nebula

Planetary Nebula NGC 3132
## Evolution of Stars

<table>
<thead>
<tr>
<th>$M &lt; 0.08 , M_{\odot}$</th>
<th>Never ignites hydrogen $\rightarrow$ cools (&quot;hydrogen white dwarf&quot;)</th>
<th>Brown dwarf</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.08 &lt; M \lesssim 0.8 , M_{\odot}$</td>
<td>Hydrogen burning not completed in Hubble time</td>
<td>Low-mass main-sequence star</td>
</tr>
</tbody>
</table>
| $0.8 \lesssim M \lesssim 2 \, M_{\odot}$ | Degenerate helium core after hydrogen exhaustion | • Carbon-oxygen white dwarf  
• Planetary nebula |
| $2 \lesssim M \lesssim 8 \, M_{\odot}$ | Helium ignition non-degenerate | • Neutron star (often pulsar)  
• Sometimes black hole  
• Supernova remnant (SNR), e.g. crab nebula |
| $8 \, M_{\odot} \lesssim M < ???$ | All burning cycles $\rightarrow$ Onion skin structure with degenerate iron core | Core collapse supernova |
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)
Color-Magnitude Diagram for Globular Clusters

Particle emission reduces helium burning lifetime, i.e. number of HB stars

Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W. Harris, 2000)
Color-Magnitude Diagram for Globular Clusters

Color-magnitude diagram synthesized from several low-metallicty globular clusters and compared with theoretical isochrones (W. Harris, 2000)

- Asymptotic Giant
- Red Giant
- Horizontal Branch
- Main-Sequence

Particle emission reduces helium burning lifetime, i.e. number of HB stars

Particle emission delays He ignition, i.e. core mass increased
Neutrinos from Thermal Processes

These processes were first discussed in 1961–63 after V–A theory.
Brightness and Core Mass at TRGB


**Fig. 2.** Core mass at helium flash, \( M_{\text{tip}} \), and mass-coordinate of the ignition point, \( M_{\text{ig}} \), as a function of \( F_{\nu} \) for \( M = 0.80, Z = 10^{-4} \), and \( Y_0 = 0.22 \) (see Table 2).

**Fig. 3.** Absolute surface brightness as a function of core mass for the \( Z = 10^{-4} \) runs of Table 2. The curves are marked with the relevant \( F_{\nu} \) values.

Parametric study: Vary standard neutrino losses with a fudge factor \( F_{\nu} \) (\( F_{\nu} = 1 \) standard, \( F_{\nu} = 0 \) no losses at all, etc.)

- Helium ignition point (mass coordinate \( M_{\text{ig}} \))
- Core mass at ignition \( M_{\text{tip}} \)
- Bolometric brightness at ignition \( M_{\text{tip}} \)
**Particle Emission from Red-Giant Core or White Dwarf**

Large Neutrino Dipole Moment
- Requires BSM physics
- Direct coupling to EM field
- Enhances plasmon decay

\[ \gamma_{L,T} \rightarrow \bar{\nu} + \nu \]

\[ \mu_\nu < 1.5 \times 10^{-12} \mu_B \text{ (95\% CL)} \]

Axions (or friends) with direct coupling to electrons
- Bremsstrahlung emission by degenerate electrons

\[ e^- \rightarrow e^- + \alpha \]

\[ g_{ae} < 1.6 \times 10^{-13} \text{ (95\% CL)} \]

Georg Raffelt, MPI Physics, Munich
Brightness increase at He ignition by nonstandard neutrino losses (increased plasmon decay by neutrino dipole moment)

\[ \log \left( \frac{L}{L_{\text{Sun}}} \right) \quad \log(T_{\text{eff}}) \]

\[ \mu_{12} = 1 \quad \mu_{12} = 2 \quad \mu_{12} = 3 \quad \mu_{12} = 4 \quad \mu_{12} = 5 \quad \mu_{12} = 6 \quad \mu_{12} = 7 \quad \mu_{12} = 8 \quad \mu_{12} = 9 \]

\[ \text{Neutrino magnetic dipole moment} \quad [10^{-12} \mu_B] \]

Upper Red Giant Branch of Globular Clusters

Brightest red giant measures nonstandard energy loss

Beccari et al., arXiv:astro-ph/0610289

Straniero et al., arXiv:2010.03833

Viaux et al., arXiv:1308.4627
Limits on Axion-Electron Coupling from GC M5

I-band brightness of tip of red-giant branch [magnitudes]

- Uncertainty dominated by distance
- Can be improved in future (GAIA mission)

Limit on axion-electron Yukawa

\[ g_{ae} < \begin{cases} 2.6 \times 10^{-13} & (68\% \text{ CL}) \\ 4.3 \times 10^{-13} & (95\% \text{ CL}) \end{cases} \]

Mass limit in DFSZ model

\[ m_a \cos^2 \beta < \begin{cases} 9.3 \text{ meV} & (68\% \text{ CL}) \\ 15.4 \text{ meV} & (95\% \text{ CL}) \end{cases} \]


New TRGB Calibration from 22 Globular Clusters

Theoretical Prediction

Including axion losses $g_{13} = 4$ (XENON1T needs $g_{13} \sim 30$)

Metallicity [M/H]

Their final axion limit: $g_{ae} < 1.2 \times 10^{-13}$ (95% CL)
NGC 4258 hosts a water megamaser
→ Quasi-geometric distance determination
→ Among the best absolute TRGB calibrations
TRGB in Different Filters


- Upper RGB for different metallicities in different color filters
- The TRGB is practically horizontal in the (I,V−I) color-magnitude diagram (CMD)
Determinations of the Hubble Constant

Freedman et al. 2019,
ApJ 882:34

Freedman et al. 2020
ApJ 891:57
Axion Bounds from TRGB Calibrations

Bounds from “water megamaser” galaxy NGC 4258, compared with stellar evolution theory (95% CL)

\[ g_{ae} < 1.6 \times 10^{-13} \]
\[ \mu_{\nu} < 1.5 \times 10^{-12} \mu_B \]

XENON1T interpretation:

\[ g_{ae} \sim 30 \times 10^{-13} \]
\[ \mu_{\nu} \sim 20 \times 10^{-12} \mu_B \]

Updated TRGB Calibrations
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000).
ALP Limits from Globular Clusters

Helium abundance and energy loss rate from modern number counts HB/RGB in 39 globular clusters

Ayala, Dominguez, Giannotti, Mirizzi & Straniero, arXiv:1406.6053
White Dwarf Luminosity Function

Stars formed in the past Gyr

Systematic deviations between WDLFs beyond stated errors

Harris et al. (2006)
Isern et al. (2008)
DeGennaro et al. (2008)
Rowell Hambly (2011)
Miller Bertolami (2014)

Miller Bertolami, Melendez, Althaus & Isern, arXiv:1406.7712
Axion Bounds from WD Luminosity Function

Limits on axion-electron coupling and mass limit in DFSZ model:

\[ g_{ae} \lesssim 3 \times 10^{-13} \quad \text{and} \quad m_a \cos^2 \beta \lesssim 10 \text{ meV} \]

Miller Bertolami, Melendez, Althaus & Isern, arXiv:1406.7712, 1410.1677

Period Change of Variable White Dwarfs

Period change $\dot{\Pi}$ of pulsating white dwarfs depends on cooling speed

White dwarf G117–B15A

Theoretical ($k=2, \Pi=215 \text{ s}$) vs observed (Kepler et al. 2011)

$d\Pi/dt + \sigma$
$d\Pi/dt = 4.19 \times 10^{-15} \text{ s/s}$
$d\Pi/dt - \sigma$

Favored by $\dot{\Pi}$

Córsico et al., arXiv:1205.6180

White dwarf PG 1351+489

Asteroseismological model vs measured

Limited by $\dot{\Pi}$

Battich et al., arXiv:1605.07668

Isern: White dwarfs as advanced physics laboratories. The Axion case [2002.08069]

Physics potential of the International Axion Observatory (IAXO) [1904.09155]

\[ \alpha_{26} = \frac{g_{ae}^2}{4\pi} \times 10^{26} \]

All results improve with a bit of extra cooling ...
Photon Dispersion Relation in Stars

Non-relativistic plasma of electrons and nuclei

Plasma frequency

\[ \omega_P^2 = \frac{4\pi\alpha n_e}{m_e} \]

Landau damping (Cherenkov absorption on electrons)
Non-relativistic plasma of electrons and nuclei

Resonant mixing with L plasmon

Scalar or vector with mass $m < \omega_P$

Hardy & Lasenby, arXiv:1611.05852
FIG. 1. *Left panel:* Direct detection constraints at 90% C.L. on solar-generated dark photon fluxes in the parameter space of vector mass $m_{A'}$ versus kinetic mixing parameter $\epsilon$. The red (blue) line is derived from the S2-only reported data by XENON1T [8] (XENON10 [26]). Solid lines apply to a “hard” St"uckelberg mass and dashed lines show how the constraint continues for a “soft” Higgsed dark photon mass with $\epsilon' = 0.1$ and following [22]. Cooling constraints from the sun, and for HB and RG stars as labeled are derived following [6, 24]. *Right panel:* Dark photon dark matter parameter space showing the favored region from a fit to XENON1T data [9] (1$\sigma$ and 2$\sigma$ ellipses). Official limits by the XENON1T collaboration using S2 [8] and S1+S2 [9] data are shown by the solid black lines as labeled. The HB constraint (and cooling hint, dotted line) are taken from [31] and the solar and RG constraints are derived following [6, 24]; see the main text for a discussion of the latter bounds.

Particles from the Sun:
- Direct search
- Back-reaction on Sun

- Lifetime of HB stars in globular clusters
- Brightness of tip of red-giant branch (TRGB)

- White dwarf luminosity function
- Period decrease of variable WDs

- Neutrino signal from SN 1987A
- Core-collapse supernova
- Neutron Star Cooling speed
- Superradiance
- Black Hole

DM axion conversion in pulsar magnetosphere
Crab Nebula – Remnant of SN 1054
Crab Nebula – Remnant of SN 1054
The Crab Pulsar

Crab Nebula

Chandra x-ray images
Supernova Remnant in Cas A (SN 1680?)

Non-pulsar compact remnant

Chandra x-ray image
Stellar Collapse and Supernova Explosion

Main-sequence star

Hydrogen Burning

Helium-burning star

Helium Burning

Hydrogen Burning
Stellar Collapse and Supernova Explosion

Onion structure

- Degenerate iron core:
  - \( \rho \approx 10^9 \) g cm\(^{-3} \)
  - \( T \approx 10^{10} \) K
  - \( M_{Fe} \approx 1.5 \) M\(_{sun} \)
  - \( R_{Fe} \approx 3000 \) km

Helium-burning star

- Helium Burning
- Hydrogen Burning
Stellar Collapse and Supernova Explosion

Onion structure

Helium burning star

Hydrogen burning

Main-sequence star

Degenerate iron core:
\[ \rho \approx 10^9 \text{ g cm}^{-3} \]
\[ T \approx 10^{10} \text{ K} \]
\[ M_{\text{Fe}} \approx 1.5 \, M_{\text{sun}} \]
\[ R_{\text{Fe}} \approx 3000 \text{ km} \]

Collapse (implosion)
Stellar Collapse and Supernova Explosion

Newborn Neutron Star

Proto-Neutron Star
\[ \rho \sim \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3} \]
\[ T \sim 10 \text{ MeV} \]

Explosion
Stellar Collapse and Supernova Explosion

Newborn Neutron Star

~ 50 km

Gravitational binding energy

\[ E_b \approx 3 \times 10^{53} \text{ erg} \approx 17\% M_{\text{SUN}} c^2 \]

This shows up as

99% Neutrinos
1% Kinetic energy of explosion
0.01% Photons, outshine host galaxy

Neutrino luminosity

\[ L_\nu \sim 3 \times 10^{53} \text{ erg} / 3 \text{ sec} \sim 3 \times 10^{19} L_{\text{SUN}} \]

While it lasts, outshines the entire visible universe
Why No Prompt Explosion?

- 0.1 M_{sun} of iron has a nuclear binding energy ≈ 1.7 \times 10^{51} \text{ erg}
- Comparable to explosion energy

• Shock wave forms within the iron core
• Dissipates its energy by dissociating the remaining layer of iron
Supernova Delayed Explosion Scenario

- Collapse
- $\nu_e$ burst
- Kelvin-Helmholtz cooling

-radius $[\text{km}]$ vs. time after onset of collapse $[\text{sec}]$
Three Phases of Neutrino Emission

- Shock breakout
- De-leptonization of outer core layers

- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

Spherically symmetric Garching model (25 M\(_\odot\)) with Boltzmann neutrino transport
Death Watch of a Million Supergiants

- Monitoring 27 galaxies within 10 Mpc for many years
- Visit typically twice per year
- $10^6$ supergiants (lifetime $10^6$ years)
- Combined SN rate: about 1 per year

First 7 years of survey:
- 6 successful core-collapse SNe
- 1 candidate failed SN

Gerke, Kochanek & Stanek, arXiv:1411.1761
Adams, Kochanek, Gerke, Stanek (& Dai), arXiv:1610.02402 (1609.01283)
• Stalled accretion shock pushed out to $\sim 150$ km as matter piles up on the PNS
• Heating (gain) region develops within some tens of ms after bounce
• Convective overturn & shock oscillations (SASI) enhance efficiency of $\nu$-heating, finally revives shock
• Successful explosions in 1D and 2D for different progenitor masses (e.g. Garching group)
• Details important (treatment of GR, $\nu$ interaction rates, etc.)
• First self-consistent 3D studies being performed, sometimes successful explosions

→ 3D Model of Princeton Group

Adapted from B. Müller
Exploding 3D Garching Model (20 $M_{\text{SUN}}$)

Melson, Janka, Bollig, Hanke, Marek & Müller, arXiv:1504.07631
Sanduleak $-69^\circ 202$

Tarantula Nebula

Large Magellanic Cloud
Distance 50 kpc
(160,000 light years)
Sanduleak $-69\,202$

Supernova 1987A
23 February 1987

Artist’s impression
http://www.eso.org/public/images/eso1032a

Foreground Star

Supernova Remnant (SNR) 1987A

Foreground Star
30th Anniversary of SN 1987A
Feb. 12, 2017 @ u. Tokyo

[Image of the cake]

[Image of a galaxy or cosmic event]
Neutrino Signal of Supernova 1987A

Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/−54 s

Within clock uncertainties, all signals are contemporaneous
M. Nakahata’s notes after the analysis (now director of Kamioka Observatory)
Kamiokande-II Detector (2140 tons of water)

Hirata et al., PRD 38 (1988) 448
Irvine–Michigan–Brookhaven (IMB) Detector

SN 1987A

6800 m³
2002 Physics Nobel Prize for Neutrino Astronomy

Ray Davis Jr. (1914–2006)  
Masatoshi Koshiba (*1926)

“for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”
Early Lightcurve of SN 1987A

Expected bolometric brightness evolution

Expected visual brightness evolution

Neutrinos several hours before light

Adapted from Arnett et al., ARAA 27 (1989)
Do Neutrinos Gravitate?

Early light curve of SN 1987A

- Neutrinos arrived several hours before photons as expected
- Transit time for $\nu$ and $\gamma$ same (160,000 yr) within a few hours

Shapiro time delay for particles moving in a gravitational potential

$$\Delta t = -2 \int_A^B dt \Phi[r(t)]$$

For trip from LMC to us, depending on galactic model,

$$\Delta t \approx 1\text{–}5\text{ months}$$

Neutrinos and photons respond to gravity the same to within

$$1\text{–}4 \times 10^{-3}$$

Longo, PRL 60:173, 1988
Krauss & Tremaine, PRL 60:176, 1988
Interpreting SN 1987A Neutrinos

Assume

- Thermal spectra
- Equipartition of energy between $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$ and $\bar{\nu}_\tau$

Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194
Interpreting SN 1987A Neutrinos

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- Thermal spectra
- Equipartition of energy between $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$ and $\bar{\nu}_\tau$

Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194
SN 1987A Burst of Neutrino Papers

inSPIRE: Citations of the papers reporting the neutrino burst

Superluminal neutrinos in the OPERA experiment
Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal

-Kamiokande
-IMB
-Baksan

Neutrino sphere

Volume emission of new particles

Neutrino diffusion

Emission of very weakly interacting particles would “steal” energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable
Cooling Time Scale

Exponential cooling model: $T = T_0 e^{-t/4\tau}$, constant radius, $L = L_0 e^{-t/\tau}$

Fit parameters are $T_0$, $\tau$, radius, 3 offset times for KII, IMB & BST detectors

Loredo and Lamb, Bayesian analysis
astro-ph/0107260
Axion Emission from a Nuclear Medium

Axion-nucleon interaction:

$$\mathcal{L}_{\text{int}} = \frac{C_N}{2 f_a} \overline{\Psi}_N \gamma_\mu \gamma_5 \Psi_N \partial^\mu a = \frac{C_N}{2 f_a} J^A_{\mu} \partial^\mu a$$

- Interaction potential (one-pion exchange OPE often used, but too simplistic)
- In-medium coupling constants
- In-medium effective nucleon properties
- Correlation effects (static and dynamical spin-spin correlations)

→ For latest discussion see Carenza et al. arXiv:1906.11844v3 (28 May 2020)

Thermal $\pi^-$ contribute significantly (dominantly?)

SN 1987A Axion Limits from Burst Duration

  Burst duration calibrated by early numerical studies
  “Generic” emission rates inspired by OPE rates
  \( f_a \gtrsim 4 \times 10^8 \text{ GeV} \) and \( m_a \lesssim 16 \text{ meV} \) (KSVZ, based on proton coupling)

  Various correction factors to emission rates, specific SN core models
  \( f_a \gtrsim 1 \times 10^8 \text{ GeV} \) and \( m_a \lesssim 60 \text{ meV} \) (KSVZ, based on proton coupling)

- Carenza, Fischer, Giannotti, Guo, Martínez-Pinedo & Mirizzi,
  JCAP 10 (2019) 016 & Erratum [1906.11844v3]
  Beyond OPE emission rates, specific SN core models: similar to Chang et al.
  \( f_a \gtrsim 4 \times 10^8 \text{ GeV} \) and \( m_a \lesssim 15 \text{ meV} \) (KSVZ, based on proton coupling)

  Including thermal pions \( \pi^- + p \rightarrow n + a \) (factor 3 larger emission)
  \( f_a \gtrsim 5 \times 10^8 \text{ GeV} \) and \( m_a \lesssim 11 \text{ meV} \) (KSVZ, based on proton coupling)

- Bar, Blum & D'Amico, Is there a supernova bound on axions? [1907.05020]
  Alternative picture of SN explosion (thermonuclear event)
  Observed signal not PNS cooling. SN1987A neutron star (or pulsar) not yet found.
Operational Detectors for Supernova Neutrinos

- **HALO (30)**
- **SNO+ (300)**
- **LVD (400)**
- **Borexino (100)**
- **Baksan (100)**
- **Daya Bay (100)**
- **Super-K (4000)**
- **KamLAND (400)**

NovA (4000 + BKG)

MicroBooNE (17 $\nu_e$)

+ Other small detectors with some SN sensitivity

IceCube ($10^6$)

In brackets events for a “fiducial SN” at distance 10 kpc
Local Group of Galaxies

Current and most next-generation neutrino detectors sensitive out to few 100 kpc

With megatonne class (30 x SK)
60 events from Andromeda
Many large detectors online for next decades
Every year a 3% chance
I am optimistic to see more SN neutrinos!
Neutron Star Cooling

Potekhin & Chabrier: Magnetic neutron star cooling and microphysics [1711.07662]
Axion Limits from Neutron Star Cooling

Selection of pulsars at different age:

- Umeda, Iwamoto, Tsuruta, Qin & Nomoto, astro-ph/9806337

Supernova Remnant Cas A (320 years)

- Leinson, arXiv:1405.6873

Supernova Remnant HESS J1731-347 (27 kyears)

  \[ g_{an}^2 < 0.77 \times 10^{-19} \]
- Leinson, arXiv:1909.03941
  \[ g_{an}^2 < 1.1 \times 10^{-19} \]
  \[ C_n m_a \lesssim 2 \text{ meV} \]

Limits broadly comparable to SN 1987A bounds \((m_a \text{ tens of meV range})\)

- Protons superconducting – bremsstrahlung from neutrons
- Neutron-axion coupling can be very small or vanish
Cooling of Neutron Star in Cas A

Measured surface temperature over 10 years reveals unusually fast cooling rate

- Neutron Cooper pair breaking and formation (PBF) as neutrino emission process?
- Evidence for extra cooling (by axions)?

Leinson, arXiv:1405.6873
Axion Bounds from Magnetic WDs and NSs

Radio Search for Axion Dark Matter in Pulsars

See Josh Foster, 9 Oct 2020, https://indico.cern.ch/event/950670/
Radio Search for Axion Dark Matter in Pulsars

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Radio Search for Axion Dark Matter in Pulsars

See Josh Foster, 9 Oct 2020, https://indico.cern.ch/event/950670/
Two viable strategies

1. Observe isolated neutron stars in clean environments

2. Observe high density targets in messy environments

See Josh Foster, 9 Oct 2020, https://indico.cern.ch/event/950670/
Superradiance

Initially slow particle scattering in the ergoregion speeds up by extracting angular momentum and energy from the BH;

Waves similarly increase in amplitude

Particles/waves trapped in orbit around the BH repeat this process continuously

**Superradiance condition:**

Angular velocity of particle slower than angular velocity of BH horizon

\[ \frac{\omega_a}{m} < \Omega_{BH} \]

(m = magnetic quantum number)

Particles in orbits that satisfy the SR condition are amplified: “Black hole bomb”

Kinematic, not resonant condition
Black Hole Spins

Five currently measured black holes combine to set limit:

\[ 2 \times 10^{-11} > \mu_a > 6 \times 10^{-13} \text{ eV} \]
\[ 3 \times 10^{17} < f_a < 1 \times 10^{19} \text{ GeV} \]

But see Fernandez, Ghalsasi & Profumo, arXiv:1911.07862
Gravitational Wave Signals

- Transitions between levels
- Annihilations to gravitons

Arvanitaki, Baryakhtar, Dimopoulos, Dubovsky & Lasenby, arXiv:1604.03958
Direct Constraints on the Ultralight Boson Mass from Searches of Continuous Gravitational Waves


Superradiance limits from LIGO O2 all-sky search for periodic GWs

FIG. 2. 95% C.L. exclusion regions in the plane $m_b - M_{BH}$ assuming a maximum distance $d = 1$ kpc (left plot) and $d = 15$ kpc (right plot), a black hole initial adimensional spin $\chi_i = 0.998$, and three possible values for $t_{age}$: $10^3$, $10^6$, $10^8$ yr (left plot) and $10^3$, $10^{4.5}$, $10^6$ yr (right plot). The larger light gray area is the accessible parameter space. As expected, the extension of the excluded region decreases for increasing $t_{age}$ (corresponding to darker color).

See also:
Search for ultralight bosons in Cygnus X-1 with Advanced LIGO, arXiv:1909.11267
**Axions and Stars**

The diagram shows a spectrum with values ranging from $10^{15}$ to $10^{18}$ for $f_a$ and $m_{\text{Planck}}$, and from $10^{-6}$ to $10^6$ for $m_a$. The spectrum is labeled with energy units such as peV, neV, $\mu$eV, meV, eV, and GeV.

### Opportunities for detection

- **Super Radiance**
- **Black Hole**
- **Astrophysical Bounds (Energy loss of stars)**
- **IAXO Solar Axion Telescope**

**Axion conversion in neutron star magnetospheres**

Georg Raffelt, MPI Physics, Munich